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U–Pb dating of Mesozoic igneous rocks from Hong Kong

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Abstract: Twenty-two new zircon and monazite U–Pb ages have been obtained for Mesozoic plutonic and volcanic rocks of Hong Kong. These have revealed the existence of four distinct periods of Mid-Jurassic to Lower Cretaceous volcano-plutonism: 164.6 ± 0.2 to 159.3 ± 0.3 Ma, 146.6 ± 0.2 to 146.2 ± 0.2 Ma, 143.7 ± 0.3 to 142.5 ± 0.3 Ma, and 140.9 ± 0.2 to 140.4 ± 0.2 Ma. A concordant monazite age of 236.3 ± 0.8 Ma has also been obtained from one intrusive body representing the first known occurrence of a Mid-Triassic granitoid in the Territory. Among these rocks, discordant U–Pb data projected to the concordia curve have given a broad range of inheritance ages from early Phanerozoic to late Archaean. A xenocrystic zircon from one sample has yielded a concordant age of 1872 ± 3 Ma. The new U–Pb ages have refined the results of recent Rb–Sr whole-rock age dating of the granitoid rocks and have considerably improved correlation between intrusive and extrusive units. The occurrence of inherited components in many of the analysed rocks indicates that they were derived from, or erupted through, older crust containing a wide variety of age components, either as primary igneous or detrital material.

Keywords: Hong Kong, U–Pb, Mesozoic, zircon, dates.

Models of crustal evolution in SE China have generally been based on Sr and Nd isotopic compositions and calculated crustal residence ages of Mesozoic granitoid rocks. These data have been used to infer the existence of crustal provinces within the Cathaysian block (Fig. 1) which might represent exotic terranes now amalgamated with the stable Yangtze block to the northwest (Chen *et al.* 1985; Huang *et al.* 1986; Darbyshire & Sewell in press). Although there is considerable debate over the timing of accretionary events and the location of tectonic boundaries, recent tectonic models for southeastern China have consistently shown a NNE-trending boundary passing through the maritime provinces of Guangdong, Fujian, and Zhejiang. Sr and Nd isotopic compositions and Nd model ages of Hong Kong granitoids (Darbyshire & Sewell in press) suggest that this boundary passes through Hong Kong and represents a deep crustal discontinuity between dominantly late Archaean crust to the northwest and Mesoproterozoic crust to the southeast.

Although Sr and Nd isotope studies of granitoid rocks provide useful constraints on models of crustal evolution, the most direct evidence for the age of crustal source materials, in the absence of lower crustal xenoliths, comes from studies of inherited accessory minerals. Zircon is particularly resistant to metamorphism, alteration and weathering and can survive crustal anatexis. It is common in granitoids and related felsic volcanic rocks and has been proven to contain a reliable U–Pb system. As analytical techniques have improved enabling very precise measurement of isotopic ratios (e.g. Krogh 1973, 1982), zircon U–Pb geochronology has become an increasingly powerful tool in the dating of stratigraphically complex magmatic provinces and in yielding information concerning the source regions of granitoid magmas (e.g. Davis & Green 1997).

The Mesozoic granitoids and related volcanic rocks of Hong Kong (herein the area encompassed by the Hong Kong Special Administrative Region) have recently been the focus of detailed remapping and stratigraphic revision (see Campbell & Sewell this volume; Sewell & Campbell this volume). Whole-rock Rb–Sr geochronology which accompanied the initial phase of this revision helped to establish broad constraints on the age of volcano-plutonism at between 158 and 135 Ma (Sewell *et al.* 1992; Darbyshire unpublished data). However, the age determinations of several units returned relatively large analytical errors whereas many other units were undated.

In order to date more accurately the timing of Mesozoic magmatic events, extend the chronological database, and determine the ages of possible source components, zircon U–Pb dating of representative Hong Kong granitoids and volcanic rocks was undertaken. This paper presents the new age data for twenty-two samples and briefly discusses their implications for crustal evolution in SE China.

