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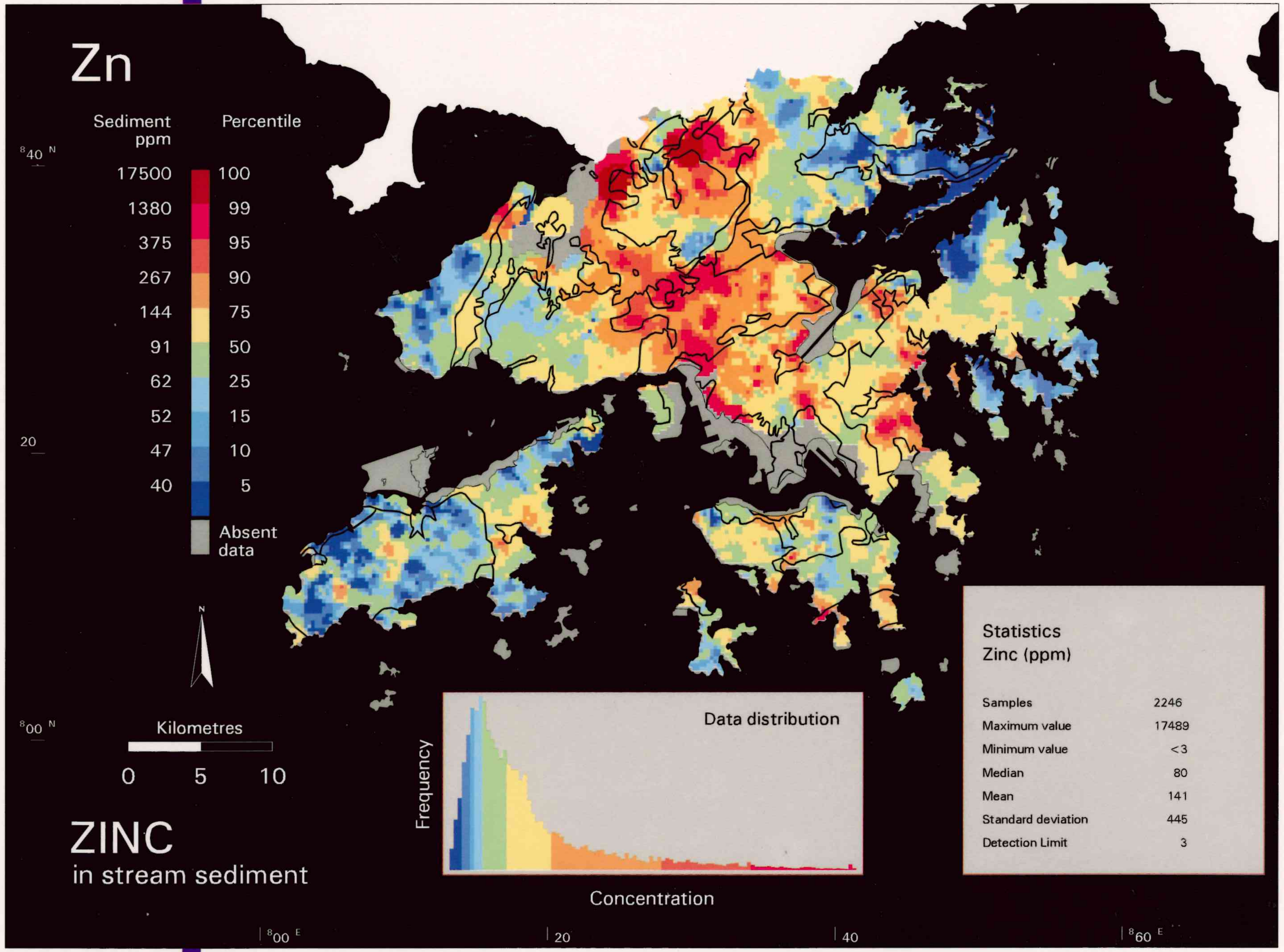
GEOCHEMICAL ATLAS OF HONG KONG



Statistics
Zinc (ppm)

Samples	2246
Maximum value	17489
Minimum value	<3
Median	80
Mean	141
Standard deviation	445
Detection Limit	3

GEOTECHNICAL ENGINEERING OFFICE
1999

GEOCHEMICAL ATLAS OF HONG KONG

R.J.Sewell

Geotechnical Engineering Office
Civil Engineering Department

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R.J. Sewell

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Geochemical image of Arsenic in stream sediment

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List of those involved in field or laboratory studies associated with this project:

Project Manager:	R.J. Sewell
BGS Liaison:	R.B. Evans (British Geological Survey)
Inception Study:	T.K. Ball (British Geological Survey)
Sample Collection:	A.E. Herdman (Herdman Geo-Services) S.J. Merrell (Herdman Geo-Services) S.K. Tse (Geo-Sense Ltd.) R. Wardall (Geo-Sense Ltd.)
Analytical Geochemistry:	B.P. Atkin (University of Nottingham) T.S. Brewer (University of Leicester)
Data and Image Processing:	P.M. Green (British Geological Survey) C.C. Johnson (British Geological Survey) G.N. Wiggans (British Geological Survey)
Element and Surface Environment Geochemistry:	N. Breward (British Geological Survey) C.C. Johnson (British Geological Survey)
Mineralogy:	E.J. Evans (British Geological Survey) N.J. Fortey (British Geological Survey) V.L. Hards (British Geological Survey)
Geology and Interpretation:	R.J. Sewell
Computing:	W.H. Ho Y.C. Leung C.B. Wong K.C. Yip
Cartography:	P.L. Chan S.W. Lam Y.L. Lee F.M. Leung
Photography:	D.L.Homer (Lloyd Homer Ltd.)

Unless otherwise stated, all those mentioned are or were employed by The Government of the Hong Kong Special Administrative Region.

Hong Kong Island View from the west looking toward Victoria Peak in the middle distance

FOREWORD

In 1993, the Hong Kong Geological Survey initiated a regional geochemical survey of Hong Kong primarily to establish the overall natural background levels of a wide range of elements for use in determining contamination criteria for offshore contaminated mud studies. The study involved the systematic collection of fine sediment and panned concentrate from all of the major streams within Hong Kong at an average sampling density of two samples per square kilometre. In addition to fulfilling the primary objective, the survey was designed to yield basic data on the distribution of trace elements in the weathering zone environment and also to indicate areas of metalliferous mineralisation. It was foreseen that this information could have many other applications, including the potential to measure the influence of man-made contamination superimposed on the natural distribution of elements controlled by the underlying geology. Other foreseen uses were with respect to environmental pollution control, such as waste management, environmental monitoring, and hazard assessment as well as geological research. Accordingly, this geochemical atlas makes the geochemical data accessible in a readable format to all parties concerned with land use planning and environmental health.

Elsewhere throughout the world, geochemical surveys have proved to be of great importance in providing basic data of direct relevance to environmental issues such as pollution detection and management, the recognition of the effects of trace element deficiency or toxicity on crops, and various aspects of human and animal health. These studies have led to improved understanding of geological processes in the surface environment, particularly in relation to waste management, and have served as an invaluable aid to geological mapping and research. In many countries, geochemical surveys have provided baseline data with respect to the determination of metalliferous mineralisation and evaluation of associated contamination.

Several members of the British Geological Survey have assisted with the production of this atlas particularly with the generation of gridded geochemical images (Wiggans & Johnson, 1996), the writing of commissioned sections of the geochemistry and surface environment behaviour of each element (Johnson & Breward, 1997), and the detailed examination study of selected panned concentrates (Fortey *et al.,* 1998). Dr T.K. Ball (formerly of the British Geological Survey) was instrumental in providing assistance on setting up the initial pilot survey, as well as giving advice on sampling methods and the choice of analytical techniques.

The Hong Kong regional geochemical survey programme was conceived and managed by Dr R.J. Sewell, who was also responsible for writing the bulk of the text and interpreting the geochemical images. Assistance was provided by Dr R.P. Martin, Mr P.G.D. Whiteside, Dr I.R. Basham (formerly Head of the Hong Kong Geological Survey 1991–94), and Dr C.J.N. Fletcher (Head of the Hong Kong Geological Survey).

R.K.S. Chan

Principal Government Geotechnical Engineer

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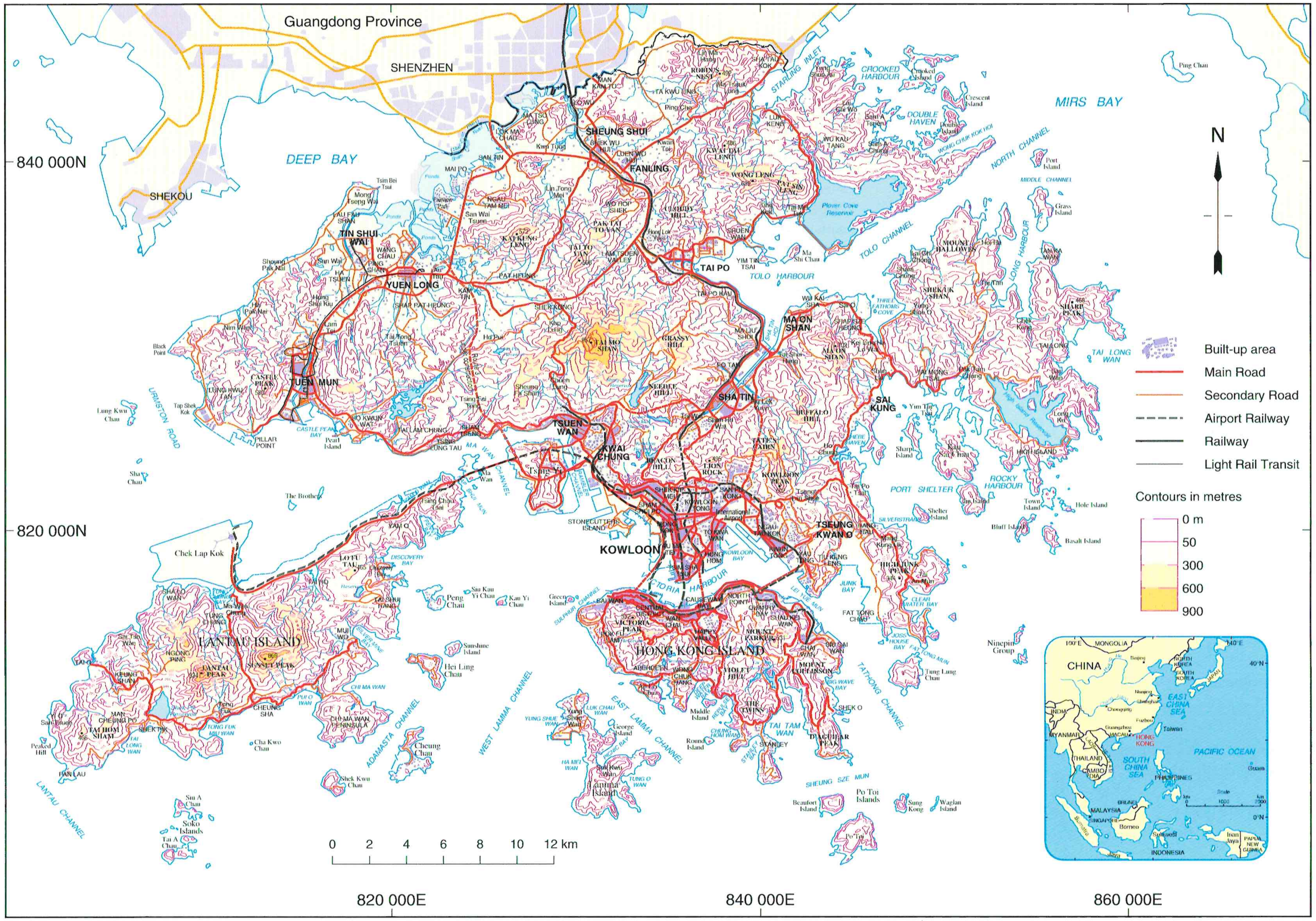


Figure 1 Topography and relief of the Hong Kong Special Administrative Region.

INTRODUCTION

The area described in this volume covers most of the Hong Kong Special Administrative Region (herein referred to as Hong Kong) including Hong Kong Island, Lantau Island, Lamma Island, Kowloon, New Territories, and several of the smaller offshore islands (Figure 1). Areas not covered by this report include Ping Chau in the northeast of Mirs Bay, Peng Chau, Hei Ling Chau, Shek Kwu Chau, Chek Lap Kok and the Soko Islands. Some 2246 sites were sampled (Figure 2) during the winters of 1993-94, 1994-95 and 1995-96 at an average density of one sample per 0.5 km^2. Where possible, sites were situated on first and second order streams.

Location and Physiography

Situated at the mouth of the Pearl River on the southeastern coast of Guangdong Province, Hong Kong has developed into one of the world's major urban communities. Its natural deep water harbour and steep, rugged topography are largely the product of a drowned river valley system which formed during an earlier period of low sea-level. The strong, northeastward trend of the major valleys and strike ridges across the area is a direct consequence of the underlying geology. The highest point is Tai Mo Shan (957 m) situated in the New Territories. Although the majority of the sediment discharge from the Pearl River is directed southwestwards past Macau, strong ebb and flow tidal channels periodically transport sediment pulses southeastwards through Hong Kong waters. The continental shelf attains a depth of 150 m at a distance of some 120 km offshore.

Sample Collection

The methods used in collecting the samples were based upon recommendations contained in a consultancy report by the British Geological Survey (Ball, 1993). Samples were collected, as far as possible, upstream of any potential source of contamination, such as concrete weirs, human habitation, tracks, or roads. A sieve set comprising a wooden dulang type pan, a coarse (2 mm) sieve and a 100 mesh (150 µm) fine sieve were employed. Sediment obtained from the middle part of the stream bed was sifted through the coarse sieve. Approximately 50 g of material finer than 150 µm was collected in the pan and transferred to a paper bag. A heavy mineral concentrate was then obtained by panning 1–2 kg of stream sediment screened through the 2 mm sieve (Plate 1).

Information on the location, site and catchment geology, contamination, land use and other features required for data interpretation was recorded on standard field forms now stored at the Hong Kong Geological Survey. The sample site location was also plotted on a field copy of the 1:10 000-scale topographic map.

Chemical Analysis

Analytical work was undertaken at two laboratories operating identical machines and software. Each sample was analysed for thirty-six elements (Figure 3) with major elements expressed in weight percent oxide (wt %) and trace elements in parts per million (ppm).

The first 625 stream sediment samples were analysed at the University of Nottingham, U.K. With the exception of Ag, Cd, Cu, Co, Mo and Se, which were carried out by inductively coupled plasma emission mass spectrometry (ICP), all the elemental concentrations reported for these samples were determined by X–ray fluorescence spectrometry (XRF). Operating conditions were 40 kV and 50 mA. Limits of detection for XRF and ICP analyses used at the University of Nottingham are shown in Table 1.

The remaining 1621 samples were analysed at the University of Leicester, U.K. Except for Ag, Cd and Se, which were measured by ICP, all the elemental data for these samples were determined by XRF. Limits of detection for XRF and ICP analyses used at the University of Leicester are shown in Table 2.

Plate 1 Sample collection. Panning of stream sediment to obtain a heavy mineral fraction.

Error Control

The accuracy and precision of the data from which the geochemical images were produced were monitored using guidelines outlined in Plant *et al.* (1975).

Sampling precision was monitored by the collection of duplicate stream sediment samples a few metres from routine sample sites at a frequency of approximately one in every 100 samples. The analysed data are presented in Appendix 1 and show that most replicate measurements fall within acceptable limits of analytical error. Those that fall outside these limits mostly remain within the same class boundaries so that the differences are not sufficient to change the colour coding on the geochemical maps (see below).

Analytical precision and accuracy were monitored using replicate measurements on a set of international laboratory reference materials. A comparison of measurements on these standards with recommended values is given in Table 3. In general, machine precision and accuracy are better than 5 % with the best precision shown by Ce, Cu, Pb, Rb, Sr, Zn, Zr, CaO and Fe_2O_3, and the poorest shown by Bi, Co, Ge, La, Sb, Sc, U and MnO.

Data and Image Processing

Data and image processing were performed at the British Geological Survey (BGS), Keyworth, using an application for handling vector-based data based on the Arc/Info Geographical Information System (GIS).

The location and geochemical data were loaded, compiled, and merged within the Hong Kong Geological Survey database, which is held on a DBASEIV database system. Data were then sent to BGS to be converted to Arc/Info compatible file format for processing using the in-house G-MAP software.

The G-MAP program, also used for the UK regional geochemical mapping programme (G-BASE), grids the geochemical data and produces coloured images with a frequency plot and percentile key. Gridding was performed using the inverse distance weighted method of interpolation with a search radius of 1500 m and

Table 1 Limits of detection for elements analysed at the University of Nottingham, U.K.

	XRF	ICP		XRF	ICP
Ag ppm	-	0.1	Nb ppm	1	-
As ppm	1	-	Ni ppm	2	-
Ba ppm	10	-	P_2O_5 wt%	0.01	-
Bi ppm	1	-	Pb ppm	2	-
CaO wt%	0.01	-	Rb ppm	1	-
Cd ppm	-	0.1	Sb ppm	1	-
Ce ppm	7	-	Sc ppm	2	-
Co ppm	2	0.1	Se ppm	-	0.2
Cr ppm	2	-	Sn ppm	1	-
Cs ppm	2	-	Sr ppm	1	-
Cu ppm	1	0.1	Th ppm	1	-
Fe_2O_3 wt%	0.01	-	TiO_2 wt%	0.01	-
Ga ppm	1	-	U ppm	1	-
Ge ppm	2	-	V ppm	2	-
Hg ppm	-	-	W ppm	1	-
La ppm	1	-	Y ppm	1	-
MnO wt%	0.01	-	Zn ppm	2	-
Mo ppm	1	0.1	Zr ppm	3	-

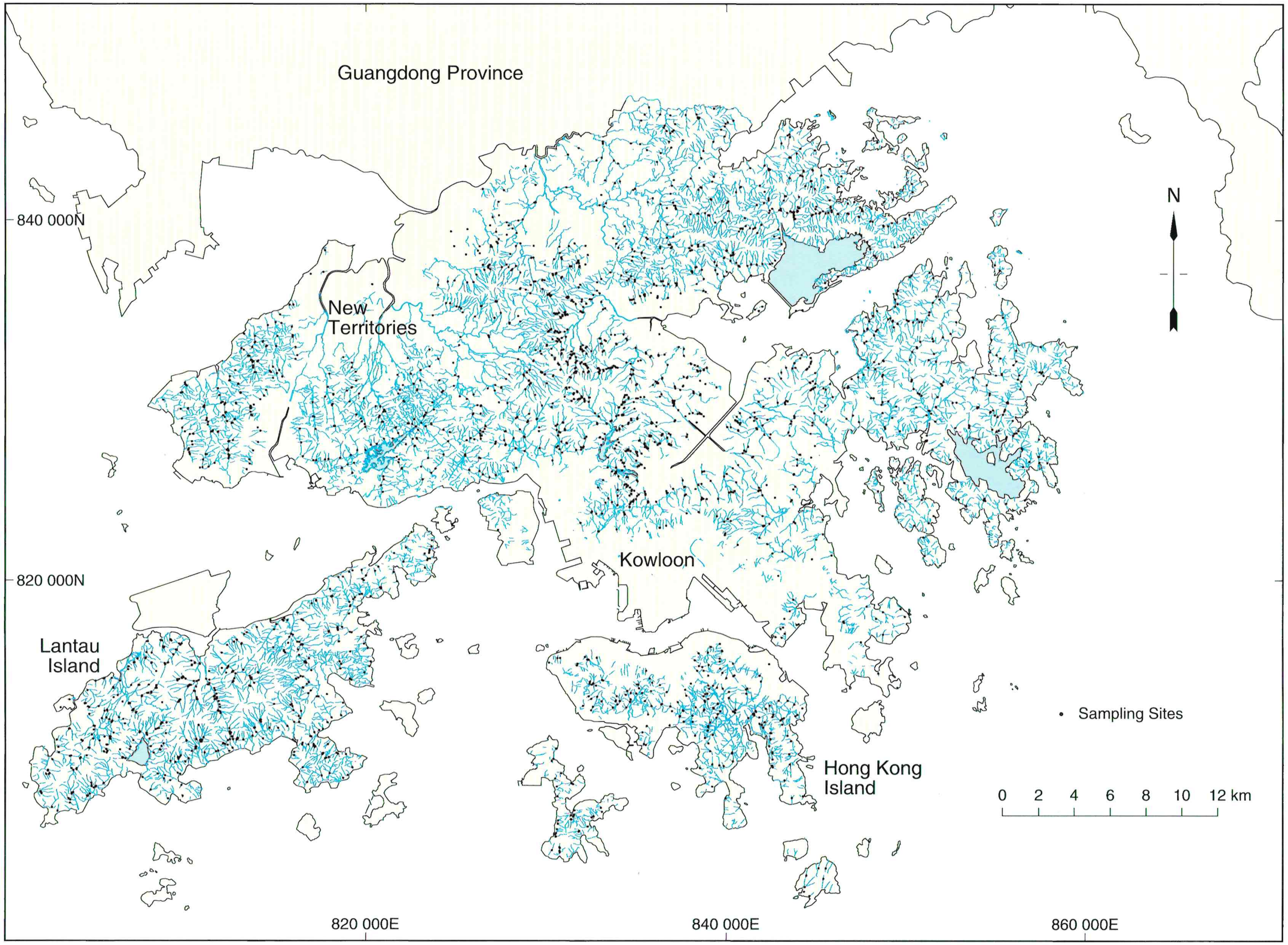


Figure 2 Drainage and sample sites.

Table 2 Limits of detection for elements analysed at the University of Leicester, U.K.

	XRF	ICP		XRF	ICP
Ag ppm	-	0.2	Nb ppm	1	-
As ppm	1	-	Ni ppm	2	-
Ba ppm	8	-	P_2O_5 wt%	0.01	-
Bi ppm	1	-	Pb ppm	2	-
CaO wt%	0.01	-	Rb ppm	1	-
Cd ppm	-	0.2	Sb ppm	1	-
Ce ppm	7	-	Sc ppm	1	-
Co ppm	3	-	Se ppm	-	0.2
Cr ppm	3	-	Sn ppm	2	-
Cs ppm	1	-	Sr ppm	1	-
Cu ppm	1	-	Th ppm	1	-
Fe_2O_3 wt%	0.01	-	TiO_2 wt%	0.01	-
Ga ppm	1	-	U ppm	1	-
Ge ppm	1	-	V ppm	2	-
Hg ppm	1	-	W ppm	2	-
La ppm	4	-	Y ppm	1	-
MnO wt%	0.01	-	Zn ppm	3	-
Mo ppm	1	-	Zr ppm	3	-

a grid cell size of 250 m. This means that the value of each grid cell is calculated using data for neighbourhood sites, but paying more attention to those which are the nearest to the grid cell and less to those farther away. The influence that a sample site has on the calculated value of any grid cell reduces as the square of its distance from the grid cell, and becomes zero when the distance is equal to 1500 m.

Single-component images

The geochemical maps in this volume are accompanied by a colour key, frequency histogram, and statistics box. The colour key and histogram describe the gridded data derived from the original point data. In calculating these parameters, all the grid cells which have a value (interpolated from the original data) are sorted into descending order and are then represented by a colour based on their position in this percentile ordering. Class boundaries are set at, or as close as possible to, the 5, 10, 15, 25, 50, 75, 90, 95 and 99 percentile levels. At the low end of the range, there may be a large number of values which are close to the detection limit and it is sometimes necessary, as in the case of Ag, to group as much as 75 % of the data into the lowest category.

The distribution of the data is often highly skewed and there is a long drawn-out tail at the high end of the concentration scale. Histograms have been truncated to omit the top few percentiles, allowing the majority of the data distribution to be viewed more easily. The cut-off point is chosen to allow enough of the tail to be seen without constricting too much the low end of the histogram. The colouring of the histogram matches that of the colour key, so approximate ppm values (ranges) can be determined from the colour key.

The statistics box presented on the images is based on data generated from within the G-MAP application. Maximum and minimum values for each element are listed along with median, arithmetic mean and standard deviation. These statistics are derived from the distribution of the sample data, whereas the histogram and class intervals used in the geochemical images are obtained from the distribution of the grid cell (pixel) data.

Three-component image

One three-component image map, also produced by G-MAP, is included on page 101. Grids for each of the three elements As, Sb and Bi, were assigned primary colours red, green and blue respectively. In each case, the highest intensity of colour reflects the highest values for each grid, whereas the lowest intensity colour reflects the lowest values. The composite map was formed by combining the three monochrome geochemical images. The concentrations of the different groups or combinations of elements can be deduced according to primary colour addition logic: red+green = yellow, red+blue = magenta, blue+green = cyan, red+green = white.

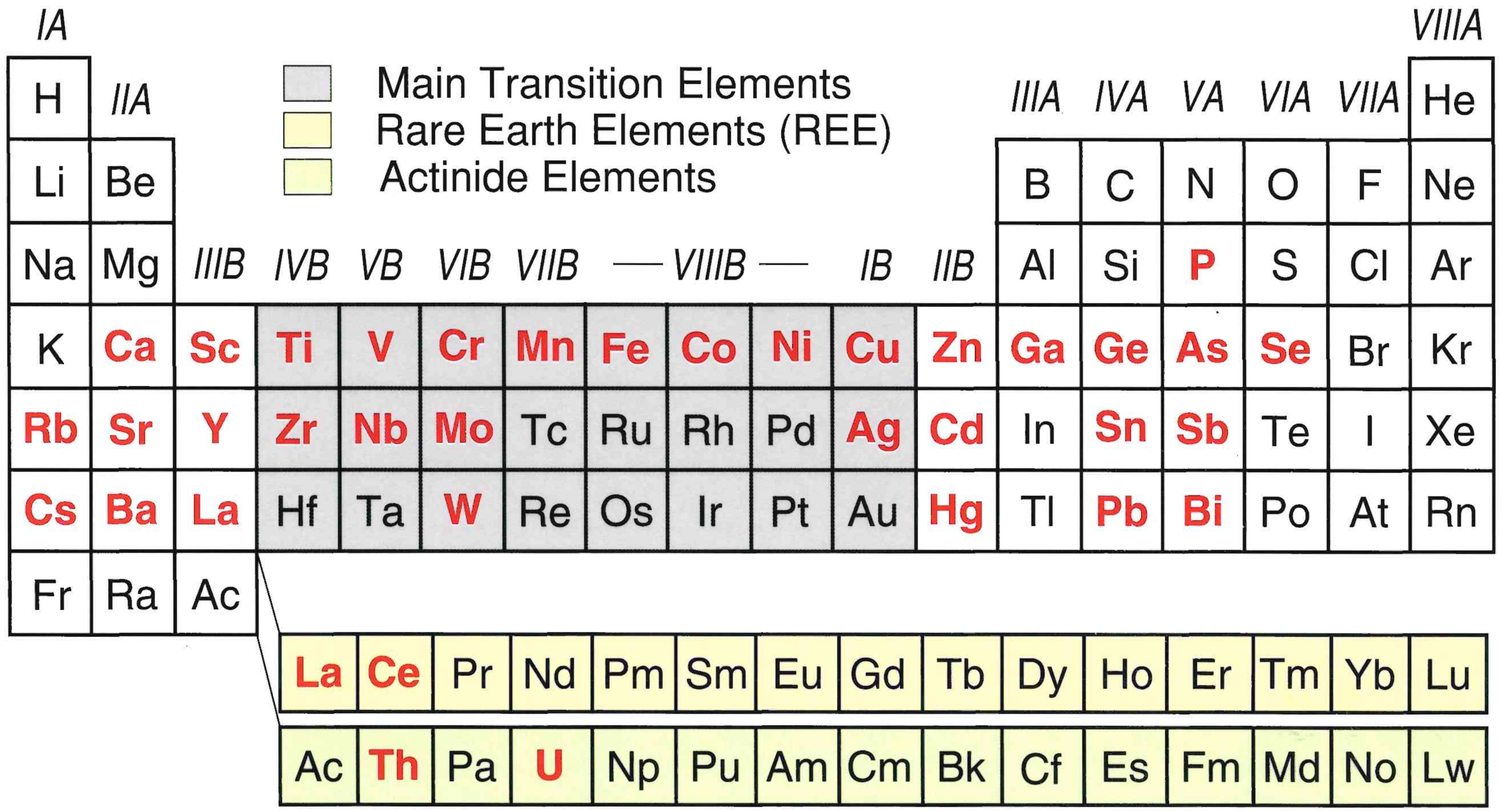


Figure 3 Periodic table of chemical elements. Elements determined in this survey are shown in red. Designation of Groups according to the Chemical Abstract Services classification.

Data Analysis

Element associations were examined by processing the raw geochemical data using SPSS® statistical software. Two statistical techniques were used; correlation analysis and factor analysis.

Correlation Analysis

A correlation matrix diagram is presented in Figure 4. Strong correlations are demonstrated by five element associations; a) Ti–Fe–V, b) La–Ce–Y, c) Nb–Th–U, d) Cu–Zn, and e) Bi–W. The Ti–Fe–V correlation is associated mainly with outcrops of the Tsuen Wan Volcanic Group and Tuen Mun Formation, whereas the La–Ce–Y correlation is mostly related to outcrops of the Kau Sai Chau Volcanic Group. The Nb–Th–U and Bi–W groupings generally identify with outcrops of highly fractionated fine-grained I-type granite (Mount Butler Granite and Chi Ma Wan Granite) and A-type granite (Chek Lap Kok Granite, Tai Lam Granite, Tsing Shan Granite and Needle Hill Granite). However, the Bi–W correlation, together with the Cu–Zn correlation, also coincide with areas of known anthropogenic contamination.

Factor Analysis

Elements with concentrations at or below the detection limit were omitted from the analysis. Five eigen factors were extracted using twenty elements, and these were rotated using the Varimax method with Kaiser normalisation. Rotation converged in six iterations. The rotated factor scores are presented in Table 4 and reveal the following element associations: a) V–Ti–Fe–Sc–Co–Se–Sr–Cd, b) Cu–Zn–P, c) La–Ce–Ni, d) Pb–Sn–Mn and e) Bi–W. The Ti–Fe–V, La–Ce, Cu–Zn and Bi–W associations identified from correlation analysis show up strongly. In addition, the results show that several other elements are related to these groupings, and that a strong association exists among Pb, Sn and Mn. The Pb–Sn–Mn association is strongest over outcrops of the Tai Po Granodiorite and in adjacent mineralised areas. These elements are also strongly correlated in several other granitic areas as well as in areas of known anthropogenic contamination.

Data Interpretation

The distribution of each element is described in relation to the major lithological and stratigraphical divisions of the district. Geological boundaries for the main rock types, based on a simplified geological map at 1:250 000 scale (Figure 5), have been superimposed on each image to assist with the interpretation of anomalies. The concentrations of related elements and the extent to which the data reflect known metalliferous mineralisation are also discussed.

The geochemical maps show the concentrations of the chemical elements (expressed as oxides for major elements) in the <150 μm fractions of stream sediment. The chemical compositions of

Table 3 Results of the analyses of international reference materials analysed with stream sediment samples, compared with their recommended (rec.) values.

	W-1 (Basalt)		**GXR-3**		**GXR-2**		**GXR-1**		**G-2 (Granite)**		**GSP-1 (Granodiorite)**		**MA-N**		**MRG-1 (Gabbro)**		**STM-1**	
Element	Rec. value	Mean	Rec. value	Mean	Rec. value	Mean	Rec. value	Mean	Rec. value	Mean	Rec. value	Mean	Rec. value	Mean	Rec. value	Mean	Rec. value	Mean
As ppm	2	1	3970	3949	25	26	427	424	0.25	3	0.10	0.00	12	11.5	0.7	0	4.6	6
Ba ppm	162	164	5000	4921	2240	2264	750	781	1882	1834	1310	1242	42	44	61	65	560	563
Bi ppm	0.04	0	6	no info.	no info.	3	1380	1375	0.04	no info.	< 1	1	no info.	7	0.13	0	0.13	0
CaO wt %	10.99	11.04	19	18.7	1.30	1.3	1.34	1.48	1.96	1.72	2.07	2.01	0.59	0.495	14.7	14.735	1.09	1.01
Ce ppm	24	24.5	18	19	51	56	17	20	160	158	399	399.5	no info.	no info.	26	27	259	260
Co ppm	47	51	46	44	8.6	6.5	8.2	10	4.6	5.5	6.6	5	1	1.5	87	85	0.9	0
Cr ppm	119	112	19	no info.	36	32	12	14	8.7	5.5	13	17	3	3	430	432	4.3	3.5
Cs ppm	0.96	0	175	171	5	1.5	3	0	1.3	1.5	1	2.5	640	638	0.57	1.5	1.5	2
Cu ppm	113	110	15	15	76	72	1110	1113	11	11	33	33	140	141	134	134	4.6	5
Fe_2O_3 wt%	11.12	10	27.2	24	2.66	3.1	33.8	34	2.66	2.63	4.29	4.28	0.47	0.45	17.94	17.56	5.22	5.51
Ga ppm	17	16	18	15	37	45	13.8	10	23	23	23	23	59	59	17	17	36	42
Ge ppm	1.7	2	110	110.5	no info.	3	no info.	6	1.14	3	1	2	3.5	6	no info.	3	1.4	1
La ppm	11	11	9	11	26	25	7.5	5	89	95	184	181	0.5	0	9.8	10	150	150
MnO wt%	0.17	0.16	2.88	2.38	0.13	0.16	0.11	0.12	0.03	0.03	0.04	0.04	0.04	0.05	0.17	0.15	0.22	0.24
Mo ppm	0.75	1	7	6	2	1.8	18	18	1.1	1	0.8	0.9	0.3	0.5	0.87	0.85	5.2	5.3
Nb ppm	9.9	8	44	45	11	11	0.8	0	12	11	27.9	31	173	174	20	20.5	268	265
Ni ppm	75	76	6	5	21	15.5	41	39	5	1.5	8.8	9	3	1.5	193	192.5	3	4.5
P_2O_5 wt%	0.13	0.14	0.25	0.27	0.24	0.19	0.15	0.12	0.14	0.15	0.28	0.17	1.39	1.4	0.08	0.07	0.16	0.13
Pb ppm	7.5	7	15	18	690	689	730	724	30	24	55	57.5	29	32	10	9.5	17.7	17.5
Rb ppm	21.4	20	92	99	78	81	14	16	170	167	254	253.5	3600	3594	8.5	9.5	118	121
Sb ppm	1.04	2	38	41	49	52	122	124	0.07	0.5	3.2	3	1.7	2.5	0.86	1.00	1.7	3
Sc ppm	35	35	16.8	17	7	6.5	1.6	3	3.5	4.5	6.2	6.5	0.2	1	55	54.5	0.6	1
Sn ppm	2.7	2.5	1.7	0	2	no info.	54	60	1.8	no info.	6.6	4.5	900	903	3.6	5.5	6.8	7.5
Sr ppm	186	186	950	956	160	160	275	273	478	479	234	236	84	82	266	265	700	712
Th ppm	2.4	2.5	2.9	0.5	8.8	11	2.4	3.5	24.7	30.5	106	99.5	1.4	0.5	0.93	1.5	31	32
TiO_2 wt%	1.07	1	0.17	0.2	0.5	0.6	0.06	0.08	0.48	0.5	0.65	0.72	0.01	0.03	3.77	3.79	0.14	0.14
U ppm	0.6	1	3	1	2.9	0.5	34.9	35	2	4	2.5	2.5	12.5	12	0.24	1.5	9	9.5
V ppm	257	254	42	46	52	50	80	76	36	35	53	53	0.2	2	526	526	8.7	4
W ppm	0.46	0	10700	10676	2	1.5	164	164	0.2	2.5	0.3	no info.	70	68.5	0.3	1	3.6	4.5
Y ppm	26	27	15	14	17	14	32	18.5	11	9.5	26	25.5	0.4	0	14	15	46	47
Zn ppm	84	82	207	212	530	500	760	752	86	83	104	105.5	220	218	191	190	235	222
Zr ppm	99	98	63	63	269	264	38	39	309	304	530	528	25	23	108	110	1210	1213

Zero values indicate that measurements were at or below the limits of detection

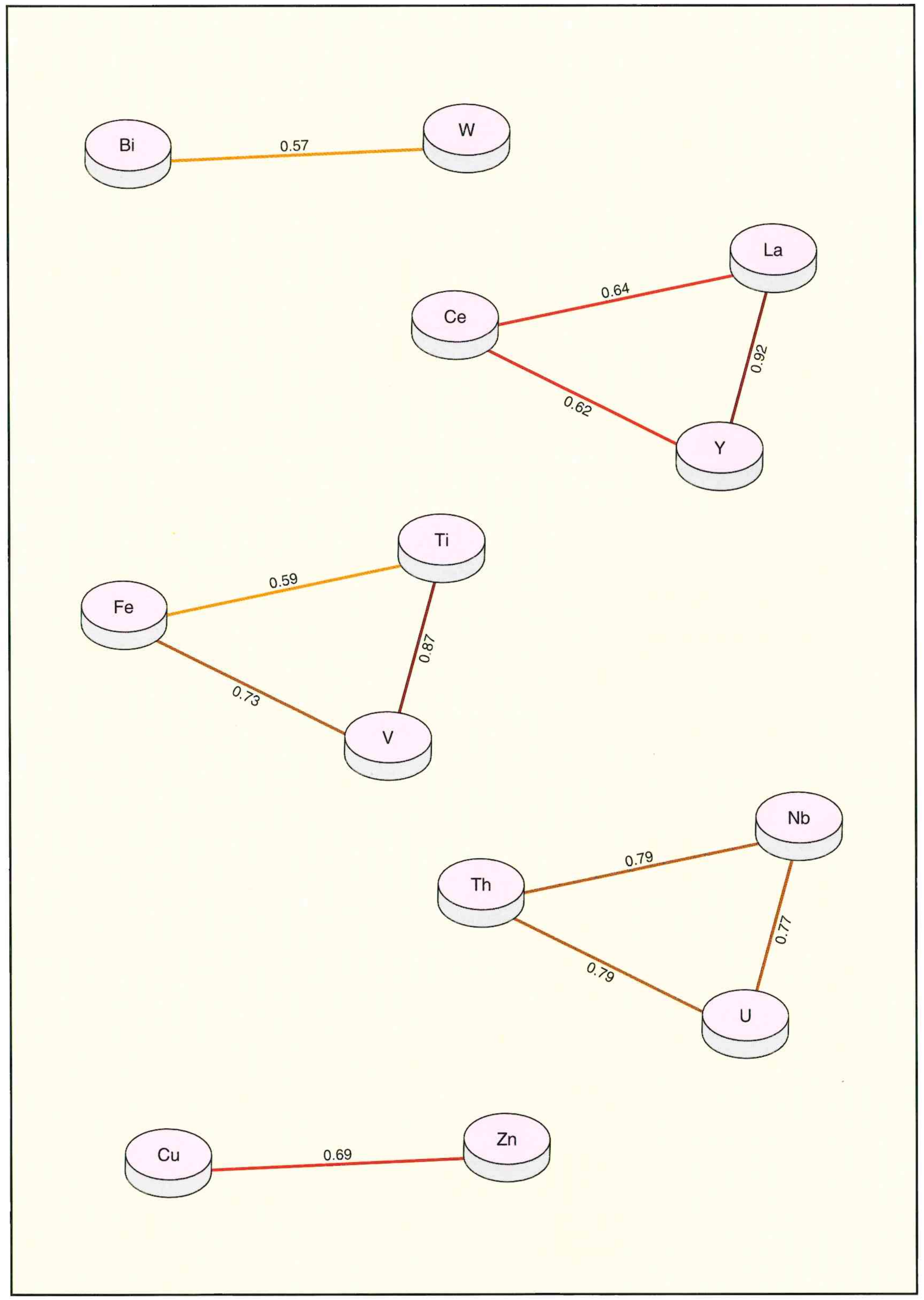


Figure 4 Correlation matrix diagram for analysed stream sediments. (Pearson correlation coefficient $r > 0.4$).

the samples generally give an indication of the composition of the dominant bedrock subject to the following conditions:

a) A small volume of a compositionally unusual rock types may have a detectable influence on the sediment chemistry downstream.

b) Chemical and physical weathering have strong influence on the derivation of stream sediment from its parent rocks. Primary rock-forming minerals such as feldspars and ferromagnesian silicates may be replaced by low temperature minerals such as clays and chlorites, and certain elements such as Ca, Mn, Fe and Sr may be mobilised in surface and ground waters. As a result, concentration of residual minerals, such as Fe–Ti oxide and zircon, may be reflected in unusually high values for Ti and Zr.

c) Stream sediment may contain material unrelated to the bedrock upstream. For example, there may be anthropogenic contamination of the stream and its catchment. This includes pollution from agriculture, industry, sewage treatment, domestic sources and illegal dumping of material. The influence of metalliferous mineralisation may also be artificially enhanced as a consequence of mining.

d) In tropical climates, heavy monsoon rain may influence the mechanical separation of coarse and fine material in fast-flowing rock channels. Elements associated with heavy minerals and resistates will be concentrated where fine material has been depleted in high energy streams. Conversely, elements associated with fine material will be enriched in low energy channels, or, more significantly, in stream sediments after the deposition of stream loads subsequent to torrential rain. Mean concentrations of elements in Hong Kong stream sediments, in the upper continental crust, and in selected igneous and sedimentary rocks, are presented in Appendix 2.

Table 4 Oblique factor scores for eigenvectors from factor analysis. Highest weightings are underlined.

Factor	1	2	3	4	5
Bi	0.042	0.034	-0.025	0.252	0.835
Ca	0.409	0.554	-0.045	0.098	-0.027
Cd	0.532	0.263	0.015	0.388	-0.075
Ce	0.022	-0.022	0.814	0.029	0.103
Co	0.719	0.185	0.177	0.067	0.046
Cu	-0.032	0.810	0.016	0.131	0.078
Fe	0.816	0.058	0.166	0.267	0.056
La	0.004	0.068	0.888	-0.020	0.030
Mn	0.449	0.010	0.194	0.540	-0.101
Ni	0.052	0.117	0.767	0.101	-0.024
P	0.206	0.713	0.236	-0.068	-0.011
Pb	0.104	0.201	0.082	0.817	0.095
Sc	0.734	-0.014	0.035	0.103	-0.031
Se	0.704	0.085	-0.030	-0.172	0.144
Sn	-0.031	0.058	-0.052	0.756	0.240
Sr	0.629	0.316	0.011	0.110	0.120
Ti	0.821	0.009	-0.082	-0.004	-0.007
V	0.915	0.068	-0.081	0.029	0.022
W	0.007	0.019	0.128	0.007	0.868
Zn	0.076	0.839	0.009	0.164	0.021

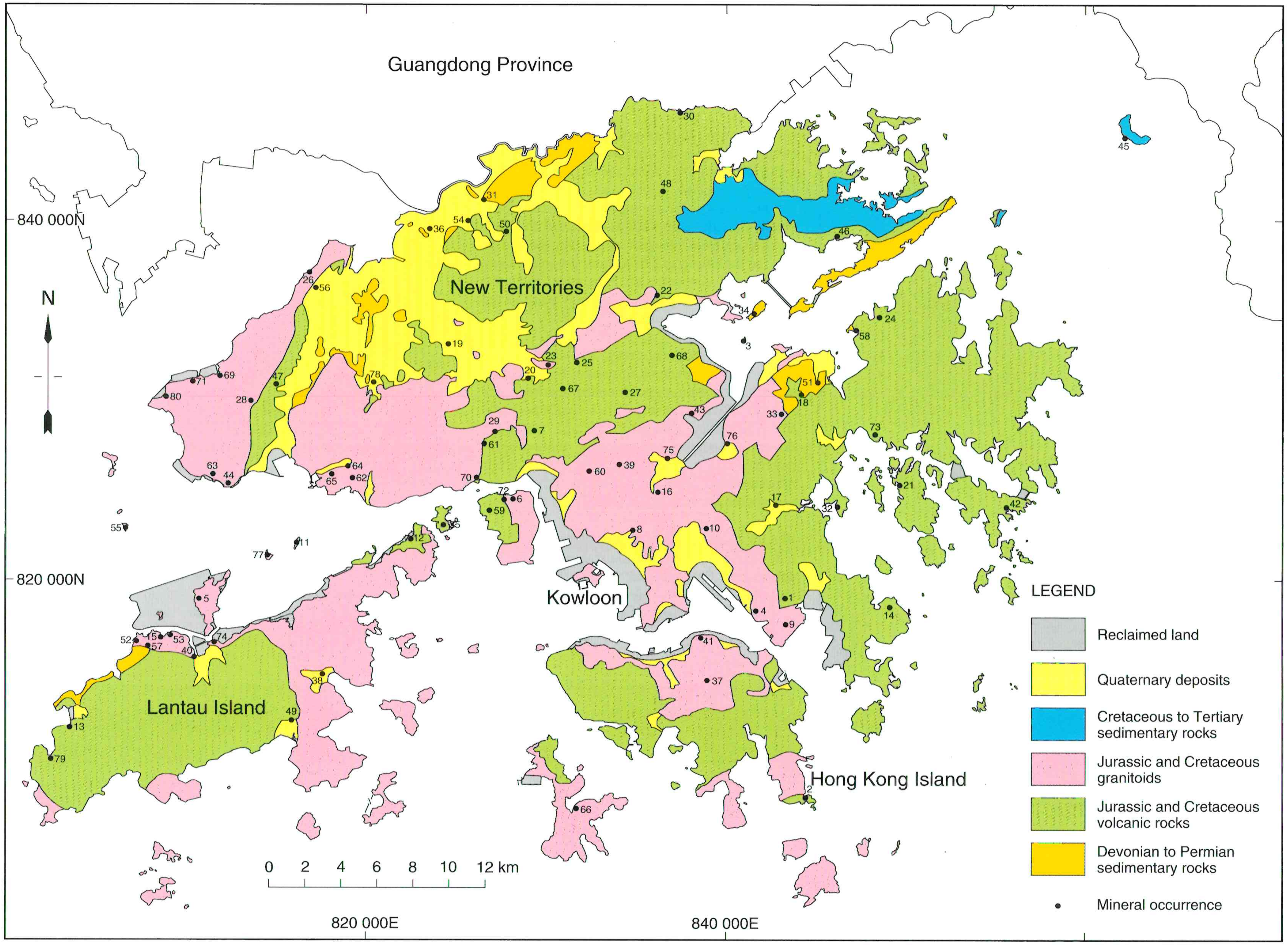


Figure 5 Simplified geological map of Hong Kong showing the main lithological boundaries used on the geochemical images and the locations of principal mineral occurrences. Details of mineral occurrences are given in Table 6.

GEOLOGY

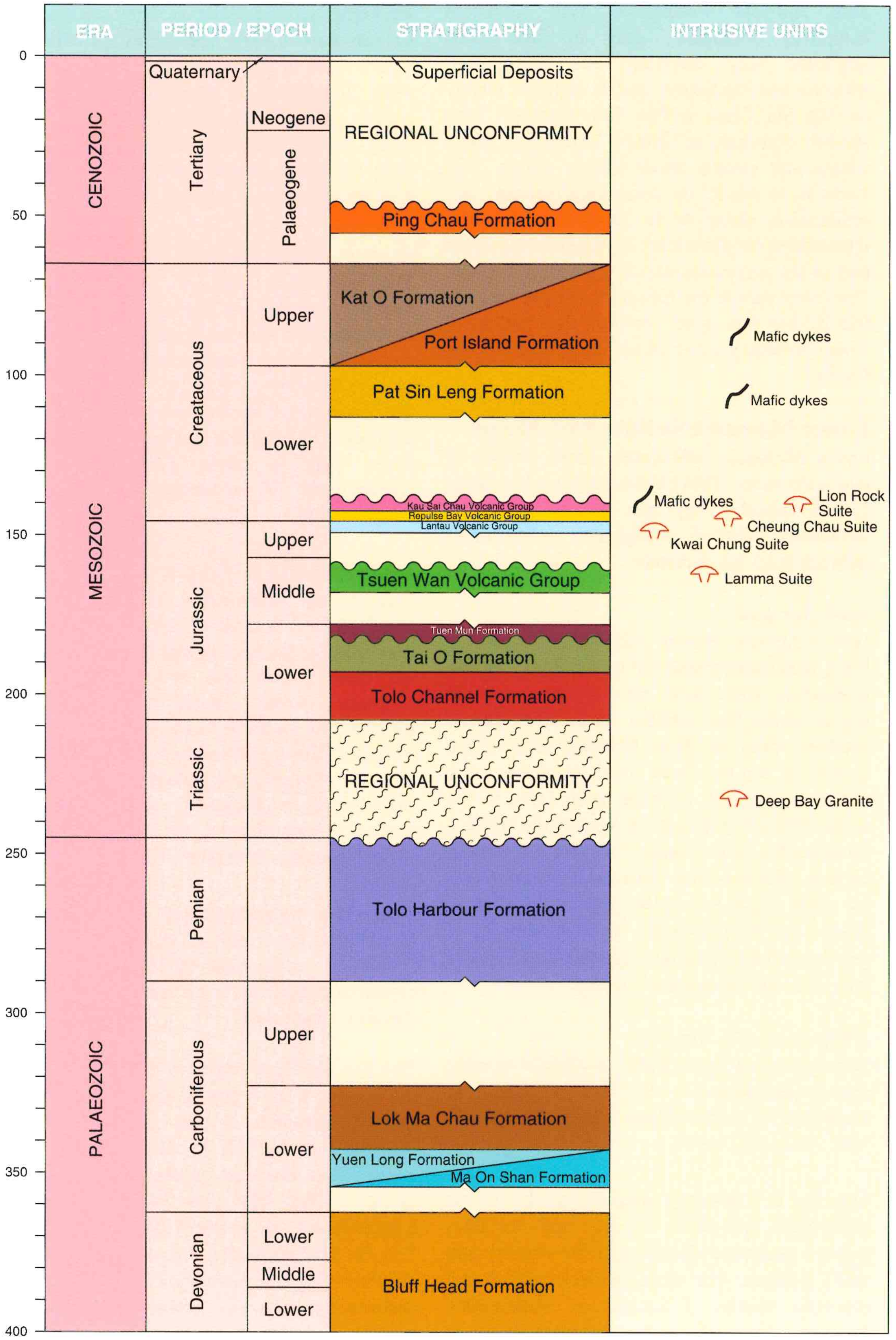


Figure 6 Simplified stratigraphic column for Hong Kong.

The geology of Hong Kong comprises a basement sedimentary succession of Devonian, Carboniferous, Permian, and Early Jurassic rocks upon which has been deposited a thick pile of Middle Jurassic to Early Cretaceous volcanic rocks accompanied by voluminous granitoid intrusions (Figure 5). The volcanic and plutonic rocks are largely responsible for the mineralisation within the district and are unconformably overlain by a relatively thin sequence of Early Cretaceous to Early Tertiary sedimentary rocks. These post-volcanic cover rocks represent the youngest lithologies exposed in the region. An impersistent mantle of Late Pleistocene to Holocene colluvial and alluvial deposits overlies the solid geology onshore. Offshore, the Quaternary deposits are thick and extensive comprising a predominantly alluvial Late Pleistocene sequence overlain by Holocene marine mud. Large reclamation projects have disturbed and concealed many of these deposits.

The stratigraphy of Hong Kong is summarised in Figure 6 and lithological relationships are illustrated on small-scale geological maps in Figures 7 and 8. Detailed descriptions of the rock units are given in published Hong Kong Geological Survey memoirs (Addison, 1986; Strange & Shaw, 1986; Langford *et al.*, 1989; Strange *et al.*, 1990; Langford *et al.*, 1995; Lai *et al.*, 1996).

Upper Palaeozoic Sedimentary and Metamorphic Rocks

Devonian

The *Bluff Head Formation* is the oldest exposed sedimentary unit in Hong Kong and crops out principally in the vicinity of Tolo Channel and Tolo Harbour (Plate 2). It comprises a non-marine to marginal marine fluvial to deltaic succession of dominantly quartz sandstone and quartzose conglomerates, with interbedded siltstone and mudstone and is in fault contact with younger rocks.

North of Tolo Channel, the succession dips steeply (60–70°) to the northwest and, in places, has been tightly folded. The quartz-rich character of the deposits together with an abundance of coarse detritus near the base of the sequence suggests that sediments were mainly derived from erosion of a nearby granitic area.

Carboniferous

Carboniferous rocks in Hong Kong are divided into three formations, two of which have only been described from boreholes. Exposed rocks of Carboniferous age are found mainly in the north and west of the region and have been assigned to the *Lok Ma Chau Formation.* These rocks comprise metamorphosed siltstone, sandstone, carbonaceous siltstone and conglomerate, and conformably overlie calcareous rocks of the *Yuen Long Formation.*

The *Yuen Long Formation* has only been detected in boreholes. At the type area in the vicinity of Yuen Long, the unit consists of a sequence of bluish grey to off-white, dolomitic marble with thin (< 1 cm) interbeds of dark grey to black siltstone. Probable correlatives of the *Yuen Long Formation* have been detected in boreholes in the Ma On Shan area (*Ma On Shan Formation*) and pods of marble have also been detected in boreholes in the vicinity of Tung Chung, Lantau Island. Fe-rich skarn is developed at the contact between granite and marble in both the Ma On Shan and Tung Chung areas. At Ma On Shan, this mineralised skarn deposit was mined for magnetite.

The *Lok Ma Chau Formation* is exposed on The Brothers islands, and in an area extending from Tuen Mun north to Lok Ma Chau in the northwestern New Territories. Bands of graphite sporadically occur within the sequence and these have been mined in several localities, the largest mine of which was on The Brothers.

Plate 2 Upper Palaeozoic sedimentary rocks. Steeply-dipping quartz sandstones and siltstones of the *Bluff Head Formation* exposed at Bluff Head, eastern New Territories.

Plate 3 Landsat Thematic Mapper (TM) natural colour (Bands 1, 2, and 3) composite image of Hong Kong produced by the British Geological Survey Remote Sensing Group.

The natural colour mosaic was computer-generated from two satellite images taken a week apart in late 1994 covering the eastern and western portions of Hong Kong. Separate contrast stretches were first taken for the land and sea areas of the western image, and then applied to the eastern image. The stretches were then compared with two earlier processed natural colour images of selected areas, filtered, and adjusted accordingly. Having defined and applied the stretch, the mosaic was formed using a slightly modified seam line with smoothing across.

The satellite image can be compared with the simplified land use map in Figure 11. The main residential, commercial and industrial areas show up as grey, whereas areas of new reclamation are brilliantly white. Mottled greenish-grey areas of northwestern New Territories consist mainly of cultivated flat land underlain by recent sediments. The dark green and brown areas of central and eastern New Territories, Hong Kong Island and Lantau Island mainly represent scrubland and woodland included within the country parks.

The straight valleys and inlets in the central and northern parts of New Territories generally follow major NE-trending faults. The most prominent of these is the Tolo Channel Fault which can be traced southwest from Tolo Channel through Sha Tin to the west of Kowloon. The strong ENE orientation of the Lantau Dyke Swarm can be distinguished in northern Lantau Island, whereas several other NNE- to NW-trending faults can also be identified. Speckled whitish green areas of western New Territories represent areas of eroded granite.

Permian

Permian rocks are found only in the vicinity of Tolo Harbour where they are represented by the *Tolo Harbour Formation*. This formation comprises dominantly grey to dark grey, laminated silty claystone and fine-grained siltstone and sandstone, and is exposed mainly on Ma Shi Chau within Tolo Harbour, with smaller exposures at Chinese University, Sham Chung and several small islands within Tolo Harbour. In places, the succession contains syn-sedimentary slump folds. Sandstone, with rare interbedded conglomerate, is present in the upper part of the succession exposed on Ma Shi Chau. The lower part of the formation contains marine fossils, but the upper part of the formation, which contains coarser clastic units, lacks marine fossils.

Lower Mesozoic Sedimentary Rocks

Lower Mesozoic sedimentary rocks outcrop in two main areas: Tolo Harbour and southwestern Lantau Island. They are divided into two formations although stratigraphic relationships between them are uncertain.

Early Jurassic

Lower Jurassic marine sedimentary rocks in Hong Kong are represented by the *Tolo Channel Formation*. These rocks are exposed on several islands within Tolo Harbour, on the northern and southern sides of Tolo Channel, and in the vicinity of Ma On Shan. Small exposures have also been mapped south of Yuen Long in the western New Territories. In the vicinity of Tolo Harbour, the *Tolo Channel Formation* is in fault contact with the *Tolo Harbour Formation* and the *Bluff Head Formation*, and is intruded by granite and rhyolite dykes. The unit consists of grey to brown, laminated siltstones and shales with rare intercalated sandy lenses.

Early to Middle Jurassic

Sedimentary rocks of Early to Middle Jurassic age are represented by the *Tai O Formation* in southwestern Lantau Island (Allen & Stephens 1971; Wu *et al.*, 1997).

The *Tai O Formation* consists chiefly of an interbedded succession of grey and red fine-grained sandstone alternating with siltstone and sandy siltstone. The strata are well bedded and generally display a variety of sedimentary structures. Sandstone is the dominant lithology and is frequently cross stratified.

Mesozoic Extrusive Rocks

Extrusive igneous rocks cover more than 50 % of the land area of Hong Kong and form much of the higher ground (Plate 3). They are mostly of Late Jurassic to Early Cretaceous age although a separate unit of dominantly andesitic rocks (*Tuen Mun Formation*) is thought to immediately predate the main eruptive period. The andesitic rocks are fault-bounded but thought to be of Early to Middle Jurassic age based on correlation with similar rocks in eastern Guangdong.

Early to Middle Jurassic

The *Tuen Mun Formation* consists chiefly of andesitic lava and tuff and is exposed as a broad N–S oriented fault-bounded band of steeply westward-dipping strata extending from Tuen Mun in the south to Hau Hoi Wan in the north. The lower part of the formation is almost entirely dominated by andesitic lava and tuff whereas the upper part is more variable containing intercalations of volcanigenic sandstone and conglomerate.

Middle Jurassic to Early Cretaceous

Calc-alkaline intermediate to silicic volcanic rocks of Late Jurassic to Early Cretaceous age dominate the geology of the Hong Kong. They are divided into four groups (Tsuen Wan Volcanic Group, Lantau Volcanic Group, Repulse Bay Volcanic Group and Kau Sai Chau Volcanic Group) (Campbell & Sewell, 1999; Table 5). Volcanic and plutonic relationships are summarised in Figure 6, and a simplified geological map showing the distribution of the various volcanic formations is given in Figure 7.

Tsuen Wan Volcanic Group

The Tsuen Wan Volcanic Group consists of five formations comprising thick successions of crystal and lapilli tuffs of dominantly dacitic to rhyolitic composition.

The *Yim Tin Tsai Formation* is the oldest unit of the Tsuen Wan Volcanic Group and consists mainly of medium or dark grey, lapilli ash to coarse ash crystal tuff. It outcrops in four main areas: Tolo Harbour, northern Lantau Island including Ma Wan and Tsing Yi, southern Lantau Island and northern Lamma Island. The *Yim Tin Tsai Formation* rests unconformably on the *Tolo Channel Formation*. Rare intercalated sedimentary horizons represent episodes of relative volcanic quiescence between major eruptive events.

Table 5 Summary of the volcanic-plutonic nomenclature and U-Pb age data for Mesozoic igneous rocks of Hong Kong. (modified after Campbell & Sewell, 1999)

VOLCANIC ROCKS			
Group		Formation	U-Pb Age (Ma)
KAU SAI CHAU VOLCANIC GROUP		High Island	140.9 ± 0.2
		Clear Water Bay	140.7 ± 0.2
		Pan Long Wan	
		Sunset Peak	
		Mang Kung Uk	
REPULSE BAY VOLCANIC GROUP	'TRACHYTIC' SUBGROUP	Che Kwu Shan	142.5 ± 0.3
		Ap Lei Chau	142.7 ± 0.2
		Ngo Mei Chau	<143.7 ± 0.1
	'RHYOLITIC' SUBGROUP	Long Harbour	142.7 ± 0.2
			142.8 ± 0.2
		Mount Davis	
LANTAU VOLCANIC GROUP		Undifferentiated	146.6 ±0.2
		Lai Chi Chong	
TSUEN WAN VOLCANIC GROUP		Sai Lau Kong	164.1 ± 0.2
		Tai Mo Shan	<164.6 ± 0.7
		Shing Mun	164.2 ± 0.3
			164.7 ± 0.3
		Yim Tin Tsai	164.5 ± 0.2
		Tuen Mun	—

GRANITOID ROCKS			
Suite		Pluton	U-Pb Age (Ma)
LION ROCK SUITE	'GRANITE' SUBGROUP	Mount Butler Granite	
		Po Toi Granite	
		Kowloon Granite	140.4 ± 0.2
		Fan Lau Granite	
		Sok Kwu Wan Granite	
	'MONZONITIC' SUBGROUP	Tei Tong Quartz Monzonite	
		Tong Fuk Quartz Monzonite	140.4 ± 0.3
		D'Aguilar Quartz Monzonite	140.6 ± 0.3
			140.6 ± 0.3
CHEUNG CHAU SUITE		Luk Keng Quartz Monzonite	
		Shan Tei Tong Rhyodacite	
		Chi Ma Wan Granite	<143.7 ± 0.2
		South Lamma Granite	
KWAI CHUNG SUITE		Sha Tin Granite	146.2 ± 0.2
		East Lantau Rhyolite	146.3 ± 0.3
		East Lantau Rhyodacite	146.5 ± 0.2
		Needle Hill Granite	146.4± 0.2
LAMMA SUITE	'A-TYPE' SUBGROUP	Tai Lam Granite	159.3 ± 0.3
		Tsing Shan Granite	<159.6 ± 0.5
		Chek Lap Kok Granite	160.4 ± 0.3
	'I-TYPE' SUBGROUP	Lantau Granite	161.5 ± 0.2
		Tai Po Granodiorite	<164.6 ± 0.2
		Deep Bay	236.3 ± 0.8

Plate 4 Lantau Volcanic Group. Rhyolite lava flows of the Lantau Volcanic Group (undifferentiated) near Ngong Ping, Lantau Island.

The *Shing Mun Formation* conformably overlies the *Yim Tin Tsai Formation* and consists of a varied assemblage of volcanic breccia, lapilli ash, coarse ash and fine ash crystal tuff, along with intercalated siltstone and mudstone. The formation crops out principally in the vicinity of the Shing Mun valley, Tai Mo Shan and Tolo Harbour, but other outcrops also occur in southern and eastern Lantau Island. The formation is commonly spatially related with the *Tai Po Granodiorite* and its heterogeneous volcanic character suggests that it could be a vent-fill facies. The abundance of volcaniclastic and epiclastic rocks in the succession also suggests accumulation close to volcanic centres. Eutaxitic coarse ash crystal tuff in southwestern Lantau Island that rests unconformably on the *Tai O Formation* is considered to belong to the *Shing Mun Formation* (Campbell & Sewell, 1999). Coarse ash crystal tuff on the south side of Tolo Channel is also now considered to belong to the *Shing Mun Formation* (Campbell & Sewell, 1999).

The *Tai Mo Shan Formation* is the most voluminous pyroclastic unit of the Tsuen Wan Volcanic Group. It is composed of dominantly pale to dark grey, lapilli ash to coarse ash crystal tuff with rare intercalated beds of tuffaceous sandstone. The formation conformably overlies the *Shing Mun Formation* and crops out in the vicinity of Tai Mo Shan and over a wide area in the northern and eastern New Territories. The widespread distribution and dominantly uniform lithological character of the *Tai Mo Shan Formation* suggest it represents the product of a number of large pyroclastic ash flow eruptions.

The *Sai Lau Kong Formation* consists of mainly dacite lavas with intercalated tuff, siltstone and sandstone. These rocks conformably overlie the *Tai Mo Shan Formation* in the northeastern New Territories near Double Haven and have an estimated minimum thickness of 300 m. The formation is thought to have been derived from a narrow NW-trending rift. Coarse tuff breccia and lapilli tuff interbeds suggest close proximity to a volcanic centre.

Lantau Volcanic Group

The Lantau Volcanic Group is confined largely to Lantau Island where it forms the main peaks in the central part of the island, but also includes variably tuffaceous sedimentary rocks and lavas on the south side of Tolo Channel in the vicinity of Lai Chi Chong (Campbell & Sewell, 1999).

On Lantau Island, the group has a maximum exposed thickness of 1500 m and is composed predominantly of lapilli-bearing coarse ash vitric tuff with subordinate rhyolite lava flows (Plate 4). Alternating crystal-rich and crystal-poor gradations within the upper part of the succession indicate these rocks were deposited as ash flows.

Repulse Bay Volcanic Group

The Repulse Volcanic Group comprises five formations which have been divided into two compositional subgroups; a rhyolitic subgroup and a trachytic subgroup (Campbell & Sewell, 1999). These are dominated by thick caldera-related successions and include both crystal and vitric tuffs, intercalated volcanigenic sedimentary rocks and sparse rhyolitic lava flows.

'Rhyolitic Subgroup'

The *Long Harbour Formation* is exposed over the northeastern part of the Sai Kung Peninsula north of the Chek Keng Fault and in the vicinity of Sai Kung (Figure 7). The formation is composed predominantly of uniform, clast-bearing coarse ash crystal tuff featuring abundant pink alkali feldspar crystals and has a minimum thickness of 400 m. West of Long Harbour, the formation rests unconformably on the *Lai Chi Chong Formation.*

The *Mount Davis Formation* is exposed in the western part of Hong Kong Island and in eastern Kowloon (Figure 7). The formation consists predominantly of coarse ash crystal tuff and has intercalations of eutaxitic fine ash tuff and volcanigenic fine sandstone. The *Mount Davis Formation* conformably overlies the *Ap Lei Chau Formation* on Hong Kong Island and in eastern Kowloon, and has geochemical affinity to the *Long Harbour Formation.*

'Trachytic Subgroup'

The *Ngo Mei Chau Formation* is juxtaposed against the *Tai Mo Shan Formation* along a NW-trending fault in the vicinity of Double Haven in the northeastern New Territories, and is exposed chiefly on Kat O Chau and Ngo Mei Chau in Mirs Bay. It comprises undifferentiated welded fine ash vitric tuff and lapilli tuff and minor intercalated sandstone and siltstone. The formation dips moderately to the northeast and has an estimated thickness of 450 m. The unit is compositionally most like the *Ap Lei Chau Formation.*

The *Ap Lei Chau Formation* crops out over a wide area on the south side of Hong Kong Island and reaches a maximum thickness of 2000 m. The formation is composed predominantly of fine ash vitric tuff and interlayered eutaxitic lithologies. Subordinate assemblages of tuff-breccia, pyroclastic breccia, tuffaceous sedimentary rock and coarse ash tuff are intercalated within the main sequence as well as discontinuous layers of epiclastic debris. The base of the formation is not exposed.

The *Che Kwu Shan Formation* consists of relatively uniform eutaxitic vitric welded tuff with rare interlayered bands of tuffaceous sedimentary rock and tuff-breccia. The formation outcrops in two main areas: eastern Hong Kong Island and Clear Water Bay. The *Che Kwu Shan Formation* consists of relatively uniform eutaxitic vitric welded tuff with rare interlayered bands of tuffaceous sediment. In the Silverstrand Bay area, the formation conformably overlies fine ash tuff of the *Ap Lei Chau Formation.* In the vicinity of Junk Bay, the formation rests conformably on coarse ash tuff of the *Mount Davis Formation.* Compositionally, the *Che Kwu Shan Formation* varies from trachyte through to alkali rhyolite.

Kau Sai Chau Volcanic Group

The Kau Sai Chau Volcanic Group is exposed mostly in the eastern New Territories, but also on Lantau Island, and consists of five formations. Fine ash vitric tuff is the dominant lithology within the group with subordinate trachydacite lava flows and tuffaceous sedimentary rocks, and minor lapilli-bearing crystal tuff and tuff-breccias.

The *Sunset Peak Formation* is restricted to the summits of Sunset Peak, Lin Fa Shan, and Lantau Peak on Lantau Island and comprises mainly lapilli-bearing crystal tuff and tuff-breccia, with minor eutaxitic fine ash vitric tuff. The formation has a minimum thickness of approximately 130 m and unconformably overlies the Lantau Volcanic Group.

The *Mang Kung Uk Formation* is exposed chiefly in the region of Mang Kung Uk village on the Clear Water Bay Peninsula, but smaller outcrops are also present in the Sai Kung Peninsula (Figure 7). On the Clear Water Bay Peninsula, the formation comprises a thick (300 m), alternating sequence of heterogeneous tuffs, tuffaceous sediments, epiclastic breccia, conglomerate, siltstone and sandstone. Impersistent rhyolite lava flows are also present but mainly confined to outcrops in the Sai Kung Peninsula.

The *Pan Long Wan Formation* consists of a thick sequence of trachydacite lava flows and tuffs exposed on Clear Water Bay Peninsula. The formation unconformably overlies the *Mang Kung Uk Formation* and crops out in two main areas: Clear Water Bay and Tai Mui Wan. It is best exposed in the southern part of Clear Water Bay Peninsula where it reaches 350 m thick. Light grey, porphyritic trachydacite lava flows are commonly separated by thick (40–50 m) bands of tuffaceous sedimentary rock.

The *Clear Water Bay Formation* comprises a sequence of banded tuffs and lava flows in the Sai Kung and Clear Water Bay peninsulas (Plate 6), and porphyritic rhyolite lava in the vicinity of Pyramid Hill and Shek Nga Shan (Figure 7). In the Clear Water Bay area, the unit conformably overlies the *Pan Long Wan Formation* whereas in the Sai Kung area, it unconformably overlies the *Mang Kung Uk Formation.* In the southern part of Clear Water Bay Peninsula, the unit comprises a heterogeneous sequence of rhyolitic tuff, tuff breccia and rhyolite lava, and is interpreted to represent a vent agglomerate. In the Pyramid Hill and Shek Nga Shan areas, the *Clear Water Bay Formation* consists of flow-banded, porphyritic rhyolite lava flows and eutaxitic crystal-bearing vitric tuff.

Plate 5 Kau Sai Chau Volcanic Group. View looking of Sharp Peak looking westward to Tai Long Wan, eastern New Territories. Sharp Peak is underlain by rhyolite lava flows of the *Clear Water Bay Formation.*

The *High Island Formation* is exposed over a large area of the Sai Kung district forming the main rock exposure on islands in Port Shelter (Figure 7). It consists entirely of massive, crystal-bearing fine ash welded tuff, displaying well-developed columnar jointing. The formation rests unconformably on fine ash tuff of the *Clear Water Bay Formation* in the vicinity of High Island west dam and reaches a maximum exposed thickness of 400 m.

Mesozoic Intrusive Rocks

With the exception of one intrusive unit in the northwestern New Territories which has returned a Triassic age (*Deep Bay Granite*), the plutonic rocks of Hong Kong are all of Middle Jurassic to Early Cretaceous age (Davis *et al.,* 1997). They belong to a broad (400 km) belt of Late Mesozoic Yanshanian intrusions passing through the maritime provinces of southeast China. A simplified geological map showing the distribution of the plutonic units in Hong Kong is given in Figure 8.

Triassic

The *Deep Bay Granite* crops out mainly offshore to the west of the Lau Fau Shan Fault in western New Territories (Figure 8). It consists of equigranular, fine- to medium-grained, leucocratic two–mica monzogranite and geochemically, is classified as a peraluminous S–type granite.

Middle Jurassic–Early Cretaceous

The Middle Jurassic to Early Cretaceous plutonic rocks of Hong Kong are divided into four main suites (Lamma Suite, Kwai Chung Suite, Cheung Chau Suite and Lion Rock Suite) based on geochemical and age relationships (Campbell & Sewell, 1999). These suites correspond in age and composition with the division of the volcanic rocks into four volcanic groups. Accordingly, the various suites of granitoids have spatial and temporal relationships with the volcanic groups.

Lamma Suite

The Lamma Suite granitoids are exposed chiefly in the northwestern parts of the Hong Kong. The suite includes a slightly older group of granitoids with dominantly I–type compositions ('I–type' subsuite; *Tai Po Granodiorite* and *Lantau Granite*), and a younger group of granitoids with dominantly A–type compositions ('A–type' subsuite; *Chek Lap Kok Granite*, *Tsing Shan Granite* and *Tai Lam Granite* (Table 5)).

The *Tai Po Granodiorite* is exposed in discontinuous outcrops across central and southern parts of Hong Kong with the largest outcrops in the central New Territories and Tsing Yi (Figure 8). The pluton is thought to have been emplaced as a large, high-level, ring-shaped intrusion centred around Tai Mo Shan, although it has been widely fragmented by subsequent intrusive and fault-related activity. The *Tai Po Granodiorite* intrudes volcanic rocks of the Tsuen Wan Volcanic Group (see previously). Lithologies are texturally variable from normal hypidiomorphic-granular granodiorite, through porphyritic microgranodiorite to densely porphyritic dacite without significant change in bulk composition.

The *Lantau Granite* forms a large, high-level, intrusion underlying much of the area in southern and western Hong Kong. The pluton crops out from Lamma Island in the east to Fan Lau on Lantau Island in the west, and from the Soko Islands in the south to Tuen Mun in the north (Figure 8). Isolated outcrops are found on many small islands including Peng Chau, Kau Yi Chau, Hei Ling Chau, Chau Keng, Sha Chau and Chek Lap Kok. The *Lantau Granite* is intruded by all known plutonic lithologies except the *Tai Po Granodiorite.*

The *Chek Lap Kok Granite* forms a subcircular pluton centred on the airport at Chek Lap Kok (Figure 8). Prior to construction of the airport, the pluton was exposed on the western half of the island Chek Lap Kok and on Lam Chau. Exposures are now confined to the area between Tin Sum and Hau Hok Wan on northern coast of Lantau Island. On the former island of Chek Lap Kok, the *Chek Lap Kok Granite* was seen to intrude *Lantau Granite*. The *Chek Lap Kok Granite* consists of an equigranular, fine-grained, leucocratic monzogranite.

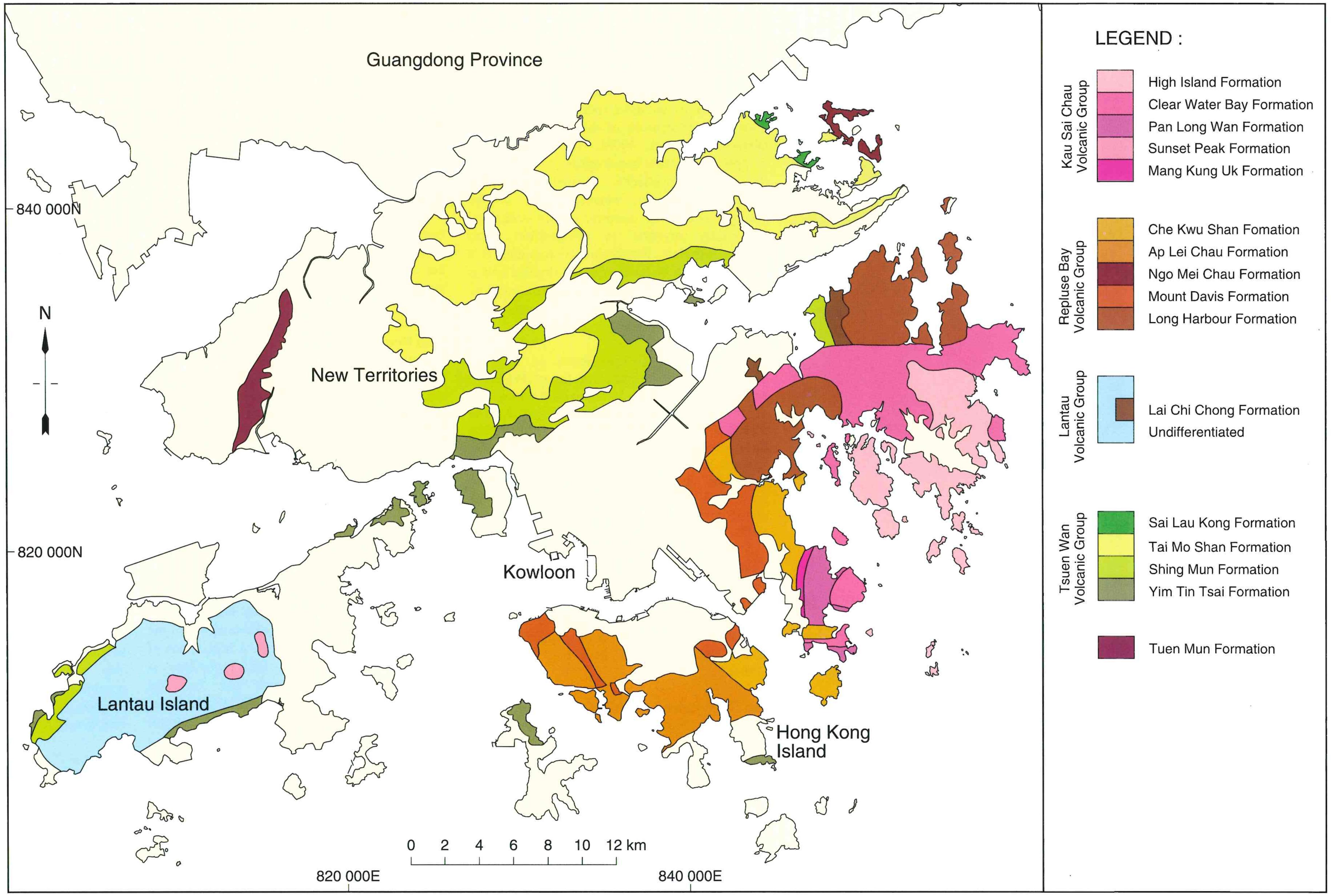


Figure 7 Geological map showing the distribution of Mesozoic volcanic formations in Hong Kong.

Plate 6 Lamma Suite. View of the deeply weathered and dissected *Tsing Shan Granite* in the Castle Peak area, western New Territories.

The *Tai Lam Granite* forms a large subcircular pluton in the northwestern New Territories, extending as far north as Yuen Long, east to Tsuen Wan, south to Ma Wan and Lantau Island, and west to Castle Peak (Figure 8). It intrudes the *Lantau Granite* in the south, Palaeozoic sedimentary rocks in the north and west, and Jurassic volcanic rocks in the east. An inlier of *Tai Po Granodiorite* is present within the Tai Lam Granite in the northeast. The *Tai Lam Granite* consists of a porphyritic medium-grained to equigranular fine-grained leucogranite.

The *Tsing Shan Granite* forms an elliptical pluton in the western New Territories with outcrops extending from Lung Kwu Chau in the south to Tsim Bei Tsui in the north (Figure 8). The *Tsing Shan Granite* is composed of variably deformed, equigranular to inequigranular fine-grained two-mica monzogranite. It is typically strongly deformed and recrystallised, and weathers to form a heavily dissected topography (Plate 6).

Kwai Chung Suite

The Kwai Chung Suite comprises four monzogranite plutons and a swarm of feldsparphyric rhyodacite and rhyolite dykes (Table 5). These rocks form extensive outcrops in the central and southern parts of Hong Kong (Figure 8).

The *Sha Tin Granite* (Strange, 1990), forms an irregular elliptical-shaped biotite monzogranite pluton centred on the Sha Tin district with the long axis oriented to the northeast (Figure 8). Outcrop extends from Tsing Yi in the southwest to Wu Kwai Sha in the northeast, and from Lion Rock in the southeast to Pak Tin in the northwest. The *Sha Tin Granite* is intruded in the southeast by the *Kowloon Granite* and to the northwest by the *Needle Hill Granite*. In the southwest, the pluton is intruded by the Lantau Dyke Swarm. On Tsing Yi, the pluton intrudes the *Tai Po Granodiorite*, *Yim Tin Tsai Formation* and *Shing Mun Formation* in the northern part of the island. The *Sha Tin Granite* comprises a coarse-grained central core surrounded by medium- to fine-grained lithologies.

Felsic dykes belonging to a dense swarm of ENE-trending feldsparphyric rhyolite dykes concentrated in northern Lantau Island (Lantau Dyke Swarm, Figure 8) are by far the most voluminous of all dyke rocks in Hong Kong. Two main generations of dykes are recognised (Sewell & James, 1995). The older swarm comprises relatively broad dykes (>5 m wide) of dominantly rhyodacitic composition (*East Lantau Rhyodacite*), whereas dykes of the younger swarm are narrower (<5 m wide) and dominantly rhyolitic in composition (*East Lantau Rhyolite*). Porphyritic microgranite is a textural variant of feldsparphyric rhyolite and is compositionally equivalent to rhyodacite dykes. These dykes are largely coeval with emplacement of the *Sha Tin Granite*.

The *Needle Hill Granite* forms an elliptical biotite monzogranite pluton on the northwestern side of the Shing Mun Valley with the long axis oriented in a northeast direction (Figure 8). The *Needle Hill Granite* is composed of porphyritic fine-grained monzogranite and equigranular medium-grained monzogranite and includes numerous fine-grained granite dykes which intrude the Sha Tin and Tsing Yi plutons. The pluton intrudes the *Tai Po Granodiorite* in the north and the *Sha Tin Granite* in the south.

Cheung Chau Suite

The granitoids of the Cheung Chau Suite comprise plutons, stocks and dykes varying in composition from quartz monzonite to biotite monzogranite and porphyritic rhyodacite. A total of four intrusive bodies have been recognised (Table 5).

The *South Lamma Granite* forms a subcircular, equigranular biotite monzogranite pluton centred on the southern part of Lamma Island (Figure 8). The granite intrudes the *Lantau Granite*. The *South Lamma Granite* is typically equigranular and medium-grained, although fine-grained equivalents are found adjacent to contacts with older granites and as late stage aplite dykes.

The *Chi Ma Wan Granite* forms a subcircular, biotite monzogranite pluton centred on the Chi Ma Wan peninsula on the eastern side of Lantau Island extending south and east to the islands of Shek Kwu Chau and Cheung Chau respectively (Figure 8). The *Chi Ma Wan Granite* intrudes the *Lantau Granite* and *East Lantau Rhyodacite* dykes at Chi Ma Wan. The *Chi Ma Wan Granite* is dominantly equigranular and medium-grained.

Shan Tei Tong Rhyodacite includes all feldsparphyric rhyodacite and rhyolite dykes intruding the Chi Ma Wan and South Lamma plutons. These dykes occur mostly in a zone extending from the Chi Ma Wan peninsula to Lamma Island in southern parts of Hong Kong (Figure 8). In thin section, the dykes are difficult to distinguish from those of the Lantau Dyke Swarm with large feldspar megacrysts being prominent within a fine-grained granular matrix of quartz, feldspar and biotite.

The *Luk Keng Quartz Monzonite* crops out in two places on the southeastern margin of the Lantau Caldera. A major outcrop occurs at Luk Keng whereas smaller outcrops are found at Fan Lau and Lo Kwu Chau (Figure 8). The pluton is typically K-feldspar megacrystic and fine-grained.

Lion Rock Suite

Granitoids belonging to the Lion Rock Suite form plutons and stocks in the southern part of Hong Kong (Figure 8). They are divided into two main compositional subsuites; a 'monzonitic' subsuite comprising three intrusive units and a 'granitic' subsuite comprising five intrusive units (Table 5). Lithologies are generally very uniform.

'Monzonitic' Subsuite

The *D'Aguilar Quartz Monzonite* includes several large stocks of quartz monzonite exposed on D'Aguilar and Stanley peninsulas, and smaller intrusions on Lamma Island, Luk Chau, Ap Lei Chau and Green Island. In the southern part of D'Aguilar Peninsula and Stanley Peninsula, the unit intrudes the *Yim Tin Tsai Formation* and the *Tai Po Granodiorite* (Figure 8). A broad zone of fine-grained porphyritic quartz monzonite is present at the contact with *Yim Tin Tsai Formation* in the southern part of D'Aguilar Peninsula. On Lamma Island, the unit intrudes the *Yim Tin Tsai Formation* and the *Sok Kwu Wan Granite*, and on Ap Lei Chau it intrudes the *Ap Lei Chau Formation* and *Mount Davis Formation*. The *D'Aguilar Quartz Monzonite* is typically porphyritic and fine- to medium-grained.

The *Tong Fuk Quartz Monzonite* crops out in a series of discontinuous stocks along the margin of the Lantau Caldera. Major outcrops occur at Sha Lo Wan on the western side of Lantau Island, at Tong Fuk on the southern side of island, and between Pui O Wan and Silver Mine Bay on the eastern side of the island (Figure 8). Smaller outcrops are found at Fan Lau and Pui O, and on nearby offshore islands of Cha Kwo Chau, Hei Ling Chau and Chau Kung To. The *Tong Fuk Quartz Monzonite* is typically fine-grained and porphyritic, with roughly equal abundances of alkali feldspar and plagioclase phenocrysts, although alkali feldspar usually predominates. The *Tong Fuk Quartz Monzonite* intrudes the *Lantau Granite*, *Tai Po Granodiorite* and Lantau Volcanic Group along the southeastern margin of the Lantau Caldera.

The *Tei Tong Tsui Quartz Monzonite* comprises several E- to NE-trending stocks and dykes of quartz monzonite and monzonitic granite outcropping in the eastern New Territories and Hong Kong Island (Figure 8). At Tai Miu Wan, the *Tei Tong Tsui Quartz Monzonite* is closely associated with volcanic deposits which are thought to represent a vent (see previously). On Hong Kong Island, it forms a 50 m-wide discontinuous quartz monzonite dyke from Lei Yue Mun Channel in the northeast to Wong Chuk Hang in the southwest. A 200 m-wide monzogranite dyke outcropping in the vicinity of Shek Mui Wan in Tseung Kwan O may be an eastern extension of this dyke. In the Sai Kung area, small stocks of quartz monzonite form a discontinuous ring around the Sai Kung Caldera, and a NE–SW swarm of dykes extending from Three Fathoms Cove to Lai King (Figure 8) and intruding the Sha Tin and Kowloon granites.

'Granitic' Subsuite

The *Sok Kwu Wan Granite* is a small porphyritic monzogranite pluton outcropping in the vicinity of Sok Kwu Wan in the northern part of Lamma Island (Figure 8). The *Sok Kwu Wan Granite* intrudes all lithologies except for dykes belonging to the *D'Aguilar Quartz Monzonite*. The *Sok Kwu Wan Granite* is typically porphyritic and medium grained featuring large megacrysts (5–10 mm) of alkali feldspar but may vary to non-porphyritic fine-grained lithologies.

The *Fan Lau Granite* is a relatively small outcrop of porphyritic monzogranite that intrudes the *Tong Fuk Quartz Monzonite* in the vicinity of Fan Lau on the southern tip of Lantau Island (Figure 8). The *Fan Lau Granite* is fine grained and porphyritic with phenocrysts of quartz and alkali feldspar set in a fine-grained matrix.