Geological setting

Hong Kong lies at the southern end of a broad (200 km) belt of Mesozoic intrusive and extrusive rocks that passes through the maritime provinces of southeastern China. These magmas are thought to have been generated largely by westerly subduction of the Kula–Pacific Plate beneath the Eurasian Plate from the late Triassic to the Cretaceous (Huan *et al.* 1982; Zhou & Lao 1990). The entire area of Hong Kong lies within the Lianhuashan Fault Zone, a 30 km wide zone bounded to the northwest by the Shenzhen Fault and to the southeast by the Haifeng Fault (Fig. 1). Tectonic maps for southeastern China indicate that this fault zone separates the South China Fold Belt to the northwest from the Southeast Maritime Fold Belt to the southeast (e.g. Huang 1978; Zhang 1983).

Plutonic and volcanic associations

Mesozoic plutonic and volcanic rocks crop out over approximately 85% of the land area of Hong Kong (1050 km^2). With the exception of one pluton and one volcanic formation, the granitoids can be divided into two suites comprising 29

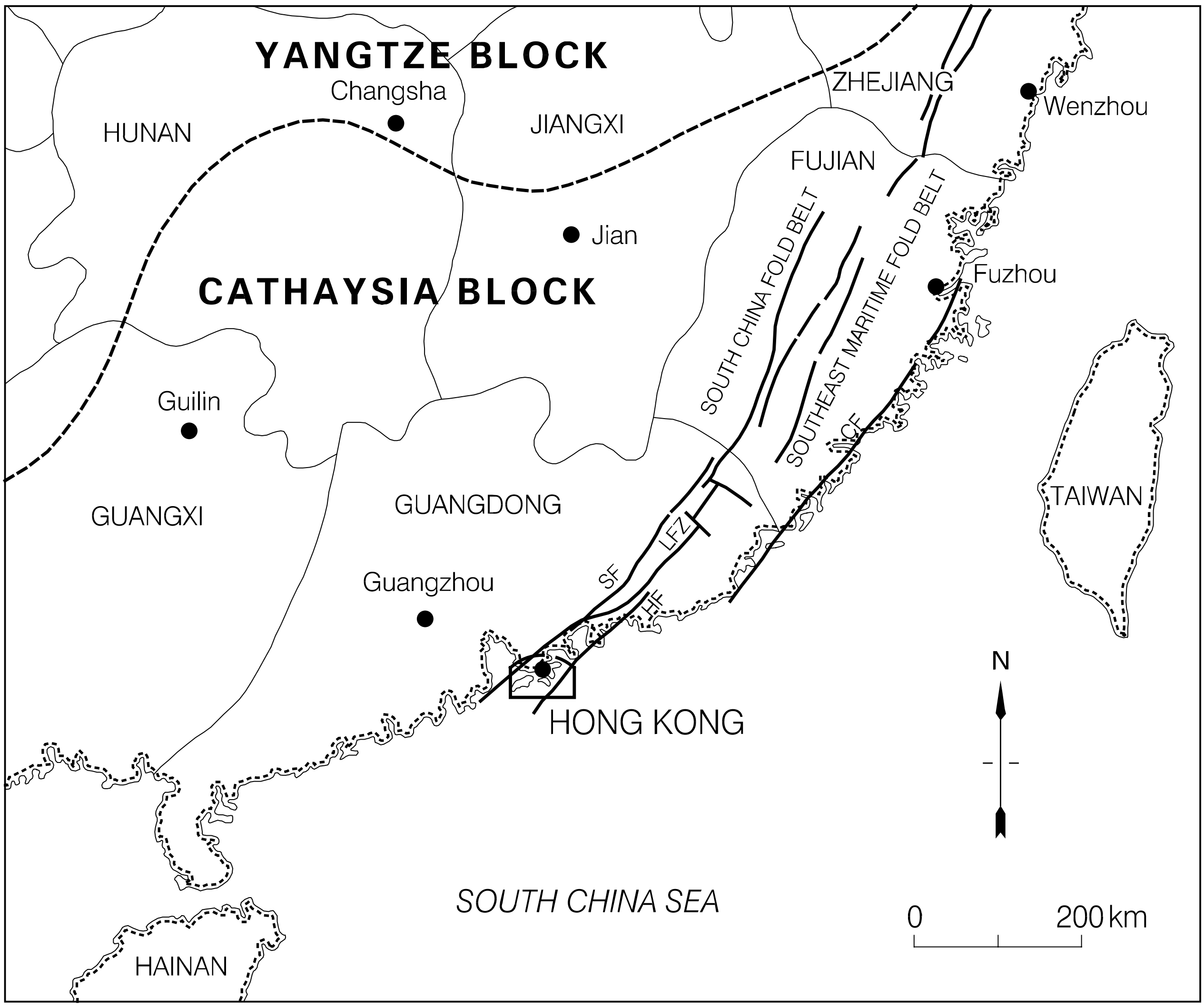

Fig. 1. Regional tectonic map of South China. SF, Shenzhen Fault; HF, Haifeng Fault; LFZ, Lianhuashan Fault Zone; CF, Changle–Na'nao Fault.

individual intrusions, and the volcanic rocks into two groups comprising 17 formations (Sewell *et al.* 1992; Campbell & Sewell this volume). Close spatial and temporal associations exist between the granitoids and volcanic rocks (Fig. 2), and co-magmatic relationships, based on petrographic and geochemical criteria, have been inferred for several volcanic-plutonic pairs (Sewell *et al.* 1993; Sewell & Campbell this volume). The plutonic suites and related volcanic groups have chemically and isotopically distinct crustal source regions (Darbyshire & Sewell in press).

Analytical methods

Samples were crushed with a jaw crusher followed by a disk mill, then passed over a Wilfley table to concentrate heavy minerals. Further heavy mineral separation was carried out by density separations with bromoform and methylene iodide and paramagnetic separations with a Frantz separator. Final sample selection was by hand picking under a microscope. Exterior surfaces of selected zircon grains were removed by air abrasion (Krogh 1982). Weights of mineral fractions were estimated by eye, a process that is found usually to be accurate to about ±30%.

Zircon was dissolved using HF in teflon bombs at 200°C, after being washed in HNO_3. ^{205}Pb–^{235}U spike was added to the dissolution capsules during sample loading. Purification of Pb and U was carried out in HCl using 0.05 ml anion exchange columns (Krogh 1973). Pb and U were loaded together on Re filaments using silica gel and analysed with a VG354 mass spectrometer in single collector mode. All of the measurements were made using a Daly collector. The mass discrimination correction for this detector has been monitored for several years and found to be constant at 0.4%/amu. Thermal mass discrimination corrections are 0.10%/amu.

Analytical Pb blanks are normally in the range 0.5–5.0 pg with occasional higher values due to particle contamination. Analyses with common Pb values less than 10 pg were corrected assuming laboratory blank isotopic composition for the common Pb component. Any common Pb component in excess of 10 pg was corrected assuming an isotopic composition on the Stacey & Kramers (1975) growth curve.

U–Pb geochronology

All the analysed samples yielded zircon in varying abundance and only crack-free crystals without evidence of cores or alteration were selected for abrasion. Except for a few cases, most zircon crystals consist of colourless, euhedral, doubly terminated prisms of varying length. Most