The *Kowloon Granite* forms a subcircular biotite monzogranite pluton centred on Kowloon and Hong Kong Island (Figure 8). The northern boundary of the pluton is along the base of the range of hills separating Kowloon from Sha Tin districts (Plate 7). In the west and south, the

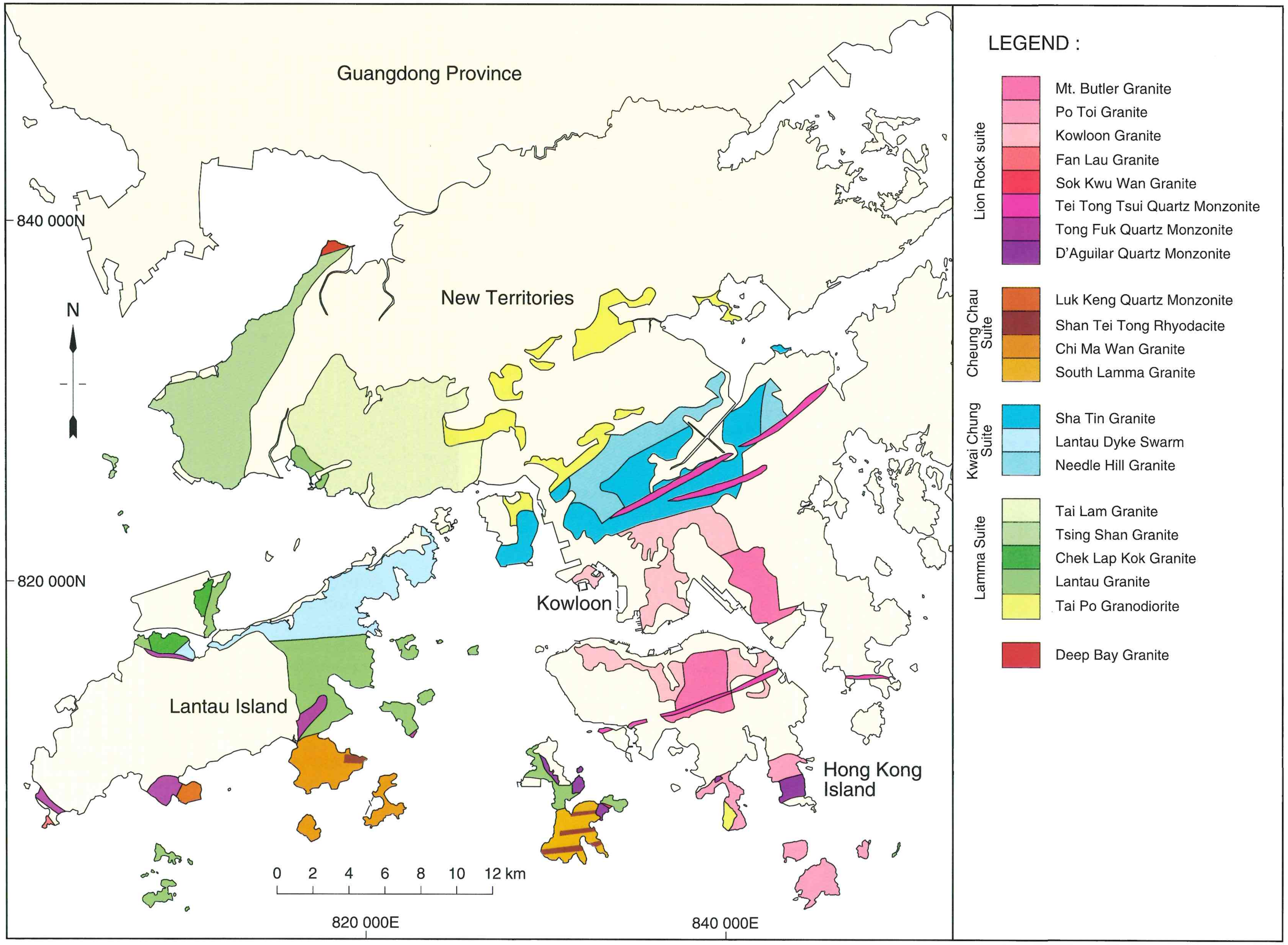


Figure 8 Geological map showing the distribution of Mesozoic plutonic rocks of Hong Kong.

pluton boundary is marked by hills comprising the volcanic roof rocks, whereas its eastern boundary is Stonecutters Island where volcanic rocks are also exposed. The *Kowloon Granite* is remarkably uniform in texture and composition and is typically an equigranular medium-grained, biotite monzogranite.

The *Po Toi Granite* forms a subcircular pluton centred on the southeastern tip of Hong Kong Island (Figure 8). It encompasses large outcrops of medium-grained granite exposed at Chung Hom Kok, Stanley Peninsula and D'Aguilar Peninsula, and granites exposed to the southeast on Sung Kong Island, Beaufort Island and Po Toi of the Po Toi Islands group. The pluton is also exposed on a reef known as Castle Rock between Stanley and the Po Toi Islands. The *Po Toi Granite* includes coarse-, medium- and fine-grained biotite monzogranite. The *Po Toi Granite* is texturally zoned with coarse-grained megacrystic lithologies predominating in the south and east, and equigranular medium- and fine-grained lithologies in the north and west. Pegmatitic veins are common in the Po Toi Islands. The *Po Toi Granite* intrudes the *Tai Po Granodiorite* and *D'Aguilar Quartz Monzonite* on Stanley and D'Aguilar peninsulas. The *Po Toi Granite* is texturally variable from alkali feldspar megacrystic coarse-grained to equigranular fine-grained lithologies. Contacts are sharp and the finer-grained granites generally intrude the coarser-grained variants.

The *Mount Butler Granite* is the name given for intrusions of leucocratic monzogranite on the southeastern and eastern margins of the Kowloon pluton in the vicinity of eastern Hong Kong Island and eastern Kowloon (Figure 8). The monzogranite is dominantly equigranular and fine-grained, but may become fine- to medium-grained in places. At Mount Butler Quarry, the *Mount Butler Granite* intrudes medium-grained granite of the Kowloon pluton and tuff of the *Ap Lei Chau Formation*. Locally around Kwun Tong, the *Mount Butler Granite* is strongly greisenised producing a saccharoidal-textured equigranular rock which is cut by number of thin (0.1–1.5 m) WNW-trending quartz veins. These invariably contain minor quantities of fluorite, chalcopyrite, molybdenite, wolframite and beryl. Pegmatite patches and miarolitic cavities are common, particularly close to the granite–volcanic contact. Field and compositional relationships suggest that the *Mount Butler Granite* may be only slightly younger than the *Kowloon Granite*.

Plate 7 Lion Rock Suite. View of Lion Rock composed of *Kowloon Granite*, looking north toward Sha Tin.

Mafic Rocks

Mafic and intermediate intrusive rocks are widespread throughout Hong Kong cutting almost all known plutonic and volcanic lithologies. They generally out crop as thin (<1 m) dykes and dykelets, but may also occur as small stocks and inclusions in granitoid rocks.

Upper Mesozoic to Lower Cenozoic Sedimentary Rocks

Sedimentary rocks of Cretaceous to Early Tertiary age are exposed in the northeastern New Territories. From oldest to youngest, they comprise the *Pat Sin Leng Formation, Port Island Formation, Kat O Formation* and *Ping Chau Formation*.

The *Pat Sin Leng Formation*, which unconformably overlies Middle Jurassic volcanic rocks of the *Tai Mo Shan Formation*, consists chiefly of non-marine sandstone, siltstone and conglomerate. It crops outs in a broad E–W oriented belt extending from Tolo Harbour in the west to offshore islands in the east (Plate 8). The *Port Island Formation* is only exposed on offshore islands east of Tolo Channel. It comprises fluvial sedimentary rocks, including channelised sandstones and conglomerates, sandstones and siltstones. Abundant volcanic detritus is present in both the Pat Sin Leng and Port Island formations.

The *Kat O Formation* is restricted to a few small outcrops on offshore islands in the northeastern New Territories and comprises calcareous breccia with conglomerate and sandstone. Lai *et al.* (1996) suggest that this formation was deposited chiefly within a small, enclosed basin.

The Early Tertiary *Ping Chau Formation* is only exposed on the island of Ping Chau in the northeastern margin of Hong Kong. The formation comprises mainly siltstone and clayey dolomitic siltstone, and is thought to have been deposited in chemical and detrital cycles in a brackish lake under tropical and subtropical conditions.

Plate 8 Upper Mesozoic sedimentary rocks. View of Ping Fung Shan looking northwestard along the Pat Sin Leng range. The foreground is composed of heavily dissected beds of the *Pat Sin Leng Formation* which dip gently towards the right.

The dominant reddish colour of all formations belonging to the post-volcanic cover sequence is thought to reflect deposition under mainly semi-arid conditions.

Structure

Hong Kong lies within the Lianhuashan Fault Zone at the southeastern margin of the Cathaysia (or Huanan) Block on the Asian Plate (Fletcher *et al.*, 1997). The Lianhuashan Fault Zone consists of a 30 km-wide NE-trending zone of subparallel, anastomosing faults extending for several hundreds of kilometres through the maritime provinces of Guangdong, Fujian, and Zhejiang. The fault zone is bounded to the north by the Shenzhen Fault and to the south by the Haifeng Fault, and is characterised by numerous ductile shears and local areas of medium to high-grade dynamic metamorphism.

Ductile deformation within the Lianhuashan Fault Zone is thought to have been most intense during the Cretaceous when substantial sinistral displacements took place. However, there is strong evidence to indicate that the fault zone was active in earlier periods (e.g. tectonically controlled distribution of Upper Jurassic to Lower Cretaceous volcanic centres; Campbell & Sewell, 1997), and may even have been periodically active since the late Proterozoic (Fletcher *et al.*, 1997).

Block-faulting is thought to have exerted a strong influence on sedimentation during deposition of the Lower to Middle Jurassic fluvial and marine sequences of Hong Kong (Tai O and Tolo Channel formations). Dextral transtension on NE-trending ductile shear zones dominated the earliest Middle Jurassic episode of volcanic-plutonic activity, whereas sinistral transtension on ENE-trending and conjugate NW-trending structures strongly influenced the Upper Jurassic to Lower Cretaceous magmatism (Campbell & Sewell, 1997). More recent fault movement in Hong Kong is thought to have been dominated by deformation on major NE-trending

Plate 9 Tai Lam Fault. Looking northeastward across Tai Lam Chung Reservoir toward Pat Heung along the strike of the Tai Lam Fault. The area in the foreground is underlain by the *Tai Lam Granite* (Lamma Suite).

and NW-trending structures (Plate 9). These fault structures are expressed in a variety of ways including brittle-ductile shear zones, linear zones of alteration and metamorphism, and swarms of oriented quartz veins (Figure 9).

Structural controls on mineralisation

NE- and NW-trending faults have played an important role in controlling the style and intensity of mineralisation in Hong Kong. Mineralisation is commonly best developed along major shear zones and is most intense at the intersections of NE-trending and NW-trending fault sets (Figure 9). The most important NE-trending structure with respect to mineralisation is the Sha Tau Kok Fault. This fault is characterised by a broad (up to 500 m) zone of dynamically metamorphosed rock and commonly hosts Pb–Zn–Cu mineralisation. The fault extends from Sha Tau Kok in the northeast to Pui O in the southwest and has a major sinistral displacement. Several subsidiary faults, such as the Ha Fa Shan Fault, Lead Mine Pass Fault and Yam O Fault, are associated with the Sha Tau Kok Fault zone and also host traces of Pb–Zn–Cu mineralisation.

Swarms of mineralised NW- to NNW-trending quartz veins are commonly associated with the major NW-trending faults. The most important structure in this respect is the Devil's Peak Mineralised Zone (DPMZ) which hosts Sn-, W-, Mo- and Be-bearing quartz veins. This zone extends from Devil's Peak in the southwest to Deep Bay in the northwest and has been sinistrally offset by the Tolo Channel, Sha Tau Kok, Tai Lam, and possibly Tuen Mun faults (Figure 9). Mineralisation is most strongly developed at Devil's Peak and Needle Hill (see later) where the quartz veins are associated with greisen and fine-grained granite of the Mount Butler and Needle Hill plutons respectively. Sn–W–Mo mineralisation is also well developed at the intersection of the DPMZ with the Sha Tau Kok Fault, and within the Tai Lam and Tsing Shan granites. Other NW-trending structures with associated vein quartz mineralisation include the East Lamma Channel Fault (Figure 9).

Quaternary Deposits and Weathering

The onshore Quaternary deposits have not been systematically described but have been broadly divided into fluvial deposits and mass wasting deposits of Pleistocene and Holocene age (Bennett, 1984). Pleistocene alluvial deposits mainly form the fluvial terraces of the larger stream valleys, whereas Holocene alluvium forms the present-day stream bed courses. Beach deposits of sand usually form the front of alluvial deposits in coastal embayments.

A regolith, or mantle of weathered rock, occurs over most of Hong Kong and the effects of weathering on the various rock types are broadly reflected in the topographic relief. Andesite, granodiorite, and Carboniferous, Permian and Lower Jurassic sedimentary rocks are the most deeply weathered and eroded rocks of Hong Kong forming much of the lower ground. The granite terrain is often hilly and littered with exhumed corestones (e.g. Plate 6) although the felsic dyke swarms and finer granites form sharper relief than the coarser grained rocks. Volcanic rocks are the most resistant to deep weathering and erosion, along with Devonian quartz sandstones.

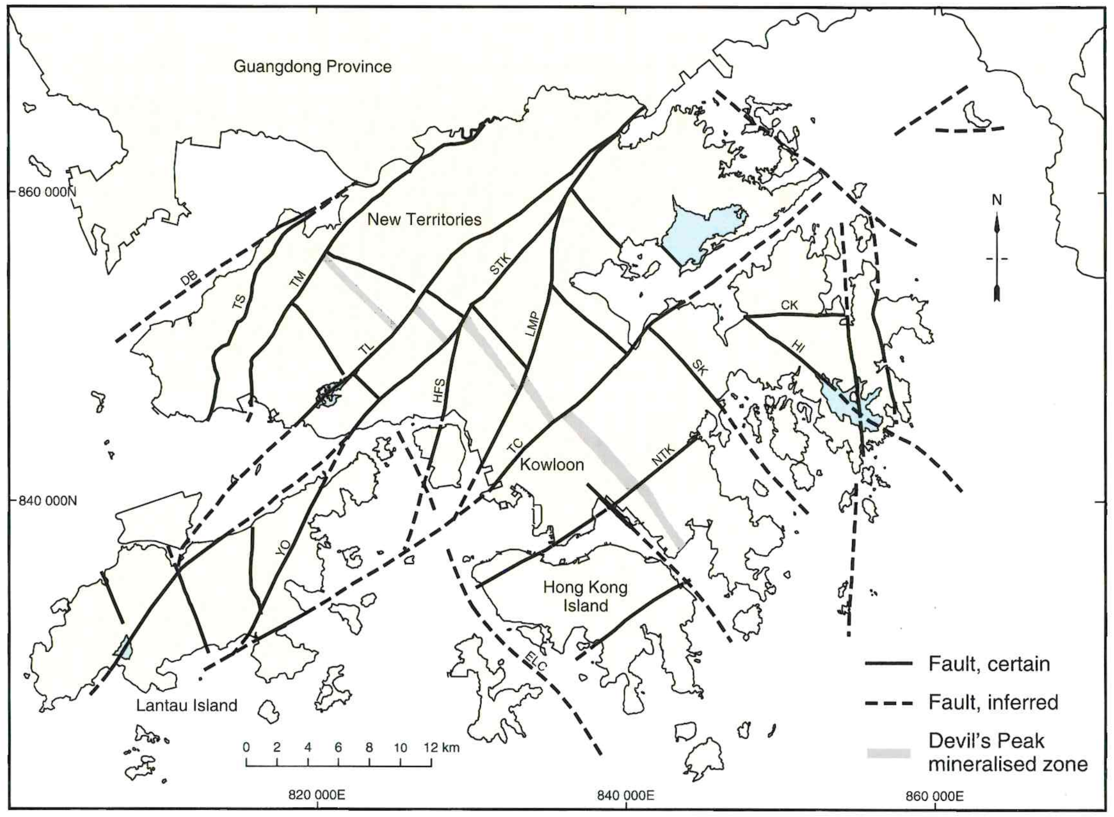


Figure 9 Map showing the main faults of Hong Kong. DB = Deep Bay, TS = Tsing Shan, TM = Tuen Mun, TL = Tai Lam, STK = Sha Tau Kok, YO = Yam O, HFS = Ha Fa Shan, LMP = Lead Mine Pass, TC = Tolo Channel, NYK = Ngau Tau Kok, SK = Sai Kung, CK = Chek Keng, HI = High Island, ELC = East Lamma Channel.

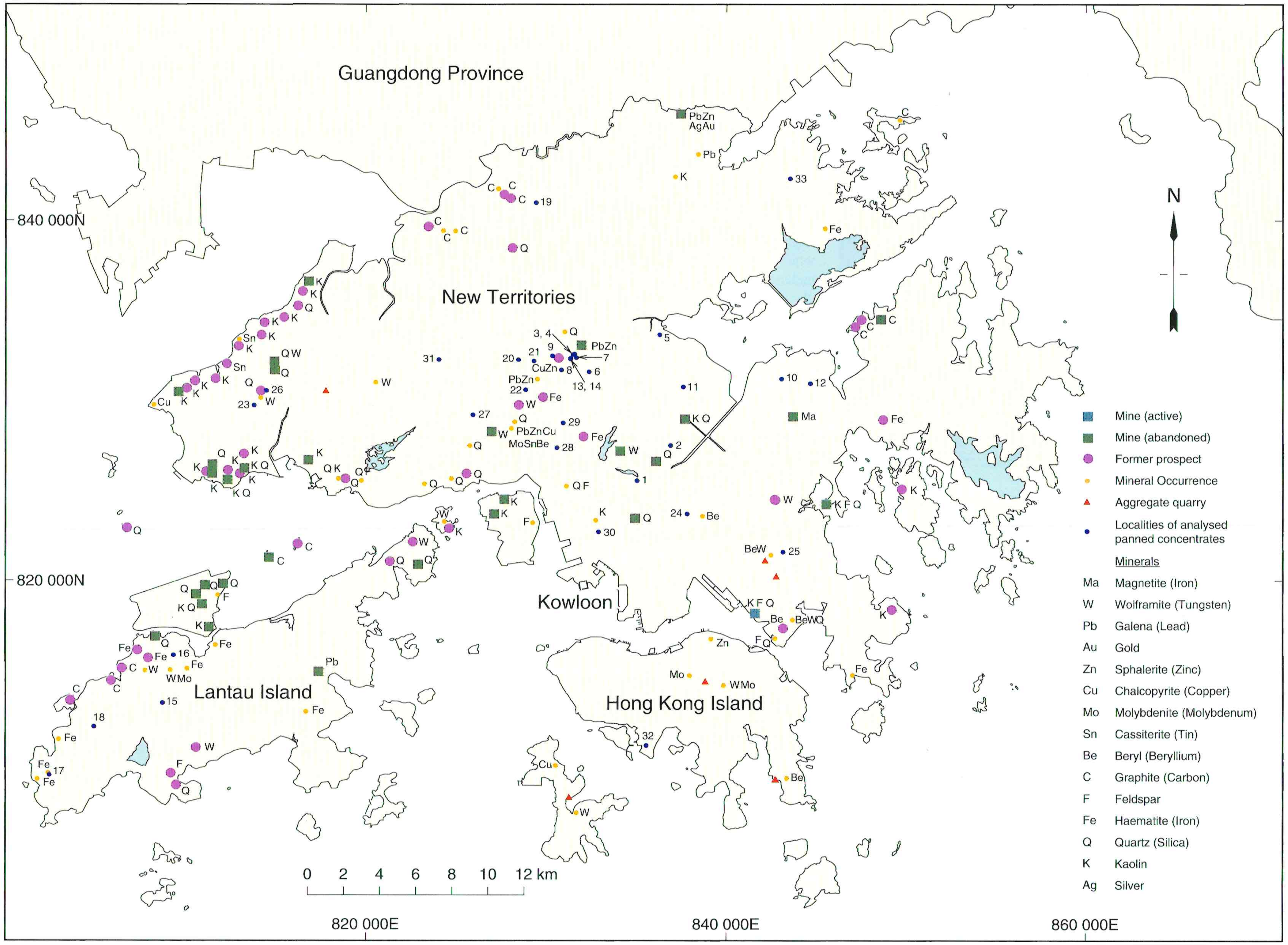


Figure 10 Location map of mines, quarries, and mineral occurrences in Hong Kong. Locations of thirty-three analysed panned concentrates are also shown.

MINERALISATION

For its size, the land area of Hong Kong contains a relatively large number of mineral resources, some of which have been commercially exploited (Table 6, Figure 10). The frequency and diversity of these mineral deposits is due mainly to aspects of the geological setting and, in particular, to the intensity of Mesozoic igneous activity and Yanshanian deformation. At present, there are no active commercial mining operations in Hong Kong.

Metalliferous Minerals

Tin–tungsten–molybdenum mineralisation

Sporadic Sn–W–Mo mineralisation is present in many parts of Hong Kong but is mostly concentrated along major NW-trending structures, often defined by swarms of oriented quartz veins, and in areas underlain by highly fractionated I–type or A–type granites. The latter include areas occupied by the Tai Lam and Tsing Shan granites in the northwest of Hong Kong, the *Needle Hill Granite* in the central region, the *Chek Lap Kok Granite* on Lantau Island, and the *Mount Butler Granite* in eastern Kowloon and Hong Kong Island. Many fractionated quartzphyric rhyolite dykes related to these intrusions also provide sites for Sn–W–Mo mineralisation which is generally manifested in thin epithermal quartz veins, pegmatites and miarolitic cavities. The richest deposits have been mined at Needle Hill, Lin Fa Shan and Sha Lo Wan, with minor workings at Castle Peak, and Devil's Peak.

Needle Hill

Eleven principal quartz veins were worked for their wolframite content at the Needle Hill mine on the southern slopes of Needle Hill, approximately 3 km west of Sha Tin (Plate 10). The mine was operative more or less continuously between 1938 and 1967. From the available mine production records, it is estimated that 240 000 tonnes of crude ore were recovered yielding approximately 1000 tonnes of wolframite concentrate. A summary of the history of mine activity and development is given by Roberts & Strange (1991).

The mineralisation is hosted by fine- and fine- to medium-grained *Needle Hill Granite*. The quartz veins vary from 20 to 40 cm wide and dip steeply (70–95°) to the southwest. Associated pegmatite veins contain a variety of accessory minerals including molybdenite, galena, sphalerite, bismuth, cassiterite, magnetite, pyrite, fluorite, muscovite and serpentine. No tungsten in the form of scheelite has been found.

Plate 10 Needle Hill Mine area. View of Needle Hill looking north toward Tai Mo Shan. The former Needle Hill Mine workings are just visible in the centre left of the photograph, in a prominent valley draining into the Lower Shing Mun Reservoir.

Lin Fa Shan

A number of discontinuous narrow (20–30 cm), NW-trending W-bearing quartz veins have been worked haphazardly in numerous small mining operations in the vicinity of Lin Fa Shan in the western New Territories. Most of the fissure veins occur within the *Tai Po Granodiorite* but may have originated from intrusion of the nearby *Tai Lam Granite*. Davis (1952) has suggested that close to the intrusion, mineralisation occurs predominantly in pegmatites which grade into quartz veins farther away. The narrower the veins, the richer the mineralisation. Typical vein deposits at Lin Fa Shan consist of two main minerals only, wolframite and quartz, but cassiterite and small amounts of scheelite have also been reported (Davis, 1952). Peng (1978) has recorded the presence of galena, sphalerite, pyrite, scheelite, cassiterite, fluorite and beryl in mine tailings from the Lin Fa Shan area. Owing to the indiscriminate mining operations at Lin Fa Shan, there are no mine plans or details of the workings available.

Sha Lo Wan

A wolframite mine was operative in the Sha Lo Wan district of western Lantau Island in the early and late 1950s. This was a relatively small-scale operation which exploited extensive mineralisation in a stockwork of narrow SSW-dipping quartz veins and shears. The host intrusion consists of a fine-grained monzogranite representing a fractionated variant of *Tong Fuk Quartz Monzonite*. The main minerals in a typical fissure vein deposit at Sha Lo Wan comprise fluorite, wolframite and quartz. Other minerals reported by Ruxton (1958) include molybdenite, chalcopyrite, arsenopyrite and pyrite. Cross-cutting quartz veins also carry very minor occurrences of these ore minerals.

Despite mining licences being in force for the Sha Lo Wan deposit between 1954 and 1961, no records of production are available. Extensive heaps of spoil and surface workings along with the remains of a mine office indicate that an organised operation once existed. There has been no sign of occupation since 1973.

Castle Peak

Small quantities of wolframite ore have been mined (Marsman Mines) from thin quartz veins within the *Tsing Shan Granite* at Leung Tin Tsuen on the northeastern slopes of Castle Peak. Along with the quartz gangue, the ore also contains traces of arsenopyrite, cassiterite, bismuth and molybdenite. The mineralised deposits occur close to the fault contact with volcanic rocks of the *Tuen Mun Formation.* No record of production figures are available and mining activity has long since ceased.

Devil's Peak

At Devil's Peak, eastern Kowloon, hydrothermally altered fine-grained granite (*Mount Butler Granite*) hosts a swarm of NW-trending quartz-filled fissure veins which are extensively mineralised. Although considerable prospecting and trial workings have been undertakn in the area, no commercial mining operations have been established. Minor quantities of fluorite, chalcopyrite, molybdenite and wolframite have been reported from the quartz veins (Davis, 1964b) in the area and Ruxton (1957c) has also described several beryl-bearing veins.

Other minor occurrences

Minor deposits of wolframite have been reported from northeastern Lantau Island and Ma Wan (Davis, 1952), Sok Kwu Wan on Lamma Island (Davis, 1952), Wong Nai Tun (Peng, 1978), Ho Chung (Davis, 1952; 1964b) and Mount Butler (Peng, 1978). In most cases, the mineralisation is associated with greisen and quartz veins within, or close to, the contact zone between fine-grained granite and roof rocks.

Lead–zinc–copper mineralisation

Pb–Zn–Cu mineralisation is found mainly in the New Territories where it is commonly associated with epithermal veins along NE-trending shear zones. Minor occurrences are also found on Lantau Island. The largest deposit is at Lin Ma Hang where Pb–Zn–Cu ore was mined on a commercial basis, but smaller operations have existed at Tai Mo Shan, Silver Mine Bay and southeast Lantau Island (Figure 10).

Lin Ma Hang

The Lin Ma Hang mine was operated intermittently from 1915 until 1958, by Hong Kong Mines Limited. An estimated 16 000 tonnes of lead metal and 10 000 kilograms of silver were produced. The mineralisation consists of a series of en-echelon, NW-oriented quartz veins intruded into the *Tai Mo Shan Formation* and dipping between 15 and 60° to the NE. The veins are lenticular, both along strike and down dip, and pinch and swell over a known strike length of approximately 2 km. The vein width can vary from a few millimetres to several metres.

Quartz and sericite are the dominant vein minerals, the sericite comprising the wall-rock alteration. According to Davis & Snelgrove (1956), the initial vein filling consisted of milky quartz, with crystals up to several centimetres long. This was followed by the injection of a fine-grained quartz vein containing the metalliferous minerals.

The metalliferous mineralisation at Lin Ma Hang consists of galena, pyrite, sphalerite and chalcopyrite in order of decreasing abundance. Silver and gold have been identified in polished sections (Davis & Snelgrove, 1956), but both elements appear to be contained within galena and chalcopyrite respectively. A detailed description of the mine development, operation, and ore reserves is contained in Williams (1991).

Tai Mo Shan

Minor workings are evident around the summit of Tai Mo Shan and in the vicinity of Lead Mine Pass. These workings were chiefly following leads of disseminated Pb–Zn–Cu mineralisation along narrow fault zones within coarse ash crystal tuff of the *Tai Mo Shan Formation.* None of the workings was on a commercial scale and

Table 6 General information on principal mineral localities in Hong Kong. Reference number in the first column refers to the location of the mineral occurrence on Figure 5. Sheet number refers to the published Geological Map Series HGM20. Grid references are based on the Hong Kong 1980 Metric Grid as shown on the 1:20 000-scale Geological Maps.

Reference No	Sheet	Easting	Northing	Element, commodity	Locality	References
1	11	843303	818986	W	Black Hill	Davis, 1964b
2	15	844432	807906	Mg,Fe	Cape D'Aguilar	Peng, 1978
3	7	840942	833310	Fe	Centre Island	Peng, 1978
4	11	841659	818293	Kaolin, feldspar	Cha Kwo Ling	Davis, 1952; Parham, 1969; Peng, 1978
5	10	810731	818949	Kaolin	Chek Lap Kok	Peng, 1978
6	6	828143	824501	Kaolin	Cheung Shue Tau	Peng, 1978
7	6	829327	828301	Pb,Zn	Chuen Lung	Peng, 1978
8	11	834806	822772	Quartz	Crow's Nest	Peng, 1978
9	11	843344	817528	Zn,Fe,Cu,W,Be,Al,Fluorite	Devil's Peak	Davis, 1964b; Peng, 1978; Ruxton, 1957c
10	11	838895	822870	Mo	Diamond Hill	Peng, 1978
11	10	816149	822066	Graphite	East Brother Island	Ruxton, 1957b
12	10	822484	822261	W	Fa Peng	Davis, 1952; Peng, 1978
13	13	803589	811790	Fe	Fan Kwai Tong	Peng, 1978
14	12	849110	818501	Kaolin	Hang Hau	Peng, 1978; Strange *et al.*, 1990
15	9	808637	816790	Quartz	Hau Hok Wan	Peng, 1978
16	7	836201	824880	Mo	Sheung Keng Hau	Addison, 1986
17	7	842772	824170	W	Ho Chung	Davis, 1952; Davis, 1964b
18	7	844178	830319	Fe	Hunchbacks	Addison, 1986
19	6	824553	833126	Sn	Kam Tin	Davis, 1952
20	6	828977	831217	Pb,Zn	Kap Lung	Peng, 1978
21	8	849651	825282	Kaolin	Kau Sai Chau	Peng, 1978; Strange *et al.*, 1990
22	7	836143	835839	Fe	Kau Shi Wai	Weld, 1915
23	7	830099	831965	Pb,Fe,Cu	Kwun Yam Shan	Peng, 1978; Addison, 1986
24	8	848513	834620	Quartz	Lai Chi Chong	Peng, 1978
25	7	831687	832095	Pb,Zn	Lam Tsuen Valley	Davis, 1952; Peng, 1978; Ruxton, 1957a
26	2	816852	837110	Quartz	Lau Fo Shan	Davis, 1952
27	7	834365	830439	Pb	Lead Mine Pass	Davis, 1952
28	5	813608	829962	Mo	Leung Tin Tsuen	Peng, 1978
29	6	827138	828253	W,Sn,Be,Pb,Zn,Fe,Fluorite	Lin Fa Shan	Davis, 1964b; Peng, 1978
30	3	837419	845989	Fe,Pb,Zn,Au,Ag	Lin Ma Hang	Davis, 1952; Davis & Snelgrove, 1956; Davis, 1964b; Peng, 1978; Ruxton, 1957a; Williams, 1991
31	2	826505	841153	Graphite	Lok Ma Chau	Peng, 1978; Langford *et al.*, 1989
32	7	846187	824075	Kaolin	Ma Lam Wat	Peng, 1978; Langford *et al.*, 1990
33	7	843081	829238	Pb,Fe,Cu,Fe,Al,W,Fluorite	Ma On Shan	Addision, 1986; Allen & Stephens, 1971; Davis, 1952; Davis, 1961a; Davis, 1964a; Davis, 1964b; Peng, 1978; Strange & Woods, 1991; Shibata, 1964
34	7	841542	834824	Fe	Ma Shi Chau	Peng, 1978
35	10	824289	823064	W	Ma Wan	Davis, 1952
36	6	823513	839528	Graphite	Mai Po	Peng, 1978
37	11	838939	814425	Mo	Mt Butler	Peng, 1978
38	10	817592	814763	Pb,Fe,Ag	Mui Wo	Peng, 1978; Davis, 1952; Davis, 1964b
39	7	834048	826416	Pb,Zn,Fe,Mo,W,Al,Fluorite	Needle Hill	Davis, 1952; Davis, 1961b; Davis, 1964b; Hui, 1978; Peng, 1978; Roberts & Strange, 1991
40	9	810462	815707	Fe	Ngau Au	Peng, 1978
41	11	838601	816778	Zn,Mo	North Point	Peng, 1978
42	8	855604	824060	Kaolin	Pak Lap	Peng, 1978

Table 6 (continued)

43	7	838067	829279	Kaolin	Pat Tsz Wo	Peng, 1978
44	5	812343	825355	Kaolin	Pillar Point	Davis, 1952; Peng, 1978
45	4	862184	844606	Fe	Ping Chau	Davis, 1952; Peng, 1967; Peng, 1971; Peng, 1976; Peng, 1978
46	4	846149	839137	Fe	Plover Cove	Allen & Stephens, 1971; Peng, 1978
47	6	815009	830877	Quartz	Po Tong Ha	Peng, 1978
48	3	836463	841621	Kaolin	Princess Hill	Peng, 1978; Lai *et al.*, 1996
49	10	815866	812187	Fe	Pui O	Peng, 1978; Tegengren, 1923
50	2	827750	839384	Quartz	Saddle Pass	Peng, 1978
51	8	845089	830991	Fe	Sai Keng	Davis, 1952
52	9	807291	816582	Fe	San Shek Wan	Peng, 1978; Langford *et al.*, 1995
53	9	809156	816919	Mo	San Tau	Peng, 1978
54	2	825642	839980	Graphite	San Tin	Peng, 1978
55	9	806681	822875	Quartz	Sha Chau	Peng, 1978
56	2	817205	836243	Kaolin	Sha Kong Wai	Peng, 1978
57	9	807928	816322	Fe,Cu,W,Be,Fluorite	Sha Lo Wan	Davis, 1952; Davis, 1964b; Nau & Yim, 1978; On Yang, 1979; Peng, 1978; Ruxton, 1958
58	8	847217	833899	Graphite	Sham Chung	Peng, 1978
59	10	826828	823868	Kaolin	Shek Wan	Sewell & Fyfe, 1995
60	7	832380	826048	Quartz	Sheung Kwai Chung	Peng, 1978
61	6	826537	827586	Sn,Au	Sheung Tong	Davis, 1952; Langford *et al.*, 1989
62	6	819245	825666	Quartz	Siu Lam	Peng, 1978; Langford *et al.*, 1989
63	5	811493	825872	Quartz, Kaolin	Siu Lang Shui	Peng, 1978; Langford *et al.*, 1989
64	6	819000	826315	Kaolin	So Kwun Wat	Peng, 1978; Langford *et al.*, 1989
65	6	818097	825872	Kaolin	So Kwun Tan	Peng, 1978; Langford *et al.*, 1989
66	15	831683	807292	W	Sok Kwu Wan	Davis, 1952
67	7	830916	830645	Pb,Fe	Tai Mo Shan	Nau, 1977; Peng, 1978; Weld, 1915
68	7	836976	832509	Fe	Tai Po Kau	Peng, 1978; Weld, 1915
69	5	811882	831338	Kaolin	Tai Shui Hang	Peng, 1978
70	6	826119	825693	Quartz	Ting Kau	Peng, 1978
71	5	810370	831028	Kaolin	Tsang Kok	Peng, 1978
72	6	827649	824468	Kaolin	Tsing Yi	Davis, 1952
73	8	848279	828104	Fe	Tso Wo Hang	Peng, 1978; Strange *et al.*, 1990
74	9	811575	816531	Mo,Fe	Tung Chung	Peng, 1978
75	7	836730	826759	Quartz, feldspar	Tung Lo Wan	Peng, 1978; Addison, 1986
76	7	840052	827592	Mo	Turret Hill, Sha Tin	Addison, 1986
77	9	814531	821363	Fe, Graphite	West Brother Island	Davis, 1952; Peng, 1978; Ruxton, 1957b; Woods & Langford, 1991
78	6	820420	830993	Fe,W	Wong Nai Tung	Davis, 1964b
79	13	802539	810036	Fe	Yi O	Peng, 1978
80	5	808906	830177	Kaolin	Yung Long	Peng, 1978

no records of their operation exist. The ores are reported by Weld (1915) and Peng (1978) to consist of galena and sphalerite, with associated minor pyrite, chalcopyrite and pyrrhotite.

Mui Wo
Mine Bay area late last century. Although no production records exist of this activity, the deposit is reported by Peng (1978) to have consisted of argentiferous galena, with subordinate sphalerite and pyrite in a gangue of quartz. The remains of the mine adit are preserved adjacent to the walkway between Mui Wo and Tai Ho Wan.

Other minor occurrences
Minor occurrences of Pb–Zn–Cu mineralisation are reported mainly from the Lam Tsuen Valley (Davis, 1952), Chuen Lung, and Sheung Tong areas. All these areas are underlain either by coarse ash crystal tuff of the *Tai Mo Shan Formation* or *Tai Po Granodiorite*. The mineralisation is mostly restricted to narrow veins within fault zones.

Iron mineralisation
Iron associated with skarn deposits has been reported in a number of localities throughout Hong Kong, the largest of which is the magnetite deposit on the southern flanks of Ma On Shan, central New Territories (Plate 11). This deposit is the only one that has been economically mined. The iron deposits are associated with intrusions of Middle Jurassic to Lower Cretaceous granite and are only found in areas where the bedrock comprises pre-Jurassic sedimentary rocks.

Ma On Shan
The Ma On Shan mine was opened in 1906 initially as an opencast operation, and subsequently went underground as the ore body was progressively mined out. The mine was closed in 1976 when extraction of the magnetite ore became uneconomic. Details of the history of mine development and exploitation are summarised by Strange & Woods (1991). Remaining ore reserves have been estimated at approximately 4 million tonnes.

Plate 11 Ma On Shan Mine area. View of the southern slopes of Ma On Shan showing the area of disturbed ground in the vicinity of the former Ma On Shan mine workings.

The magnetite ore at Ma On Shan is intimately associated with a major skarn body. The ore is contained in a calc-silicate skarn envelope surrounding a lenticular-shaped mass of dolomitic marble at the contact between granite and Palaeozoic sedimentary rocks (Devonian and Carboniferous). The host skarn contains a rich and varied mineral assemblage mostly comprising tremolite, actinolite, diopside and garnet (Peng, 1978). However, other minerals are reported to include apatite, calcite, chalcopyrite, epidote, fluorite, galena, azurite, malachite, palygorskite, pyrite, pyrrhotite, rhodonite, serpentine, stilpnomelane, topaz, vesuvianite and wollastonite.

A small, magnetite-bearing skarn of similar character to that in the Ma On Shan mine has been encountered in boreholes beneath the Ma On Shan reclamation (Sewell, 1996). The skarn has developed at the contact between *Sha Tin Granite* and the *Ma On Shan Formation,* and contains a rich mineral assemblage dominated by actinolite, diopside, epidote and tremolite. Veins of tremolite are commonly encountered in the dolomitic marble of the *Ma On Shan Formation* close to the contact zone with granite.

Sha Lo Wan
A small magnetite-bearing skarn deposit has been reported from the Sha Lo Wan area on the west coast of Lantau Island (Tegengren, 1923; Ruxton, 1958). The skarn zone occurs within the *Chek Lap Kok Granite* and probably originated from the incorporation of fragments of dolomitic marble within the granite during intrusion into the Carboniferous basement succession. Marble and skarn-related mineralisation has also been detected in boreholes at Tung Chung Wan and near The Brothers (Langford *et al.,* 1995).

Tai Po and Tai Mo Shan
Minor occurrences of skarn-related iron mineralisation have been reported from the Tai Mo Shan and Tai Po areas (Weld, 1915). No details of these occurrences are given but it is likely that they refer to blocks of metasomatised marble caught up in coarse ash crystal tuff of the *Tai Mo Shan Formation* (e.g. Wong, 1991).

Other occurrences
Peng (1978) and Weld (1915) make passing reference to magnetite-bearing quartz veins in south Lantau Island at Yi O and Pui O. Very little is known of these deposits, but it is thought that they are possibly related to skarn mineralisation resulting from the intrusion of granite into Carboniferous carbonate rocks.

Minor occurrences of haematite have been reported from veins in sandstone of the *Bluff Head Formation* at Plover Cove, and in sandstone of the *Tolo Harbour Formation* on Ma Shi Chau (Peng, 1978). In a recent geophysical survey of Tolo Harbour (EGS, 1993), a pronounced positive magnetic anomaly was detected immediately to the southeast of Ma Shi Chau which was interpreted as indicating the presence of an iron-bearing skarn between subcropping granite and carbonate rocks. Some of the mineralisation in the overlying Permian rocks may therefore have originated from this contact zone.

Davis (1952) drew attention to a deposit of haematite at Three Fathoms Cove, within the *Bluff Head Formation.* He described the deposit as being of possible stratiform origin but it is more likely that the mineralisation has been ultimately derived from mineralised skarn similar to that associated with the ore body at nearby Ma On Shan.

Although a prospecting licence for iron ore was once issued for the Sai Kung area, there is virtually no sign of mineralisation in the area. A small outcrop of haematite on the beach at Tai Mui Wan may be related to a nearby intrusion of quartz monzonite (Strange *et al.,* 1990), but few other details are known.

Placer deposits of tin and gold
Sheung Tong
Davis (1952) reported traces of alluvial gold and tin from the Sheung Tong area. Based on samples taken from twelve trial pits, he estimated a concentration of alluvial tin at approximately 2 kg/m^3. The cassiterite probably originated from quartz veins emanating from the nearby *Tai Lam Granite.* Davis (1952) also reported traces of alluvial gold from the same area, but recent attempts at panning have proved fruitless. There appears little likelihood that anything more than a trace of gold will be found in Hong Kong.

Kam Tin
Deposits of elluvial tin have been reported to exist at the foothills of the Kam Tin Plain (Davis, 1952). However, despite prospective yields of 500 g/50 Kg, the deposit has never been proven or exploited.

Non-metalliferous minerals

Kaolin
Major deposits of kaolin clay have been mined at Cha Kwo Ling, Chek Lap Kok and Tsing Yi although there have also been numerous other small occurrences mainly in the northwest of Hong Kong. Except for the deposit at Cha Kwo Ling, all the main kaolin deposits consist of altered aplite or rhyolite dykes within in granite and are commonly associated with quartz veins.

Cha Kwo Ling
A lensoidal vein of feldspar-rich pegmatite within the granite was mined as a source of kaolin and feldspar for almost 50 years (Davis, 1952). This lensoidal vein seems to have been very localised, perhaps only about 25 m wide and 150 m long. Remnants of the vein are exposed on the northwestern wall of the pit where the feldspar is exceptionally pink in colour. Feldspar debris collected from boulders on the road at the eastern end of the pit suggest that the main mineral body was composed of relatively pure white alkali feldspar. The persistence of drusy cavities and coarse crystal size indicates that the vein is almost certainly of pegmatitic origin rather than a syenite dyke as has been previously suggested.

Kaolin was probably initially mined from the weathered mantle overlying the pegmatite vein. Once this overburden had been exhausted, feldspar was then mined for use in ceramics and enamels with exports to Japan. It seems that the mining was abandoned after the feldspar became too uneconomic to extract, or the vein pinched out.

Chek Lap Kok
Residual kaolin clay was mined at Chek Lap Kok chiefly in the Cheung Sha Lan area (Langford, 1994). The operation involved the washing of clay from residual granitic soils of the *Chek Lap Kok Granite.* Between 1981 and 1988, approximately 10 000 tonnes of kaolin were extracted leaving a silica sand by-product of approximately 190 000 tonnes. This by-product eventually proved more valuable than the kaolin and the mine operation was abandoned on expiration of the licence in 1988.

Tsing Yi
Kaolin was mined on Tsing Yi in two areas: Shek Wan and Cheung Shue Tau. At Shek Wan, the kaolin was mined from a kaolinised rhyolite dyke between 1976 and 1983 but no production figures are available. At Cheung Shue Tau, kaolin was also mined from a kaolinised rhyolite dyke adjacent to a prominent N–S trending quartz vein. However, little information is available of the mining activity.

Other occurrences

Numerous other minor kaolin deposits have been reported from the northern and western parts of Hong Kong (Langford *et al.,* 1989; Lai *et al.,* 1996). Most of these occur in the area underlain by the *Tsing Shan Granite* at Mong Hau Shek, and along the coast near Pak Nai, but also include areas underlain by the *Tai Lam Granite*. Most of these operations were in deeply weathered residual soils and involved sluicing to extract the kaolin. Elsewhere in Hong Kong, kaolin has been extracted locally from very small deposits of deeply weathered tuffaceous sediments intercalated with rhyolitic tuffs of the Repulse Bay Volcanic Group. These include a deposit in the *Ap Lei Chau Formation* at Brick Hill, Deep Water Bay, and a deposit in the *High Island Formation* at Kao Sai Chau, Sai Kung (Davis, 1952; Strange *et al.,* 1990).

Feldspar

Feldspar was once mined from a pegmatite at Tung Lo Wan, Sha Tin, for use in ceramics, tile and glass manufacture. The pegmatite occurs in the *Sha Tin Granite* and is thought to be one of the largest in Hong Kong. According to Peng (1978), the pegmatite was at least 25 m long and 15 m wide and 10 m deep. A mining licence was granted to exploit the deposit in 1976 but operations ceased in 1984.

Quartz

Numerous mining operations for quartz have been active in the past, mainly exploiting residual granitic soils, but also thick quartz veins which cross-cut the region. The largest operation in recent years was on Chek Lap Kok where silica sand was produced as a by-product of kaolin mining. However, smaller operations have existed at Pak Kok and Mong Hau Shek, Tsing Yi, Mong Tung Hang on Lantau Island, Siu Lam, Mai Po, Tung Lo Wan, Needle Hill, Sheung Kwai Chung and Lai Chi Kok.

Two mining operations once existed on Chek Lap Kok: Sham Wan and Cheung Sha Lan. The largest of these was at Cheung Sha Lan where more than 190 000 tonnes of silica sand were produced over a seven year period (see previously). At Sham Wan, approximately 1400 tonnes of silica sand were produced between 1968 and 1971. Production figures at the other sites are not available.

Beryl

High grade beryl ore from the Devil's Peak area was first described by Ruxton (1957c). The beryl occurs in quartz veins within hydrothermally altered *Mount Butler Granite* and is associated with tungsten vein mineralisation (see previously). Despite the high quality of the material, the ore is in extremely low abundance and its value is more of scientific rather than commercial interest. Beryl was also reported from the D'Aguilar Peak area by Ruxton (1957c) and Peng (1978). It is likely that the beryl occurs in veins close to the contact of *Kowloon Granite* and *D'Aguilar Quartz Monzonite*.

Graphite

Graphite in sedimentary rocks on West Brother island was first reported by Heanley (1923) and later fully described by Ruxton (1957b). The graphite occurs in three moderately (60°) NE-dipping seams, with maximum thicknesses of 0.15, 0.3 and 4.5 m respectively, and are interbedded with quartzite, sandstone, siltstone and mudstone belonging to the Mai Po Member of the *Lok Ma Chau Formation* (Langford *et al.,* 1989). The graphite is thought to have originated from coal seams within the sedimentary rock succession which was later metamorphosed by intrusion of granite. Ruxton (1957b) reported that the fixed carbon content of the graphite averaged 80 %, with ash accounting for an average of 16 %, and volatile content from 1 to 3 %, with the remainder as moisture.

An underground graphite mine was opened in 1952 to exploit the mineral resource and remained operational until 1971 when extraction became uneconomic. Only the lower, thickest (0.3–4.5 m) seam was worked. By 1964, the mine had reached a depth of 90 m below ground and was subject to periodic flooding (Knapp, 1964). A full description of the history of mine development is contained in Woods & Langford (1991).

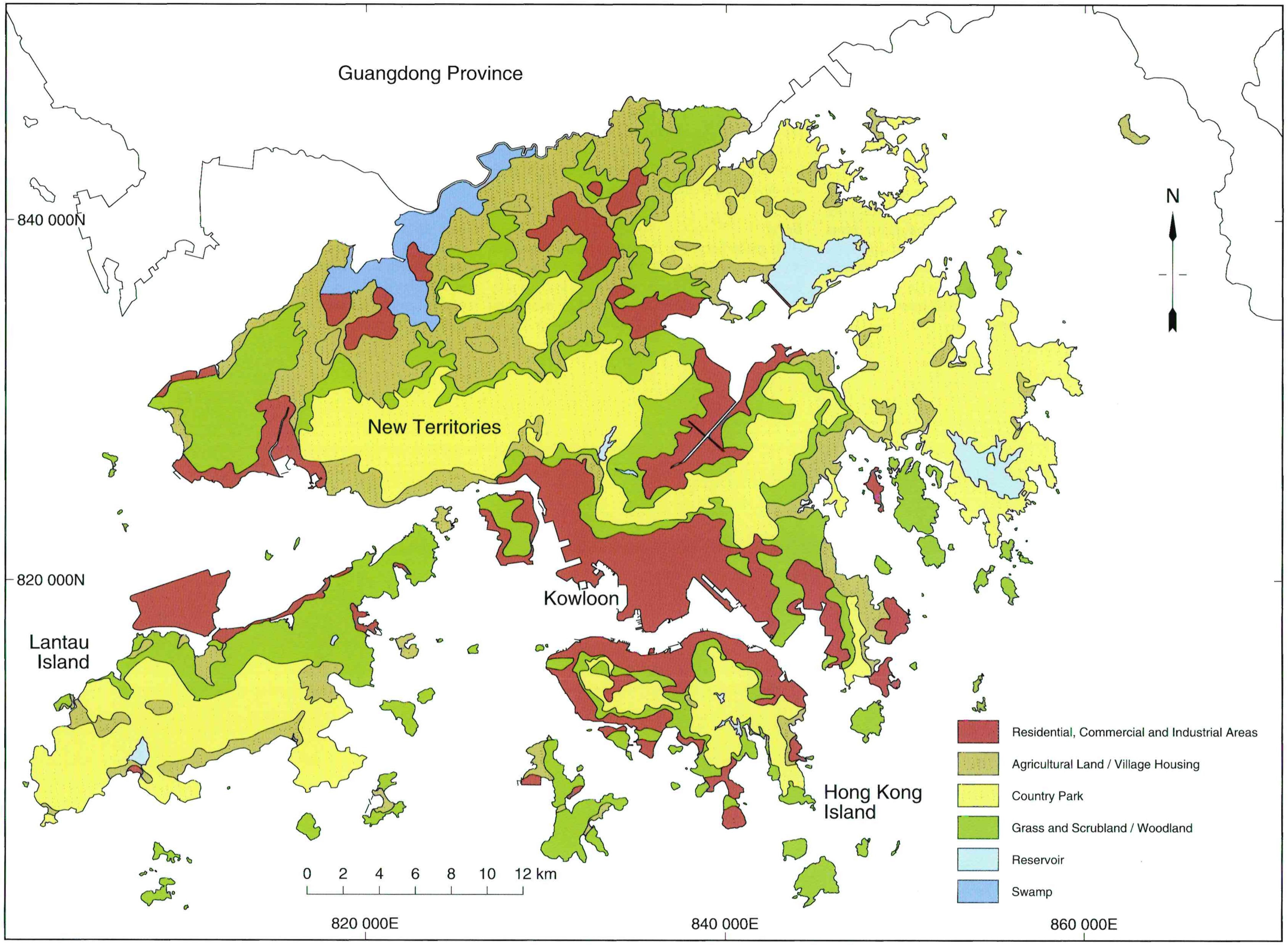


Figure 11 Simplified land use map of Hong Kong based on the land utilisation map of Hong Kong (Series and Sheet No. LUM/HK/75) published by the Town Planning Office, Building and Lands Department, 1988.

ANTHROPOGENIC ACTIVITY

The bulk sediment geochemical analyses indicate that a complex pattern of metalliferous enrichment is present in Hong Kong. This enrichment may have a variety of origins, including the presence of heavy mineral grains derived by natural erosion, liberation of mineral grains from mine sites, stack discharge from fossil fuel power generation, and a wide range of other anthropogenic sources. A simplified land use map showing the main urban and industrial areas of Hong Kong is presented in Figure 11.

Analysis of panned concentrates

A detailed mineralogical investigation was undertaken on a fraction of the panned concentrates in order to identify the sources of enrichment and to assist with the interpretation of anomalous concentrations of elements on the accompanying geochemical maps. Selection of samples was based on the high concentration of metallic elements revealed by the bulk sediment chemistry.

The mineralogical investigation was carried out at the laboratories of the British Geological Survey using a variety of techniques including gravity and magnetic separation of the panned concentrates, optical microscopy, electron-probe microanalysis and scanning electron microscopy (Fortey *et al.,* 1998). Thirty-three panned concentrates were analysed, the locations of which are plotted on Figure 10, and a summary of results is presented in Table 7.

Overall, most of the analysed samples contained angular to weakly rounded grains, indicating local derivation with little aggradation during sediment transportation. These included conspicuously euhedral fine-grained crystals of zircon and anatase, euhedral grains of doubly terminated quartz (indicating a primary igneous origin), rounded to subangular grains of altered pyrite and angular, irregular and anhedral grains of anthropogenic contaminants, such as ferruginous shards and flakes. Other contaminants, such as wire fragments, silver foil and microspheres, were found to preserve original shapes.

Naturally derived minerals

The low density fractions of the analysed panned concentrates (commonly comprising over 90 % of each sample), are dominated by angular to weakly rounded grains of quartz and feldspar, with accessory mica and hornblende. These minerals are interpreted as predominantly naturally derived.

Fine grains of minerals such as magnetite, ilmenite, rutile, sphene, monazite and epidote, together with very fine conspicuously euhedral crystals of zircon, comprise the denser fraction of the majority of panned concentrates. These minerals are also interpreted as naturally derived. The magnetic fractions commonly include dark grey opaque grains of ilmenite and magnetite, a variety of amber coloured grains provisionally identified as sphene or rutile, and pale green grains of epidote. Individual grains of cassiterite (Figure 12a), and corundum (Figure 12b) were identified in a few samples along with rare grains of pyroxene (Figure 12c) and Cr-spinel (Figure 12d). In one sample, euhedral tabular grains of a Pb-S rich phase are probably anglesite (Figure 12e), whereas in another sample, a deep brown, non-magnetic grain of an U-Th rich mineral is probably thorogummite or coffinite. Cuboid grains of altered pyrite or "martite" (Figure 12f) are common in many samples.

Anthropogenic contaminants

The most common contaminants in the panned concentrates comprise flakes and shards of dark grey, highly magnetic material interpreted as cast iron or steel, possibly derived from machinery or rusting pipes. These vary from rough surface 'scale' (Figure 13a) to smoother flakes with manufactured forms (Figure 13b). Traces of Pt coating on one grain suggest derivation from a catalytic converter in a vehicle exhaust system. Certain other metallic flakes of exotic composition (e.g. Ag foil, Figure 13b) are also present. Another widespread contaminant in many of the panned concentrates is tiny black lustrous microspheres (Figure 13c and 13d). These moderately magnetic to highly magnetic spheres are interpreted as fly-ash derived from ironworks or power stations. Microspheres of non-magnetic Sn-rich material (Figure 13e and 13f) are also present in some samples suggesting an origin from tin smelting. Irregular grains of black lustrous material displaying a microscopically botryoidal surface are interpreted as glassy slag, possibly derived from the same industrial processes as the iron-rich microspheres. Furnace slag is represented by a variety of generally irregular grains, some noticeably glassy, but others are of inconspicuous appearance. These generally have Fe-, Si- and Al-rich compositions, but at least one of the slag-derived grains retained remnants of a tenuous coating of Sn metal, suggesting an origin from tin smelting. Fragments of Fe- and Cu-rich wire are present in many of the analysed samples.

Table 7 Summary of contaminants and metalliferous minerals in analysed panned concentrates.

Sample	Wt % sinks	Pyite and/or oxidized pyrite	Fe-rich flakes	Fe-rich microspheres	Additional results/comments
1	3.4	x	✓	x	Wolframite, cassiterite, molybdenite
2	2.6	✓	✓	✓	Rutile, Fe-bearing slag
3	5.3	✓	✓	✓	Cu wire; sphalerite and cassiterite suspected
4	1.4	x	✓	x	Rutile suspected
5	2.3	✓	✓	✓	Sphalerite suspected
6	2.6	✓	x	x	No contaminants identified
7	1.4	✓	✓	x	–
8	2.7	✓	✓	✓	Grains of Th-U rich Al-Si mineral (possibly thorogummite)
9	14.6	✓	✓	✓	Cu wire; cassiterite
10	18.5	✓	x	x	Probable cassiterite
11	3.5	✓	x	x	Cassiterite, probable anglesite, Sn-bearing slag
12	7.3	✓	✓	x	Probable anglesite; Fe-bearing slag
13	3.5	✓	x	x	Zn, Cu and traces Sn and located in slag grains
14	1.1	✓	x	x	Zr in zircon, martite
15	13.0	x	x	✓	Zr in zircon
16	2.5	✓	x	x	Zr in zircon; No contaminants identified
17	0.4	x	x	✓	Zr in zircon; traces of malachite
18	2.3	✓	✓	✓	Zr in zircon, flakes of grey steel.
19	3.9	✓	✓	✓	Anatase
20	9.6	x	✓	✓	Sn-oxide microspheres, Cu wire, rutile
21	10.3	✓	✓	✓	Sn microspheres, Fe wire, Cu wire
22	5.1	✓	✓	x	Fe wire
23	0.3	✓	✓	x	Zr in zircon
24	6.0	✓	✓	✓	Cr-spinel, Cu wire
25	1.8	x	✓	✓	Ag-rich foil, periclase, cassiterite, corundum, anatase, Cu wire
26	1.2	✓	✓	x	Rutile
27	1.1	✓	✓	x	Ag-rich foil, corundum, flakes of blue paint, chalcopyrite
28	4.6	x	✓	✓	Cu wire and turnings, corundum, malachite
29	0.3	✓	x	x	Flakes of metallic foil and tissue backing
30	5.4	✓	✓	✓	Fe-rich flake with Pt on surface. Fe-wire, andalusite, cassiterite
31	0.2	x	✓	✓	Lustrous platy material, poss, Cu sulphate phase
32	3.6	✓	✓	✓	Flakes of grey steel, traces of Co-bearing glass, rutile
33	4.6	✓	✓	x	Martite

Fly-ash

Systematic examination of the coarse sediment fractions has revealed that fly-ash is widespread in the stream sediments of Hong Kong, with the highest concentrations found in the central and northwestern New Territories, and southern Hong Kong Island (Figure 14). The majority of fly-ash particles are moderately magnetic to highly magnetic solid spheres, although low density or hollow microspheres may comprise up to 5 % of the particle fraction (cf. Wigmore & Kubrychit, 1989; CLP, 1990).

Fly-ash arises as an airborne residue of the combustion of coal, and is made up principally of silicate and non-silicate minerals. The bulk of the silicate fraction consists of alumino-silicates and a number of alkaline oxides. The non-silicate material comprises mainly ferrous sulphide (FeS), but also contains a large number of other sulphides in trace quantities, including Cu, Pb, As, Hg and Zn. Carbonates, chlorides, and selenides are typically the other types of non-silicate materials present.

The composition of fly-ash varies in terms of the trace element, and in particular heavy metal content, depending on the origins of the coal, the specific design of the power station, and its combustion conditions. Trace metals become adsorbed on exchange sites on the fly-ash surface due to their high affinity for Fe and Al oxides. Amorphous oxides of Fe exert the primary control on most metals in the ashes, whereas Cd, Ni, and to some extent Pb, exhibit a preference for the Mn portion of the surface coating.

Interpretation of anomalies

The interpretation of geochemical anomalies in descriptions of the accompanying geochemical maps is inevitably subjective because variations in element enrichment are sensitive to a number of contributing factors (see below). However, for the purposes of this report, element concentrations which exceed the 95 percentile value are generally regarded as being anomalous. Each element description is based on real values taken from the raw analytical data. The actual range of values for a particular element is given for each "anomaly", along with the ranges of any associated elements. Where possible, reference is made to natural minerals or anthropogenic contaminants which could be responsible for the element enrichments, and to any other useful information gleaned from observations recorded at the sampling sites. Average whole-rock element values for the major rock sequences in Hong Kong are given in Table 8.

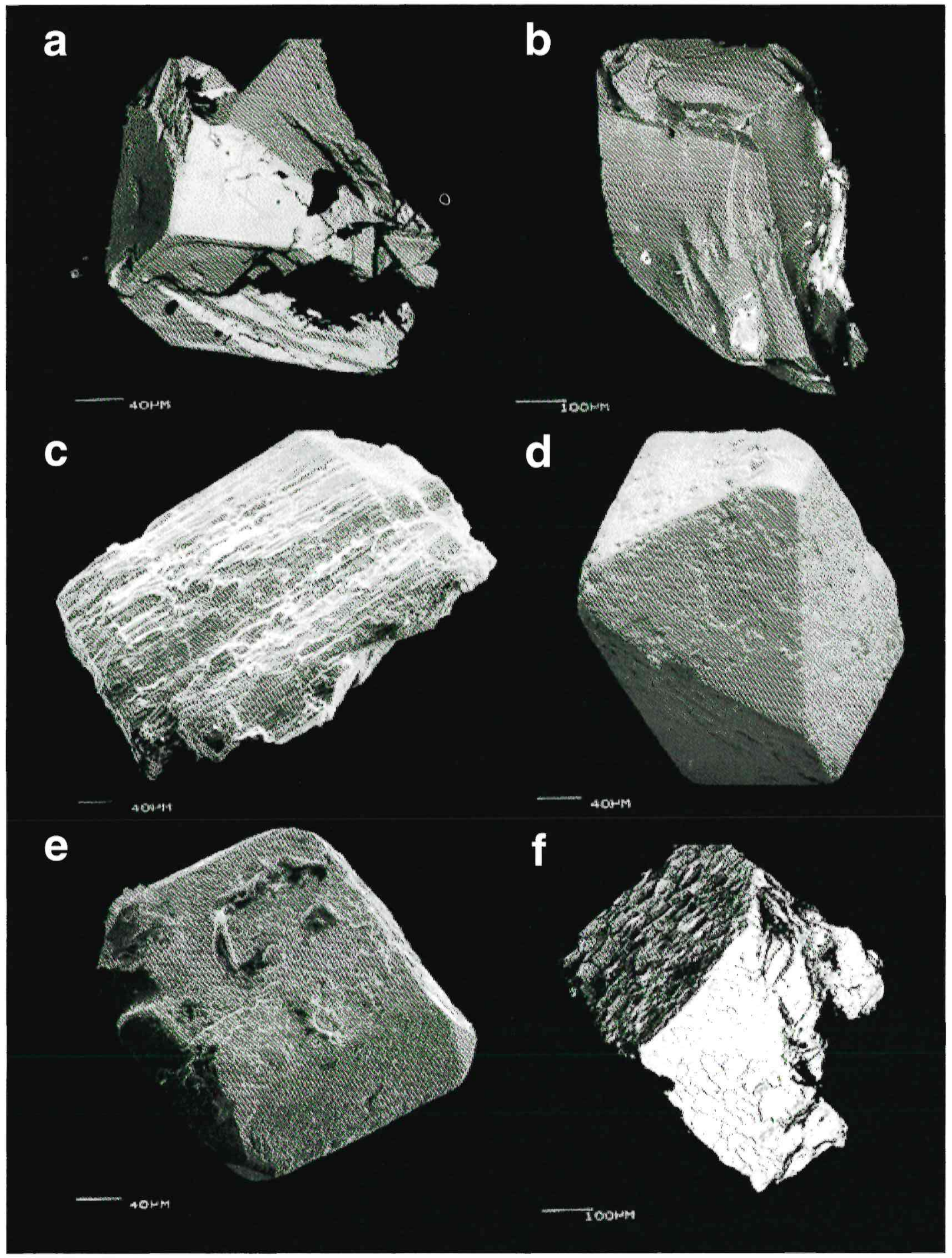


Figure 12 SEM photographs of selected mineral components in analysed panned concentrates.

The mineralogical study has shown that several factors restrict the extent to which the chemical analyses of the fine sediment fraction can be used as a guide to the presence of particular minerals or contaminants. For example, some elements occur predominantly in the common minerals that are present throughout the samples. Thus, Ca, Rb and Sr are likely to occur in feldspars, while Ti and Fe will occur largely in widespread heavy minerals such as magnetite and ilmenite. High concentrations of these elements are, in general, dispersed throughout the common minerals and are not as such anomalous.

Several panned concentrates were chemically analysed to determine whether the element concentrations accurately reflected the presence of particular minerals or contaminants, and the compositions of their respective fine sediment fractions. The analytical results are summarised in Table 9. These data show that in areas of known mineralisation or contamination, the metallic element concentrations in the panned concentrate are generally higher than those of the fine sediment fraction, whereas in areas of little or no known mineralisation, the metallic element concentrations in the panned concentrate are generally lower than those of the fine sediment fraction. Overall, however, elemental abundances in the two sediment fractions are sufficiently similar to infer that the mineralogy of the panned concentrates is being expressed by the bulk sediment chemistry. Many elements occur at relatively low concentrations, despite being statistically anomalous. They may occur as minor components of minerals rather than as the principal constituents of isolated grains. Thus, Zn may occur in ilmenite and Cu as inclusions in pyrite (or altered pyrite). Similarly, Zr may occur as minute zircon inclusions in the common grains of the float fractions rather than as free grains in the non-magnetic fractions. There is considerable

Table 8 Average whole-rock concentrations of elements for the major groups of Hong Kong.

Element	Devonian Sandstone *n = 8*	Carboniferous Siltstone *n = 5*	Permian Siltstone *n = 1*	Jurassic Andesite *n = 9*	Jura. - Cret. Volcanic *n = 309*	Jura. - Cret. Granite *n = 372*	Cretaceous Sandstone *n = 15*
As ppm	4.1	1.8	24	4.1	6.6	1.4	1
Ba ppm	343	130	762	492	455	181	161
Bi ppm	<1	<1	<1	<1	<1	<1	<1
CaO wt%	0.24	0.61	0.01	5.9	1.7	0.91	0.64
Ce ppm	45	45	34	57	91	68	27
Co ppm	2.5	2.8	5	17	4.4	2.6	0.47
Cr ppm	44	17	90	22	25	20	8.9
Cs ppm	<2	<2	<2	<2	3.5	<2	<2
Cu ppm	<1	4.8	24	8	5.7	2.9	2.9
Fe_2O_3 wt%	4.4	2.8	4.7	7.8	2.8	1.6	2.6
Ga ppm	7.9	15	32	17	15	14	4.9
La ppm	16.8	18.6	23	27	48	33	13
MnO wt%	0.02	0.06	0.01	0.14	0.34	0.05	0.04
Mo ppm	<1	1.8	<1	1.8	1.8	1.1	<1
Nb ppm	5.4	22	17	12	19	24	5.7
Ni ppm	7.4	4	27	10.3	8.6	8.6	1.3
P_2O_5 wt%	0.05	0.04	0.03	0.27	0.09	0.03	0.07
Pb ppm	5.63	26	20	18	28	39	8.6
Rb ppm	77	248	253	124	235	344	76
Sc ppm	<2	5	21	<2	2.4	<2	<2
Sn ppm	<1	5.6	7	<1	4.4	3.8	<1
Sr ppm	7.9	84	63	498	156	65	46
Th ppm	8.25	32	19	15	28	36	7.6
TiO_2 wt%	0.6	0.14	0.97	0.91	0.34	0.36	0.33
U ppm	1.3	9.8	1	3.3	5.6	9.8	1.5
V ppm	<2	5.2	102	20	14.8	4.1	4.1
W ppm	4.4	<1	<1	3.4	5.8	5.4	<1
Y ppm	14	70	50	35	47	65	11
Zn ppm	4.5	21	47	75	52	29	10
Zr ppm	136	110	175	190	197	129	54

Ag, Cd, Ge, Hg, Sb and Se not analysed in whole rocks.

uncertainty as to the partitioning of many elements between floats and sinks.

Despite the use of sophisticated analytical techniques to identify the metalliferous grains in selected panned concentrates, these identifications are incomplete because the choice of grains for such analysis is subjective. Although several successes can be claimed in linking chemical anomalies to the presence of metalliferous grains (e.g. cassiterite and anthropogenic tin contamination), there is a little evidence of sphalerite or contaminants that would account for the widespread Zn enrichment in many samples. One possibility is that the zinc may be contained within non-magnetic tin microspheres, which may represent a solder contaminant. For these reasons, the mineralogical results do not provide an exhaustive record of every substance in the panned concentrates. Equally, they do not provide a record of the complete distributions of particular elements among the substances present in the samples.

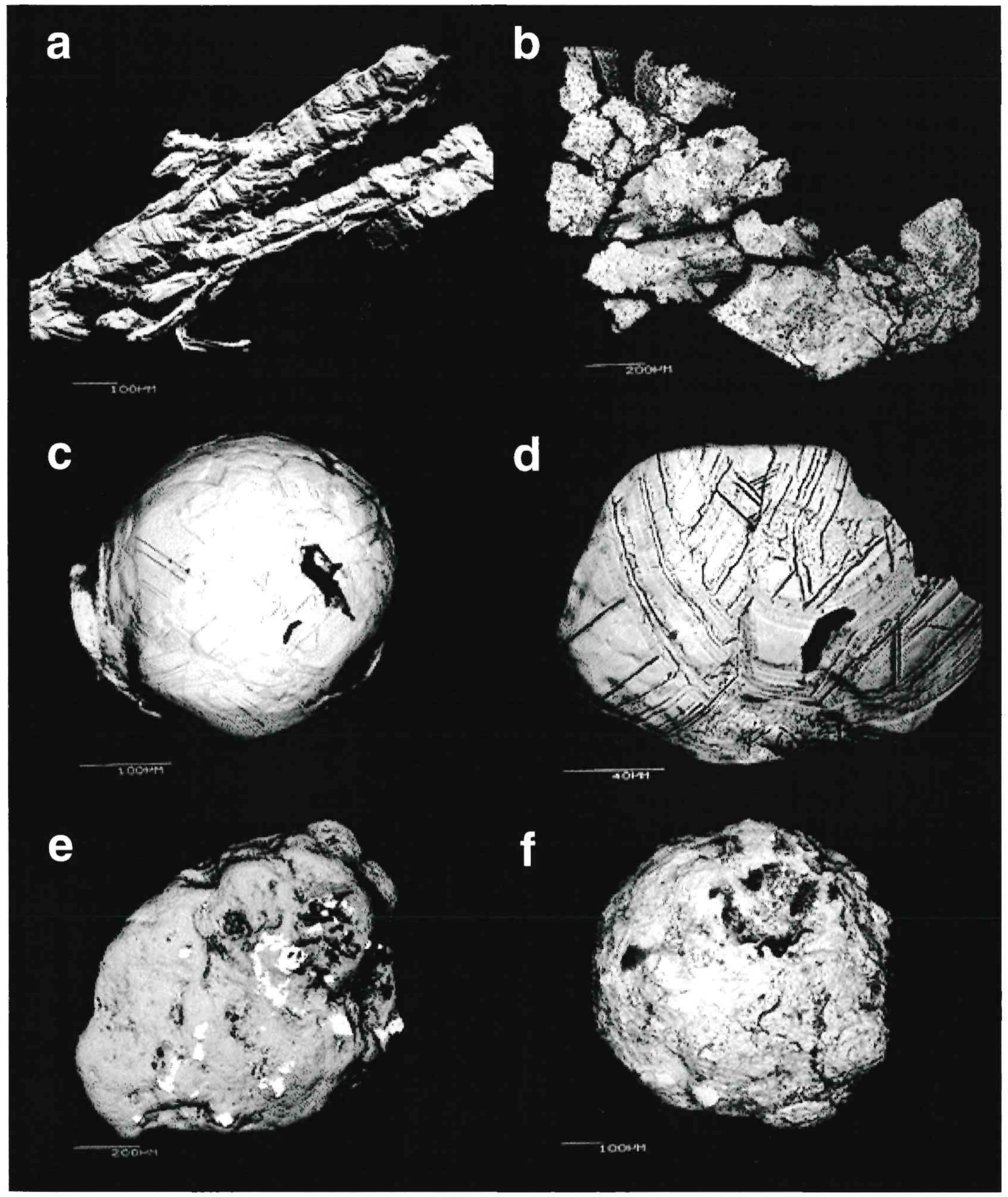


Figure 13 SEM photographs of anthropogenic contaminants in analysed panned concentrates.

Table 9 Analyses of representative sediment and panned concentrate pairs for samples containing known metalliferous minerals and metal contaminants.

Element	Sediment 0009	Pan 0009	Sediment 0019	Pan 0019	Sediment 0026	Pan 0026	Sediment 0035	Pan 0035	Sediment 0038	Pan 0038	Sediment 0039	Pan 0039	Sediment 0049	Pan 0049	Sediment 0050	Pan 0050
Ag ppm	<1	2	<1	4	<1	<1	<1	8	<1	2	2	5	7	<1	<1	<1
As ppm	22	31	16	10	22	10	28	91	37	118	52	139	42	113	33	177
Ba ppm	498	304	526	128	436	198	349	363	332	435	354	424	<8	<8	163	39
Bi ppm	7	5	3	<1	4	2	2	3	4	7	5	6	158	400	73	314
CaO wt%	1.61	0.7	0.33	0.1	0.18	0.1	0.40	0.1	0.41	0.1	0.37	0.1	0.19	0.13	0.37	0.59
Cd ppm	3	<1	<1	3	<1	<1	3	<1	<1	<1	<1	<1	<1	<1	<1	<1
Ce ppm	103	62	53	14	93	44	98	62	117	62	105	41	58	41	67	71
Co ppm	19	10	8	<3	<3	3	11	14	21	16	10	15	<3	<3	9	5
Cr ppm	26	28	24	6	21	4	31	53	35	42	25	41	11	9	30	25
Cs ppm	2	<1	16	7	24	5	13	12	12	13	12	5	5	3	4	10
Cu ppm	38	28	13	1	1	<1	24	49	41	57	34	60	79	71	25	98
Fe_2O_3 wt%	6.55	4.4	4.01	0.8	3.52	1.3	4.29	7.6	4.70	8.0	4.66	8.4	2.91	3.66	4.55	5.88
Ga ppm	21	13	13	4	13	5	14	12	14	12	14	15	11	9	14	14
Ge ppm	4	1	<1	<1	<1	<1	<1	<1	<1	<1	<1	2	2	5	<1	9
La ppm	39	15	24	7	40	26	68	21	62	21	47	22	22	13	33	22
MnO wt%	0.37	0.5	0.23	0.0	0.03	0.0	0.26	0.6	0.33	0.6	0.32	0.6	0.08	0.10	0.07	0.08
Mo ppm	4	14	<1	<1	<1	<1	2	4	2	5	2	6	234	1044	79	978
Nb ppm	30	15	22	5	25	7	20	13	19	14	23	17	54	32	37	25
Ni ppm	12	9	11	<2	7	2	22	15	30	16	23	22	8	<2	12	3
P_2O_5 wt%	0.11	0.0	0.12	0.0	0.05	0.0	0.12	0.0	0.15	0.0	0.12	0.0	0.06	0.01	0.09	0.04
Pb ppm	645	825	36	8	28	8	66	139	101	161	104	192	548	1840	203	1946
Rb ppm	285	151	133	42	168	57	141	123	131	145	166	151	119	69	150	61
Sb ppm	<1	2	5	2	7	2	4	3	4	3	2	6	<1	<1	3	<1
Se ppm	<1	<1	<1	<1	<1	<1	<1	<1	3	<1	<1	2	<1	3	<1	3
Sn ppm	276	262	9	<2	4	3	18	22	16	28	22	47	585	1910	547	1584
Sr ppm	91	38	23	5	14	5	27	17	26	18	31	19	4	3	12	7
Th ppm	27	15	18	4	24	9	29	15	23	17	25	16	62	103	53	92
TiO_2 wt%	1.28	0.7	0.58	0.1	0.63	0.1	0.54	0.4	0.59	0.5	0.47	0.5	0.15	0.05	0.57	0.17
U ppm	10	<1	3	<1	6	<1	7	2	10	4	7	3	9	3	7	3
V ppm	106	53	41	9	46	16	37	46	49	53	33	48	10	4	44	17
W ppm	12	9	<2	<2	5	<2	3	6	4	8	12	15	123	603	70	771
Y ppm	37	18	29	11	42	15	48	20	51	22	46	23	79	34	55	59
Zn ppm	784	483	105	11	33	11	171	197	224	231	249	279	320	134	92	86
Zr ppm	1821	118	984	60	1029	72	688	213	473	246	759	249	344	248	684	275

Metalliferous minerals and/or contaminants :

0009	pyrite, cassiterite
0019	Fe-flakes, steel, wire, pottery
0026	No known metalliferous minerals
0035	Fe-flakes, steel
0038 :	Pyrite, magnetite
0039 :	Pyrite, magnetite
0049 :	Fe-flakes, steel, tin wire, pyrite, magnetite
0050 :	Fe-flakes, steel, tin wire, pyrite, magnetite

In the following discussion of the geochemical maps, an attempt has been made to account for the various anomalies using information obtained from the mineralogical study and sampling records. In many instances, particularly in areas where no mineralogical data is available, a subjective assessment is made as to the source of the anomalies using what is known of the behaviour of elements in other areas. This is not entirely satisfactory, and, therefore, the interpretation of such anomalies should be treated with caution. A general summary of the natural concentrations of elements in stream sediments controlled by the underlying geology is given in Appendix 3.

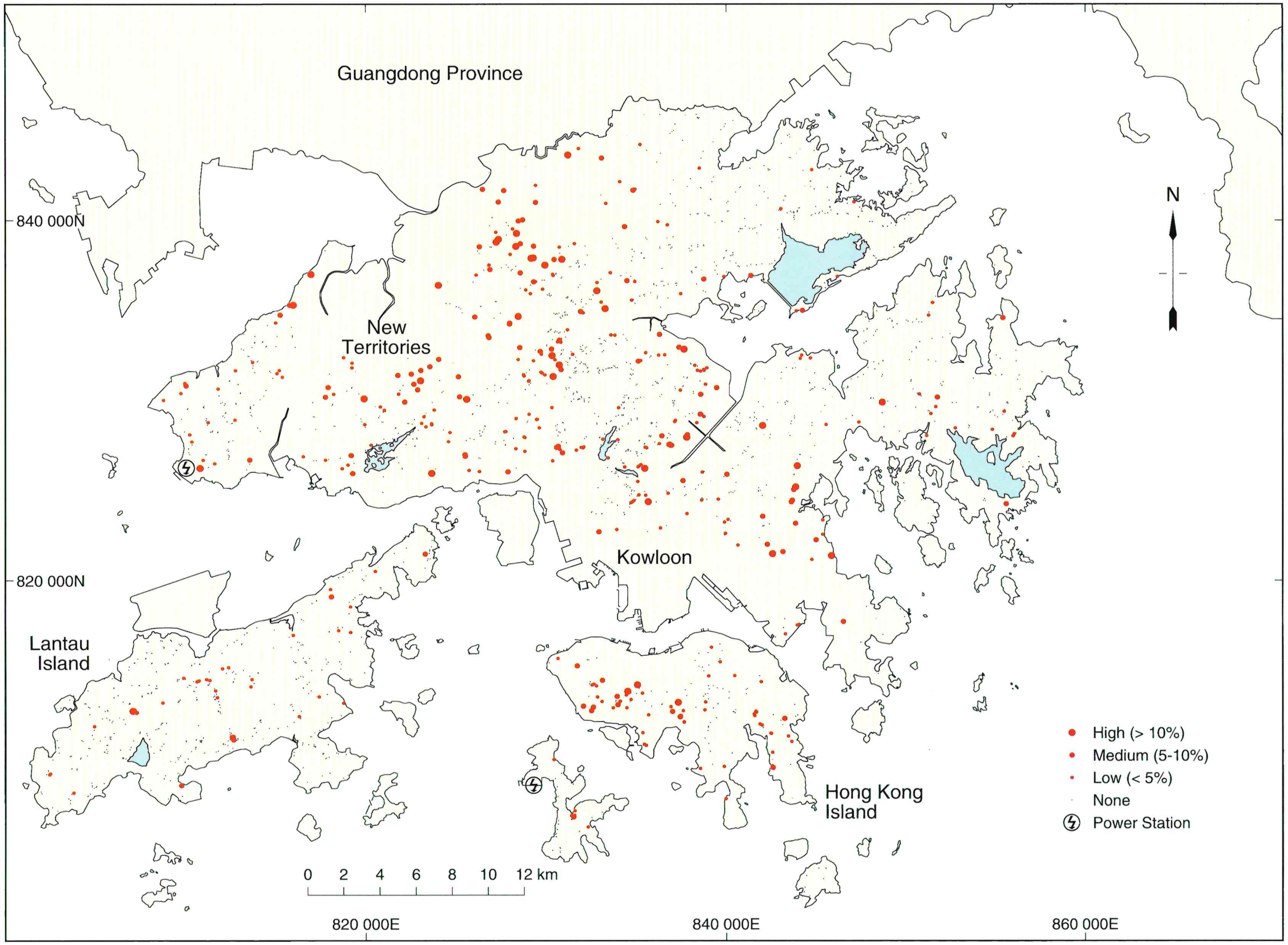
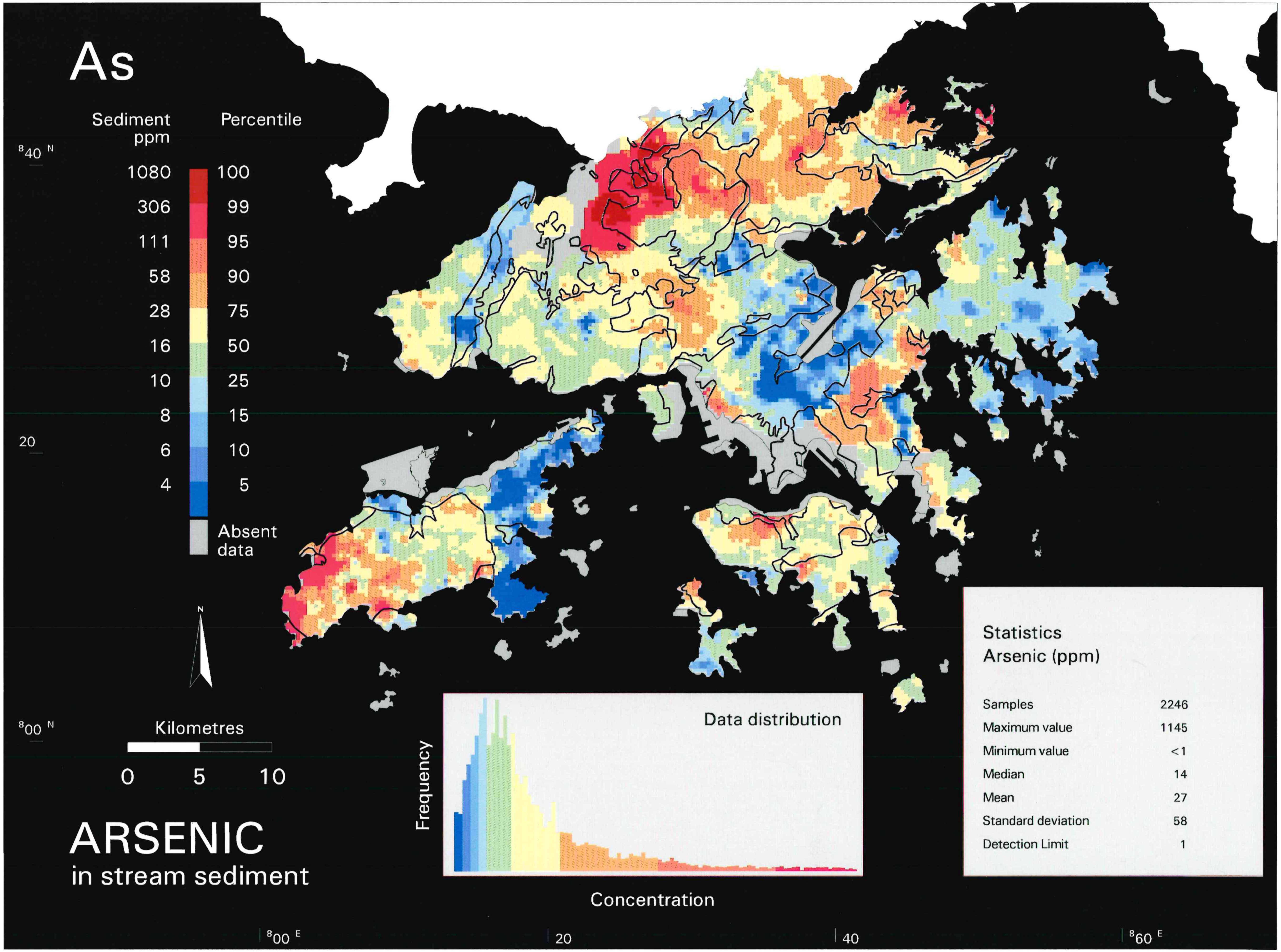


Figure 14 Distribution of fly-ash in stream sediments of Hong Kong.

GEOCHEMICAL MAPS



ARSENIC
in stream sediment

Statistics
Arsenic (ppm)

Samples	2246
Maximum value	1145
Minimum value	<1
Median	14
Mean	27
Standard deviation	58
Detection Limit	1

Arsenic

As

Synopsis

Arsenic values are generally low (<10 ppm) over the central and eastern New Territories, and northeastern Lantau Island, whereas moderate values (10–28 ppm) characterise much of the western New Territories, Kowloon and Hong Kong Island. High levels of arsenic (>28 ppm) are present over a broad area of the northern New Territories, and prominent anomalies occur in the vicinities of Tai Mo Shan, Ma On Shan, Sai Kung, Lai Chi Chong and southwestern Lantau Island.

Over the northern New Territories, the high arsenic levels are associated mostly with outcrops of coarse ash crystal tuff (Tsuen Wan Volcanic Group). Strong anomalies in the Ngau Tam Mei, Lok Ma Chau, and Lin Tong Mei areas are influenced by anthropogenic contamination superimposed on a high natural background level. Arsenic minerals have not been reported from the district but are probably associated with Pb–Zn–Cu mineralisation similar to that found at Lin Ma Hang.

In the central and eastern New Territories, moderate to strong arsenic anomalies (28–111 ppm) at Tai Mo Shan, Ma On Shan, and Lai Chi Chong are associated with outcrops of coarse ash crystal tuff (Tsuen Wan Volcanic Group). By contrast, arsenic values are distinctly lower (<16 ppm) to the southeast over granitic areas (Kwai Chung Suite).

Moderate arsenic values (10–28 ppm) in the western New Territories coincide with outcrops of fine- and medium-grained Tsing Shan and Tai Lam granites (Lamma Suite). Arsenic values are low (<10 ppm) over intervening outcrops of andesite of the Tuen Mun Formation.

In Kowloon, Hong Kong Island and Po Toi Island, moderate levels of arsenic (10–28 ppm) are associated with granitic rocks (Lion Rock Suite) and volcanic rocks (Repulse Bay Volcanic Group). Small anomalies in the Central and Southern districts are due mainly to anthropogenic contamination.

On Lamma Island, arsenic values are generally low to moderate (8–16 ppm) in the south over granite outcrops (Cheung Chau Suite), and are moderate to high (16–58 ppm) in the north over outcrops of volcanic and granitic rocks belonging to the Tsuen Wan Volcanic Group and Lamma Suite respectively.

High levels of arsenic (>111 ppm) in the southwestern part of Lantau Island mainly coincide with outcrops of coarse ash crystal tuff (Tsuen Wan Volcanic Group). Although arsenic-bearing minerals have not been reported from this area, they are known to occur farther north in association with Fe mineralisation. In central Lantau Island, moderate arsenic values (10–28 ppm) characterise much of the area underlain by the Lantau Volcanic Group. By contrast, arsenic values are low (<6 ppm) over outcrops of granitic rocks (Lamma, Kwai Chung and Cheung Chau suites) in northern and eastern parts of the island.

Geochemistry of arsenic

Arsenic, along with P, Sb and Bi is a chemical element belonging to Group VA of the periodic table. It is not preferentially enriched in silicic or basic igneous rocks, though hydrothermal processes lead to its enrichment. Mielke (1979) reports an average crustal abundance of 1.8 ppm, and for igneous rocks: ultrabasic, 1 ppm; basaltic 2 ppm; and granitic 1.5–1.9 ppm. The use of arsenic as a pathfinder element for Au, Ag and other precious metals is well documented (e.g. Boyle & Jonasson, 1973; Dunn, 1989; Plant *et al.*, 1989; 1991). High As anomalies are a common characteristic of epithermal and mesothermal gold deposits. Arsenic is strongly chalcophile and is partitioned into sulphides and sulpharsenides, notably arsenopyrite [FeAsS]. In primary rock-forming silicate minerals, arsenic is incorporated to a limited extent through the replacement of Fe^{3+} or Al^{3+} by As^{3+}. Substitution of P^{5+} by As^{5+} may also give rise to arsenic concentration in phosphates such as apatite (Tremearne & Jacob, 1941) due to the similarity of the PO_4^{3-} and AsO_4^{3-} anionic groups.

In sedimentary rocks, arsenic is concentrated in clays, hydrous Fe and Mn oxides, sulphides and phosphates (Ure & Berrow, 1982). The average As concentration in shales (13 ppm) is thus greater than that in sandstones (<5 ppm; Davies, 1980) and carbonates (Wedepohl, 1978). The highest concentrations (*c.* 20 ppm) are typically found in phosphatic sediments (Tremearne & Jacob, 1941), although coals and ironstones (particularly phosphatic) can also contain appreciable amounts of arsenic.