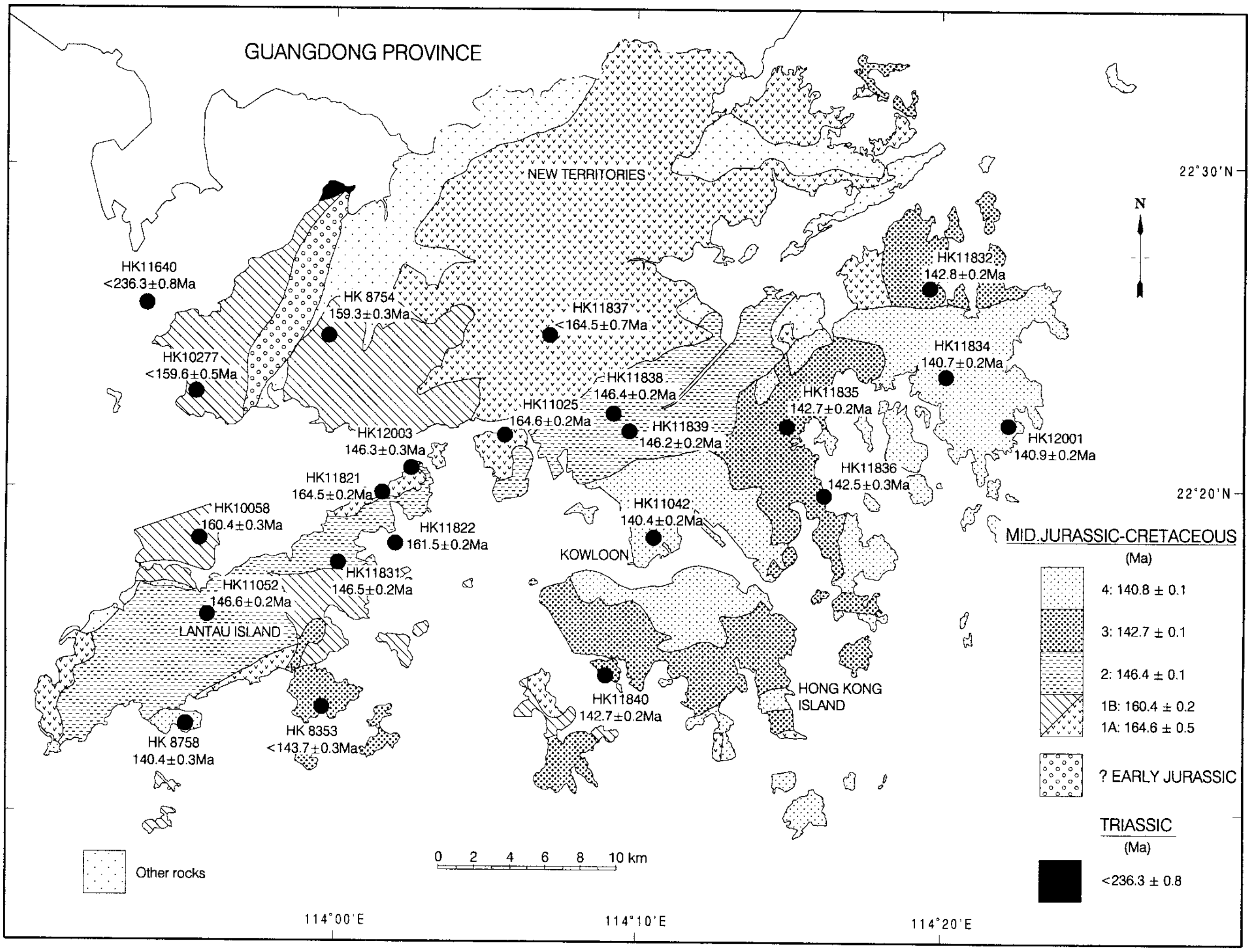

Fig. 2. Simplified geological map of Hong Kong and location of analysed samples.

grains display well-developed, low-order crystal faces and contain an abundance of inclusions, including amorphous melt inclusions, apatite rods and sulphide inclusions. Single grain dating could only be carried out on exceptionally large crystals due to the low U concentrations of most of the grains. Most analysed fractions consisted of several grains. To avoid inheritance, zircons having characteristics typical of the igneous population, such as a euhedral shape and an abundance of melt or rod-like inclusions, were chosen for analysis. However, slight to moderate amounts of inheritance were encountered in many of the samples, probably due to the presence of xenocrysts or invisible cores.

Owing to depletion of the shorter half-life ^{235}U isotope, relatively young samples generally contain much less ^{207}Pb than ^{206}Pb. For Mesozoic and younger rocks, ^{206}Pb/^{238}U ages are much more precise and reliable than ^{207}Pb/^{235}U ages, whereas ^{207}Pb/^{206}Pb ages are quite imprecise because the concordia curve is nearly parallel to a line through the origin. Therefore, ages for the Hong Kong samples are calculated as ^{206}Pb/^{238}U ages. Although ^{206}Pb/^{238}U ages are sensitive to secondary Pb loss, this is likely to have been eliminated by the abrasion treatment for most zircons in the present samples because of their low U concentrations and young ages (limited radiation damage). For most samples, ^{206}Pb/^{238}U ages could be reproduced within error for youngest concordant data points. This is taken as evidence that these data points are not disturbed by secondary Pb loss or inheritance and that they record the crystallization age of the host rock.

U–Pb isotope data are presented in Table 1 and summary plots are presented in Figs 3 to 7. The concordia co-ordinates and ages, as well as plotted data, are corrected for ^{230}Th disequilibrium, assuming a Th/U ratio in the magma of 4.2, the terrestrial average. This increases the ^{206}Pb/^{238}U ages by about 0.09 Ma in all of the samples.

Ages, errors and probabilities of fit are calculated from the Davis (1982) program, modified for averaging ^{206}Pb/^{238}U data. Probability of fit is a measure of the likelihood that data points overlap within error. In a random distribution of coeval data with correctly assigned errors, this would be expected to be 50% on average. Values below 10% are considered to indicate non-coeval data. Averaged age errors are quoted at the 95% confidence level in the text and Table 2. Error ellipses on Figs 3 to 7, as well as errors in Table 1, are given as 2σ.

Brief descriptions of the twenty-two analysed samples, together with a summary of the new ages compared with those obtained from previous work are presented in Table 2. With the exception of the Deep Bay Granite, which has given a Triassic age, all the analysed samples have returned Mid-Jurassic to Early Cretaceous ages.

Triassic magmatism

Deep Bay Granite Pluton (HK11640). Zircons from the Deep Bay Granite are generally small, stubby to elongate and multifaceted with sharp terminations and few inclusions. It is difficult to determine a reliable age from the zircon data in this sample. Only two fractions are concordant and in near agreement whereas two give younger ages and two others appear to be affected by inheritance (Fig. 3a). A small amount of

Table 1. *U–Pb isotopic data on abraded zircon and monazite from Hong Kong rocks*

Fraction analysed	Weight (mg)	U (ppm)	Th/U	Pbcom (pg)	$^{206}Pb/^{204}Pb$*	$^{208}Pb/^{206}Pb$†	$^{206}Pb/^{238}U$†	2σ	$^{207}Pb/^{235}U$†	2σ	$^{207}Pb/^{206}Pb$†	2σ	$^{206}Pb/^{238}U$‡ age (Ma)	2σ	$^{207}Pb/^{235}U$‡ age (Ma)	2σ	$^{207}Pb/^{206}Pb$‡ age (Ma)	2σ	Corr. coef.	Disc. (%)
HK11640 Deep Bay Granite																				
1 1 MONAZITE	0.001	1850	9.74	1.1	4055	3.093	0.03734	14	0.2615	20	0.05081	34	236.30	0.81	235.91	1.60	232.0	15.0	0.517	− 1.9
2 13 ZR	0.005	616	0.71	0.8	9831	0.238	0.03742	14	0.2633	12	0.05103	124	236.79	0.85	237.29	1.00	242.2	6.4	0.803	2.3
3 3 ZR NEEDLES	0.001	484	0.80	2.0	606	0.257	0.03754	14	0.2632	57	0.05084	108	237.60	0.82	237.23	4.60	233.6	49	0.160	− 1.8
4 18 ZR	0.006	431	0.63	2.3	2716	0.206	0.03667	10	0.2598	17	0.05139	30	232.14	0.60	234.52	1.40	258.4	13.7	0.449	10
5 7 ZR, INCL	0.004	815	0.51	4.8	1589	0.168	0.03609	10	0.2543	23	0.05111	44	228.57	0.60	230.09	1.84	245.7	19.4	0.325	7.1
6 4 ZR, INCL	0.017	405	1.58	1.4	13 187	0.517	0.04047	10	0.2892	9	0.05183	10	255.75	0.57	257.93	0.69	277.8	4.5	0.759	8.1
7 11 ZR TIPS	0.007	290	0.27	1.5	6680	0.177	0.07622	20	0.7426	25	0.07066	14	473.51	1.17	563.91	1.47	947.6	4.0	0.811	52
HK11837 Tai Mo Shan Formation																				
8 1 ZR, MELT INCL	0.025	202	0.59	1.2	7143	0.193	0.02584	12	0.1758	10	0.04934	18	164.49	0.73	164.45	0.86	163.9	8.9	0.740	− 0.3
9 8 ZR, MELT INCL	0.040	175	0.60	3.8	3091	0.199	0.02589	6	0.1778	9	0.04980	22	164.78	0.41	166.15	0.79	185.7	10.4	0.483	11
10 5 ZR, MELT INCL	0.050	258	0.54	3.2	6756	0.178	0.02603	8	0.1786	6	0.04977	14	165.63	0.49	166.85	0.55	184.2	6.2	0.685	10
11 2 ZR, MELT INCL	0.030	158	0.52	1.6	5004	0.173	0.02641	8	0.1819	11	0.04998	28	168.06	0.47	169.71	0.99	192.9	12.8	0.489	13
12 1 PINK RND ZR	0.003	304	0.28	1.1	17 274	0.084	0.3359	14	5.302	21	0.11450	20	1866.8	6.60	1869.2	3.4	1872.0	3.0	0.917	0.3