Surface environment geochemistry

Arsenic is mobilised in the weathering of rocks to produce arsenites and arsenates (Irgolic *et al.*, 1995). During lateritic weathering (especially in arid environments) hydromorphic dispersion haloes of As, leached during sulphide oxidation, are best developed in ferruginous lateritic horizons due to co-precipitation with Fe oxyhydroxides (Butt, 1992).

Arsenic in stream sediments occurs mainly as the oxides As_2O_3 and As_2O_5 (which are soluble in acidic waters) and as sulphides (e.g. FeAsS and As_2S_3), heavy–metal arsenates and co-precipitated complexes with iron oxides, which are much less soluble (Wedepohl, 1978). The relatively small flux of arsenic, which is released into stream waters during weathering, may remain mobile only if pH and Eh values are sufficiently low to favour its persistence in trivalent form. Otherwise, dissolved arsenic is rapidly oxidised to the relatively insoluble As^{5+} state and, as arsenate (AsO_4^{3-}), becomes sorbed to hydrous oxides of Fe and Mn, clays and organic matter (compare the behaviour of the similar phosphate anion, PO_4^{3-}). Consequently, dissolved concentrations of arsenic rarely exceed a few µg/l except in perturbed waters such as mine drainage. Fordyce *et al.* (1995) note that the retention of arsenic in solution is constrained by co-precipitation with Fe along with other elements such as Ba, Co, Ni, Pb and Zn.

Arsenic contamination of the environment has arisen as a result of mining and smelting (Breward *et al.*, 1994; Thornton, 1996). Other anthropogenic activities in the urban environment that may lead to an increase of As in stream sediments are cited in Cooper & Thornton (1994). For example, Angino *et al.* (1970) report the presence of As in common household detergents. Arsenic has great notoriety as a poison, though there are great differences in the toxicity of different arsenic compounds.

Detailed description

In the northern New Territories, the highest levels of arsenic are recorded in the Lok Ma Chau (117–492 ppm), Ngau Tam Mei (118–922 ppm), Lin Tong Mei (149–1145 ppm) and Pat Heung (124–494 ppm) areas. These anomalies are commonly accompanied by high Sb (6–11 ppm), Ag (0.5–3.2 ppm), Pb (29–587 ppm), Zn (73–678 ppm), W (6–44 ppm) and Hg (1–3.4 ppm) suggesting that they are likely to represent the combined effect of high natural background levels and anthropogenic contamination. High natural background levels over northern New Territories are indicated by the broad distribution of high values.

In the central New Territories, elevated arsenic levels (28–111 ppm) surrounding Tai Mo Shan are associated mainly with outcrops of coarse ash crystal tuff (Tsuen Wan Volcanic Group). The arsenic anomaly coincides with high levels of Cu (18–73 ppm), Cd (1.0–1.4 ppm), Sc (15.7–19 ppm), Pb (226–421 ppm) and Zn (144–375 ppm) and is likely to be related to the known Cu–Fe–Pb–Zn mineralisation in the district.

A small arsenic anomaly in the Kwai Chung area (118 ppm) is present over outcrops of the fine-grained Needle Hill Granite (Kwai Chung Suite). Arsenic minerals are not known from the area and the associated high levels of Cu (365 ppm), Pb (883 ppm), Zn (847 ppm), Sn (120 ppm) and W (143 ppm) strongly suggest that anthropogenic contamination has affected the sediment samples.

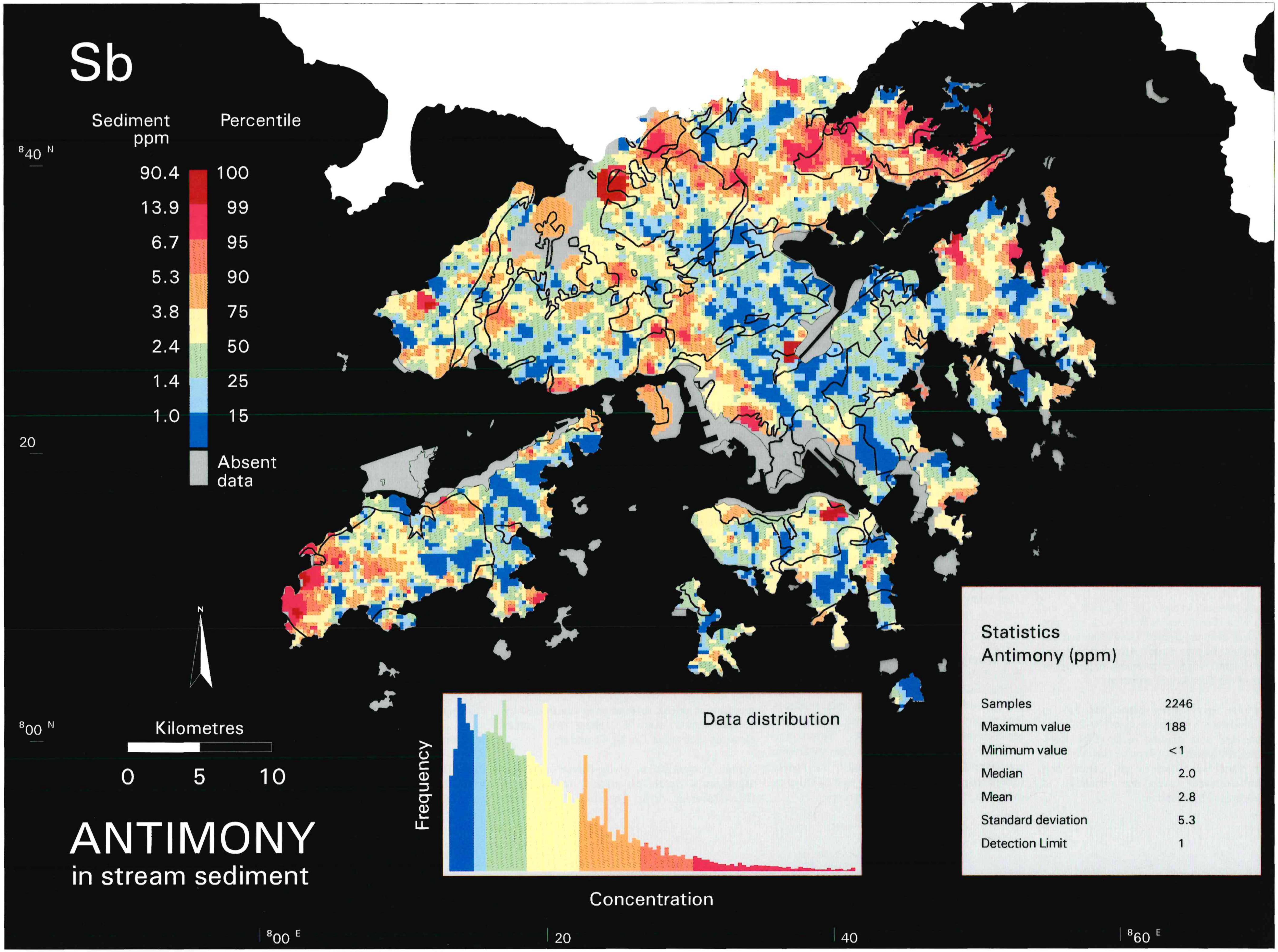
A distinctive arsenic anomaly (111 ppm) in the vicinity of the Ma On Shan mine coincides with a strong Bi anomaly (361 ppm). Although the area is well-known for Fe-related skarn mineralisation, arsenic minerals have not been reported. The accompanying high concentrations of Cu (303 ppm), Pb (896 ppm), Zn (490 ppm), Sn (449 ppm) and W (152 ppm) suggest that the high levels of arsenic are probably related to mining waste.

A broad arsenic anomaly (28–117 ppm) is present in the Sai Kung area coinciding with outcrops of coarse ash crystal tuff (Repulse Bay Volcanic Group). No arsenic mineralisation is known from this area and, therefore, the moderate to high arsenic levels probably reflect the natural background.

Background levels over Hong Kong Island generally lie between 10 and 28 ppm with several small arsenic anomalies (>28 ppm) in the Central, Shau Kei Wan and Deep Water Bay districts. The anomalies are associated with moderate levels of Cu, Cr and Pb, and are thought to be due to local anthropogenic contamination.

A small arsenic anomaly (28–111 ppm) on the northern tip of Lamma Island coincides with outcrops of coarse ash crystal tuff (Tsuen Wan Volcanic Group). By contrast, arsenic levels are low to moderate over outcrops of the South Lamma Granite (Cheung Chau Suite) in the southern part of the island. The low abundance of industrial metals in samples related to the arsenic anomaly suggest that the elevated arsenic values probably reflect natural background levels.

A broad area of high arsenic values (>111 ppm) is present in southwestern Lantau Island, which coincides largely with outcrops of coarse ash crystal tuff belonging to the Tsuen Wan Volcanic Group. Prominent anomalies at Tai O (123–182 ppm), Yi O (131–243 ppm) and Fan Lau (162–210 ppm) are accompanied by moderate to high Ag (0.5–5.3 ppm), Co (5–11 ppm), Cs (10–27 ppm), Mo (4–9 ppm), Sb (4–21 ppm) and W (5–21 ppm) values. This assemblage of metals suggests that the area is strongly mineralised.



Sediment ppm	Percentile
90.4	100
13.9	99
6.7	95
5.3	90
3.8	75
2.4	50
1.4	25
1.0	15
▨	Absent data

ANTIMONY
in stream sediment

Statistics
Antimony (ppm)

Samples	2246
Maximum value	188
Minimum value	<1
Median	2.0
Mean	2.8
Standard deviation	5.3
Detection Limit	1

Antimony

Sb

Synopsis

Background levels of antimony are generally low (<2.4 ppm) over areas underlain by granitic rock. These include the central and western New Territories, Kowloon and Hong Kong Island. The highest levels of antimony (>6.7 ppm) are found in four main areas: northern New Territories, eastern New Territories, parts of central New Territories, and western Lantau Island.

In the northern New Territories, the strongest antimony anomalies (>13.9 ppm) are found in areas which are heavily contaminated by industrial metals. However, high natural values coincide with outcrops of Upper Mesozoic sedimentary rock in the northeast, and antimony values are moderate to high (2.4–13.9 ppm) over large areas of Middle Jurassic volcanic rock (Tsuen Wan Volcanic Group).

Natural background levels are moderate to high (2.4–13.9 ppm) in the eastern New Territories, particularly over outcrops of Lower Cretaceous volcanic rocks (Repulse Bay Volcanic Group). In the central New Territories, west of Tai Mo Shan, antimony levels are high (2.4–13.9 ppm) in areas of Sn–W mineralisation. The anomalies mostly occur in the vicinity of intrusive contacts between granodiorite (Lamma Suite) and volcanic rocks (Tsuen Wan Volcanic Group).

On Lantau Island, background levels of antimony are most pronounced (>6.7 ppm) over outcrops of coarse ash crystal tuff (Tsuen Wan Volcanic Group) in the southwest. Other smaller anomalies are present over volcanic outcrops of the Lantau Volcanic Group, and over granites of the Cheung Chau Suite. Antimony levels are generally low (<2.4 ppm) over granitic rocks (Kwai Chung Suite and Lamma Suite) in the north of the island, except for the far northeast where W mineralisation has been reported.

Geochemistry of antimony

Antimony is a Group VA element in the periodic table, a group that includes P, As and Bi, and the crystal chemistry and geochemistry of antimony are similar to As. In the natural environment antimony occurs most commonly as the Sb^{3+} ion, but can also occur as Sb^{5+} and as the native metal.

During magmatic processes antimony can substitute for Fe in minerals such as olivine and ilmenite, but it tends not to be preferentially enriched at any stage of magmatic fractionation (Ure & Berrow, 1982). Consequently, its abundances in intermediate and silicic rocks and in basic rocks are similar. Mielke (1979) cites a crustal abundance of 0.2 ppm and the following averages in igneous rocks: ultrabasic, 0.1 ppm; basaltic 0.2 ppm; and granitic 0.2 ppm. Known antimony minerals include antimonides, sulphides, complex sulphides and oxides, with the commonest phase being stibnite [Sb_2S_3]. Antimony is a strongly chalcophile element and its distribution relates to that of sulphide minerals (Boyle, 1968). The highest concentrations (>3 ppm) typically occur in the vicinity of hydrothermal deposits of galena and sphalerite. Antimony can be used as a pathfinder element for Au mineralisation, especially in combination with other pathfinders such as As and Bi (Plant *et al.*, 1989, 1991).

Fine-grained argillaceous and organic-rich sediments are typically enriched in antimony (>1 ppm) relative to igneous lithologies, reflecting the strong tendency for the element to become sorbed to hydrous oxides, organic residues and clay minerals in favourable environments (Ure & Berrow, 1982). Pyritic black shales and mudstones may also contain relatively high antimony levels in the authigenic sulphide phase. Coarse quartzo–feldspathic sediments, quartzites and carbonates usually contain less than 0.5 ppm Sb. Mielke (1979) cites levels of antimony in shales, sandstones and carbonates as 1.5, <0.1 and 0.15 ppm respectively.

Surface environment geochemistry

In stream sediments antimony is present primarily as detrital sulphide minerals (e.g. stibnite, sphalerite, galena), some of which may weather relatively rapidly under acid, oxidising conditions. The further remobilisation of antimony is rather limited due to the tendency of Sb^{3+} to hydrolyse, giving the antimonyl group SbO^+ which tends to precipitate in the form of insoluble basic salts and to be adsorbed by secondary hydrous oxides of Fe, Al and Mn at pH levels in the range 4.0–8.0. Antimony in the form of Sb_2O_3 is largely immobile.

Anthropogenic anomalies are associated with metalliferous mining (gold and sulphides) and metal smelting (Edwards *et al.*, 1995), and in urban waste with lead in solder, composite body panels and car dashboards. Shuman *et al.* (1978) in studies of polluted stream sediments from North Carolina, USA, found that in clean sediments most antimony was in crystalline minerals, whereas in the polluted sediment (which contained higher levels of antimony) the element was largely held in oxide coatings and partly in the organic fraction.

Detailed description

In the western New Territories, small antimony anomalies are present over outcrops of Tsing Shan and Tai Lam granite at Nim Wan (7–24 ppm), south of Lam Tei (9 ppm), and at Tai Lam Chung Tin (7 ppm). These are mostly accompanied by low levels of other metals, but occasionally they have moderate to high values of Cu (47–343 ppm), Pb (51–124 ppm) and Hg (1.0–2.6 ppm) indicating local anthropogenic contamination.

In the northern New Territories, strong anomalies are present at Mai Po (9–88 ppm), Kwu Tung (8–11 ppm), Fan Ling (7–11 ppm), Lin Ma Hang (8–9 ppm), Kwai Tau Leng (7–11 ppm), Lai Che Wo (7–12 ppm) and Double Island (7–12 ppm). At Mai Po, the high antimony levels are accompanied by very high Cu (20–2849 ppm), Pb (154–884 ppm), Zn (105–17 489 ppm), As (160–648 ppm) and Sn (8–151 ppm) indicating a high degree of contamination. Similar high levels of industrial metals accompany the anomalies at Kwu Tung (e.g. Cu 15–875 ppm, Pb 102–587 ppm, Zn 48–9369 ppm, As 49–1145 ppm), and at Fan Ling (e.g. Pb 29–340 ppm, Zn 52–234 ppm, Sn 2–102 ppm, As 20–130 ppm). The anomaly at Lin Ma Hang coincides with a known occurrence of Pb–Zn–Cu mineralisation. Moderate to high levels of Pb (26–232 ppm), Zn (59–193 ppm) and As (7–75 ppm) in stream sediments probably reflect the combined affect of high natural background levels and anthropogenic contamination due to mining waste. Anomalies at Kwai Tau Leng, Lai Che Wo and Double Island are thought largely to reflect high natural background levels of antimony. These are associated mainly with outcrops of Cretaceous sedimentary rock and coarse ash crystal tuff (Tsuen Wan Volcanic Group). Samples from the Kwai Tau Leng area typically contain moderate to high levels of Cu (3–87 ppm), Pb (26–283 ppm), Zn (43–505 ppm) and As (16–210 ppm). Those from the Lai Che Wo area show slightly lower levels of Pb (46–143 ppm), Zn (39–189 ppm), and As (31–131 ppm). On Double Island, the high antimony levels are accompanied by high Pb (27–342 ppm), As (13–135 ppm) and Hg (1.1–2.7 ppm).

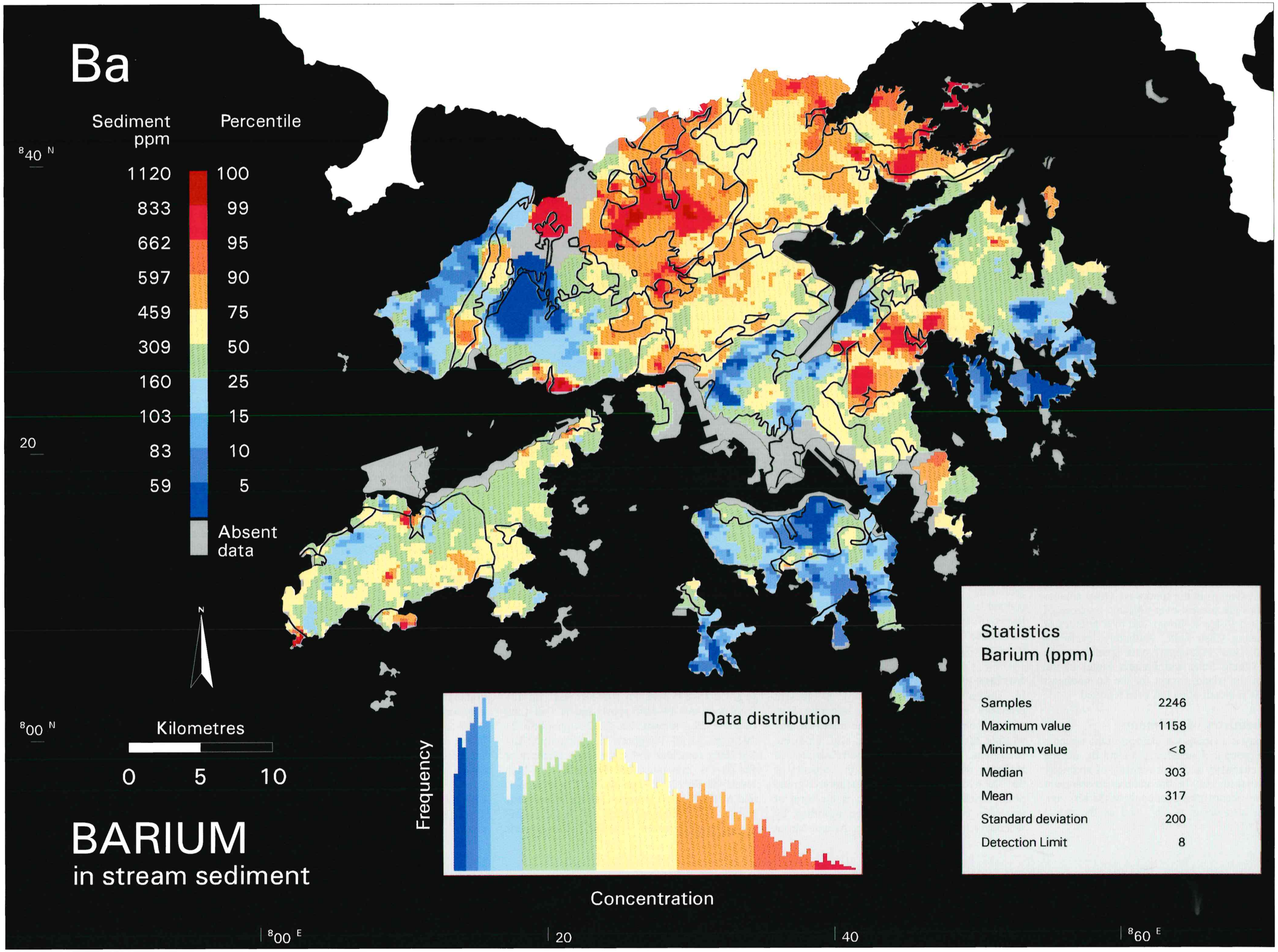
Over the central New Territories, small antimony anomalies are present at Sheung Fa Shan (7–13 ppm), Chuen Lung (7–8 ppm), Sha Tin (188 ppm) and Kwai Chung (11 ppm). At Sheung Fa Shan and Chuen Lung, these are related to known sites of Pb–Zn–Cu mineralisation. At Sheung Fa Shan, Sn–W–Mo mineralisation is also present and the high levels of antimony are typically accompanied by high levels of Pb (72–773 ppm), Zn (163–272 ppm), As (30–86 ppm), Bi (11–488 ppm), W (27–528 ppm) and Mo (4–29 ppm). Samples from Chuen Lung contain similar high levels of Pb (142–219 ppm) and Zn (273–487 ppm), but relatively low Bi (5–10 ppm), W (8–18 ppm), and Mo (2.8–4.6 ppm). The anomaly at Sha Tin is due to a single highly contaminated sample as indicated by the very high levels of accompanying Pb (2256 ppm), Zn (318 ppm) and Sn (8881 ppm). Moderate levels of these metals (e.g. Pb 96 ppm, Zn 103 ppm, and Sn 20 ppm) are associated with the antimony anomaly at Kwai Chung, which occurs over outcrops of fine-grained Needle Hill Granite, and is thought to be only weakly contaminated.

In the eastern New Territories, antimony levels are generally slightly elevated over outcrops of coarse ash crystal tuff (Repulse Bay Volcanic Group) with prominent anomalies at Lai Chi Chong (7–26 ppm), Tai Tan (10 ppm) and Chek Keng (8–9 ppm). Except for slightly enhanced levels of As (9–48 ppm), these antimony anomalies are not accompanied by high levels of other metals. Typical values are as follows: Pb 14–63 ppm, Zn 18–134 ppm, Sn 8–13 ppm, W 2–13 ppm, Mo 0.1–2.7 ppm. This suggests that there has been minimal anthropogenic contamination of stream sediments.

On Hong Kong Island, a prominent antimony anomaly (91 ppm) is present at North Point. Although Zn mineralisation has been reported from the area (Peng, 1978), the accompanying high levels of Sn (1256 ppm) and Pb (857 ppm) suggest that stream sediment has been affected by anthropogenic contamination. Other minor anomalies at Mount Collinson and Pokfulam are also accompanied by moderate to high Pb (60–129 ppm) and Zn (70–134 ppm) suggesting that they are similarly affected by contamination.

On Lantau Island, small anomalies at Yam O (8–10 ppm), Mui Wo (9 ppm), Chi Ma Wan (7–11 ppm), Shek Pik (7–9 ppm), Tung Chung (7–9 ppm) and Ngong Ping (7 ppm) are mostly due to local contamination. However, most of the high values in the Yi O area of southwestern Lantau Island (>6.7 ppm) are thought to be natural. This area is underlain principally by coarse ash crystal tuff (Tsuen Wan Volcanic Group) and the elevated levels of antimony coincide with an area of known Fe mineralisation (Peng, 1978). Although accompanying levels of Pb (38–77 ppm) and Zn (47–93 ppm) are relatively low, the stream sediments contain unusually high concentrations of As (94–330 ppm) and Sb (8–10 ppm), and moderate Bi (7–10 ppm). This element association of Sb–Bi–As has been used as a pathfinder for gold mineralisation (Plant *et al.*, 1989, 1991) and further investigations are required in this area to determine whether there is any mineral potential. A Sb–Bi–As component image is shown at the end of this section. High values of all three elements are shown as a white colour; high Sb–As and moderate Bi are indicated by a light yellow colour. This three component image also shows a similar, but broader, Sb–Bi–As high in the northwestern New Territories, although this enrichment is mainly of anthropogenic origin.

BARIUM
in stream sediment



Statistics
Barium (ppm)

Samples	2246
Maximum value	1158
Minimum value	<8
Median	303
Mean	317
Standard deviation	200
Detection Limit	8

Barium

Ba

Synopsis

Background levels of barium are generally low to moderate (60–300 ppm) over outcrops of granite and fine ash vitric tuff, and moderate to high (300–660 ppm) over outcrops of sedimentary rocks, granodiorite, quartz monzonite and coarse ash crystal tuff. The highest values (>660 ppm) are mostly present in the central and northern New Territories, whereas the lowest values (<60 ppm) occur in the western and eastern New Territories and on Hong Kong Island.

In the western New Territories, barium levels are low (<160 ppm) over outcrops of the Tsing Shan and Tai Lam granites (Lamma Suite), but are moderate to high (160–600 ppm) over outcrops of andesite of the Tuen Mun Formation. Some barium values may be enhanced by anthropogenic activity.

Moderate to high barium values (300–800 ppm) characterise much of central and northern New Territories, including offshore islands in the northeast. These anomalous values coincide mainly with outcrops of volcanic rocks belonging to the Tsuen Wan Volcanic Group, although barium levels are also high over outcrops of Upper Palaeozoic and Upper Mesozoic sedimentary rocks.

In the eastern New Territories, the highest barium levels (700–800 ppm) are found in the Sai Kung area in association with outcrops of coarse ash crystal tuff (Repulse Bay Volcanic Group) and quartz monzonite (Lion Rock Suite). Elsewhere, moderate to high barium levels (460–660 ppm) are present over outcrops of trachydacite lava (Kau Sai Chau Volcanic Group).

Low barium levels (<160 ppm) characterise most of Hong Kong Island, Lamma Island and Po Toi Island. Slightly elevated values (160–300 ppm) in the west and east of Hong Kong Island, and the north of Lamma Island coincide with outcrops of coarse ash crystal tuff (Tsuen Wan Volcanic Group) and quartz monzonite (Lion Rock Suite).

Moderate levels of barium (160–460 ppm) are present over most of Lantau Island. In the south and west of the island, elevated values (300–600 ppm) coincide with outcrops of quartz monzonite (Cheung Chau Suite) and coarse ash crystal tuff (Tsuen Wan Volcanic Group).

Geochemistry of barium

Barium is a member of the Group IIA elements of the periodic table (with Be, Mg, Ca, Sr and Ra). These elements are all highly electropositive metals, forming M^{2+} cations.

In igneous rocks, barium occurs mostly in K–feldspars and micas through the substitution of K^+ by Ba^{2+}, which have similar ionic radii (Ba^{2+}, 135 pm; K^+, 138 pm). Barium concentrations tend to be higher in K–feldspars than in phyllosilicates. The Ba^{2+} ion also substitutes for Ca^{2+} in plagioclase, pyroxenes and amphiboles, and in the non–silicate minerals apatite and calcite. The barium content of igneous rocks generally increases with increasing Si content (Ure & Berrow, 1982) from basic to silicic, though some highly evolved granites contain very low levels (<200 ppm; Plant *et al.*, 1980). Mielke (1979) quotes values of barium in igneous rocks as: ultrabasic, 0.4 ppm; basaltic, 330 ppm; granitic, 420–840 ppm; and syenitic, 1600 ppm. Sewell *et al.* (1992) report a large range of barium values for 17 representative Hong Kong granites (7–759 ppm, average 274 ppm) and suggest that an increase in the Rb/Ba ratio in the finer–grained lithologies is indicative of more pronounced feldspar fractionation. The principal barium mineral, baryte, is frequently associated with metalliferous mineral deposits. Secondary barium minerals may include authigenic baryte and witherite [$BaCO_3$].

In sedimentary rocks the concentration of barium is related to the abundance of K–feldspars, clay minerals and hydrous Fe and Mn oxides, onto which the element may be adsorbed (Wedepohl, 1978). Highest barium concentrations are found in shales (580 ppm) whilst carbonates and sandstones contain only *c.* 10 ppm (Mielke, 1979).

Surface environment geochemistry

Detrital feldspars, micas and, to a lesser extent, baryte are the principal carriers of barium in stream sediments (Ure & Berrow, 1982), so background levels of barium in sediments should be highest downstream of lithologies enriched in these minerals. Dissolution of barium from these minerals is generally slow, though biotite has been reported to release barium relatively rapidly under conditions of high Eh and low pH (Boettcher, 1966). Irfan (1996) reports that oxidation is an important process in weathering of Fe-bearing minerals, such as biotite, commonly found in Hong Kong granites and volcanic rocks. The dispersal of barium in surface waters is controlled by the presence or absence of hydrous Mn and Fe oxides, which adsorb Ba^{2+}. Co-precipitation of barium with Mn to form authigenic psilomelane may also occur (e.g. Burns & Burns, 1977). Elevated levels of barium occur where anoxic groundwaters enter oxidising streams. In less acidic environments, barium may also be removed from solution by sorption to clay minerals and organic matter (Wedepohl, 1978).

Barium is used as a filler in paint, rubber and plastics, and is used in a number of construction materials. Anthropogenic activities such as mineral extraction, have had considerable influence on the distribution of barium in the surface environment (British Geological Survey, 1996).

Detailed description

In the western New Territories, small barium anomalies (459–662 ppm) north of Tuen Mun and at Ha Tsuen are present over andesite outcrops of the Tuen Mun Formation. These contrast markedly with the low levels of barium (<160 ppm) over adjacent granite areas. At Tin Shui Wai, high levels of barium (832 ppm) over outcrops of Upper Palaeozoic sedimentary rocks are accompanied by moderate to high Sr (91 ppm), CaO (1.47 wt %), Co (13 ppm), Cd (1.5 ppm), V (77 ppm), Cu (60 ppm), Pb (120 ppm) and Zn (114 ppm). These high values may be partly enhanced by anthropogenic activity.

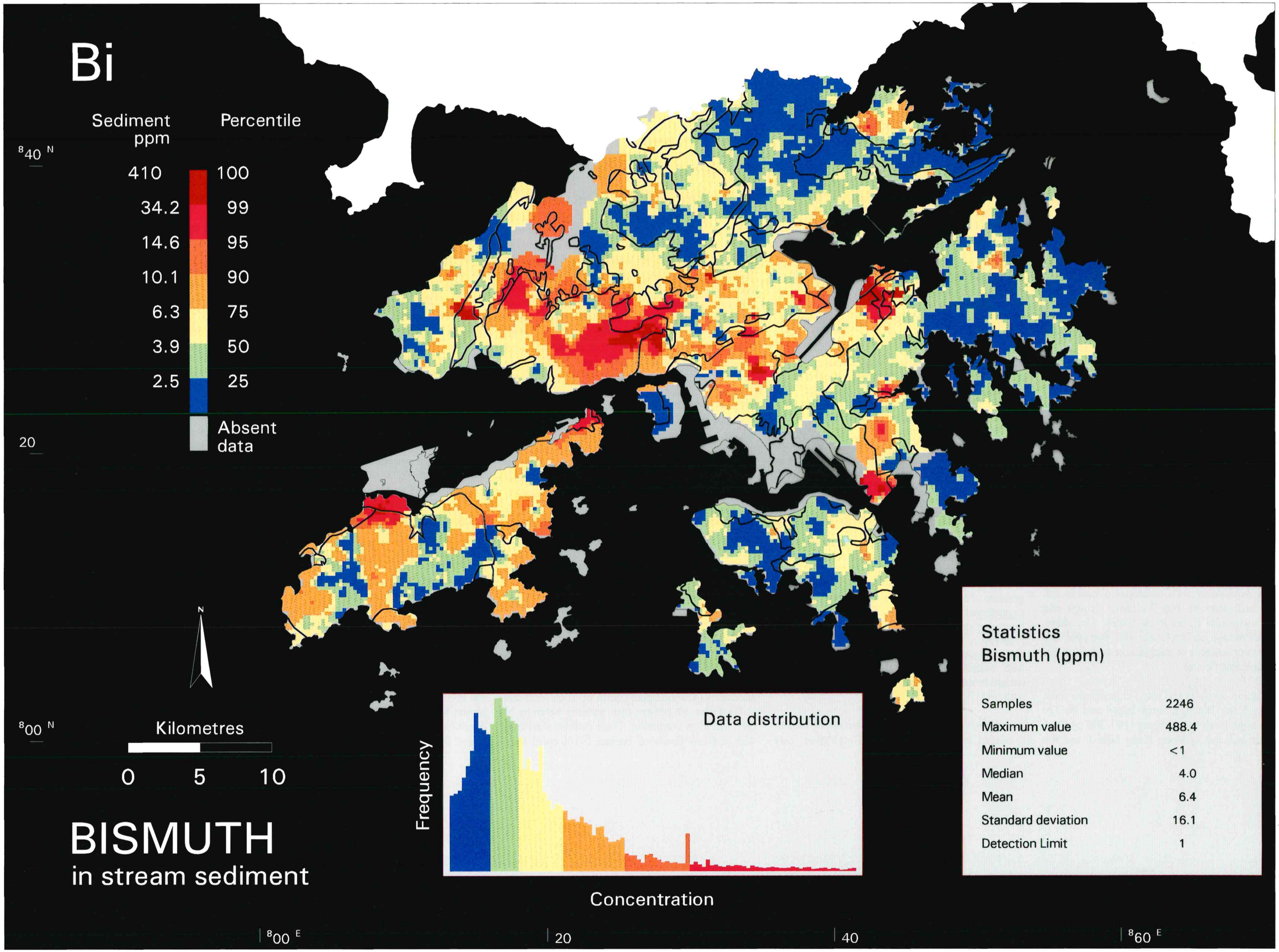
Barium levels are moderate to high over large areas of central and northern New Territories. Elevated values generally correspond with outcrops of coarse ash crystal tuff (Tsuen Wan Volcanic Group) and Upper Mesozoic sedimentary rocks. The highest values are at Kai Kung Leng (728–1082 ppm), Ngau Tam Mei (774–1082 ppm) and Lin Tong Mei (696–1122 ppm) in the north and these are typically accompanied by high Sr (29–83 ppm), Co (10–25 ppm), V (58–94 ppm), Pb (43–225 ppm) and Zn (63–649 ppm), and relatively low Cu (14–52 ppm) and Sn (5–20 ppm).

In northeastern New Territories, strong barium anomalies are present at Lin Ma Hang (785 ppm), Yung Shue Au (678–682 ppm), Lai Che Wo (713–773 ppm) and San A Tsuen (719 ppm), and also on several adjacent offshore islands (*c.* 720 ppm). At Lin Ma Hang, the high barium contents coincide with high Pb (142 ppm) and Zn (153 ppm) values but relatively low Sr (24 ppm), Cd (0.4 ppm) and Co (13 ppm). At Yung Shue Au, Lai Che Wo, and San A Tsuen, the high barium values accompany high Sc (17–22 ppm), Se (1.3 ppm), Cr (260–344 ppm) and Hg (1.0–3.7 ppm), but relatively low Cd (0.2–0.4 ppm), V (38–79 ppm), Pb (22–68 ppm) and Zn (33–86 ppm) values.

Elevated barium levels surrounding Tai Mo Shan are associated mainly with contact zones between Tai Po Granodiorite (Lamma Suite) and coarse ash crystal tuff (Tsuen Wan Volcanic Group), which commonly host Pb–Zn–Cu mineralisation. At Kap Lung, the barium anomaly (711 ppm) coincides with moderate to high Sr (148 ppm), Cd (2.6 ppm), V (79 ppm), Pb (219 ppm) and Zn (460 ppm). Similar values for these metals accompany a barium anomaly (891 ppm) at Tai Lam Chung (Sr 148 ppm, Cd 2.6 ppm, V 63 ppm, Pb 51 ppm and Zn 120 ppm), although values for Pb and Zn are notably lower.

In the eastern New Territories, barium anomalies are present mainly in the Sai Kung district and correspond with outcrops of coarse ash crystal tuff (Repulse Bay Volcanic Group). At Sai Kung, the high barium values (811–813 ppm) coincide with moderate to high Sr (82–170 ppm), Cd (1.5 – 3.1 ppm), Zn (127–160 ppm) and Hg (2.4–3.3 ppm) and may be enhanced by nearby outcrops of quartz monzonite (Lion Rock Suite) at Pyramid Hill. Farther to the southwest at Tai No, high barium values (693–794 ppm) are similarly accompanied by moderate to high Sr (109–120 ppm), Cd (1.9–2.2 ppm), Zn (98–110 ppm) and Hg (1.7–3.2 ppm). A barium anomaly (797–900 ppm) at Siu Lek Yuen in the Sha Tin area coincides with high levels of Sr (209–225 ppm), Zn (110–165 ppm) and Hg (1.53–1.83 ppm). In the Clear Water Bay area, background levels of barium (459–662 ppm) are slightly elevated over outcrops of trachydacite lava flows of the Pan Long Wan Formation (Kau Sai Chau Volcanic Group).

Barium levels are generally low to moderate over Hong Kong Island, Lamma Island and Po Toi Island, and moderate over large areas of Lantau Island. On Lantau Island, small barium anomalies are present at Tung Chung (731–868 ppm), Fan Lau (1158 ppm), Shek Pik (758 ppm) and Lo Kei Wan (759 ppm). These are mostly accompanied by moderate levels of Sr (57–90 ppm), V (18–91 ppm), Pb (46–125 ppm) and Zn (65–168 ppm), but relatively low levels of Cd (0.2–1 ppm) and Hg (0.2–0.95 ppm).



BISMUTH
in stream sediment

Statistics
Bismuth (ppm)

Samples	2246
Maximum value	488.4
Minimum value	<1
Median	4.0
Mean	6.4
Standard deviation	16.1
Detection Limit	1

Bismuth Bi

Synopsis

Low levels of bismuth (<2.5 ppm) are found over much of the northern and eastern New Territories, and parts of Hong Kong Island and Lamma Island. Moderate to high levels of bismuth (>6.3 ppm) are present over the central and western New Territories, and Lantau Island.

In the central and western New Territories, strong bismuth anomalies (>14.6 ppm) generally coincide with outcrops of the fine- and medium-grained Tsing Shan and Tai Lam granite (Lamma Suite). Small, local anomalies are also present in densely urbanised areas suggesting anthropogenic contamination.

In the northern New Territories, low to moderate levels of bismuth (<3.9 ppm) are present over outcrops of coarse ash crystal tuff (Tsuen Wan Volcanic Group), and low levels of bismuth (<2.5 ppm) generally predominate over outcrops of Upper Palaeozoic and Upper Mesozoic sedimentary rocks. Local anomalies are present in the vicinity of Yung Shue Au in northeast, and around the Tai Mo Shan area in the south.

In the central and eastern New Territories, moderate to high levels of bismuth (3.9–14.6 ppm) are present over outcrops of Sha Tin and Needle Hill granites (Kwai Chung Suite), with strong anomalies in the Needle Hill and Ma On Shan areas. Bismuth levels are generally low over outcrops of volcanic rocks belonging to the Repulse Bay, and Kau Sai Chau volcanic groups. In eastern Kowloon, local anomalies are present close to intrusive contacts with fine-grained Kwun Tong Granite (Lion Rock Suite).

On Hong Kong Island, small bismuth anomalies are present over outcrops of quartz monzonite near D'Aguilar Peak and Chai Wan (Lion Rock Suite). In general, however, bismuth levels are low to moderate (<6.3 ppm) over outcrops of volcanic rock (Repulse Bay Volcanic Group). Low to moderate levels of bismuth (<6.3 ppm) also characterise most of the volcanic and granitic areas of Lamma Island and Po Toi Island, except for small outcrops of quartz monzonite.

Moderate to strong bismuth anomalies (6.3–34.2 ppm) in the northern and eastern parts of Lantau Island coincide with outcrops of granite (Lamma, Kwai Chung, and Cheung Chau suites), whereas in the southwestern part of the island, moderate to high levels of bismuth (6.3–14.6 ppm) are present over volcanic rocks of the Tsuen Wan and Lantau volcanic groups.

Geochemistry of bismuth

Bismuth is a Group VA element of the periodic table (which also includes P, As and Sb) and most commonly occurs as the trivalent cation Bi^{3+} which is a relatively large ion (103 pm) and has the same electron configuration as Pb^{2+}.

During magmatic processes Bi^{3+} may substitute for Pb^{2+}, Y^{3+} and the trivalent light rare earth elements, all of which display similarities of charge and/or size. There is also evidence of substitution for Ca^{2+} in apatite (Goldschmidt, 1954). Like Pb, bismuth does not easily enter silicate lattices and so accumulates in late-stage magmatic products in evolved granites and pegmatites. Data on its distribution are too scarce to make any reliable estimates of the concentrations of Bi in igneous rocks.

Bismuth has marked chalcophile properties which, though less pronounced than in As and Sb, result in its being partitioned into sulphides such as galena, where the substitution for Pb^{2+} is especially favoured. Bismuth minerals are rare, the commonest ones being bismuthinite [Bi_2S_3] and bismite [Bi_2O_3] which are occasionally found in small amounts in association with galena and other minerals, such as those of As and Sb. The element bismuth is also found as a native metal, often with traces of As, S and Te.

In sedimentary rocks, the abundance of bismuth is related to the presence of granitic detritus and organic matter. Bismuth shows a tendency to co-precipitation with hydrous Fe and Mn oxides, and bismite has been observed as a secondary mineral in some sediments (Wedepohl, 1978), where it is probably derived from the oxidation of sulphides. Sedimentary rocks most enriched in Bi (>5 ppm) are coals and bituminous materials (Brandenstein *et al.*, 1960), though Goldschmidt (1954) reports similar enrichment in ferruginous bauxites and sedimentary iron ores. Values of up to 24 ppm have been recorded in oceanic ferromanganese nodules (Ahrens *et al.*, 1967). Somewhat lower values are typical of normal shales (0.2–1.0 ppm) and sandstones (*c.* 0.3 ppm).

Bismuth is useful as a gold pathfinder element, as it often indicates the presence of granitic intrusive centres and discordant structures which focus lode gold mineralising systems (e.g. Plant *et al.*, 1989). Because of its chalcophile affinity with galena and its presence in late-stage magmatic products, high values of Bi would be expected in pegmatitic mineralisation such as that associated with the Needle Hill Granite in the central New Territories.

Surface environment geochemistry

Close to mineralisation, Bi in stream sediments may be held in primary sulphides, but it is most typically held in secondary phases. The chemical processes of hydrolysis and solution are described by Irfan (1996) as being the two most important chemical processes in the humid environment of Hong Kong. (Hydrolysis is oxidation accompanied by a reaction with water, which in the case of silicates produces hydroxyl anions, cations and dissolved silica). Following its release during weathering, Bi^{3+} is rapidly hydrolysed under normal surface Eh and pH conditions and tends to form insoluble basic salts. Like As, Sb and Pb, it is also readily adsorbed by secondary Fe and Mn oxides and organic matter in soils and stream sediments.

Detailed description

In the western New Territories, moderate to high concentrations of bismuth (>6.3 ppm) are present over outcrops of the fine- and medium-grained Tsing Shan and Tai Lam granites (Lamma Suite). Prominent anomalies occur in the vicinities of Sheung Fa Shan and Tsing Fai Tong (15–61 ppm), Lam Tei (15–46 ppm), and northern Tuen Mun (124 ppm). The broad anomaly over the Sheung Fa Shan and Tsing Fai Tong areas is accompanied by moderate to high levels of Zn (35–399 ppm), Sn (32–147 ppm), and W (13–80 ppm) reflecting the known Sn and W mineralisation of the district (see Figure 10). At Lam Tei, the bismuth anomaly also coincides with moderate to high levels of Zn (49–328 ppm), Sn (23–117 ppm) and W (9–67 ppm), but with the addition of Pb (114–420 ppm). North of Tuen Mun, the prominent anomaly on the flanks of Castle Peak corresponds to an area of known W mineralisation from which Davis (1961a) has reported high levels of Bi (1.87 wt %). This mineralisation occurs in the contact zone between the Tsing Shan Granite and andesite of the Tuen Mun Formation. Several small bismuth anomalies (6.2–22 ppm) are present over the Tsing Shan Granite farther to the north and these are accompanied by moderate to high levels of Sn (229 ppm) and W (12 ppm). Moderate levels of bismuth around the Tin Shui Wai, San Tin and Sheung Shui areas come from samples with extremely high concentrations of industrial metals (see descriptions for Pb, Cu, Sn and Zn). Therefore, the elevated bismuth concentrations at these sites are considered to be mainly of anthropogenic origin.

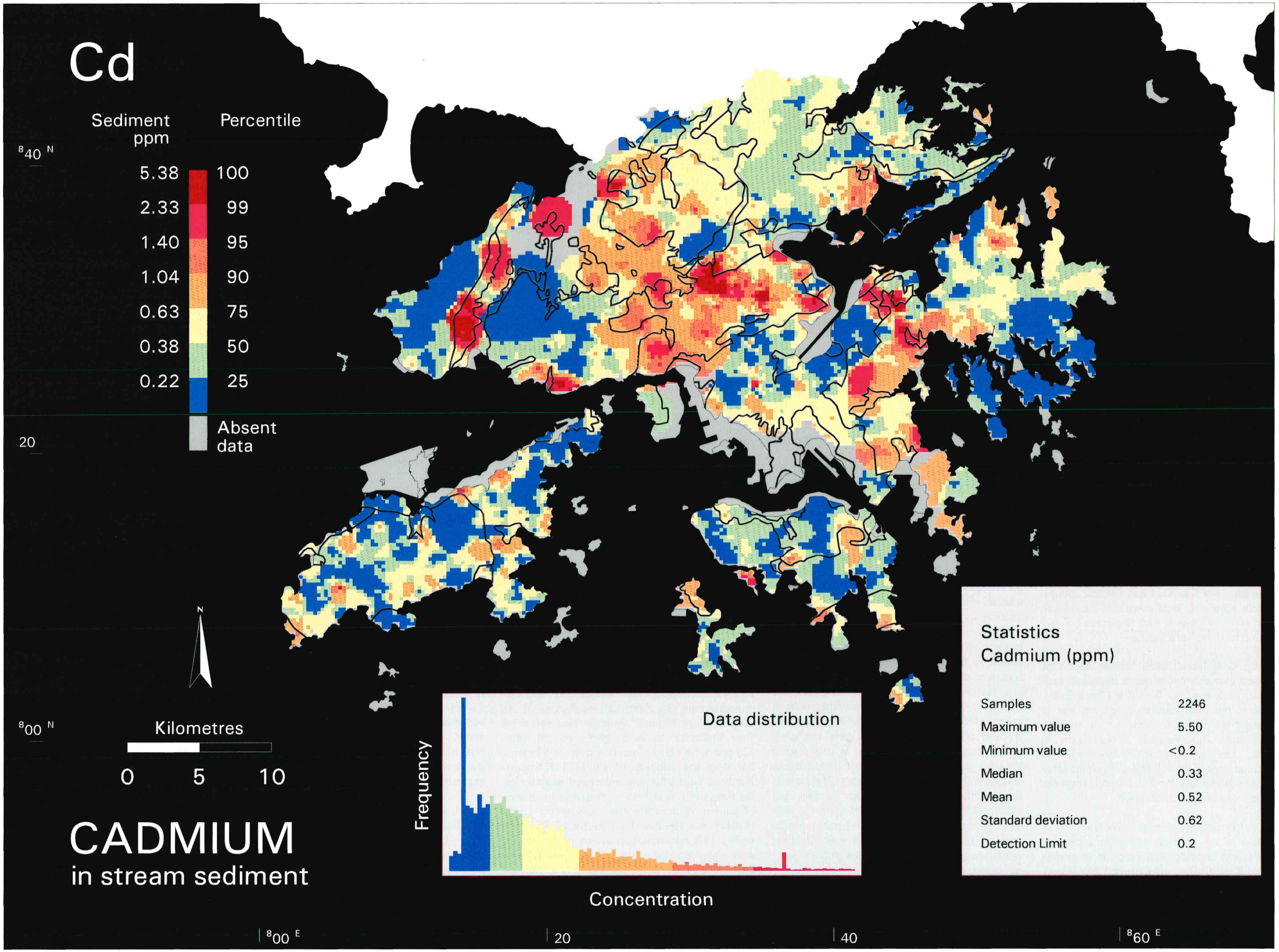
Over northern New Territories, low bismuth levels characterise most of the area underlain by coarse ash crystal tuff (Tsuen Wan Volcanic Group). However, the exception is at Yung Shue Au where moderate to high bismuth concentrations (15–20 ppm) overlie tuffs of the Sai Lau Kong Formation. The bismuth anomaly in this relatively remote area is coincident with moderate levels of Pb (76–114 ppm), Zn (99–168 ppm) and As (20–39 ppm) suggesting the presence of mineralisation similar to that found at Lin Ma Hang. Moderate bismuth levels (3.9–10 ppm) also accompany the Pb–Zn–Cu mineralisation found in the vicinity of Tai Mo Shan in the central New Territories.

In the central New Territories, bismuth levels are moderate to high (6.3–14.6 ppm) over outcrops of the Needle Hill Granite (Kwai Chung Suite). The highest values coincide with areas of Sn–W mineralisation at Needle Hill. However, a very strong bismuth anomaly (172 ppm) in the Shing Mun Valley is accompanied by unusually high levels of Zn (635 ppm), Sn (404 ppm) and W (271 ppm) indicating man-made contamination. Bismuth levels are also very high (28–361 ppm) in the vicinity of Ma On Shan which is well-known for skarn-related Fe mineralisation. However, the associated high As (25–111 ppm), Cu (21–303 ppm), Pb (145–896 ppm), Zn (194–662 ppm), Sn (65–589 ppm), W (11–152 ppm) and Ag (0.3–12.8 ppm) values suggest that the bismuth levels may be strongly overprinted by anthropogenic contamination, perhaps in relation to mining activity.

Small, local bismuth anomalies in the Tai Tan, Ho Chung and Tseng Lan Shue areas of eastern New Territories are strongly controlled by anthropogenic contamination with high levels of associated metals including As (70 ppm), Cu (41–185 ppm), Pb (92–258 ppm), Sb (2–6 ppm), Sn (57–69 ppm) and Zn (318–594 ppm). In the Yau Tong area, high levels of bismuth are associated with elevated concentrations of As (13–25 ppm), Pb (76–179 ppm), Sn (40–65 ppm), W (15–29 ppm) and Zn (106–117 ppm). This is an area of known W mineralisation within the Kwun Tong Granite (Lion Rock Suite).

In northeastern Lantau Island, elevated bismuth levels (17–24 ppm) are associated with areas of weak W mineralisation. This area is underlain by granites and rhyolite dykes of the Lamma Suite and Kwai Chung Suite respectively. The strongest bismuth anomaly (15–73 ppm) on Lantau Island is present over outcrops of fine-grained Chek Lap Kok Granite (Lamma Suite) and quartz monzonite (Lion Rock Suite) in the Sha Lo Wan area, south of Chek Lap Kok. This area is known for W mineralisation (9–80 ppm) and is accompanied by moderate to high levels of As (3–35 ppm), Sb (3–4 ppm) and Sn (7–57 ppm).

In the southern and western part of Lantau Island, moderate to high bismuth concentrations are present in the Yi O valley (7–10 ppm), Shek Pik (7–13 ppm) and Chi Ma Wan (8–13 ppm). In the Yi O valley, the bismuth anomaly occurs over outcrops of volcanic rock belonging to the Tsuen Wan Volcanic Group and is associated with high background concentrations of As (94–330 ppm), Sb (8–20 ppm) and Ag (0.2–3.5 ppm). In the Shek Pik area, a broad anomaly extends from Tong Fuk in the south, through Ngong Ping, towards Sha Lo Wan in the north of the island. The anomaly is principally underlain by volcanic rock belonging to the Lantau Volcanic Group, but is strongly influenced by local anthropogenic contamination in the Ngong Ping area. This is indicated by moderate to high levels of Pb (24–166 ppm), Zn (36–190 ppm), Cu (9–90 ppm), and TiO_2 (1.64 wt %). On Chi Ma Wan peninsula, moderate to high levels of bismuth are present over outcrops of Chi Ma Wan Granite (Cheung Chau Suite). Although metallic mineralisation is not known from this area, levels of U (16–41 ppm), Th (89–185 ppm) and Y (97–167 ppm) are unusually high.



CADMIUM
in stream sediment

Statistics
Cadmium (ppm)

Samples	2246
Maximum value	5.50
Minimum value	<0.2
Median	0.33
Mean	0.52
Standard deviation	0.62
Detection Limit	0.2

Cadmium

Cd

Synopsis

Cadmium levels are generally low to moderate (<0.38 ppm) in areas underlain by granite and fine ash vitric tuff, and are generally moderate to high (>0.38 ppm) in areas underlain by coarse ash crystal tuff and quartz monzonite.

The highest cadmium values (>2.33 ppm) are found in the central New Territories and are associated with Pb–Zn–Cu mineralisation in coarse ash crystal tuff (Tsuen Wan Volcanic Group). Much of the mineralisation is concentrated close to the contact zones with Tai Po Granodiorite (Lamma Suite).

Moderate levels of cadmium are found over a broad area of the northern New Territories with minor anomalies around Plover Cove related to nearby outcrops of Tai Po Granodiorite. Anomalies in the vicinity of Tin Shui Wai and Mai Po are mostly attributed to anthropogenic contamination.

In the western New Territories, high levels of cadmium are associated with outcrops of andesite of the Tuen Mun Formation. Over much of the surrounding granite areas, cadmium values are low, except for isolated anomalies at Tai Lam Chung and So Kwun Wat which are affected by contamination.

In the eastern New Territories, cadmium highs (>1.4 ppm) are associated with outcrops of quartz monzonite (Lion Rock Suite), and with Fe mineralisation surrounding Ma On Shan. Moderate to high levels of cadmium are also present in areas underlain by coarse ash crystal tuff (Repulse Bay Volcanic Group), including Long Harbour and Sai Kung.

In eastern Kowloon, Hong Kong Island and Lamma Island, moderate to high values (0.38–1.4 ppm) of cadmium mostly coincide with outcrops of quartz monzonite (Lion Rock Suite) and trachydacite (Kau Sai Chau Volcanic Group). Cadmium values are low to moderate (<0.38 ppm) over much of Lantau Island, with elevated values (0.38–1.04 ppm) generally present in areas underlain by coarse ash crystal tuff (Tsuen Wan Volcanic Group) and quartz monzonite (Cheung Chau and Lion Rock suites).

Geochemistry of cadmium

Cadmium, along with Zn and Hg, is a member of Group IIB of the periodic table, and the chemistry of cadmium is similar to that of Zn, both having similar electronegativities. The Cd^{2+} ion has an ionic radius of 95 pm, higher than that of Zn^{2+} (74 pm), the element with which it is most closely associated, but smaller than those of Hg^{2+} or Pb^{2+}.

The average crustal abundance of cadmium is rather low, around 0.2 ppm, with generally lower levels in igneous and metamorphic rocks (granites typically 0.09 ppm, basalts 0.13 ppm), sandstones and limestones, but higher levels in shales (0.8 ppm), especially organic-rich sediments, and in marine manganese nodules and phosphorites (Fergusson, 1990).

The geochemistry of cadmium is dominated by its strong chalcophile properties (Goldschmidt, 1954) suggesting it is more chalcophilic than Zn and consequently it is concentrated in sulphide minerals. Occasionally, a pure cadmium sulphide mineral (greenockite, [CdS]) is formed, but more often cadmium occurs as a substitution element in other sulphides, notably those of Hg, Cu, Pb and Zn. The cadmium content of Zn sulphide (sphalerite, [ZnS]) varies widely, but is normally in the range 0.02–1.5 % with a median value of around 0.3 %, though contents up to 5 % have been reported (Fergusson, 1990). The cadmium levels in sphalerite are reported to be dependent on temperature (Levinson, 1980) and deposit type (Ivanov, 1964).

There is evidence of an affinity with organic matter, some coals (20 ppm), peats (up to 190 ppm) and crude oils (16 ppm) containing relatively high cadmium levels, which may be due to selective adsorption and complexation by humic compounds.

Surface environment geochemistry

Cadmium in stream sediments may be present in detrital sulphide minerals near sources of hydrothermal mineralisation. However, under acid, oxidising conditions these weather fairly rapidly and release Cd^{2+} into solution. Since Cd^{2+} is the only stable oxidation state, the solubility of Cd is largely unaffected by changes in Eh, and Cd^{2+} is the dominant aqueous species below pH 8 (Fergusson, 1990; Brookins, 1988). However, the sulphate and carbonate of cadmium are less soluble than those of Zn (Rubin, 1974), so Cd^{2+} mobility is more restricted in carbonate-rich sediments and soils (Bowen, 1982). Fuge *et al.* (1993) note that because cadmium is more chalcophile than Zn, it persists as a sulphide longer than Zn and is consequently concentrated in the outer regions of weathered sphalerite fragments. It is therefore more enriched relative to Zn in fine-grained tip material. Cadmium has a stronger affinity than Zn for organic matter and is more likely to be sorbed by clay minerals and secondary iron oxides. This may lead to a differentiation in the dispersal patterns of Zn and cadmium from a single source.

In industrialised countries there is concern over anthropogenic accumulations of cadmium in the environment and it is classified as a potentially harmful element (PHE). Toxic amounts of cadmium are particularly associated with waste tips from old mine workings such as described by Fuge *et al.* (1993) in Wales. Cadmium has no essential biological function but is highly toxic to both plants and animals.

Detailed description

In the western New Territories, cadmium anomalies are associated with andesite outcrops of the Tuen Mun Formation. North of Tuen Mun, the high cadmium values (1.7–5.0 ppm) coincide with high Hg (1.0–2.8 ppm), MnO (0.15–0.20 %), Fe_2O_3 (7.1–12.6 %) and Co (13–22 ppm). Farther north at Ha Tsuen, the cadmium values are slightly lower (1.4–2.0 ppm), but continue to be associated with moderate to high Co (10–14 ppm) and MnO (0.05–0.23 %). An isolated cadmium anomaly at Tin Shui Wai (15 ppm) coincides with high Co (13.5 ppm), moderate Pb (120 ppm) and Zn (114 ppm), and low Hg (0.4 ppm) and MnO (0.05 %). Field records indicate an abundance of metal contamination in the area suggesting that the high Cd levels are of anthropogenic origin.

At Mai Po, the high values of cadmium are attributed to strongly contaminated samples, as indicated by high levels of Cu (11–2849 ppm), Pb (29–884 ppm), Zn (109–17 489 ppm) and Sn (2–151 ppm). However, some of the cadmium content may also be due to the high natural background levels of cadmium contained in coarse ash crystal tuffs (Tsuen Wan Volcanic Group) of the surrounding area.

Elevated values of cadmium are present over much of the central New Territories in association with outcrops of coarse ash crystal tuff (Tsuen Wan Volcanic Group) and Tai Po Granodiorite (Lamma Suite). The highest values are found in the Lam Tsuen Valley close to the contact between these two main rock types. At Kap Lung, the cadmium levels reach 2.6 ppm and are accompanied by high MnO (0.21–0.24 %), Co (10–12 ppm), Pb (219–300 ppm) and Zn (366–460 ppm). In the Lam Tsuen Valley, the background cadmium values are even higher (1.7–5.5 ppm) with very high values of associated MnO (0.25–0.59 %), Pb (149–2431 ppm) and Zn (290–992 ppm). The area is known to have strong Pb–Zn–Cu mineralisation and it is very likely that the high cadmium values are associated with this mineralised zone. An isolated cadmium high (1.5 ppm) in the Plover Cove area is close to outcrops of granodiorite and possibly reflects the presence of Pb–Zn–Cu mineralisation nearby. Cadmium anomalies at Sheung Fa Shan (1.4–1.9 ppm) and Ma Liu Shui (1.9 ppm) are accompanied by high Pb (72–202 ppm) and Zn (126–245 ppm) values, but relatively low Cu (10–33 ppm) and Sn (32–51 ppm).

Relatively high cadmium values (1.6–2.6 ppm) at Tai Lam Chung and So Kwun Wat occur in an area underlain by the Tai Lam Granite (Lamma Suite). These high cadmium levels are accompanied by moderate to high Hg (1.8–2.6 ppm), MnO (0.18–0.23 %) and Co (12 ppm), and may be related to the presence of ceramic contaminants reported during field sampling.

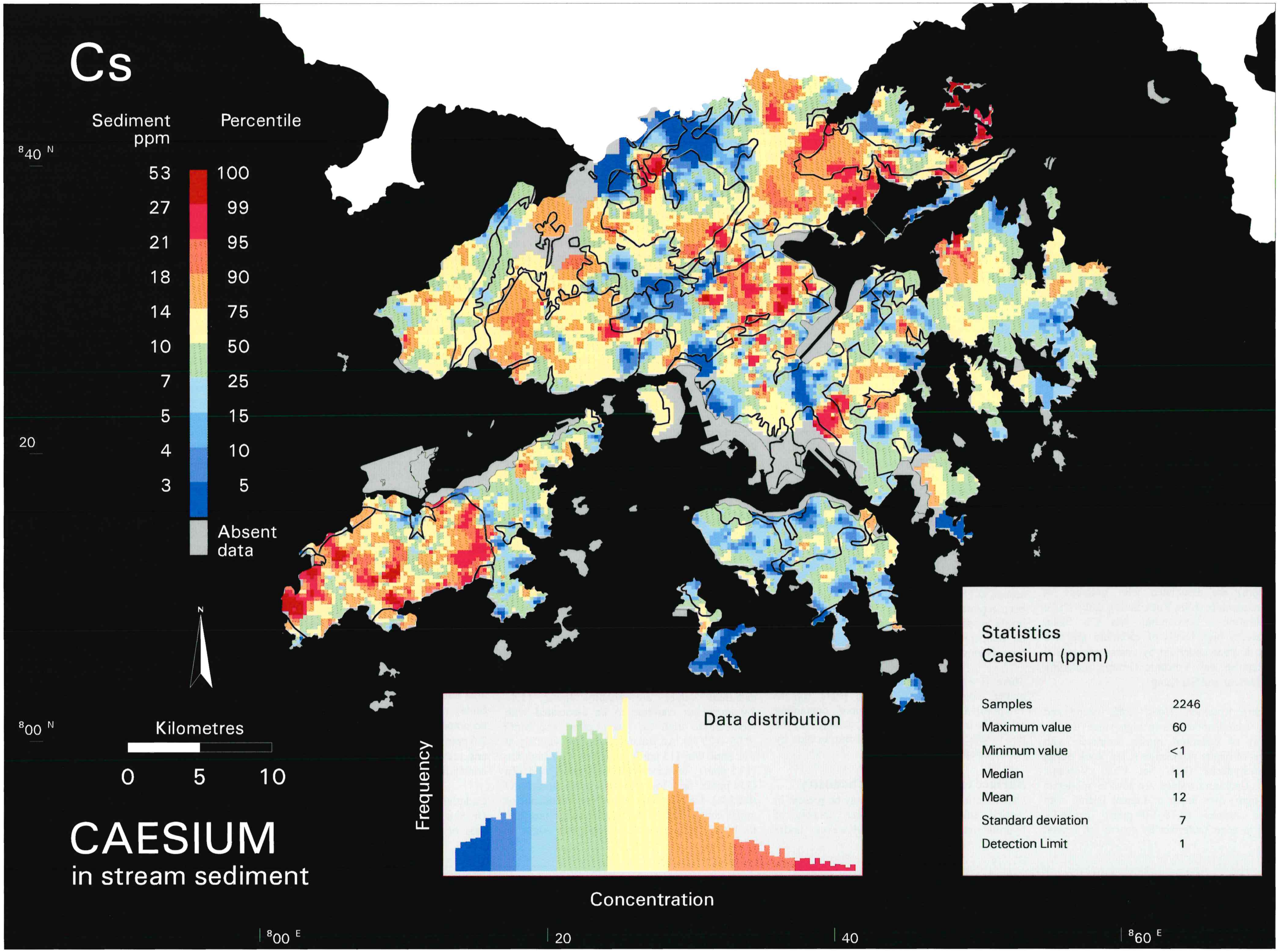
Cadmium levels are high in the vicinity of Ma On Shan and are almost certainly related to the area of known Fe mineralisation. The highest levels of cadmium (3.7 ppm) are associated with high MnO (0.40 %) and Zn (804 ppm), and moderate Co (5.2 ppm), Cu (73 ppm) and Pb (273 ppm).

Southeast of Ma On Shan, a broad area of elevated cadmium values corresponds with dykes of quartz monzonite (Lion Rock Suite) extending from Tate's Cairn in the southwest to Pak Tam Chung in the northeast. Prominent cadmium anomalies at Pyramid Hill and Tai No (2.2–3.1 ppm) are accompanied by high Hg (3.2–3.3 ppm), MnO (0.23–0.35 %) and Co (9.2–12 ppm), but low Cu (5–10 ppm), Pb (41–48 ppm) and Sn (7–18 ppm). Low to moderate values of cadmium over much of the Long Harbour area correspond to outcrops of coarse ash crystal tuff (Repulse Bay Volcanic Group). Minor anomalies in this area may point to local areas of Pb–Zn–Cu mineralisation.

In eastern Kowloon, slightly elevated cadmium values (0.63–1.4 ppm) are present in areas underlain by trachydacite lava flows and quartz monzonite. These highs also coincide with elevated levels of Hg (1.7 ppm), MnO (0.08 %) and Co (8 ppm) although in the Silverstrand area, some of the high cadmium content may be partly related to anthropogenic contamination (see descriptions of Sn and Cu).

On Hong Kong Island and Lamma Island, elevated cadmium values coincide with high levels of Hg (1.7–2.0 ppm), MnO (0.05–0.08 %) and Co (5–7 ppm) and are mostly related to outcrops of quartz monzonite (Lion Rock Suite).

Background levels of cadmium are generally low to moderate over much of Lantau Island. However, weak anomalies are present in several areas including Mui Wo, Tong Fuk, Fan Lau, and east of Tung Chung. Most of the higher values are associated with outcrops of quartz monzonite (Lion Rock Suite), or coarse ash crystal tuff (Tsuen Wan Volcanic Group). Minor anomalies at Shek Pik and east of Tung Chung are partly due to anthropogenic contamination.



CAESIUM

in stream sediment

Statistics
Caesium (ppm)

Samples	2246
Maximum value	60
Minimum value	<1
Median	11
Mean	12
Standard deviation	7
Detection Limit	1

Caesium

Cs

Synopsis

Moderate levels of caesium are present over much of the western New Territories, particularly over outcrops of Lamma Suite granitic rocks. In the northern New Territories, caesium levels are very low (<3 ppm) over outcrops of Upper Palaeozoic sedimentary rocks, but moderate to high (10–27 ppm) over outcrops of Middle Jurassic volcanic rocks (Tsuen Wan Volcanic Group). The highest caesium values (>27 ppm) are found in areas underlain by Upper Mesozoic sedimentary rocks.

In the central New Territories, moderate to high levels (10–27 ppm) of caesium are present over outcrops of coarse ash crystal tuff of the Tsuen Wan Volcanic Group. Isolated anomalies in the granitic areas are mostly due to local contamination.

In the eastern New Territories, moderate to high levels of caesium coincide with outcrops of volcanigenic sedimentary rocks and coarse ash crystal tuff (Repulse Bay Volcanic Group). Caesium values are generally low (<10 ppm) over outcrops of fine ash vitric tuff (Kau Sai Chau Volcanic Group) and quartz monzonite (Lion Rock Suite).

Over Hong Kong Island, Lamma Island and Po Toi Island, caesium values are generally low (<10 ppm). However, on Lantau Island there is a marked distinction in caesium content between the volcanic and granitic rock areas. Caesium levels are particularly high (14–27 ppm) over outcrops of the Lantau and Tsuen Wan volcanic groups. By contrast, levels of caesium are low to moderate over granitic rocks of the Lamma, Kwai Chung and Cheung Chau suites.

Geochemistry of caesium

Caesium (or cesium in American English) is the heaviest stable alkali–metal group element (Group IA of the periodic table) and has a large ionic radius of 174 pm in 8-fold co-ordination, a value that places caesium closest to Rb (161 pm in 8-fold co-ordination).

Caesium is a relatively rare element, present at a crustal abundance of about 2.6 ppm. The large ionic radius renders it incompatible with many rock-forming silicate minerals, but it can make a limited substitution for K in micas and K-feldspars, which contain most of the caesium in the earth's crust. Typically for an incompatible element, caesium accumulates in the late-stage volatile phase of igneous activity.

The highest caesium contents of ordinary rock-forming minerals are found in pegmatite micas. Heier & Adams (1964) report a range of 140–3400 ppm for 11 muscovite samples and Foster (1960) reported caesium levels of more than 1 % in Li-rich micas. Gordiyenko (1973) describes caesium levels in lepidolites from pegmatite of several % Cs. Beryl is another mineral enriched in caesium, with Sosedko (1957) recording a value of 3.9 % Cs.

Caesium levels in ultrabasic and basic rocks are <0.1 ppm. In volcanic rocks values of 0.04–5.1 ppm are reported (Wedepohl, 1978). The concentration of caesium in igneous rocks is related to the degree of differentiation. Levels in gabbros are estimated to be 0.1 ppm, granodiorites 2–3 ppm, and granites 3–6 ppm (Wedepohl, 1978).

Sands generally contain less caesium than finer sediments. Hirst (1962) reports values of 1–3.2 ppm for modern marine sands and 7.9–13 ppm in modern marine clays; the increase in caesium is a function of finer grain size and increased clay/ion exchange sites, caesium having the strong tendency to bind with clays. There is very little data available for the caesium content of sedimentary rocks, though Horstman (1957) reports average values of 5 ppm for marine shales and 1 ppm for sandstones and limestones.

Evaporite deposits might be expected to be enriched in caesium, especially deposits of K salts, but data on these are sparse.

Surface environment geochemistry

Caesium released by weathering of rocks and minerals is rapidly and strongly adsorbed by solid soil material (Davis, 1963). The tendency to bind strongly with clays has already been noted, a function of the more open structure of clay minerals and negatively–charged exchange sites. Humic materials possess similar features and also have a strong affinity for Cs ions, although Cremers *et al.* (1988) found in their studies of radiocaesium that soil organic matter plays no part in the specific caesium retention. The work of Cremers *et al.* (1988) demonstrated that the retention behaviour of radiocaesium in soils and sediments is controlled by the clay mineral illite. Like the other alkali metals, the Cs^+ (aq) ion is stable in solution over all normal pH and Eh ranges and in the presence of all common anions, so sorption processes are the dominant influence on caesium contents in the surface environment.

A stimulus to the understanding of caesium cycling processes in the surface environment was the Chernobyl nuclear reactor explosion in 1986, which liberated considerable quantities of radioactive ^{137}Cs to the atmosphere (e.g. Higgit *et al.*, 1993). The strong adsorption of caesium to clays has been widely demonstrated but it has also been reported that in upland areas of more acidic, low-clay and peaty soils, radioactive caesium has persisted longer than would be expected. This is attributed to efficient trace-element recycling by the upland vegetation and could be temporarily stored within the vegetation (Kirk & Staunton, 1989). Studies on the migration of radioactive caesium in the environment suggest that caesium would be a relatively immobile element in the Hong Kong surface environment, and in drainage sediment it would be associated with the fine clay fraction.

Detailed description

Moderate levels of caesium are present in the western New Territories with elevated concentrations over outcrops of the Tsing Shan and Tai Lam granites (Lamma Suite). At Lung Kwu Tang, caesium levels range from 21–26 ppm and are accompanied by high levels of As (20–25 ppm) and Pb (152–156 ppm). Some of these enhanced caesium values may be related to heavy metal contamination associated with spent military ordnance in the Castle Peak Firing Range. A broad area of elevated caesium values (14–21 ppm) is present over the Tai Lam Granite east of Tuen Mun. These high values coincide with moderate to high Bi (6.3–34.2 ppm) and Sb (3.8–6.7 ppm) and probably reflect high natural background values.

In the northern New Territories, caesium values are generally low over outcrops of Palaeozoic sedimentary rocks but moderate to high over outcrops of volcanic rocks. Local anomalies are present at Kwu Tung, Lam Tsuen Valley, Ta Kwu Ling and Kwai Tau Leng, and a broad area of elevated values occurs over outcrops of Cretaceous sedimentary rocks at Pat Sin Leng. At Kwu Tang, the high caesium values (21–36 ppm) coincide with unusually high As (55–648 ppm), and moderate to high Bi (0.1–10 ppm), Cu (3.5–29 ppm), Pb (21–154 ppm) and Zn (31–180 ppm), suggesting moderate degrees of contamination. Similar concentrations of associated metals coincide with the caesium anomalies at Ta Kwu Ling (21–23 ppm), Lam Tsuen Valley (22–30 ppm) and Kwai Tau Leng (25 ppm). At Pat Sin Leng, the high caesium values (21–35 ppm) are accompanied by moderate to high As (16–56 ppm) and Bi (2–7 ppm), but relatively low Cu (3–24 ppm), Pb (26–54 ppm) and Zn (41–147 ppm). These values are thought largely to reflect the natural background concentrations.

In the northeastern New Territories, caesium anomalies at Sam A Chung (27 ppm) and nearby offshore islands (25–31 ppm) coincide with high As (14–139 ppm) and Sb (1–20 ppm) values. These areas are underlain by outcrops of Cretaceous sedimentary rocks and volcanic rocks, with intercalated volcanigenic siltstone and sandstone.

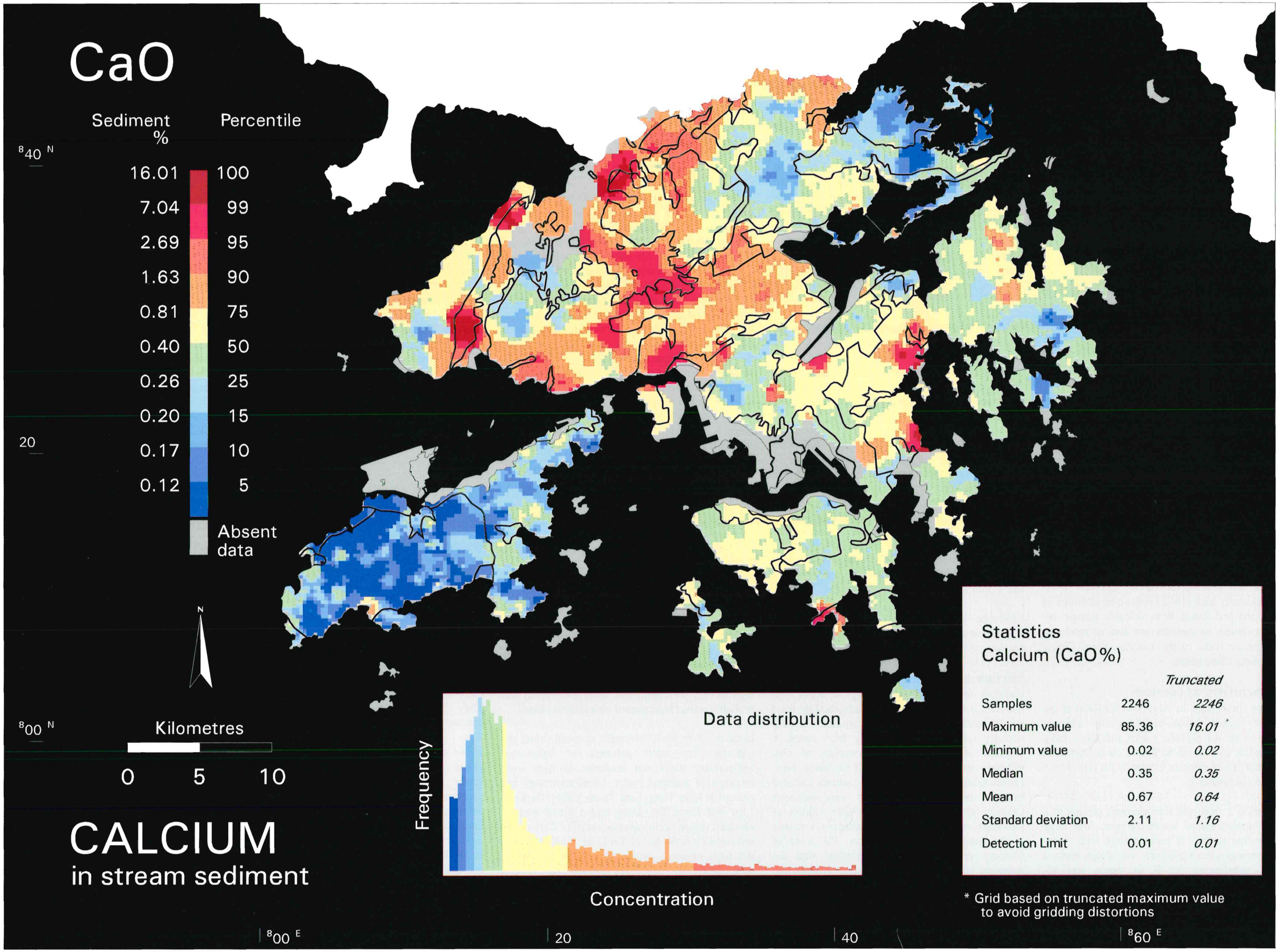
Moderate to high levels of caesium (21–26 ppm) are present in several areas of central New Territories which are underlain by coarse ash crystal tuff of the Tai Mo Shan Formation. These include areas surrounding Tai Mo Shan and Tai Po Kau. Most of the caesium anomalies coincide with sites of known Pb–Zn–Cu mineralisation and typically are accompanied by high levels of Pb (75–246 ppm) and Zn (77–269 ppm). A small caesium anomaly (26 ppm) north of Tsing Fu Tsai is also associated with high Pb (107 ppm) and Zn (223 ppm) values.

Several isolated caesium anomalies occur over outcrops of granite in the Sha Tin and Shing Mun areas. These anomalies are commonly associated with high levels of Sn (52–176 ppm), Bi (8–19 ppm), and W (15–29 ppm), but relatively low Pb (43–60 ppm) and Zn (48–118 ppm) values. They probably represent locally enhanced concentrations due to contamination.

In the eastern New Territories, elevated caesium values are mainly associated with outcrops of coarse ash crystal tuff and volcanic rocks containing intercalated siltstone and mudstone deposits. Northeast of Three Fathoms Cove, a broad caesium anomaly (14–47 ppm) occurs over outcrops of the Lai Chi Chong Formation (Lantau Volcanic Group). Samples also contain high levels of As (72 ppm) and Sb (26 ppm), but relatively low contents of Pb (31 ppm), Zn (10 ppm) and Sn (12 ppm). Slightly elevated caesium values occur farther east over outcrops of volcanigenic sedimentary rocks near Chek Keng, and over outcrops of coarse ash crystal tuff southeast of Sai Kung. Similar elevated caesium values also occur to the west of High Junk Peak over outcrops of volcanigenic mudstone and siltstone belonging to the Mang Kung Uk Formation (Kau Sai Chau Volcanic Group).

A prominent caesium anomaly (21–36 ppm) is present in the Kowloon area, west of Kowloon Peak. These high caesium values are associated with moderate to high concentrations of As (3–109 ppm), Pb (43–101 ppm) and Zn (75–157 ppm). The catchment area to the north is underlain mainly by coarse ash crystal tuff with intercalated volcanigenic siltstones and mudstones. Pb–Zn–Cu mineralisation is not known from the area.

Caesium levels over Hong Kong Island, Lamma Island, and Po Toi Island seldom exceed 10 ppm. On Lantau Island, however, there is a marked distinction in caesium values between outcrops of granitic rocks in the north and volcanic rocks in the south. Caesium anomalies are most pronounced in the Mui Wo and Pui O areas (21–31 ppm), and at Tong Fuk (28 ppm), Lantau Peak (60 ppm), Tai O (22–46 ppm) and Yi O (22–31 ppm) in the south and west of the island. The elevated caesium values at Mui Wo, Pui O, Cheung Sha and Tong Fuk are associated with moderate to high As (2–27 ppm), Pb (25–110 ppm) and Zn (25–110 ppm) values. Volcanic rocks underlying these areas comprise coarse and fine ash crystal tuff with intercalated beds of volcanigenic siltstone and mudstone (Lantau Volcanic Group). At Lantau Peak, the caesium anomaly (60 ppm) is accompanied by unusually high As (124 ppm), and moderate to high Pb (49 ppm) and Zn (168 ppm) contents. Similar contents of these metals, with the addition of moderate to high Sb (3–8 ppm) and Bi (7–9 ppm), accompany the high caesium values at Tai O (22–46 ppm). At Yi O farther to the southwest, the strong caesium anomaly is accompanied by high As (94–330 ppm), Bi (7–10 ppm) and Sb (8–20 ppm), but relatively low Pb (38–77 ppm) and Zn (47–93 ppm) values. The area is underlain mainly by coarse ash crystal tuff of the Tsuen Wan Volcanic Group containing intercalated siltstone and sandstone layers.



CALCIUM

in stream sediment

Statistics
Calcium (CaO%)

		Truncated
Samples	2246	*2246*
Maximum value	85.36	*16.01* *
Minimum value	0.02	*0.02*
Median	0.35	*0.35*
Mean	0.67	*0.64*
Standard deviation	2.11	*1.16*
Detection Limit	0.01	*0.01*

* Grid based on truncated maximum value to avoid gridding distortions

Calcium

CaO

Synopsis

In the western New Territories, calcium anomalies (>0.8 % CaO) are present over andesite outcrops of the Tuen Mun Formation and in low-lying areas underlain by Quaternary deposits. Elevated calcium values (>0.8 % CaO) are present over much of the low-lying areas of northern New Territories, with strong anomalies in the floors of major valleys and over outcrops of Upper Palaeozoic sedimentary rocks. The anomalies generally coincide with areas of intensive agriculture and in many cases can be directly related to anthropogenic activity. Low levels (<0.2 % CaO) of calcium are generally present over outcrops of Upper Palaeozoic and Upper Mesozoic sedimentary rocks in the northeast New Territories.

In the central New Territories, moderate to high calcium values (>0.8 % CaO) coincide with outcrops of coarse ash crystal tuff (Tsuen Wan Volcanic Group). These lithic-bearing volcanics are known to contain fragments of marble. Calcium values are also high over outcrops of Tai Po Granodiorite (Lamma Suite). Local anomalies occur close to contact zones between the intrusive and extrusive rocks, which are thought to mark vent complexes.

Moderate levels (0.2–0.8 % CaO) of calcium characterise most of the eastern New Territories south of Tolo Harbour, Kowloon, Hong Kong Island, Lamma Island and Po Toi Island. There are local anomalies in several places but most coincide with development areas and are likely to be partly influenced by anthropogenic activity. Calcium values are slightly elevated over outcrops of coarse ash crystal tuff (Repulse Bay Volcanic Group) and quartz monzonite (Lion Rock Suite).

Low levels (<0.2 % CaO) of calcium are present over much of Lantau Island, particularly in areas underlain by volcanic rocks of the Lantau Volcanic Group. Slightly elevated values are present in the southwest and northeast, mainly associated with outcrops of volcanic and granitic rocks belonging to the older Tsuen Wan Volcanic Group and Lamma Suite.

Geochemistry of calcium

Calcium belongs to the Group IIA elements of the periodic table, along with Be, Mg, Sr, Ba and Ra. It is the fifth most abundant of all the elements, constituting approximately 3.5 % by weight (equivalent to 4.2 % CaO) of the upper continental crust (Ure & Berrow, 1982). It is a major component of primary rock-forming minerals such as plagioclase and diopside, and so is enriched in basic and ultrabasic rocks, particularly in plagioclase-phyric varieties, relative to silicic rocks. Estimates for the CaO contents of igneous rocks are very variable, but Mielke (1979) quotes: ultrabasic, 3.5 %; basaltic 10.6 %; high-Ca granites 3.5 % and low-Ca granites 0.7 %; syenites 2.5 %; and average crustal abundance, 6.5 %.

Calcium is generally unaffected by medium and high-grade metamorphism, but it may be mobilised during low-temperature alteration, forming secondary calcium minerals such as dolomite, calcite and garnet (Wedepohl, 1978). Calcite and fluorite are also common gangue minerals in hydrothermal veins.

Limestone and dolomite are an important sink for calcium in its geochemical cycle. Levels of calcium in most sedimentary rocks reflect the abundance of carbonate minerals (calcite and dolomite), though sulphate minerals, (gypsum and anhydrite) can also be important, particularly in sandstones and evaporites. Plagioclase is the principal host for calcium in some detrital sediments. Calcium levels in pelites vary widely, some deep-water shales having less than 0.05 % CaO while some calcareous mudstones may have several % CaO and grade into impure limestones.

Surface environment geochemistry

In streams, calcium is released during weathering from plagioclase feldspars, pyroxenes, amphiboles and epidote, as well as sedimentary carbonates and sulphates. Of these phases, $CaCO_3$ has the lowest solubility in alkaline waters but dissolves rapidly in mildly acid environments, given a sufficient ambient concentration of dissolved CO_2.

$$Ca(HCO_3)_2 <=> CaCO_3 + H_2O + CO_2$$

The concentration of dissolved CO_2 is a function of temperature and pressure, with low temperature and high pressure increasing the amount of dissolved CO_2. An increase in temperature, or decrease in pressure, will push the equilibrium of the equation shown above to the right, resulting in the deposition of $CaCO_3$ as calc tufa or, in volcanic hot springs, as travertine.

The chemical weathering of silicate minerals in humid tropical climates is discussed by Trescases (1992), who reports how weathering can lead to the formation of ferrallitic soils (laterites) with calcium being removed as a soluble phase. In areas more arid than Hong Kong (with rainfall 100–600 mm per annum) weathering can lead to the formation of calcrete, defined by Butt (1992) as "terrestrial material composed dominantly, but not exclusively, of calcium carbonate, and involving the cementation of, accumulation in and/or replacement of greater or lesser quantities of soil, rock or weathered material". Calcretes do exist outside arid regions and are interpreted as evidence for climatic change.

In solution, calcium occurs mostly as dissociated Ca^{2+} ions (except under strongly alkaline conditions), but may be removed by cation exchange with H^+ at electronegative sites on clay-mineral surfaces and by incorporation into living organic matter.

The main anthropogenic activity that would lead to an increase of calcium in the drainage system, is the long-established agricultural practice of liming land to correct for soil acidity.

Detailed description

In the western New Territories, elevated calcium values are present at Nim Wan and Ha Tsuen with prominent anomalies north of Tuen Mun and at Lau Fa Shan. North of Tuen Mun, the CaO values range from 3–15 % and are accompanied by high Sr (73–283 ppm), Se (1.1–2.2 ppm), V (86–154 ppm), Cd (1.2–5.0 ppm), Hg (1.4–2.8 ppm) and Co (13–20 ppm). This strongly anomalous area coincides with andesite outcrops of the Tuen Mun Formation and may be partly influenced by local contamination. At Lau Fau Shan, the calcium anomaly (16 % CaO) is associated with one isolated sample. This sample contains high levels of V (24 ppm), Zn (551 ppm) and Cu (174 ppm) and is likely to be heavily contaminated. A similar explanation can be given for a small CaO anomaly over the adjacent Tin Shui Wai area.

Calcium levels are particularly high over low lying areas of the northern New Territories with prominent anomalies in the Mai Po and Pat Heung areas. At Mai Po, the high CaO values (2.9–85 %) are partly influenced by strongly contaminated samples which have very high concentrations of associated metals. These include Sr (34–267 ppm), V (50–83 ppm), Cd (0.5–3.2 ppm), Hg (<0.2–6.1 ppm), Co (5–35 ppm), Pb (40–884 ppm), Zn (143–17 489 ppm), Cu (43–2849 ppm) and Sn (16–151 ppm). The elevated CaO values may also be partly related to high natural calcium levels in the underlying Upper Palaeozoic sedimentary rocks. In the Pat Heung area, a broad CaO anomaly (2.8–7.01 %) corresponds with areas which have been intensively cropped and urbanised. Many stream sediment samples contain elevated levels of Sr (48–89 ppm), V (68–91 ppm), Co (10–20 ppm), Pb (70–239 ppm), Zn (205–740 ppm), Cu (19–117 ppm) and Sn (10–1103 ppm) indicating a strong overprint by anthropogenic contamination. Farmers in the area are known to use lime periodically to assist in neutralising the slightly acidic soils.

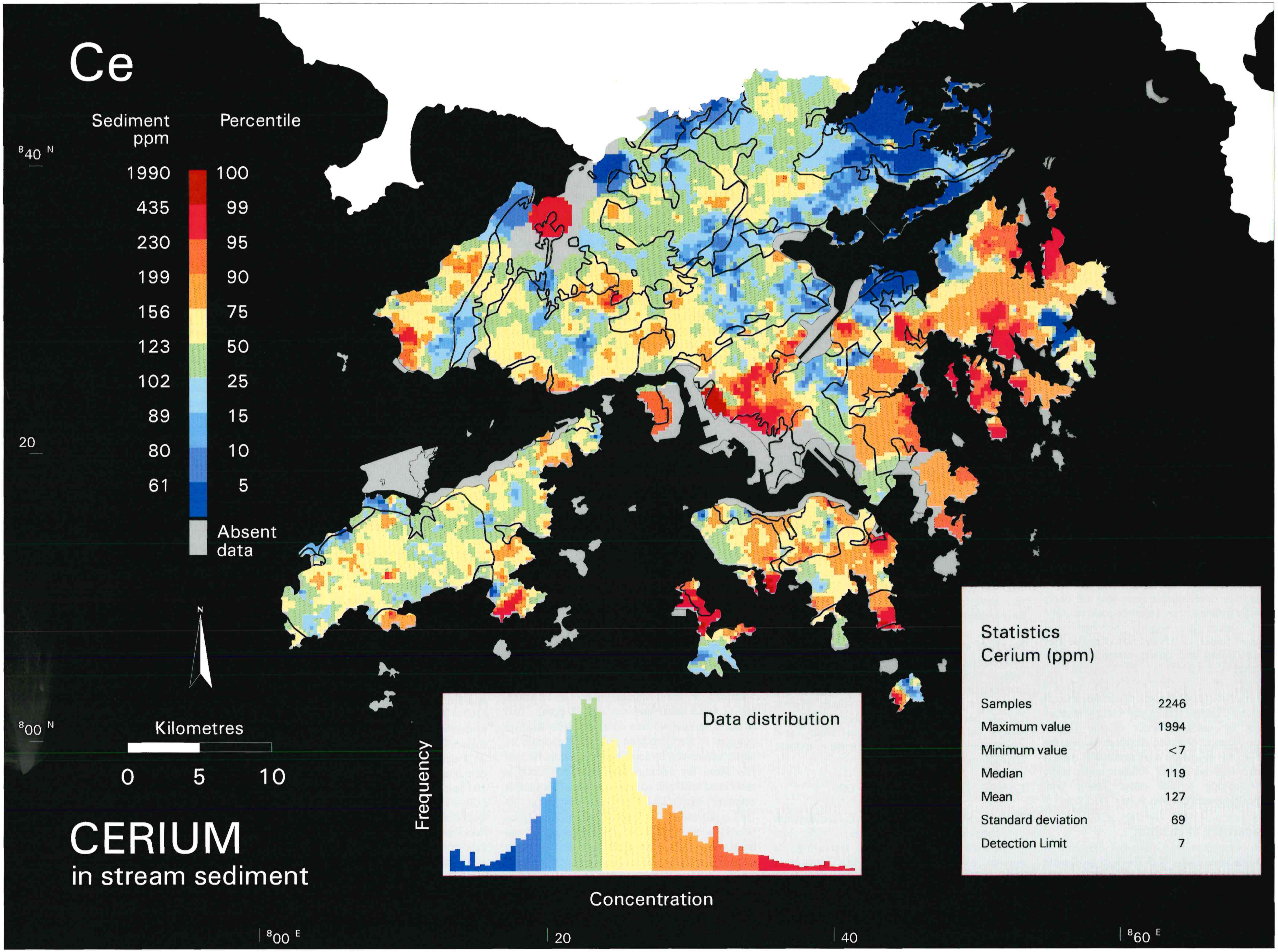
In the central New Territories, calcium levels are moderate to high over a broad area underlain by outcrops of coarse ash crystal tuff (Tsuen Wan Volcanic Group) and granitic rocks (Lamma Suite). Prominent anomalies are present at Tai Lam Chung, Ho Pui Reservoir, Tsing Fai Tong, Kap Lung, Lam Tsuen Valley, and west of Tsuen Wan. At Tai Lam Chung, the high CaO values (3.2 %) are accompanied by moderate Sr (23 ppm), V (21 ppm), Pb (92 ppm), Zn (76 ppm) Cu (10 ppm) and Sn (28 ppm) values which are likely to reflect the natural background levels. Similar abundances of these metals accompany CaO anomalies at Ho Pui Reservoir and Tsing Fai Tong, although slightly higher Pb (107–137 ppm) and Zn (160–223 ppm) contents probably reflect local sites of Pb–Zn–Cu mineralisation (see descriptions for Pb and Zn). At Tsuen Wan, the high CaO values (3.2–7.0 %) coincide with high Sr (45–109 ppm), V (48–103 ppm), Co (6–18 ppm), Pb (86–532 ppm), Zn (120–342 ppm), and Sn (13–1891 ppm), indicating a combination of high natural background and local contamination. Strong calcium anomalies in the Kap Lung (6.2–9.1 %) and Lam Tsuen Valley (3.7 %) areas coincide with sites of known Pb–Zn–Cu mineralisation. These areas also lie across shear zones and contact zones between volcanic and intrusive rocks. At Kap Lung the high CaO values are accompanied by high Sr (102–148 ppm), V (77–79 ppm), Pb (219–300 ppm), and Zn (366–460 ppm). In the Lam Tsuen Valley, the levels of associated metals are much higher (e.g. Pb 3080 ppm, Zn 2694 ppm, Cu 821 ppm, Sn 11 838 ppm) suggesting a contribution from anthropogenic activity.

Calcium values in the eastern New Territories, Kowloon, Hong Kong Island, Lamma Island, Po Toi Island and Lantau Island are distinctly lower than those in the northern and western parts of Hong Kong, mainly due to compositional differences between the major groups of volcanic rocks and granitic rocks. Regions of slightly elevated calcium values generally coincide with outcrops of coarse ash crystal tuff (Tsuen Wan Volcanic Group). In Sha Tin, the small CaO anomalies (7.1–8.1 %) are accompanied by moderate to high Sr (47–97 ppm), V (21–33 ppm), Pb (46–60 ppm) and Zn (42–164 ppm), but rather low Co (1.3–2.1 ppm), Cu (12.8–20.2 ppm) and Sn (8–18 ppm). At Sai Kung and Silverstrand, the high CaO values (8.9–9.9 %) are associated with moderate to high Sr (58–102 ppm), V (22–144 ppm), Cu (29–68 ppm), Pb (59–190 ppm) and Zn (272–448 ppm). The high Pb and Zn values may be partly related to local contamination. A small CaO anomaly at Chung Hom Wan on Hong Kong Island (7.5 %) is accompanied by similar moderate to high Pb (177 ppm), Zn (462 ppm), Cu (56 ppm) and Sn (29 ppm) values also suggesting the influence of local contamination.

Background levels of CaO are low over most of Lantau Island except for the south and west where slightly elevated values correspond to outcrops of fine-grained Chek Lap Kok Granite (Lamma Suite) and coarse ash crystal tuff (Tsuen Wan Volcanic Group). CaO levels are particularly low over outcrops of the Lantau Volcanic Group. A small CaO anomaly (1.4 %) at Shek Pik is accompanied by moderate to high levels of Sr (76 ppm), Pb (126 ppm) and Zn (90 ppm) suggesting local contamination.

Ce

Sediment ppm	Percentile
1990	100
435	99
230	95
199	90
156	75
123	50
102	25
89	15
80	10
61	5
▨	Absent data



CERIUM
in stream sediment

Statistics
Cerium (ppm)

Samples	2246
Maximum value	1994
Minimum value	<7
Median	119
Mean	127
Standard deviation	69
Detection Limit	7

Cerium

Ce

Synopsis

In the western New Territories, rather variable cerium values are found over the Tai Lam and Tsing Shan granites (Lamma Suite). However, there is a general tendency for slightly higher cerium contents to be found over areas of fine- to medium-grained and coarse-grained rocks, compared to the fine-grained rocks.

In the northern and northeastern New Territories, moderate levels (102–156 ppm) of cerium are found over outcrops of coarse ash crystal tuff (Tsuen Wan Volcanic Group). However, cerium values are generally very low (<61 ppm) over outcrops of sedimentary rocks.

Overall levels of cerium are high over granitic and volcanic areas of the central and eastern New Territories, and Kowloon. The highest values (>230 ppm) over granitic areas generally correspond with outcrops of the coarse-grained Sha Tin Granite (Kwai Chung Suite), medium-grained Kowloon Granite (Lion Rock Suite), and quartz monzonite in Sai Kung (Lion Rock Suite). Over the volcanic areas, the highest cerium values (>230 ppm) coincide with outcrops of fine ash vitric tuff (Kau Sai Chau Volcanic Group).

The highest cerium values over Hong Kong Island, Lamma Island and Po Toi Island generally correspond with outcrops of fine ash vitric tuff (Repulse Bay Volcanic Group), quartz monzonite (Lion Rock Suite) and coarse-grained granite (Lion Rock Suite).

On Lantau Island, cerium values are highest (199–435 ppm) over outcrops of quartz monzonite (Lion Rock Suite) and medium-grained granite (Cheung Chau Suite). However, moderate levels of cerium characterise the majority of the volcanic and granitic areas of the island.

Geochemistry of cerium

Cerium is one of the rare earth elements (REE) which are the range of elements from lanthanum to lutetium (atomic numbers 57–71) and are members of Group IIIB in the periodic table. The term 'lanthanon' (abbreviated to Ln) is also used for any member of the REE plus Y. The REE all have very similar chemical and physical properties, a uniformity arising from their electronic configurations which lead to a particularly stable 3^+ oxidation state (Henderson, 1984), and a general contraction in Ln^{3+} ionic radius from La to Lu which causes a systematic variation in properties.

Most accounts of the geochemistry of REE discuss concentrations in terms of the summation of REE concentrations. Wedepohl (1978) notes that the term 'rare earth' is somewhat inappropriate as cerium is more abundant in igneous rocks of the upper crust than several better–known metals (e.g. Pb, Co, Sn, Mo and W).

Cerium, like the other REE, is strongly electropositive and most of its chemistry is characterised by ionic bonding. The relatively large ionic radius of Ce^{3+} (101 pm) precludes significant substitution into minerals except where the substituted cation is also large (Henderson, 1984), such as Ca^{2+} (100 pm), Y^{3+} (90 pm) and Th^{4+} (94 pm). Cerium differs from other REE in that it can also occur in the Ce^{4+} oxidation state, which has a smaller solid–state ionic radius (87 pm). The occurrence of cerianite [$(Ce,Th)O_2$)], by hydrothermal alteration of bastnaesite [$(Ce,La)(CO_3)F$], is reported by Vlasov (1966), and it might be expected to occur in direct substitution for Zr(IV) and Th(IV) in zircon and thorite, and possibly for U(IV) in pitchblende [UO_2].

The crustal average for cerium is 60 ppm, with granites (230 ppm) higher than basic igneous rocks (30 ppm) (Mason, 1966). Wedepohl (1978) quotes average cerium values for basalts (16 ppm), intermediate rocks (60 ppm) and granitic rocks (104 ppm). Sewell *et al.* (1992) report a range of 29–304 ppm cerium in 18 representative samples of Hong Kong granites (average 105 ppm).

Accessory minerals, such as allanite, apatite, zircon and sphene are important in the enrichment of cerium in igneous rocks. Cerium minerals such as fluocerite [$(Ce,La)F_3$], loparite [$(Na,Ce,Ca)TiO_3$] and monazite [$Ce(PO_4)$] are primarily associated with alkalic and granitic rocks and their pegmatites, and with hydrothermal mineralisation.

The lanthanides are generally stable towards metamorphic processes.

Monazite is a remarkably resistant mineral (cf. its similar phosphate analogue, xenotime, [YPO_4]) under surface environment conditions, and primary igneous monazite may persist into sedimentary rocks, though authigenic nodular monazite may also form in sediments during diagenesis. Absolute abundances of cerium in sedimentary rocks are reported by Wedepohl (1978): shales (67–91 ppm) > greywackes (62 ppm) > sandstones (33 ppm) > limestones (6.5 ppm). However, sandstones and other sedimentary rocks containing large quantities of resistant heavy mineral such as zircon and sphene will have elevated cerium levels. Many important monazite deposits are secondary accumulations, e.g. beach placers in India (Wedepohl, 1978).

Oceanic manganese nodules are particularly enriched in cerium (Fleet, 1984) and sea waters are strongly depleted in cerium relative to other REE, suggesting that cerium sorption by Mn nodules may be the primary control on cerium in the marine environment.

Surface environment geochemistry

Brookins (1988) shows a large theoretical stability field for CeO_2 on the Eh–pH diagram for cerium in conditions common in the surface environment, especially under oxidising conditions above pH 6, but Ce^{4+} ions in solution will be rapidly reduced to Ce^{3+} unless CeO_2 forms first. The large stability field for Ce^{3+} might suggest that cerium is relatively mobile under acid conditions, despite the low solubility product of its carbonate and hydroxide, and it is probably a combination of sorption by Fe and Mn oxides, and the very low solubility of the phosphate which governs geochemical mobility of cerium. It is unclear whether fresh-water Mn oxides have the same strong affinity for cerium, as do their marine equivalents.

Detailed description

In the western New Territories, elevated levels of cerium are present over outcrops of the fine- to medium-grained Tsing Shan Granite (Lamma Suite) north of Lung Kwu Tan and medium-grained Lantau Granite (Lamma Suite) in the vicinity Tai Lam Chung. A small cerium anomaly north of Lung Kwu Tan (231–381 ppm) is accompanied by moderate to high levels of P_2O_5 (0.02–0.78 %), Cs (12–26 ppm) and Pb (53–313 ppm). At Tin Shui Wai, a prominent cerium anomaly coincides with high levels of Ba (832 ppm), Sr (91 ppm), and Co (13 ppm). This anomaly lies over outcrops of Carboniferous sedimentary rocks, although elsewhere in the northern New Territories, cerium values are low to very low over similar rocks.

A small cerium anomaly (243–313 ppm) west of Ho Pui Reservoir is associated with moderate to high values of La (55–124 ppm), Ba (195–221 ppm), Cs (16–18 ppm), Pb (124–185 ppm) and Zn (107–176 ppm). The area is underlain by medium-grained Tai Lam Granite (Lamma Suite). Elevated cerium values in the vicinity of Sheung Fa Shan and west of Tai Mo Shan range from 123 to 199 ppm, and mainly overlie outcrops of coarse ash crystal tuff (Tsuen Wan Volcanic Group) and Tai Po Granodiorite (Lamma Suite).

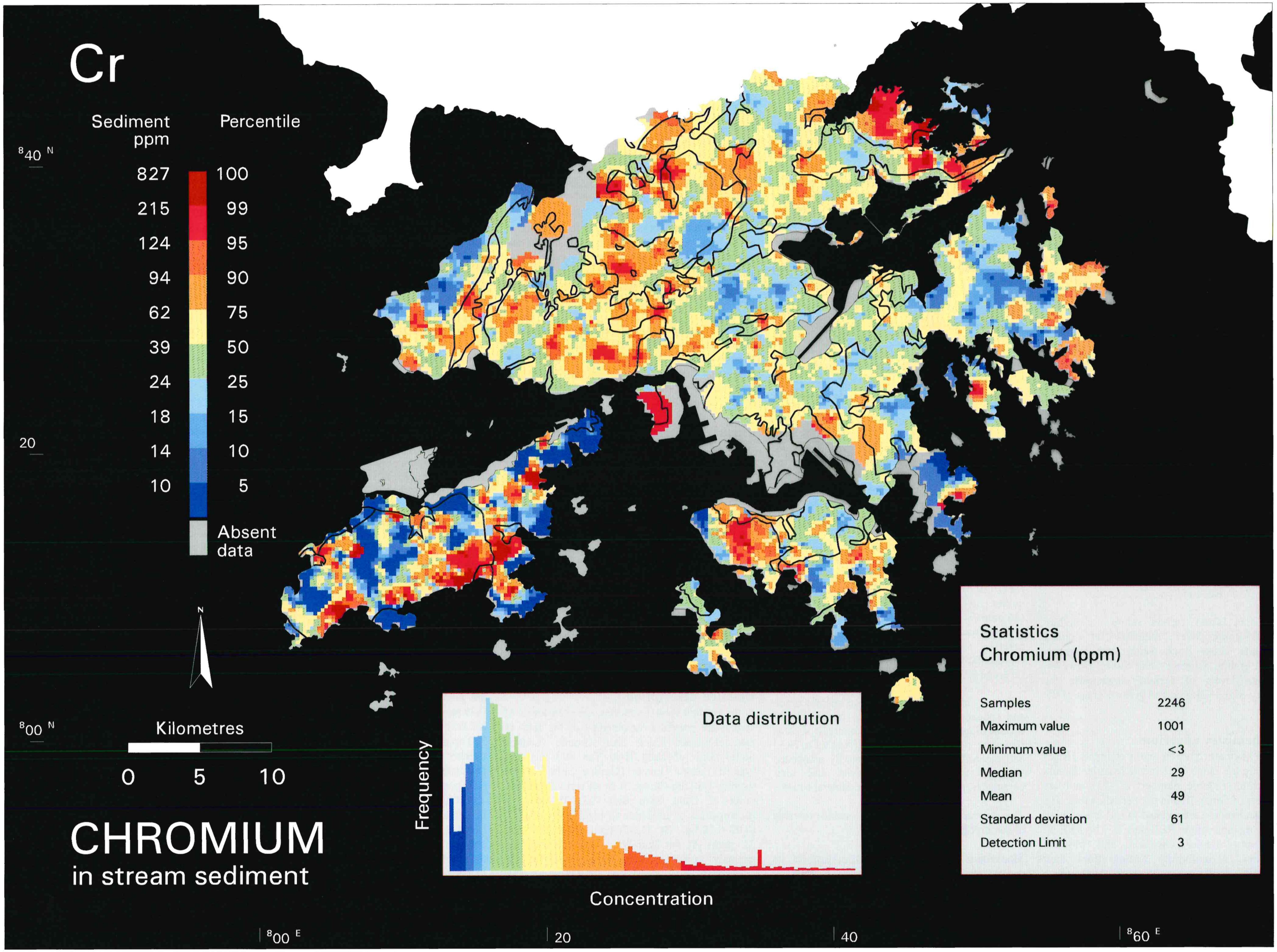
In the central New Territories and Kowloon, high cerium values in the Sha Tin Granite (120–290 ppm) contrast strongly with the moderate cerium values in the adjacent Needle Hill Granite (Kwai Chung Suite). At Kwai Chung, extremely high levels of cerium (240–1994 ppm) are accompanied by moderate to high levels of La (104–4933 ppm), P_2O_5 (0.08–1.84 %), Cu (12–365 ppm), Pb (87–883 ppm), Zn (103–1490 ppm) and Co (<1–20 ppm) suggesting local contamination. However, some enhanced concentrations may also be due to nearby outcrops of quartz monzonite dykes. Farther north in the Shing Mun area, the high cerium values coincide with high La (17–192 ppm), Cs (<1–25 ppm), Pb (92–402 ppm) and Zn (75–365 ppm). A small cerium anomaly (244–332 ppm) in the Siu Lek Yuen area is accompanied by lower concentrations of these elements (e.g. La 31–40 ppm, Pb 47–65 ppm, Zn 60–77 ppm). This area is underlain by dykes of quartz monzonite.

In the eastern New Territories cerium anomalies are present at Pyramid Hill west of Sai Kung (339 ppm), Pak Tam Chung (250–430 ppm), Tan Ka Wan (235–256 ppm) and Kau Sai Chau (242–328 ppm). At Pyramid Hill, the cerium anomaly overlies outcrops of quartz monzonite dykes and is associated with high levels of La (180 ppm), Ba (603 ppm), Cs (27 ppm) and Hg (2.1 ppm). At Pak Tam Chung, the high cerium values coincide with moderate to high levels of La (74–135 ppm), Ba (39–427 ppm), Co (4–11 ppm) and Cs (7–16 ppm) and similar values of these elements accompany the cerium anomaly at Tan Ka Wan (e.g. La 69–88 ppm, Ba 247–497 ppm, Co 4–12 ppm and Cs 2–16 ppm). On Kau Sai Chau, the high cerium values are associated with moderate to high levels of La (10–128 ppm), Cs (5–13 ppm), Pb (40–119 ppm) and Zn (41–233 ppm).

On Hong Kong Island, strong cerium anomalies at Mount Collinson (246 ppm) and D'Aguilar Peak (540 ppm) are associated with moderate levels of La (58–191 ppm), Ba (149–295 ppm), Cs (7 ppm), Pb (64–76 ppm) and Zn (130–171 ppm). Both these areas are partly underlain by intrusions of quartz monzonite (Lion Rock Suite).

High cerium values (260–509 ppm) in the north and east of Lamma Island coincide with outcrops of coarse ash crystal tuff (Tsuen Wan Volcanic Group) and Lantau Granite (Lamma Suite) which have been intruded by quartz monzonite (Lion Rock Suite). Typical values of associated metals are as follows: La (88–152 ppm), Ba (27–332 ppm), Cs (6–13 ppm), Pb (52–182 ppm) and Zn (56–304 ppm). On Po Toi Island, a small cerium anomaly over outcrops of coarse-grained granite (Lion Rock Suite) is accompanied by moderate La (106 ppm), Ba (233 ppm), Cs (8 ppm), Pb (143 ppm) and Zn (93 ppm).

Small cerium anomalies are present at Chi Ma Wan (276–336 ppm) and Shek Pik (262 ppm) on Lantau Island, and elevated levels (156–199 ppm) are present in the vicinity of Mui Wo and Penny's Bay. At Shek Pik and Mui Wo, the moderate to high cerium values coincide with outcrops of quartz monzonite (Cheung Chau Suite and Lion Rock Suite). Typical samples from Shek Pik contain moderate to high levels of La (101 ppm), Ba (758 ppm), Cs (60 ppm), Co (14 ppm) and Zn (168 ppm). The cerium anomaly at Chi Ma Wan is underlain by outcrops of medium- and fine-grained Chi Ma Wan Granite (Cheung Chau Suite). Typical ranges of values of associated metals are as follows: La (116–146 ppm), Ba (233–363 ppm), Cs (1–60 ppm), Pb (39–152 ppm) and Co (4–12 ppm). In the northern part of the island, the slightly elevated cerium values correspond with outcrops of Lantau Granite (Lamma Suite) and coarse ash crystal tuff (Tsuen Wan Volcanic Group).



CHROMIUM
in stream sediment

Statistics
Chromium (ppm)

Samples	2246
Maximum value	1001
Minimum value	<3
Median	29
Mean	49
Standard deviation	61
Detection Limit	3

Chromium

Cr

Synopsis

Chromium values are rather variable across most of Hong Kong, with little direct relationship to the underlying rocks. Elevated values are possibly more common in areas underlain by tuffaceous sedimentary rocks but in general, local variations are mainly controlled by the degree of anthropogenic contamination.

Over the western New Territories, background values of chromium are generally low (<39 ppm) over the granitic areas and slightly higher (39–62 ppm) over outcrops andesitic rocks of the Tuen Mun Formation. Local anomalies in the granitic areas are thought to be largely due to contamination.

Sporadic chromium anomalies over the central and northern New Territories are largely associated with anthropogenic contamination. Over the granitic areas, some of this contamination is related to mining waste.

In the northeastern New Territories, high values of chromium (>124 ppm) coincide with outcrops of tuffaceous sandstone and mudstone interbedded with coarse ash crystal tuff (Tsuen Wan Volcanic Group). High chromium values (124–215 ppm) are also locally associated with outcrops of Upper Palaeozoic and Upper Mesozoic sedimentary rocks.

Chromium values are generally low to moderate (14–39 ppm) over the eastern New Territories and Kowloon, with local anomalies over outcrops of tuffaceous sandstone and mudstone (Kau Sai Chau Volcanic Group). Several other anomalies are thought to be related to contamination.

On Hong Kong Island and Lamma Island, chromium values are rather variable. Local anomalies present in the western and eastern parts of Hong Kong Island and in the eastern parts of Lamma Island, are thought to be largely influenced by anthropogenic contamination.

Strong anomalies are present in several areas of Lantau Island. Most are associated with development areas and are clearly influenced by contamination. However, in the southwestern part of the island, high chromium values (>124 ppm) may be associated with outcrops of tuffaceous mudstone within the volcanic succession (Lantau Volcanic Group).

Geochemistry of chromium

Chromium, a Group VIB element, is a member of the first transition series of elements of the periodic table, i.e. Ti, V, Cr, Mn, Fe, Co, Ni and Cu. The trivalent ion Cr^{3+} (ionic radius 62 pm), like other transition elements with intermediate radii, readily substitutes for Fe and Mg and is partitioned into spinels and pyroxenes during the earliest stages of crystal fractionation. As a result, chromium is enriched in ultrabasic rocks (1000–3000 ppm), along with elements such as Ni. While the principal chromium ore mineral, chromite $[(FeCr_2O_4)]$, is generally mined from ultrabasic rocks, it is also a major carrier of chromium in basaltic magmas, along with Cr–enriched magnetite and ilmenite (Wedepohl, 1978). Olivines are generally poor in chromium, but pyroxenes, amphiboles and micas may be enriched (Ure & Berrow, 1982). Mielke (1979) cites chromium values for igneous rocks as: ultrabasic, 1600 ppm; basaltic, 170 ppm; granitic, 4–22 ppm; and an average crustal abundance of 122 ppm.

In sedimentary rocks, chromium may be present in primary detrital phases such as chromite, magnetite and ilmenite. During weathering, the behaviour of Cr^{3+} resembles that of Fe^{3+} and Al^{3+}, leading to widespread accumulation in secondary oxides and clays. The average concentration of chromium in shales is reported by Mielke (1979) to be 90 ppm, with rather lower mean values in sandstones (35 ppm) and limestones (11 ppm) .

Surface environment geochemistry

In stream environments, chromium is mostly held in minerals which are highly resistant to weathering, such as spinels and other detrital oxides (ilmenite, magnetite, chromite). In the Hong Kong environment, where seasonal heavy rain will lead to a high-energy environment in the river channel, it might be anticipated that the selective removal of fine, less dense material will lead to an enrichment of chromium in the remaining coarse-grained sediment. As Cr-rich minerals are resistant to weathering, the release of chromium into solution is slow. Some Cr^{3+} may be released by the dissolution of ferromagnesian silicates under conditions of high Eh and low pH, but subsequent dispersal is restricted by its tendency to co-precipitate with Fe oxides or become sorbed onto clays and organic matter.

Chromium is used in steel alloys (10–26 %) and for coating steel (chrome plating). Chromates and dichromates, containing Cr^{6+}, are sometimes released in industrial effluents (especially from leather tanning and electroplating operations) and are highly poisonous and readily soluble. However, as powerful oxidising agents they are rapidly reduced and sorbed by organic residues. Chromium has been demonstrated to be an essential trace element for animals, but high excesses are toxic.

Detailed description

In the western New Territories, chromium values are generally moderate to high over outcrops of andesitic rocks of the Tuen Mun Formation, and slightly lower over the granitic areas. In the granitic areas, local anomalies are present at Lung Kwu Tan, Nim Wan and Castle Peak with the Castle Peak Firing Range. The high chromium values (126–249 ppm) are typically associated with moderate to high Ni (12–21 ppm), Pb (114–257 ppm) and Sb (4–5 ppm), and are probably related to waste metal associated with spent military ordnance. West of Lam Tei, high chromium values (141 ppm) over outcrops of andesitic rocks are accompanied by high Cd (3.2 ppm), Hg (2.3 ppm) and Zn (140 ppm). Elevated chromium values (144–177 ppm) over outcrops of granitic rocks east of the Tuen Mun Valley coincide with moderate to high values of V (23 ppm), Ni (17–18 ppm), Pb (81–132 ppm) and Sn (27–80 ppm) and are likely to be related to anthropogenic contamination.

In the central New Territories, west of Tai Mo Shan, several chromium anomalies coincide with known mineral prospects associated with outcrops of granodiorite. These include anomalies near Tai Lam Reservoir (175 ppm), Tsing Fai Tong (184 ppm), Chuen Lung (175 ppm), and Kap Lung (306 ppm). Most of these high chromium values are associated with moderate to high V (17–153 ppm), Sc (8–21 ppm), Ni (12–26 ppm), Hg (0.2–3.1 ppm), Pb (68–232 ppm), Zn (71–538 ppm) and Sn (37–147 ppm), and in most cases are related to contamination by mining waste.

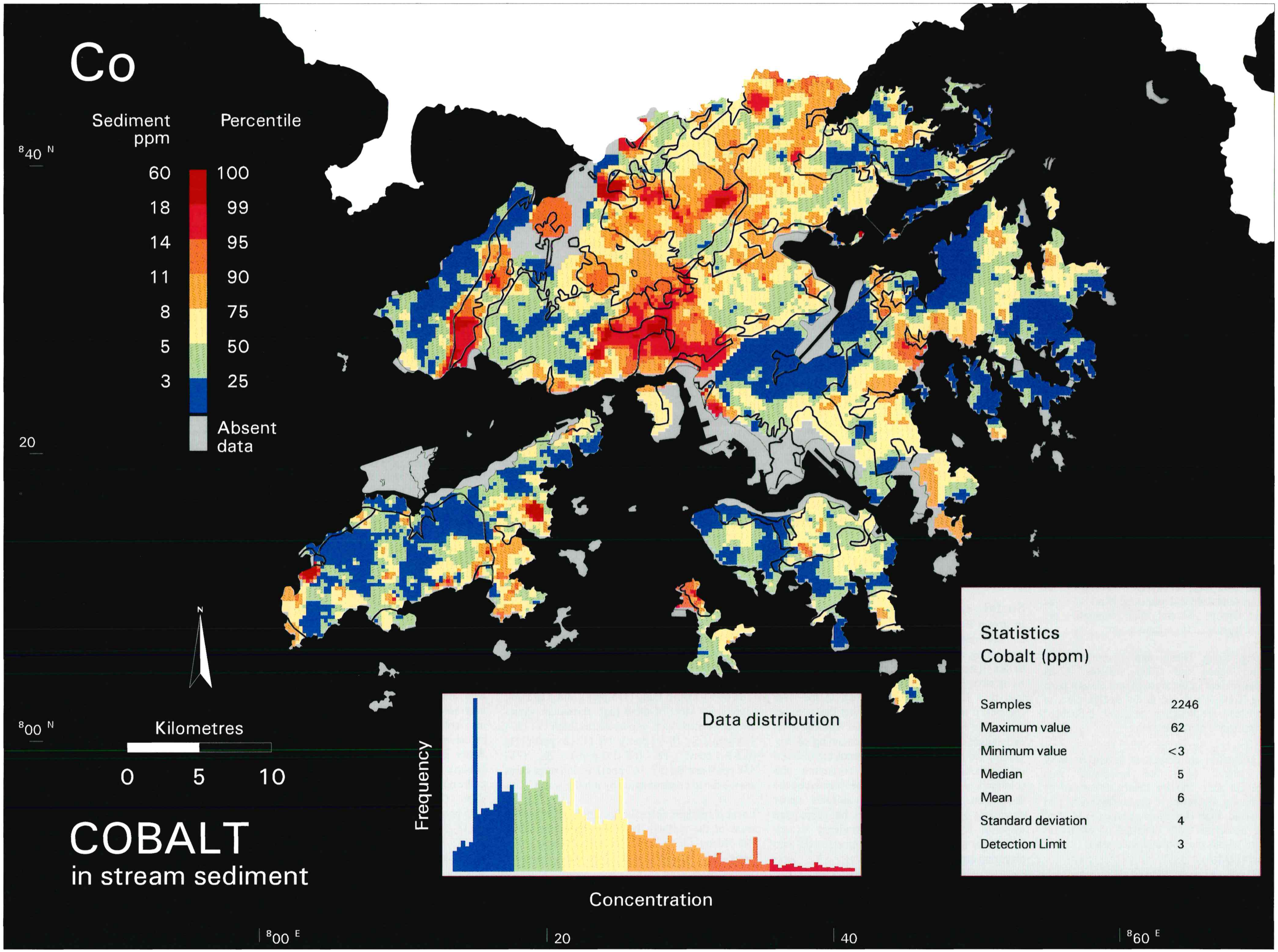
Local chromium anomalies are present in several areas of the northern New Territories, including Pat Heung (236 ppm), Mai Po (232 ppm), Lin Tong Mei (269 ppm) and Kwan Tei (216 ppm). Most of these chromium anomalies are associated with high V (50–64 ppm), Sc (8–11 ppm), Ni (13–37 ppm), Hg (0.3–6.1 ppm), Cu (82–2849 ppm), Pb (89–884 ppm), Zn (259–17 489 ppm) and Sn (24–151 ppm). The high levels of associated metals, together with the absence of known iron mineralisation in these areas, suggest that the high chromium values are largely due to anthropogenic contamination.

Very high chromium values are present in several areas of northeastern New Territories, particularly in the vicinity of Yung Shue Au (344 ppm), Lai Che Wo (287 ppm), Sam A Tsuen (260 ppm) and Sam A Chung (181 ppm). These anomalies coincide with high levels of Sc (9–17 ppm), TiO_2 (0.52–1.21 %), V (58–84 ppm), Hg (0.2–2.5 ppm) and Sb (4–11 ppm). Several outcrops of tuffaceous siltstone and sandstone are known to be interbedded with the coarse ash crystal tuff succession and may be partly responsible for the elevated values.

Background levels of chromium are generally low to moderate over most of the central New Territories, east of Tai Mo Shan, and over large parts of eastern New Territories. Small anomalies are present on Tsing Yi, and in several areas to the east of Sai Kung. On Tsing Yi, the high chromium value (165 ppm) is associated with moderate to high Sc (13 ppm), Sb (5 ppm), Ni (21 ppm) and MnO (0.31 %) and is probably partly related to an outcrop of granodiorite nearby, along with an anthropogenic overprint. East of Sai Kung, slightly elevated chromium values are present over outcrops of tuffaceous sandstone and mudstone of the Lai Chi Chong Formation (Lantau Volcanic Group) and Mang Kung Uk Formation (Kau Sai Chau Volcanic Group). In the vicinity of Long Ke, near High Island Reservoir, the high chromium values (129–202 ppm) are not obviously associated with other metallic contamination. These values may be reflecting high natural background levels in volcanigenic breccias, sandstones and mudstones interbedded with tuffs of the Clear Water Bay Formation (Kau Sai Chau Volcanic Group), exposed in the vicinity of Tai Long Wan to the north. Local chromium anomalies at Kau Sai Chau (225 ppm) and in Clear Water Bay (135 ppm) are associated with moderate levels of V (16–23 ppm), Sc (9–13 ppm), Ni (10–11 ppm), Pb (53–92 ppm) and Zn (62–109 ppm), and may be partly related to contamination.

Chromium values are rather variable on Hong Kong Island and Lamma Island with local anomalies at Victoria Peak (130–345 ppm), Deep Water Bay (126–247 ppm), and Mount Collinson (159–230 ppm). The highest values at Victoria Peak coincide with the moderate to high levels of Ni (11–25 ppm), Pb (50–160 ppm), Zn (46–124 ppm), and Sn (7–52 ppm) and are probably largely related to local construction waste. Slightly higher concentrations of these metals are associated with the other chromium anomalies on Hong Kong Island suggesting that contamination of stream sediment by construction waste is widespread. On Lamma Island, a small chromium anomaly at Sok Kwu Wan (201 ppm) coincides with a reported occurrence of tungsten mineralisation. Levels of associated metals are also high, and the high chromium values is likely to be related to contamination by prospecting waste.

Chromium levels on Lantau Island are remarkably variable with areas of very low concentration contrasting with those of very high concentration. In particular, the highest chromium values are mostly associated with areas of urban development along the south coast and at Discovery Bay. The high chromium values in the Mui Wo area (440 ppm) coincide with high values of V (55 ppm), Pb (186 ppm), Zn (112 ppm) and Sn (530 ppm) and are likely to be mostly related to contamination by construction waste. However, Pb–Zn–Cu mineralisation is known from nearby areas and a contribution of chromium from this source can not be ruled out. Similar levels of associated metals are present at Discovery Bay, Cheung Sha and Tong Fuk. High values of chromium (1001 ppm) are present in stream sediments from the Shek Pik area. These high values are not associated with other metals and may reflect high natural background values in the underlying tuffaceous rocks. Isolated chromium anomalies at Tai O (293 ppm), Sai Tso Wan (1001 ppm), Tung Chung (585 ppm) and Yam O (227 ppm) are mostly accompanied by moderate to high Sn (4–239 ppm), Mo (5–14 ppm) and Bi (4–40 ppm), and are likely to be related to mining and construction waste.



COBALT
in stream sediment

Statistics
Cobalt (ppm)

Samples	2246
Maximum value	62
Minimum value	<3
Median	5
Mean	6
Standard deviation	4
Detection Limit	3

Cobalt

Co

Synopsis

Levels of cobalt are generally low (<3 ppm) over the granitic areas of western New Territories, central New Territories, and western Hong Kong Island. They are low to moderate (<5 ppm) over outcrops of Upper Palaeozoic and Upper Mesozoic sedimentary rocks, and generally low (<3 ppm) over volcanic rocks of the Kau Sai Chau and Lantau volcanic groups.

The highest cobalt values (>8 ppm) are found mostly in areas underlain by Tai Po Granodiorite (Lamma Suite) and coarse ash crystal tuff (Tsuen Wan Volcanic Group). This covers most of central and northern New Territories but high levels of cobalt are also associated with andesitic rocks (Tuen Mun Formation) in the western New Territories. In eastern Kowloon and Hong Kong Island, the highest cobalt values are generally associated with areas of quartz monzonite (Lion Rock Suite) and coarse ash crystal tuff (Repulse Bay Volcanic Group).

On Lantau Island, moderate to high values of cobalt (5–14 ppm) are mainly associated with outcrops of quartz monzonite (Lion Rock Suite) and coarse ash crystal tuff (Tsuen Wan Volcanic Group).

Geochemistry of cobalt

Cobalt is a member of the first transition series of elements and Group VIII in the periodic table, i.e. Ti, V, Cr, Mn, Fe, Co, Ni and Cu. In early magmatic processes, Co^{2+} substitutes for Fe^{2+} and Mg^{2+} which are similar in charge and ionic radius, so that cobalt is generally enriched in basic relative to silicic igneous rocks (Wedepohl, 1978). This is shown by the average abundances cited by Mielke (1979): ultrabasic, 150 ppm; basaltic 48 ppm; granitic 1–7 ppm; syenitic 1 ppm; and average crustal abundance 29 ppm. Cobalt displays chalcophile properties and is partitioned into sulphide and sulpharsenide phases, of which linnaeite [$(Co,Ni)_3S_4$]and cobaltite [CoAsS] are the pure cobalt end–member minerals. It may also be associated with the pyrite, arsenopyrite and pyrrhotite, and in oxide accessory minerals such as magnetite (Ure & Berrow, 1982).

Cobalt is considered to be immobile during metamorphism (Condie, 1976; Nicollet & Andriambololona, 1980). Minerals such as quartz, feldspar and pure calcium carbonate generally hold very little cobalt (<2 ppm), so pure sandstones and limestones are very low in cobalt. In sedimentary rocks cobalt tends to vary with the Fe and Mn content and is concentrated in the fine-grained fractions. Arkoses and greywackes are more enriched, their cobalt concentrations usually reflecting the abundance of mafic minerals (Ure & Berrow, 1982). Cobalt values of *c.* 50 ppm are common in very fine-grained mudrocks but mean cobalt concentrations in black shales are somewhat lower (e.g. Vine & Tourtelot, 1970), indicating that organo-metallic complexing is not an important enrichment mechanism for cobalt in natural sedimentary processes. Mielke (1979) cites average values for shales, sandstones and carbonates as 19, 0.3 and 0.1 ppm cobalt respectively.

Surface environment geochemistry

A large proportion of the cobalt in stream sediments is usually held in detrital phases, including ferromagnesian silicates, primary oxides and metastable sulphides. Several of these minerals (notably Co sulphides and sulpharsenides) liberate Co^{2+} during weathering under acid conditions (McKenzie, 1975), following which the extent of cobalt dispersal depends on the clay content of the sediment and the presence, speciation and valency of Fe and Mn (Calvert & Price, 1977; Ure & Berrow, 1982). Hydrous Fe phases (such as goethite) are generally the most important scavengers of cobalt, although co-precipitation with authigenic Mn hydrous oxide phases such as birnessite may be equally important in certain pH conditions.

In streams of sufficiently low pH and/or Eh, where the formation of high valency phases of Fe and Mn is inhibited, cobalt is likely to remain mobile, but it will rapidly be removed from solution by co-precipitation and sorption in most oxidising, near-neutral or alkaline stream waters as the dissolved Fe and Mn precipitate out as secondary oxides.

Cooper & Thornton (1994) note that, with the exception of metalliferous mining, anthropogenic anomalies in drainage are rarely recorded. Cobalt has an essential role in living organisms (e.g. vitamin B_{12}) and interest is mainly in deficiency rather than excesses. Environmental pollution problems are less significant than those associated with some other heavy metals (Smith & Patterson, 1995).

Detailed description

Background levels of cobalt are high over outcrops of the Tuen Mun Formation in the western New Territories, with prominent anomalies in the vicinity of Tuen Mun (16–24 ppm) and Ha Tsuen (14–20 ppm). Near Tuen Mun, the cobalt anomaly coincides with high levels of MnO (0.12–0.20 %) and Fe_2O_3 (11.5–13.1 %), Cd (0.4–3.1 ppm), Hg (0.6–2.8 ppm), Se (1.7–2.2 ppm), Sr (102–283 ppm), TiO_2 (0.82–1.2 %), V (86–154 ppm) and W (21–22 ppm). The site is close to an area which was once mined for wolframite (Davis, 1958). Therefore, some of the high metal concentrations in stream sediments may be due to contamination by mining waste. In the Ha Tsuen area, the high cobalt values are accompanied by moderate to high MnO (0.14–0.19 %), Cd (1.2–1.7 ppm) and Fe_2O_3 (4.7–7.7 %).

A strong anomaly at Mai Po (35 ppm) in the northern New Territories coincides with high levels of Cu (2849 ppm), Zn (17 489 ppm), Pb (884 ppm), Hg (6.1 ppm) and Sn (151 ppm), suggesting strong contamination. Anomalies at Lok Ma Chau and Lin Ma Tei have low contents of these metals and are probably reflecting high natural background levels of cobalt in the Carboniferous metasedimentary rocks.

In the northern New Territories, cobalt values are generally moderate to high over outcrops of the Tsuen Wan Volcanic Group, with prominent anomalies at Lin Tong Mei (20 ppm), Wo Hop Shek (14–23 ppm), Kwai Tau Leng (15–21 ppm) and Ta Kwu Leng (15–18 ppm). These anomalies are commonly accompanied by moderate to high As (16–58 ppm), Fe_2O_3 (5.3–6.8 %), Sc (9.1–15.7 ppm), Se (0.64–1.01 ppm), TiO_2 (0.56–1.05 %), V (37–81 ppm) and W (8–15 ppm).

In the central New Territories, the highest cobalt values are found to the southwest of Tai Mo Shan (29–32 ppm) close to contact zones between granodiorite and granite of the Lamma Suite, and between granodiorite and volcanic rocks of the Tsuen Wan Volcanic Group. A broad area of elevated cobalt values (14–23 ppm) occurs to the north of Tai Mo Shan and is possibly associated with zones of shearing and dynamic metamorphism within the Tai Mo Shan Formation (Tsuen Wan Volcanic Group).

Southwest of Tai Mo Shan, the cobalt anomalies are accompanied by high Fe_2O_3, moderate Zn and Pb, and low Cu values. This area is known for Pb–Zn–Cu and Sn–W–Mo mineralisation, particularly adjacent to intrusive contact zones. A small cobalt anomaly in the Kwai Chung area to the southeast of Tai Mo Shan is accompanied by high Cu (365 ppm), Ni (392 ppm), Zn (847 ppm) Pb (883 ppm) and Sn (120 ppm), indicating a high degree of metallic contamination.

Small cobalt anomalies are present over outcrops of Permian rocks (Tolo Harbour Formation) at Chinese University and Ma Shi Chau. These are accompanied by relatively low background concentrations of Cu, Pb, and Zn.

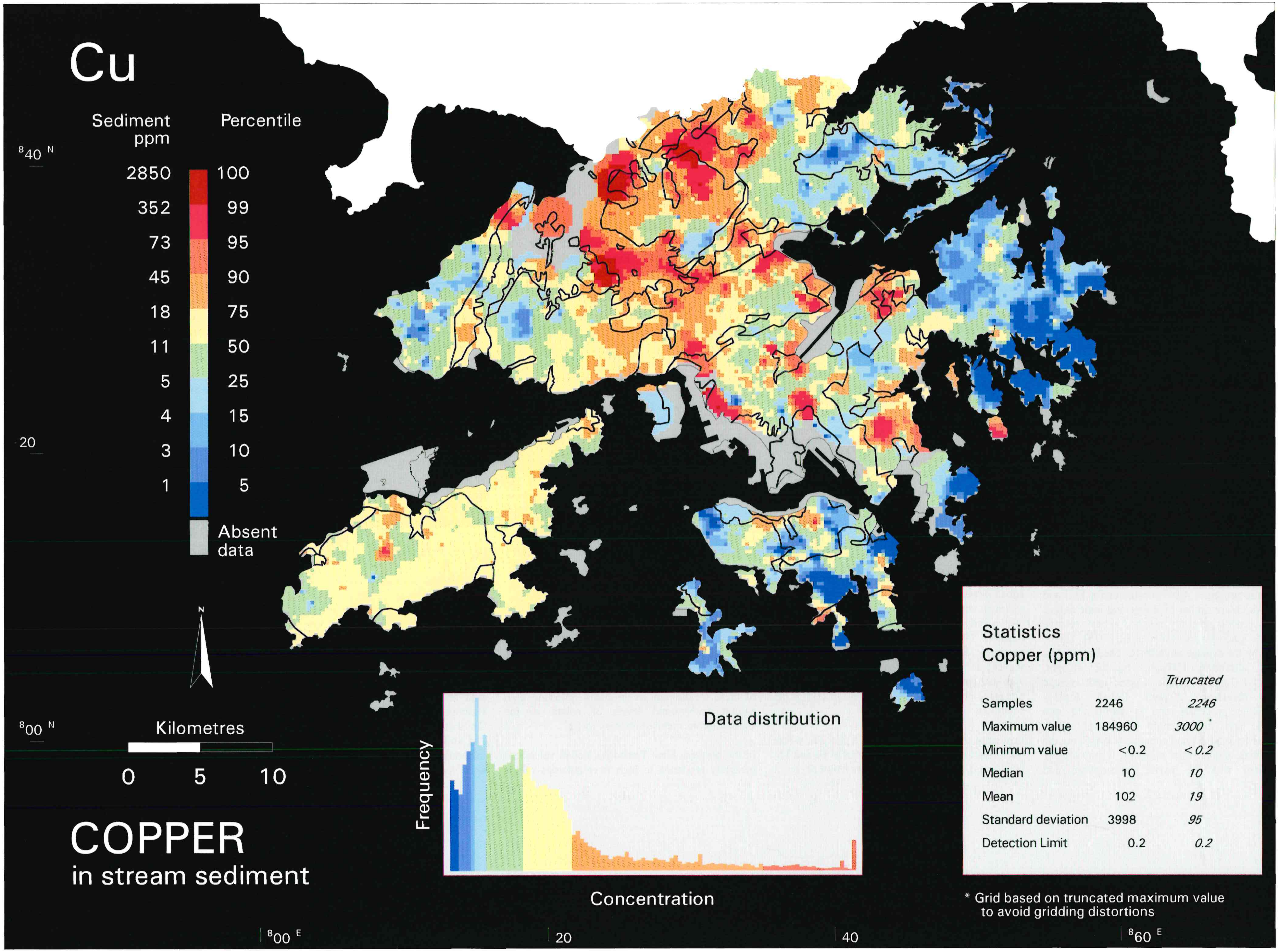
In the eastern New Territories, moderate to high cobalt values are present around the Ma On Shan area, and extending east from Sai Kung to Long Harbour. The high cobalt values surrounding Ma On Shan are associated with high values of Fe_2O_3 and MnO. They are most likely to be related to Fe mineralisation within Devonian sedimentary rocks and volcanic rocks of the Lai Chi Chong Formation (Lantau Volcanic Group). East of Sai Kung, the high cobalt values coincide with high levels of Fe_2O_3 and MnO and may be partly related to outcrops of quartz monzonite. At Pak Kong, a typical sample contains the following: Co (14 ppm), MnO (0.22 %), Fe_2O_3 (7.12 %), Cu (11 ppm), Zn (127 ppm) and Pb (39 ppm). Rather high Hg (2.4 ppm) is also present.

Cobalt levels are low to moderate over much of eastern Kowloon and eastern Hong Kong Island, with elevated values at Clear Water Bay, D'Aguilar Peak, and Mount Butler. High cobalt values generally coincide with outcrops of quartz monzonite (Lion Rock Suite), strengthening a natural association seen between quartz monzonite and high cobalt concentrations farther north. High cobalt values are also present in northern Lamma Island which is largely underlain by intrusions of quartz monzonite (Lion Rock Suite).

On Lantau Island, the highest cobalt values are found on the southern side of the island at Tai Shui Hang, Mui Wo and Chi Ma Wan. Other anomalies are present at Tsing Chau Tsai, Tai O, Yi O and Fan Lau with isolated anomalies at Ngong Ping and Cheung Sha Wan. With the exception of Tai Shui Hang, most of the anomalies on the south side of the island coincide with outcrops of quartz monzonite (Lion Rock Suite). At Tai Shui Hang, the high cobalt values (15–62 ppm) are accompanied by high Fe_2O_3 (3.8–18.6 %), Pb (117–640 ppm), and Zn (125–368 ppm), suggesting that the stream sediments have been partly contaminated.

At Tai O and Yi O, the moderate to high cobalt values (15–17 ppm) coincide with high MnO (0.09–0.12 %) and Fe_2O_3 (3.8–5.1 %). In central Lantau Island, several small cobalt anomalies are accompanied by high concentrations of Cu, Pb, Zn and Sn and are likely to reflect local metallic contamination.

Cu



COPPER

in stream sediment

Statistics
Copper (ppm)

		Truncated
Samples	2246	*2246*
Maximum value	184960	*3000* *
Minimum value	<0.2	*<0.2*
Median	10	*10*
Mean	102	*19*
Standard deviation	3998	*95*
Detection Limit	0.2	*0.2*

* Grid based on truncated maximum value to avoid gridding distortions

Copper

Cu

Synopsis

Copper levels are moderate to high (>18 ppm) over the northern New Territories, and parts of the western New Territories in the vicinity of Tai Mo Shan. They are moderate (5–18 ppm) over much of Lantau Island, and low to moderate concentrations of copper (<11 ppm) characterise much of the western New Territories (Tuen Mun area), and parts of Kowloon and Hong Kong Island. The lowest copper levels (<3 ppm) are present over the eastern New Territories.

In the northern New Territories and around Tai Mo Shan, the moderate to high copper levels mostly coincide with outcrops of coarse ash crystal tuff (Tsuen Wan Volcanic Group). However, there is a strong anthropogenic overprint, particularly in the northern part of New Territories. Strong natural anomalies are present in areas of known copper mineralisation, such as around Tai Mo Shan, Lin Ma Hang, Lam Tsuen Valley, Ma On Shan and Sha Lo Wan.

Several strong copper anomalies in the Lau Fa Shan, Tin Shui Wai, Mai Po and Sheung Shui areas are from highly contaminated samples. The strong copper anomalies in the Sha Tin Valley, Kwai Chung, Kowloon and Sai Kung areas are also largely due to anthropogenic contamination.

The moderate copper values in Lantau Island are mostly related to the high background levels present in the Lamma Suite granitoids and volcanic rocks of the Lantau Volcanic Group. Small anomalies close to urban areas, such as Discovery Bay and Mui Wo, are due to anthropogenic contamination.

Geochemistry of copper

Copper belongs to Group IB of the periodic table (with Ag and Au) and is a member of the first transition series of elements. In spite of a similarity in electronic structure, there are few resemblances between the chemistries of the three elements in Group IB. One of the similarities is that all of them in the III valence state have similar complexes, and certain complexes of Cu^{2+} and Ag^{2+} are isomorphous (Cotton & Wilkinson, 1972). Transition elements with incomplete inner electron shells (including Fe, Cu, Cr and Ag) tend to be less soluble and are more strongly adsorbed than non–transition ions of similar charge and ionic radius (Rose *et al.*, 1979).

During magmatic processes, the univalent ion Cu^{+} is primarily concentrated in early differentiates. It tends not to be incorporated into silicates, but being strongly chalcophile is partitioned into sulphides and oxides as determined by the relative fugacities of sulphur and oxygen (Curtis, 1964; Helgeson, 1969). Average copper values for silicate minerals are given by Ure & Berrow (1982) as 115 ppm for olivines, 120 ppm for pyroxenes, 78 ppm for amphiboles, 86 ppm for biotites and 62 ppm for plagioclases. Chalcopyrite [CuFeS$_2$] is a common accessory mineral and primary copper carrier in basic igneous rocks. Basalts and gabbros (40–60 ppm) and ultrabasic rocks (40 ppm) typically contain more copper than intermediate (*c.* 20 ppm) and granitic (*c.* 12 ppm) rocks (Wedepohl, 1978). A crustal average for copper is 68 ppm (Mielke, 1979).

Copper may be redistributed during low-grade metamorphism and metasomatism (Senior & Leake, 1978), but its mobility is more restricted at higher metamorphic grades (Nicollet & Andriambololona, 1980). In common with other chalcophile elements, copper is strongly concentrated into sulphide minerals during hydrothermal mineralisation.

In unmineralised sediments, copper concentrations are principally determined by basic detritus, secondary Fe and Mn oxides (Forbes *et al.*, 1976), clay minerals (Heydemann, 1959) and organic matter (Stevenson & Ardakani, 1972). Fine-grained clastic rocks (particularly black shales) are typically enriched in copper (*c.* 50 ppm) relative to quartzo–feldspathic and carbonate sediments (5–15 ppm).

Surface environment geochemistry

Copper may be hosted by detrital silicates and oxides in stream sediments, but near mineralisation centres it is mainly carried in sulphide phases such as chalcopyrite. The release of Cu^{2+} from these minerals is relatively rapid under acid conditions (pH <5.0), but subsequent dispersion is controlled by humic acids, organic ligands, clay minerals, hydrous oxides and soluble carbonates. Tooms & Webb (1961) concluded that hydromorphic dispersion was the principal factor for dispersing copper in the Zambian Copperbelt, with mechanical dispersion a contributing factor. However, in Botswana, Coope (1958) found dispersion by sheetwash was only 15–20 m on a 1–3° slope.

Copper compounds are widely used in agriculture and are a possible source of drainage anomalies. The affinity of copper for organic matter has been widely documented (e.g. Rashid, 1974; Rippey, 1982) and may explain the significant amounts of non–detrital copper in stream waters in areas of peaty drainage or high algal productivity. In sediments containing hydrous Fe and Mn oxides, copper is removed from solution more by adsorption than by co-precipitation (Robinson, 1981). However, precipitation of CaCO$_3$ (usually in response to a pH increase) may cause the rapid removal of copper and Zn from stream waters by co-precipitation (Rubin, 1974). Diagenetic covellite [CuS] has been observed in anoxic sub-surface sediments and may account for the immobilisation of small amounts of copper following its release from detrital minerals in organic-rich sediments (Carignan & Nriagu, 1985; Williams, 1992).

Contaminant sources are numerous, including the use of copper as a metal alloy (e.g. brass) and in electrical wire.

Detailed description

In the northwestern New Territories, a small anomaly at Lau Fau Shan (Cu 174 ppm) is associated with moderate to high levels of As (10.5 ppm), Cr (34 ppm), P$_2$O$_5$ (2.62 %) and Zn (551 ppm) indicating that this is a contaminated sample. A similar explanation can be given for the isolated anomaly at Tin Shui Wai where the high copper value is coincident with high levels of As (25 ppm), Bi (12 ppm), Pb (120 ppm), Sb (4.5 ppm) and Zn (114 ppm).

A broad area of moderate to high copper levels extends from Ngau Tam Mei through to Sheung Shui with prominent anomalies at Mai Po (254–2849 ppm) and Shek Wu Hui (210–876 ppm). Although this area is underlain by Tai Mo Shan Formation, the anomalously high copper concentrations are due to the presence of heavily contaminated samples. At Mai Po, the high copper values are accompanied by high concentrations of industrial metals including As (117–160 ppm), Cd (0.8–3.2 ppm), Cr (31–232 ppm), Hg (1.0–6.1 ppm), Pb (139–884 ppm), Sb (3–88 ppm), Sn (16–151 ppm) and Zn (678–17 489 ppm). Similarly, at Shek Wu Hui, the high copper values are coincident with high levels of associated metals (e.g. As 68–122 ppm, Pb 107–316 ppm and Zn 1899–9639 ppm).

A small copper anomaly (131 ppm) at Ta Kwu Ling is associated with high Pb (202 ppm) and Zn (421 ppm) values but low values of other metallic elements suggesting that this may be an area of mineralisation. The site is close to an area of known Pb–Zn–Cu mineralisation at Lin Ma Hang which also has revealed traces of copper mineralisation (Peng, 1978).

In the central New Territories, a small anomaly at Tai Po Kau (131 ppm) is possibly related to anthropogenic contamination because of moderate to high values of As (9 ppm), Pb (98 ppm) and Zn (134 ppm), and the presence of ceramics and industrial effluent in the stream course. However, in the major stream draining Lead Mine Pass south of Tai Po Kau, elevated copper values (106–282 ppm) are associated primarily with high Pb (232–439 ppm) and Zn (191–563 ppm) values. These are considered to reflect the high natural background values surrounding the area of known Pb–Zn–Cu mineralisation on Tai Mo Shan. Although the host lithology is coarse ash crystal tuff of the Tai Mo Shan Formation (Tsuen Wan Volcanic Group), the source of the mineralisation is thought to be in the adjacent contact zone with Tai Po Granodiorite (Lamma Suite). Elevated copper values (81–282 ppm) in the vicinity of Shek Kong are associated with high values of Cd (0.3–5.5 ppm), As (6–24 ppm), Ag (0.2–1.9 ppm) Pb (124–2431 ppm), Sn (123–461 ppm) and Zn (191–1048 ppm) suggesting that at least some of the anomalous levels are related to anthropogenic contamination. The same can be implied for the large copper anomaly at Kam Tin, where an extreme value of 18.9 % Cu is almost certainly related to industrial metal contamination. Levels of associated metals in this sample are also high (e.g. As 29 ppm, Zn 220 ppm, Pb 239 ppm).

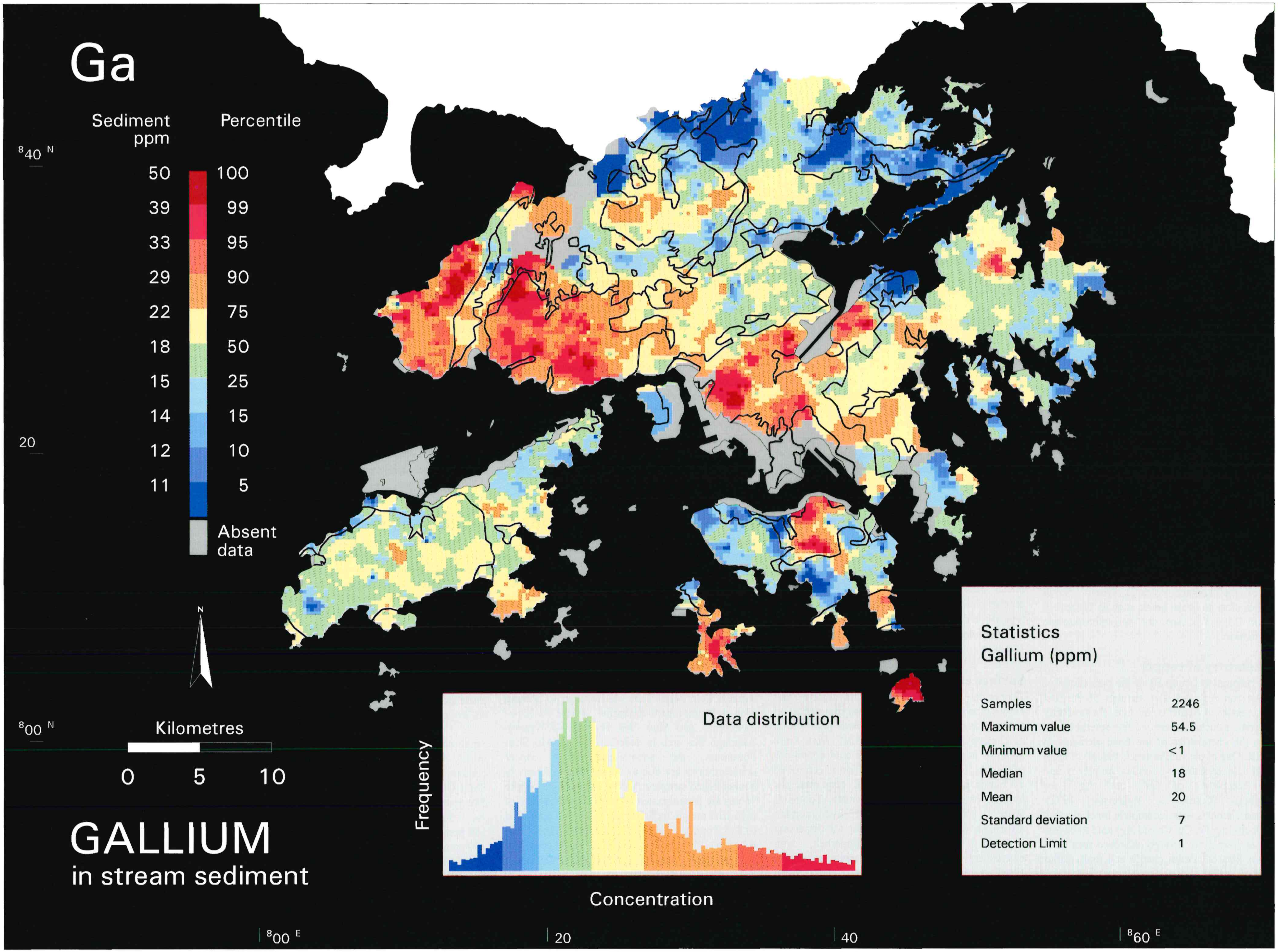
Small copper anomalies in the Sha Tin Valley are mostly associated with anthropogenic contamination. These include anomalies at Ma Liu Shui (Cu 140 ppm, Bi 80 ppm, Mo 218 ppm, Sn 589 ppm, Zn 662 ppm), Shing Mun (Cu 55 ppm, As 6.5 ppm, Pb 2256 ppm, Sn 8881 ppm, Sb 188 ppm), and San Po King (Cu 170 ppm, Pb 129 ppm, Sn 161 ppm, Zn 494 ppm). High copper levels (83–303 ppm) are found in the vicinity of the magnetite mine at Ma On Shan where chalcopyrite is commonly seen in black siltstone bands within the Ma On Shan marble. However, the natural copper concentrations may be heavily overprinted by contamination due to mining waste as indicated by high levels of industrial metals in some samples (e.g. Pb 896 ppm, Zn 490 ppm, Sn 449 ppm, As 111 ppm, Bi 361 ppm and Ag 12.8 ppm).

A strong anomaly at Kwai Chung in western Kowloon is largely due to one highly contaminated sample. The high level of copper (365 ppm) is associated with high Ag (7.7 ppm), As (118 ppm), Pb (883 ppm), Sn (120 ppm), W (143 ppm) and Zn (847 ppm). Anomalies at Tseng Lan Shue and Jin Island in eastern Kowloon are also related to industrial metal contamination. For example, at Tseng Lan Shue, the high copper level (185 ppm) is associated with high Bi (18 pm), Mo (15 ppm), Pb (258 ppm), Sn (57 ppm) and Zn (594 ppm), whereas on Jin Island, moderate levels of As (17 ppm), Pb (119 ppm), Zn (77 ppm) and Fe (3.89 %) strongly suggest contamination.

On Hong Kong Island, background levels of copper are rather low (<11 ppm) with small elevated levels at Central, North Point, Big Wave Bay, Shek O and Chung Hom Wan. Samples from these areas contain high levels of industrial metals indicating anthropogenic contamination. A typical sample from Chung Hom Wan (Cu 56 ppm) has the following metal concentrations: Ag (1.8 ppm), As (22 ppm), Pb (177 ppm), Sn (29 ppm) and Zn (462 ppm).

Copper values on Lantau Island are remarkably uniform with levels mostly in the range 11–18 ppm. This probably reflects the similarity in composition of the dominant volcanic and granite lithologies (Lantau Volcanic Group and Kwai Chung Suite). Very small anomalies exist in the Mui Wo area and at Tsing Chau Tsai. At Mui Wo, the anomaly is likely to be associated with known Pb–Zn–Cu mineralisation. The small isolated copper anomaly (90 ppm) at Ngong Ping is due to one contaminated sample which contains high levels of industrial metals, including As (5 ppm), Pb (166 ppm), Sn (31 ppm), Sb (3 ppm) and Zn (183 ppm). At Sha Lo Wan, slightly elevated copper values (18–45 ppm) in stream sediment are probably due to the presence of weak copper mineralisation in association with hydrothermal tungsten deposits reported by Peng (1978).

Ga



Statistics
Gallium (ppm)

Samples	2246
Maximum value	54.5
Minimum value	<1
Median	18
Mean	20
Standard deviation	7
Detection Limit	1

GALLIUM
in stream sediment

Gallium

Ga

Synopsis

In the western New Territories, high levels of gallium (>22 ppm) are present over outcrops of the Tsing Shan and Tai Lam granites (Lamma Suite), and the Triassic Deep Bay Granite. These anomalous levels contrast with moderate values (15–22 ppm) over intervening volcanic and sedimentary rock areas. In the Tai Lam and Tsing Shan areas, the highest gallium values coincide with the fine-grained granite lithologies.

Gallium values are low (<11 ppm) over outcrops of Upper Palaeozoic and Upper Mesozoic sedimentary rock in the northern New Territories, and are generally low to moderate (<18 ppm) over outcrops of Middle Jurassic volcanic rocks (Tsuen Wan Volcanic Group).

In the central New Territories, background levels of gallium are high over outcrops of the Needle Hill and Sha Tin granites (Kwai Chung Suite), and the Kowloon Granite (Lion Rock Suite). The highest values (>33 ppm) are again most closely associated with the fine-grained lithologies, which commonly occur as dykes adjacent to quartz monzonite intrusions.

Moderate to high levels of gallium (15–22 ppm) surround outcrops of Kwun Tong Granite (Lion Rock Suite) in eastern Kowloon, and high levels (>22 ppm) coincide with the Mount Butler Granite (Lion Rock Suite) on Hong Kong Island. Gallium values are relatively low over adjacent volcanic rock areas (Repulse Bay Volcanic Group).

On Lamma Island, high gallium values (>22 ppm) mainly occur over outcrops of the South Lamma Granite (Cheung Chau Suite), although elevated levels also coincide with outcrops of fine-grained Sok Kwu Wan Granite (Lion Rock Suite) in the north of the island. Fine-grained lithologies of the Po Toi Granite (Lion Rock Suite) are responsible for the high gallium values (>29 ppm) on Po Toi Island, and also the slightly elevated levels (22–29 ppm) at Stanley and D'Aguilar peninsulas on Hong Kong Island.

There is generally little variation in gallium contents above low to moderate levels (15–22 ppm) on Lantau Island. Slightly elevated values (22–29 ppm) are present over the Chi Ma Wan Granite (Cheung Chau Suite) on the Chi Ma Wan Peninsula, and slightly lower levels (12–15 ppm) overlie outcrops of Upper Jurassic rhyolite dykes (Kwai Chung Suite) in the northern part of the island.

Geochemistry of gallium

Gallium is a member of the Group IIIA elements of the periodic table which also includes B, Al, In and Ti. The geochemical behaviour of gallium is very similar to that of its period group neighbour Al. Each element possesses a single M^{3+} oxidation state, though gallium has a greater ionic radius in both four-fold and six-fold co-ordination sites (47 and 62 pm respectively for Ga^{3+} compared with 39 and 53.5 pm for Al^{3+}). The association is such that Ga/Al ratios show little variability across a wide range of igneous lithologies, though strong magmatic fractionation may lead to preferential enrichment of gallium in late-stage differentiates as the larger Ga^{3+} ion is selectively excluded from early-formed minerals. Möller (1989) reports that notable enrichment of gallium is seen in leucogranites and pegmatitic granites being parental to fields of rare–element pegmatites. Feldspars and micas are the dominant host minerals for gallium in igneous and metamorphic rocks, as for Al. Although the charge and ionic radius of Fe^{3+} and Ga^{3+} ions are very similar (64.5 and 62 pm respectively) there is generally no close correlation between Fe and Ga in geological materials as Fe is more mobile in its reduced Fe^{2+} state. Mielke (1979) cites the following values for gallium in igneous rocks: ultrabasic, 1.5 ppm; basaltic, 17 ppm; granitic, 17 ppm; syenitic 30 ppm; and a crustal average of 19 ppm. Sewell *et al.* (1992) reported a narrow range of 13–21 ppm (average 16 ppm) for 18 representative Hong Kong granites.

Gallium is essentially immobile during metamorphism, being held in feldspars and garnets at high grades and in association with Al in micas at lower grades. Very low Ga/Al ratios result from greisenisation under strongly acid conditions (Beus & Grigorian, 1977).

As may be predicted from its position in the periodic table, the Ga^{3+} ion has the same electronic configuration as its period row neighbour Zn^{2+} but is slightly smaller. Consequently gallium exhibits weak Zn-related chalcophile behaviour under certain hydrothermal conditions, possibly promoting gallium enrichment in sphalerite.

In the sedimentary environment, gallium is concentrated with Al in clay minerals during the weathering process, though some may remain in detrital feldspars. Gallium concentrations are thus generally higher in aluminous shales, greywackes and feldspathic sandstones, and lowest in pure quartzites and carbonates. This is confirmed by Mielke (1979) who quotes values of 19 ppm, 12 ppm and 4 ppm for gallium in shales, sandstones and carbonates respectively.

Surface environment geochemistry

Gallium, like Al, is relatively immobile in the surface environment because of the low solubility of the dominant hydroxide, $Ga(OH)_3$. Although the thermodynamic differences between Al and Ga are small, some differences in weathering behaviour are suggested (Bowen, 1982; Brookins, 1988), gallium being rather more soluble than Al between pH 4 and pH 5 and thus possibly more mobile under these conditions. In stream sediments, gallium is principally associated with feldspathic detritus, clay minerals and secondary Fe and Al oxides, though it is not known if there is any enrichment relative to Al consistent with the theoretically greater mobility of gallium. Although Ga^{3+} and Fe^{3+} are very similar in charge and ionic radius, and both possess a low-solubility hydroxide, Fe is transported as the more soluble Fe^{2+} and is therefore separated from gallium during weathering.

Detailed description

In the western New Territories, high levels of gallium (>33 ppm) are present over almost all outcrop areas of the Tsing Shan and Tai Lam granites (Lamma Suite) and the Triassic Deep Bay Granite. Prominent anomalies are present at Tsim Bei Tsui (36 ppm), Ha Pak Nai (34–50 ppm), Lam Tei (35–45 ppm), Tai Lam Chung Reservoir (33–52 ppm), So Kwun Wat (33–40 ppm) and Tsing Fai Tong (34–47 ppm).

High gallium values over the Deep Bay Granite at Tsim Bei Tsui, and over the Tsing Shan Granite at Ha Pak Nai, are accompanied by moderate to high levels of Rb (139–623 ppm), Nb (41–81 ppm), Y (25–96 ppm) and Th (58–113 ppm). Similar high values of Rb (429–632 ppm), Nb (59–83 ppm), Y (50–152 ppm) and Th (90–109 ppm) accompany the gallium anomaly over the Tai Lam Granite at Lam Tei. At Tai Lam Chung Reservoir, So Kwun Wat and Tsing Fai Tong, the high gallium values are also accompanied by high U (8–29 ppm), in addition to high Th (47–121 ppm), Rb (273–617 ppm), Nb (26–84 ppm) and Y (27–252 ppm). The highest levels of gallium are generally associated with the fine-grained lithologies of each granite pluton.

In the northern New Territories, gallium levels are low (<11 ppm) over outcrops of Upper Palaeozoic and Upper Mesozoic sedimentary rocks and moderate (15–22 ppm) over outcrops of Middle Jurassic volcanic rocks (Tsuen Wan Volcanic Group). Slightly elevated levels (22–29 ppm) are present in the Ngau Tam Mei and Wo Hop Shek areas.

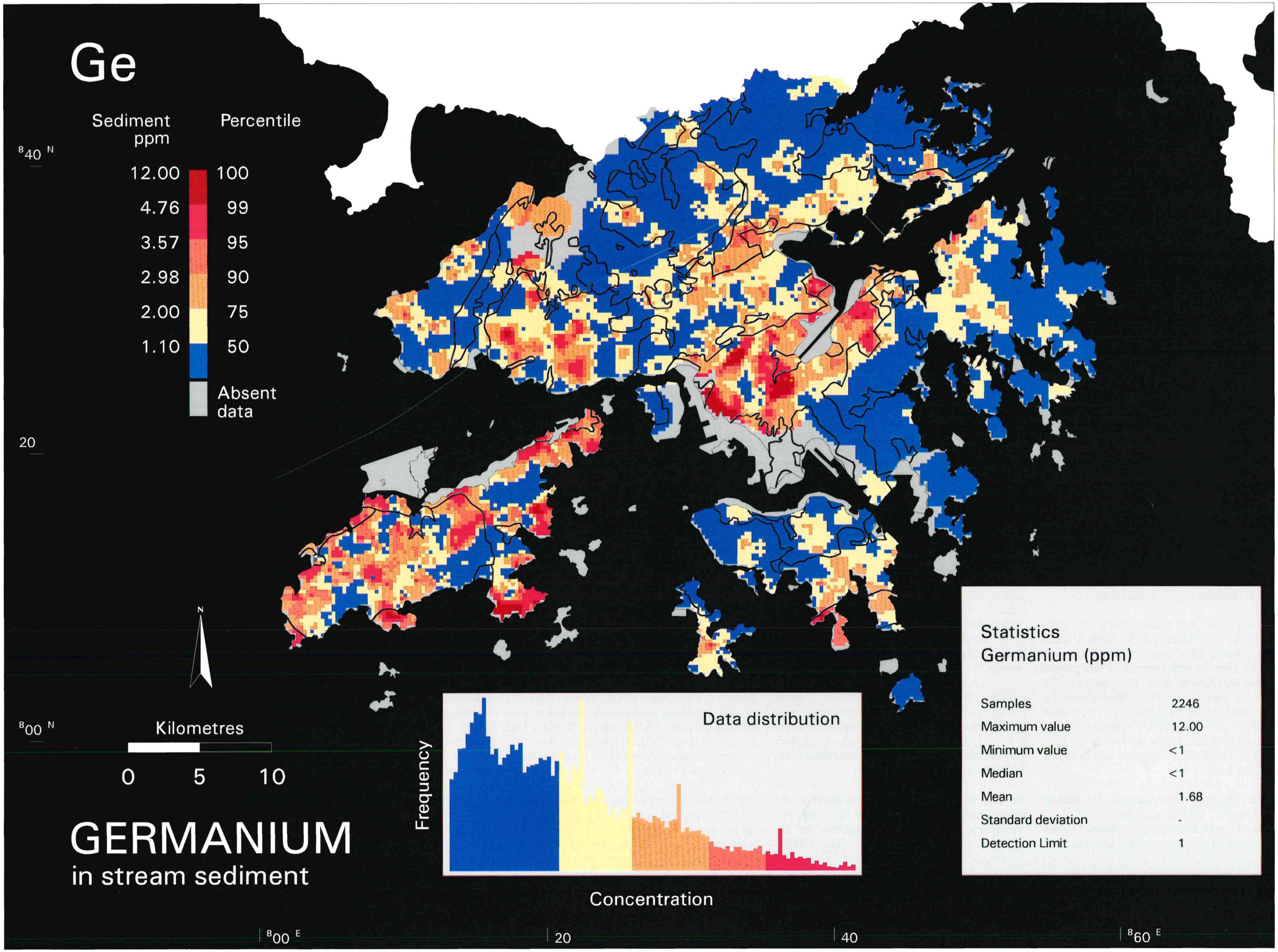
High gallium levels in the central New Territories mostly coincide with outcrops of fine-grained Needle Hill Granite (Kwai Chung Suite). However, gallium levels are also high over outcrops of the Kowloon and Sha Tin granites, where dykes of fine-grained granite are closely associated with quartz monzonite intrusions. Prominent anomalies over the Needle Hill Granite are present at Kwai Chung (33–49 ppm) and Sha Tin (34–49 ppm). At Kwai Chung, the high gallium values are accompanied by high Rb (108–439 ppm), Zr (265–1256 ppm), Nb (46–364 ppm), Y (26–161 ppm), U (4–35 ppm), Th (71–137 ppm) and Zn (54–319 ppm). The unusually high levels of some industrial metals suggests that stream sediments have been affected by local contamination. Similar high values for Rb (86–404 ppm), Zr (626–1815 ppm), Nb (48–113 ppm), Y (55–147 ppm), U (10–19 ppm), Th (84–184 ppm) and Zn (55–359 ppm) accompany the gallium anomaly at Sha Tin. Anomalies at San Po King (33–36 ppm) and Tai Shui Hang (35–38 ppm) are underlain mainly by fine-grained granite dykes intruding the Sha Tin and Kowloon granites. They are typically associated with high levels of Rb (200–373 ppm), Y (69–157 ppm), U (11–20 ppm) and Th (73–119 ppm).

Over eastern Kowloon, elevated levels of gallium (18–29 ppm) are present over outcrops of the fine-grained Kwun Tong Granite. Small anomalies at Sai Kung (22–29 ppm) and Tai Tan (22–39 ppm) in the eastern New Territories are underlain principally by coarse ash crystal tuff. Moderate to high values of Pb (18–169 ppm), Ni (14–21 ppm), W (9–18 ppm), Cs (15–20 ppm) and Sn (13–86 ppm) at these localities suggest that the sediments and may be partly affected by local contamination.

On Hong Kong Island, a prominent gallium anomaly (35–45 ppm) at North Point coincides with outcrops of the fine-grained Mount Butler Granite (Lion Rock Suite). The high levels of gallium are associated with high Nb (79–106 ppm), Y (43–247 ppm), U (6–25 ppm) and Th (77–131 ppm). Moderate to high levels of Zn (28–313 ppm) and Pb (50–242 ppm) in some samples suggest the existence of local anthropogenic contamination. Small gallium anomalies are present over outcrops of the Po Toi Granite at Stanley Peninsula (22–29 ppm) and D'Aguilar Peak (18–33 ppm). On Po Toi Island, gallium values (38–48 ppm) are particularly high over fine-grained lithologies, and are accompanied by moderate to high Nb (75–162 ppm), Y (68–82 ppm), U (6–11 ppm) and Th (76–106 ppm).

High gallium levels (34–41 ppm) are present over outcrops of the South Lamma Granite (Cheung Chau Suite) in the southern part of Lamma Island. The South Lamma Granite is intruded by a swarm of porphyritic rhyodacite dykes which may have also contributed to the high gallium levels. Moderate to high levels of Rb (80–287 ppm), Zr (298–1032 ppm), Y (43–102 ppm) and Th (67–91 ppm) accompany the high gallium values.

Gallium values are rather moderate (15–22 ppm) in most areas of Lantau Island. Slightly elevated values (22–29 ppm) are present over the Chi Ma Wan Granite in the southern part of the island, and near Ngong Ping and Mui Wo. The moderate to high gallium levels near Ngong Ping are possibly influenced by local contamination as indicated by high levels of associated metals (see descriptions for Cu, TiO_2 and Zn). Northwest of Mui Wo, gallium levels are moderate to high over dykes of fine-grained granite intruding the Lantau Granite.



GERMANIUM

in stream sediment

Statistics
Germanium (ppm)

Samples	2246
Maximum value	12.00
Minimum value	<1
Median	<1
Mean	1.68
Standard deviation	-
Detection Limit	1

Germanium

Ge

Synopsis

In the western New Territories, germanium levels are generally low (<1.1 ppm) over outcrops of the Tsing Shan Granite (Lamma Suite), whereas several prominent anomalies (3.0–4.8 ppm) overlie outcrops of the adjacent Tai Lam Granite (Lamma Suite).

Low germanium values (<1.1 ppm) characterise outcrops of volcanic and sedimentary rocks in the northern and eastern parts of the northern New Territories. These contrast with moderate to high values (1.1–3.0 ppm) over outcrops of the Tai Po Granodiorite (Lamma Suite) and sedimentary rocks in the southern part of the northern New Territories.

In the central New Territories, high germanium values (>2.0 ppm) coincide with outcrops of the Needle Hill and Sha Tin granites (Kwai Chung Suite), and the Kowloon Granite (Lion Rock Suite). The high germanium values may also be related to dykes of quartz monzonite and fine-grained granite which intrude the Sha Tin and Kowloon granites (Kwai Chung Suite). Germanium values are also high (>3.6 ppm) over outcrops of Permian sedimentary rocks in Tolo Harbour.

Germanium anomalies (>2.0 ppm) in Hong Kong Island mainly coincide with outcrops of the Po Toi Granite (Lion Rock Suite) and D'Aguilar Quartz Monzonite (Lion Rock Suite). Elevated values (>1.1 ppm) also occur over the Mount Butler Granite (Lion Rock Suite) and fine ash vitric tuff (Repulse Bay Volcanic Group) in the east of the island. On Lamma Island, high germanium values (>2.0 ppm) coincide with outcrops of the South Lamma Granite (Cheung Chau Suite), but may also be partly related to rhyodacite dykes which intrude the granite.

On Lantau Island, germanium values are high (>2.0 ppm) over outcrops of the Tai Lam and Lantau granites (Lamma Suite) which are intruded by rhyolite and rhyodacite dykes (Kwai Chung Suite). In the south, high germanium values coincide with outcrops of the Chi Ma Wan Granite (Cheung Chau Suite) and also with outcrops of quartz monzonite (Cheung Chau and Lion Rock suites) at Shek Pik. In general, germanium values are moderate to high (>1.1 ppm) over outcrops of volcanic rocks (Tsuen Wan and Lantau volcanic groups).

Geochemistry of germanium

Germanium is a 'metalloid' element and a member of Group IVA of the periodic table. Its nearest group analogues are Si and Sn. It is also intermediate in metallic character, like its 'period' neighbours Ga and As. In common with the lighter group members it has predominantly a 4-covalent bonding property, and elemental germanium has the diamond-type crystal structure also shown by Si. The close affinity with Si is also marked in its compounds with oxygen, and many germanium analogues of silicates and aluminosilicates have been prepared. However, substitution of Ge for Si is not thermodynamically favoured because of the larger size of the germanium covalent radius (122 pm, cf. 117 pm for Si). There is some evidence for germanium substitution for Fe in spinels, and germanium also has marked chalcophile properties and an affinity for organic matter, properties which clearly distinguish it from Si. In reducing conditions the Ge^{2+} ion may also form, and this may be present in some minerals, especially sulphides.

Germanium is a rare element, with an estimated crustal abundance of only 1.5 ppm. This value is also typical of most igneous, metamorphic and clastic sedimentary rocks and their dominant minerals, there being relatively little differentiation between ultrabasic, basic, intermediate and granitic rocks (1.3–1.5 ppm, Mielke, 1979).

Granite pegmatites, however, often show substantially higher germanium values (typically 10 ppm) with some minerals such as white micas, garnets and (especially) topaz showing germanium contents up to several hundred ppm. Pegmatites, developing from the late stages of magmatic differentiation, are usually enriched in those elements which do not readily enter silicate lattices, for example volatiles such as B, Cl, F and S and elements such as Ge, which may be transported at elevated temperatures as volatile complexes with these light elements. The high enrichment of germanium in topaz [$Al_2(SiO_4)(OH,F)_2$] suggests that F is probably the main germanium carrier. In contrast, quartz from granite pegmatites is usually depleted relative to the content in granites, so simple substitution of Ge for Si in SiO_2 is not an important process, and F is probably preferentially stripping Ge from the melt by complexation.

In hydrothermal mineralisation, however, the chalcophile properties of germanium are much more marked than its lithophile behaviour in silicate systems. High levels of germanium have been found in several sulphide minerals such as the copper minerals chalcopyrite [$CuFeS_2$], enargite [Cu_3AsS_4], bornite [Cu_5FeS_4] and tennantite [$(Cu,Fe)_{12}As_4S_{13}$], and others such as low-temperature sphalerites [$(Zn,Fe)S$] and galena [PbS].

Germanium levels in clastic sedimentary rocks are usually in the 1–2 ppm range, similar to those of most igneous rocks. Evaporites and pure limestones, however, show markedly low germanium values, typically <0.1 ppm. Organic-rich sediments such as black shales show a moderate elevation of germanium values, typically up to 3.3 ppm, and coals show substantially higher germanium values with up to several hundred ppm Ge. Whereas the germanium levels in black shales are believed to be mainly authigenic, the wide spatial variation of germanium levels in coal seams suggests that much of the germanium is of a post-depositional diagenetic origin (Wedepohl, 1978) and that the germanium is predominantly bound by complexation with the humic acid component of the organic matter. Coal ashes are often strongly enriched in germanium, with the highest values reported from Italian lignites (66 000 ppm).

Surface environment geochemistry

Brookins (1988) shows a theoretical Eh–pH diagram for germanium with a large insoluble GeO_2 field under acid conditions and soluble germanate anions above pH 8. Narrow fields of GeS_2 and GeO may be seen under low Eh conditions, but GeO lies wholly below the water stability field and cannot exist naturally in solution. Marine Mn oxides do not concentrate germanium, so it is also unlikely that their freshwater equivalents are effective sorption agents for germanium either. Incorporation into clay minerals is more likely, but given the affinity of germanium for organic matter in lignites and coals, these humic substances in surface waters, soils and sediments may also play a significant role.

Germanium is not known to have any biological function, and is generally supposed to have a low toxicity.

Detailed description

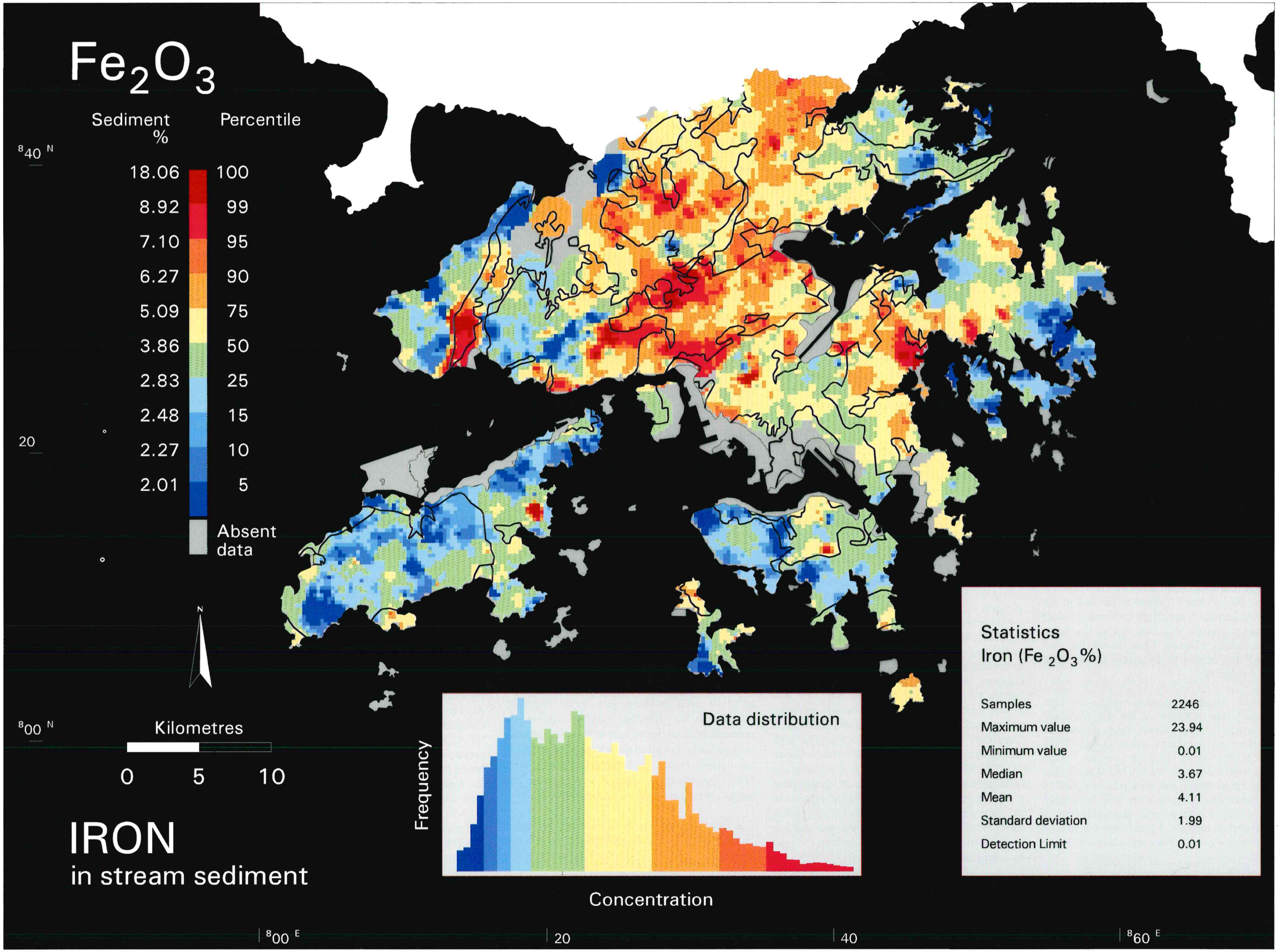
In the western New Territories, germanium values are generally low (<1.1 ppm) over the Tsing Shan Granite except for slightly elevated levels (>2 ppm) at Ha Pak Nai, Black Point, and Pillar Point. These local germanium highs are accompanied by high Ga (30–45 ppm), Rb (186–620 ppm), Nb (45–96 ppm) and Th (75–90 ppm). Several prominent germanium anomalies are present over the Tai Lam Granite at Tai Tong Tsuen (6 ppm), So Kwun Wat (6 ppm), and Tsing Fai Tong (4–5 ppm). The main anomalous area is at Tsing Fai Tong extending north to the Tai Lam Chung Reservoir. The high germanium values are accompanied by high Ga (27–42 ppm), Rb (363–606 ppm), U (14–25 ppm), Th (55–100 ppm) and Sn (28–637 ppm).