HK11025 Tai Po Granodiorite																				
13 4 ELONG ZR, INCL	0.040	121	0.58	12.5	657	0.189	0.02586	6	0.1766	19	0.04954	52	164.60	0.37	165.16	1.67	173.3	25	0.276	5.1
14 3 ELONG ZR, INCL	0.040	100	0.63	3.1	2168	0.205	0.02587	6	0.1763	8	0.04943	18	164.67	0.38	164.91	0.71	168.4	8.9	0.583	2.2
15 7 ZR NEEDLES	0.025	103	0.74	1.8	2338	0.241	0.02583	6	0.1763	9	0.04952	22	164.38	0.43	164.91	0.81	172.6	10.5	0.540	4.8
16 2 ZR, INCL	0.040	135	0.31	3.4	2895	0.169	0.02856	10	0.2065	9	0.05243	18	181.50	0.66	190.58	0.78	304.1	8.1	0.634	41
HK11821 Yim Tin Tsai Formation																				
17 1 ZR, INCL	0.015	81	0.54	0.9	2150	0.177	0.02587	6	0.1767	13	0.04953	34	164.67	0.43	165.21	1.13	173.0	16.3	0.326	4.9
18 1ZR, INCL	0.015	151	0.93	1.5	2507	0.302	0.02583	8	0.1756	9	0.04933	22	164.42	0.47	164.28	0.80	162.2	10.8	0.482	− 1.4
19 1 ZR, INCL	0.005	139	0.54	2.3	520	0.180	0.02580	8	0.1773	39	0.04982	104	164.22	0.54	165.70	3.35	186.8	48	0.375	12
20 1 ZR, ABUND INCL	0.030	162	0.12	1.9	28 246	0.094	0.17497	54	4.174	12	0.17302	34	1039.4	3.0	1668.9	2.4	2587.0	3.2	0.784	65
HK11822 Lantau Granite																				
21 5 ELONG ZR, INCL	0.013	498	0.37	1.5	6966	0.121	0.02537	6	0.1728	6	0.04940	12	161.52	0.40	161.86	0.50	166.8	5.2	0.742	3.2
22 2 ZR, INCL	0.011	447	0.37	2.3	3478	0.122	0.02536	6	0.1727	7	0.04940	14	161.42	0.37	161.78	0.58	167.0	6.6	0.691	3.4
23 2 ELONG ZR, INCL	0.014	465	0.38	1.7	6424	0.124	0.02539	6	0.1731	5	0.04943	8	161.66	0.33	162.08	0.45	168.3	4.2	0.805	4.0
24 4 ZR, INCL	0.011	405	0.43	1.9	4203	0.148	0.02782	8	0.1950	7	0.05084	12	176.87	0.45	180.89	0.60	233.8	5.8	0.714	25
HK10058 Chek Lap Kok Granite																				
25 1 ZR, ABUND INCL	0.008	362	0.44	1.5	3066	0.145	0.02519	6	0.1714	10	0.04935	24	160.39	0.40	160.65	0.82	164.4	11.6	0.445	2.5
26 1 BR ZR FRAG	0.003	6206	0.27	1.3	22 409	0.087	0.02521	8	0.1715	6	0.04934	6	160.50	0.46	160.72	0.48	163.9	3.0	0.920	2.1
27 1 BR CK ZR FRAG	0.001	3779	0.23	1.0	6307	0.074	0.02511	8	0.1710	7	0.04940	18	159.86	0.46	160.31	0.62	166.9	8.0	0.580	4.2
28 1 PINK ZR CORE	0.002	1133	0.92	2.9	1277	0.304	0.02529	20	0.1729	5	0.04959	12	161.06	0.18	161.93	0.62	174.8	8.2	0.306	7.8
HK10277 Tsing Shan Granite																				
29 14 ZR	0.004	626	0.55	0.5	7632	0.178	0.02506	8	0.1706	9	0.04936	22	159.56	0.46	159.90	0.77	165.0	10.0	0.562	3.3
30 13 ZR	0.012	556	0.51	0.7	15 519	0.169	0.02511	8	0.1717	7	0.04962	12	159.84	0.47	160.93	0.59	177.0	5.4	0.810	9.8
31 14 ZR, INCL	0.009	398	0.60	1.1	5418	0.195	0.02516	6	0.1717	8	0.04948	20	160.20	0.36	160.85	0.72	170.4	9.2	0.595	6.1
32 18 ZR	0.008	632	0.45	0.7	11 510	0.157	0.02542	6	0.1771	6	0.05053	12	161.82	0.36	165.55	0.51	219.3	5.1	0.755	27
33 6 ZR	0.006	413	0.44	2.0	2085	0.150	0.02598	6	0.1801	12	0.05029	32	165.34	0.34	168.17	1.02	208.3	14.3	0.353	21
34 13 ZR	0.005	462	0.45	13.2	314	0.156	0.02627	8	0.1834	77	0.05062	214	167.19	0.28	170.96	3.3	223.5	48	0.093	26
HK8754 Tai Lam Granite																				
35 2 ZR, INCL	0.015	270	0.39	1.4	4608	0.129	0.02499	8	0.1701	8	0.04935	18	159.14	0.45	159.49	0.70	164.6	8.6	0.620	3.4
36 9 ZR, INCL	0.030	259	0.48	1.3	9783	0.157	0.02504	10	0.1703	7	0.04937	10	159.42	0.60	159.70	0.65	164.0	4.7	0.887	2.8
37 5 ELONG ZR, INCL	0.030	221	0.53	1.9	5736	0.177	0.02504	8	0.1702	6	0.04930	10	159.43	0.45	159.61	0.53	162.3	4.3	0.854	1.8