In the central New Territories, prominent anomalies are present over the Sha Tin and Needle Hill granites at Kwai Chung (5–12 ppm), Needle Hill (4–6 ppm), Fo Tan (4 ppm), Sha Tin (4–10 ppm) and Tai Hang Shui (4–5 ppm). At Kwai Chung, the high germanium values coincide with moderate to high Ga (23–49 ppm), Nb (42–278 ppm), Y (71–3563 ppm), U (5–21 ppm), Th (54–114 ppm), Cu (2–365 ppm), Pb (67–883 ppm), Zn (62–1490 ppm) and Sn (15–149 ppm) suggesting that some samples may have been affected by anthropogenic contamination. Sn–W–Mo mineralisation is known from Needle Hill where the high germanium levels are accompanied by moderate to high Ga (23–37 ppm), Rb (209–449 ppm), Zr (391–1694 ppm), Nb (43–80 ppm), Y (61–180 ppm), Cu (3–288 ppm), Pb (43–230 ppm) Zn (90–362 ppm) and Sn (27–289 ppm). The germanium anomaly over Sha Tin similarly coincides with moderate to high values of Rb (236–625 ppm), Zr (301–6259 ppm), Nb (30–176 ppm), Y (42–148 ppm), U (8–19 ppm), Th (28–108 ppm) and Sn (72–801 ppm). At Fo Tan, however, most values for these elements are low to moderate. The exception is for Sn (22–250 ppm), suggesting that the high germanium contents may be contained within the lattice of tin-bearing minerals. At Tai Shui Hang, the high germanium values are accompanied by high Ga (13–39 ppm), Rb (124–766 ppm), Zr (315–3131 ppm), Nb (30–164 ppm), Y (38–250 ppm), U (7–17 ppm), Y (33–125 ppm), Zn (45–396 ppm) and Sn (10–432 ppm). This anomaly is close to outcrops of fine-grained granite and quartz monzonite dykes which intrude the Sha Tin Granite (Kwai Chung Suite).

Slightly elevated germanium values (1.1–3.6 ppm) in southeastern Hong Kong Island coincide mainly with outcrops of the Po Toi Granite (Lion Rock Suite). However, the moderate to high values may also be influenced by outcrops of quartz monzonite (Lion Rock Suite) on both the D'Aguilar and Stanley peninsulas. On Lamma Island, moderate to high germanium values (1.1–4.8 ppm) are found over outcrops of the South Lamma Granite (Cheung Chau Suite), where rhyodacite dykes may also contribute to the elevated germanium levels.

On Lantau Island, germanium anomalies are present at Tong Fuk (4–6 ppm), Chi Ma Wan (4–6 ppm), Tai Shui Hang (4–7 ppm) and Yam O (4–6 ppm). Other strong anomalies are present at Yi O (4–5 ppm), Sha Lo Wan (4–5 ppm) and Tung Chung (4–5 ppm). At Tong Fuk, the high germanium values occur over outcrops of quartz monzonite (Cheung Chau and Lion Rock suites) and are associated with high Rb (169–200 ppm), Zr (1109–2457 ppm) and Nb (41–69 ppm). In the vicinity of Chi Ma Wan, high germanium values (4–6 ppm) overlie outcrops of Chi Ma Wan Granite (Cheung Chau Suite) and are accompanied by high Rb (112–416 ppm), Zr (452–2553 ppm), Nb (28–106 ppm), Y (24–195 ppm), U (9–41 ppm) and Th (21–248 ppm). At Tai Shui Hang, a prominent germanium anomaly overlying outcrops of rhyodacite and rhyolite dykes (Kwai Chung Suite) is accompanied by moderate to high Zr (163–741 ppm), but low to moderate levels of Rb (104–233 ppm), Nb 12–41 ppm), Y (32–42 ppm) and U (8–13 ppm). At Yi O and Yam O, the germanium anomalies are accompanied by high levels of Zr (395–2049 ppm), but low to moderate levels of Ga (12–21 ppm), Rb (131–236 ppm), Nb (29–47 ppm), Y (22–59 ppm) and U (8–16 ppm). South and east of Tung Chung, germanium anomalies overlying outcrops of the Lantau Volcanic Group are generally coincident with moderate to high Zr (581–929 ppm), and low to moderate Ga (19–20 ppm), Rb (194–209 ppm), Nb (32–38 ppm), Y (38–41 ppm) and Th (35–37 ppm).

Fe_2O_3



Statistics
Iron (Fe_2O_3%)

Samples	2246
Maximum value	23.94
Minimum value	0.01
Median	3.67
Mean	4.11
Standard deviation	1.99
Detection Limit	0.01

IRON

in stream sediment

Iron

Fe_2O_3

Synopsis

Background levels of iron are generally low to moderate (<3.8 % Fe_2O_3) over the main granitic areas and in areas underlain by Upper Palaeozoic and Upper Mesozoic sedimentary rocks. They are also low to moderate over outcrops of volcanic rocks belonging to the Lantau, Repulse Bay and Kau Sai Chau volcanic groups in the southern and eastern parts of Hong Kong. Moderate to high levels of iron (>5 % Fe_2O_3) are largely found in areas underlain by the Tsuen Wan Volcanic Group in the central and northern New Territories. High levels of iron (>7.1 % Fe_2O_3) are found over outcrops of Middle Jurassic Tuen Mun Formation in the western New Territories.

The highest levels of iron in stream sediment are found close to contact zones between the rocks of the Tsuen Wan Volcanic Group and the Jurassic granitoids. In many cases, anomalies correspond to areas of known iron mineralisation.

Isolated anomalies on Hong Kong Island and Lantau Island are related to anthropogenic contamination.

Geochemistry of iron

Iron is a Group VIII element and, along with Co and Ni from this group, it is a member of the transitions series of elements. It is the fourth most abundant element, and second most abundant metal, in the earth's crust.

Iron is a major constituent of ferromagnesian silicates such as olivines, pyroxenes, amphiboles and biotite. It is also abundant in a range of oxides (e.g. magnetite) and sulphides (pyrite, pyrrhotite etc.). It becomes concentrated in mid-stage fractionates during magmatic processes and is generally enriched in basic rocks relative to silicic, intermediate or ultrabasic types. Concentrations of iron will have a wide range within different rock classifications depending on mineralogical composition but as a guide Mielke (1979) reports values as: ultrabasic, 94 300 ppm; basaltic, 86 500 ppm; granitic, 14 200–29 600 ppm; syenitic, 36 700 ppm; and a crustal average, 62 200 ppm.

Iron has been shown to be immobile at medium and high metamorphic grades in basic rocks (Nicollet & Andriambololona, 1980), but Sheraton *et al.* (1973) and Beach & Tarney (1978) suggest that iron may be lost during retrogressive metamorphism. Iron may also be concentrated by mineralising fluids during metasomatic alteration into oxides such as hematite and sulphides such as pyrite.

The abundance of iron in sedimentary rocks is determined by various factors including provenance, pH–Eh conditions, the extent of diagenetic alteration and the granularity of the sediment. In most instances, secondary hydrous oxides are the dominant iron phases, though primary oxides (e.g. magnetite, [$(Fe,Mg)Fe_2O_4$)]), ferromagnesian silicates (amphiboles, pyroxenes etc.) and sulphides (e.g. pyrrhotite, [$Fe_{1-n}S$]) may account for some of the iron. Authigenic pyrite [FeS_2] and siderite [$FeCO_3$] may also be identifiable in fine-grained facies (e.g. Berner 1970; 1981). The tendency for hydrous iron phases to form surface oxide coatings may be reflected in a direct relationship between total iron content and the specific surface areas of sedimentary particles (Ure & Berrow, 1982). Hence, clays, shales and greywackes are generally enriched relative to arkoses, quartzo–feldspathic sandstones and carbonate rocks. Sedimentary ironstones in which the dominant iron minerals are siderite, ankerite or oxides of the goethite–limonite type may contain >30 % Fe_2O_3. Typical levels for iron in sedimentary rocks are given by Mielke (1979) as: limestone 3800 ppm; sandstone 9800 ppm; and shale 47 000 ppm.

Surface environment geochemistry

Iron may be introduced into stream sediments in a variety of mineral species including ferromagnesian silicates, oxides (e.g. magnetite) and a wide range of hydrous phases (e.g. limonite, goethite), but its subsequent behaviour and dispersal are controlled by the ambient redox regime. In circumstances where organic carbon remains in stream sediments after the exhaustion of O_2 for direct oxidation, a series of microbially–mediated processes facilitate further organic decomposition, involving the reduction of electron acceptors such as Fe^{3+}. Until recently, the Fe^{3+} ion was considered to be derived almost solely from amorphous and weakly structured species (e.g. Krauskopf, 1967), but recent recalculations of phase equilibria for the Fe–S–Si–H_2O system (e.g. Henshaw, 1978; Henshaw & Merrill, 1980) and empirical observations of Fe_3O_4 dissolution in anoxic sediments (e.g. Karlin, 1984; Canfield & Berner, 1987) have demonstrated that crystalline oxides and silicates may also be involved. Once released, the low-valency Fe^{2+} ion is highly soluble and may greatly increase the dissolved iron content of streams in boggy areas which are strongly acid and/or reducing. However, dissolved iron is generally precipitated rapidly with increasing pH or Eh, and this is responsible for the presence of hydrous oxide coatings (e.g. goethite, limonite and lepidocrocite) on stream clasts in aerobic environments. In the Hong Kong environment such alternate oxidation and reduction of iron can be produced in seasonally fluctuating groundwater environments, with reduction occurring at water-logged locations where anaerobic bacteria are active (Irfan, 1996). In addition to influencing the regional iron distribution, hydrous oxide coatings in stream clasts are a big influence on the distribution of Ba, Mo and As, and the first row transition metals, all of which are subject to adsorption by (and co-precipitation with) hydrous iron oxides. This behaviour of iron in the surface environment exerts a major control over the distribution of many other elements and is of fundamental importance in understanding geochemical patterns in stream sediments.

Dehydration of iron minerals is a further consideration in humid tropical environments with seasonal variation in rainfall. During the wet season, the humidity, the water table, water activity in the soil and weathering profile are all high. During the dry season there is little or no water activity in the upper horizons, and dehydration of goethite to hematite occurs (Nahon & Tardy, 1992). A similar process would happen to the surface layer of stream sediments if the stream bed dries out during the dry season.

A contact metamorphic iron deposit is described at the Ma On Shan iron mine by Davis (1961b). In similar geological settings there is potential for other such iron skarns, and these will give locally elevated levels of iron in the stream sediments, particularly where more alkaline conditions will reduce the mobility of iron in solution.

Detailed description

In the western New Territories, elevated levels of iron are present in association with dynamically metamorphosed Early to Middle Jurassic andesites (Tuen Mun Formation). Stream sediment samples from the area immediately to the north of Tuen Mun contain from 7–13 % Fe_2O_3 and are accompanied by moderate levels of Cu (8–22 ppm), Pb (11–95 ppm), Zn (73–193 ppm) and Sn (10–25 ppm). The concentrations of these metals suggests that the iron values probably reflect natural background levels although iron mineralisation has not been reported from the district.

In the northern New Territories, moderate to high levels of iron (3.8–7.1 % Fe_2O_3) are present over a broad area corresponding to outcrops of the Tai Mo Shan Formation (Tsuen Wan Volcanic Group). Local iron anomalies at San Wai Tsuen (7.1–8.0 % Fe_2O_3) and Lin Tong Mei (7.5–10.0 % Fe_2O_3) are generally accompanied by moderate to high levels of Cu (11–86 ppm), Zn (56–542 ppm), Pb (68–253 ppm) and As (27–494 ppm) suggesting contamination by industrial metals. Elevated iron levels (5.1–7.9 % Fe_2O_3) around the Lin Ma Hang area are probably associated with minor iron sulphide mineralisation accompanying the known Pb–Zn–Cu mineralisation.

In the central New Territories there is a clear correlation between high iron anomalies and contact zones between Lamma Suite granitoids and coarse ash crystal tuff of the Tsuen Wan Volcanic Group. Specific areas of iron mineralisation have been reported at Tai Po Kau, the Lam Tsuen Valley and at Kap Lung (Peng 1978). These show the highest iron anomalies typically reaching values of 8–11 % Fe_2O_3. The highest value of 23 % Fe_2O_3 comes from a sample near Kadoorie Farm at the head of the Lam Tsuen Valley. Microprobe analysis of the panned concentrate from this locality has confirmed the presence of magnetite and pyrite indicating local iron mineralisation. Sn-rich slag grains and fragments of Fe-rich Al–Si industrially-derived glass, containing traces of Zn and Cu, have also been identified. These data suggest the presence of anthropogenic contamination and help to explain the high concentration of accompanying metals in the stream sediment (e.g. Mo 110 ppm, Sn 11 848 ppm, W 67 ppm, Pb 3080 ppm, Zn 2694 ppm, Cu 821 ppm, Bi 244 ppm and Ag 34.2 ppm).

At Tsing Fai Tong, the iron anomaly is accompanied by slightly elevated concentrations of industrial metals. This area is known for its Pb–Zn–Cu sulphide mineralisation as well as Sn–W–Mo mineralisation. A small iron anomaly at Tai Lam Chung (7.68 % Fe_2O_3) is accompanied by low Mo (2.3 ppm), Sn (12 ppm), W (3 ppm) and Cu (44 ppm), but moderate to high Pb (191 ppm) and Zn (193 ppm).

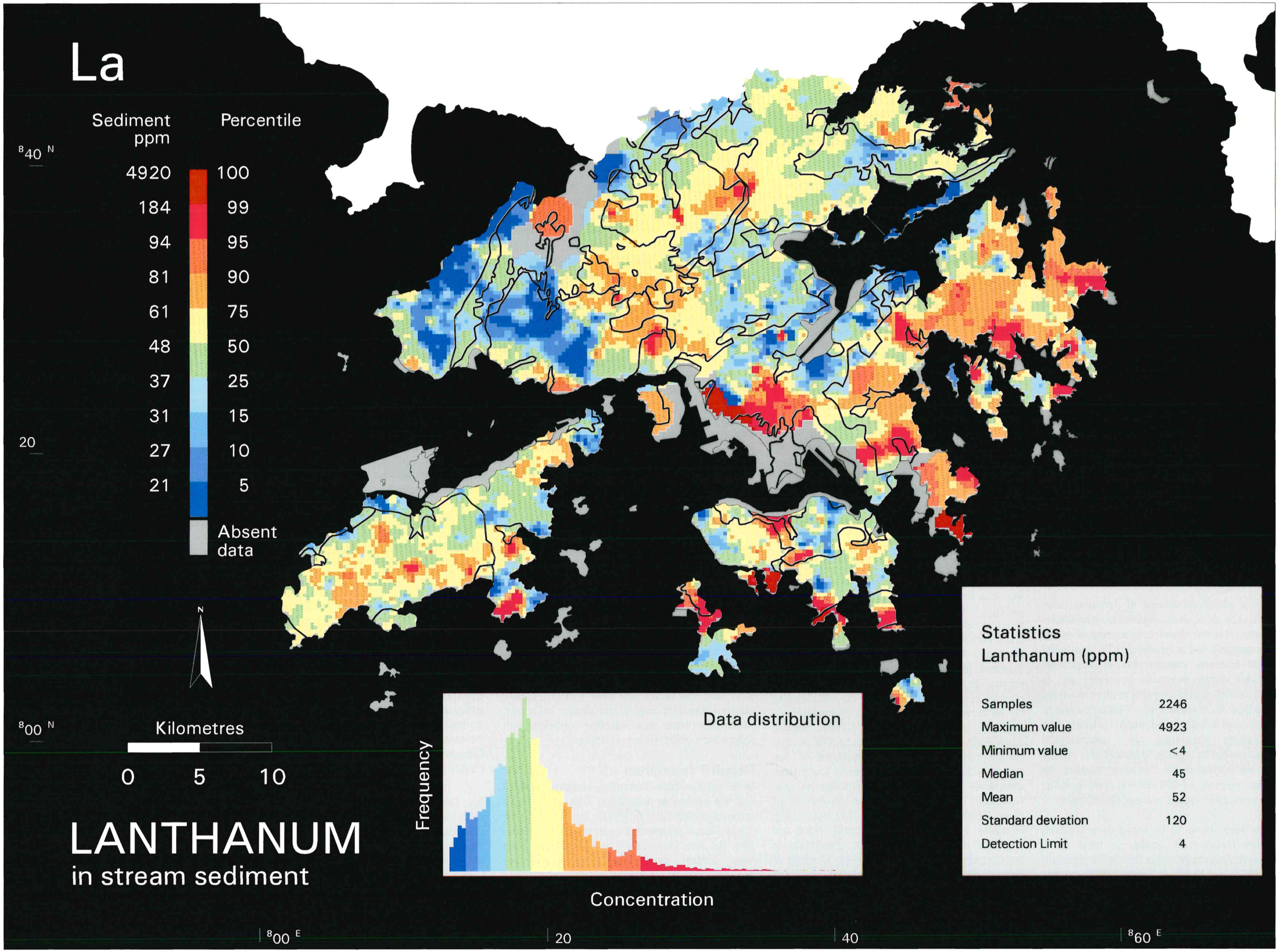
A broad area of elevated iron values is present at Chuen Lung to the north of Tsuen Wan. This corresponds to the reported occurrence of Pb–Zn–Cu mineralisation with associated iron (Peng, 1978).

At Shing Mun, unusually high iron values (17 % Fe_2O_3) are accompanied by low Mo (1.7 ppm), W (10 ppm) and Cu (9.2 ppm), but moderate to high Pb (157 ppm), Zn (185 ppm) and Sn (263 ppm). Fe-rich wire has been identified in the panned concentrate from this locality which indicates that the anomalous Fe_2O_3 values are due to anthropogenic contamination.

Despite the presence of skarn-related iron mineralisation Ma On Shan, iron values are only slightly above average background in the immediate vicinity of the mine. However, a broad area of elevated iron values is present in the Sai Kung area suggesting that iron has been enriched in stream sediments draining to the southeast of Ma On Shan. Typical values of iron and associated metals from the Pak Kong area near Sai Kung are as follows: Fe_2O_3 10.8 %, Mo 6 ppm, Sn 7 ppm, W 5 ppm, Cu 291 ppm, Pb 59 ppm and Zn 448 ppm. The high copper content of these sediments suggests that Cu–Fe sulphides are likely to be the main source of mineralisation.

On Hong Kong Island, an isolated iron anomaly occurs west of Mount Parker. This anomalously high iron value (10.7 % Fe_2O_3) is accompanied by moderate to high As (21 ppm) and Sn (15 ppm) and is probably related to local contamination. A similar explanation is suggested for an iron anomaly (18.6 % Fe_2O_3) at Tai Shui Hang on Lantau Island where the sample contains high Pb (117 ppm) and Zn (125 ppm) and was reported in field notes to contain precipitates of iron oxide (bright orange sludge).

There is no obvious iron anomaly from southwest Lantau Island where iron-bearing skarn has been reported from the Sha Lo Wan and Yi O areas. Similarly, there are no elevated levels in the vicinity of Pui O where magnetite veins have been reported by Tegengren (1923).



LANTHANUM

in stream sediment

Statistics
Lanthanum (ppm)

Samples	2246
Maximum value	4923
Minimum value	<4
Median	45
Mean	52
Standard deviation	120
Detection Limit	4

Lanthanum

La

Synopsis

In the western and northern New Territories, lanthanum values are low (<27 ppm) over outcrops of the Tsing Shan and Tai Lam granites (Lamma Suite), and over outcrops of Palaeozoic metasedimentary rocks. Over the central and northern New Territories, elevated levels of lanthanum (>48 ppm) mainly correspond with outcrops of coarse ash crystal tuff (Tsuen Wan Volcanic Group) and Tai Po Granodiorite (Lamma Suite).

Moderate to high values of lanthanum (>48 ppm) are found over broad areas of the eastern New Territories. The anomalies mainly coincide with outcrops of coarse ash crystal tuff (Repulse Bay Volcanic Group) and fine ash vitric tuff (Kau Sai Chau Volcanic Group). However, lanthanum levels are also high (>61 ppm) over outcrops of trachydacite lava and quartz monzonite dykes. In Kowloon, lanthanum levels are particularly high (>94 ppm) over outcrops of Kowloon Granite (Lion Rock Suite).

Lanthanum levels are rather variable over Hong Kong Island, Lamma Island and Po Toi Island. In general, however, the moderate to high values (>48 ppm) coincide with outcrops of coarse ash crystal tuff (Repulse Bay Volcanic Group), quartz monzonite and Kowloon Granite (Lion Rock Suite), and low values (<27 ppm) correspond with outcrops of the Mount Butler Granite.

On Lantau Island, moderate to high levels of lanthanum (>48 ppm) are mainly associated with outcrops of volcanic rocks (Lantau Volcanic Group) in the south and west. Slightly lower levels are present over outcrops of rhyolitic dykes (Kwai Chung Suite) and differentiated granite (>75 wt % SiO_2, Lamma Suite) in the north. Small anomalies are related to outcrops of quartz monzonite, and to local anthropogenic contamination.

Geochemistry of lanthanum

Lanthanum is a rare–earth element (REE) belonging to Group IIIB in the periodic table and should not be confused with the term "lanthanon" (abbreviated to Ln) which is used in geochemical texts to describe the REE plus Y, or "lanthanide", the collective name for the fourteen elements following lanthanum in the periodic table (Ce to Lu). The REE are further subdivided on the basis of their atomic number and mass, La to Sm being described as light rare–earth elements (LREE) and Gd to Lu as heavy rare–earth elements (HREE) (Henderson, 1984).

The geochemistry of the REE is generally influenced by an inverse relationship between ionic size and atomic number, known as the "lanthanide contraction" (Ure & Berrow, 1982). During magmatic processes, systematic fractionation of LREE and HREE occurs in accordance with this relationship and the large (103 pm) La^{3+} ion follows Ce into accessory minerals such as monazite, allanite and bastnasite. Both La and Ce have strong silicic igneous affinities and have low concentrations in ultrabasic rocks (<10 ppm). In granites, the ratio of LREE to HREE (normalised to chondritic abundance) increases with evolution to a critical threshold, beyond which the fractionation of plagioclase and accessory phases induces the loss of La and Ce (Wedepohl, 1978). Mielke (1979) cites lanthanum levels in igneous rocks as: basalts, 15 ppm; granites, 45–55 ppm; and an average crustal abundance of 37 ppm. Sewell *et al.* (1992) reported lanthanum results for a selection of Hong Kong granites ranging from 11 to 172 ppm La (average 56 ppm). The highest result (172 ppm) is for a syenite and the lowest (11 ppm) is for a fine-grained granite.

The behaviour of lanthanum during metamorphism is not well understood, but partial melting is known to induce enrichment in the leucosome during migmatisation. There is good evidence that lanthanum and most other REEs may be transported in alkaline hydrothermal solutions (Kosterin, 1959).

In sedimentary rocks, a major fraction of the total lanthanum content is held in resistate accessory minerals such as monazite. Feldspars may also contain lanthanum and provide an important supply of the element for incorporation into secondary clay minerals during weathering (e.g. Ronov *et al.*, 1974). Quartzitic sandstones typically have very low concentrations of lanthanum (*c.* 20 ppm) compared with shales or greywackes (*c.* 50 ppm). In limestones, lanthanum is mostly associated with fine clastic impurities, although direct precipitation of lanthanum in carbonates has also been recorded (Wedepohl, 1978). Mielke (1979) cites levels of lanthanum in shales, sandstones and carbonates as 92, 30 and *c.* 1 ppm respectively. Diagenetic enrichment of lanthanum and other light REEs is widely reported in association with hydrous oxide phases in laterites, bauxites and oolitic ironstones (e.g. Ure & Berrow, 1982).

Surface environment geochemistry

In stream sediments, the release of lanthanum from resistate phases such as monazite is generally slow. A small fraction of the total lanthanum burden may also be held in apatite and biotite, both of which are weathered relatively rapidly at low pH. The La^{3+} ion is only sparingly soluble under normal surface conditions, and its dispersal is typically restricted by adsorption to clays and hydrous oxides (e.g. Piper, 1974), or by precipitation in authigenic carbonates at high pH (e.g. Balashov *et al.*, 1964).

Detailed description

In the western New Territories, the lowest lanthanum values (<21 ppm) coincide with fine- to medium-grained lithologies of the Tai Lam and Tsing Shan granites (Lamma Suite). Slightly higher values (27–48 ppm) are present in areas underlain by medium-grained granite lithologies and andesite outcrops of the Tuen Mun Formation.

Over parts of the northern New Territories, local anomalies are apparent at Mai Po (118 ppm), Lin Tong Mei (269 ppm) and Fan Ling (197 ppm). In these areas, the high lanthanum values are accompanied by high Ce (141–189 ppm), Ba (625–769 ppm), Zn (71–649 ppm) and Hg (0.9–2.8 ppm), and are likely to be related to local contamination. In the northeastern New Territories, slightly elevated lanthanum levels (48–81 ppm) values are present over outcrops of volcanic rocks in the Lai Che Wo area, and on nearby offshore islands.

In the central New Territories, moderate to high levels of lanthanum are present over outcrops of granodiorite (Lamma Suite) and coarse ash crystal tuff (Tsuen Wan Volcanic Group) to the west of Tai Mo Shan, but are low in adjacent granite areas to the east. Local anomalies occur are Sheung Fa Shan (112–120 ppm) and at Ho Pui Reservoir (124 ppm). At Sheung Fa Shan, the high lanthanum values are accompanied by high Ce (139–240 ppm), Ba (332–458 ppm), Zn (148–255 ppm), and Co (15–29 ppm). Similar values for these elements are present at Ho Pui Reservoir (e.g. Ce 313 ppm, Ba 221 ppm, Zn 176 ppm). In the Sha Tin area, lanthanum levels are generally low over outcrops of Sha Tin Granite and Needle Hill Granite (Kwai Chung Suite). However, unusually high lanthanum values (96–357 ppm) are present in the Kwai Chung area to the southwest. This area is partly underlain by the Needle Hill and Sha Tin granites, and also by dykes of quartz monzonite. The high values of industrial metals (e.g. Ce 155–296 ppm, Ba 172–596 ppm, Pb 35–400 ppm, Zn 71–635 ppm and Hg <1.38 ppm) in some samples suggest that the lanthanum values may also be partly enhanced by local contamination.

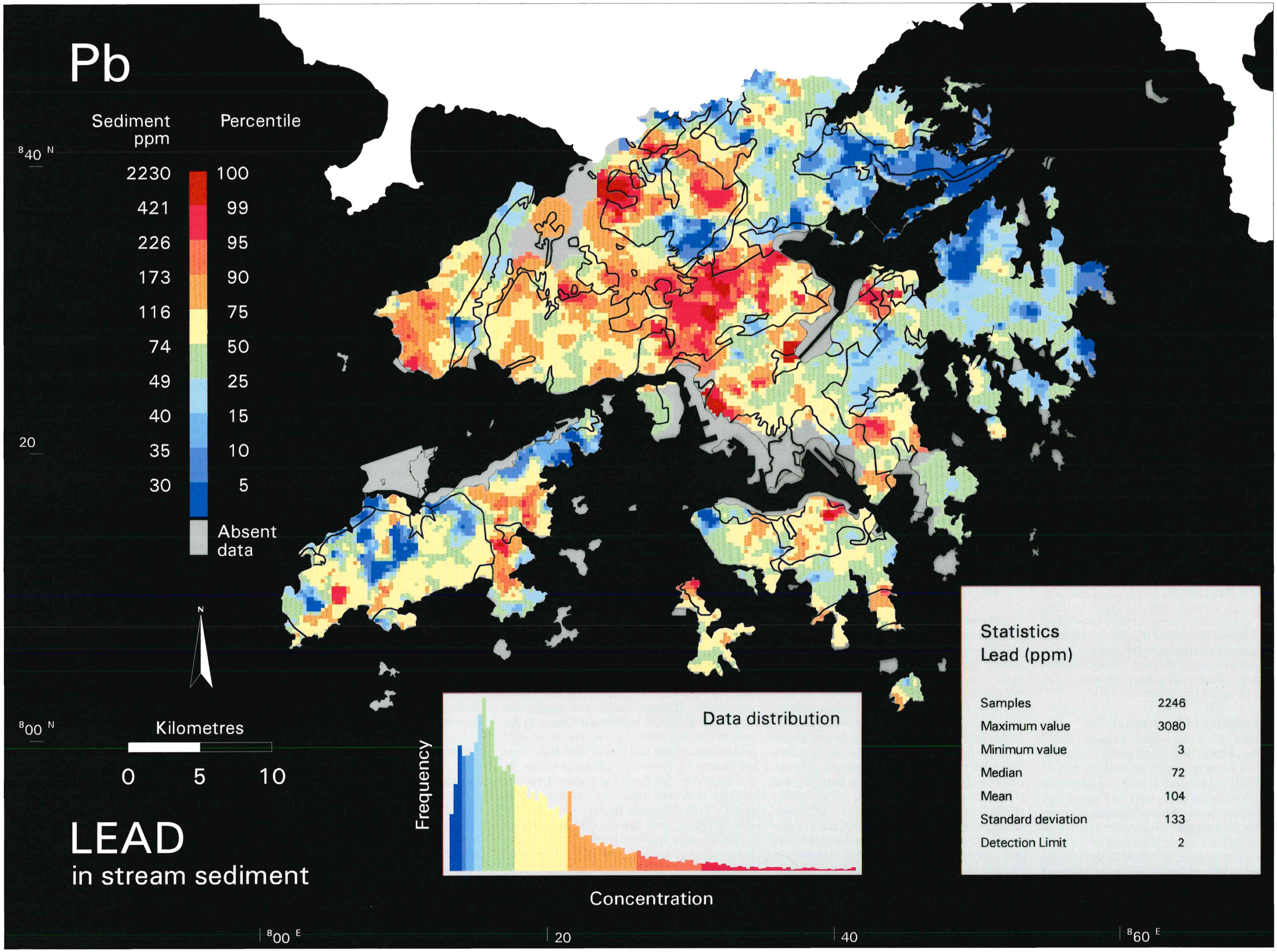
Over much of the eastern New Territories, lanthanum highs are present at Pyramid Hill to the west of Sai Kung (176–180 ppm), Pak Tam Chung (97–135 ppm), Sai Wan (172 ppm) and Tai Long Wan (98–137 ppm). At Pyramid Hill, the high lanthanum values are accompanied by high levels of Ce (308–309 ppm), Ba (476–813 ppm), Cs (3–27 ppm), Pb (48–176 ppm), Zn (133–320 ppm), and Hg (0.2–3.3 ppm). Similar values for these elements are found in the Tai No area to the southwest. The Pyramid Hill and Tai No areas are both known to host outcrops of quartz monzonite dykes. At Pak Tam Chung, Sai Wan and Tai Long Wan, typical values for the associated elements are as follows: Ce 145–430 ppm, Ba 57–293 ppm, Cs 7–14 ppm, Pb 26–114 ppm, Zn 63–139 and Hg <1.5 ppm. In these areas, the dominant rocks are fine ash vitric tuff. Farther south in the Tseung Kwan O and Clear Water Bay areas, local lanthanum anomalies are associated with outcrops of coarse ash crystal tuff, trachydacite lava and quartz monzonite dykes. At Tseung Kwan O, the high lanthanum values (112–146 ppm) coincide with high Ce (174–199 ppm), Ba (164–293 ppm) and Hg (0.7–2.4 ppm), but relatively low Pb (52–59 ppm) and Zn (97–109 ppm). At Clear Water Bay, the lanthanum anomaly (103–125 ppm) is accompanied by high Ce (184–216 ppm) and Ba (232–541 ppm), and relatively low Pb (52–63 ppm), Zn (85–92 ppm) and Hg (<0.1 ppm).

On Hong Kong Island, lanthanum anomalies are present at Mount Nicholson (96–156 ppm), Nam Shan (1348–2151 ppm), Violet Hill, (136 ppm), Chung Hom Wan (134–328 ppm) and D'Aguilar Peak (191 ppm). In general, the elevated lanthanum values correspond with outcrops of coarse ash crystal tuff (Repulse Bay Volcanic Group), quartz monzonite dykes and Kowloon Granite (Lion Rock Suite). At Mount Nicholson, the high lanthanum values coincide with high Ce (167–270 ppm), Cs (4–20 ppm), Pb (63–201 ppm), Zn (81–487 ppm) and Hg (<2.3 ppm) suggesting the presence of local contamination. Extremely high levels of lanthanum at Nam Sham are also associated with high Ce (373–656 ppm), Cs (4–16 ppm), Pb (81–100 ppm), Zn (129–200 ppm) and Hg (1.1–1.7 ppm). At Violet Hill, the lanthanum anomaly coincides with outcrops of quartz monzonite dykes and is accompanied by high Ce (215 ppm), Ba (560 ppm) and Co (15 ppm), but relatively low Pb (85 ppm) and Zn (72 ppm). At D'Aguilar Peak and Chung Hom Wan, the high lanthanum values also coincide with outcrops of quartz monzonite and typical values for associated elements are: Ce 146–208 ppm, Ba 139–295 ppm, Co 8–10 ppm, Pb 64–92 ppm and Zn 171–214 ppm.

A strong lanthanum anomaly (95–171 ppm) is present over outcrops of coarse ash crystal tuff (Lamma Suite) and quartz monzonite (Lion Rock Suite) in northern Lamma Island. This anomaly is associated with moderate to high Ce (28–509 ppm), Ba (27–332 ppm), Pb (52–182 ppm, Zn (48–304 ppm) and Co (4–28 ppm). Slightly elevated lanthanum values (48–81 ppm) are present in the east of Mo Tat island over outcrops of quartz monzonite dykes (Lion Rock Suite) and Lantau Granite (Lamma Suite).

Variable lanthanum levels characterise much of Lantau Island. In general, elevated values correspond with outcrops of Lantau Granite (Lamma Suite), quartz monzonite (Cheung Chau Suite) and volcanic rocks of the Lantau Volcanic Group. Prominent anomalies are present at Mui Wo (159 ppm), Chi Ma Wan (116–146 ppm) and Tong Fuk (97–147 ppm). The anomaly at Chi Ma Wan is associated with the medium-grained Chi Ma Wan Granite (Cheung Chau Suite) and is accompanied by moderate to high levels of Ce (228–336 ppm), Ba (233–360 ppm), Cs (1–11 ppm) and Pb (39–141 ppm), but relatively low Zn (41–89 ppm). Similar levels of these elements accompany the lanthanum anomalies at Tong Fuk and Mui Wo (e.g. Ce 112–243 ppm, Ba 126–481 ppm, Cs 9–18 ppm, Pb 106–152 ppm and Zn 17–118 ppm).

Pb



Sediment ppm		Percentile
2230	🟥	100
421	🟥	99
226	🟧	95
173	🟧	90
116	🟨	75
74	🟩	50
49	🟦	25
40	🟦	15
35	🟦	10
30	🟦	5
	⬜	Absent data

LEAD

in stream sediment

Statistics
Lead (ppm)

Samples	2246
Maximum value	3080
Minimum value	3
Median	72
Mean	104
Standard deviation	133
Detection Limit	2

Lead Pb

Synopsis

Lead levels are generally high (>116 ppm) in the central and western New Territories, in association with outcrops of Tai Po Granodiorite (Lamma Suite) and volcanic rocks of the Tsuen Wan Volcanic Group. Over much of the northeastern New Territories and Kowloon, lead levels are low to moderate (<74 ppm). Moderate lead levels (49–116 ppm) are present in Kowloon, Hong Kong Island, and Lamma Island, whereas values on Lantau Island vary considerably.

The highest natural lead concentrations (>226 ppm) occur in the vicinity of Tai Mo Shan, Ma On Shan and Sheung Fa Shan, although in the northern New Territories, natural anomalies are present in the vicinity of Wo Hop Shek and Lin Ma Hang. Pb–Zn–Cu mineralisation at Lin Ma Hang shows only a small anomaly (74–173 ppm).

Widespread contamination is present in samples from the Castle Peak area where anomalously high lead levels do not coincide with high concentrations of related naturally occurring metals. Strongly contaminated samples also contribute to the anomalies at Mai Po, Ma Liu Shui, Sha Tin, Kwai Chung and Tseng Lan Shue. The broad anomaly surrounding Ma On Shan is related partly to the Fe mineralisation and partly to anthropogenic activity.

Minor lead highs (116–421 ppm) on Hong Kong Island are considered to be largely anthropogenic in origin and coincide with high levels of Sn, As and Sb. On Lamma Island, a small lead anomaly may be related to the outcrop of coarse ash crystal tuff (Tsuen Wan Volcanic Group). Several small lead highs (116–421 ppm) in the Mui Wo and Shek Pik areas on Lantau Island are related to weak lead mineralisation. This occurs chiefly along the contact margins between dykes of the Lantau Dyke Swarm (Kwai Chung Suite) and the host Lantau Granite (Lamma Suite) in the vicinity of major NE-trending faults.

Geochemistry of Lead

Lead is a member of the Group IVA elements of the periodic table (C, Si, Ge, Sn and Pb), a group in which lead has the most metallic characteristics. The Pb^{2+} ion (119 pm) is intermediate in size between K^+ (138 pm) and Ca^{2+} (100 pm) and so it replaces these ions in K–feldspars, micas and, to a lesser extent, plagioclase and apatite. As a consequence, it is enriched in silicic igneous rocks relative to basic rocks, and lead is mobile in late-stage magmatic processes (MacDonald *et al.*, 1973). The enrichment in silicic igneous rocks is confirmed by the values quoted by Mielke (1979): ultrabasic, 1 ppm; basaltic 6 ppm; granitic 15–19 ppm; syenitic 12 ppm; and crustal abundance of 13 ppm. Lead is strongly chalcophile, occurring widely as the sulphide galena [PbS] in hydrothermal mineral veins. It may be lost during low-grade metamorphism (Gebauer & Grunenfelder, 1977).

In sedimentary rocks, the distribution of lead is controlled by the presence of primary detrital minerals (such as feldspars, micas and sulphides), clay minerals (Heinrichs, 1974) and organic matter. Pure limestones (*c.* 5 ppm) and quartzitic sandstones (*c.* 10 ppm) are thus typically depleted relative to shales and greywackes (*c.* 23 ppm). The sedimentary rocks with the highest concentrations are black shales, reflecting the affinity of lead for organic matter.

Surface environment geochemistry

The principal Pb-bearing phases in stream sediments are K–feldspars, micas and, to a lesser extent, plagioclase feldspars and Fe–Mg silicates. Near to hydrothermal mineralisation, lead sulphides such as galena may also be present. Oxidation of galena in chloride-rich groundwaters will mobilise lead, but slightly alkaline or sulphate-rich waters will cause low-solubility phosphates and sulphates to form (e.g. plumbogummite [$PbAl_3(PO_4)_2$] and beudantite, [$PbFe_3SO_4$]). At high pH, particularly in arid environments, these phases may persist and accumulate to significant concentrations to form protective low-solubility coatings on grains of remnant galena (Thornber & Taylor, 1992). However, under acid conditions, such as are typical of granitic or peat–covered terrain, PbS is dissolved and is liable to dispersion at a rate determined largely by the availability of hydrous Fe and Mn oxides for sorption. Hydromorphic dispersion haloes of lead leached during sulphide oxidation are best developed in the ferruginous laterite horizon of soils, probably due to co-precipitation with Fe oxyhydroxides (Lecomte & Zeegers, 1992). Hydromorphic seepage into the drainage channels, or mechanical dispersion of the ferruginous laterite, will give rise to higher than background levels of lead in stream sediments. This will occur in association with other elements (Fe, Mn, Co, Ba, As, Sb, Cu, Mo and Zn) that have a tendency for hydromorphic dispersion and co-precipitation with Mn and Fe oxides.

Lead from vehicle exhausts is an important source of contamination, and associated elevated soil lead concentrations are reported for Hong Kong (Mitchell, 1964). In urban environments road dusts can contain very high levels of lead derived from petrol combustion (Archer & Barret, 1976), although the introduction of lead–free petrol has reduced this potentially toxic hazard in developed industrialised countries. Rain washed from roads, particularly first flush run–off, will introduce high levels of lead into the drainage system via culverts and as fine particulate matter, and it will be dispersed for a long distance down the drainage channel. Contamination of stream sediments is fairly widespread and, in addition to atmospheric dust near roads, metalliferous mining (especially sulphide ores), metallic detritus, Pb-bearing glass and pottery glazes are all sources of anomalously high lead.

Butt & Nichol (1979) observed the presence of metal-rich seepages and soils containing hydromorphically dispersed lead and Zn in cultivated or reafforested areas in Northern Ireland, rather than in the natural woodland. This was attributed to the changes in the local hydrology after clearing, particularly changes in the water table and acidity. Zeegers & Butt (1992) suggest that the occurrence of hydromorphic anomalies in other environments may similarly have been caused, or enhanced, by changes in the vegetation related to anthropogenic activity.

Lead is well known for being poisonous to mammals (e.g. causing mental impairment in young children), and it has not been demonstrated that lead has any essential role for plants or animals.

Detailed description

Elevated lead levels (>116 ppm) in the Castle Peak area coincide with low levels of Cu, Zn, Fe and Bi, and moderate levels of As. The area is underlain by the Tsing Shan Granite, which is known only to host weak Sn–W mineralisation. Most of the catchments drain part of the Castle Peak firing range and, therefore, the anomalous lead and As levels are probably associated with arsenical lead used in bullet heads and lead shot. Typical samples from this area contain the following metal concentrations: Pb (343 ppm), Cu (34 ppm), Zn (71 ppm), Sn (19 ppm) and Bi (4 ppm).

Anthropogenic contamination is partly responsible for the lead anomaly (239 ppm) at Shap Pat Heung south of Yuen Long, where the concentration of other industrial metals is unusually high. These include Cu (18.9 %), Zn (220 ppm), Sn (47 ppm), Bi (9 ppm) and As (29 ppm). At Mai Po in the northern New Territories, the strong lead anomaly (260–884 ppm) is associated with very high levels of Cu (29–2849 ppm), Zn (73–17 489 ppm), Sn (10–151 ppm), Sb (3–88 ppm) and As (95–922 ppm), which are also strongly indicative of contamination.

Lead anomalies are present in the Lin Ma Hang (232 ppm) and Wo Hop Shek (298–486 ppm) areas of the northern New Territories. At Lin Ma Hang, the anomaly is associated with an area of known lead mineralisation (Davis & Snelgrove, 1956) within coarse ash crystal tuff (Tsuen Wan Volcanic Group). Minor Cu, Fe and Zn, and traces of Ag, Mn, As, Cd, Ga and Mo are also noted, although the levels of these metals (e.g. Cu 17 ppm, Fe_2O_3 5.06 %, Zn 96 ppm, Ag 0.2 ppm, MnO 0.07 %, As 75 ppm, Cd 0.3 ppm, Ga 22 ppm, Mo 3.6 ppm) in the stream sediments are relatively low. In the Wo Hop Shek area, the broad lead anomaly is associated with high Zn (285–363 ppm), As (90–130 ppm) and Fe_2O_3 (6.3–7.2 %) levels and relatively low Cu (25–45 ppm) and Sn (9–25 ppm) levels.

A prominent lead anomaly (>226 ppm) is present over the central New Territories in association the known area of Pb–Zn–Cu mineralisation surrounding Tai Mo Shan. Galena-bearing quartz veins occur mostly in coarse ash tuffs of Tai Mo Shan Formation (Tsuen Wan Volcanic Group). In the Sheung Fa Shan area, a lead anomaly is present in an area of known Sn–W–Pb–Zn mineralisation. A typical sample from this region contains Pb (532 ppm), Cu (22.5 ppm) Zn (342 ppm), Sn (1891 ppm), Sb (4 ppm) and (As 3 ppm).

Isolated strong lead anomalies in the Sha Tin, Kowloon Reservoir and Kwai Chung areas are mainly due to anthropogenic contamination. For example, at Sha Tin, the very high lead level (2226 ppm) is coincident with high Sn (8881 ppm), Sb (188 ppm) and Ag (6.5 ppm) indicative of industrial metal waste. At Kwai Chung, a typical sample contains high Pb (883 ppm), Cu (365 ppm), Zn (847 ppm), Sn (120 ppm), As (118 ppm) and Ag (7.7 ppm) concentrations.

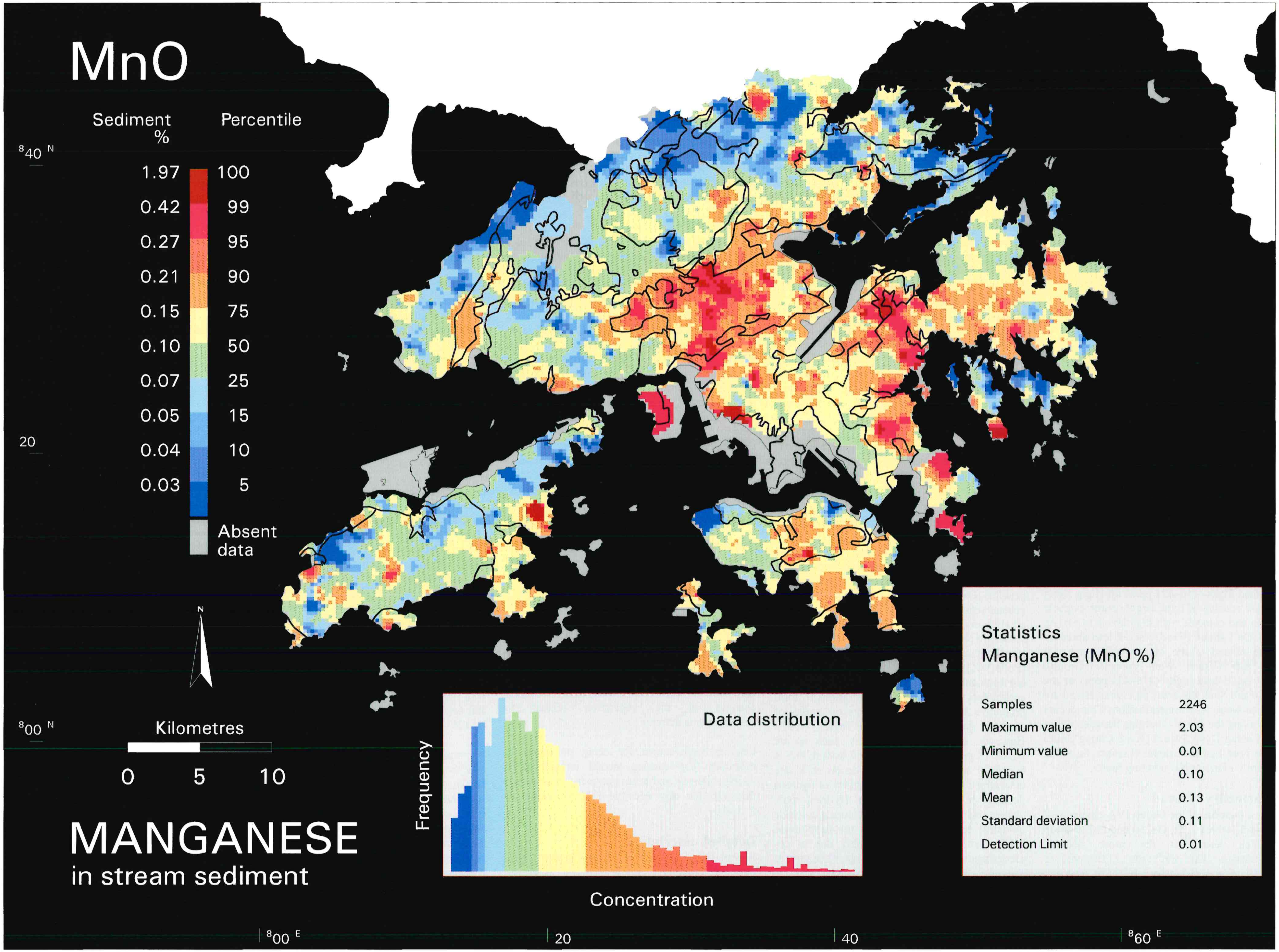
At Ma On Shan, the strong lead anomaly is associated with the skarn-related Fe mineralisation and anglesite [$PbSO_4$] has been identified in panned concentrates. However, part of this anomaly is likely to be due to an anthropogenic overprint introduced by mining waste deposits as indicated by the unusually high concentrations of Sn (449 ppm), Bi (361 ppm), Ag (12.8 ppm) and As (111 ppm) in stream sediments.

On Hong Kong Island, elevated lead levels at North Point (242 ppm) may possibly be related to the reported occurrence of Zn mineralisation in the district (Peng, 1978). However, zinc levels are relatively low (28–65 ppm), whereas the levels of accompanying Sn (10–1256 ppm) and Sb (2–91 ppm) are unusually high. This strongly suggests that the sediment samples at North Point have been affected by industrial metal contamination.

Lead levels are variable across most of Lantau Island, although anomalous values are mostly found in the northeastern part of the island. An area of lead mineralisation has been reported from the Mui Wo area (Davis, 1952) and it is likely that the small anomalies in this area generally reflect elevated background levels. On southern Lantau Island, an isolated lead anomaly (283–368 ppm) occurs in the vicinity of Shek Pik (Keung Shan). The high lead values are associated with moderate to high Zn (126–325 ppm), Sn (7–95 ppm) and As (10–90 ppm), and the panned concentrate contains an abundance of metalliferous minerals (e.g. pyrite and galena) suggesting that this may be a site of natural mineralisation.

MANGANESE

in stream sediment



Statistics
Manganese (MnO %)

Samples	2246
Maximum value	2.03
Minimum value	0.01
Median	0.10
Mean	0.13
Standard deviation	0.11
Detection Limit	0.01

Manganese

MnO

Synopsis

Manganese concentrations are generally low (<0.10 % MnO) over much of the western and northern New Territories, and in northern and western Lantau Island. These areas are underlain by highly differentiated granites (>75 wt % SiO_2), and volcanic and sedimentary rocks which are distant from major intrusive contacts.

The highest concentrations of manganese (>0.27 % MnO) are found in the central New Territories in association with granodiorite intrusions (Lamma Suite) and volcanic rocks of the Tsuen Wan Volcanic Group. In the eastern New Territories and Hong Kong Island, moderate concentrations of manganese (0.10–0.21 % MnO) are commonly found in the vicinity of quartz monzonite intrusions. On Lamma Island and Lantau Island, moderate levels of manganese (0.10–0.21 % MnO) also frequently coincide with contact zones between quartz monzonite intrusions and volcanic rocks.

Manganese anomalies (>0.27 % MnO) frequently correspond with iron anomalies and are particularly strong (>0.42 % MnO) in the vicinity of Ma On Shan where a magnetite deposit was mined. Isolated anomalies, which are distant from intrusive contacts, mostly have a strong anthropogenic overprint.

Geochemistry of manganese

Manganese is a Group VIIB transition element in the periodic table with first transition row neighbours of Cr and Fe. It is a strongly lithophile element and is a relatively abundant element with an average crustal abundance of 950 ppm. Only Fe of the heavy metals is more abundant in the earth's crust.

The Mn^{2+} state is the most stable oxidation state for manganese during magmatic processes (at low O_2 fugacity), manganese readily substitutes for Fe^{2+} and Mg^{2+} (Ure & Berrow, 1982). The ionic radius of Mn^{2+} (67 pm) is comparable to that of Fe^{2+} and Mg^{2+} (61 and 72 pm respectively). Manganese is partitioned into ferromagnesian silicates and Fe–Ti oxides, becoming enriched in basic and ultrabasic rocks relative to silicic lithologies. This is shown by the values reported by Mielke (1979) for igneous rocks: ultrabasic, 1600 ppm; basaltic, 1500 ppm; granitic 390–540 ppm; and syenitic 850 ppm. There is a close correlation between manganese and ferrous iron in most igneous rocks, with Mn/Fe ratios generally lying in the range 0.015–0.02.

Manganese is immobile during prograde regional and contact metamorphism (Wedepohl, 1978; Nicollet & Andriambololona, 1980), but may be redistributed extensively during granulite–amphibolite facies retrogression (Tobschall, 1971; Beach & Tarney, 1978). Remobilisation of manganese may also occur as a result of hydrothermal activity or regional metasomatism (Senior & Leake, 1978).

The manganese content of sedimentary rocks is controlled by both the geochemistry of the source rock and the redox conditions of the depositional environment (Wedepohl, 1978). Manganese may occur in detrital phases such as mafic silicates, magnetite and ilmenite, but the largest proportion is typically held in secondary Mn^{4+} oxides (e.g. pyrolusite, $[MnO_2]$), which form either discrete concretions or surface coatings on primary minerals and lithic fragments (see 'Surface environment geochemistry' below). Shales and greywackes have generally higher levels of manganese (*c.* 700 ppm) relative to coarser quartzitic sandstones and grits (*c.* 170 ppm). Further enrichment of certain fine-grained sediments may occur through the diagenetic formation of ferromanganese nodules (e.g. Jenkyns, 1977; Williams & Owen, 1990, 1992). Carbonate rocks (particularly dolomites) may also contain high concentrations of manganese (average *c.* 550 ppm) (Wedepohl, 1978).

Surface environment geochemistry

Manganese enters stream sediments in a variety of solid phases, including detrital ferromagnesian silicates, Fe–Ti oxides, and adsorbed coatings on clay minerals. The dissolution of these phases is relatively slow in oxic or alkaline environments but is rapid under acid or reducing conditions, the subsequent behaviour and dispersal of manganese being governed mainly by ambient Eh. Tetravalent manganese species act as electron acceptors during the early stages of the anaerobic decomposition of organic matter (for details see the Fe description). As a result, the insoluble Mn^{4+} ion is rapidly reduced and replaced by highly soluble Mn^{2+} in localities where Eh falls below *c.* 0.8 V (at pH values of *c.* 5.5): for example, in peaty areas with impeded drainage (where stream waters may contain >100 mg/l dissolved Mn) or in deeply buried stream sediments (where manganese tends to accumulate within the interstitial pore-waters). Subsequent precipitation of Mn^{4+} oxides occurs rapidly where such water flows into channels where oxidising conditions prevail, with birnessite $[(Na,Ca)Mn_7O_{14}]$ and todorokite $[(Mn,Ca,Mg)Mn_3O_7]$ constituting the principal authigenic phases. This precipitation process occurs at a similar (though slightly higher) redox potential to that of Fe^{3+}, and is accompanied by the scavenging of trace elements such as Ba, Co, Cu and Zn from solution through adsorption and co-precipitation. These processes can dominate the Mn and Fe distribution pattern, creating high local anomalies.

In the tropical environment of southern Sumatra, lithological control is a dominant factor in the distribution of manganese in stream sediments. The flat-lying Tertiary sediments average 250 ppm whilst the stream sediments from the Barisan Mountains (Mesozoic metasediments, volcanics and intrusives) averaged two to three times this value (*c.* 550–700 ppm) (Johnson, 1994). Such lithological control with secondary environmental influences are also reported from the UK (e.g. British Geological Survey, 1996).

Manganese is an essential element for mammals, and interest is mainly with respect to deficiencies rather than excesses.

Detailed description

Manganese levels are generally low (<0.10 % MnO) over both the Tsing Shan and Tai Lam granites (Lamma Suite) in the western New Territories. Slightly elevated levels (0.15–0.21 % MnO) north of Tuen Mun correspond with andesite outcrops of the Tuen Mun Formation, which is known to have higher whole-rock manganese concentrations (*c.* 0.14 % MnO) than the surrounding granitic rocks (*c.* 0.05 % MnO).

Except for isolated highs at Ta Kwu Leng and Kwai Tau Leng, manganese concentrations are low over much of the northern New Territories. The anomaly at Ta Kwu Ling (0.37 % MnO) is associated with elevated concentrations of Fe_2O_3 (5.38 %), Hg (2.2 ppm) and Co (18 ppm) and is likely to be affected by anthropogenic contamination. At Kwai Tau Leng, the anomaly coincides with a major shear zone within coarse ash crystal tuff (Tsuen Wan Volcanic Group).

In the central New Territories, manganese concentrations are particularly high in the Lam Tsuen Valley (>0.42 % MnO) where they are associated with high levels of Fe_2O_3 (5.8–8.1 %), Zn (400–992 ppm) and Pb (111–485 ppm). This zone of elevated manganese concentrations extends northeastward to Tai Po and along the south side of Pat Sin Leng, following the main contact between Tai Po Granodiorite (Lamma Suite) and volcanic rocks of the Tsuen Wan Volcanic Group. A strong MnO anomaly (0.27–0.35 %) at Ho Pui Reservoir has moderate to high Fe_2O_3 (5.8–7.0 %), Co (10–15 ppm), Pb (103–259 ppm) and Zn (246–441 ppm). At Kap Lung, high MnO levels (0.28–0.35 %) coincide with high Fe_2O_3 (8.7–9.3 %), Co (15–20 ppm), Pb (170–239 ppm), Zn (262–740 ppm) and Sn (76–369 ppm). Similar values are present in stream sediment samples on the southern flanks of Tai Mo Shan.

An isolated manganese anomaly (1.09 % MnO) at Kwai Chung has high levels of Fe_2O_3 (7.1 %), and Zn (221 ppm), but relatively low levels of Pb (81 ppm), Cu (32.6 ppm) and Sn (14 ppm). This manganese anomaly may be partly related to dykes of quartz monzonite in the immediate vicinity. A small manganese anomaly is present at Shing Mun (0.31–0.53 % MnO), but these samples have moderate to high Pb (120–182 ppm), Zn (182–265 ppm) and Sn (121–610 ppm) in addition to high Fe_2O_3 (5.2–17.4 %), suggesting that they are partly contaminated. On Tsing Yi, a manganese anomaly (0.31 % MnO) is present over minor outcrops of granodiorite.

Manganese values are high (0.30–0.56 % MnO) in the Ma On Shan area and correspond with moderate to high levels of Fe_2O_3 (4.9–7.6 %) and associated minerals related to the mineralised skarn deposit. Dendritic growths of pyrolusite are commonly observed on joint surfaces in contact metamorphosed Devonian sandstone at Ma On Shan, and accumulations of black manganese (wad) have been found in veins within the sandstone. An anomaly (0.51 % MnO) south of Ma On Shan, near Sai Kung, is accompanied by high Fe_2O_3 (10.82 %) and Zn (448 ppm), but low Pb (59 ppm) and Cu (29 ppm).

A broad area of elevated manganese concentrations (0.10–0.21 % MnO) in the eastern New Territories coincides with dykes and stocks of quartz monzonite (Lion Rock Suite) intruded along the Chek Keng Fault. The anomalies are generally associated with slightly elevated concentrations of Zn (91–267 ppm) and Fe_2O_3 (3.9–6.2 %), but other metals are relatively low in abundance.

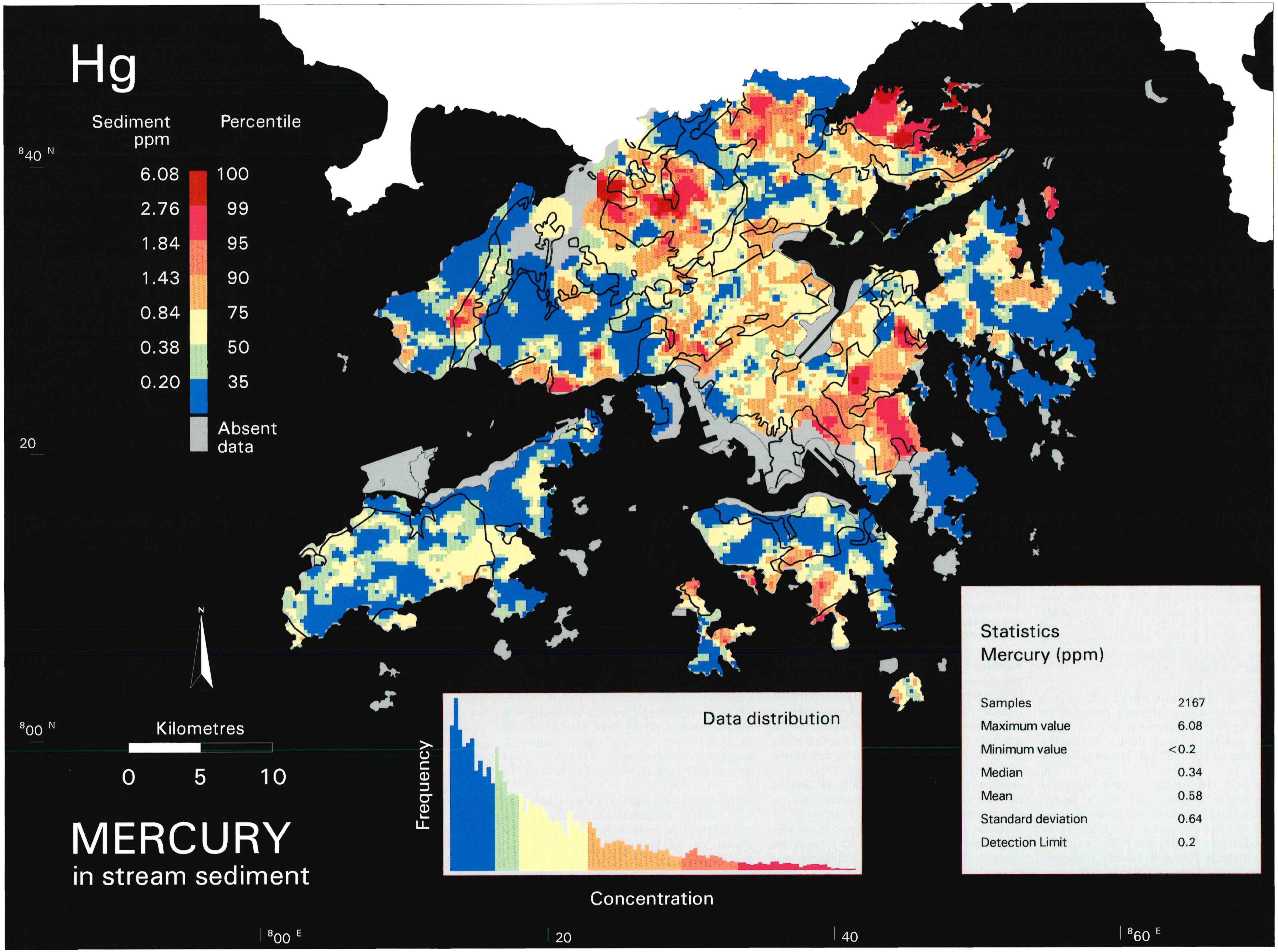
In eastern Kowloon, manganese anomalies are present at Ho Chung (0.34–0.36 %), Tseng Lan Shue (0.43–0.52 %), Mang Kung Uk (0.37 %), and Clear Water Bay (0.36 %). The anomalous areas are accompanied by relatively low Cu and Pb, and moderate to high Zn, except for Tseng Lan Shue where moderate to high Cu (58–185 ppm), Pb (98–258 ppm) and Sn (57–71 ppm) suggest an anthropogenic overprint. On Jin Island, the high MnO value (0.66 %) is associated with moderate Pb (119 ppm), Cu (84 ppm) and Sb (3.8 ppm), and also probably reflects partial contamination.

Elevated manganese levels (0.10–0.21 % MnO) are present in the central and southeastern parts of Hong Kong Island and generally coincide with dykes and stocks of quartz monzonite (Lion Rock Suite). Typical values from the Mount Butler area are as follows: MnO (0.63 %), Fe_2O_3 (5.53 %), Cu (0.4 ppm), Zn (72 ppm) and Pb (85 ppm).

Slightly elevated manganese values (0.10–0.21 % MnO) are present in the northern and southern parts of Lamma Island. Quartz monzonite (Lion Rock Suite) outcropping in the northern part island is probably partly responsible for these elevated concentrations. In the south, the South Lamma Granite (Cheung Chau Suite) and accompanying rhyodacite dykes are very slightly enriched in MnO (0.08–0.11 %) relative to the surrounding Lantau Granite (0.04–0.07 %).

Minor manganese anomalies are present on Lantau Island at Tai Shui Hang (2.03 %), Mui Wo (0.45 %), Shek Pik Reservoir (0.42 %), Tong Fuk (0.32 %) and Tai O (0.45 %). Some of these anomalies, such as at Mui Wo, are clearly related to anthropogenic activities with very high concentrations of Fe_2O_3 (18.59 %), Pb (117 ppm) and Zn (125 ppm).

Hg



MERCURY

in stream sediment

Statistics
Mercury (ppm)

Samples	2167
Maximum value	6.08
Minimum value	<0.2
Median	0.34
Mean	0.58
Standard deviation	0.64
Detection Limit	0.2

Mercury

Hg

Synopsis

The highest levels of mercury (>1.8 ppm) are found in the northern and northeastern New Territories which are underlain mostly by volcanic rocks of the Tsuen Wan Volcanic Group. High concentrations are also found in areas underlain by volcanic rocks of the Repulse Bay Volcanic Group on Kat O Chau, Crescent Island and Double Island.

Elevated levels of mercury (>0.8 ppm) are present in the central New Territories and eastern Kowloon. Most of these anomalies are associated with outcrops of coarse ash crystal tuff (Tsuen Wan Volcanic Group) and quartz monzonite dykes (Lion Rock Suite). However, some anomalies occur in granite areas, and in areas underlain by volcaniclastic sedimentary rocks of the Repulse Bay and Kau Sai Chau volcanic groups. Mercury levels are also high (>1.8 ppm) in areas underlain by trachytic rocks (Repulse Bay Volcanic Group), but low to moderate (0.2–0.8 ppm) over areas of coarse ash crystal tuff (Repulse Bay Volcanic Group).

Isolated anomalies, such as those at Tai Lam Chung and Tin Fai Tong, are mostly associated with local contamination, possibly as a by–product of mining activities.

Geochemistry of mercury

Mercury is a heavy metal from Group IIB of the periodic table, along with Zn and Cd. Gold and Tl are its period neighbours. It is unique among metals in being liquid at normal temperatures. It is only weakly electropositive, and much of its chemical bonding is covalent in type. Like its group analogues Zn and Cd, it forms divalent ions, but only in compounds such as HgF_2 is the bonding predominantly ionic. Mercury also forms the dimeric mercurous ion $[Hg_2]^{2+}$ which contains a Hg–Hg metallic bond. A further similarity with Zn and Cd is that mercury is very strongly chalcophile, the principal ore mineral being cinnabar [HgS].

Mercury is a very rare element, despite being known from antiquity because of its occasional appearances as the distinctive native metal and the relative ease of its preparation from its main ore. Its average content in crustal rocks is probably less than 0.08 ppm (Greenwood & Earnshaw, 1984), though there is considerable disagreement on the actual value (Wedepohl, 1978).

The large size of the nominal Hg^{2+} ion, whether it is regarded as a true ion (radius 96 pm in fourfold co-ordination) or wholly covalent (radius 144 pm), and its low degree of ionic character, precludes its incorporation into many rock-forming silicate minerals. In igneous rocks, basalts and gabbros have generally much lower mercury contents (typically 0.01 ppm) than granites (average 0.08 ppm), although much higher mercury levels (up to 1.5 ppm) have been found in eclogites and peridotites in inclusions in kimberlite pipes, suggesting that the deep crust and upper mantle may be considerably richer in mercury than the upper crustal rocks. As an incompatible element, mercury concentrates in late-stage magmatic fluids and is somewhat enriched in pegmatites, and especially the products of very late-stage phreatic activity related to declining volcanicity.

Volcanic hot springs and sedimentary rocks altered by phreatic activity are the principal locations of mercury mineralisation. The principal mineral produced is cinnabar [HgS] along with the metacinnabar group of minerals in which variable amounts of Zn and Fe substitute for Hg, and Se substitutes for S. Other primary mercury minerals include native mercury, corderite $[Hg_2S_2Cl_2]$, and livingstonite $[HgSb_4O_7]$. Secondary mercury minerals may include schuettite $[HgSO_4.2H_2O]$ and calomel $[Hg_2Cl_2]$.

In sedimentary rocks, average mercury levels are higher in shales (0.4 ppm) than in carbonate rocks (0.04 ppm) and sandstones (0.03 ppm) (Wedepohl, 1978). The relative enrichment of mercury in shales is even more marked in some organic-rich black shales, which may hold several ppm mercury bound to clay minerals, organic residues and sulphides. Coals show very variable mercury levels, from <0.01 ppm to >1.0 ppm, and some very high levels have been recorded in crude oils (up to 30 ppm) (Hutchinson & Meema, 1987).

Surface environment geochemistry

Growing concern over the toxicity of mercury and its compounds in the environment, due to well-publicised pollution incidents and related impacts on human health, has ensured the development of a better understanding of the environmental geochemistry of mercury over the past few years. Mercury is a highly toxic element to most forms of life, though its toxicity depends strongly on its chemical speciation. Liquid mercury is relatively inert and not readily taken up by organisms, but the vapour is dangerous. Mercuric salts are highly toxic (e.g. the original source of the mercury in the Minamata poisoning event in Japan). However, of even greater concern is the ability of certain micro-organisms, such as anaerobic bacteria (e.g. *Clostidium* spp.), to methylate mercury and its salts to create such soluble species as methylmercury $[CH_3Hg]$ and dimethylmercury $[(CH_3)_2Hg]$. These compounds are readily taken up by aquatic organisms, especially fish and shellfish, and may be concentrated in the food chain to levels of several thousand ppm. If eaten by humans in sufficient quantities this may cause the typical neurotoxic symptoms of mercury poisoning (Fergusson, 1990).

Background levels of mercury in natural surface waters are usually very low, typically <30 ng/l. Much of this may be derived from atmospheric wash-out by rain, and only local contamination will raise levels higher than this. Mercury minerals such as cinnabar and metacinnabar are insoluble under normal conditions, and metallic mercury will not react with stream water directly (see, for example, Eh–pH diagram in Brookins, 1988). However, this apparently inert behaviour is a cause of concern, since spills of metallic mercury into water courses (e.g. small-scale gold mining activities) constitute a long-term contamination risk. This is because the mercury may persist within the stream sediment for many years but may still be mobilised in small, but significant, quantities by microbial methylation under the appropriate conditions.

Industrial regions are often associated with elevated background levels of mercury in stream sediments. Nriagu & Pacyna (1988) estimated an anthropogenic mobilisation of 11 000 tonnes of mercury per year into the biosphere, and this would include contributions from chloro–alkalis and hydrocarbon combustion and refining. The problems of mercury contamination appear to be more severe in some newly developing nations, especially in the tropics, where rapid industrial development and less strict environmental controls (or inability to enforce such controls) prevail.

From studies in SE Asia, Fletcher (1996) describes how fine sediment is cleansed from the drainage system by frequent tropical storms, leaving heavy minerals to lag behind in the process. Under such conditions, mercury and its minerals will remain with the heavy fraction, resulting in enhanced levels of this element.

Detailed description

In the western New Territories, elevated values of mercury are present mainly in association with andesite outcrops of the Tuen Mun Formation. Anomalies in the vicinity of Tuen Mun (2.3–2.8 ppm) are typically accompanied by high Co (16–22 ppm), MnO (0.15–0.21 %) and Fe_2O_3 (9–13 %), and low Cu (8–18 ppm), Pb (11–33 ppm), and Sn (11–22 ppm). Slightly elevated levels of mercury (0.4–1.4 ppm) are also found near Lung Kwu Tan.

Background levels of mercury are rather high over the northern and central New Territories. A prominent anomaly at Mai Po (6.1 ppm) comes from a sample that appears to be strongly affected by contamination, as shown by extremely high values of industrial metals (e.g. Cu 2849 ppm, Pb 884 ppm, Zn 17 489 ppm and Sn 151 ppm). More typically, the anomalous areas are accompanied by high Co (9–22 ppm), MnO (0.08–0.13 %) and Fe_2O_3 (4.91–8.03 %), moderate Pb (58–260 ppm) and Zn (73–242 ppm), and low Cu (14–44 ppm) and Sn (10–16 ppm). These elemental values more realistically reflect the natural background. Although there are certain areas in the northern and central New Territories, where mercury levels are very low (<0.2 ppm), most of the elevated concentrations occur over outcrops of the Tsuen Wan Volcanic Group. In the vicinity of Ta Kwu Ling, high mercury levels are accompanied by moderate values of associated metals including Co (5–18 ppm), Fe_2O_3 (4.83–6.61 %), Cu (9–83 ppm), Pb (9–71 ppm) and Sn (3–29 ppm).

Mercury levels are unusually high in the northeastern New Territories and several islands in Mirs Bay. At Lai Che Wo and Yung Shue Au, mercury values exceed 3 ppm, although the concentrations of associated metals are rather low. Much of this area is underlain by volcanic rocks of the Tsuen Wan Volcanic Group. On Kat O Chau and Double Island, the mercury levels are again rather high compared to the levels of associated elements, such as Co (<4 ppm), MnO (0.12 %), Fe_2O_3 (3.52 %), Cu (4 ppm), Pb 42 ppm, Zn (51 ppm) and Sn (6 ppm). This suggests that the background levels of mercury have been partly affected by anthropogenic contamination.

In the eastern New Territories and Kowloon, anomalous concentrations of mercury are mainly associated with outcrops of quartz monzonite (Lion Rock Suite) and trachytic rocks of the Repulse Bay Volcanic Group. Prominent anomalies in areas underlain by quartz monzonite, such as Pyramid Hill and Tai No, contain >3.2 ppm Hg and are accompanied by high Fe_2O_3 (5.8–8.3 %), Cd (2.2–10.2 ppm), and moderate Zn (104–160 ppm) contents. These elemental concentrations are similar to those found with mercury in other areas underlain by quartz monzonite (e.g. Chek Keng). North of Tseung Kwan O, high mercury values are associated with outcrops of the trachytic Ap Lei Chau Formation (Repulse Bay Volcanic Group). A typical sample contains: Hg (2.4 ppm), Co (6 ppm), MnO (0.24 %), Fe_2O_3 (5.15 %), Cd (0.6 ppm), Pb (59 ppm) and Zn (109 ppm).

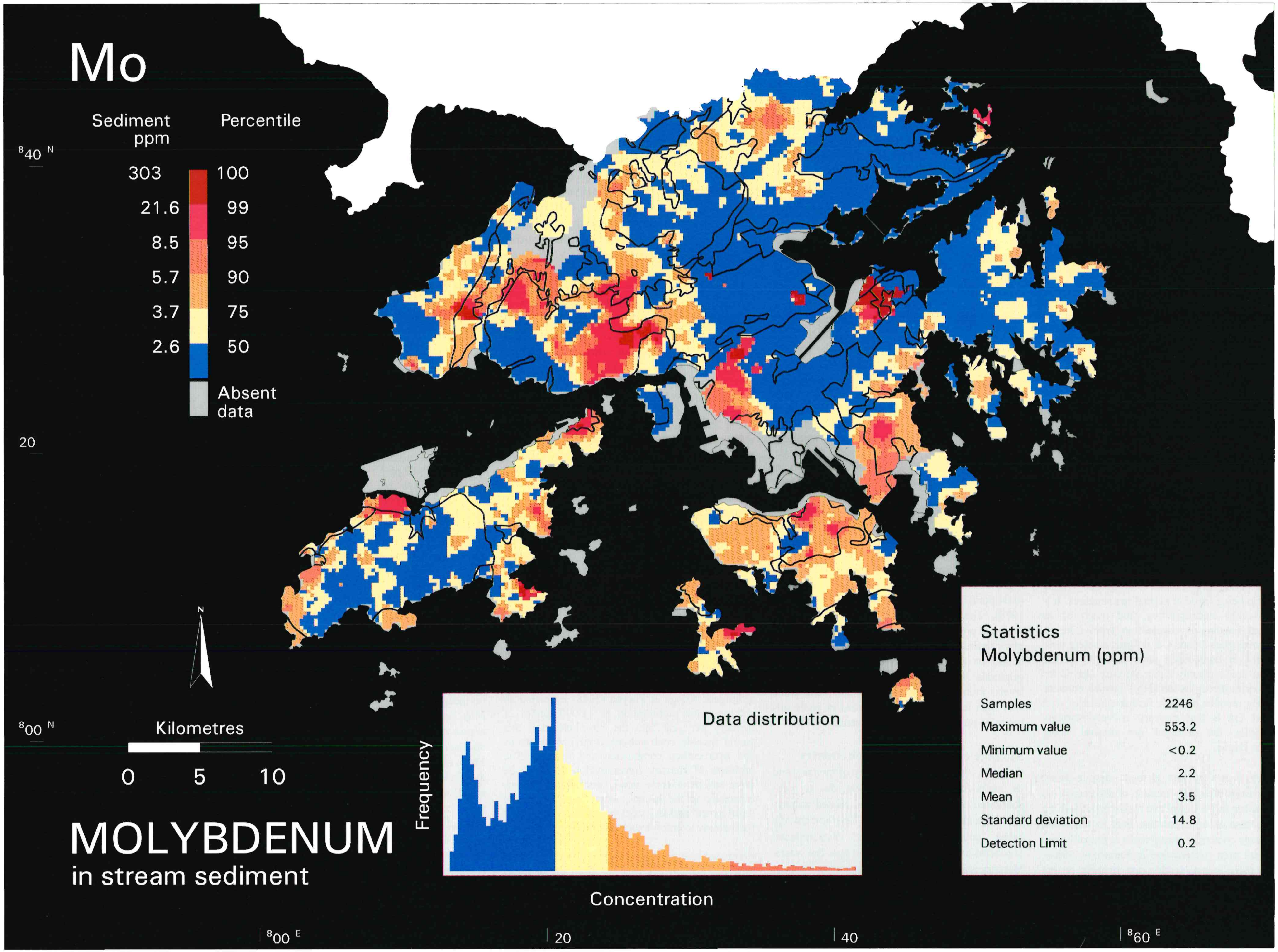
On Hong Kong Island, elevated values of mercury are associated mainly with outcrops of Ap Lei Chau Formation and quartz monzonite (Lion Rock Suite). At Nam Shan, a typical stream sediment sample contains: Hg (2 ppm), Co (5 ppm), MnO (0.05 %), Fe_2O_3 (2.79 %), Cd (1.8 ppm), Cu (14 ppm), Zn (60 ppm) and Pb (47 ppm). At Chung Hom Wan, the mercury anomaly is accompanied by high Pb (177 ppm) and Zn (462 ppm), as well as high Cd (1.3 ppm) and MnO (0.12 %), suggesting that this sample is partly affected by contamination.

Mercury anomalies are present in the north and east of Lamma Island. In the north, the high mercury values are associated with outcrops of quartz monzonite (Lion Rock Suite) and are accompanied by moderate to high values of Co (9–28 ppm), Pb (129–311 ppm) and Zn (115–304 ppm). In the east of the island, a small mercury anomaly (2.3 ppm) is present over an area of rhyodacite dykes, and is accompanied by high MnO (0.14 %), and moderate Pb (129 ppm) and Zn (115 ppm).

Low to moderate levels of mercury are present in southwestern Lantau Island, mainly in association with outcrops of quartz monzonite at Mui Wo, Tong Fuk, Fan Lau and Sha Lo Wan (Cheung Chau and Lion Rock suites).

MOLYBDENUM

in stream sediment



Statistics
Molybdenum (ppm)

Samples	2246
Maximum value	553.2
Minimum value	<0.2
Median	2.2
Mean	3.5
Standard deviation	14.8
Detection Limit	0.2

Molybdenum

Mo

Synopsis

Anomalously high levels of molybdenum (>8.6 ppm) are present over outcrops of fine-grained granite (Lamma Suite, Kwai Chung Suite, Lion Rock Suite), particularly in areas close to contact zones with overlying volcanic rock. The strongest anomalies coincide with areas of known molybdenum mineralisation and are commonly accompanied by high levels of Sn and W. These include areas immediately north of Tuen Mun, and around Sheung Fa Shan and Needle Hill. A pronounced molybdenum anomaly (>22 ppm) also occurs over the Ma On Shan area.

In Kowloon, broad molybdenum highs (3.8–8.6 ppm) are present over outcrops of fine-grained granite (Lion Rock Suite) in the Kwai Chung, Tseng Lan Shue and Yau Tong areas. These moderate to high concentrations do not coincide with known sites of molybdenum mineralisation, but are associated with high W and Sn values.

Molybdenum values are moderate to high (3.8–22 ppm) on Hong Kong Island with the strongest anomalies coinciding with known sites of Mo mineralisation within fine-grained granite (Lion Rock Suite). Moderate to high values on Lamma Island (8.6–22 ppm) occur close to W-bearing quartz veins within medium-grained granite (Cheung Chau Suite) at Sok Kwu Wan.

On Lantau Island, anomalously high molybdenum values (>8.6 ppm) occur over areas underlain by the Tai Lam and Chek Lap Kok granites (Lamma Suite). Both granites are known to host molybdenite-bearing quartz veins. Minor anomalies over Yi O, Shek Pik and Chi Ma Wan may point to further zones of weak molybdenum mineralisation.

Geochemistry of molybdenum

Molybdenum is a member of Group VIB in the periodic table (with Cr and W) and in the second row of transition elements. Molybdenum and W are similar chemically, with a wide variety of oxidation states, and their chemistries are among the most complex of the transition elements (Cotton & Wilkinson, 1972).

During magmatic fractionation, molybdenum behaves incompatibly and is only sparingly incorporated in major rock-forming silicates. It may substitute to a limited extent for Ti^{4+} and Fe^{3+} in accessory phases such as sphene and titanomagnetite, but is most readily partitioned into W minerals (Ure & Berrow, 1982). It is strongly chalcophile and frequently appears as molybdenite [MoS_2] in pegmatites and porphyry-style Cu–Mo deposits. It is also incorporated into the common sulphide minerals pyrite, galena and sphalerite (Ure & Berrow, 1982), particularly during metamorphism. Molybdenum has a crustal abundance of 1.2 ppm (Mielke, 1979). The average abundance of molybdenum in silicic igneous rocks is 1.5 ppm (Vinogradov, 1962), of which some 80% may be associated with minute traces in feldspars and biotite. A mean molybdenum value of 1 ppm is reported for basic rocks (Krauskopf, 1967). It is common for molybdenum to accumulate in areas of discrete mineralisation during metamorphism (Wedepohl, 1978).

In sediments, molybdenum tends to follow Cu in its behaviour and is strongly complexed by organic matter. Black shales are, therefore, enriched (up to 70 ppm) relative to quartzo–feldspathic and carbonate rocks, which typically have molybdenum values of 0.5–2 ppm (Ure & Berrow, 1982). Molybdenum is enriched in marine ferromanganous nodules, with an average abundance several times the crustal average (Cronan, 1976).

Surface environment geochemistry

Molybdenite weathers quickly and the molybdenum forms soluble molybdate complexes under conditions of high Eh and pH, but it co-precipitates with secondary hydrous oxides of Fe, Al and Mn in acid environments. It may also be immobilised by incorporation into Fe sulphides under anoxic conditions and is strongly complexed by organic matter.

The behaviour of molybdenite in the drainage system is in many respects different from other metal ore minerals. Firstly, as a flaky mineral it settles slowly from suspension, despite its relatively high specific gravity, and it is rarely concentrated in placer deposits (Jensen & Bateman, 1979). Secondly, it breaks down to a very fine particulate size and will occur with the clay-sized fraction, which is rare for an ore mineral. Molybdenum derived from primary molybdenite also provides an example of variation in mobility with environment (Ottesen & Theobald, 1994). Where the environment is acidic, molybdenite is either stable or molybdenite in solution forms stable ferrimolybdate [$Fe_2(MoO_4)_3$] or Mo-rich lepidocrocite [FeO(OH)]. These minerals degrade to fine particle size, and are dispersed with the suspended load, and are hardly detectable even at the site of the mineralisation. In neutral to alkaline waters, molybdenite weathers to stable detrital minerals and dissolves. Molybdenum anomalies are recognisable in stream sediments for many kilometres down–stream from the deposit, illustrating the use of molybdenite as a pathfinder element in geochemical exploration. Unlike many other elements therefore, molybdenite is more mobile under alkaline, oxidising conditions than under acid, reducing conditions.

Molybdenum is a vital trace element for many plants, but high molybdenite levels in vegetation can induce Cu deficiency in animals, so consequently there is considerable interest in the level of molybdenite and its activity in the environment. Base metal mining gives rise to the most significant anthropogenic contamination. Cooper & Thornton (1994) show that in Wales stream sediment contamination by mining gives molybdenite levels up to 8 times the natural background (1–5 ppm Mo).

Detailed description

In the western New Territories, a strong molybdenum anomaly (>8.6 ppm) is present north of Tuen Mun and this corresponds to the occurrence of molybdenum–mineralised quartz veins in the Tsing Shan Granite (Lamma Suite). A typical stream sediment sample from this locality has yielded the following metal concentrations: Mo 11.6 ppm, Sn 29 ppm, W 42 ppm, Cu 21 ppm, Pb 7 ppm and Zn 140 ppm. Many quartz veins have been mapped along the eastern boundary of the Tsing Shan Granite.

In the northern New Territories, slightly elevated molybdenum values (3.8–8.6 ppm) are present in the Mai Po, Sheung Shui, Ta Kwu Leng and Cloudy Hill areas. At Mai Po and Sheung Shui, the anomalies are affected by anthropogenic contamination (see descriptions for Sn and W) whereas at Ta Kwu Ling and Cloudy Hill, the anomalies probably reflect slightly high natural background levels. Overall, however, molybdenum values are low to moderate in areas underlain by coarse ash crystal tuff.

Near Lam Tei, a large molybdenum anomaly (9.1–26 ppm) is present within the fine-grained Tai Lam Granite (Lamma Suite) close to the contacts with Carboniferous sedimentary rocks and Jurassic volcanic rocks. Associated metal concentrations are generally low (e.g. Sn 51 ppm, W 9 ppm, Cu 3 ppm, Pb 59 ppm, Zn 49 ppm) suggesting that the anomaly probably reflects the presence of local molybdenite-bearing quartz veins. The highest molybdenum values over the Tai Lam Granite are present in the Tsing Fai Tong (12–21 ppm), Ho Pui (8.9–17 ppm) and Sheung Fa Shan (9.3–44 ppm) areas close to the contacts with Tai Po Granodiorite (Lamma Suite) and volcanic rocks of the Tsuen Wan Volcanic Group. These areas are well-known for Sn–W mineralisation and a typical sample from Tsing Fai Tong contains Mo 28 ppm, Sn 129 ppm and W 50 ppm. High values of Mo (44 ppm) farther east at Sheung Fa Shan have similar concentrations of associated metals (Sn 88 ppm, W 80 ppm).

A strong molybdenum anomaly (8.6–53 ppm) is present over the Needle Hill Granite (Kwai Chung Suite) in the Shing Mun area. The anomaly coincides with high values of Sn (70–336 ppm) and W (11–661 ppm) and reflects the presence of mineralised quartz veins particularly in the vicinity of the Needle Hill mine.

Isolated molybdenum anomalies at Ma Liu Shui (218 ppm) and Lam Tsuen Valley (110 ppm) are partly related to anthropogenic contamination. For example, at Ma Liu Shui, the high molybdenum value is accompanied by high levels of industrial metals such as Cu (140 ppm), Pb (769 ppm), Zn (662 ppm) and Sn (589 ppm). The concentration of industrial metals is much stronger in sediment from the Lam Tsuen Valley, where the high molybdenum value is associated with very high Sn (11 838 ppm), Cu (821 ppm), Pb (3 080 ppm), and Zn (2 694 ppm).

In the Ma On Shan area, a strong molybdenum anomaly (15–553 ppm) coincides with the Fe-mineralised skarn deposit. The high concentrations of associated industrial metals, such as Cu (46–303 ppm), Sn (65–449 ppm), W (11–152 ppm), Pb (170–896 ppm) and Zn (194–662 ppm), strongly suggests that the natural molybdenum concentrations in stream sediment have been enhanced by natural mining waste.

In eastern Kowloon, a broad molybdenum anomaly (3.8–22.1 ppm) is present over the Tseng Lan Shue and Yau Tong areas. These areas are partly underlain by the fine-grained Kwun Tong Granite (Lion Rock Suite) which is known to host W and Be mineralisation. However, some samples in the Tseng Lan Shue area contain unusually high Pb (258 ppm), Cu (185 ppm) and Zn (594 ppm) values, suggesting that they have been locally contaminated by industrial waste.

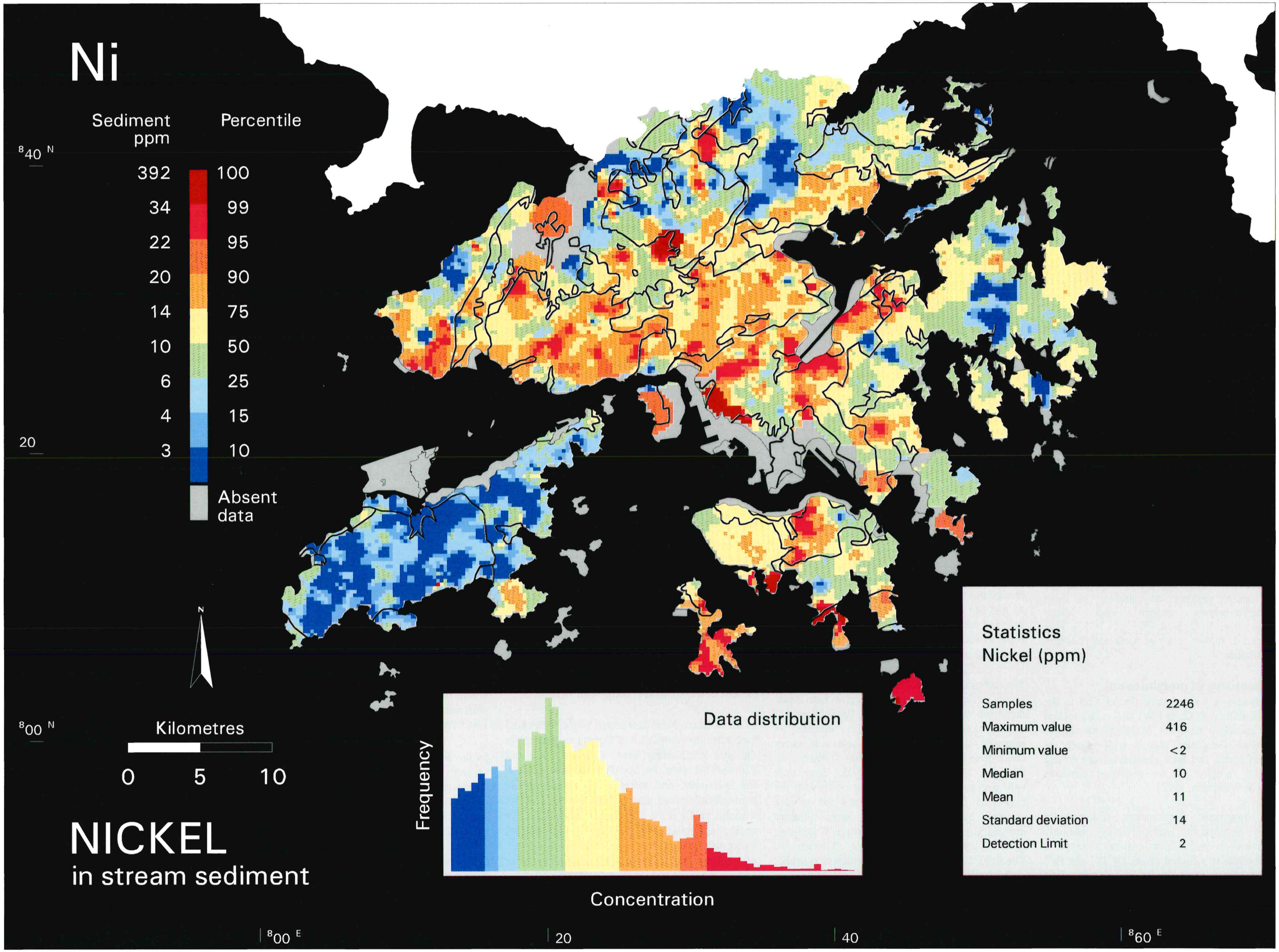
On Hong Kong Island, molybdenum values are generally moderate to high over the granite areas (3.8–8.6 ppm), particularly over the fine-grained Mount Butler Granite (Lion Rock Suite). Molybdenite has been reported from quartz veins at Mount Butler (Peng, 1978) and, therefore, the anomalies probably reflect an area of natural mineralisation.

On Lamma Island, a small molybdenum anomaly (29 ppm) is present on the south side of Sok Kwu Wan. The high molybdenum value comes from one sample which overlies an outcrop of quartz monzonite (Lion Rock Suite). Concentrations of other associated metals are low. A wolframite-bearing quartz vein within the medium-grained South Lamma Granite (Cheung Chau Suite) was once worked nearby (Peng, 1978).

Two main areas of high molybdenum values (>8.6 ppm) are present on Lantau Island (Sha Lo Wan and Tsing Chau Tsai), and both occur over outcrops of fine-grained granite belonging to the Lamma Suite. At Sha Lo Wan, molybdenite has been reported in association with W mineralisation (Ruxton, 1958). The high molybdenum values in stream sediment (8.9–18 ppm) are accompanied by moderate to high Sn (21–88 ppm), W (11–80 ppm), As (3–35 ppm) and Bi (4–73 ppm). At Tsing Chau Tsai, elevated molybdenum values (8.9–25 ppm) also coincide with known W mineralisation and are accompanied by moderate to high Sn (27–45 ppm), W (14–21 ppm), Bi (12–22 ppm). Slightly elevated levels of molybdenum (3.8–22 ppm) are present in other parts of Lantau Island including Yi O, Chi Ma Wan, Shek Pik and Tai Shui Hang.

NICKEL

in stream sediment



Statistics
Nickel (ppm)

Samples	2246
Maximum value	416
Minimum value	<2
Median	10
Mean	11
Standard deviation	14
Detection Limit	2

Nickel Ni

Synopsis

Background levels of nickel are moderate to high (>10 ppm) over the western and central New Territories, Kowloon and Hong Kong Island, and high (>20 ppm) over Lamma Island and Po Toi Island. Low to moderate levels of nickel (<10 ppm) are present over much of the northern and eastern New Territories, and very low values (<4 ppm) characterise most of Lantau Island. Variations in nickel values do not obviously correlate with the underlying geology. In general, however, background levels are slightly higher in areas underlain by granitoids of the Lamma Suite and coarse ash crystal tuff of the Tsuen Wan Volcanic Group.

In the western New Territories, nickel anomalies in the granitic areas are commonly related to areas of local contamination. However, elevated background levels (10–20 ppm) over the Tai Lam Granite (Lamma Suite) may be partly related to outcrops of Tai Po Granodiorite (Lamma Suite) forming roof pendants within the pluton.

Nickel anomalies (>22 ppm) in the northern New Territories are mostly associated with high concentrations of other metals reflecting extensive anthropogenic contamination. Background values are generally low (<6 ppm) over outcrops of volcanic and sedimentary rocks.

Moderate to high nickel values (10–22 ppm) characterise much of the central New Territories, and several anomalies coincide with areas of known mineralisation. However, in the Sha Tin and Kwai Chung areas, the highest (>34 ppm) values come from heavily contaminated samples. At Ma On Shan, high nickel values are associated with iron mineralisation but are also partly related to enrichment from mining waste.

Sporadic nickel anomalies (>22 ppm) in Kowloon and Hong Kong Island are mostly associated with contamination. On Lamma Island and Po Toi Island, the high background levels may be related to the presence of mafic to intermediate intrusive rocks.

Geochemistry of nickel

Nickel is an element from the first series of transition elements and Group VIII in the periodic table. The divalent Ni^{2+} is the only oxidation state of importance in the aqueous and non–aqueous chemistry of nickel. The Ni^{2+} ion is intermediate in size (69 pm) between Mg^{2+} and Fe^{2+} (72 and 61 pm respectively) for which it substitutes during fractionation, and it is partitioned into ferromagnesian minerals such as olivine (3000 ppm Ni), orthopyroxene and spinels. It is therefore strongly enriched in ultrabasic and basic lithologies relative to silicic igneous rocks. Mielke (1979) reports values for nickel in igneous rocks as: ultrabasic, 2000 ppm; basaltic, 130 ppm; granitic, 4.5–15 ppm; and crustal abundance 99 ppm. Nickel, like Co, is a siderophile element but in the earth's crust it also exhibits both chalcophile and lithophile characteristics. The abundance of nickel in igneous rocks therefore generally correlates with that of Mg, Cr and Co, and it is also present in appreciable amounts in common sulphides, such as pyrite and chalcopyrite, and often correlates well with Cu in sulphide-rich rocks (Wedepohl, 1978).

Nickel shows very limited mobility during low-temperature hydrothermal activity, low-or high-grade metamorphism (Eade & Fahrig, 1973), or retrogressive metamorphism (Beach & Tarney, 1978).

In sedimentary rocks, nickel is mostly held in detrital ferromagnesian silicates, detrital primary Fe oxides, hydrous Fe and Mn oxides, and clay minerals. It is concentrated in shales (up to 90 ppm) relative to greywackes (*c.* 40 ppm), quartzitic sandstones (*c.* 20 ppm) and limestones (<5 ppm). Mielke (1979) cites levels of nickel in shales, sandstones and carbonates as 68, 2 and 20 ppm respectively. It becomes enriched in laterites in tropical environments due to its resistance to differential weathering (Ure & Berrow, 1982).

Surface environment geochemistry

A large proportion of the nickel in stream sediments is held in detrital silicates and oxides which are resistant to weathering. Limited solution of Ni^{2+} may occur at low pH, but mobility is generally restricted by the element's tendency to be sorbed by clay minerals (Short, 1961) or hydrous oxides of Fe and Mn (Ure & Berrow, 1982). Although it may be sorbed by secondary Fe and Mn oxides, this behaviour is not so well developed as for some other first–row transition elements such as Co. The monosulphide millerite [NiS] precipitates readily in reducing pore-water environments with sufficient dissolved HS^- (Carignan & Nriagu, 1985), but this is unlikely to be important under normal surface stream conditions.

Nickel has been shown to be essential for micro-organisms and has been implicated has having an essential role in human metabolism (McGrath, 1995). Extreme excesses of nickel are both toxic and carcinogenic.

Detailed description

Elevated nickel values are present in the western New Territories over outcrops of Tsing Shan Granite (Lamma Suite) in the vicinity of Lung Kwu Tan and Castle Peak. The highest nickel values (22–31 ppm) are associated with moderate to high Cr (24–173 ppm), Pb (95–288 ppm), Zn (56–178 ppm) and As (13–35 ppm). The high contents of associated metals suggests that samples are heavily contaminated. A small anomaly at Lau Fa Shan (28 ppm) has similar contents of associated metals, suggesting that contamination is mostly likely responsible for the elevated nickel values.

A prominent nickel anomaly (>22 ppm) over the Lam Tei area of the western New Territories is accompanied by moderate to high Cr (12 ppm), Pb (180 ppm), Zn (87 ppm) and Sn (94 ppm). The area is located close to a major aggregate quarry and it is likely that stream sediment samples have been locally contaminated by metallic waste.

In the northern New Territories, nickel anomalies are present at Mai Po (37 ppm), Pat Heung (30 ppm), Chuk Hang (416 ppm) and Sheung Shui (31 ppm). These areas are located close to major urban communities and the high values of associated metals, such as Cr (31–232 ppm), TiO_2 (0.5–0.74 %), Cu (118–2849 ppm), Pb (43–884 ppm), Zn (180–17 489 ppm) and Sn (22–151 ppm), indicate a high degree of anthropogenic contamination.

Nickel values are moderate to high (14–24 ppm) over a broad area of the central New Territories extending from Tai Lam Chung in the southwest toward Tolo Harbour in the northeast. West of Tai Mo Shan, nickel anomalies are present at Tai Lam Chung (22–29 ppm), Ho Pui 24 ppm), Tsing Fai Tong (22–26 ppm) and Sheung Fa Shan (22–28 ppm). These anomalies are accompanied by moderate to high Cr (50–184 ppm), V (19–117 ppm), Pb (67–169 ppm), Zn (35–375 ppm), but relatively low Cu (8–27 ppm), and Sn (35–86 ppm). They probably reflect a combination of high natural background values and a nickel contribution from local contamination. Elevated nickel values in the natural background are probably associated with sporadic zones of iron mineralisation found close to contacts between the granodiorite and volcanic rocks (see description for Fe). Nickel values are also high in several other areas including Chinese University (25 ppm), Kadoorie Farm (29 ppm) and Ma Shi Chau (24 ppm).

South and east of Tai Mo Shan, elevated nickel values are present at Kwai Chung (45–392 ppm), Tsuen Wan (24–27 ppm), Sha Tin (22–31 ppm) and Ma On Shan (22–31 ppm). In Kwai Chung and Sha Tin, the high nickel values are accompanied by high levels of industrial metals including Cu (22–365 ppm), Sn (120–8881 ppm), Pb (81–2256 ppm) and Zn (195–1490 ppm) and can largely be attributed to contamination. At Tsuen Wan and Ma On Shan, the high levels of nickel occur in areas of known iron mineralisation and probably reflect high natural background values. However, at Ma On Shan, the natural background level may be enhanced by contamination from mining waste.

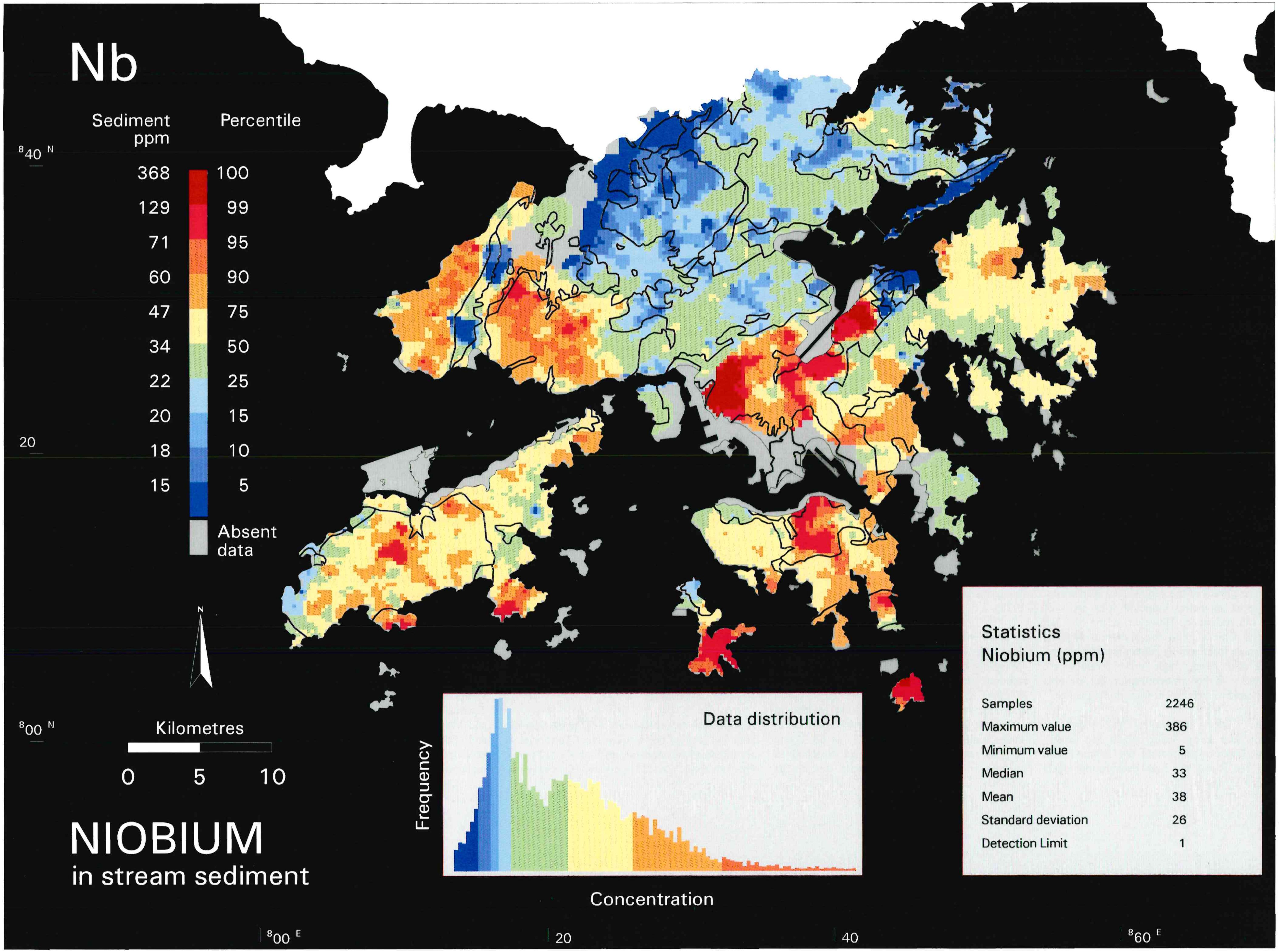
In the Kowloon area, nickel anomalies are mainly present at San Po Kong (25 ppm), Tseng Lan Shue (25 ppm) and Yau Tong (29 ppm), whereas an area of slightly elevated values occurs in the vicinity of Clear Water Bay. At Tseng Lan Shue and San Po King, the high nickel values coincide with high levels of industrial metals, indicating a strong degree of local contamination. These metals include Cu (170–185 ppm), Pb (129–258 ppm), Zn (491–594 ppm) and Sn (57–161 ppm). At Yau Tong, accompanying Pb (179 ppm) and Zn (106 ppm) values are high whereas at Clear Water Bay, the elevated nickel values are accompanied by moderate to high Cd (0.63–1.04 ppm) and Co (8–11 ppm).

On Hong Kong Island, nickel anomalies are present at North Point (23–30 ppm), Wong Chuk Hang (124 ppm), and Chung Hom Wan (121 ppm). In most cases, these elevated values can be attributed to local contamination, as indicated by moderate to high concentrations of accompanying Pb (71–201 ppm) and Zn (81–446 ppm).

On Lamma Island and Po Toi Island, moderate to high levels of nickel (22–37 ppm) are thought to reflect the high natural background. Concentrations of associated metals are rather low except for Cr (30–70 ppm), V (21–53 ppm) and TiO_2 (0.46–0.87 %). The high nickel values may be associated with mafic to intermediate dykes and local outcrops of Tai Po Granodiorite (Lamma Suite).

NIOBIUM

in stream sediment



Statistics
Niobium (ppm)

Samples	2246
Maximum value	386
Minimum value	5
Median	33
Mean	38
Standard deviation	26
Detection Limit	1

Niobium

Nb

Synopsis

In the western New Territories, high levels of niobium (>47 ppm) are present over outcrops of the Tai Lam and Tsing Shan granites (Lamma Suite). The highest values (>60 ppm) generally coincide with the fine-grained granites, whereas slightly lower values are found over outcrops of medium- and coarse-grained granites.

In the central New Territories, high niobium levels (>47 ppm) mostly coincide with outcrops of fine-grained Needle Hill Granite (Kwai Chung Suite). High values are also present over dykes of fine-grained granite and quartz monzonite (Lion Rock Suite) which intrude the Sha Tin Granite (Kwai Chung Suite).

In Kowloon, moderate to high values of niobium (34–71 ppm) are associated with outcrops of medium- and fine-grained Kowloon Granite (Lion Rock Suite). In the eastern New Territories, similar levels of niobium are found over outcrops of coarse ash crystal tuff (Repulse Bay Volcanic Group) and dykes of quartz monzonite (Lion Rock Suite).

On Hong Kong Island, strong niobium anomalies (>71 ppm) are associated with outcrops of fine-grained Mount Butler and Po Toi granites (Lion Rock Suite). Moderate to high levels (34–71 ppm) over the rest of the island correspond mainly with outcrops of fine ash vitric tuff (Repulse Bay Volcanic Group).

In the southern part of Lamma Island, background levels of niobium are high (>71 ppm) over outcrops of medium-grained South Lamma Granite (Cheung Chau Suite). On Po Toi Island to the east, high levels of niobium (>71 ppm) coincide with fine-grained lithologies of the Po Toi Granite (Lion Rock Suite).

The main niobium anomalies (>71 ppm) on Lantau Island are associated with fine-grained Chi Ma Wan Granite (Cheung Chau Suite), and fine-grained granite associated with quartz monzonite near Shek Pik.

Geochemistry of niobium

Niobium belongs to Group VB (V, Nb and Ta) of the periodic table and is part of the second series of transition elements. Although it is metallic in many respects, its chemistry in the 5^+ oxidation state gives it properties typical of non-metals, forming numerous anionic species and very few cationic compounds. Niobium has an ionic radius of 64 pm (Nb^{5+}) which is identical to that of Ta^{5+} and so these elements are usually found together in minerals and discussed together in geochemical texts.

Nb and Ta accumulate during magmatic differentiation, and so later differentiates are characterised by higher concentrations (Parker & Fleischer, 1968). Under favourable conditions, the REE group of elements and niobium are enriched in complex granitic pegmatites but not both at the same time (except in carbonatite–alkalic rock complexes) as the two groups follow different fractionation trends (Möller, 1989). Niobium substitutes for Ti, Zr, W and Sn and enrichment is closely linked with the petrogenesis of the pegmatite. Möller (1989) notes that the Ta–Nb fractionation can be related to the Ti content of the parental magma. The highest concentrations of niobium are seen in the outer zones of individual pegmatites (Vlasov, 1966). In granitic pegmatites, the early formed Nb–Ta minerals tend to be niobium rich, with later species becoming enriched in Ta (Wedepohl, 1978).

The crustal abundance of niobium is estimated to be 20 ppm (Wedepohl, 1978), based on computed averages for granitic rocks, granodiorites, and diorites of 22 ppm; gabbros, basalts 10 ppm; syenites, alkalic rocks 100 ppm; and peridotites 1.5 ppm. Sewell *et al.* (1992) reported a range of 10–39 ppm (average 20.2 ppm) for a selection of 18 granites from Hong Kong and the lowest niobium results are associated with granodiorite of the Lamma Suite.

Data on niobium contents of sedimentary rocks are scarce though there are sufficient analyses for Wedepohl (1978) to quote a value of 17 ppm Nb for argillaceous rocks. Willis (1970) presents data for Mn nodules from different oceans, giving average niobium values in the range 32–41 ppm. Data on metamorphic rocks is similarly scarce, but an average of 26 ppm is computed by Wedepohl (1978) for quartzofeldspathic rocks from the Canadian Shield.

The most important ore minerals of niobium are oxide minerals; silicate niobium minerals occur exclusively in peralkaline igneous and metasomatic suites of anorogenic descent (Cerný & Ercit, 1989). Apart from minerals in which niobium is an essential stoichiometric component (e.g. pyrochlore [$(Na,Ca,Ce)_2NbO_6(OH,F)$]; stibiocolumbite [$SbNbO_4$]), niobium is also found substituting in other minerals, though only in rutile and cassiterite has this attained economic importance. Pollard (1989) reports that Ta and Nb mineralisation is often associated with granites characterised by high fluorine levels and by the development of pervasive, post-magmatic alteration.

Surface environment geochemistry

Niobium is chemically unusual in that most of its compounds are almost insoluble in acid and alkaline media (Wedepohl, 1978). Nb_2O_5 is totally stable over all Eh–pH ranges (Brookins, 1988).

Columbite [$(Fe,Mn)Nb_2O_6$)], along with other such resistant minerals as chromite and beryl, will persist longer in the weathering zone than most other minerals. Niobium is also present in other resistate minerals such as ilmenite, sphene and zircon, and accumulates in placer deposits. Destruction of other host species such as biotite and amphibole will release niobium into solution which will rapidly be hydrolysed to Nb_2O_5. Watts *et al.* (1963) (whose work includes some diagrams cited in Rose *et al.* (1979)), report that niobium, occurring as pyrochlore, persists in the –80 mesh fraction of stream sediments 20 km downstream from a carbonatite deposit in Zambia. The pattern of geochemical anomalies derives not from niobium entering solution, but from mechanical dispersion of residual pyrochlore and niobian magnetite grains.

Detailed description

In the western New Territories, moderate to high values of niobium (34–129 ppm) over both the Tai Lam and Tsing Shan granites (Lamma Suite) generally coincide with the fine-grained lithologies. Over the Tsing Shan Granite, from San Wai in the north to Pillar Point in the south, the niobium anomalies (73–96 ppm) are accompanied by high Y (45–184 ppm), Ga (30–54 ppm) and Th (99–110 ppm). Similar high values of Y (152 ppm), Ga (45 ppm) and Th (109 ppm) accompany the niobium anomaly at Lam Tei (83 ppm), which is representative of the high niobium values over the Tai Lam Granite. At Tai Lam Chung, the niobium anomaly (72–77 ppm) is associated with high Y (90–131 ppm), Rb (523–582 ppm), Ga (27–40 ppm) as well as high Pb (89–189 ppm) and Sn (71–100 ppm).

In the central New Territories, niobium values are high over outcrops of fine-grained Needle Hill (Kwai Chung Suite) and Kowloon (Lion Rock Suite) granite. They are also high over dykes of fine-grained granite and quartz monzonite which intrude parts of the Sha Tin Granite. Strong anomalies are present at Kwai Chung (72–386 ppm), Sha Tin Valley (195–285 ppm), San Po King (880–132 ppm) and Tai Shui Hang (73–243 ppm). At Kwai Chung, the high niobium values are associated with high Y (56–3 563 ppm), Zr (1065–1272 ppm), La (9–4 923 ppm), Ce (110–1994 ppm), Cu (2–365 ppm), Pb (67–883 ppm), Zn (1490 ppm) and Sn (13–347 ppm). The extremely high levels of Pb, Zn and Sn suggest that the samples have been partly affected by local contamination. In the Sha Tin Valley, the high niobium values are also accompanied by high Y (77–147 ppm), Zr (446–3093 ppm), Pb (41–2256 ppm) and Sn (22–8881 ppm), suggesting local contamination. At San Po King, the niobium anomaly is associated with high Y (74–154 ppm), Zr (631–1779 ppm), Rb (345–538 ppm), U (8–26 ppm) and Th (36–94 ppm), whereas at Tai Shui Hang, it is accompanied by high levels of Y (69–157 ppm), Zr (385–1767 ppm), Cs (1–27 ppm) and Sn (19–575 ppm).

In eastern Kowloon and the eastern New Territories, elevated levels of niobium (34–60 ppm) are present over outcrops of fine-grained Kwun Tong Granite (Lion Rock Suite), coarse ash crystal tuff and fine ash vitric tuff (Repulse Bay Volcanic Group). Local anomalies in the Tai Tan and Sharp Peak areas may be also be partly related to dykes of quartz monzonite (Lion Rock Suite).

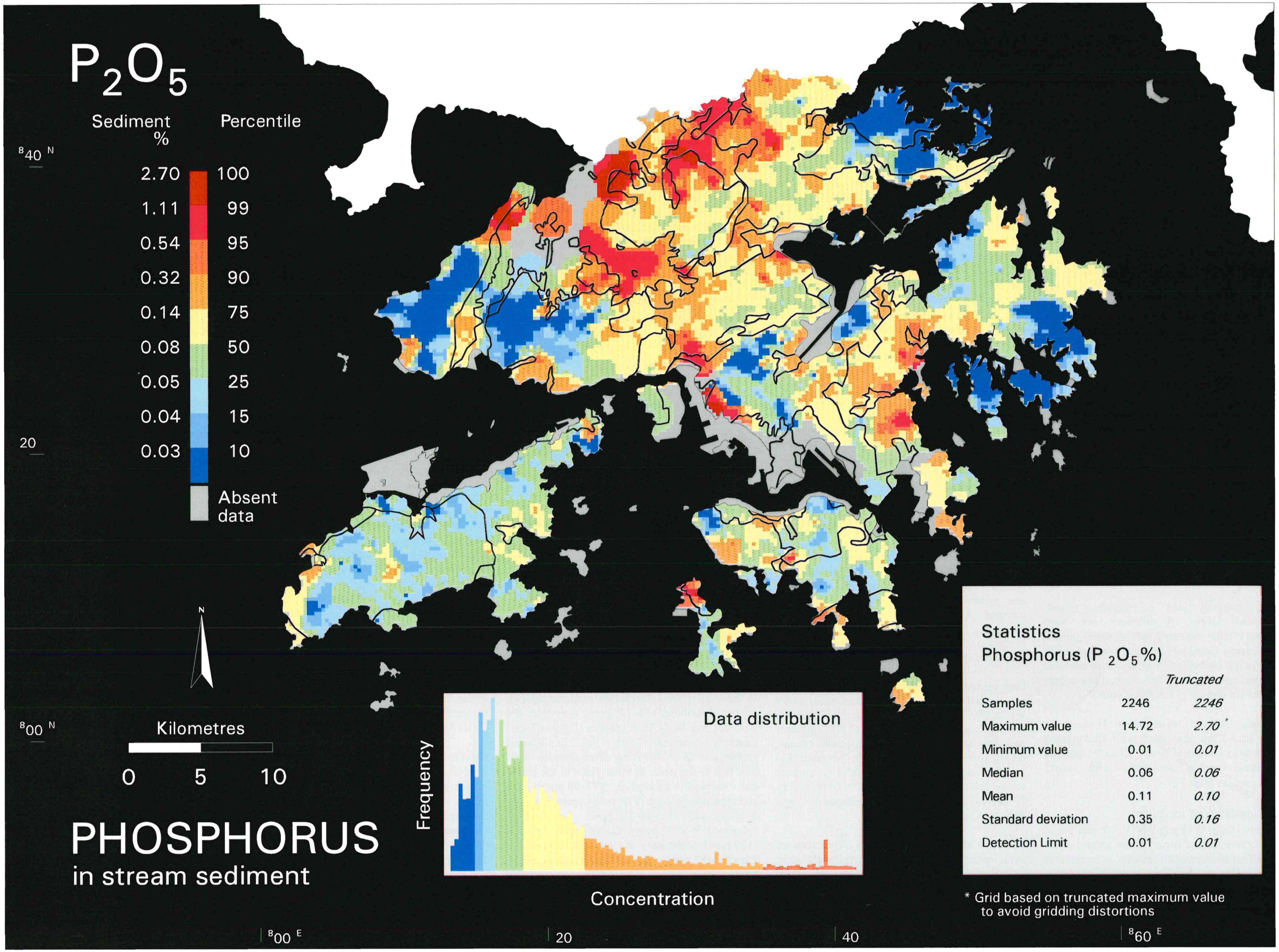
On Hong Kong Island, a prominent niobium anomaly (74–106 ppm) coincides with outcrops of fine-grained Mount Butler Granite (Lion Rock Suite). The high niobium values are accompanied by high Y (25–260 ppm), Zr (161–661 ppm), Ce (80–266 ppm), Cs (1–15 ppm), Ga (22–44 ppm), U (6–25 ppm) and Th (71–131 ppm). At D'Aguilar Peak in the southeast of the island, a small niobium anomaly (72–85 ppm) is present over fine-grained Po Toi Granite (Lion Rock Suite) and similar values (75–162 ppm) occur over fine-grained lithologies on Po Toi Island. In both areas, the high niobium contents are accompanied by moderate to high levels of Rb (206–364 ppm), Ga (25–48 ppm) and Th (61–100 ppm).

Background levels of niobium are high (71–119 ppm) over the southern part of Lamma Island coincident with outcrops of medium-grained South Lamma Granite (Cheung Chau Suite). The niobium values may be partly enhanced by a swarm of rhyodacite dykes which intrude the granite. Typical ranges of accompanying elements are as follows: Y 43–215 ppm, Zr 254–1147 ppm, Ce 63–356 ppm, Rb 80–465 ppm, Ga 19–41 ppm, U 8–17 ppm and Th 39–91 ppm.

Moderate to high levels of niobium (34–129 ppm) are present over a broad area of Lantau Island, with prominent anomalies at Chi Ma Wan (74–111 ppm), Ngong Ping (81–11 ppm), and Shek Pik (71–86 ppm). At Chi Ma Wan and Shek Pik, the high niobium values coincide with outcrops of fine-grained Chi Ma Wan Granite (Cheung Chau Suite) and Luk Keng Quartz Monzonite (Cheung Chau Suite) respectively. At Chi Ma Wan, the niobium anomaly is accompanied by high Y (103–195 ppm), Zr (1107–2553 ppm), La (31–146 ppm), Cs (10–17 ppm), Rb (145–416 ppm), Ga (23–28 ppm), U (18–41 ppm) and Th (164–248 ppm). High levels of Zr (447–2555 ppm), Rb (147–201 ppm) and Th (35–71 ppm) also accompany the niobium anomaly at Shek Pik. Over central Lantau Island, elevated levels of niobium mainly correspond to outcrops of volcanic rocks belonging to the Lantau Volcanic Group. The niobium anomaly at Ngong Ping is associated with high levels of Y (118–167 ppm), Zr (1107–3287 ppm), Rb (100–196 ppm), Th (33–40 ppm), Pb (108–231 ppm), and Sn (14–428 ppm). The high levels of metallic elements suggest that the stream sediments surrounding Ngong Ping are likely to have been partly enhanced by anthropogenic contamination. In the northeastern part of Lantau Island, small niobium anomalies are present over outcrops of fine- and medium-grained Tai Lam Granite (Lamma Suite).

PHOSPHORUS

in stream sediment



Statistics
Phosphorus (P_2O_5%)

		Truncated
Samples	2246	*2246*
Maximum value	14.72	*2.70* *
Minimum value	0.01	*0.01*
Median	0.06	*0.06*
Mean	0.11	*0.10*
Standard deviation	0.35	*0.16*
Detection Limit	0.01	*0.01*

* Grid based on truncated maximum value to avoid gridding distortions

Phosphorus

P_2O_5

Synopsis

The strongest phosphorus anomalies (>0.54 % P_2O_5) are present in the central and northern New Territories, mainly in association with outcrops of coarse ash crystal tuff (Tsuen Wan Volcanic Group). Phosphorus values are also high (>0.14 % P_2O_5) over outcrops of granodiorite (Lamma Suite). Slightly enhanced phosphorus levels in the low-lying agricultural areas compared to the surrounding hill sides, can be partly attributed to the application of fertilizer.

In the eastern New Territories, phosphorus levels are very low (<0.03 % P_2O_5) over outcrops of fine ash vitric tuff (Kau Sai Chau Volcanic Group), but are moderate to high (>0.05 % P_2O_5) in areas dominated by coarse ash crystal tuff (Repulse Bay Volcanic Group).

Background levels of phosphorus are low to moderate (<0.08 % P_2O_5) over most of Hong Kong Island except for slightly elevated values over outcrops of coarse ash crystal tuff (Repulse Bay Volcanic Group) and small exposures of quartz monzonite (Lion Rock Suite) in the east and south of the island. Phosphorus values are high over outcrops of quartz monzonite (Lion Rock Suite) and coarse ash crystal tuff (Tsuen Wan Volcanic Group) in the northern parts of Lamma Island.

Low to moderate levels (<0.08 % P_2O_5) of phosphorus are found over most of Lantau Island, except for slightly higher levels over outcrops of coarse ash crystal tuff (Tsuen Wan Volcanic Group) in the southwest. Small anomalies (0.08–0.32 % P_2O_5) in other areas are mostly related to local anthropogenic contamination.

Geochemistry of phosphorus

Phosphorous is a Group VA element in the periodic table, along with N, As, Sb and Bi, and in the lithosphere the only stable ion that it forms is P^{5+} as $[PO4]^{3-}$. There are two factors affecting the differentiation of phosphorus in magmas (Wedepohl, 1978). Firstly, with the exception of the rare–earth minerals monazite [$CePO_4$] and xenotime [YPO_4] in some P-rich pegmatites, only apatite [$Ca_5(PO_4)_3(OH,F,Cl)$] crystallises as a separate mineral from the magma. Secondly, there is the replacement of Si^{4+} by P^{5+} in silicate rock-forming minerals, as these ions have similar radii (40 and 38 pm respectively); replacement of SiO_4 units by PO_4 requires a coupled substitution, for example of Al^{3+} by Ca^{2+}, to maintain charge balance. Koritnig (1965) reported that up to 0.3 % of SiO_4 tetrahedra can be replaced by PO_4 tetrahedra in silicate minerals.

Phosphorus belongs to the volatile components of magmas, though great variation of phosphorus levels are found for magmatic rocks even with rocks of a similar type (Wedepohl, 1978). In magmatic differentiation phosphorus tends to follow Ti, though not because of chemical similarities but because the minerals apatite, sphene and ilmenite tend to separate out at the same time. Apatite is found mainly in a middle or late stage crystallisation, sometimes replacing pre–existing minerals (Moorhouse, 1956). Mielke (1979) reports a crustal average for phosphorus of 1120 ppm; ultrabasic, 220 ppm; basaltic 1100 ppm; and granitic 600–920 ppm.

Data on abundances for phosphorus in metamorphic rocks are rare, but there is a trend of increasing phosphorus with increasing metamorphic grade (Wedepohl, 1978).

The phosphorus content of clastic rocks depends on their origin and grain size with the phosphorus content generally increasing with decrease in grain size. The main phosphorus mineral is apatite (often derived from organic sources), though some occurs as co-precipitated $FePO_4$ (nominal) with Fe oxides. Levels in shales are reported as 700 ppm; sandstones, 170 ppm; and carbonates, 400 ppm (Mielke, 1979). High levels occur in the rare sedimentary bone beds, and also in organic-rich black shales where associations of Fe phosphates and uranium often occur.

Surface environment geochemistry

The solubility of the apatite mineral group and Fe–Al phosphates, and the adsorption on clay minerals are the two most important factors in weathering. In acid environments, apatites are remarkably soluble, as HPO_4^{2-} and H_2PO^{4-} ions formed by the equilibrium reaction of H^+ with PO_4^{3-} are soluble in the presence of Ca^{2+}. However, fluorapatites are rather less soluble than chloro– or hydroxyapatites, and in neutral and alkaline conditions, calcium orthophosphate is largely insoluble. Except in very acid conditions (pH <3.0), Al and Fe phosphates are highly insoluble, and their formation limits the mobility of phosphorus in soils and stream sediments. In soils, phosphorus also forms low solubility minerals with Pb and Ca such as plumbogummites (e.g. [$PbAl_3(PO_4)_2(OH)_5$]) and pyromorphite [$(PbCl)Pb_4(PO_4)_3$], which are even less soluble than common Ca–phosphates.

Phosphate is also strongly sorbed by secondary Fe oxides in stream sediments, so natural PO_4^{3-} levels in solution in fresh waters are low. However, since phosphorus is a biologically essential major element and an important plant nutrient, it is used in fertilisers and is common in organic wastes such as sewage. High levels of anthropogenic phosphorus in rivers and lakes can cause eutrophication and algal blooms. The persistence of high phosphorus levels in lake sediments can cause serious long-term environmental effects.

Detailed description

In the western New Territories, elevated phosphorus values are present over andesite outcrops of the Tuen Mun Formation north of Tuen Mun. These moderate to high values (0.14–0.32 % P_2O_5) contrast strongly with very low phosphorus levels (<0.03 % P_2O_5) in the surrounding granitic areas. In the Lau Fau Shan area, a phosphorus anomaly (2.62 % P_2O_5) is accompanied by high levels of other metals including Ba (132 ppm), CaO (16.0 %), Cd (1.5 ppm), Cu (174 ppm) and Zn (551 ppm). The presence of microspheres and rust flakes in the panned concentrates suggests local metallic contamination is strongly influencing the stream sediment chemistry. Local anthropogenic contamination is also probably responsible for the elevated phosphorus levels (0.38 % P_2O_5) in the vicinity of Tin Shui Wai which is associated with moderate to high Ba (832 ppm), CaO (1.47 %), Co (13.5 ppm), V (77 ppm), Pb (120 ppm) and Zn (114 ppm).

Moderate to high levels (>0.08 % P_2O_5) of phosphorus are present over a broad area of the central and northern New Territories, with strong anomalies in the Mai Po, Kwu Tung, Man Kam To, Kwan Tei and Lin Tong Mei areas. The area is principally underlain by coarse ash crystal tuff (Tsuen Wan Volcanic Group). The highest levels of phosphorus (0.79–14.72 % P_2O_5) are found in the Mai Po area and are associated with very high levels of Ba (367–769 ppm), CaO (2.04–85.4 %), Sr (24–267 ppm), Co (2–35 ppm), Cd (0.3–3.2 ppm), Cu (58–2849 ppm), Pb (55–884 ppm), Zn (494–17 489 ppm) and Sn (16–169 ppm). These elevated concentrations are largely due to local anthropogenic contamination. At Kwan Tei, the high phosphorus levels (1.38 % P_2O_5) coincide with high Ba (420 ppm), V (72 ppm) and Zn (142 ppm) levels, whereas at Man Kam To, high phosphorus values (0.66–0.69 % P_2O_5) are accompanied by moderate to high Ba (654–673 ppm), Co (6–11 ppm) and Zn (89–130 ppm). At Kwu Tung, the anomalous phosphorus values (1.1–1.5 % P_2O_5) are likely to have been enhanced by local contamination, as indicated by high levels of metals including Ba (526–803 ppm), CaO (1.86–2.96 %), V (43–83 ppm) and Cu (210–875 ppm). In the Lin Tong Mei area, the high phosphorus values (0.80–0.82 % P_2O_5) are similarly accompanied by high levels of Ba (656–786 ppm), CaO (2.89–3.01 %) and V (67–74 ppm), in addition to high levels of Hg (2.3–3.5 ppm).

In the central New Territories, phosphorus levels are high (0.12–1.78 % P_2O_5) over a broad low-lying area at Pat Heung. These elevated values are typically accompanied by high Ba (512–619 ppm), CaO (0.79–4.82 %), Cu (49–138 ppm), Pb (94–175 ppm), Zn (232–404 ppm) and Sn (37–156 ppm). Evidence of microspheres and rust fragments in many of the panned concentrates indicates the high values are likely to be related to local anthropogenic contamination, including a contribution from the application of fertilizer on agricultural land. At Tsuen Wan, the high phosphorus values (0.65–1.06 % P_2O_5) are accompanied by high Ba (425–518 ppm), CaO (0.95–1.09 %), V (70–84 ppm), Pb (119–207 ppm), Zn (603–633 ppm) and Sn (233–476 ppm). Similar elevated values for these associated metals (e.g. Ba 415–488 ppm, CaO 0.89–56 %, V 81–84 ppm, Pb 262–439 ppm, Zn 467–563 ppm and Sn 37–128 ppm) accompany the high values of phosphorus (0.66–0.79 % P_2O_5) in the Tai Po area.

At Kwai Chung, a small phosphorus anomaly (0.8–1.84 % P_2O_5) over outcrops of granitic rock contrasts with the low to moderate phosphorus values in adjacent granitic areas. However, the very high levels of Cu (156–365 ppm), Pb (391–883 ppm), Zn (847–1490 ppm) and Sn (120–149 ppm) associated with this anomaly strongly suggest local anthropogenic contamination.

In the eastern New Territories, low levels of phosphorus (<0.05 % P_2O_5) generally characterise areas underlain by fine ash vitric tuff (Kau Sai Chau Volcanic Group), whereas moderate to high levels of phosphorus (0.05–0.32 % P_2O_5) are commonly found over outcrops of coarse ash crystal tuff (Repulse Bay Volcanic Group). At Sai Kung, the high phosphorus values (0.43–0.65 % P_2O_5) are accompanied by moderate to high Ba (442–599 ppm), CaO (0.54–9.92 %), Co (7–12 ppm), Pb (59–115 ppm), Zn (318–448 ppm) and Sn (7–69 ppm). Similar values for these metals accompany the phosphorus anomaly at Tseng Lan Shue (0.47–1.17 % P_2O_5) and suggest that background levels of phosphorus have been enhanced by local contamination.

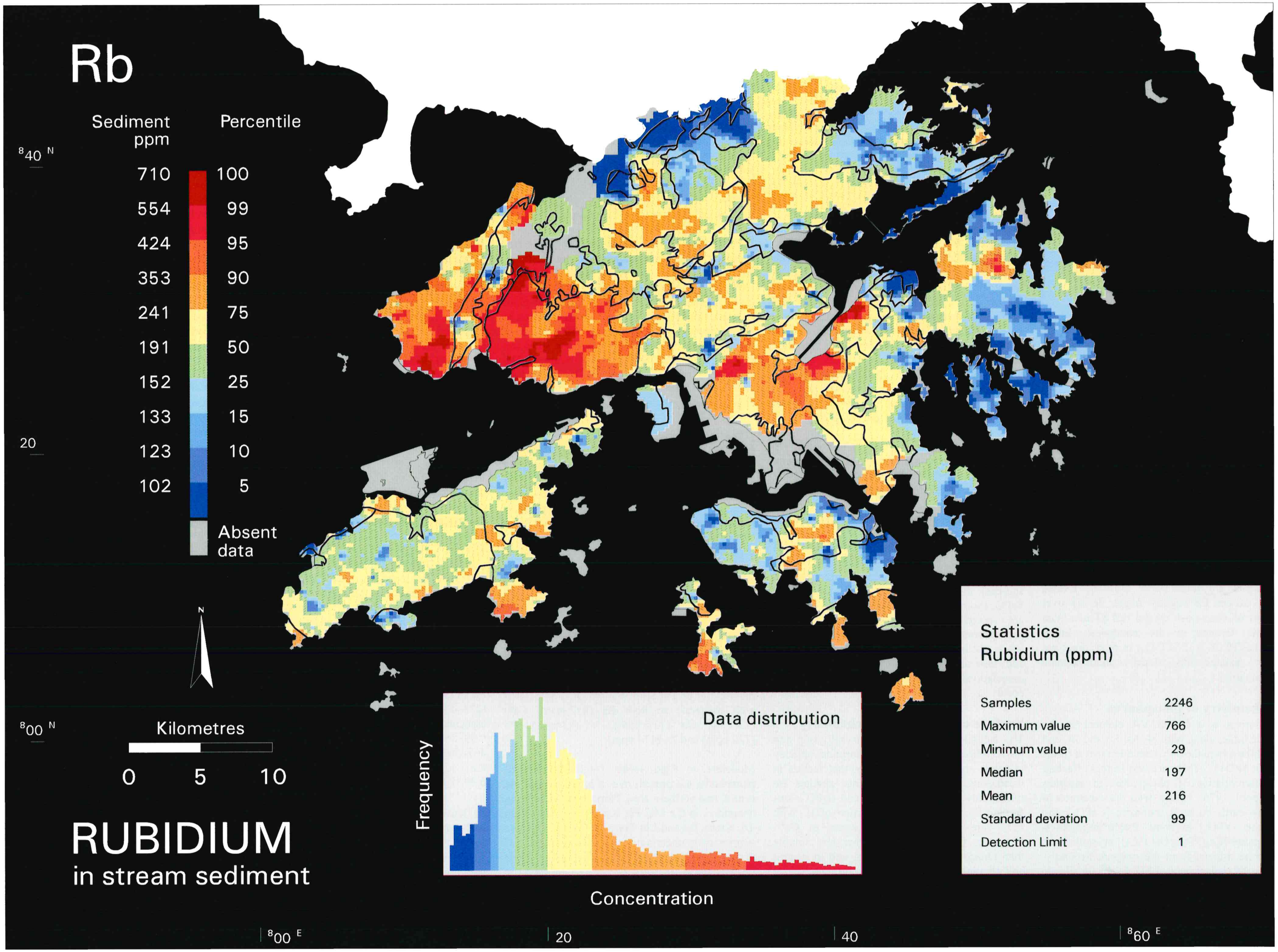
Phosphorus levels are rather variable on Hong Kong Island, but are generally slightly elevated over outcrops of coarse ash crystal tuff (Repulse Bay Volcanic Group) and quartz monzonite dykes (Lion Rock Suite). North of Wong Chuk Hang, the high phosphorus values (0.90 % P_2O_5) are accompanied by high Ba (488 ppm), Pb (159 ppm), Zn (487 ppm) and Hg (1.7 ppm) suggesting they have been enhanced by local contamination. These metal concentrations are similar to those surrounding the phosphorus anomaly (0.46 % P_2O_5) at Chung Hom Wan (e.g. Ba 139 ppm, Pb 177 ppm, Zn 462 ppm, and Hg 2.0 ppm).

On Lamma Island, a phosphorus anomaly (1.53 % P_2O_5) in the vicinity of Yung Shue Wan is present over outcrops of coarse ash crystal tuff (Tsuen Wan Volcanic Group) intruded by quartz monzonite dykes (Lion Rock Suite). The high phosphorus values in the north of the island occur with moderate to high Ba (332 ppm), CaO (1.03 %), V (38 ppm), Pb (182 ppm), Zn (304 ppm) and Hg (2.0 ppm), and may be partly due to local contamination.

On Lantau Island, the elevated phosphorus values (0.08–0.32 % P_2O_5) are accompanied by moderate to high concentrations of Ba, CaO, Pb and Zn. In the Shek Pik Reservoir and Tai O areas, the phosphorus values may be enhanced by local contamination (see descriptions for Ba and Sr).

RUBIDIUM

in stream sediment



Statistics
Rubidium (ppm)

Samples	2246
Maximum value	766
Minimum value	29
Median	197
Mean	216
Standard deviation	99
Detection Limit	1

Rubidium Rb

Synopsis

Rubidium levels are generally high (>353 ppm) over granitic areas in the western New Territories, and moderate to high (191–353 ppm) over volcanic and granitic outcrops in the central New Territories. Moderate levels or rubidium (152–241 ppm) are present over volcanic areas in the northern New Territories, whereas background levels are low (<152 ppm) over outcrops of sedimentary rocks. Low to moderate rubidium levels (<191 ppm) characterise volcanic and granitic areas of eastern New Territories, Kowloon, Hong Kong Island, Lamma Island and Po Toi Island, and levels are generally moderate (152–241 ppm) over volcanic and granitic rocks of Lantau Island.

In the western New Territories, high levels (>353 ppm) of rubidium coincide mainly with outcrops of the Tsing Shan and Tai Lam granites (Lamma Suite). Moderate to high levels (>241 ppm) are also present over outcrops of the Triassic Deep Bay Granite, whereas slightly lower levels (152–241 ppm) occur over the outcrops of Middle Jurassic andesitic rocks.

In northern and northeastern New Territories, low levels of rubidium (<152 ppm) characterise outcrops of Upper Palaeozoic to Upper Mesozoic sedimentary rocks, whereas moderate levels (152–241 ppm) are present over outcrops of Middle Jurassic to Early Cretaceous volcanic rocks (Tsuen Wan and Repulse Bay volcanic groups).

Over the central New Territories, moderate to high levels of rubidium (191–353 ppm) coincide mainly with outcrops of the Sha Tin and Needle Hill granites (Kwai Chung Suite). The Sha Tin Granite is intruded by fine-grained granite and quartz monzonite dykes (Lion Rock Suite).

In the eastern New Territories and Kowloon, slightly elevated levels of rubidium (191–353 ppm) are found over outcrops of trachytic and monzonitic rocks (Repulse Bay Volcanic Group and Lion Rock Suite), whereas low levels (<152 ppm) are present over areas of rhyolitic rocks (Kau Sai Chau Volcanic Group). On Hong Kong Island, Lamma Island and Po Toi Island, slightly elevated rubidium values (191–353 ppm) correspond with outcrops of medium- and fine-grained granite (Lion Rock Suite) and quartz monzonite (Lion Rock Suite), whereas low to moderate levels (<191 ppm) characterise most of the volcanic areas.

Over much of Lantau Island, moderate levels of rubidium (152–241 ppm) coincide with outcrops of volcanic rocks (Lantau Volcanic Group) and rhyolite porphyry dykes (Kwai Chung Suite). However, rubidium values are slightly higher (191–353 ppm) over outcrops of medium- and fine-grained granite (Lamma Suite and Cheung Chau Suite) in the northwestern and southern parts of the island.

Geochemistry of rubidium

Rubidium is a member of the alkali metal group (Group IA) in the periodic table, along with Li, Na, K and Cs, and its only natural oxidation state is as Rb$^+$. In the natural environment, rubidium does not form any minerals of its own but is dispersed in potassium minerals. The Rb$^+$ ion (ionic radius 152 pm) substitutes for K$^+$ (ionic radius 138 pm) during magmatic processes in micas such as muscovite and, to a lesser extent, in K–feldspars such as microcline and orthoclase. However, because Rb$^+$ has a larger ionic radius and therefore behaves incompatibly, it becomes concentrated in late stage differentiates. The values quoted by Mielke (1979) are: ultrabasic, 0.2 ppm; basaltic 30 ppm; granitic 110–170 ppm; syenitic 110 ppm; and crustal abundance 78 ppm. Sewell *et al.* (1992) reported an average value of 312 ppm Rb for a selection of 18 Hong Kong granites (range 169–698 ppm Rb). Enhancement of the levels of rubidium, and other Large Ion Lithophile (LIL) elements relative to incompatible High Field Strength (HFS) elements, is often pronounced in alkaline and calc–alkaline rocks, and may relate to enrichment of the magma source by metasomatic processes (Saunders *et al.*, 1980). The K/Rb ratio provides an important petrogenetic index, generally decreasing with magmatic evolution (Shaw, 1968).

Pervasive redistribution of rubidium has been reported during deuteric and hydrothermal alteration of granite plutons (Bailey & Macdonald, 1975; O'Brien *et al.*, 1985). Rubidium is an element associated with greisen-type Sn deposits (Pokorny, 1975), and is found enriched in most ore zones of porphyry–Cu deposits (Armbrust *et al.*, 1977). A general decrease in rubidium levels occurs at high metamorphic grades (Heier, 1973; Tarney & Windley, 1977).

In sedimentary rocks, rubidium is present mainly in K–feldspars, micas and clay minerals. The average rubidium content of arkoses and feldspathic sandstones (>60 ppm) is therefore higher than that of pure quartzites (<45 ppm) or dolomites (30–60 ppm). During weathering, ion exchange and differential adsorption mechanisms tend to concentrate rubidium relative to K (Heier & Billings, 1970). Many shales and mudstones thus have high levels of rubidium (ca 160 ppm) mainly held in clay minerals such as illite, leading to lower K/Rb ratios than those of igneous rocks. Mielke (1979) cites levels of rubidium in shales, sandstones and carbonates as 140, 60 and 3 ppm respectively.

Surface environment geochemistry

In stream sediments, rubidium normally occurs in detrital K–feldspars, micas and clay minerals. Small amounts of rubidium may be mobilised during the weathering of these minerals, particularly in acid conditions. However, despite the high solubility of the Rb$^+$ ion and its compounds, subsequent dispersal is restricted by a strong adsorption onto clays such as illite (Butler, 1957), the sorption being stronger than that for K. Rubidium is most readily sorbed by clays at high pH, so in alkaline stream environments, any clay fraction of the sediment is likely to be higher in rubidium than more acidic stream channels.

Detailed description

In the western New Territories, the strongest rubidium anomalies (425–623 ppm) over the Tsing Shan Granite (Lamma Suite) are present in the vicinity of Castle Peak. These are accompanied by moderate to high values of U (7–17 ppm), Th (47–127 ppm), Y (31–137 ppm), Nb (39–75 ppm), Ga (26–38 ppm) and Pb (89–313 ppm). Farther north, a minor anomaly at Sheung Pak Nai (576 ppm) is similarly accompanied by moderate to high Th (110 ppm), Y (184 ppm), Nb (96 ppm), Ga (54 ppm) and Pb (81 ppm). Rubidium values over the Triassic Deep Bay Granite close to Tsim Bei Tsui are also high (241–554 ppm), and at Mong Tseng Wai reach 468 ppm.

High levels of rubidium are present over outcrops of the Tai Lam Granite (Lamma Suite) to the east of Tuen Mun. The highest values are found in the vicinity of Lam Tei (429–632 ppm) and Tai Lam Chung Reservoir (424–617 ppm), and coincide mostly with fine-grained and fine- to medium-grained rocks. At Lam Tei, moderate to high levels of Th (101–109 ppm), Y (50–152 ppm), Nb (62–83 ppm), and Ga (36–45 ppm) accompany the high rubidium values. At Tai Lam Chung Reservoir, typical values for these elements are as follows: Th 33–116 ppm, Y 28–184 ppm, Nb 18–82 ppm, Ga 25–42 ppm.

In the northern New Territories, rubidium values are generally low (<152 ppm) over outcrops of Upper Palaeozoic sedimentary rocks, but are slightly elevated (191–353 ppm) over outcrops of coarse ash crystal tuff (Tsuen Wan Volcanic Group). In the northeastern New Territories, rubidium values are low over outcrops of Upper Mesozoic sedimentary rocks.

Most of the elevated rubidium values in the central New Territories coincide with outcrops of the Needle Hill and Sha Tin granites (Kwai Chung Suite). Rubidium anomalies are present at Shing Mun (449–625 ppm), Siu Lek Yuen (450–538 ppm) and Tai Shui Hang (608–766 ppm). At Shing Mun, the high rubidium values are associated with high U (12–21 ppm), Th (44–124 ppm), Y (72–148 ppm), Nb (32–176 ppm) and Ga (28–39). Similar levels of these elements (e.g. U 17–26 ppm, Th 73–94 ppm, Y 91–154 ppm, Nb 66–132 ppm, Ga 25–30 ppm) accompany the high rubidium levels at Siu Lek Yuen. At Tai Shui Hang, the rubidium anomaly coincides with high levels of U (14–24 ppm), Th (88–125 ppm), Y (96–250 ppm), Nb (126–243 ppm) and Ga (28–39 ppm). The unusually high values of Th, Y and Nb may be partly influenced by nearby dykes of fine-grained granite and quartz monzonite (Lion Rock Suite) which intrude the Sha Tin Granite.

In the eastern New Territories, moderate levels of rubidium (152–353 ppm) are present over outcrops of coarse ash crystal tuff (Repulse Bay Volcanic Group), whereas low levels (<152 ppm) characterise areas underlain by fine ash vitric tuff (Kau Sai Chau Volcanic Group). In the vicinity of Three Fathoms Cove, elevated rubidium values correspond with outcrops of the Lai Chi Chong Formation (Lantau Volcanic Group). Nearby dykes of quartz monzonite (Lion Rock Suite) may also partly account for the anomaly in the Tai Tun area, although the levels of U (14–15 ppm), Th (82–86 ppm), Y (47–101 ppm), Nb (55–69 ppm) and Ga (31–39 ppm) are slightly lower than expected. It is possible that the high rubidium values at Tai Tun may be affected local anthropogenic contamination, as indicated by the presence of microspheres and rust flakes in some panned concentrates.

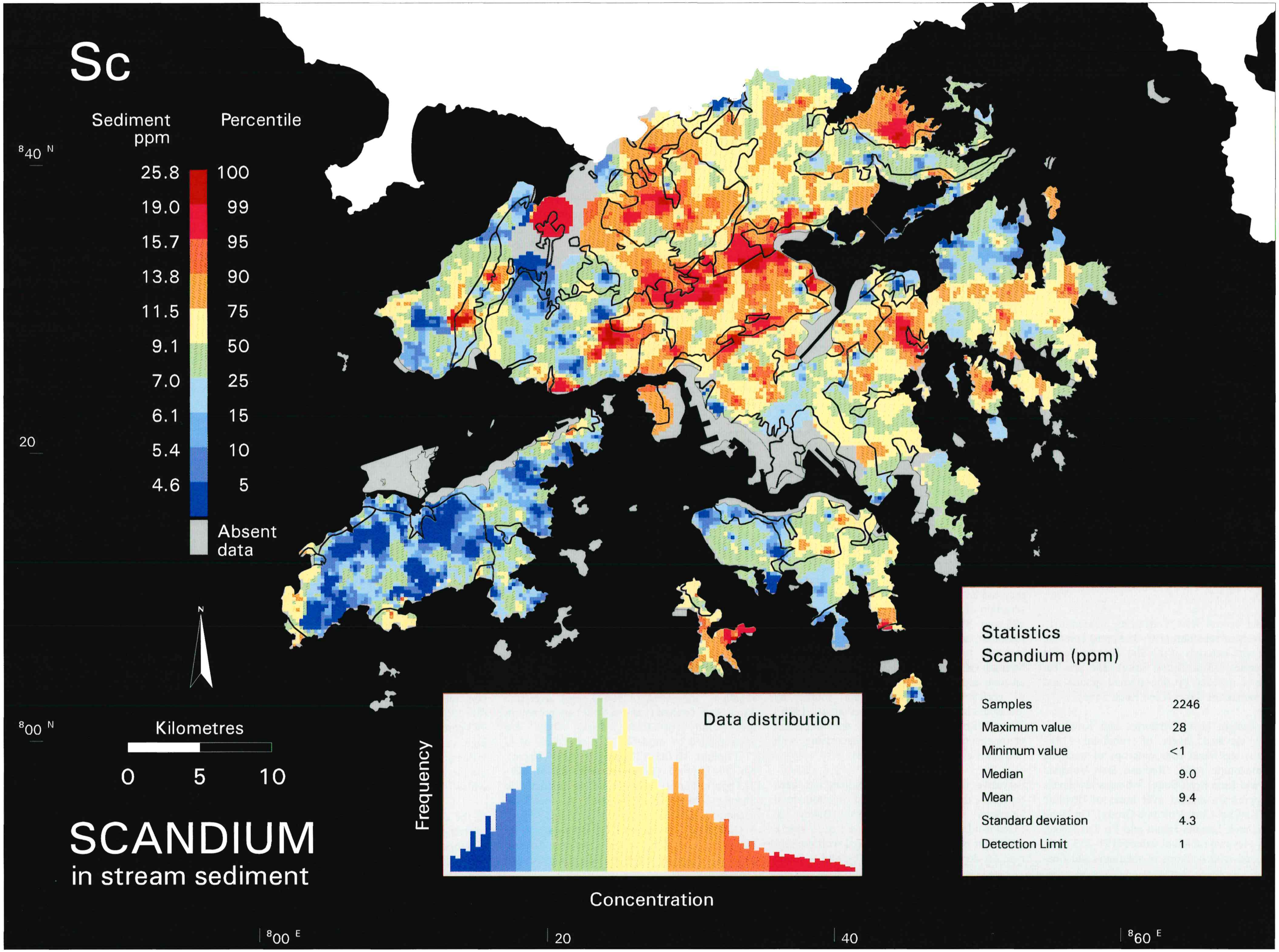
Moderate levels of rubidium (152–353 ppm) are present over much of eastern Kowloon, which is largely underlain by medium-grained granite (Lion Rock Suite) and trachytic volcanic rocks (Repulse Bay Volcanic Group). On Hong Kong Island, slightly higher rubidium values (241–424 ppm) coincide with outcrops of the fine-grained Mount Butler and Po Toi granites (Lion Rock Suite), and D'Aguilar Quartz Monzonite (Lion Rock Suite). On Lamma Island and Po Toi Island, moderate to high levels of rubidium also coincide mainly with outcrops of granitic rock (Cheung Chau Suite and Lion Rock Suite). The high rubidium values on Lamma Island are accompanied by moderate to high U (11–16 ppm), Th (44–66 ppm), Y (78–158 ppm), Nb (59–102 ppm) and Ga (22–30 ppm). These enriched concentrations may also be partly derived from rhyodacite dykes which intrude the South Lamma Granite (Cheung Chau Suite).

Moderate levels of rubidium (152–241 ppm) characterise most of Lantau Island and are generally similar over areas of granite and volcanic rock outcrop. The exceptions are slightly elevated levels over the Chi Ma Wan Granite (Cheung Chau Suite) (241–424 ppm) in the southeast, and the Chek Lap Kok Granite (Lamma Suite) (241–353 ppm) in the northwest. Other minor anomalies occur over quartz monzonite near Mui Wo (Lion Rock Suite) and at Fan Lau (Cheung Chau Suite), and over rhyolite porphyry dykes (Kwai Chung Suite) at Ta Shui Hang and Cheung Sha.

Sc

SCANDIUM

in stream sediment



Sediment ppm	Percentile
25.8	100
19.0	99
15.7	95
13.8	90
11.5	75
9.1	50
7.0	25
6.1	15
5.4	10
4.6	5
Absent data	

Statistics
Scandium (ppm)

Samples	2246
Maximum value	28
Minimum value	<1
Median	9.0
Mean	9.4
Standard deviation	4.3
Detection Limit	1

Scandium

Sc

Synopsis

In the western New Territories, small scandium anomalies (>15.7 ppm) are present over andesite outcrops of the Tuen Mun Formation and these contrast with the low to moderate background values (<9.1 ppm) in the surrounding Tsing Shan and Tai Lam granites (Lamma Suite).

Over central and northern New Territories, scandium anomalies (>15.7 ppm) generally coincide with outcrops of granodiorite (Lamma Suite) and volcanic rocks (Tsuen Wan Volcanic Group). The highest values (>19.0 ppm) mostly occur close to intrusive contacts between the granodiorite and volcanic rocks. In northeastern New Territories, a prominent scandium anomaly (>15.7 ppm) occurs over a suspected NW-trending shear zone.

Scandium anomalies in the eastern New Territories mainly surround outcrops of quartz monzonite (Lion Rock Suite), although high values (>15.7 ppm) are also associated with coarse ash crystal tuff (Repulse Bay Volcanic Group) and volcanigenic sedimentary rock (Kau Sai Chau Volcanic Group). Background levels of scandium are generally moderate (7.0–11.5 ppm) over outcrops of fine ash vitric tuff (Kau Sai Chau Volcanic Group).

On Hong Kong Island and Lamma Island, small scandium anomalies are associated with outcrops of quartz monzonite (Lion Rock Suite) and granodiorite (Lamma Suite). On Lantau Island, slightly elevated levels of scandium (9.1–13.8 ppm) are associated mostly with outcrops of quartz monzonite (Cheung Chau Suite) and coarse ash crystal tuff (Tsuen Wan Volcanic Group).

Geochemistry of scandium

Scandium is classified in Group IIIB of the periodic table, along with Y and the lanthanides, but its geochemistry is quite distinct from the heavier group members (Y, La and Ac). Its chemistry shows a greater similarity with Al and Fe^{3+} but the relatively large Sc^{3+} ionic radius (75 pm) precludes favourable substitution for Al and Fe. Its crustal abundance is 22 ppm (Taylor, 1964) and it has a dispersed lithophile behaviour, rarely forming minerals in which it is a major constituent. Most of the scandium in the lithosphere is held by ferromagnesian minerals, especially Fe-rich pyroxenes in which Sc^{3+} substitutes for Fe^{3+}. In contrast, scandium levels are low in olivine as Sc^{3+} cannot substitute for Fe^{2+}. Some substitution of Sc^{3+} for Sn in cassiterite [SnO_2] has been noted, charge balance being maintained by a coupled substitution with $(Nb,Ta)^{5+}$.

Excluding olivine-rich rocks, such as dunites and peridotites, scandium levels in igneous rocks are usually inversely proportional to the SiO_2 content. Thus scandium levels in gabbros and basalts levels are 30–40 ppm, andesites and dacites 10–30 ppm and granites usually less than 10 ppm. However, granite pegmatites often contain minerals enriched in scandium, such as beryl, Y minerals such as xenotime, and garnets. Rare scandium minerals such as thortveite [$Sc_2Si_2O_7$] and bazzite [$Be_3(Sc,Fe)_2Al_2O_6$] (a beryl–like mineral), and Nb–Ta–Sc minerals also occur in such pegmatites.

In metamorphic rocks, scandium appears to be immobile in pyroxenes, amphiboles and spinels, but garnets developed from prograde metamorphism of clay minerals and chlorites are often a major host mineral for scandium. The scandium content of garnets may fall with increasing metamorphism to migmatite facies, in which anatexis may release scandium into pegmatitic fluids (Engel & Engel; *in* Wedepohl, 1978).

Scandium is rare in hydrothermal sulphide mineralisation suites, typically only being present at the 1–2 ppm level. Levels are higher in high-temperature hydrothermal oxide mineralisation, with elevated levels in such minerals as cassiterite and wolframite, which may contain up to 0.2 % and 0.4 % Sc_2O_3 respectively.

Scandium contents of sedimentary rocks are generally low in pure sandstones and limestones (often <2 ppm) but much higher in argillaceous rocks (typically 10–30 ppm Sc). Sedimentary ironstones and phosphatic shales tend to be enriched in scandium, probably because of the low solubility of $ScPO_4$ (like $FePO_4$, $AlPO_4$ etc.) and its capacity to co-precipitate with Fe hydroxides, and may have up to a few hundred ppm Sc. Mielke (1979) cites levels of scandium in shales, sandstones and carbonates as 13, 1 and 1 ppm respectively. Residual deposits such as impure bauxites and, especially, laterites and placer sands, may also be enriched in scandium with contents well above normal crustal levels. Laterites are particularly important in some humid tropical environments and often contain up to 100 ppm Sc.

Surface environment geochemistry

Brookins (1988) shows an Eh–pH diagram having some similarities with those of Al and Fe. However, unlike Fe, scandium possesses only the single 3^+ oxidation state, and does not form a stable sulphide under normal conditions. Below pH 4, Sc^{3+}(aq) is nominally stable in pure solutions, with hydrolysis to $ScOH^{2+}$ between pH 4 and 7 and an insoluble $Sc(OH)_3$ field between pH 7 and 11. Above pH 11 (very rare in natural waters) the amphoteric character of $Sc(OH)_3$ is revealed and the scandate anion forms. However, in real systems, sorption by clay minerals and organic residues are the controlling influence on scandium solubility and reported concentrations of scandium in natural waters are very low (probably <0.00001 ppm). Scandium is not known to be an essential element to either plants or animals and is not believed to have a high toxicity.

Detailed description

In the western New Territories, small scandium anomalies are present immediately to the north of Tuen Mun and at Ha Tsuen. Both areas are underlain by andesitic rocks of the Tuen Mun Formation. Typical scandium values in the vicinity of Tuen Mun range from 16–28 ppm and are accompanied by moderate to high contents of V (86–154 ppm), Cd (1.2–5 ppm), Hg (1.4–2.8 ppm) and Fe_2O_3 (8–13 %). Similar values are present in samples from Ha Tsuen. A scandium anomaly at Tin Shui Wai (19 ppm) is accompanied by high V (77 ppm), Cr (70 ppm), Ni (22 ppm), Pb (120 ppm) and Zn (114 ppm). The sample also contains moderate Cu (60 ppm) and Sn (20 ppm) values suggesting that it is partly contaminated.

Elevated values of scandium are present in several parts of the northern New Territories, with local anomalies at Ngau Tam Mei and Lin Tong Mei. The high scandium values at Ngau Tam Mei (19 ppm) are coincident with high V (70 ppm), Cr (92 ppm), Hg (2 ppm), Pb (133 ppm) and Zn (185 ppm). Similar values of these associated metals are present at Lin Tong Mei, although Cr is slightly lower (27 ppm) and Hg is slightly higher (3.2 ppm).

At Lai Che Wo in the northeastern New Territories, the high scandium values overlying coarse ash crystal tuff and interbedded tuffaceous mudstone (Tsuen Wan Volcanic Group) are accompanied by high V (59–101 ppm), Cr (44–220 ppm), Hg (2.4–3.6 ppm), Pb (93–179 ppm) and Zn (67–197 ppm). Cu and Sn values are rather low suggesting that these metal concentrations are reflecting the natural background values.

In the central New Territories, scandium anomalies are most pronounced along a line from Tin Fai Tong, through Kap Lung, to Tai Po and Shuen Wan. At Tin Fai Tong, the high scandium values (21 ppm) are accompanied by very high V (153 ppm), Cr (184 ppm), Hg (3.1 ppm) and Sn (86 ppm), and moderate to high Pb (94 ppm) and Zn (123 ppm) suggesting possible contamination. At Kap Lung and Tai Mo Shan, the concentrations of these metals are similar, except for Hg (0.58–1.46 ppm) and Sn (10–54 ppm) which are distinctly lower. A scandium anomaly at Shuen Wan east of Tai Po (23 ppm) is associated with high V (113 ppm) and Zn (145 ppm) but relatively low values of Cr (33 ppm), Cd (0.2 ppm), Hg (0.85 ppm), Cu (6.6 ppm), Pb (52 ppm) and Sn (10 ppm).

South of Tai Mo Shan, scandium anomalies are present at Tsuen Wan (17 ppm), Shing Mun (26 ppm), Needle Hill (19 ppm), and the Chinese University (21 ppm). These anomalies coincide with a NE-trending contact zone between granodiorite and volcanic rocks. At Tsuen Wan, the high scandium values coincide with high concentrations of V (83 ppm), Pb (177 ppm), Zn (240 ppm) and Sn (172 ppm). At Shing Mun, the values for V (91–103 ppm) and Sn (38–195 ppm) are similar although those for Pb (44–96 ppm) and Zn (80–135 ppm) are lower. Similar concentrations of these metals are present at Needle Hill and the Chinese University.

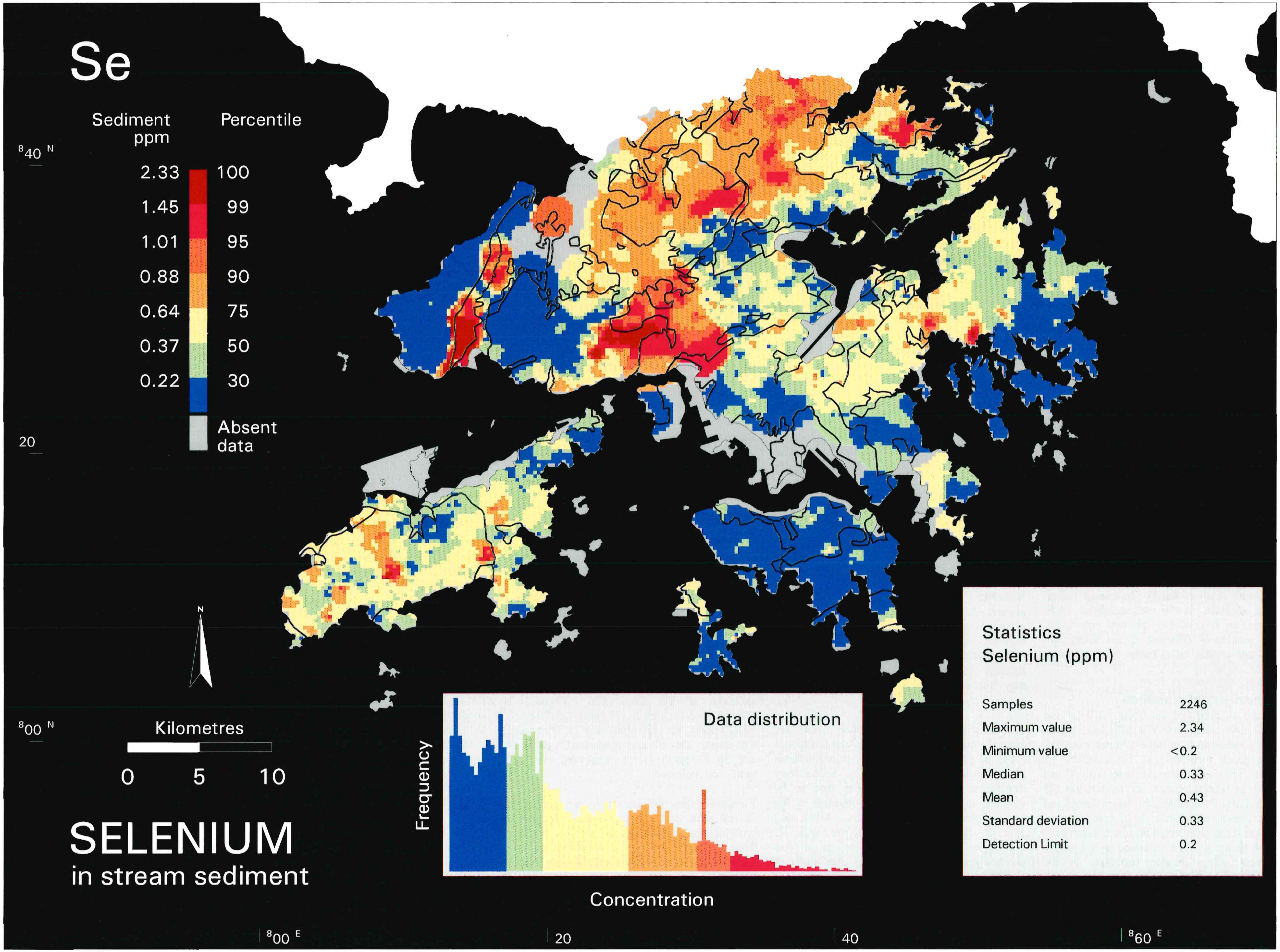
At Tai Lam Chung, a small scandium anomaly (18 ppm) coincides with moderate V (63 ppm) and Zn (120 ppm), and high Cd (2.6 ppm) and Hg (2.6 ppm). This area is underlain principally by medium-grained granite (Lamma Suite) although there are nearby outcrops of granodiorite surrounded by the granite.

In the eastern New Territories, scandium anomalies mostly coincide with outcrops of quartz monzonite (Lion Rock Suite). Less commonly, anomalies are found in association with coarse ash crystal tuff (Repulse Bay Volcanic Group), and tuffaceous sandstone and mudstone (Kau Sai Chau Volcanic Group). The strongest anomaly (20 ppm) occurs in the vicinity of Pyramid Hill and is associated with high Cd (3.1 ppm), Hg (3.3 ppm), Zn (160 ppm), and MnO (0.37 %) values. Small scandium anomalies are present over outcrops of quartz monzonite from Three Fathoms Cove to Chek Keng, and in the vicinity of Kau Sai Chau.

Elevated scandium values are present in the west of Hong Kong Island, with minor anomalies coincident with outcrops of fine-grained granite and quartz monzonite. The highest values are present in association with outcrops of granodiorite (Lamma Suite) and quartz monzonite (Lion Rock Suite) in the vicinity of D'Aguilar Peak.

On Lamma Island, relatively high scandium values are present over outcrops of quartz monzonite (Lion Rock Suite) and coarse-grained granite (Lamma Suite) in the Sok Kwu Wan area in the east of the island. Granodiorite (Lamma Suite) is also known to outcrop at Ha Mei Wan on the west of the island. The high scandium values (16–26 ppm) are associated with moderate to high V (30–59 ppm), Cr (29–44 ppm), Ni (15–27 ppm), Pb (94–149 ppm) and Zn (67–153 ppm).

Background levels of scandium are low to moderate (<9.1 ppm) over most of Lantau Island. Slightly elevated values mainly correspond to outcrops of coarse ash crystal tuff of the Tsuen Wan Volcanic Group in the northeast and southwest of the island. In the south and east of the island, moderate levels of scandium mostly coincide with outcrops of quartz monzonite.



SELENIUM
in stream sediment

Statistics
Selenium (ppm)

Samples	2246
Maximum value	2.34
Minimum value	<0.2
Median	0.33
Mean	0.43
Standard deviation	0.33
Detection Limit	0.2

Selenium

Se

Synopsis

Background levels of selenium in Hong Kong are generally well above the average crustal abundance (see Appendix 2), with a mean value of 0.43 ppm. This high average value may be partly influenced by the burning of fossil fuels (e.g. coal–burning power stations). In general, the lowest selenium values (<0.22 ppm) are found in areas underlain by high-Si granites and vitric tuffs, whereas the highest values (>1.01 ppm) are found mostly in areas underlain by granodiorite and coarse ash crystal tuff.

In the western New Territories, high selenium levels (>1.45 ppm) are associated with andesite outcrops of the Tuen Mun Formation, in marked contrast to low levels above granite in the surrounding area.

Elevated selenium levels (>0.64 ppm) are present over much of the western central and northern New Territories. The highest values are associated with contact zones between granodiorite (Lamma Suite) and volcanic rocks (Tsuen Wan Volcanic Group) to the west of Tai Mo Shan, and they coincide with areas of Pb–Zn–Cu mineralisation. Over the northern and northeastern New Territories, the elevated values are associated mainly with outcrops of coarse ash crystal tuff (Tsuen Wan Volcanic Group). In low-lying agricultural areas, some elevated values may be associated with the use of phosphate fertilizer.

Selenium values are moderate (0.22–0.64 ppm) over much of the central and eastern New Territories, mostly in areas underlain by coarse ash crystal tuff (Tsuen Wan and Repulse Bay volcanic groups), quartz monzonite (Lion Rock Suite) and coarse-grained granite (Kwai Chung Suite). Isolated anomalies coincide with areas of Fe mineralisation .

Low values of selenium (<0.22 ppm) are present in Kowloon, Hong Kong Island, Lamma Island and eastern New Territories south of Long Harbour. These areas are underlain mostly by fine ash vitric tuffs (Repulse Bay Volcanic Group) and medium- to fine-grained granite (Lion Rock Suite). Slightly elevated values are present over areas of trachydacite (Kau Sai Chau Volcanic Group) and quartz monzonite (Lion Rock Suite).

Low to moderate values of selenium (<0.64 ppm) are present over much of central and southern Lantau Island with the lowest values (<0.22 ppm) found mainly in the north. Isolated anomalies coincide with areas of coarse ash crystal tuff (Tsuen Wan Volcanic Group) and quartz monzonite (Cheung Chau Suite).

Geochemistry of selenium

Selenium belongs to Group VIA of the periodic table, with S, Te and Po, and much of its geochemical behaviour can be attributed to similarities between anions of Se and S.

During volcanic activity, selenium escapes with high-temperature volcanic gases and so selenium concentrations in volcanic rocks are generally low. The average crustal abundance of selenium is 0.05–0.09 ppm and average concentrations in magmatic rocks rarely exceed these values. Kabata–Pendias & Pendias (1984) cite a value for granite of 0.01–0.05 ppm. Because of similarities in the chemistry of selenium and S, selenium is a chalcophile element and is concentrated in sulphide ore deposits, in uranium deposits in sandstones, and in the diagenetic pyrite of fine-grained sediments (Howard, 1977).

Ebens & Shacklette (1982) report levels of selenium in sedimentary rocks as: limestones (0.08 ppm), shales (0.06 ppm) and sandstones (<0.05 ppm). Organic-rich sediments are enriched in selenium (e.g. black shales up to 675 ppm (Adriano, 1986)) and phosphate rocks are reported to contain 1–300 ppm (NAS–NRC, 1976).

Surface environment geochemistry

Selenium is an essential element in human health and nutrition and because of this the behaviour of selenium in the surface environment, particularly in soils, has been well documented (e.g. Jacobs, 1989). It is also a toxic element and the range between beneficial and harmful levels is not as large as for some of the essential heavy metals. Elemental selenium or metal selenides will form in low pH and Eh conditions. In soils of moderate redox in humid environments selenite (SeO_3^{2-}) is the predominant species in soils, whereas in more arid regions, in conditions of high pH and high Eh, the more mobile (more soluble) selenate (SeO_4^{2-}) species predominates (Elrashidi *et al.*, 1989). Mobile selenate entering the drainage system is reduced to selenite if the Eh drops, and at lower pH, selenites are likely to be strongly adsorbed by hydrated surfaces of ferric oxides (Howard, 1977). The presence of organic matter and clays in drainage sediments is also likely to lead to elevated levels of selenium. Hamdy & Gissel–Nielsen (1977) demonstrated that clays and ferric oxide have the capacity to remove Se^{4+} from solution.

In industrial areas the burning of fossil fuels (e.g. combustion of coal in electricity generation) leads to an increase of selenium in the environment from atmospheric deposition (Nriagu & Pacyna, 1988).

Detailed description

In the western New Territories, high selenium values are present over andesite outcrops of the Tuen Mun Formation and these contrast markedly with the low values over adjacent granite areas. In the Tuen Mun area, selenium contents in stream sediments range from 1.1 to 2.3 ppm and coincide with high levels of V, Cd, Hg, MnO and Co. Farther north at Ha Tsuen, typical samples contain the following element concentrations: Se 1.2 ppm, V 84 ppm, Cd 1.7 ppm, Hg 0.8 ppm, MnO 0.23 % and Co 14 ppm.

A broad area of elevated selenium values over much of the northern New Territories coincides with outcrops of coarse ash crystal tuff (Tsuen Wan Volcanic Group). Local anomalies occur southeast of Lin Tong Mei, at Wong Hop Shek, and in several areas extending from Tung Shan Ha to Ta Kwu Ling. At Wo Hop Shek, the high Se values (1.3 ppm) coincide with high V (90 ppm), MnO (0.4 %), Co (23 ppm), Pb (340 ppm) and Zn (234 ppm) values. Similar relationships are found in samples farther north toward Lin Ma Hang and suggest that the high selenium values may be associated with areas of Pb–Zn–Cu mineralisation. The elevated concentrations of selenium in the northern New Territories also correspond to areas of intensive agriculture. Relatively high concentrations (up to 300 ppm) of selenium have been reported in phosphate rocks (Mayland *et al.*, 1989). Therefore, the elevated selenium values in low-land areas such as Pat Heung and Ma Tso Lung may be partly related to the application of phosphate fertilizers.

A strong anomaly is present in the Lai Chi Wo area of the northeastern New Territories, which is underlain mostly by coarse ash crystal tuff and interbedded tuffaceous siltstone of the Tai Mo Shan Formation. The high selenium levels (1.1–1.3 ppm) are coincident with high levels of V (84–101 ppm), Hg (2.4–3.6 ppm), MnO (0.08–0.22 %), Co 7–11 ppm), Pb (93–179 ppm) and Zn (67–197 ppm) and low to moderate Cu (9–16 ppm) and Sn (12–42 ppm). These concentrations may be related to local zones of Pb–Zn–Cu mineralisation although none has been reported from this district.

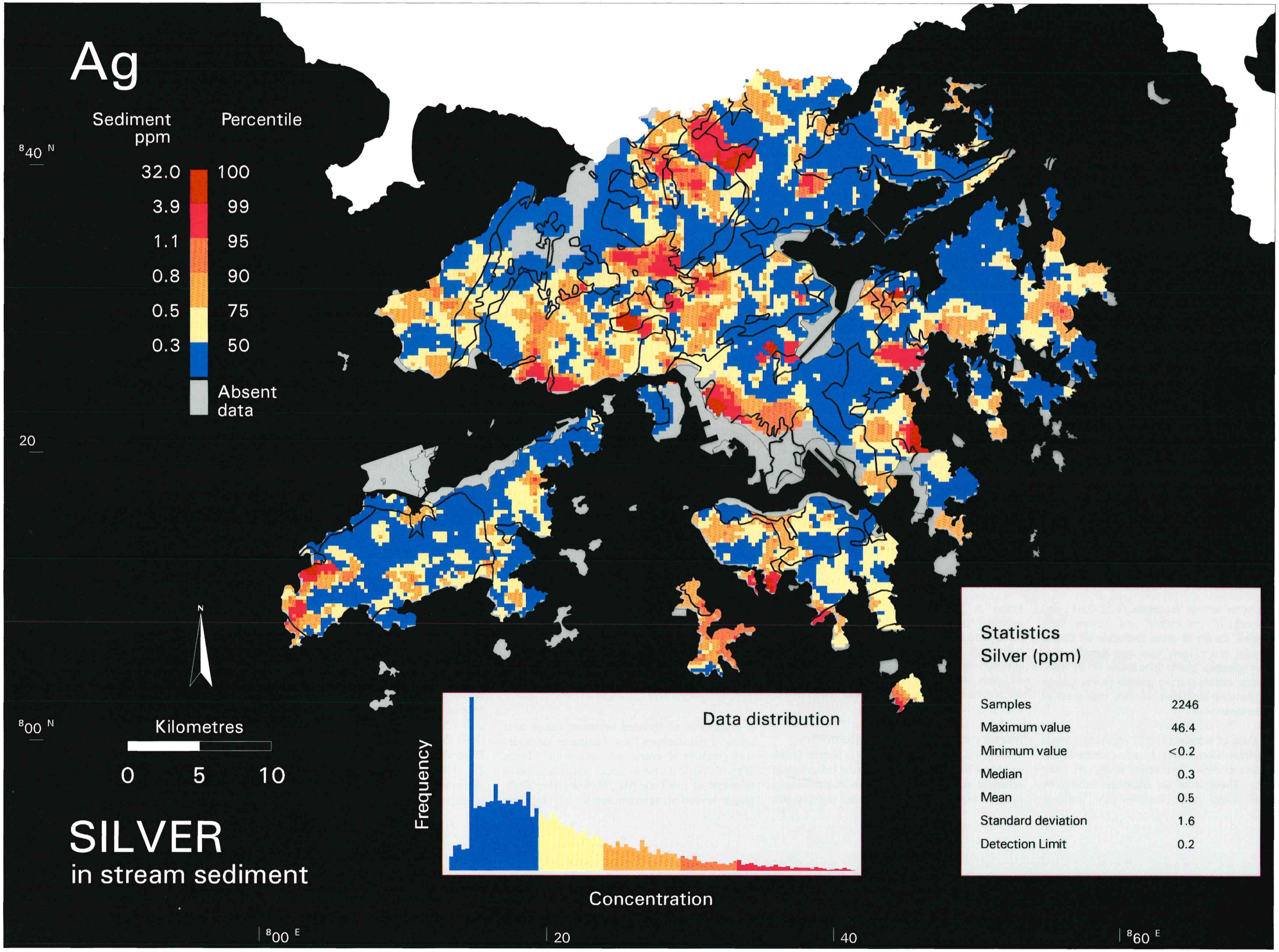
The highest levels of selenium are found in the central New Territories, mostly to the south and west of Tai Mo Shan. The anomalies coincide with areas of known Pb–Zn–Cu and Sn–W mineralisation and are associated with contact zones between granodiorite (Lamma Suite) and coarse ash crystal tuff (Tsuen Wan Volcanic Group). At Tsing Fai Tong and Sheung Tong west of Tai Mo Shan, the high selenium values (1.7–2.3 ppm) coincide with high levels of V (92–115 ppm), Hg (0.2–3.2 ppm), Co (14–19 ppm), Fe_2O_3 (8–11 %), Pb (60–187 ppm) and Zn (108–399 ppm). Similar values for these elements are found in association with the selenium anomaly to the south of Tai Mo Shan.

Moderate levels of selenium are present over much of the central and eastern New Territories, mostly in areas underlain by coarse-grained granite (Kwai Chung Suite), quartz monzonite (Lion Rock Suite) and coarse ash crystal tuff (Repulse Bay Volcanic Group). However, Se values only exceed 1 ppm in two isolated localities: Tai Mong Tsai and Shan Liu. Slightly elevated values for selenium are found to the southwest of Ma On Shan. In most cases, the selenium anomalies are associated with high V, Cd, Co, Pb and Zn values, and moderate to high Fe_2O_3 contents.

Selenium levels are low (<0.22 ppm) over most of Kowloon and Hong Kong Island, and in the eastern New Territories south of Chek Keng. Most of these areas are underlain by medium- to fine-grained granite and fine ash vitric tuff. However, slightly elevated selenium values are present over outcrops of trachydacite and quartz monzonite. On Lamma Island, moderate selenium values in the north and east coincide with outcrops of quartz monzonite and coarse-grained granite.

Background levels of selenium are rather variable over much of Lantau Island. However, moderate to high values are found associated with outcrops of quartz monzonite (Cheung Chau Suite) and coarse ash crystal tuff (Tsuen Wan Volcanic Group), particularly around Mui Wo, Yi O and Tai O. North of Mui Wo, a small selenium anomaly coincides with an area of Pb–Zn–Cu mineralisation within host rocks of coarse-grained granite (Lamma Suite) and rhyolite dykes (Kwai Chung Suite). Between Mui Wo and Pui Wo, slightly elevated values of selenium are present over outcrops of quartz monzonite. A small anomalous area around Shek Pik Reservoir, and extending towards Sai Tso Wan, is associated with high lead values, but low Cd, V, Hg, Co, and Zn values suggesting that it is probably related to anthropogenic contamination.

SILVER
in stream sediment



Statistics
Silver (ppm)

Samples	2246
Maximum value	46.4
Minimum value	<0.2
Median	0.3
Mean	0.5
Standard deviation	1.6
Detection Limit	0.2

Silver

Ag

Synopsis

Background levels of silver (<0.3 ppm Ag) make up approximately 50 % of the data and are largely confined to the mountainous regions in the central, northern, and eastern New Territories, Hong Kong Island, and Lantau Island. Moderate to high (>0.5 ppm) levels of silver characterise much of the western New Territories, and areas of urban development in the northern New Territories, Kowloon and Hong Kong Island.

In the northern New Territories, moderate to high silver values (0.5–3.9 ppm) occur in scattered areas underlain by coarse ash crystal tuff (Tsuen Wan Volcanic Group), with the highest values in the Sheung Shui and Cloudy Hill areas. Slightly elevated values are present in the vicinity of the Lin Ma Hang mine where silver mineralisation (argentiferous galena) has been reported (see earlier).

In the western New Territories, moderate to high silver values (>0.3 ppm) occur in areas underlain by the Tsing Shan and Tai Lam granites (Lamma Suite), and the Tsuen Wan Volcanic Group, particularly near sites of known Pb–Zn–Cu mineralisation. Silver values are also high overlying areas of superficial deposits in the vicinity of Pat Heung.

In the central and eastern New Territories, moderate to high silver values (>0.3 ppm) generally coincide with outcrops of coarse ash crystal tuff (Repulse Bay Volcanic Group), fine ash tuff (Kau Sai Chau Volcanic Group) and fine-grained granite (Lion Rock Suite). Strong silver anomalies (>3.9 ppm) also occur at Ma On Shan, Needle Hill, Kwai Chung and Silverstrand.

On Hong Kong Island, Lamma Island, and Po Toi Island, moderate to high silver values (>0.3 ppm) are found over outcrops of fine ash tuff (Repulse Bay Volcanic Group) and fine-grained granite (Cheung Chau and Lion Rock suites). Anomalies on Ap Lei Chau and at Chung Hom Kok may be related to anthropogenic contamination.

On Lantau Island, slightly elevated silver values (0.3–0.5 ppm) occur in the vicinity of Silver Mine Bay where argentiferous galena has been reported. Silver concentrations are also moderate in eastern and southern parts of the island over outcrops of coarse ash crystal tuff belonging to Tsuen Wan Volcanic Group.

Many of the anomalous values close to urban areas can be directly attributed to anthropogenic contamination, whereas in the more remote areas, they are considered to indicate areas of mineralisation and past mining activity.

Geochemistry of Silver

Silver, the most reactive of the precious metals (Ag, Au and Pt), belongs to the Group IB elements of the periodic table (Cu, Ag and Au) and is also a transition element.

Silver is found at levels of <0.1 ppm in igneous rocks. It shows no consistent preference for silicic or basic magmas though Boyle (1968) reports that substitution of Na$^+$ by Ag$^+$ can lead to enrichment in alkaline rocks. Mielke (1979) cites abundances in igneous rocks as: ultrabasic, 0.06 ppm; basaltic, 0.11 ppm; granitic 0.04–0.05 ppm; and an average crustal abundance of 0.08 ppm. The strongly chalcophile nature of silver means that it is common in sulphide ores, often associated with other chalcophile elements such as Pb, Co, Ni, Sb and As (Ure & Berrow, 1982), and silver is found up to levels of several per cent in galena. Silver occurs as native silver, and alloys of silver and gold are widely documented (e.g. Boyle, 1968; Leake *et al.*, 1993).

In sediments, silver concentrations are typically in the range 0.05–0.12 ppm (Boyle, 1968), levels of enrichment during deposition generally being controlled by pH and the presence of organic matter, as well as the source material. Under conditions of low acidity, Ag$^+$ may substitute for K$^+$ in clay minerals (Ure & Berrow, 1982) and this, coupled with preferential sorption, leads to silver being more concentrated in clays than in silts or sands (Chao & Anderson, 1974).

Surface environment geochemistry

The surface environment geochemistry of silver is largely controlled by pH and Eh conditions and the concentration of halide ions, the latter being locally important in coastal areas. In most soils and stream sediments, silver salts are immobile at pH values greater than 4.0, while the retention of silver in solution also requires a high redox potential, as the accumulation of Fe^{2+} relative to Fe^{3+} tends to induce precipitation.

Silver can exist as a native metal or a cation, and in the latter state it is more mobile in highly oxidising environments associated with solutions of high ionic strength in which soluble complexes with anions can form (Thornber, 1992). However, when present with sulphides, a lower oxidation potential also helps mobility by incomplete oxidation of the sulphide, allowing thiosulphate ($S_2O_3^{2-}$) anions to form soluble complexes (Webster & Mann, 1984). The formation of a soluble complex with the thiosulphate ion is an important factor in the weathering of native silver when associated with gold and sulphides, and the silver will remain mobile until entering more oxidising conditions such as near the water table (Mann, 1984). In seasonally humid tropical climates, where the water table significantly varies, mobilisation and precipitation of silver could be affected by seasonal variations.

Secondary concentrations of silver, resulting from metal–organic complexation and adsorption processes, occur under a range of conditions. Boyle (1968) has noted that basic Fe sulphates can scavenge silver in topsoils, and hydrous Mn oxides have the potential to accumulate silver in streams (Chao & Anderson, 1974).

Cooper & Thornton (1994) list some of the most likely anthropogenic contributions to elevated silver levels in stream sediments from urban areas, including photographic products and sewage. Silver has great potency as a microbial poison but it is relatively harmless to higher life forms (Edwards *et al.*, 1995).

Detailed Description

Silver is commonly associated with the ores of Pb, Zn, and Cu, and also occurs as an arsenide, antimonide and chloride. Therefore, in areas of Pb, Zn and Cu mineralisation, silver levels are likely to be higher than natural background. On the other hand, anomalous concentrations of silver related to anthropogenic activities will be associated with industrial materials known to contain silver. These include electronic components, electrical machinery, mirrors, batteries, medical products, photographic products and industrial glass.

In the western New Territories, elevated levels of silver are present over the Tsing Shan and Tai Lam granites (Lamma Suite). The strongest anomalies occur over the Tai Lam Granite at Tai Lam Chung (1.3–1.9 ppm) and Ho Pui Reservoir (1.1–20.6 ppm). At Ho Pui, the high silver values are accompanied by moderate to high levels of As (12–36 ppm), Bi (18–52 ppm), Sn (45–88 ppm), W (3–80 ppm), Pb (94–259 ppm) and Zn (123–441 ppm). Similar levels of these metals are associated with the silver anomaly at Tai Lam Chung (e.g. As 11–23 ppm, Sn 3–86 ppm, W 9–22 ppm, Pb 35–169 ppm, and Zn 70–160 ppm).

In the northern New Territories, the highest concentrations of silver coincide with areas of known anthropogenic contamination. These include areas surrounding Pat Heung (1.1–1.2 ppm), Ngau Tam Mei (1.3–1.7 ppm) and Sheung Shui (1.2–13.5 ppm). The silver anomalies are typically accompanied by very high levels of industrial metals including As (29–1145 ppm), Sn (2–78 ppm), Cu (15–529 ppm), Pb (21–587 ppm), and Zn (31–1235 ppm). Silver levels are low to moderate (0.3–1.1 ppm) in the Lin Ma Hang area where argentiferous galena has been proven (Davis, 1952). An isolated anomaly at Cloudy Hill (1.1–1.3 ppm) is accompanied by moderate levels of As (46–67 ppm), Pb (55–114 ppm), Zn (94–102 ppm) and Hg (0.2–2.2 ppm) and may represent an area of natural mineralisation.

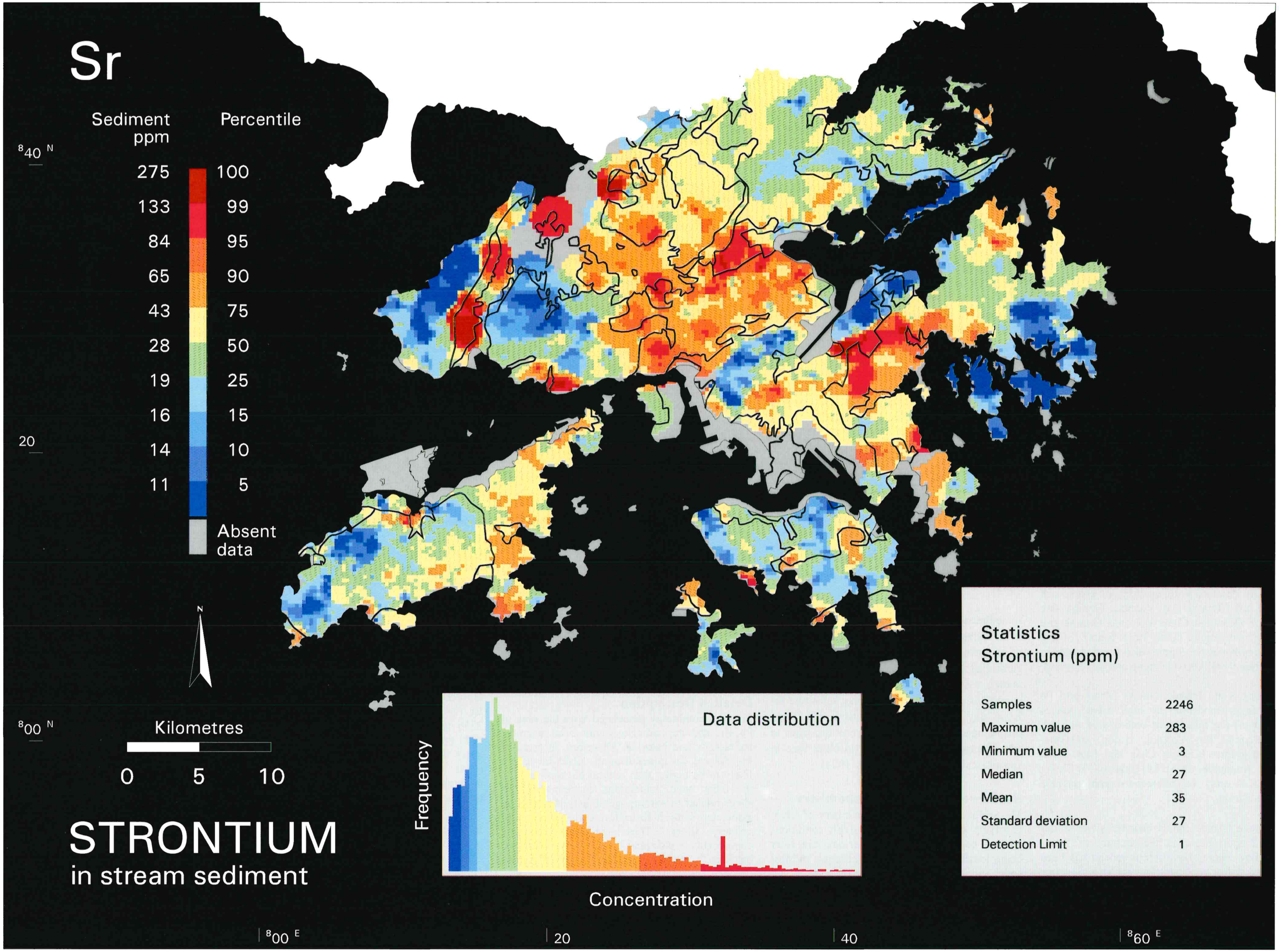
In the central New Territories, strong silver anomalies are present in the Shing Mun Valley (1.3–46.4 ppm), at Kwai Chung (2.4–7.7 ppm), and at Ma On Shan (1.3–12.8 ppm). Most of these anomalies occur over outcrops of medium- to fine-grained granite (Kwai Chung Suite) and are accompanied by moderate to high levels of Bi (2–361 ppm), Cu (12–303 ppm), Pb (73–2256 ppm), Zn (132–485 ppm), and Sn (16–8881 ppm), indicating a strong anthropogenic overprint. At Ma On Shan, some of the high silver contents may be related to natural mineralisation associated with the magnetite-bearing skarn deposit.

In the eastern New Territories, moderate to high levels of silver are present in areas underlain by coarse ash crystal tuff (Repulse Bay Volcanic Group). At Sai Kung, the anomalous silver values (1.1–3.2 ppm) are accompanied by moderate to high As (9–43 ppm) and Zn (48–448 ppm), suggesting the involvement of anthropogenic contamination. At Tai Mong Tsai, moderate to high silver values (0.5–1.1 ppm) are associated with weak Fe mineralisation, whereas over the Tai Long area in eastern Sai Kung, elevated silver values (0.3–1.1 ppm) mainly occur in natural terrain. A strong silver anomaly at Silverstrand (8.9 ppm) is accompanied by moderate to high Pb (190 ppm), Zn (272 ppm), Cu (69 ppm) and As (34 ppm), and is likely to be related to local contamination.

On Hong Kong Island, silver anomalies are present near Wong Chuk Hang (2.9–6.8 ppm) and at Chung Hom Wan (1.8 ppm). At Wong Chuk Hang, the high silver values are accompanied by moderate Pb (81–100 ppm), Zn (129–200 ppm), and Hg (1.1–1.7 ppm), suggesting the influence of anthropogenic contamination. Similar moderate to high values of these elements (Pb 177 ppm, Zn 462 ppm, Hg 2 ppm) accompany the silver anomaly at Chung Hom Wan.

Moderate to high levels of silver (1.1–1.3 ppm) are present over most of Lamma Island and the western part of Po Toi Island (1.1 ppm). The elevated silver values mostly occur over natural terrain and are accompanied by moderate to high levels of Nb (34–129 ppm), Y (55–179 ppm), Sn (12–144 ppm) and Mo (2.2–5.8 ppm).

On Lantau Island, strong silver anomalies are present over outcrops of coarse ash crystal tuff (Tsuen Wan Volcanic Group) at Tai O (1.5–5.3 ppm) and Yi O (1.2–3.5 ppm). At Tai O, the high silver levels are accompanied by moderate to high As (159–191 ppm), Pb (59–84 ppm), Zn (50–123 ppm) and Sn (11–747 ppm), suggesting the influence of anthropogenic contamination. At Yi O, the Pb (49–77 ppm), Zn (42–54 ppm) and Sn (9–13 ppm) values are slightly lower, whereas As (209–330 ppm) values are slightly higher. The absence of any urban development at Yi O suggests that the silver anomaly probably reflects an area of natural mineralisation (see descriptions for As, Sb and Bi).



STRONTIUM

in stream sediment

Statistics
Strontium (ppm)

Samples	2246
Maximum value	283
Minimum value	3
Median	27
Mean	35
Standard deviation	27
Detection Limit	1

Strontium

Sr

Synopsis

In the western New Territories, strontium values are high (>84 ppm) over andesite outcrops of the Tuen Mun Formation but low in the adjacent granitic areas (Lamma Suite). Some of the anomalously high values may be affected by local contamination.

Background levels of strontium are moderate to high (28–65 ppm) over central and northern New Territories. The highest values (>84 ppm) are concentrated along contact zones between outcrops of granodiorite (Lamma Suite) and volcanic rocks (Tsuen Wan Volcanic Group). Elevated levels of strontium (43–65 ppm) are also found in low lying areas, particularly in the vicinity of Pat Heung, and may be influenced by anthropogenic activity. Low to moderate levels of strontium (<28 ppm) are present over outcrops of Upper Mesozoic sedimentary rocks and low levels (<11 ppm) are found over outcrops of Upper Palaeozoic sedimentary rocks.

Moderate to high levels of strontium (>28 ppm) are present over much of the eastern New Territories and Kowloon, especially in areas underlain by coarse ash crystal tuff (Repulse Bay Volcanic Group) and quartz monzonite (Lion Rock Suite).

Strontium levels are low to moderate (<28 ppm) over most of Hong Kong Island, Lamma Island and Po Toi Island. Isolated anomalies are mainly related to sporadic outcrops of quartz monzonite (Lion Rock Suite) and granodiorite (Lamma Suite).

Low to moderate levels of strontium (<28 ppm) characterise much of southwestern Lantau Island, whereas moderate to high levels of strontium (>28 ppm) characterise the northeastern part. Elevated values in eastern parts of the island mostly coincide with outcrops of quartz monzonite (Lion Rock Suite) and granite (Cheung Chau and Lamma suites).

Geochemistry of strontium

Strontium is a member of the Group IIA elements in the periodic table, with Mg, Ca, Ba and Ra, and always occurs in the 2^+ oxidation state. The size of the Sr^{2+} ion (118 pm) is intermediate between those of Ca^{2+} (100 pm) and K^+ (138 pm), for which it may substitute in plagioclase and K–feldspars. The concentration of strontium in other major rock-forming minerals is considerably lower, most notably in micas which hold the element at concentrations of only a few ppm. During magmatic processes, strontium is partitioned into mid–stage fractionates and thus tends to be enriched in intermediate rocks (*c.* 500 ppm) relative to evolved granites (<300 ppm) or basic igneous rocks (<450 ppm). Particularly high concentrations (*c.* 1000 ppm) have been recorded in anorthosites (Wedepohl, 1978). Mielke (1979) cites levels of strontium in ultrabasic, basaltic and granitic rocks as 1465 and 100–440 ppm respectively, and a crustal average of 384 ppm. Sewell *et al.* (1992) reported values of 7–329 ppm Sr (average 103 ppm) for 18 representative granite samples from Hong Kong. The ratios of Rb/Sr, Sr/Ca and Ba/Sr are widely used to determine petrogenesis, the first two increasing and the last decreasing with magmatic evolution.

Minerals of strontium are rare and are found mainly associated with hydrothermal deposits or pegmatites, important minerals being strontianite [$SrCO_3$] and celestine [$SrSO_4$].

Strontium is relatively immobile at high metamorphic grades, often becoming concentrated in association with Ba and Zr in granulites (Drury, 1973). However, pervasive redistribution may occur during hydrothermal alteration and contact metamorphism (Gale & Roberts, 1974), and high strontium values in granulites have been attributed to the transfer of strontium to the lower crust during mantle degassing (Korringa & Noble, 1971). Anomalous strontium concentrations have been reported in altered veins in granitoids (White, 1966).

In sedimentary rocks, strontium is mainly held in the Ca^{2+} and Ba^{2+} lattice sites of carbonates and sulphates. Enrichment of strontium to concentrations of *c.* 1000 ppm is, therefore, common in limestones and evaporites. Discrete strontium minerals are relatively uncommon, though sulphate and carbonate phases may occur in evaporites and hydrothermal veins (Ure & Berrow, 1982) and high strontium levels can be associated with Ba minerals (baryte, witherite) due to preferential substitution for the larger (135 pm) Ba^{2+} ion. Feldspars are otherwise the principal strontium carriers, and pure quartzites (<40 ppm) and shales (<400 ppm) are generally poor in strontium relative to quartzo–feldspathic rocks (*c.* 600 ppm). Mielke (1979) cites levels of strontium in shales, sandstones and carbonates as 300, 20 and 610 ppm respectively.

Surface environment geochemistry

Most of the strontium in stream sediments is contained in lithic fragments and detrital feldspars, but it may also be present in mineralised areas in such minerals as baryte and witherite. The release of Sr^{2+} from these minerals is relatively slow, but subsequent dispersal can be widespread under pH conditions of below 5.5 (Short, 1961). At higher pH values, or in the presence of high CO_2 concentrations, strontium tends to precipitate as an authigenic carbonate. Limestone is the principal rock type in the global strontium cycle, and some 80% of the strontium in the world's water courses derives from the weathering of carbonates (Ure & Berrow, 1982).

In stream sediments, some differences have been noted between strontium levels in the drainage sediments and soils. In eastern Bolivia, Appleton & Llanos (1985) report higher strontium in the stream sediments than in the soil. Ridgway & Midobatu (1991) suggested that, for drainage sediments from the Solomon Islands, significant depletion in strontium (and Rb) over a period of 15 months was caused by the introduction of landslide material into the drainage system. In environments where landslides are common, such as Hong Kong where 21% of the land area is classified having "general instability" (Styles & Hansen, 1989), dilution by landslip material is an important consideration in explaining element distributions. If strontium is generally lower in the soils of Hong Kong than in the sediments, the element could be used as an indicator of dilution of sediments by landslide material.

Detailed description

Strontium anomalies are pronounced over andesite outcrops of the Tuen Mun Formation immediately to the north of Tuen Mun and at Ha Tsuen in the western New Territories, and these contrast markedly with the relatively low levels of strontium in the adjacent granitic areas. North of Tuen Mun, the high levels (102–283 ppm) are accompanied by moderate to high CaO (4.6–14.8 %), Se (1.7–2.2 ppm), V (86–154 ppm), Cd (1.7–5.0 ppm), Co (15–22 ppm) and Fe_2O_3 (7.2–13.1 %). Similar values for these metals accompany the strontium anomaly (102 ppm) at Ha Tsuen farther north suggesting that they largely reflect the natural background. At Lau Fau Shan immediately to the north of Ha Tsuen, a small strontium anomaly within an outcrop of granitic rock is accompanied by high concentrations of CaO (16 %), Zn (551 ppm) and Cu (174 ppm). This sample is most likely to be affected by local anthropogenic contamination. A similar anomaly (Sr 148 ppm) over granitic rock at Tai Lam Chung is coincident with high levels of Ti (1.04 %), V (63 ppm), Cd (2.6 ppm) and Hg (2.6 ppm), but relatively low levels of Zn (120 ppm) and Cu (11.8 ppm). The anomalous values may be partly related to roof pendants of granodiorite exposed within the granite nearby.

A marked strontium anomaly at Tin Shui Wai (94 ppm) coincides with high values of TiO_2 (1.02 %), V (77 ppm), Co (13 ppm), Pb (120 ppm), Zn (114 ppm) and Cu (60 ppm). These values strongly indicate local contamination of the stream sediment.

Prominent strontium anomalies occur at Mai Po and in the vicinity of Kai Kung Leng. At Mai Po, extreme levels of strontium (267 ppm) are accompanied by very high levels of V (62 ppm), Cd (3.2 ppm), Hg (6.1 ppm), Co (35 ppm), Pb (884 ppm), Zn (17 489 ppm), Cu (2049 ppm) and Sn (151 ppm), indicating strong contamination. Samples from the southeastern slopes of Kai Kung Leng have high strontium values (92–100 ppm) but much lower contents of associated metals. Typical values of these metals are Cd (1.7 ppm), Hg (0.3 ppm), Co (12 ppm), Pb (58 ppm), Zn (96 ppm), Cu (9.5 ppm) and Sn (10 ppm).

In the central New Territories, the highest strontium values (>84 ppm) coincide with contact zones between volcanic rocks (Tsuen Wan Volcanic Group) and granodiorite intrusions (Lamma Suite), which also host Pb–Zn–Cu mineralisation (see descriptions for Pb and Zn). The high strontium values are thought to be partly related to the presence of large blocks of marble within the coarse ash crystal tuff (see description for CaO). In the Lam Tsuen Valley, strontium values typically range from 92–148 ppm and are accompanied by high V (55–89 ppm), Pb (142–647 ppm) and Zn (124–779 ppm). At Kap Lung, the high strontium values (85–148 ppm) are accompanied by high CaO (6.2–9.1 %) and Fe_2O_3 (6.6–10.2 %), in addition to high V (77–92 ppm), Pb (216–300 ppm) and Zn (366–538 ppm). Similar values of CaO (1.3–7.0 %), Fe_2O_3 (4.6–8.0 %), V (70–103 ppm), Pb (35–117 ppm) and Zn (97–204 ppm) are present with high Sr (85–109 ppm) values in the Sheung Fa Shan area.

In the Sai Kung and Tai No areas of the eastern New Territories, typical strontium values range from 103–170 ppm and coincide with moderate V (41–54 ppm), Cd (1.9–3.1 ppm), Hg (1.7–3.3 ppm) and Zn (99–160 ppm). CaO (0.41–0.71 %), Pb (36–79 ppm) and Fe_2O_3 (2.9–7.0 %) values are relatively low. Slightly elevated strontium values (28–65 ppm) are present over the Kowloon area, with small anomalies (65–84 ppm) coincident with outcrops of quartz monzonite. In the Long Harbour area and Silverstrand areas, minor strontium anomalies are associated with local contamination as indicated by anomalously high values for accompanying Pb (45–190 ppm) and Zn (119–272 ppm). A band of elevated strontium values (43–65 ppm) in the Clear Water Bay peninsula coincides with outcrops of trachydacite lava flows.

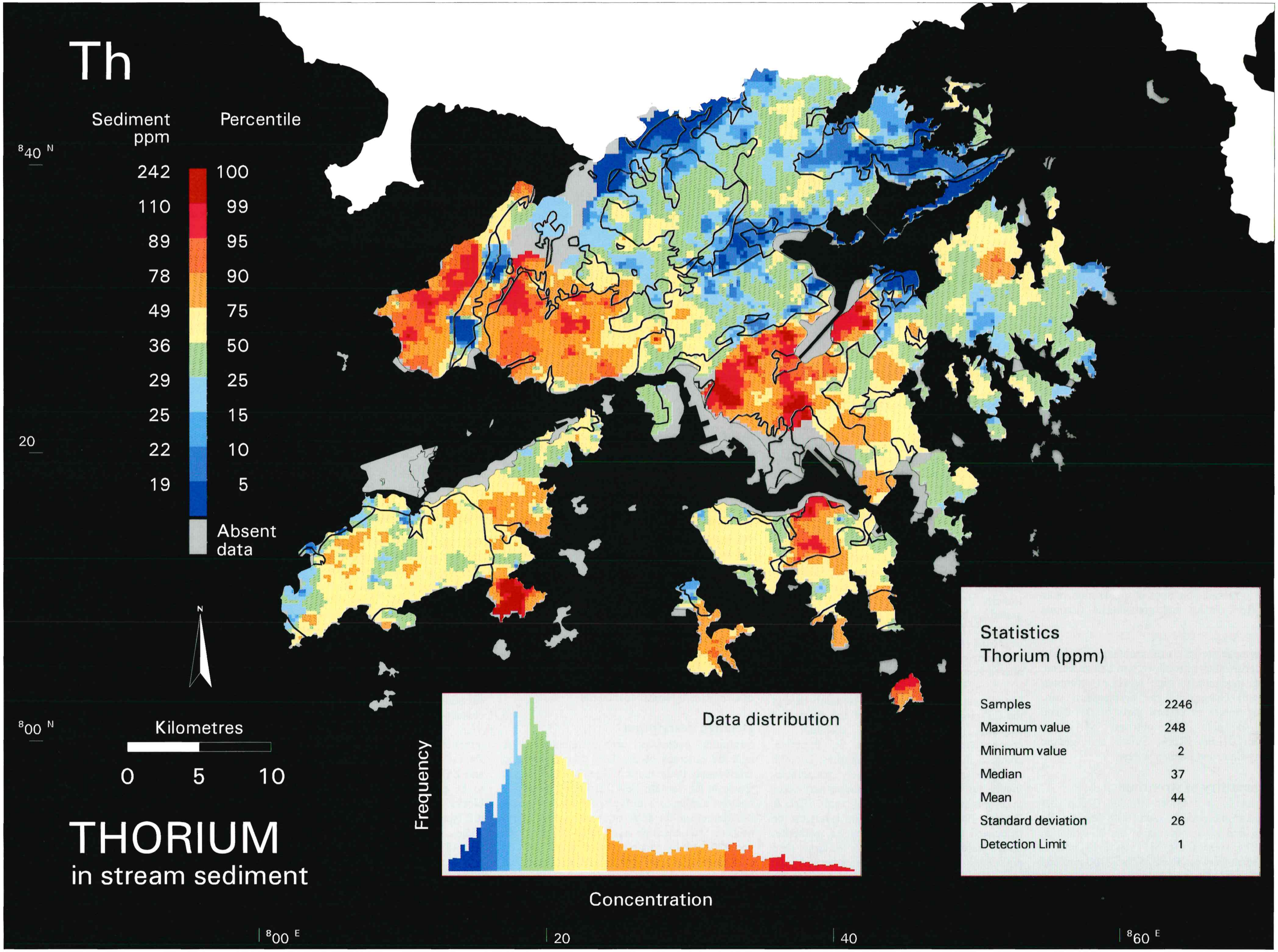
On Hong Kong Island and Lamma Island, small strontium anomalies are present at Mount Nicholson, Ap Lei Chau and Chung Hom Wan, and Yung Shue Wan. These small anomalies (86–106 ppm) are mostly associated with minor outcrops of quartz monzonite (Lion Rock Suite) and Tai Po Granodiorite (Lamma Suite). At Chung Hom Wan, however, the high values of some associated metals (e.g. Hg 2 ppm, Pb 177 ppm and Zn 462 ppm) suggests that stream sediments have been partly contaminated.

On Lantau Island, low to moderate levels of strontium are present over volcanic areas (Lantau and Tsuen Wan volcanic groups) in the south and west, and moderate to high levels over granitic areas (Lamma, Kwai Chung and Cheung Chau suites) in the north and east. On Chi Ma Wan peninsula, strontium values reach 85 ppm, and typical samples contain low to moderate levels of V (17 ppm), Pb (51 ppm), Zn (51 ppm), Cu (9.6 ppm) and Sn (23 ppm).

Th

THORIUM

in stream sediment



Statistics
Thorium (ppm)

Samples	2246
Maximum value	248
Minimum value	2
Median	37
Mean	44
Standard deviation	26
Detection Limit	1

Thorium

Th

Synopsis

In the western New Territories, high thorium values (>49 ppm) coincide with outcrops of the Tsing Shan and Tai Lam granites (Lamma Suite) and the Triassic Deep Bay Granite. Low values (<29 ppm) are present in the intervening areas underlain by Middle Jurassic volcanic rocks (Tuen Mun Formation).

In the northern and northeastern New Territories, thorium values are very low (<19 ppm) over outcrops of Upper Palaeozoic and Upper Mesozoic sedimentary rocks. They are slightly higher (29–36 ppm) over adjacent volcanic areas (Tsuen Wan Volcanic Group), but low (<29 ppm) over outcrops of Tai Po Granodiorite (Lamma Suite) in the vicinity of Tolo Harbour.

High thorium values (>49 ppm) in the central New Territories are closely associated with outcrops of the Sha Tin and Needle Hill granites (Kwai Chung Suite). Fine-grained granite and quartz monzonite dykes (Lion Rock Suite) which intrude the Sha Tin Granite may also contribute to the elevated thorium levels.

On Hong Kong Island, high levels of thorium (>49 ppm) in the vicinity of North Point coincide with outcrops of the Mount Butler Granite (Lion Rock Suite). Moderate thorium levels (29–49 ppm) are found over adjacent volcanic areas (Repulse Bay Volcanic Group). In the southeast of the island, slightly elevated thorium values (49–78 ppm) are present over outcrops of Po Toi Granite (Lion Rock Suite) and D'Aguilar Quartz Monzonite (Lion Rock Suite). High levels of thorium (>89 ppm) on Po Toi Island coincide with outcrops of the fine-grained Po Toi Granite (Lion Rock Suite).

On Lamma Island, elevated thorium values (>49 ppm) are associated with outcrops of South Lamma Granite (Cheung Chau Suite) and D'Aguilar Quartz Monzonite (Lion Rock Suite). Thorium levels are low (<29 ppm) over outcrops of coarse ash crystal tuff (Tsuen Wan Volcanic Group) in the northern part of the island.

The highest thorium values (>110 ppm) on Lantau Island are associated with outcrops of the Chi Ma Wan Granite (Cheung Chau Suite). Moderate thorium values (29–49 ppm) characterise outcrops of the Lantau Volcanic Group in the south of the island, and slightly higher levels (49–78 ppm) are present over granite areas (Lamma and Kwai Chung suites) in the northeast. In general, thorium values are low (<29 ppm) over outcrops of the Tsuen Wan Volcanic Group.

Geochemistry of thorium

Thorium is a member of the actinide series of elements, within row 7 of the periodic table, along with uranium and the man–made elements such as plutonium. Like uranium, it is a radioactive element and its most stable isotope ^{232}Th has a very long half-life (1.4 x 10^{10} years). It is the most abundant of the heavy elements (i.e. elements with atomic number greater than 83 (Bi)), having a crustal abundance of between 9.6 and 12 ppm, making it more abundant than Sn, and only slightly less abundant than Pb. Thorium is a strongly lithophile element, its abundance in crustal rocks being substantially greater than that in meteorites and mantle-type rocks such as dunites.

Although it is a transition element, possessing more than one valency state, its geochemistry is dominated by the Th^{4+} ion, which has an ionic radius of 94 pm, and shows greatest affinity with other M^{4+} elements such as U, Ce and Zr. The minerals of these elements are often isostructural, with replacement and solid–solution gradations between the end–members. Examples are: thorianite [ThO_2], cerianite [CeO_2] and uraninite [UO_2]; thorite [$ThSiO_4$] and zircon [$ZrSiO_4$]; and monazite [$(Ce,La,Th,U)PO_4$]. Thorium may also be present at elevated levels in accessory minerals such as epidote, allanite, sphene and apatite in igneous rocks.

Thorium is generally more abundant in granitic than in basic igneous rocks. Since it can enter some rock-forming minerals such as biotite, it is not as strongly concentrated in the incompatible pegmatite phase as uranium, although some thorium–containing minerals, such as allanite, do occur in pegmatites. Granites typically contain 10–40 ppm Th, though there is much local and provincial variation. Intermediate rocks such as andesites have about 1–4 ppm Th, while gabbros usually have less than 3.5 ppm and basalts less than 1 ppm. In metamorphic rocks, thorium is generally immobile up to the highest grades, but anatexis will result in concentration in the mobile granitic phase.

Thorium in sedimentary rocks is essentially resistate in character, as its major host minerals such as monazite and zircon are highly resistant to both chemical and physical breakdown. Any thorium released by weathering has a transient existence in solution as it is strongly sorbed by clays. Thus sandstones, arkoses and greywackes may have up to 10 ppm, and normal shales and mudstones 10–13 ppm. Mielke (1979) cites levels of thorium in shales, sandstones and carbonates as 12, 1.7 and 1.7 ppm respectively.

Black shales may have higher thorium levels, but never as high as the U content, because of the much stronger affinity of U for organic material and the greater mobility of oxidised UO_2^{2+} in solution. Placer deposits such as monazite sands, however, may be exceptionally rich in thorium and constitute one of the major ores of thorium. Limestones are normally very low in thorium, since Th^{4+} cannot form a stable carbonate (unlike UO_2^{2+}), and similarly thorium is almost completely absent from evaporites.

Surface environment geochemistry

As in sedimentary rocks, the surface environment geochemistry of thorium is essentially resistate in character, as its major host minerals such as monazite and zircon are highly resistant to both chemical and physical breakdown. Unlike U, thorium cannot be oxidised to a stable cation equivalent to the highly mobile uranyl ion UO_2^{2+}, so it is essentially insoluble and immobile in solution. Thorium is therefore a useful pathfinder element in stream sediments for localising uranium deposits associated with magmatic rocks, since almost all the thorium is transported as solid mineral material with minimal loss to solution.

Any thorium released into solution will be rapidly sorbed by clay minerals and hydrolysed to the hydrous oxide $Th(OH)_4$, which will be intimately associated with the clay-mineral fraction. Thus thorium is essentially insoluble in surface and groundwaters, and levels in all waters are extremely low (Langmuir & Herman, 1980). Thorium has no known biological function and is not regarded as particularly toxic, but gaseous daughter isotopes are a potential radioactive hazard, particularly in enclosed areas such as tunnels.

Detailed description

In the western New Territories, prominent anomalies over the Tsing Shan Granite (Lamma Suite) in the vicinity of Ha Pak Nai (89–113 ppm), Nim Wan (92–118 ppm) and Lung Kwu Tan (95–127 ppm), are typically accompanied by moderate to high levels of U (5–21 ppm), Rb (173–493 ppm), Y (29–96 ppm), Nb (44–81 ppm) and Ga (23–50 ppm). Several samples also contain moderate to high concentrations of Pb (40–343 ppm), Cr (18–118 ppm) and Ni (4–25 ppm), but these are thought to be mostly due to anthropogenic contamination (see descriptions for Pb, Cr, and Ni). Moderate to high levels of thorium (>49 ppm) over the Deep Bay Granite at Tsim Bei Tsui are accompanied by moderate to high U (11 ppm), Rb (468 ppm), Y (184 ppm), Nb (96 ppm) and Ga (54 ppm).

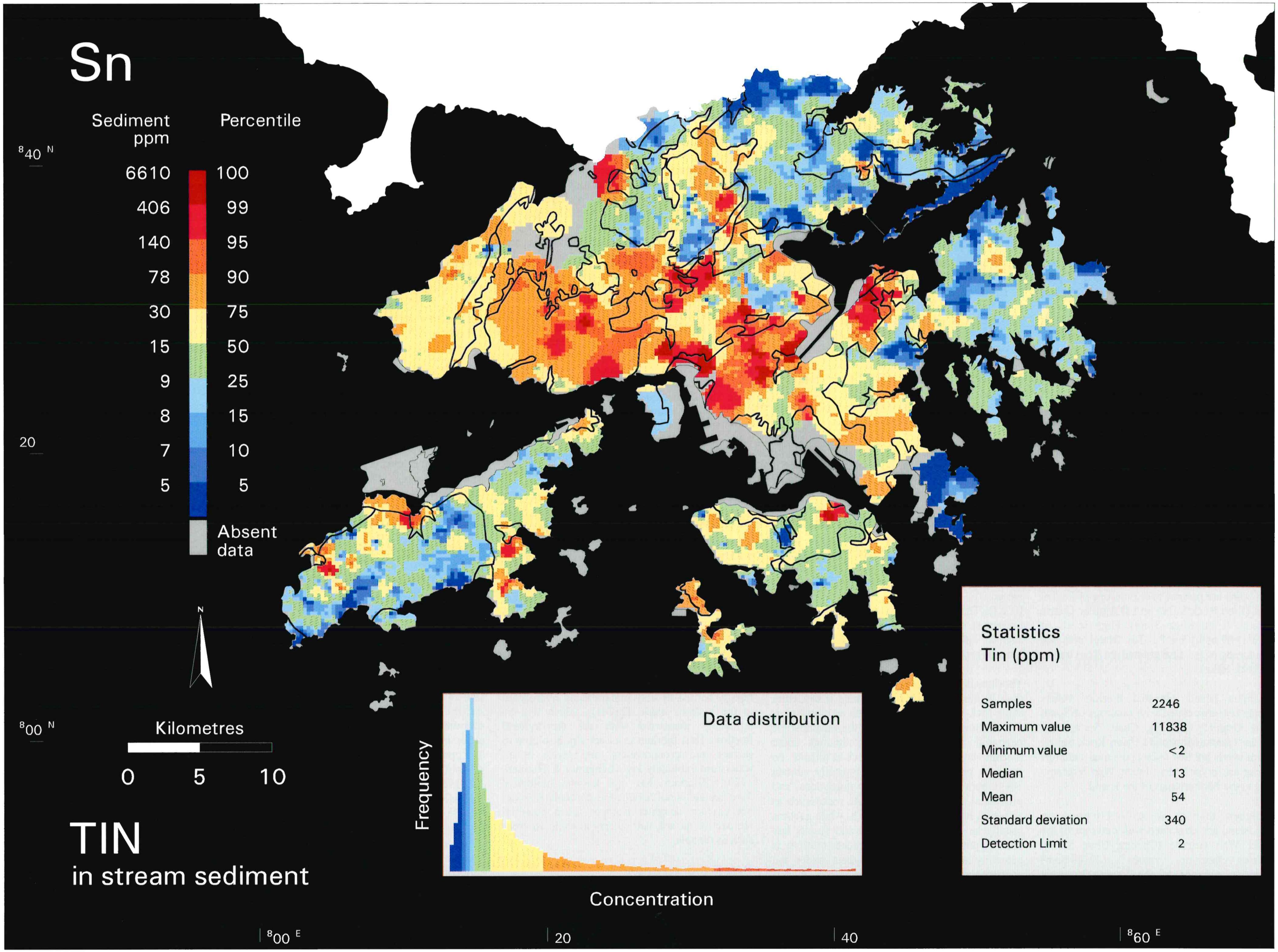
Thorium levels over the Tai Lam Granite lie mostly between 49 and 78 ppm with the highest levels found in the vicinity of Lam Tei (101–109 ppm) and Tai Lam Chung Reservoir (89–127 ppm). These areas are predominantly underlain by fine-grained granite. At Lam Tei, the high thorium values are associated with moderate to high Rb (429–632 ppm), Y (50–152 ppm), Nb (62–83 ppm) and Ga (35–45 ppm). Similar values for these elements (e.g. Rb 273–614 ppm, Y 42–252 ppm, Nb 50–84 ppm, and Ga 27–52) accompany the thorium anomaly at Tai Lam Chung Reservoir. Moderate to high Sn (71–668 ppm) and W (9–23 ppm) values associated with the anomalies reflect local Sn–W mineralisation.

In the central New Territories, strong anomalies (>49 ppm) over the Sha Tin and Needle Hill granites (Kwai Chung Suite) are present in the vicinity of the Kowloon Reservoirs (111–137 ppm), Needle Hill (93–125 ppm), Sha Tin (90–94 ppm) and Tai Shui Hang (95–113 ppm). At the Kowloon Reservoirs the anomalous thorium levels over the Needle Hill Granite are accompanied by high U (13–35 ppm), Y (71–161 ppm), Nb (146–386 ppm), and Ga (35–49 ppm). Moderate to high Pb (67–125 ppm), Zn (78–191 ppm) and Sn (78–341 ppm) reflect local mineralisation within the Needle Hill Granite. At Needle Hill, U (7–21 ppm), Rb (86–442 ppm), Y (59–160 ppm), Nb (49–139 ppm) and Ga (26–37 ppm) are also high and accompanied by high levels of Sn (32–3276 ppm) and W (4–169 ppm), reflecting the known Sn–W mineralisation of the area. Farther north, similar levels of U (12–31 ppm), Rb (86–407 ppm), Y (59–147 ppm), Nb (49–139 ppm) and Ga (26–49 ppm) are associated with the small thorium anomaly near Fo Tan. At Lion Rock, the thorium anomaly coincides with dykes of quartz monzonite and fine-grained granite intruding the Sha Tin Granite. This anomaly is accompanied by moderate to high levels of U (13–16 ppm), Rb (205–642 ppm), Y (59–130 ppm), Nb (70–132 ppm) and Ga (20–30 ppm). Thorium levels in the vicinity of Tai Shui Hang may also be influenced by adjacent quartz monzonite and fine-grained granite intrusions. The anomaly in this area is associated with moderate to high U (10–24 ppm), Rb (282–643 ppm), Y (69–157 ppm), Nb (89–243 ppm), and Ga (28–38 ppm).

On Hong Kong Island, high thorium levels (49–100 ppm) over the Mount Butler Granite (Lion Rock Suite) are accompanied by high Y (25–289 ppm), Nb (52–162 ppm), Pb (32–242 ppm), Zn (28–104 ppm) and Ga (26–48 ppm). The moderate to high Pb and Zn values may be related to local mineralisation (see descriptions for Pb and Zn). In the southeast, elevated thorium levels (49–100 ppm) over outcrops of medium- and fine-grained Po Toi Granite are accompanied by high Y (68–72 ppm), Nb (75–162 ppm), and Ga (42–48 ppm). Similar levels of Y (45–72 ppm), Nb (105–107 ppm) and Ga (39–41 ppm) are associated with the moderate to high levels of thorium (*c.* 90 ppm) on Lamma Island

On Lantau Island, the highest thorium values (89–185 ppm) are present over outcrops of the Chi Ma Wan Granite in the southeast. The strong thorium anomaly coincides with dominantly medium-grained rocks and is accompanied by high U (16–29 ppm), Rb (162–320 ppm), Y (74–142 ppm) and Nb (43–81 ppm). Over the remainder of Lantau Island, thorium values are generally moderate (29–49 ppm) over outcrops of the Lantau Volcanic Group in the south, and moderate to high (>36 ppm) over outcrops of the granitic rocks (Lamma and Kwai Chung suites) in the north. Low levels of thorium (<29 ppm) are generally present over outcrops of coarse ash crystal tuff (Tsuen Wan Volcanic Group) in the far south of the island.

Sn



TIN
in stream sediment

Statistics
Tin (ppm)

Samples	2246
Maximum value	11838
Minimum value	<2
Median	13
Mean	54
Standard deviation	340
Detection Limit	2

Tin

Sn

Synopsis

Background levels of tin are generally low (<15 ppm) over the northern and eastern New Territories, and over western Lantau Island. Low to moderate levels (9–30 ppm) are present on Hong Kong Island, Lamma Island and eastern Lantau Island. The highest concentrations (>78 ppm) occur in the granitic areas of the central and western New Territories, and are generally associated with areas of known Sn–Mo–W mineralisation. Several areas of extreme tin concentration, particularly in the Mai Po and Sha Tin areas, can be related directly to anthropogenic contamination.

Tin levels are low (<15 ppm) over volcanic areas (Lantau Volcanic Group) in the western part of Lantau Island. Anomalies near Tung Chung, Tsing Chau Tsai and Chi Ma Wan occur in areas underlain by granitic rocks (Lamma and Cheung Chau suites). Some of the anomalies around Mui Wo are related to anthropogenic contamination.

Geochemistry of tin

Tin is a Group IVA element in the periodic table, along with Si, Ge and Pb. Like Pb, tin is a relatively rare metal (crustal abundance 2.1 ppm) but it is well known as an element because of its technological usage and the relative ease of its extraction from natural sources. Tin is found in nature in the metallic state and as Sn^{2+} and Sn^{4+} ions.

During magmatic processes, Sn^{4+} may replace Ti^{4+} and Fe^{3+} (ionic radii of 55 pm, 42 pm and 49 pm respectively) in accessory minerals such as sphene, ilmenite, rutile and magnetite. The small, highly charged Sn^{4+} ion is strongly concentrated in $(SnO_4)^{4-}$ complexes in residual melts and thus becomes enriched in silicic relative to basic igneous rocks. Mielke (1979) cites values for the tin content of igneous rocks: ultrabasic, 0.5 ppm; basalt, 1.5 ppm; and granite, 1.5–3 ppm. Tin is generally associated with oxygen in high-temperature minerals and sulphur at lower temperatures (Mielke, 1979). In later stages of magmatic differentiation tin will become concentrated in the remaining melt until cassiterite [SnO_2] is formed, and tin may also substitute for Nb, Ta and W. Cassiterite is often present as a disseminated accessory phase in evolved granites and accumulates to economic levels in discrete hydrothermal veins and metasomatic deposits closely associated with highly siliceous lithologies (Ganeev *et al.*, 1961; Ure & Berrow, 1982).

In sedimentary rocks, the concentration of tin is primarily determined by the abundance of resistate minerals such as cassiterite, sphene and magnetite. Small amounts of tin dissolved during the weathering of micas may precipitate with Al-rich hydrolysates, thus accounting for the widespread accumulation of the metal in bauxites (Wedepohl, 1978). Argillaceous and calcareous sediments typically hold tin at levels in excess of the crustal average (4–6 ppm), while sandstones (*c.* 1 ppm) are generally depleted. In tropical soils, values of up to 60 ppm tin have been recorded, with a large proportion held in clays and organic matter (Aubert & Pinta, 1977). Mielke (1979) reports tin levels as 6 ppm in shales and <1 ppm in sandstones and carbonates.

Surface environment geochemistry

Dispersion patterns of tin in stream sediments are often erratic, a nugget–effect feature that is seen for other elements associated with resistate minerals. Fletcher *et al.* (1987) reported that in Malaysia, dispersion of cassiterite from aplites and pegmatites in granites was strongly influenced by local hydraulic conditions, and this is a factor that must be important in the Hong Kong environment. Sirinawin *et al.* (1987) showed how stream sediments can give high anomalies of tin due to the winnowing of light minerals in the drainage channel. Such high anomalies cannot always be matched with similarly high tin levels in soils and bedrock.

In stream sediments, most detrital tin is held in resistant oxide phases such as cassiterite [SnO_2], which release tin very slowly during weathering. In contrast, tin as a contaminant from anthropogenic activity is often present in the form of a thin coating on ferrous waste and may be mobilised rapidly because of the inherent weakness of the metal–couple to electrolytic attack. Other anthropogenic tin sources include alloys, such as solder (Sn–Pb), and agricultural pesticides and wood preservatives in which organo–tin compounds have been used. The weathering of such compounds is also faster than that of cassiterite. Such differences of weathering behaviour are consistent with the typically high magnitude of contaminant anomalies compared with those resulting from high tin values in bedrock. Contaminated samples are often indicated by the presence of high levels of other metals such as Pb, Zn and As with which natural tin mineralisation would not usually be associated. Weathering of both natural and anthropogenic tin carriers is intensified under acid, reducing conditions, but any Sn^{2+} released oxidises rapidly and is subsequently bound to secondary oxides of Fe or Al as $Sn(OH)_4$ or $Sn(OH)_3O^-$. In areas free of tin mineralisation, tin is an excellent indicator of contamination. Cooper & Thornton (1994) present data for the Harlech Dome area, North Wales showing how tin in drainage–sediment panned concentrates closely correlates with principal roads and towns.

Detailed description

Tin levels are generally low to moderate (<15 ppm) over the northern New Territories, except for anomalies at Mai Po and in the vicinity of Fan Ling and Sheung Shui. At Mai Po, the tin anomaly (11 838 ppm) is associated with high levels of Pb (884 ppm), Zn (17 489 ppm), Cu (2849 ppm), Sb (88 ppm) and As (160 ppm), indicating that the sample is strongly contaminated.

Moderate to high levels of tin (>30 ppm) are present over a broad area of the central and western New Territories, with the highest values present in areas of known Sn–W–Mo mineralisation (Sheung Fa Shan and Needle Hill). In the western New Territories, the anomalies correspond to outcrops of the Tsing Shan and Tai Lam granites (Lamma Suite), whereas in the central New Territories, anomalies are mainly concentrated in areas underlain by the Sha Tin and Needle Hill granites (Kwai Chung Suite), and Tai Po Granodiorite (Lamma Suite). Low to moderate tin levels (<15 ppm) are present to the northeast of Tai Mo Shan in areas underlain mainly by volcanic rocks.

Over the Tai Lam Granite, tin anomalies are present at Tai Lam Chung Reservoir (205–257 ppm), Ho Pui (147–272 ppm) and Tsing Fai Tong (211–244 ppm). In these areas, the elevated tin values are accompanied by relatively high W (10–44 ppm) and Bi (4–26 ppm), and low Cu (3–19 ppm), suggesting that these areas mark zones of tin mineralisation.

In the Lam Tsuen Valley and at Shek Kong, the tin anomalies (341–793 ppm) are associated with high concentrations of industrial metals and natural zones of Pb–Zn–Cu mineralisation. However, it is likely that most of the elevated tin concentrations in these areas are due to anthropogenic activity.

At Kap Lung, west of Tai Mo Shan, a small tin anomaly coincides with a former tungsten prospect. The high tin value (1103 ppm) coincides with moderate W (16 ppm) and Bi (10 ppm) values and may be related to tin mineralisation. However, the presence of high Pb (223 ppm), Cu (117 ppm), and Zn (617 ppm) suggest that some of the tin may be derived from waste material associated with the prospecting operations.

Very high tin anomalies at Chuen Lung (1891 ppm) and Tsuen Wan (1388 ppm) are associated with high Pb and Zn values, but low Cu values. The anomalies occur close to areas of known Sn–W and Pb–Zn–Cu mineralisation at Sheung Tong and may be related to a linear zone of mineralisation extending from the Needle Hill area to Sheung Tong. This area corresponds to the southwestern boundary of the Yim Tin Tsai–Shing Mun caldera (Campbell & Sewell, 1997).

A prominent natural tin anomaly occurs in the vicinity of the Needle Hill mine where tin and W were mined commercially. The very high tin values (1729 ppm) are accompanied by high W (160 ppm) and Bi (68 ppm), moderate Pb (129 ppm) and Zn (164 ppm), and low Cu (6 ppm). Cassiterite and wolframite are present in panned concentrates from this area.

High levels of tin are present in the area underlain by Needle Hill Granite (Kwai Chung Suite) at Kwai Chung. The elevated tin values (199–341 ppm) are accompanied by high W (37–46 ppm), moderate Pb (81–125 ppm) and Zn (67–121 ppm), and relatively low Cu (1.1–4.5 ppm), and may be partly influenced by local metallic contamination.

In the Sha Tin area, a prominent tin anomaly coincides with an area of known stream sediment contamination. Panned concentrates from a typical sample have yielded an abundance of magnetic spherules, tramp iron and solder. A similar explanation can be given for an anomaly in the vicinity of San Po Kong, Kowloon (161 ppm), which is also associated with high concentrations of industrial metals (e.g. Pb 124 ppm, Zn 494 ppm, Cu 170 ppm).

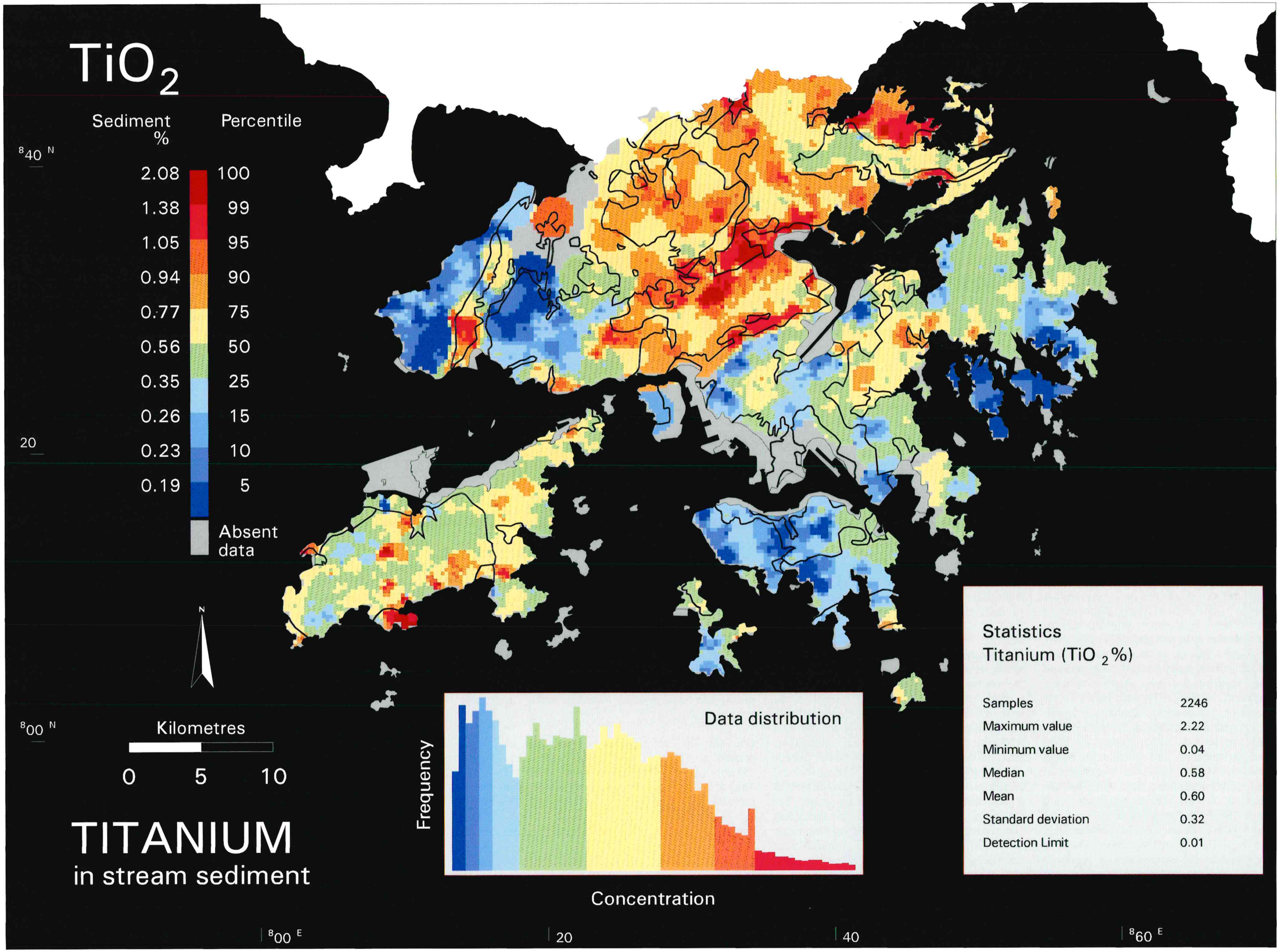
A tin anomaly (150–589 ppm), present in the area surrounding the Ma On Shan mine, may be partly natural and partly related to mining waste. Tin mineralisation is not known from the Ma On Shan area, but it is possibly associated with nearby dykes of Needle Hill Granite (Kwai Chung Suite) and quartz monzonite (Lion Rock Suite).

In eastern Kowloon, slightly enhanced tin levels (30–78 ppm) are present over outcrops of fine-grained Kwun Tong Granite (Lion Rock Suite). At Yau Tong, the anomaly is close to an area of known W mineralisation and may reflect associated minor tin mineralisation

On Hong Kong Island, a prominent tin anomaly at North Point (1256 ppm) coincides with a reported occurrence of Zn mineralisation (Peng, 1978). However, the high value of associated Pb (857 ppm) in this sample strongly suggests that it has been affected by anthropogenic contamination. Peng (1978) reported weak W and Mo mineralisation at nearby Mount Butler (Mount Butler Granite) and it is possible that small amounts of tin derived from this site could have contributed to the anomaly at North Point.

Slightly elevated levels of tin (30–140 ppm) are present in the northern part of Lamma Island overlying outcrops of the fine-grained Sok Kwu Wan Granite (Lion Rock Suite) and coarse ash crystal tuff (Tsuen Wan Volcanic Group). Tungsten mineralisation has been reported from the south side of Sok Kwu Wan (Peng, 1978), and therefore the potential exists for some accompanying tin mineralisation.

On Lantau Island, tin anomalies are present in the Mui Wo (530 ppm), Chi Ma Wan (202–428 ppm), Sha Lo Wan (142–314 ppm) and Tai O (747 ppm) areas. At Sha Lo Wan, the anomaly coincides with an area of W–Mo mineralisation within the Chek Lap Kok Granite (Lamma Suite). Elsewhere, the high tin levels are associated with moderate to high Pb (59–231 ppm) and Zn (45–112 ppm) values, suggesting that anthropogenic contamination has influenced the sediment samples.



TITANIUM
in stream sediment

Statistics
Titanium (TiO$_2$%)

Samples	2246
Maximum value	2.22
Minimum value	0.04
Median	0.58
Mean	0.60
Standard deviation	0.32
Detection Limit	0.01

Titanium TiO_2

Synopsis

Titanium values are generally moderate to high (>0.56 % TiO_2) over the central and northern New Territories, low to moderate (<0.56 % TiO_2) over the eastern New Territories, Kowloon, and Lantau Island, and low over the western New Territories and Hong Kong Island.

In the western New Territories, prominent titanium anomalies (>1.05 % TiO_2) are present over andesite outcrops of the Tuen Mun Formation, but low (<0.35 % TiO_2) in the surrounding granite areas.

Over the central and northern New Territories, elevated titanium values are generally associated with outcrops of coarse ash crystal tuff (Tsuen Wan Volcanic Group) and Tai Po Granodiorite (Lamma Suite). In most cases, the strongest titanium anomalies coincide with contact zones between the granodiorite and coarse ash crystal tuff. One exception is in the northeastern New Territories where a prominent titanium anomaly (>1.05 % TiO_2) occurs within coarse ash crystal tuff, without an associated intrusion of granodiorite.

In the eastern New Territories, titanium values are generally low to moderate (<0.56 % TiO_2) over outcrops of fine ash vitric tuff (Repulse Bay and Kau Sai Chau volcanic groups) although they are slightly elevated (0.56–1.05 % TiO_2) over outcrops of coarse ash crystal tuff (Repulse Bay Volcanic Group).

Relatively low titanium values (<0.56 % TiO_2) occur over parts of Kowloon, Hong Kong Island, and Lamma Island. These areas are mainly underlain by fine ash vitric tuff (Repulse Bay Volcanic Group) and medium- to fine-grained granite (Lion Rock Suite). Slightly elevated titanium values (0.56–0.77 % TiO_2) surround outcrops of trachydacite and quartz monzonite.

Moderate to high levels of titanium (>0.35 % TiO_2) are found over most of Lantau Island, with the highest values generally associated with outcrops of quartz monzonite (Cheung Chau and Lion Rock suites) and coarse ash crystal tuff (Tsuen Wan Volcanic Group).

Geochemistry of titanium

Titanium is one of the lightest members of the transition series of elements (Group IVB in the periodic table) with transition row neighbours of Sc and V. It is a relatively abundant metal in the earth's crust (6320 ppm), (Mielke, 1979)).

During magmatic processes, titanium follows Fe in magmatic crystallisation and Ti^{4+} is predominantly partitioned into Fe–Ti or Fe oxides, such as ilmenite and magnetite, or into one or more of the TiO_2 phases, rutile, anatase and brookite. Titanium may also enter silicates through substitution for Mg^{2+} or Fe^{2+}, leading to enrichment of the element in amphiboles and micas. The compatibility displayed by titanium during the early stages of fractionation results in enrichment in basic (>1 % TiO_2) and ultrabasic (>2 % TiO_2) rocks relative to silicic igneous lithologies (*c.* 0.2 % TiO_2). Mielke (1979) cites titanium levels for ultrabasic, basic and granitic igneous rocks as 300, 13 800 and 1200–3400 ppm respectively. In basalts, fine-grained ilmenite, titanomagnetite and rutile can all constitute important titanium minerals, while in granites, sphene may be a major titanium carrier (Ure & Berrow, 1982).

Titanium is relatively immobile during pro-grade metamorphism (Nicollet & Adriambololona, 1980). However, it may be mobilised and enriched in amphibole during granulite–amphibolite retrogression (Beach & Tarney, 1978), with rutile authigenesis occurring commonly (Ure & Berrow, 1982). Titanium is not involved in normal hydrothermal sulphide mineralisation processes, but metasomatism may give rise to magnetite-rich rocks containing appreciable titanium. In sedimentary rocks, the concentration of TiO_2 is determined by the abundance of detrital oxides, detrital silicates such as chlorite and clay minerals, and diagenetic phases such as anatase (Correns, 1978). Consequently, the TiO_2 contents of carbonates and quartzites (<0.25 %) are generally lower than those of shales and greywackes (>0.5 %). Mielke (1979) cites levels of titanium in shales, sandstones and carbonates as 4600, 1500 and 400 ppm respectively.

Surface environment geochemistry

Mielke (1979) reports that bauxites and laterites may contain up to 4 % TiO_2. In stream sediments, a large proportion of the titanium is held in minerals such as rutile, ilmenite and sphene, all of which are relatively insoluble. Some titanium may be taken into solution in stream waters through the weathering of ferromagnesian minerals and authigenic phases such as anatase, but dispersal is generally restricted by adsorption to clays. Titanium is mobilised more readily in peats and podzols (e.g. Hutton *et al.*, 1972), at low pH (<4.5) and in the presence of organic acids which can form chelation complexes with Ti^{4+}.

Cooper and Thornton (1994) report that anthropogenic anomalies in drainage are rarely recorded for titanium, which would be anticipated given the generally high background levels for this minor element in the environment.

Detailed description

In the western New Territories, titanium values (TiO_2) over andesite outcrops of the Tuen Mun Formation north of Tuen Mun range from 1.09–1.47 % and are associated with high V (127–160 ppm), Se (1.23–2.3 ppm), Cd (0.4–5 ppm), MnO (0.12–0.21 %), and Co (16–24 ppm). Pb and Zn values are rather low.

In the northern New Territories, isolated titanium anomalies (>1.05 % TiO_2) over outcrops of coarse ash crystal tuff (Tsuen Wan Volcanic Group) occur at Lin Tong Mei, Wo Hop Shek and Ha Shan. Most of these anomalies are accompanied by high levels of V (74–80 ppm), Se (1.0–1.1 ppm), Hg (1.1–3.1 ppm) and Zn (129–221 ppm). Pb (17–226 ppm) and Co (5–13 ppm) are also commonly high (17–226 ppm). However, farther north at Man Kam To, a titanium anomaly (1.51 % TiO_2) is accompanied by unusually low Hg (<0.2 ppm), Cu (<0.2 ppm) and Pb (<2 ppm).

Titanium values are particularly high (1.05–1.57 % TiO_2) in the Luk Keng to Lai Che Wo areas of northeastern New Territories. Levels of associated elements are also high including V (56–83 ppm), Se (0.6–1.0 ppm), Cd (0.2–0.9 ppm), Hg (1.5–2.9 ppm), MnO (0.05–0.15 ppm), Pb (53–111 ppm) and zinc (63–189 ppm). Most of the area is underlain by coarse ash crystal tuff and interbedded tuffaceous siltstone (Tsuen Wan Volcanic Group). The high values of metals in the stream sediments in this relatively remote area suggests the presence of Pb–Zn–Cu mineralisation.

The highest titanium values are associated with intrusions of Tai Po Granodiorite (Lamma Suite) in the central New Territories. In particular, titanium anomalies are concentrated along contact zones between coarse ash crystal tuff (Tsuen Wan Volcanic Group) and granodiorite at Tin Fu Tsai, Kap Lung, Lam Tsuen, Shing Mun and Fo Tan. In the Lam Tsuen Valley, the titanium anomalies (1.33–2.14 % TiO_2) coincide with areas of Pb–Zn–Cu mineralisation. Stream sediment samples typically have high levels of associated metals including V (93–115 ppm), Cd (0.2–0.7 ppm), MnO (0.18–0.28 %), Pb (50–235 ppm) and Zn (158–263 ppm). South of Tai Mo Shan, a strong titanium anomaly (1.05–1.24 % TiO_2) is accompanied by very high Pb (399–1084 ppm) and Zn (240–417 ppm) values. In the Shing Mun and Fo Tan areas, the titanium values (TiO_2) in stream sediments are typically between 1.00 and 1.8 % and are associated with high V (77–103 ppm), Se (0.15–0.44 ppm), Hg (0.49–1.08 ppm) and MnO (0.07–1.15 %), and low to moderate Pb (38–94 ppm) and Zn (80–224 ppm).

In the Plover Cove area, elevated levels of titanium coincide with outcrops of coarse ash crystal tuff (Tsuen Wan Volcanic Group). These are commonly intruded by small stocks of granodiorite. A small titanium anomaly (1.53 % TiO_2) at the eastern end of Plover Cove Reservoir corresponds to the reported occurrence of iron mineralisation. Levels of associated elements such as V (88 ppm) and Se (0.14 ppm) (Table 4), are also high.

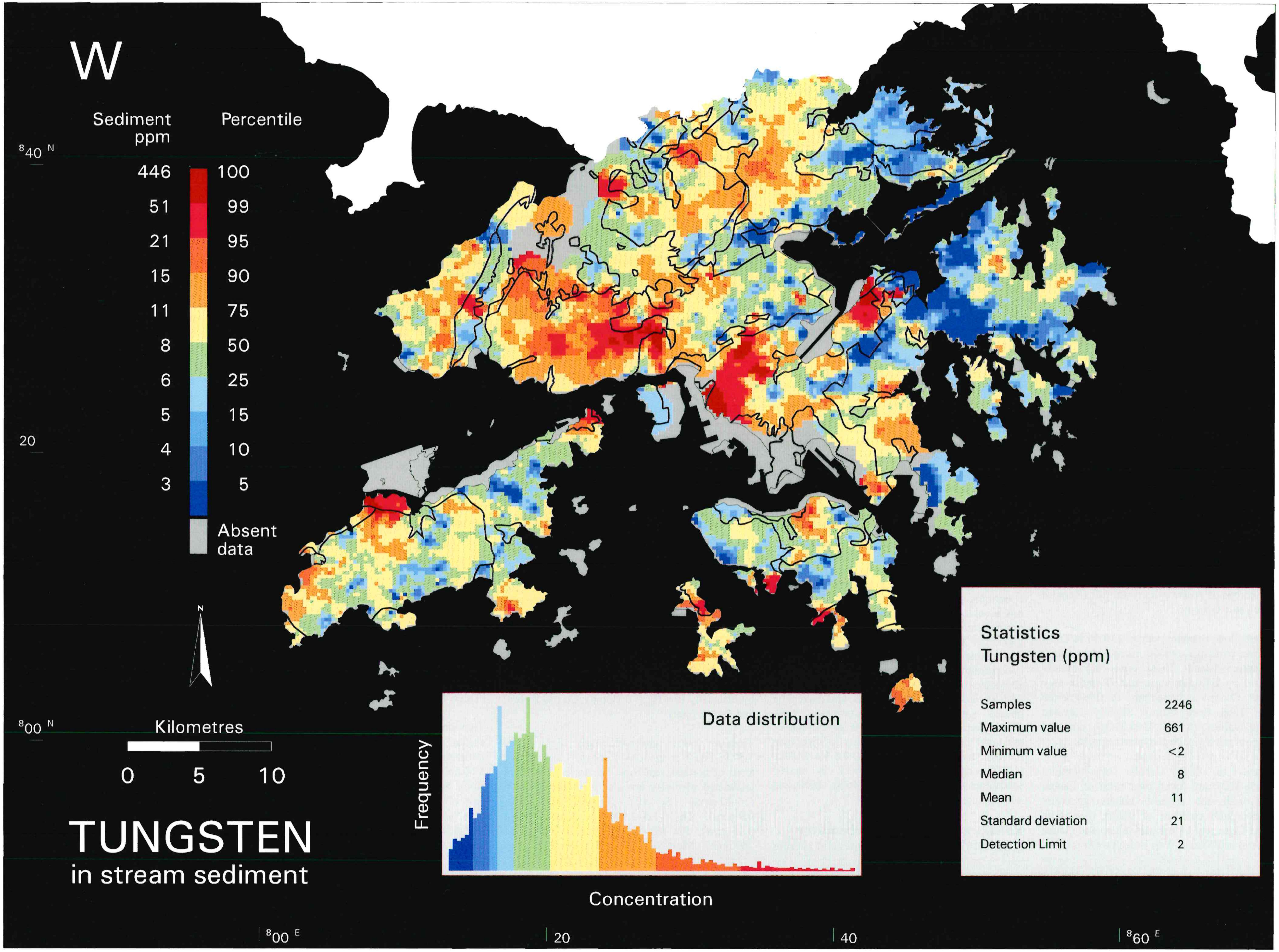
Titanium values are moderate to high over the eastern New Territories, particularly in areas underlain by coarse ash crystal tuff (Repulse Bay Volcanic Group) and quartz monzonite (Lion Rock Suite). This includes the area south and east of Ma On Shan. Small anomalies (0.77–0.94 % TiO_2) at Pyramid Hill and Tai No are coincident with high levels of Cd, Hg, Co, Fe_2O_3, and MnO.

Background levels of titanium are generally low to moderate over much of the eastern New Territories south of High Island Reservoir, Kowloon, Hong Kong Island and Lamma Island. These areas are mostly underlain by medium- to fine-grained granite (Lion Rock Suite) and fine ash vitric tuff (Repulse Bay and Kau Sai Chau volcanic groups). Slightly elevated levels of titanium (0.56–0.77 % TiO_2) in the Clear Water Bay area correspond with outcrops of trachydacite (Kau Sai Chau Volcanic Group) and quartz monzonite (Lion Rock Suite). Similar rocks are responsible for the slightly elevated levels of titanium in the southeastern part of Hong Kong Island. On Lamma Island, slightly elevated levels of titanium (0.56–0.77 % TiO_2) correspond with minor outcrops of Lantau Granite (Lamma Suite) and quartz monzonite (Lion Rock Suite).

On Lantau Island, the highest titanium values are present over outcrops of quartz monzonite (Cheung Chau and Lion Rock suites) and coarse ash crystal tuff (Tsuen Wan Volcanic Group) on the south side of the island. At Luk Keng Shan, high titanium values (1.35–1.57 % TiO_2) are accompanied by moderate levels of associated metals including V (51–76 ppm), Hg (0.61–0.87 ppm), Pb (29–88 ppm), Zn (31–87 ppm), and Fe_2O_3 (8–10 %). Isolated anomalies at Ngong Ping and Shek Pik generally have low to moderate values of associated metals and may be partly contaminated by anthropogenic activity. Slightly elevated titanium levels north of Mui Wo correspond with known areas of Pb–Zn–Cu mineralisation within outcrops of coarse-grained granite and porphyry dykes. In the Tsing Chau Tsai area of northeastern Lantau Island, a small TiO_2 anomaly (1.05 %) is accompanied by unusually low concentrations of associated elements (see Table 4) including Se (0.2 ppm), Cd (0.2 ppm), MnO (0.1 %), Pb (25 ppm) and Zn (92 ppm). This area is likely to be partly contaminated by mining activity associated with recovery of small quantities of wolframite (see description for W).

TUNGSTEN

in stream sediment



Statistics
Tungsten (ppm)

Samples	2246
Maximum value	661
Minimum value	<2
Median	8
Mean	11
Standard deviation	21
Detection Limit	2

Tungsten

W

Synopsis

In the western New Territories, high levels of tungsten (>11 ppm) coincide with outcrops of the Tsing Shan and Tai Lam granites (Lamma Suite). The highest tungsten levels (>21 ppm) are associated with contact zones between the Tai Lam Granite and Tai Po Granodiorite (Lamma Suite) to the west of Tai Mo Shan and coincide with known areas of Sn–W mineralisation.

Broad areas of elevated tungsten values (8–21 ppm) occur in the northern New Territories over outcrops of coarse ash crystal tuff (Tsuen Wan Volcanic Group). Tungsten levels are low (<6 ppm) in adjacent areas underlain by Upper Palaeozoic and Upper Mesozoic sedimentary rocks.

In the central New Territories, prominent tungsten anomalies (>21 ppm) coincide with outcrops of Needle Hill Granite (Kwai Chung Suite) and are particularly strong in areas of known Sn–W mineralisation. A prominent anomaly is also present at Ma On Shan reflecting the known area of Fe mineralisation .

Minor tungsten anomalies (11–51 ppm) are present in Kowloon, Hong Kong Island, Lamma Island and Po Toi Island. Most are associated with outcrops of fine-grained granite but several anomalies can also be related to anthropogenic contamination.

On Lantau Island, small anomalies (>11 ppm) coincide with known areas of tungsten mineralisation particularly over the Chek Lap Kok Granite (Lamma Suite) at Sha Lo Wan, and over outcrops of coarse ash crystal tuff (Tsuen Wan Volcanic Group) at Yi O and Tsing Chau Tsai.

Geochemistry of tungsten

Tungsten, or wolfram, is a heavy metal classified in Group VIB of the periodic table along with Mo and Cr. It is a relatively rare element, with a crustal abundance of around 1.0–1.5 ppm, similar to that of its group neighbour Mo, with which it has a close geochemical affinity. Tungsten is a strongly lithophile element in the earth's crust, although it is siderophile in iron meteorites, and is markedly less chalcophile than Mo.

Apart from sulphides where it occurs as the W^{4+} cation in the rare mineral tungstenite [WS_2] (cf. molybdenite, [MoS_2]), tungsten has an essentially anionic geochemistry based on the tungstate WO_4^{2-} ion in which the W^{6+} ion is present in four- or six-fold co-ordination. The W^{4+} ion has a radius of 66 pm, close to that of Zr^{4+} (72 pm) and Mo^{4+} (65 pm); the ionic radius of W^{6+} is given as 60 pm in six-fold co-ordination and 42 pm in four-fold co-ordination, compared with 59 pm and 41 pm for the equivalent Mo ions and co-ordination numbers. This close similarity between W and Mo is marked by their minerals, which are often isostructural and show variable replacement and solid–solution between nominal W and Mo end members. The principal tungsten ore minerals wolframite [$(Fe,Mn)WO_4$] and scheelite [$CaWO_4$] can be compared with powellite [$CaMoO_4$] and wulfenite [$Pb(Mo,W)O_4$]. Tungsten does occur at trace levels (*c.* 1 ppm) in several rock-forming minerals, and it is notably enriched in micas which may commonly contain 5–50 ppm, and muscovites in altered granites near tungsten deposits may contain up to 500 ppm (Wedepohl, 1978). Accessory Fe–Ti oxide minerals in igneous rocks contain up to 10 ppm W.

Tungsten levels are generally somewhat higher in granitic rocks (1.5 ppm) than in basic rocks (0.5–1.0 ppm) and ultrabasic rocks (0.1–0.8 ppm). Late-stage magmatic processes tend to concentrate tungsten, and wolframite often occurs in pegmatites and associated quartz veins. Scheelite is more common in skarn deposits at granite-limestone contacts. The limited available data for tungsten in metamorphic rocks shows little evidence of mobilisation. However, it is possible that Na-rich fluids may dissolve tungsten during metasomatism, and transport it as Na_2WO_4 at high temperatures, with subsequent concentration elsewhere. Graphitic schists and phyllites often show relatively high tungsten levels (*c.* 20 ppm).

Common clastic sedimentary rocks such as sandstones and shales usually contain tungsten levels similar to those in igneous rocks, typically 1–2 ppm. Lithogeochemical data for tungsten are scarce, but limestones are generally low in tungsten (typically <0.5 ppm), while coal ashes are relatively enriched (Wedepohl, 1978). Black shales may also be enriched in tungsten.

Surface environment geochemistry

Although minerals containing the tungstate oxo–anion WO_4^{2-} are generally insoluble in neutral and acid waters, the WO_4^{2-} (aq) ion is itself stable and soluble above about pH 3, in the absence of heavy metal M^{2+} ions and in oxidising conditions (Brookins, 1988). Above pH 7, scheelite is relatively soluble, and in alkaline conditions, therefore, tungsten is relatively mobile. Wolfram is less soluble than scheelite, but may also show solution in alkaline waters. There is some evidence of strong sorption of tungsten by secondary Mn oxides and clays in stream sediments, so tungsten concentrations in most surface waters remain very low, typically <<0.001 ppm. The only significant exceptions to this are found in some hydrothermal spring waters and alkaline salt lakes in W–mineralised areas.

In stream sediments in the equatorial and tropical conditions of central Africa, tungsten minerals are broken down to a fine size, partly dissolved, partly mixed with fine alluvium, and can be transported for tens of kilometres from the source (Varlamoff, 1971). In contrast, Theobald & Allcot (1973) describe an example where even with scheelite of a grain size in the order of centimetres, tungsten is rarely detected in the fine-grained stream sediments, and without care it may be lost by sieving before heavy mineral concentration by panning. Coats *et al.* (1994) noted that where tungsten minerals such as wolframite are associated with cassiterite in SW England, the relative concentration of tungsten between fine sediment and panned concentrate is much lower than for Sn. This is because wolframite is much less stable than cassiterite, and it tends to break down into secondary products, possibly hydrous oxides, which are associated with hydrous iron oxides and are not concentrated by panning.

Contamination in industrial areas is likely as tungsten is widely used as an alloy in steel. Evidence for a significant biological role for tungsten is sparse (unlike for Mo which is an essential trace element) although minor concentration in some plants may suggest a specialised function, or perhaps substitution for Mo when this is deficient. Higher than trace levels in solution, however, are generally toxic.

Detailed description

In the western New Territories, a tungsten anomaly (42 ppm) north of Tuen Mun coincides with a reported occurrence of wolframite in quartz veins (Davis, 1958). Moderate levels of Sn (29 ppm), Pb (70 ppm) and Zn (140 ppm) are also present. Tungsten levels are particularly high (>21 ppm) over outcrops of fine-grained Tai Lam Granite (Lamma Suite) with strong anomalies at Sheung Fa Shan and Tsing Fai Tong. These areas host known sites of Sn–W mineralisation and are generally associated with contact zones between the fine-grained Tai Lam Granite, Tai Po Granodiorite, and coarse ash crystal tuff (Tsuen Wan Volcanic Group). At Tsing Fai Tong, the high tungsten values (21–68 ppm) are associated with moderate to high Sn (48–137 ppm), Bi (21–47 ppm), Pb (101–182) ppm and Zn (142–227 ppm). Similar high levels of these metals accompany the tungsten anomaly (24–80 ppm) at Sheung Fa Shan (e.g. Sn 65–131 ppm, Bi 11–61 ppm, Pb 60–165 ppm and Zn 145–348 ppm).

Tungsten levels are moderate to high over much of the northern New Territories in association with outcrops of coarse ash crystal tuff (Tsuen Wan Volcanic Group) even though no known tungsten mineralisation is known from the area. A prominent tungsten anomaly (44 ppm) in the Mai Po area is associated with very high levels of Sn (151 ppm), Pb (884 ppm), Zn (17 489 ppm), Cu (2847 ppm), Sb (88 ppm) and As (160 ppm). This strongly suggests that the high concentration is related to anthropogenic contamination.

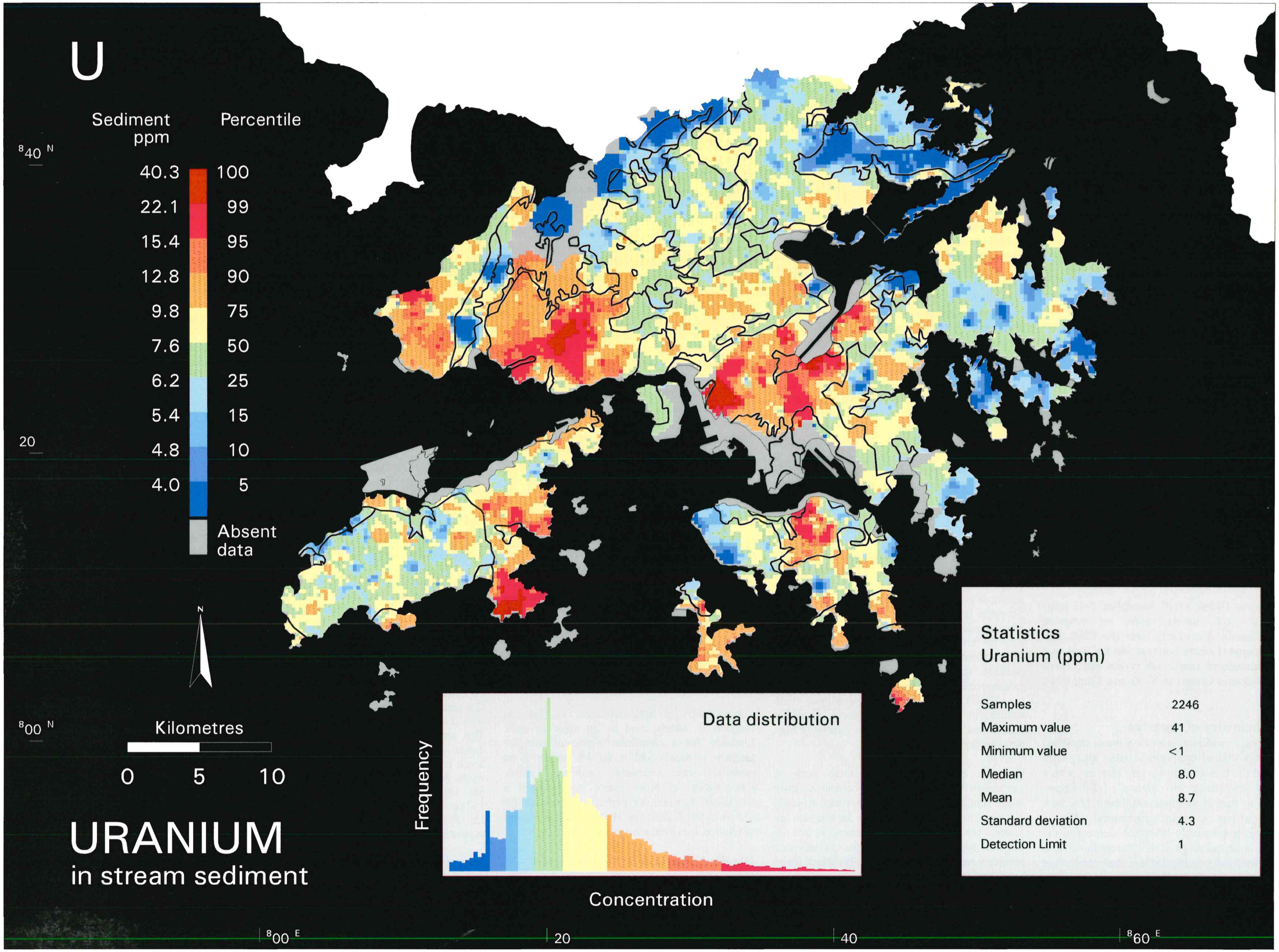
In the central New Territories, a prominent tungsten anomaly underlies the Needle Hill Granite where Sn–W mineralisation is well-known. In this area, the high tungsten values are commonly accompanied by high Sn, but relatively low Cu, Pb and Zn levels. For example, at Kwai Chung the high tungsten levels (46 ppm) are associated with high Sn (242 ppm), but moderate Pb (108 ppm) and Zn (121 ppm) but low Cu (3.6 ppm). A strong tungsten anomaly coincides with the mineralisation present at Ma On Shan. This area is known to host wolframite-bearing quartz veins, but some of the anomalously high levels may derive from contamination by mining waste. A typical stream sediment analysis from the Ma On Shan area yields the following: W 152 ppm, Sn 449 ppm, Pb 896 ppm, Zn 490 ppm, Cu 303 ppm, Bi 361 ppm and As 111 ppm, suggesting a strong anthropogenic overprint.

Isolated tungsten anomalies in eastern Sai Kung and are mostly due to local contamination. These include Tai Tan (11 ppm) and Sai Kung (23 ppm) where the high tungsten values are associated with moderate to high Pb (147 ppm) and Zn (283 ppm). A small anomaly at Ho Chung (25 ppm) coincides with a reported occurrence of wolframite (Peng, 1978), but the high level of associated Pb (115 ppm) and Zn (401 ppm) suggests the influence of metallic contamination.

On Hong Kong Island, elevated tungsten levels are present at North Point (24–25 ppm), Chung Hom Wan (35 ppm) and Wong Chuk Hang (21–68 ppm). Wolframite has been reported at North Point and Mount Butler in quartz veins within Mount Butler Granite (Lion Rock Suite) (Peng, 1978). At Chung Hom Wan, the high tungsten value is associated with high Pb (177 ppm) and Zn (462 ppm) and these indicate potential metallic contamination. At Wong Chuk Hang, the high tungsten values are associated with moderate Pb (100 ppm) and Zn (200 ppm) and low Cu (8.7 ppm). Although wolframite has not been reported from the area, these metal values may reflect an area of weak tungsten mineralisation.

Elevated tungsten levels (21–44 ppm) on Lamma Island coincide with reported occurrences of wolframite at Sok Kwu Wan (Peng, 1978) and are probably related to weak mineralisation in the Sok Kwu Wan Granite (Lion Rock Suite).

On Lantau Island, pronounced tungsten anomalies are present at Tsing Chau Tsai, Sha Lo Wan and Yi O, with small anomalies at Chi Ma Wan and Tai Shui Hang. Elevated levels at Tsing Chau Tsai coincide with reported occurrences of wolframite in quartz veins (Peng, 1978) within the Tai Lam Granite (Lamma Suite). The high tungsten values (44 ppm) are associated with rather low Pb (62 ppm), Zn (57 ppm), Cu (11.5 ppm) and tin (26 ppm) but high Bi (24 ppm). At Sha Lo Wan, quartz–wolframite veins are present in the Chek Lap Kok Granite (Lamma Suite) and Tong Fuk Quartz Monzonite (Lion Rock Suite). A typical stream sediment from this area contains high W (50 ppm), moderate Sn (31 ppm), Pb (32 ppm) and Zn (98 ppm), and low Cu (9 ppm). Farther to the southwest, elevated tungsten values near Yi O overlying outcrops of coarse ash crystal tuff (Tsuen Wan Volcanic Group) coincide with moderate Pb, Zn, Sn and high As values.



URANIUM
in stream sediment

Statistics
Uranium (ppm)

Samples	2246
Maximum value	41
Minimum value	<1
Median	8.0
Mean	8.7
Standard deviation	4.3
Detection Limit	1

Uranium

Synopsis

In the western New Territories, uranium levels are high (>9.8 ppm) over outcrops of the Tsing Shan and Tai Lam Granites (Lamma Suite), whereas very low levels (<4.0 ppm) characterise the intervening volcanic rock areas (Tuen Mun Formation).

In the northern and northeastern New Territories, uranium values are very low (<4.0 ppm) over outcrops of Upper Palaeozoic and Upper Mesozoic sedimentary rocks, and generally low to moderate (6.2–9.8 ppm) over the adjacent volcanic rock areas (Tsuen Wan Volcanic Group). Uranium levels are slightly elevated (7.6–12.8 ppm) over outcrops of coarse ash crystal tuff (Tsuen Wan Volcanic Group) in the vicinity of Tai Mo Shan.

High uranium values (>9.8 ppm) over the central New Territories are coincident with outcrops of Sha Tin and Needle Hill granites (Kwai Chung Suite). Moderate to high values (7.6–12.8 ppm) in eastern Kowloon correspond with outcrops of the Kowloon and Kwun Tong granites (Lion Rock Suite).

In the eastern New Territories, uranium values are generally low (<6.2 ppm) over outcrops of fine ash vitric tuff (Kau Sai Chau Volcanic Group), but are slightly elevated (7.6–12.8 ppm) over outcrops of coarse ash crystal tuff (Repulse Bay Volcanic Group).

On Hong Kong Island, high uranium levels (>9.8 ppm) in the vicinity of North Point coincide with outcrops of fine-grained Mount Butler Granite (Lion Rock Suite). Farther to the southeast, elevated uranium values (9.8–22.1 ppm) are also present over outcrops of the Po Toi Granite.

Moderate to high uranium values (7.6–15.4 ppm) over the southern part of Lamma Island coincide with outcrops of the South Lamma Granite (Cheung Chau Suite). Low uranium values (<6.2 ppm) in the north of the island coincide with outcrops of coarse ash crystal tuff (Tsuen Wan Volcanic Group).

On Lantau Island, a strong anomaly (>22.1 ppm) over the Chi Ma Wan peninsula coincides with outcrops of the Chi Ma Wan Granite (Cheung Chau Suite), whereas north of Mui Wo, elevated uranium values (>9.8 ppm) are present over outcrops of Lantau Granite (Lamma Suite), cut by rhyolite and rhyodacite dykes (Kwai Chung Suite).

Geochemistry of uranium

Uranium is an actinide element, a group of elements in which all isotopes are radioactive. The isotopes ^{235}U and ^{238}U have long half lives, and have been able to persist in nature since their formation.

In magmas, the highly charged U^{4+} ion (ionic radii 89 pm), behaves incompatibly, becoming concentrated in late-stage differentiates, often in accessory minerals such as zircon and allanite. Uranium is a lithophile element and its geochemistry is similar to that of Th. Granites and pegmatites, especially those produced from evolved magmas, are therefore richer in uranium than basic igneous rocks. Secondary concentration of uranium may occur as a result of deuteric and hydrothermal activity associated with the emplacement of silicic volcanics and intrusives. Mielke (1979) cites very low levels of uranium in ultrabasic rocks (0.001 ppm), other igneous rocks at levels 1–3 ppm, and a crustal abundance of 2.3 ppm.

In sedimentary rocks, the levels of uranium are closely related to the redox conditions. Highest concentrations are found in organic-rich facies (6–1000 ppm) associated with anoxic environments, and phosphatic sediments (50–300 ppm). Lower values are recorded in coarse-grained inorganic rocks (e.g. quartzites, 0.5–1.5 ppm and arkoses 1.5 ppm) with clay-rich sediments being generally higher. The average value cited for shales is 3.7 ppm and for carbonates 2.2 ppm (Mielke, 1979). Anomalous levels are commonly observed at palaeo–redox fronts, where the soluble uranyl ion (UO_2^{2+}) is precipitated as insoluble U^{4+}.

Surface environment geochemistry

The behaviour of uranium in the surface environment, particularly with reference to its drainage geochemistry and uranium exploration, is described by Rose (1994). The most important factor affecting the migration of uranium is the generally high mobility of uranium as UO_2^{2+} or as a complex with CO_3^{2-} , HPO_4^{2-}, OH^-, F^- and other anions, and the general immobility of U^{4+} (Langmuir, 1978). Uranium is therefore generally soluble in oxidising surface water and shallow groundwaters (i.e. typical Hong Kong surface conditions) but in near–surface and deep–seated reducing environments it is insoluble. Dispersion of uranium in aqueous solution is limited by adsorption and complexation with humic organic material, clay minerals, phosphates and iron oxides (Wedepohl, 1978; Drever, 1988), in which it shows some similarities with the behaviour of Cu and Mo. Some uranium in stream sediments may be present in resistate minerals such as zircon, monazite and allanite, derived from primary or secondary rock sources, and this uranium is dispersed mechanically. Uranium is extensively leached from rocks and soils in regions of high rainfall leaving low amounts of uranium to be dissolved and leached by later soil water and groundwater (Rose, 1994).

Detailed description

In the western New Territories, uranium concentrations over the Tsing Shan Granite (Lamma Suite) lie mostly between 9.9 and 15.4 ppm with the highest values present in the vicinity of Nim Wan (16–23 ppm) and Castle Peak (16–18 ppm). At Nim Wan, the high uranium levels are accompanied by moderate to high Th (80–93 ppm), Rb (300–422 ppm) and Ga (22–32 ppm), whereas at Castle Peak they area accompanied by high Rb (63–562 ppm), Y (45–137 ppm), Ga (25–34 ppm), Pb (99–228 ppm) and Ni (2–31 ppm). The high concentrations of Pb, Ni and Cr are thought to be related mainly to anthropogenic contamination (see descriptions for Pb, Ni and Cr).

Uranium concentrations over the Tai Lam Granite (Lamma Suite) are consistently greater than 9.8 ppm with the highest values (>15.4 ppm) covering a broad area surrounding the Tai Lam Chung Reservoir. Moderate to high values for Th (35–105 ppm), Rb (290–551 ppm), Y (49–252 ppm), Nb (34–84 ppm), Ga (20–37 ppm) and Sn (52–668 ppm) accompany the high uranium values. The high Sn and W values reflect known areas of Sn–W mineralisation within the Tai Lam Granite.

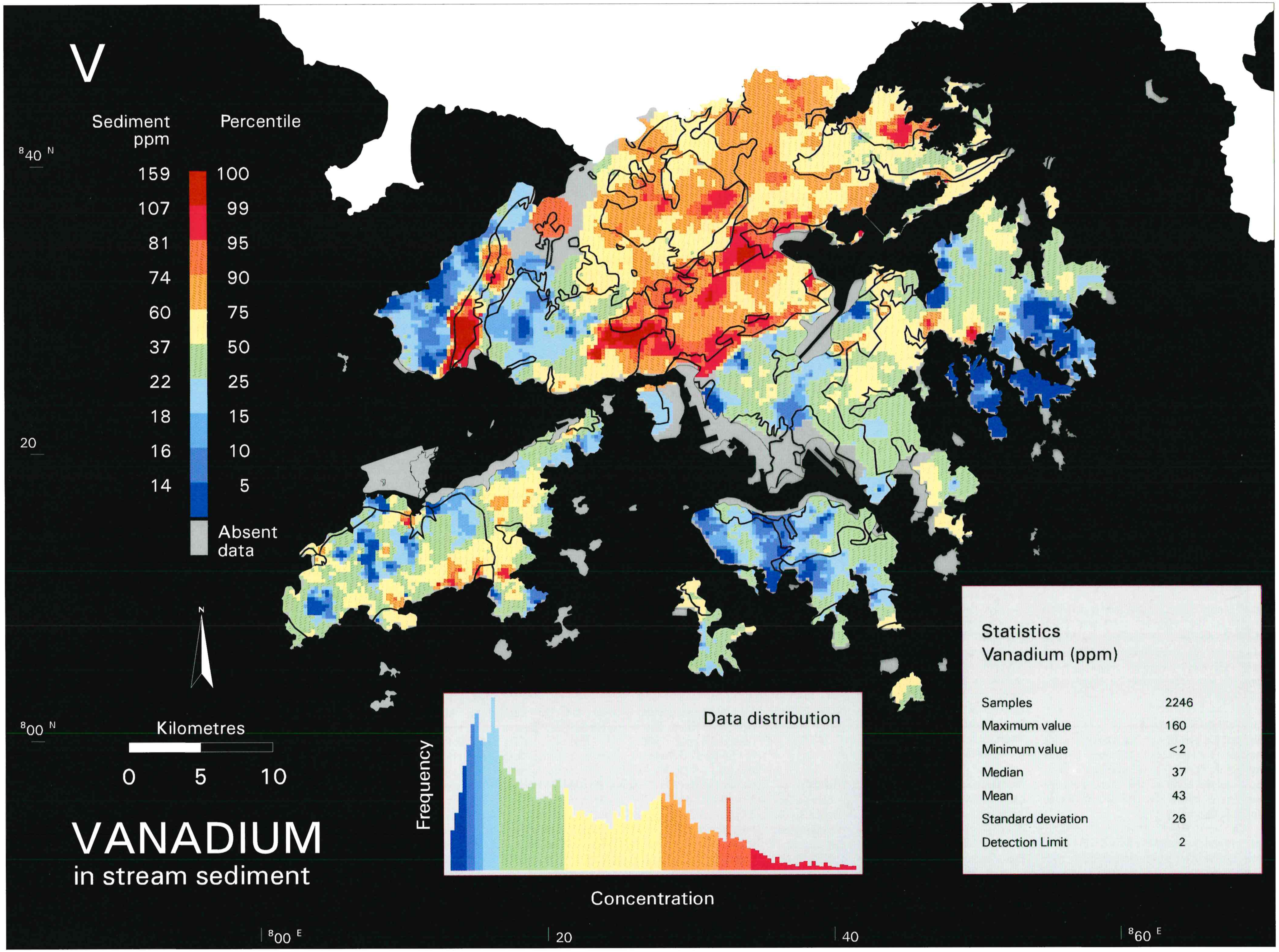
Low to moderate values of uranium (5.4–9.8 ppm) are found over most of the outcrop area of the Tsuen Wan Volcanic Group, except in the vicinity of Tai Mo Shan, where uranium values are moderate to high (7.6–12.8 ppm). These slightly elevated values may be associated with Pb–Zn–Cu mineralisation known from the area. Low uranium values (<4.8 ppm) are typically found over outcrops of Upper Palaeozoic and Upper Mesozoic sedimentary rocks in the northern and northeastern New Territories.

In the central New Territories, uranium levels over outcrops of the Sha Tin and Needle Hill granites (Kwai Chung Suite) are typically high (>12.8 ppm) with the highest values present at Kwai Chung (18–35 ppm), Kowloon Reservoirs (17–19 ppm), Lion Rock (16–26 ppm), Tai Shui Hang (17–24 ppm), Shan Ha Wai (18–41 ppm) and Fo Tan (8–31 ppm). At Kwai Chung, the high uranium values are accompanied by high Th (81–137 ppm), Rb (259–377 ppm), Y (121–3563 ppm), Nb (113–386 ppm), Ga (23–46 ppm), Cu (4–365 ppm), Pb (81–883 ppm), Zn (67–1496 ppm) and Sn (199–341 ppm). The values for these elements are generally much lower in the neighbouring Kowloon Reservoirs area suggesting that at Kwai Chung, some samples have been contaminated by anthropogenic activity. The high uranium values at Lion Rock, Tai Shui Hang, Shan Ha Wai and Fo Tan occur mostly over outcrops of medium-grained Sha Tin Granite which have been intruded by dykes of fine-grained granite and quartz monzonite. At Lion Rock, the uranium anomaly is associated with high Th (73–95 ppm), Rb (416–538 ppm), Y (91–154 ppm) and Nb (66–132 ppm), and, with the addition of high Ga (20–49 ppm). Similar values for these elements accompany the uranium anomalies at Tai Shui Hang (e.g. Th 95–109 ppm, Rb 282–643 ppm, Y 96–157 ppm and Nb 153–243 ppm); Sha Ha Wai (Th 78–100 ppm, Rb 334–407 ppm, Y 96–111 ppm and Nb 105–139 ppm); and Fo Tan (Th 86–184 ppm, Rb 86–330 ppm, Y 87–147 ppm and Nb 70–113 ppm). Unusually high Pb (59–2256 ppm), Zn (48–318 ppm) and Sn (22–8881 ppm) values at Tai Shui Hang and Fo Tan suggest that some samples have been contaminated by anthropogenic activity.

On Hong Kong Island, the highest uranium values (17–25 ppm) coincide with outcrops of the Mount Butler Granite (Lion Rock Suite) and are accompanied by high Th (64–119 ppm), Rb (187–355 ppm), Y (84–289 ppm), Nb (52–106 ppm) and Ga (18–37 ppm). In the southeast of the island, moderate to high uranium values are also present over outcrops of the Po Toi Granite (Lion Rock Suite). The high natural background uranium values over the Po Toi Granite are also shown by the moderate to high values (6–17 ppm) on Po Toi Island where they are accompanied by moderate to high Th (85–100 ppm, Rb (206–334 ppm), Y (68–119 ppm), Nb (63–162 ppm) and Ga (29–48 ppm).

Moderate to high uranium values (9.8–15.4 ppm) over the southern part of Lamma Island mainly coincide with outcrops of the South Lamma Granite (Cheung Chau Suite) which has been intruded by a swarm of E-trending rhyodacite dykes. The highest uranium values (16–17 ppm) are associated with high Th (39–71 ppm), Rb (283–452 ppm), Y (82–244 ppm), Nb (63–85 ppm) and Ga (19–29 ppm).

A strong uranium anomaly (16–41 ppm) is present over the Chi Ma Wan Granite (Cheung Chau Suite) on the south side of Lantau Island. The high uranium values are accompanied by high Th (53–48 ppm), Rb (109–416 ppm), Y (26–195 ppm), and Nb (30–111 ppm). Moderate to high Pb (40–231 ppm), Zn (34–137 ppm) and Sn (5–428 ppm) suggest that some samples have been affected by anthropogenic contamination. However, the majority of samples reflect high natural background levels of uranium. Moderate to high uranium levels (7.6–22.6 ppm) are also present over outcrops of rhyolite and rhyodacite dykes (Kwai Chung Suite), and Lantau Granite (Lamma Suite) in the eastern part of Lantau Island. In the western part of Lantau Island, uranium values are generally moderate (6.2–9.8 ppm) over outcrops of the Lantau Volcanic Group. Minor uranium anomalies (16–19 ppm) are present over granite and quartz monzonite outcrops at Tung Chung and Shek Pik and these are also accompanied by moderate to high levels of Th (50–93 ppm), Rb (153–320 ppm), Y (40–82 ppm), Nb (35–52 ppm) and Ga (16–27 ppm).



VANADIUM
in stream sediment

Statistics
Vanadium (ppm)

Samples	2246
Maximum value	160
Minimum value	<2
Median	37
Mean	43
Standard deviation	26
Detection Limit	2

Vanadium

V

Synopsis

Vanadium levels are generally low to moderate (<37 ppm) over the granitic areas and in areas underlain by fine ash vitric tuff. They are highest (>81 ppm) over outcrops of granodiorite, coarse ash crystal tuff, and andesitic rocks. There is a strong regional distribution of moderate to high vanadium values (>37 ppm) in the New Territories which may be partly influenced by the burning of fossil fuels.

In the western New Territories, levels of vanadium are particularly high (>81 ppm) in areas underlain by andesite of the Tuen Mun Formation, but low (<22 ppm) over the surrounding Tsing Shan, Tai Lam, and Deep Bay granites.

In the northern and northeastern New Territories, vanadium levels are moderate to high (>37 ppm) over outcrops of coarse ash crystal tuff (Tsuen Wan Volcanic Group). Moderate levels of vanadium (22–60 ppm) are present in areas underlain by Upper Palaeozoic and Upper Mesozoic sedimentary rocks.

The highest levels of vanadium (>107 ppm) are found in the central New Territories in association with outcrops of the Tai Po Granodiorite (Lamma Suite) and coarse ash crystal tuff (Tsuen Wan Volcanic Group). Small anomalies are present over outcrops of Permian sedimentary rocks.

Vanadium levels are low to moderate (<37 ppm) over granitic and volcanic areas of eastern New Territories, Kowloon, Hong Kong Island and the islands to the south. In particular, vanadium levels are generally low (<22 ppm) over outcrops of fine ash vitric tuff (Repulse Bay and Kau Sai Chau volcanic groups) and moderate over outcrops of coarse ash crystal tuff (Tsuen Wan and Repulse Bay volcanic groups).

On Lantau Island, the background levels of vanadium are generally low to moderate (<60 ppm) with slight anomalies in areas underlain by coarse ash crystal tuff (Tsuen Wan Volcanic Group).

Geochemistry of vanadium

Vanadium is a transition row element in the periodic table Group VB, with transition element neighbours of Ti and Cr. The trivalent ion V^{3+} has an ionic radius (64 pm), almost identical to that of Fe^{3+} (65 pm). Because of this, vanadium is frequently found as a substitute for Fe in magnetite and in the ferromagnesian silicates formed during primary magmatic processes (Curtis, 1964). Basic rocks are typically enriched in vanadium relative to most intermediate and silicic rocks. Primitive magma types including calc–alkaline, alkaline and tholeiitic rocks have broadly similar vanadium concentrations (Taylor *et al.*, 1969). Mielke (1979) cites values: ultrabasic, 40 ppm; basaltic, 250 ppm; granitic 44–88 ppm; and average crustal abundance of 136 ppm. In ultrabasic rocks the vanadium content generally reflects the abundance of minerals such as Fe–Ti–Cr oxides and pyroxenes. Described as a trace element, vanadium is relatively abundant though it only rarely forms independent minerals in igneous rocks.

Vanadium is largely immobile during metamorphism (Condie, 1976; Eade & Fahrig, 1973; Nicollet & Adriambololona, 1980). The vanadium content of sedimentary rocks primarily reflects the abundance of detrital Fe oxides, clay minerals, hydrous oxides of Fe and Mn, and organic matter. The redox regime is important, vanadium remaining mobile under oxidising conditions but being subject to precipitation just above the sulphate/sulphide redox threshold within a pH range of 5.0–8.0 (Krauskopf, 1956; Brookins, 1988). The average vanadium content of quartzitic sandstones and pure carbonate sediments is low (<15 ppm), with higher values in greywackes (40–150 ppm), shales (90–260 ppm) and clays (*c.* 200 ppm). Coals may also contain appreciable amounts of vanadium. The most V-rich sedimentary rocks are black shales, reflecting both the affinity of the element for organic sorption sites and its relative immobility under reducing conditions.

Surface environment geochemistry

Soil and stream environments favour the concentration of vanadium in two distinct geochemical fractions: resistate minerals, such as detrital Fe oxides and Fe–Mg silicates, and phases sorbed by organic matter, hydrous Fe and Mn oxides and clay minerals. Following its release from primary minerals, the behaviour of vanadium is largely determined by its oxidation state. Under reducing conditions the relatively immobile V^{3+} state is dominant. Solubility increases markedly with conversion to V^{4+} or V^{5+} (and the resultant formation of vanadyl cations such as $VO_2(OH)_3^{2-}$, H_2VO^{4-} or HVO_4^{2-}) in oxic environments. Accordingly, well-drained, lowland areas are likely to host the highest vanadium concentrations in stream waters and, in almost all instances, the limits for vanadium dispersal will be controlled by the prevailing rates of sorption to hydrous Fe and Mn oxides, clays and organic matter (Krauskopf, 1956). The mineral carnotite (a vandate of U and K) is found associated with calcretes in arid environments where evaporation is a dominant feature of the hydrological system.

Vanadium has a variety of industrial uses in metallurgy, electronics and dyeing, but amounts of vanadium used are small and thus these would be an insignificant anthropogenic input to the environment. However, the combustion of coal and the waste from such processes (fly-ash) make a more significant contribution to environmental contamination.

Detailed description

Vanadium levels are high over andesite outcrops of the Tuen Mun Formation in the western New Territories and are in marked contrast to the low contents of vanadium in the surrounding granitic areas. North of Tuen Mun, the vanadium levels reach 154 ppm and are accompanied by high values of Cd (3.9 ppm), Hg (2.4 ppm), MnO (0.18 %), Co (20 ppm) and Fe_2O_3 (13 %). Similar values are present over outcrops of andesite farther north in the Ha Tsuen area.

In the northern New Territories, vanadium anomalies (>81 ppm) at Lin Tong Mei (81–91 ppm) and Wo Hop Shek (90–97 ppm) are accompanied by moderate to high Co (14–23 ppm), Pb (147–340 ppm), Zn (123–234 ppm) and Hg (0.8–3.2 ppm). In the northeastern New Territories, a prominent vanadium anomaly (98 ppm) at Lai Chi Wo is associated with high levels of Hg (3.2 ppm), Pb (340 ppm) and Zn (189 ppm). This area is underlain by coarse ash crystal tuff (Tsuen Wan Volcanic Group) containing siltstone interbeds.

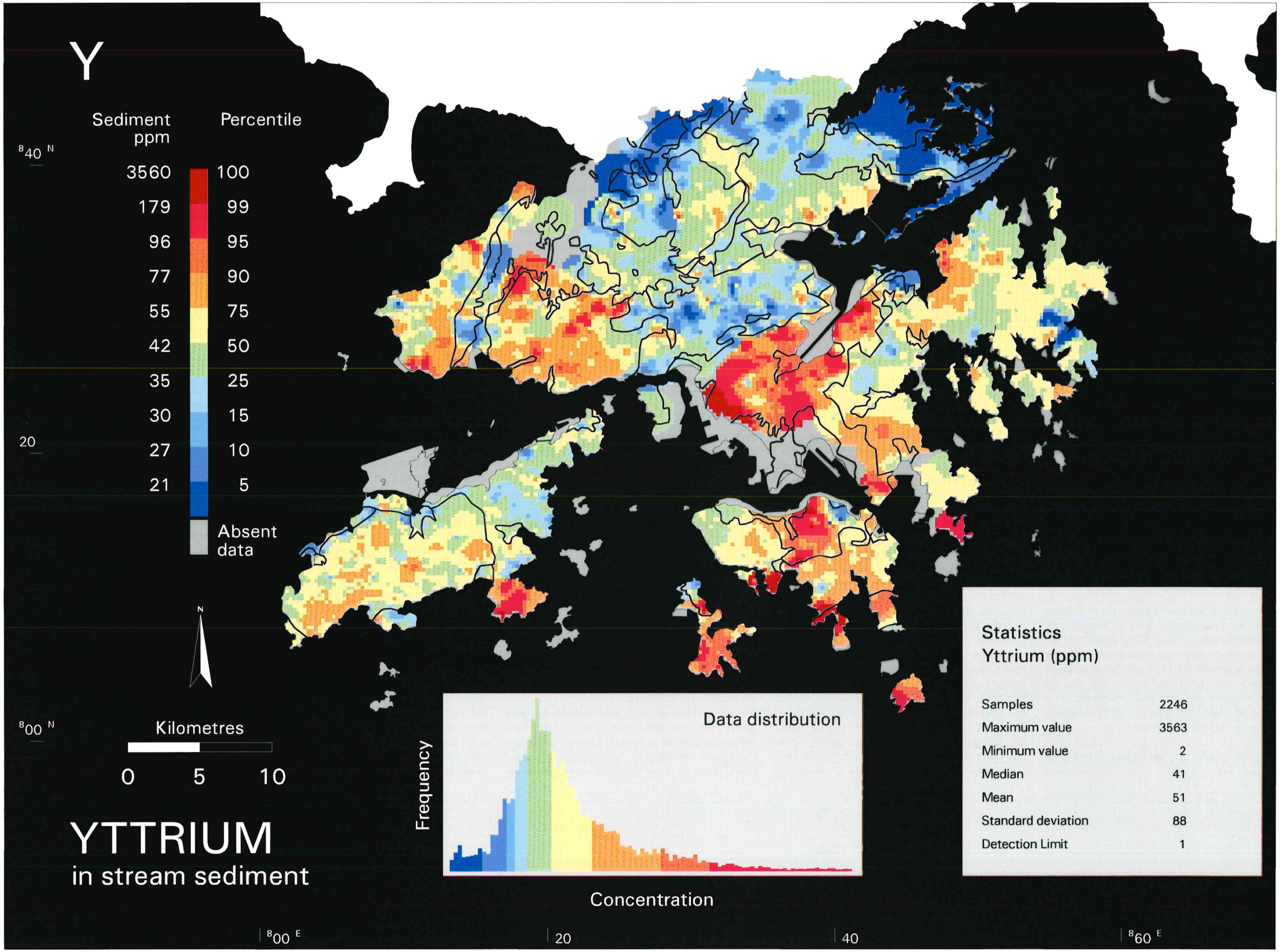
In the central New Territories, strong anomalies occur close to the intrusive contacts between the Tai Po Granodiorite and coarse ash crystal tuff (Tsuen Wan Volcanic Group) and coincide with known areas of Pb–Zn–Cu mineralisation. In contrast to the stream sediments farther north, the high levels vanadium are not accompanied by high levels of Hg. However, levels of other associated metals are high. For example, at Sheung Tong, high vanadium values (>100 ppm) are accompanied by high Co (12–23 ppm), Pb (60–180 ppm), Zn (108–399 ppm) and MnO (0.08–0.27 %). South of Tai Mo Shan there is a marked contrast in vanadium values across the contact between the dominantly Lamma Suite and Tsuen Wan Volcanic Group rocks to the northwest and younger granitic and volcanic rocks to the southeast.

The broad regional pattern of moderate to high vanadium values over much of the central and northern New Territories may be partly related to the concentration of fly-ash derived from the burning of fossil fuels. Concentrations of fly-ash (i.e. microspheres) in stream sediments are particularly high in areas of the central and northern New Territories (see Figure 14).

Low to moderate levels of vanadium characterise most of the area to the southeast of Tai Mo Shan, including most of Sha Tin, eastern New Territories, Kowloon and Hong Kong Island. Vanadium levels are generally low over outcrops of fine ash vitric tuff (Repulse Bay and Kau Sai Chau volcanic groups), but slightly higher over outcrops of coarse ash crystal tuff (Repulse Bay Volcanic Group). Slightly elevated levels of vanadium are present around Ma On Shan and in the Sai Kung area to the southeast. Minor vanadium anomalies at Shan Liu and Tai Mong Tsai are accompanied by moderate Cd (1.3–1.4 ppm), variable Hg (0.4–1.5 ppm) and high Zn (103–113 ppm).

Moderate levels of vanadium in the Clear Water Bay area, in southern Hong Kong Island, and northern Lamma Island are related to outcrops of trachydacite (Kau Sai Chau Volcanic Group) and quartz monzonite (Lion Rock Suite) (see descriptions for Cd and Hg).

On Lantau Island, background levels of vanadium are low to moderate over volcanic rocks of the Lantau Volcanic Group, and moderate over outcrops of granitic rocks (Lamma and Kwai Chung suites) west of Discovery Bay. The elevated values in the granitic areas correspond to known areas of weak Pb–Zn–Cu mineralisation. Slightly elevated values (37–60 ppm) in the southeastern part of the island coincide mainly with outcrops of coarse ash crystal tuff (Tsuen Wan Volcanic Group) and quartz monzonite (Cheung Chau and Lion Rock suites). A typical sample from Chi Ma Wan contains: V (125 ppm), Cd (0.7 ppm), Hg (0.39 ppm) MnO (0.1 %), Fe_2O_3 (5.58 %) and Zn (70 ppm). West of Tung Chung, an isolated vanadium anomaly (91 ppm) is accompanied by unusually high Sn (314 ppm), but low Cd (<0.3 ppm), Hg (0.2 ppm), MnO (0.1 %), Fe_2O_3 (3.63 %), Cu (12.9 ppm) and Zn (65 ppm), suggesting that this sample is partly contaminated.



YTTRIUM

in stream sediment

Statistics
Yttrium (ppm)

Samples	2246
Maximum value	3563
Minimum value	2
Median	41
Mean	51
Standard deviation	88
Detection Limit	1

Yttrium

Synopsis

In the western New Territories, moderate to high levels of yttrium (42–96 ppm) are mainly associated with outcrops of the Tsing Shan and Tai Lam granites (Lamma Suite). Low levels are present over intervening outcrops of andesitic rocks (Tuen Mun Formation).

Low to moderate levels of yttrium (<42 ppm) are found over outcrops of coarse ash crystal tuff (Tsuen Wan Volcanic Group) in the northern New Territories, and low levels (<42 ppm) are associated with outcrops of Upper Palaeozoic and Upper Mesozoic sedimentary rocks.

In the central New Territories and Kowloon, high levels of yttrium (>96 ppm) coincide with outcrops of the Sha Tin and Needle Hill granites (Kwai Chung Suite), and the Kowloon and Kwun Tong granites (Lion Rock Suite).

In the eastern New Territories, yttrium levels are high (55–179 ppm) over outcrops of rhyolite lava (Kau Sai Chau Volcanic Group), but are mostly moderate (35–55 ppm) over the remaining volcanic rock areas. Slightly elevated values are found in areas where quartz monzonites (Lion Rock Suite) are known to outcrop.

Yttrium anomalies (>96 ppm) on Hong Kong Island are mainly confined to outcrops of fine-grained Mount Butler and Po Toi granites (Lion Rock Suite). However, elevated values (55–77 ppm) in the eastern part of the island are associated with outcrops of fine ash vitric tuff (Repulse Bay Volcanic Group). On Lamma Island and Po Toi Island, the yttrium anomalies (>55 ppm) mostly coincide with outcrops of granitic rocks (Cheung Chau and Lion Rock suites).

The highest yttrium values on Lantau Island (>96 ppm) are found over the outcrops of the Chi Ma Wan Granite (Cheung Chau Suite) in the south. Moderate to high levels characterise the areas underlain by the Lantau Volcanic Group, whereas slightly lower levels are found over outcrops of the Tsuen Wan Volcanic Group and related granitic rocks (Lamma Suite).

Geochemistry of yttrium

Yttrium is a Group IIIB element in the periodic table and, as it has a similar chemistry to the rare earth elements (REE), it is included in the group of elements known as the lanthanons (La–Lu + Y). The electron configuration and ionic radius of Y^{3+} (90 pm) resembles those of the heavier REE, with which it is associated in minerals and rocks. This is seen during magmatic processes, in which the behaviour of yttrium is very like that of the heavy REE. It is strongly partitioned into garnet, hornblende, clinopyroxene and biotite, but nevertheless shows slight enrichment in granitic (*c.* 40 ppm) relative to intermediate (*c.* 35 ppm) and basaltic (*c.* 32 ppm) igneous rocks. Mielke (1979) gives a value of 31 ppm for the crustal average of yttrium, a crustal abundance higher than more well-known elements such as Sn and Pb. In basalts, its concentration is sensitive to the degree of partial melting (Wedepohl, 1978). Disproportionately low yttrium concentrations may occur in calc–alkaline magmas as a result of the stabilisation of phases rich in heavy REEs in the source region and/or their fractionation from the magmas. Sewell *et al.* (1992) give an average value of 59 ppm (range 23–156 ppm) for a selection of 18 Hong Kong granites, the lowest results being associated with the Lamma Suite. The highest concentrations in granites are found in sub–alkaline lithologies.

Both yttrium and the heavy REE form more stable complexes than light REE (particularly with carbonate, fluoride or sulphate anions in alkaline solutions) and they are thus more prone to hydrothermal mobilisation (Kosterin, 1959). However, there is little evidence of yttrium mobility during metamorphism (O'Nions & Pankhurst, 1974; Drury, 1978).

The concentration of yttrium in sedimentary rocks is largely determined by the abundance of heavy resistate minerals such as zircon, xenotime [YPO_4] and garnet. In low-energy depositional environments, some yttrium may also occur in stable organic compounds and alkali carbonate complexes. Shales (*c.* 40 ppm) and greywackes (*c.* 30 ppm) are typically enriched in yttrium compared with carbonate rocks (*c.* 4 ppm) and sandstones (*c.* 15 ppm). There is evidence that yttrium is enriched in clays and shales of marine origin relative to their lacustrine counterparts (Balashov *et al.*, 1964). Yttrium enrichment has been reported in laterites (e.g. Calliere *et al.*, 1976) and oolitic ferro–manganese deposits (e.g. Goldberg *et al.*, 1963).

Surface environment geochemistry

In stream sediments most of the yttrium is held in accessory minerals such as garnet, apatite, sphene, monazite and zircon, all of which are resistant to weathering. The relative rates of light and heavy REE mobilisation are subject to considerable contention (e.g. Burkov & Podporina, 1967), but there is evidence that the latter may be preferentially leached on account of the greater stability of the fluoride and carbonate complexes with which they are associated (e.g. Balashov & Khitrov, 1967). In acid environments, yttrium may be mobilised through the dissolution of ferromagnesian silicates (notably clinopyroxenes), but subsequent dispersal is typically restricted by sorption to hydrous Fe oxides and clay minerals. In neutral and alkaline waters, the formation of insoluble carbonate complexes further inhibits mobility and yttrium becomes prone to precipitation in much the same manner as Al (Balashov *et al.*, 1964).

Detailed description

In the western New Territories, yttrium values are moderate to high over the Tsing Shan, Deep Bay, and Tai Lam granites, with anomalies at Sheung Pak Nai (184 ppm), Castle Peak (96–137 ppm), Lam Tei (116–152 ppm) and Ho Pui Reservoir (184 ppm). The highest values generally coincide with fine-grained lithologies, and at Sheung Pak Nai and Castle Peak, the anomalies are associated with high Nb (50–96 ppm), La (39–98 ppm), Rb (507–611 ppm), Ga (28–54 ppm) and Th (79–110 ppm). At Lam Tei and Ho Pui Reservoir, the high yttrium values are accompanied by high Nb (48–83 ppm), Rb (379–632 ppm), Ga (25–45 ppm), Th (67–109 ppm), U (12–17 ppm) and Pb (118–246).

In the central New Territories, high yttrium values coincide with outcrops of fine-grained Needle Hill Granite (Kwai Chung Suite) and Kowloon Granite (Lion Rock Suite), and with fine-grained granite dykes which intrude the Sha Tin Granite (Kwai Chung Suite). Strong anomalies are present in the Kwai Chung (99–3563 ppm), Sha Tin (99–148 ppm), Needle Hill (96–180 ppm), Shan Ha Wai (102–127 ppm), and Tai Shui Hang (101–154 ppm) areas.

At Kwai Chung, the high yttrium values are accompanied by high Nb (42–386 ppm), Zr (151–1168 ppm), La (13–4923 ppm), Rb (108–439 ppm), Ga (23–48 ppm), U (7–35 ppm), Th (54–135 ppm), Pb (81–883 ppm), Zn (67–1490 ppm) and Sn (13–341 ppm). Similar values for these elements accompany the yttrium anomalies at Sha Tin and Needle Hill. For example, at Sha Tin, typical ranges of values are: Nb (54–176 ppm), Zr (446–2037 ppm), Rb (86–625 ppm), Ga (20–49 ppm), U (13–39 ppm), Th (77–184 ppm), Sn (22–398 ppm); and for Needle Hill: Nb (43–80 ppm), Zr (387–1694 ppm), La 4–357 ppm), Rb (209–449 ppm), Ga (22–33 ppm), Th (77–184 ppm). Both areas are principally underlain by fine-grained Needle Hill Granite (Kwai Chung Suite).

At Sha Ha Wai and Tai Shui Hang, the high yttrium values are accompanied by high Nb (99–153 ppm), Rb (38–635 ppm), Ga (25–30 ppm), U (10–26 ppm) and Th (73–95 ppm) but relatively low Zr (591–663 ppm) and Sn (19–29 ppm). These areas are underlain by dykes of fine-grained granite and related quartz monzonite (Lion Rock Suite) which intrude the Sha Tin Granite (Kwai Chung Suite).

A strong yttrium anomaly (123–250 ppm) west of Ma On Shan coincides with high Nb (50–164 ppm), U (16–17 ppm), Th (60–125 ppm), Cu 19–140 ppm), Pb (113–769 ppm), Zn (199–662 ppm) and Sn (18–589 ppm). The area is adjacent to a major outcrop of fine-grained granite and high values of associated metals are likely to be partly related to Fe mineralisation in the nearby abandoned Ma On Shan mine.

In the Sham Chung area, high values of yttrium (105–115 ppm) are associated with outcrops of the rhyolite within the Lai Chi Chong Formation (Lantau Volcanic Group). These high values are accompanied by moderate to high Nb (66–80 ppm) and Cs (8–19 ppm), but relatively low values of other elements such as U (8–13 ppm), Th (45–51 ppm) and Ga (18–20 ppm).

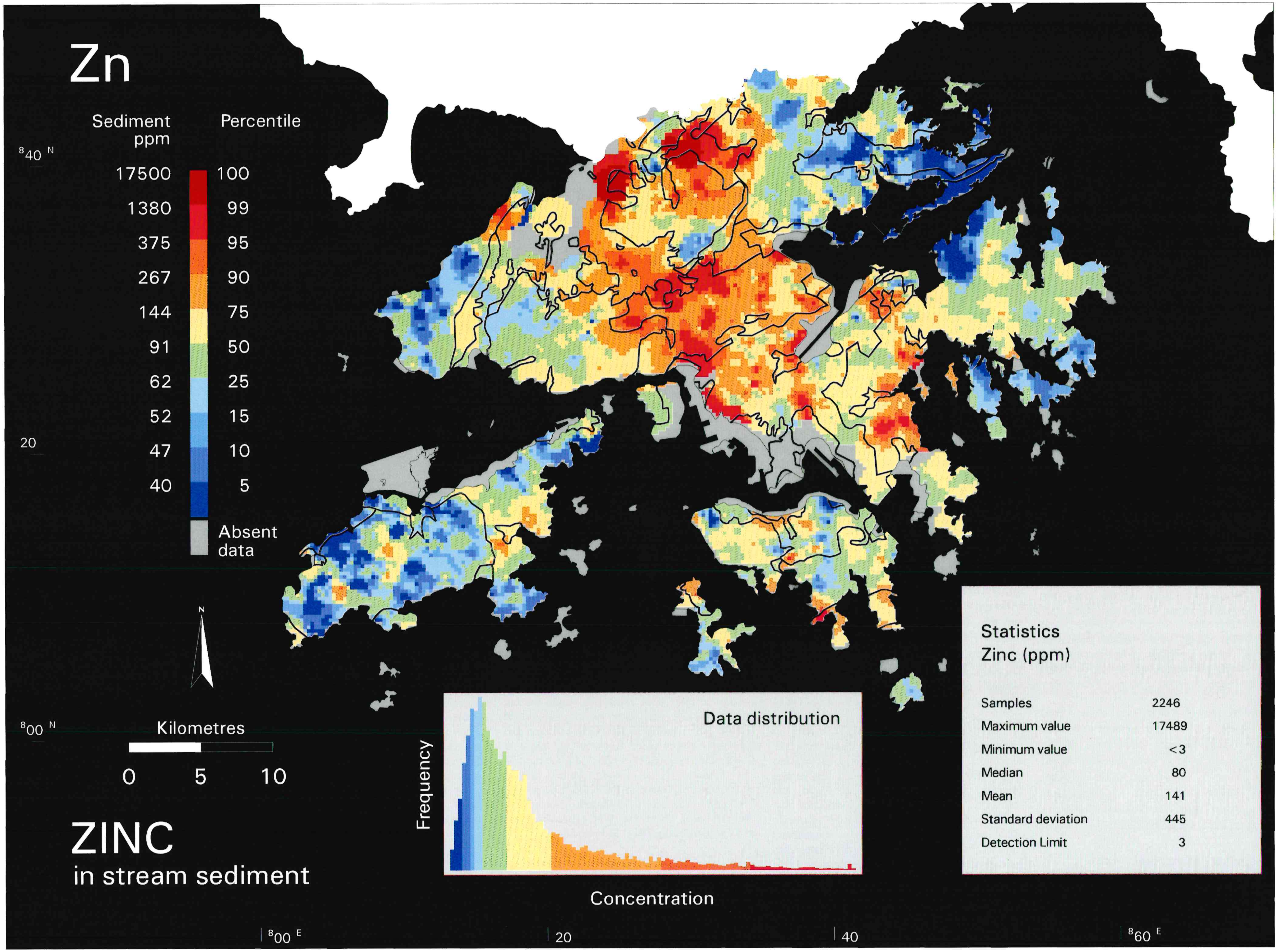
In eastern Kowloon, yttrium values are slightly elevated over outcrops of the Kwun Tong Granite (Lion Rock Suite), and a small anomaly (190 ppm) is present at Yau Tong. This area is known to host minor W–Mo–Sn mineralisation (see descriptions for Be, Sn and W).

On Hong Kong Island, yttrium anomalies are associated with outcrops of fine-grained granite at North Point (96–289 ppm), Chung Hom Wan (997 ppm), and D'Aguilar Peak (64–91 ppm). High yttrium values are also present over outcrops of fine ash vitric tuff at Wong Chuk Hang (811–1126 ppm). The high yttrium values at North Point are accompanied by moderate to high Zr (161–1402 ppm), Nb (46–103 ppm), La (26–158 ppm), Ce (80–270 ppm), Ga (18–35 ppm), U (10–25 ppm) and Th (53–119 ppm). At Chung Hom Wan, high values of La (328 ppm), Ce (146 ppm), Pb (177 ppm) and Zn (462 ppm) accompany the yttrium anomaly, whereas values of Ga (18 ppm), Rb (219 ppm), U (7 ppm) and Th (51 ppm) are relatively low. This suggests that the stream sediments may be partly affected by local anthropogenic contamination. At D'Aguilar Peak, the moderate to high yttrium values coincide with moderate to high Rb (269–310 ppm), Ga (25–33 ppm), and Th (61–75 ppm). Unusually high values of yttrium (811–1126 ppm) are present at Wong Chuk Hang and these are accompanied by relatively high levels of La (1348–2151 ppm), Ce (373–656 ppm), Rb (209–419 ppm), Ga (22–37 ppm) and Th (38–80 ppm). These high levels again suggest the influence of anthropogenic activity.

On Lamma Island, high levels of yttrium (96–244 ppm) over outcrops of medium-grained South Lamma Granite (Cheung Chau Suite) are accompanied by high Zr (375–2262 ppm), Nb (70–11 ppm), Rb (132–465 ppm), Ga (22–37 ppm, U (11–17 ppm) and Th (38–87 ppm). High levels of yttrium (119–124 ppm) on Po Toi Island are associated with outcrops of fine-grained Po Toi Granite (Lion Rock Suite) and coincide with moderate to high Rb (277–696 ppm), Ce (180–313 ppm), Ga (25–29 ppm), U (15–17 ppm) and Th (56–85 ppm).

Elevated levels of yttrium (42–77 ppm) on Lantau Island mostly coincide with outcrops of volcanic rocks belonging to the Lantau Volcanic Group. However, the highest yttrium values (97–167 ppm) are present over outcrops of medium- and fine-grained Chi Ma Wan Granite (Cheung Chau Suite) on the side of the island. These high values are accompanied by relatively high levels of Zr (1252–3287 ppm), Nb (48–111 ppm), La (21–133 ppm), Ce (77–315 ppm), Pb (34–231 ppm), Rb (145–227 ppm), Ga (13–28 ppm), U (18–41 ppm), Th (112–248 ppm) and Sn (5–428 ppm).

Zn



Sediment ppm	Percentile
17500	100
1380	99
375	95
267	90
144	75
91	50
62	25
52	15
47	10
40	5
▨	Absent data

Statistics
Zinc (ppm)

Samples	2246
Maximum value	17489
Minimum value	<3
Median	80
Mean	141
Standard deviation	445
Detection Limit	3

ZINC
in stream sediment

Zinc

Zn

Synopsis

Elevated concentrations of zinc (>144 ppm) are found mostly in the central and northern New Territories where they are principally associated with volcanic rocks of the Tsuen Wan Volcanic Group. Low to moderate zinc levels (<144 ppm) characterise most other areas of Mesozoic granitic and volcanic rocks, and low to very low concentrations (<62 ppm) are present over outcrops of Upper Palaeozoic and Upper Mesozoic sedimentary rocks.

The strongest zinc anomalies (>375 ppm) occur in the vicinity of Tai Mo Shan in association with known areas of Pb–Zn–Cu mineralisation (Tsuen Wan Volcanic Group). In the northern New Territories, the anomalously high levels of zinc (>1380 ppm) are commonly due to industrial waste metal contamination with the strongest contamination being in the Mai Po and Sheung Shui districts.

Small, local zinc anomalies (>375 ppm) in Sha Tin, Kwai Chung and Kowloon are associated mainly with industrial metal contamination, although in the vicinity of Ma On Shan, the zinc anomaly is thought to be due to a combination of high natural background levels and contamination by mining waste.

Over most of Hong Kong Island and Lamma Island, zinc levels are generally low to moderate (<144 ppm) with minor elevated concentrations associated with local contamination.

Background levels of zinc are generally low (<91 ppm) over the volcanic rocks of Lantau Island with small local anomalies due to contamination. However, in the northeastern part of the island, the zinc levels are slightly elevated due to the presence of mineralisation in the granitic rocks (Lamma and Kwai Chung suites).

Geochemistry of zinc

Zinc, along with Cd and Hg, is a Group IIB element in the periodic table, zinc being considerably more electropositive than its transition neighbour Cu. It is found only in the 2^+ valency state. During magmatic processes, zinc (like most other first–row transition metals) shows compatibility during early fractionation and thus becomes enriched in basic relative to silicic rocks (ultrabasic 50 ppm; basaltic 105 ppm; granitic 39–60 ppm; syenitic, 130 ppm; and crustal average 76 ppm (Mielke, 1979)). It is readily partitioned into oxides and silicates by substitution for Fe^{2+} and Mg^{2+}, both of which have similar ionic radii to Zn^{2+} (74 pm). Zinc and Ni also have similar ionic radii, though Ni^{2+} can substitute for Mg^{2+} and Fe^{2+} in six-fold co-ordination sites in minerals such as olivine, and Zn^{2+} preferentially occupies four-fold co-ordination sites (Wedepohl, 1969). In basic rocks the principal zinc carrier is magnetite, while biotite is generally the most important in granites (Ure & Berrow, 1982). Where the two minerals co-exist, biotite typically holds more zinc. Enrichment in chrome spinels has been suggested as an explanation for the abundance of zinc in layered ultrabasic bodies (Carter, 1970). Zinc exhibits its chalcophile nature by occurring in sulphide minerals. Sphalerite [ZnS] is the commonest zinc mineral.

Mobilisation of zinc is limited during the low-grade alteration of volcanic rocks (Condie, 1976). Only minor loss occurs at medium and high grades of metamorphism (e.g. van de Kamp, 1970; Nicollet & Andriambololona, 1980).

In sedimentary rocks zinc is primarily related to the abundance of detrital ferromagnesian silicates, magnetite and clay minerals (Wedepohl, 1978). It is also readily adsorbed onto ferric oxides, and co-variation with total Fe is common (Knezek & Ellis, 1980). Carbonate rocks (*c.* 50 ppm Zn) and quartzo–feldspathic sands (30–50 ppm) are generally poor in zinc compared with greywackes (70–100 ppm) and shales (50–190 ppm). Zinc has an affinity for organic matter, and high values occur in oil shales (Wedepohl, 1978). High values of zinc (to *c.* 1 %) have been recorded in oolitic ironstones and recent ferro–manganese nodules (Jenkyns, 1977).

Surface environment geochemistry

In stream sediments, zinc primarily occurs in detrital oxides and ferromagnesian silicates, which weather slowly in most environments. It may be mobilised more rapidly through the dissolution of sulphides and galvanised metallic contaminants in acid stream waters (Ure & Berrow, 1982). Weathering of sulphide minerals in oxidising conditions may give rise to high concentrations (>100 µg/l) of dissolved zinc sulphates and carbonates (Massey & Barnhisel, 1972). Elsewhere, zinc is rapidly sorbed to secondary oxides (e.g. Jenne, 1968; Robinson, 1981), clay minerals (e.g. Kurki, 1974) and organic matter (e.g. Ure & Berrow, 1982) in all but the most acid conditions (pH <4.5).

The complexity of zinc dispersion in stream sediments can be seen in cumulative probability plots of regional data (Coats *et al.*, 1994; Johnson, 1994). Coarse-grained sphalerite can show detrital dispersion, though zinc in fine-grained sphalerite can readily be removed in solution (especially if subjected to surficial leaching). The dispersion by zinc in solution is then controlled by co-precipitation with secondary oxides from solution. Furthermore, biotite is the main carrier of zinc in granitic rocks and this is the rock constituent which is least resistant to decomposition, unlike the Zn-bearing magnetite in basic rocks. In regional geochemical mapping of Sumatra (Johnson, 1994), zinc was strongly associated with Co-Mn–Cu and to a lesser extent Fe, indicating a hydromorphic dispersion of zinc in the tropical environment and precipitation with Mn and Fe oxides.

Cooper & Thornton (1994) list many potential sources of possible contamination in addition to the obvious source of metal mining and smelting. A significant contaminant is likely to be brass and galvanised products. In Sumatra, numerous isolated zinc highs were noted in stream sediments in fairly remote localities. Johnson *et al.* (1993) observed the widespread use of galvanised sheets for roofing, even in remote villages, and suggested this as a likely source of contamination. Zinc is an essential trace element for humans, animals and higher plants.

Detailed description

In the western New Territories, zinc levels are generally low to moderate (<91 ppm) over outcrops of the Tsing Shan and Tai Lam granites (Lamma Suite). A small zinc anomaly (551 ppm) in the Lau Fau Shan district is associated with low levels of Pb (36 ppm), Sn (14 ppm) and As (10.5 ppm) and high Cu (174 ppm), indicating the presence of metallic contamination.

In the northern New Territories, extremely high zinc levels are present in the vicinity of Mai Po (17 489 ppm) and Sheung Shui (9639 ppm). In both areas, the concentrations are coincident with high levels of industrial metals including Cu (875–2849 ppm), Pb (316–884 ppm), Sn (18–181 ppm), Sb (9–88 ppm) and As (122–160 ppm), indicating that the anomalies are principally of anthropogenic origin. This is confirmed by the field observation of nearby ceramic and metal contamination at both sites. Background levels of zinc in the vicinity of the Lin Ma Hang lead mine are in the range 91–267 ppm and are typically associated with low to moderate levels of Cu (11–45 ppm). Similar low levels of Cu (14 ppm), along with low Sn (19 ppm), moderate Pb (120 ppm) and moderate As (30 ppm), accompanies a small zinc anomaly (197 ppm) near Lai Che Wo to the southeast of Lin Ma Hang.

Anthropogenic contamination is largely responsible for the elevated zinc levels in the Lin Tong Mei (558 ppm) and Pat Hueng areas (440 ppm). A typical sample from Lin Tong Mei contains: Pb (214 ppm), Cu (492 ppm), Sn (56 ppm), Sb (10 ppm), As (81 ppm) and Ag (1.6 ppm).

Elevated concentrations of zinc in the Tai Mo Shan area (>144 ppm) are mostly associated with zones of Pb–Zn–Cu mineralisation in the contact zone between Tai Po Granodiorite and coarse ash crystal tuff of the Tsuen Wan Volcanic Group. High concentrations of zinc are present in stream sediments both to the north and south of Tai Mo Shan, and closely match the Pb anomalies. However, in the Shek Kong area, some of the zinc may be of anthropogenic origin as suggested by associated high levels of Sn (441 ppm). In the area surrounding Ho Pui Reservoir, the high zinc values (441–432 ppm) are associated with unusually high Ag concentrations. A representative sample contains the following: Pb 259 ppm, Cu 21 ppm, Sn 63 ppm, Sb 7 ppm, Bi 22 ppm, As 36 ppm, W 12 ppm and Ag 20 ppm. A broad zinc anomaly (377–1009 ppm) north of Tsuen Wan coincides with a Pb–Zn deposit reported from Chuen Lung (Peng, 1978). The high levels of zinc are associated with high Pb (119–456 ppm), Sn (13–1388 ppm), and Cu (20–269 ppm) values suggesting that some of the metallic concentrations may be of anthropogenic origin.

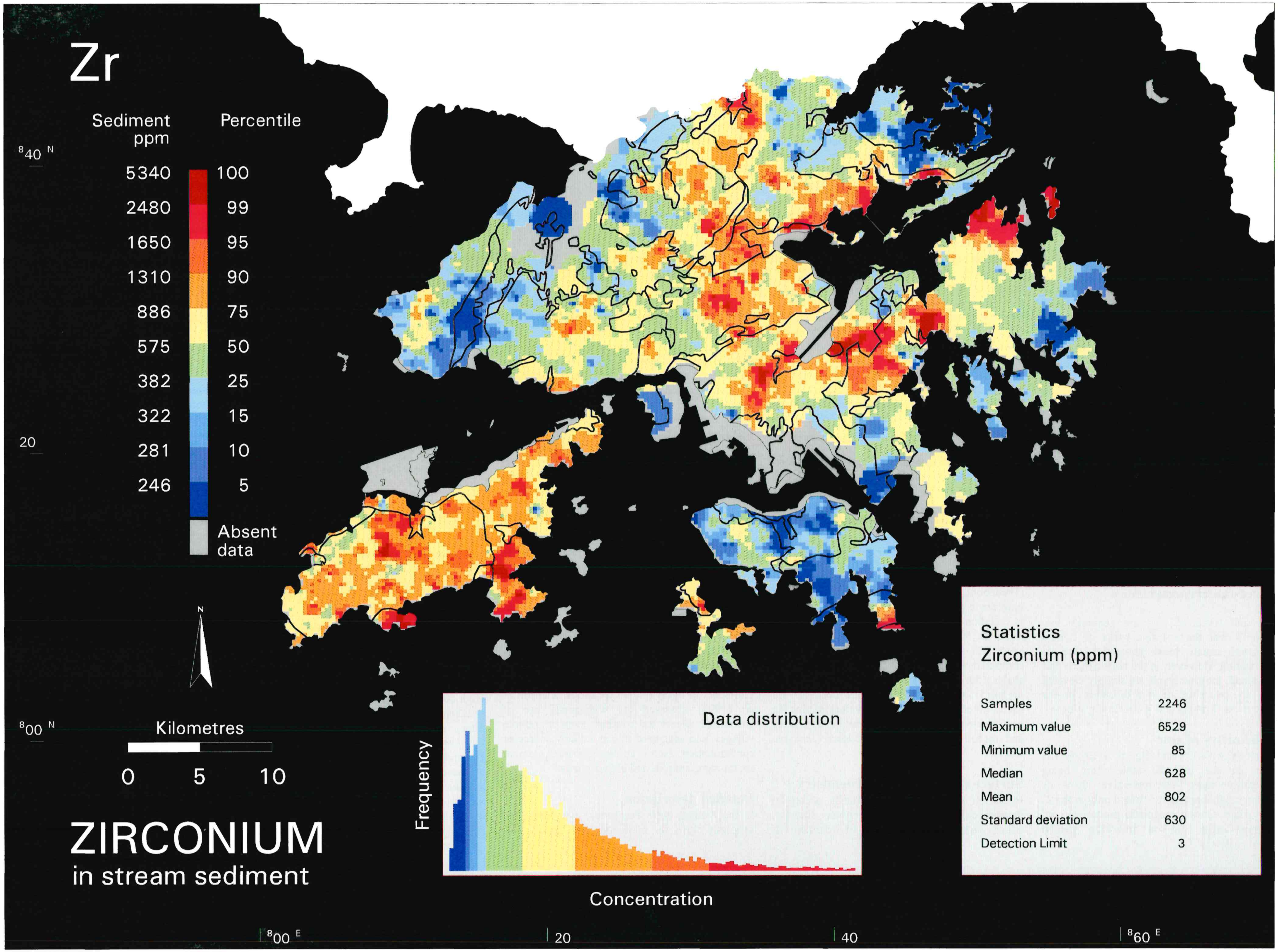
Isolated zinc anomalies over Sha Tin, Kwai Chung, and Kowloon are mainly associated with strongly contaminated samples. The samples typically contain very high concentrations of Cu, Pb, Sn, As and W.

At Ma On Shan, elevated zinc values (405–421 ppm) are associated with Fe mineralisation , although some samples show evidence of contamination with mining waste. For example, a typical contaminated sample has the following metal concentrations: Zn 490 ppm, Pb 896 ppm, Cu 303 ppm, Sn 449 ppm, Bi 361 ppm, As 111 ppm and Ag 12.8 ppm.

In the eastern New Territories, zinc anomalies are present at Sai Kung (448 ppm), Ho Chung (401 ppm), and Tai Po Tsai (582–594 ppm). At Ho Chung and Tai Po Tsai, the high zinc values are accompanied by moderate to high values of Pb (115–258 ppm), Bi (3–18 ppm), Cu (58–492 ppm) and Sn (57–71 ppm), suggesting the involvement of metallic contamination.

On Hong Kong Island, the small zinc anomalies are commonly accompanied by high levels of associated metals including Pb, Cu and Sn indicating a strong anthropogenic overprint. Zinc levels are unusually low (<40 ppm) in the vicinity of North Point despite the reported occurrence of Zn mineralisation (Peng, 1978).

There are four small zinc anomalies on Lantau Island. The greatest (144–267 ppm) occurs in the vicinity of Mui Wo and is associated with Pb–Zn–Cu mineralisation. Other anomalies near Ngong Ping and Shek Pik are related mainly to anthropogenic contamination.



ZIRCONIUM
in stream sediment

Statistics
Zirconium (ppm)

Samples	2246
Maximum value	6529
Minimum value	85
Median	628
Mean	802
Standard deviation	630
Detection Limit	3

Zirconium

Zr

Synopsis

In the western New Territories, low to moderate levels of zirconium (<575 ppm) are present over outcrops of the Tsing Shan and Tai Lam granites (Lamma Suite) whereas very low levels (<246 ppm) are found over andesite outcrops of the Tuen Mun Formation.

Moderate to high levels of zirconium (>575 ppm) in the central and northern New Territories coincide with outcrops of coarse ash crystal tuff (Tsuen Wan Volcanic Group) and with the Tai Po Granodiorite (Lamma Suite). Low to moderate levels of zirconium (<575 ppm) are found over outcrops of Upper Palaeozoic and Upper Mesozoic sedimentary rocks.

In the eastern New Territories and Kowloon, moderate to high levels of zirconium (>575 ppm) are present over outcrops of quartz monzonite (Lion Rock Suite), coarse ash crystal tuff (Repulse Bay Volcanic Group) and medium-grained granite (Lion Rock Suite). Zirconium values are generally low (<575 ppm) over outcrops of fine ash vitric tuff (Repulse Bay and Kau Sai Chau volcanic groups).

On Hong Kong Island, zirconium levels are generally low to moderate (<575 ppm), except over outcrops of quartz monzonite (Lion Rock Suite) in the southeast. Moderate to high levels of zirconium (>382 ppm) characterise most of Lamma Island, with the highest values coincident with outcrops of quartz monzonite (Lion Rock Suite) and coarse-grained Lantau Granite (Lamma Suite).

Zirconium values are moderate to high (>575 ppm) over most of Lantau Island, with little difference between granitic and volcanic areas. Local anomalies are present over outcrops of quartz monzonite (Cheung Chau and Lion Rock suites) and medium-grained granite (Cheung Chau Suite).

Geochemistry of zirconium

Zirconium is a Group IVB element (along with Ti and Hf) and an element of the second transition series of elements. The ionic radii of Zr^{4+} and Hf^{4+} (72 and 71 pm respectively) are almost identical, resulting in very similar chemical behaviour of the two elements. Zirconium is a lithophile element and forms its own silicate mineral zircon [$ZrSiO_4$]. Zircon accounts for most of the zirconium in igneous rocks. During magmatic processes the highly charged Zr^{4+} ion is incompatible with the lattice sites of most common rock-forming silicates. It is therefore preferentially partitioned into accessory phases such as zircon, baddeleyite [ZrO_2] and sphene. It can substitute for Ti in ilmenite and rutile and is also present in clinopyroxenes, amphiboles and garnets. Silicic igneous rocks are generally enriched in zirconium relative to basic lithologies, though zirconium levels may decrease markedly in the silicic members of calc–alkaline suites. Mielke (1979) reports a crustal average of 162 ppm, and for specific rock types; ultrabasic, 45 ppm; basaltic, 140 ppm; granitic, 140–175; and syenitic 500 ppm. Sewell *et al.* (1992) give a wider range of zirconium values (88–389 ppm, average 153 ppm) for 18 representative Hong Kong granites. Many alkaline rocks are enriched in zirconium as a result of the formation of stable Na complexes (Watson, 1979).

Limited remobilisation of zirconium may occur during intense metasomatism and granite-related hydrothermal alteration (Simpson *et al.*, 1979; Hynes, 1980). Under most other circumstances, the element appears to be immobile, with comparable levels prevailing in metamorphic rocks of all grades (Shaw, 1954; Engel & Engel, 1960; Tarney & Saunders, 1979).

The zirconium content of sedimentary rocks is very much related to the presence of detrital heavy minerals such as zircon and sphene. Variations in energy regimes within stream channels can lead to varying amounts of zirconium in sediments. Trace quantities of authigenic zircon may also occur as adsorbed coatings on diagenetic clays (Nicholls & Loring, 1962). The concentration of zirconium in greywackes (140–800 ppm) is typically higher than that in sandstones (160–220 ppm), shales or other mudstones (100–300 ppm). The abundance of zirconium in limestones is generally very low (20–130 ppm).

Surface environment geochemistry

The primary carriers of zirconium in stream sediments are minerals such as zircon and sphene which are very resistant to weathering and only release zirconium very slowly. Most of the zirconium which is mobilised is derived from the weathering of mafic minerals and is typically rapidly adsorbed onto clays as $Zr(OH)_4$.

Detailed description

In the western New Territories, low to moderate levels of zirconium are present over outcrops of fine-grained granite Tsing Shan and Tai Lam granites (Lamma Suite), whereas very low levels are found over andesite outcrops of the Tuen Mun Formation. Slightly elevated zirconium levels south of Nim Wan (382–886 ppm), and in the vicinity of Tai Lam Chung (575–1310 ppm), correspond with outcrops of fine- to medium-grained granite and coarse-grained granite. North of Tai Lam Chung Reservoir, a small zirconium anomaly (1697 ppm) near Tai Tong Tsuen is accompanied moderate to high levels of Nb (72 ppm), Y (131 ppm) and Ce (193 ppm). These elevated values may also be partly related to outcrops of medium-grained Tai Lam Granite (Lamma Suite).

Zirconium values are moderate to high over a broad area of central and northern New Territories with prominent anomalies at Ta Kwu Ling (2084–2531 ppm), Plover Cove (1650–3131 ppm), Lam Tsuen Valley (1707–3028 ppm), Tai Mo Shan (1682–3515 ppm) and Sha Tin Valley (1674–6529 ppm). The localities are underlain principally by coarse ash crystal tuff (Tsuen Wan Volcanic Group) and Tai Po Granodiorite (Lamma Suite), although in the Sha Tin Valley, the anomaly mainly lies over outcrops of coarse-grained Sha Tin Granite. At Ta Kwu Ling in the north, high zirconium values are associated with moderate to high Cu (37–131 ppm), Pb (43–202 ppm), Zn (142–421 ppm) and Hg (<0.1–0.8 ppm). High zirconium values at Plover Cove are accompanied by moderate to high Ce (96–116 ppm), Cs (12–31 ppm) and TiO_2 (1.06–1.53 %), whereas at Lam Tsuen Valley, they are associated with high values of Pb (17–212 ppm), Zn (161–204 ppm), Cs (14–17 ppm) and Sn (6–134 ppm), the latter suggesting the presence of anthropogenic activity. Similar high values of Pb (211–410 ppm), Zn (206–417 ppm) and Cs (8–120 ppm) accompany the high zirconium values in the vicinity of Tai Mo Shan. In the Sha Tin Valley, the marked zirconium anomaly is associated with unusually high values of Pb (43–2256 ppm), Zn (48–662 ppm), Cs (1–27 ppm) and Sn (41–8881 ppm), which strongly suggest local contamination.

To the east of Sha Tin, a prominent zirconium anomaly is present over Siu Lek Yuen and extends eastwards towards Pyramid Hill. Rocks in this area consist of coarse- and medium-grained Sha Tin Granite (Kwai Chung Suite) which has subsequently been intruded by dykes of quartz monzonite and fine-grained granite (Lion Rock Suite). At Siu Shek Yuen, the high zirconium values (2322–4805 ppm), are accompanied by moderate to high La (51–68 ppm), Ce (140–189 ppm), Cs (2–9 ppm) and Zn (110–165 ppm).

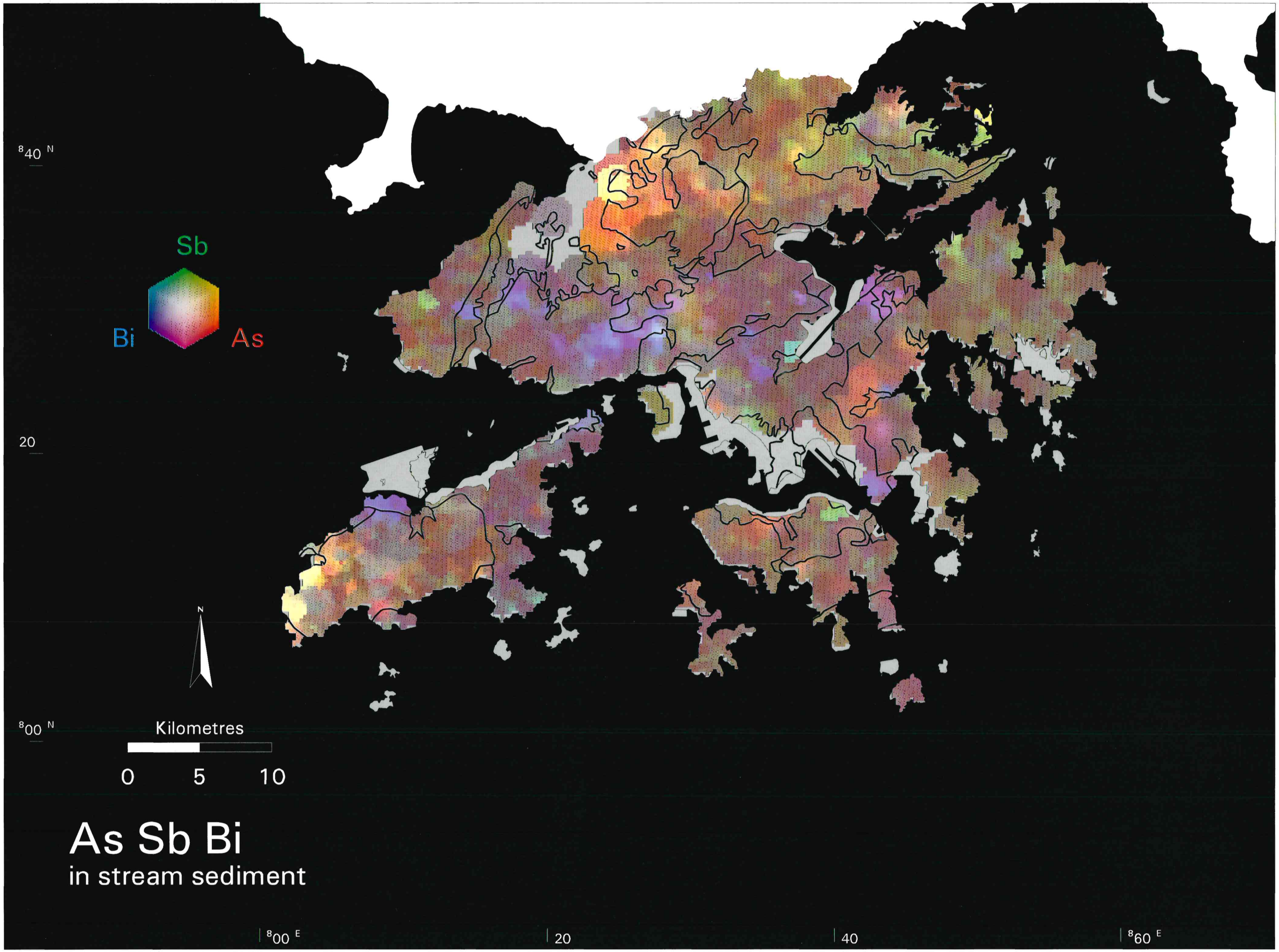
In the eastern New Territories, prominent zirconium anomalies are present south of Ma On Shan (2710 ppm), at Shan Liu (1980–5666 ppm), Buffalo Hill (1828–2364 ppm), Mount Hallowes (2176–5395 ppm) and Grass Island (4066 ppm). The main rock type underlying the Shan Liu, Buffalo Hill, Mount Hallowes and Tap Mun areas is coarse ash crystal tuff (Repulse Bay Volcanic Group), whereas south of Ma On Shan, dykes of quartz monzonite (Lion Rock Suite) and flow-banded rhyolite (Kau Sai Chau Volcanic Group) intrude outcrops of coarse ash crystal tuff (Repulse Bay Volcanic Group). The zirconium anomaly south of Ma On Shan is of similar magnitude to that at Siu Lek Yuen and has similar levels of accompanying metals (e.g. La 69 ppm, Ce 160 ppm, Cs 11 ppm, and Zn 101 ppm). Farther south at Buffalo Hill, slightly higher abundances of these elements (e.g. La 68–96 ppm, Ce 191–229 ppm, Cs 20–21 ppm and Zn 97–104 ppm) accompany the high zirconium values. At Shan Liu, the very high levels of zirconium are accompanied by moderate to high La (88–89 ppm), Ce (203–251 ppm), Zn (113–155 ppm) and Sn (8–73). Moderate levels of these metals are associated with the zirconium anomalies at Mount Hallowes and Grass Island.

In the Clear Water Bay area, slightly elevated zirconium values coincide with outcrops of trachydacite lava (Kau Sai Chau Volcanic Group) and quartz monzonite (Lion Rock Suite), whereas over the rest of eastern New Territories, zirconium levels are low to moderate over outcrops of fine ash vitric tuff (Kau Sai Chau Volcanic Group).

On Hong Kong Island, a small zirconium anomaly (1913–1942 ppm) near D'Aguilar Peak coincides with outcrops of quartz monzonite (Lion Rock Suite) and Tai Po Granodiorite (Lamma Suite). The high zirconium values are accompanied by moderate to high La (72–191 ppm), Ce (184–540 ppm), Cs (7–16 ppm), and Pb (64–123 ppm). Over most other areas of Hong Kong Island, background levels of zirconium are generally low.

On Lamma Island, moderate to high levels of zirconium (2407–2262 ppm) over outcrops of coarse ash crystal tuff (Tsuen Wan Volcanic Group), quartz monzonite (Lion Rock Suite), and coarse-grained granite (Lamma Suite) are accompanied by moderate to high values of La (95–105 ppm), Ce (281–356 ppm), Y (98–244 ppm), Cs (6–12 ppm) and Pb (99–113 ppm).

Zirconium levels are generally moderate to high over most of Lantau Island with prominent anomalies at Chi Ma Wan (1712–3287 ppm), Shek Pik (1669–2555 ppm), Mui Wo (2329 ppm), Discovery Bay (1670 ppm), Tung Chung (2098–2868 ppm), and Penny's Bay (2041 ppm). Overall, the zirconium levels do not vary significantly across areas underlain by volcanic rocks and granitic rocks. However, the anomalous values on the south coast generally correspond with outcrops of quartz monzonite (Cheung Chau and Lion Rock suites) and coarse ash crystal tuff (Tsuen Wan Volcanic Group). In these areas (e.g. Mui Wo and Shek Pik), typical ranges of associated metals are as follows: La (42–159 ppm), Ce (130–278 ppm), Cs (15–19 ppm), Pb (36–152 ppm) and Zn (49–118 ppm). At Chi Ma Wan, a prominent zirconium anomaly (1712–3287 ppm) is present over outcrops of medium-grained granite (Cheung Chau Suite). This is accompanied by high values of associated metals such as La (26–133 ppm), Ce (105–315 ppm), Cs (3–12 ppm), Pb (88–226 ppm) and Sn (5–548 ppm). Slightly lower values for these metals are found in association with the zirconium anomaly at Tung Chung (e.g. La 25–51 ppm, Ce 30–57 ppm, Pb 69–118 ppm and Sn 56–314 ppm). At Discovery Bay and Penny's Bay, the high zirconium values in each area are accompanied by generally moderate levels of La (44–45 ppm), Pb (26–56 ppm) and Zn (37–42 ppm), but high levels of Ce (104–128 ppm) and Cs (10–22 ppm).



As Sb Bi
in stream sediment

Combined anomaly map for Arsenic–Antimony–Bismuth

As–Sb–Bi

High values of all three elements are shown as a white colour; high Sb–As and moderate Bi are indicated by a light yellow colour.

This three component image shows an area of enrichment in southeastern Lantau Island, which corresponds to reported occurrences of Fe mineralisation (Peng, 1978). Further investigation is required to establish whether there is any mineral potential.

A similar but broader Sb–Bi–As high in northwestern New Territories is mainly of anthropogenic origin. Levels of other metallic elements, such as Cu and Zn, are very high, and field records indicate the presence of ceramic and metalliferous contamination.

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APPENDICES

Appendix 1 Analyses of representative duplicate control samples used to monitor variability in sampling and analytical drift between sample batches.

Element/	Sample	Duplicate	Sample	Duplicate	Sample	Duplicate	Sample	Duplicate	Sample	Duplicate	Sample	Duplicate	Sample	Duplicate
Sample No.	1546	1572	1574	1575	1901	1926	1914	1925	1999	2012	1923	2003	2261	2279
Ag ppm	0.4	0.6	0.4	0.0	0.4	0.2	0.0	0.5	1.2	0.3	0.3	0.7	0.2	0.3
As ppm	76	69	29	18	55	50	37	37	7	10	6	3	22	23
Ba ppm	613	469	436	429	495	471	693	726	506	516	404	386	606	567
Bi ppm	3	3	4	0	0	0	4	7	0	0	10	11	0	5
CaO wt%	1.03	0.28	0.19	0.18	0.18	0.17	0.3	0.31	0.37	0.38	1.22	1.32	0.3	0.3
Cd ppm	0.5	0.4	0.3	0.3	0.3	0.3	0.9	0.8	0.5	0.5	1.7	1.7	0.3	0.3
Ce ppm	95	113	118	198	112	104	121	125	91	87	119	110	94	94
Co ppm	7	7	3	9	9	7	8	11	11	11	10	14	0	0
Cr ppm	40	18	26	24	15	10	23	52	20	29	35	40	18	100
Cs ppm	11	27	14	23	13	11	7	7	14	12	8	6	10	11
Cu ppm	8.2	3.8	4.1	6.7	10.4	5.1	14.9	16.3	15.1	15.9	11.6	14.5	2.7	4.9
Fe_2O_3 wt%	5.43	4.7	5.28	6.15	5.41	4.92	6.82	6.89	6.14	6.08	4.91	4.71	3.12	2.99
Ga ppm	14	12	16	19	18	15	23	22	18	20	11	10	13	14
Ge ppm	0	0	0	0	3	0	1	2	2	1	2	3	0	2
Hg ppm	0.0	0.5	1.7	2.0	0.3	0.2	0.5	0.5	1.6	1.0	0.0	0.0	1.6	0.0
La ppm	45	51	46	43	52	49	67	65	69	65	43	42	51	53
MnO wt%	0.1	0.08	0.01	0.05	0.1	0.07	0.13	0.13	0.15	0.13	0.13	0.14	0.04	0.05
Mo ppm	1.4	1.9	4.5	3.9	2.1	2.5	1.6	1.3	2.8	2.6	2.0	1.1	0.8	0.4
Nb ppm	18	19	16	22	20	21	24	23	21	18	8	11	20	25
Ni ppm	9	9	4	6	0	0	6	11	4	7	4	6	11	8
P_2O_5 wt%	0.16	0.14	0.06	0.05	0.14	0.13	0.08	0.08	0.04	0.04	0.04	0.06	0.05	0.05
Pb ppm	42	37	106	67	36	33	117	120	61	49	34	45	29	26
Rb ppm	207	193	189	176	224	220	224	219	291	289	104	111	159	150
Sb ppm	6	0	0	0	10	11	6	2	9	4	4	2	7	8
Sc ppm	11	12	11	12	8	9	12	16	9	11	12	12	11	7
Se ppm	0.8	0.7	0.9	1.0	0.6	0.6	1.0	1.2	0.8	0.8	1.0	0.9	0.4	0.4
Sn ppm	8	8	7	8	10	8	6	12	11	8	39	41	5	8
Sr ppm	29	27	19	22	22	23	54	51	31	32	101	102	24	25
Th ppm	27	23	35	45	28	28	31	31	23	23	11	15	20	13
TiO_2 wt%	0.75	0.59	0.74	0.76	0.45	0.49	0.87	0.83	0.72	0.67	0.65	0.63	0.48	0.49
U ppm	5	6	8	7	7	4	11	7	8	4	3	4	3	4
V ppm	64	59	69	78	48	46	75	86	63	59	74	67	37	38
W ppm	14	8	10	8	8	2	17	14	6	10	9	5	7	6
Y ppm	38	34	34	31	29	30	43	43	38	34	28	29	29	30
Zn ppm	63	58	42	47	63	54	205	208	229	220	102	107	38	36
Zr ppm	309	308	473	511	250	340	554	421	92	101	518	452	316	345

Appendix 2 Mean concentrations of elements in Hong Kong stream sediments, the upper continental crust, and selected igneous and sedimentary rocks

Element	Hong Kong	Earth's crust	Igneous rocks			Sedimentary rocks		
			Ultrabasic	Basaltic	Granitic	Shale	Sandstone	Carbonate
Ag ppm	0.5	0.08	0.06	0.11	0.04-0.05	<	0.05-0.12	.... >
As ppm	27	1.8	1	2	1.5-1.9	13	<5	<5
Ba ppm	317	390	0.4	330	420-840	580	ca10	10
Bi ppm	6.4	<0.01	-	-	-	-	-	-
CaO %	0.67	4.66	2.5	7.6	5.1-25.3	-	-	-
Cd ppm	0.52	0.2	-	0.13	0.09	0.8	-	-
Ce ppm	127	60	-	16	104	67-91	33	6.5
Co ppm	6	29	150	48	1-7	19	0.3	0.1
Cr ppm	49	122	1,600	170	4-22	90	35	11
Cs ppm	12	2.6	<0.1	<0.1	3-6	5 (marine)	1	1
Cu ppm	102	68	40	40-60	12	50	-	5-15
Fe_2O_3 %	4.11	6.22	9.43	8.65	1.42-2.96	4.7	0.98	0.38
Ga ppm	20	19	1.5	17	17	19	12	4
Ge ppm	1.68	1.5	1.5	1.3	1.3	1.6	0.8	0.2
Hg ppm	0.58	<0.08	-	0.01	0.08	0.4	0.03	0.04
La ppm	52	37	<10	15	45-55	92	30	ca1
MnO %	0.13	950	1,600	1,500	390-540	ca700	ca170	ca550
Mo ppm	3.5	1.2	<	1-1.5	.... >	<	0.5-2	.... >
Nb ppm	38	ca20	1.5	10	22	-	-	-
Ni ppm	11	99	2,000	130	4.5-15	68	2	20
P_2O_5 %	0.11	1,120	220	1,100	600-920	700	170	400
Pb ppm	104	13	1	6	15-19	ca23	ca10	ca5
Rb ppm	216	78	0.2	30	110-170	140	60	3
Sb ppm	2.8	0.2	0.1	0.2	0.2	1.5	<0.1	0.15
Sc ppm	9.4	22	-	30-40	<10	13	1	1
Se ppm	0.43	0.05-0.09	-	-	0.01-0.05	0.06	<0.05	0.08
Sn ppm	54	2.1	0.5	1.5	1.5-3	6	<1	<1
Sr ppm	35	384	1	465	100-440	300	20	610
Th ppm	44	9.6-12	-	<1	10-40	12	1.7	1.7
TiO_2 %	0.6	0.63	300	1.38	0.12-0.34	0.46	0.15	400
U ppm	8.7	2.3	0.001	<	1-3 ...... >	3.7	0.5-1.5	2.2
V ppm	43	136	40	250	44-88	90-260	<15	<15
W ppm	11	1-1.5	0.1-0.8	0.5-1	1.5	1-2	-	<0.5
Y ppm	51	31	ca32	ca32	ca40	ca40	ca15	ca4
Zn ppm	141	76	50	105	39-60	50-190	16	ca50
Zr ppm	802	162	45	140	140-175	100-300	160-220	20-130

This table is a summary of element means cited in the text (refer to text for source of citation).

Data sources : This study, Ebens and Shacklette (1982), Fergusson (1990), Greenwood and Earnshaw (1984), Heinrichs (1974), Horstman (1957), Kabata-Pendias and Pendias (1984), Mason (1966), Mielke (1979), Taylor (1964), Vinogradov (1962), Wedepohl (1978).

Appendix 3 Summary of natural elemental abundances in stream sediments derived from selected formations and plutons.

Formation/Pluton	Ag	As	Ba	Bi	CaO	Cd	Ce	Co	Cr	Cs	Cu	Fe_2O_3	Ga	Ge	Hg	La	MnO	Mo	Nb	Ni	P_2O_5	Pb	Rb	Sb	Sc	Se	Sn	Sr	Th	TiO_2	U	V	W	Y	Zn	Zr
Extrusive rocks																																				
High Island			○				◑	○						○	○	●					○		○			○		○		○		○				
Clear Water Bay									●																											
Mang Kung Uk									◑	◑																										
Ap Lei Chau															●											○										
Lai Chi Chong		●		◑				●	◑	◑		◑	○										◑	●					○		○			●		
Sai Lau Kong				◑																																
Tai Mo Shan								●		◑	◑	◑														◑			○							
Tuen Mun					●	●		●	●			●			●	◑	◑				●				●	●		●	○	●	○	●		○		○
Intrusive rocks																																				
Mount Butler Granite													●	●		○		●	●	◑						○			●		●					
Po Toi Granite													●					●	●	◑									●		●					
Kowloon Granite							●						●	●		●			◑	◑						○								●		
Sok Kwu Wan Granite													◑														◑									
D'Aguilar Quartz Monzonite														●									◑						◑							
Luk Keng Quartz Monzonite																			●																	
Chi Ma Wan Granite				◑			●						◑	●		●			●				◑						●		●			●		
South Lamma Granite													●	●			◑		●				○						◑		◑			●		
Sha Tin Granite							●						●	◑		○							◑													●
Lantau Dykes						○											○									○									○	
Needle Hill Granite		●		◑			◑						●					●	●			◑	◑	◑					●		●		●	●		
Tai Tam Granite	◑		○	◑		◑	◑			◑			●	●		○	○	●	●	●		◑		●		○	◑	○	●		●		●	●	○	○
Tsing Shan Granite		◑	○	●									●	○		○	○	●	●	●		◑	●			○	○	○	●		●				○	○
Chek Lap Kok Granite				●	◑																		●				●									
Lantau Granite							◑							◑		◑														◑	◑		◑			◑
Tai Po Granodiorite			◑		◑	◑	◑	●						◑		◑				◑		●					◑		◑	◑		●				◑
Deep Bay													●										◑						●							
Sedimentary rocks																																				
Tolo Harbour				○				●																												
Bluff Head				○	○							◑											○					○						○		

● = high, ◑ = moderate to high, ○ = very low

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