Table 1. *Cont*

Fraction analysed	Weight (mg)	U (ppm)	Th/U	Pbcom (pg)	^{206}Pb/^{204}Pb*	^{208}Pb/^{206}Pb†	^{206}Pb/^{238}U†	2σ	^{207}Pb/^{235}U†	2σ	^{207}Pb/^{206}Pb†	2σ	^{206}Pb/^{238}U‡ age (Ma)	2σ	^{207}Pb/^{235}U‡ age (Ma)	2σ	^{207}Pb/^{206}Pb‡ age (Ma)	2σ	Corr. coef.	Disc. (%)
HK11052 Lantau Formation																				
38 2 ZR, ABUND INCL	0.020	131	0.71	3.2	1211	0.235	0.02297	6	0.1558	19	0.04921	56	146.39	0.36	147.06	1.63	157.9	27	0.255	7.4
39 7 ZR, NO INCL	0.020	166	0.71	5.5	913	0.232	0.02301	6	0.1556	24	0.04604	74	146.68	0.36	146.86	2.08	149.8	35	0.210	2.1
40 12 ZR, ABUND INCL	0.060	97	0.68	2.5	3503	0.222	0.02305	6	0.1560	8	0.04909	20	146.88	0.38	147.20	0.66	152.3	9.6	0.536	3.6
HK11831 Lantau Dyke I																				
41 3 ZR, ABUND INCL	0.040	114	0.62	3.6	1908	0.203	0.02298	6	0.1556	12	0.04910	36	146.46	0.40	146.81	1.03	152.5	16.6	0.324	4.0
42 6 ZR, FEW INCL	0.040	76	0.66	1.2	3821	0.218	0.02297	6	0.1555	8	0.04910	20	146.40	0.37	146.75	0.66	152.4	9.3	0.576	4.0
43 9 ZR, INCL	0.070	64	0.71	3.3	2020	0.235	0.02300	4	0.1559	12	0.04917	36	146.56	0.30	147.12	1.05	156.0	16.7	0.359	6.1
44 8 ZR, NO INCL	0.040	106	0.68	1.7	3839	0.223	0.02346	6	0.1591	8	0.04918	20	149.50	0.43	149.90	0.72	156.2	9.5	0.614	4.4
HK11838 Needle Hill Granite																				
45 9 ZR, ABUND INCL	0.030	230	0.66	1.9	5491	0.217	0.02296	4	0.1554	6	0.04910	14	146.31	0.31	146.67	0.50	152.5	6.4	0.662	4.1
46 1 ZR, ABUND INCL	0.020	161	0.86	4.3	1125	0.281	0.02298	6	0.1558	19	0.04919	58	146.46	0.34	147.06	1.67	156.7	28	0.222	6.6
47 1 ZR, ABUND INCL	0.015	162	0.70	2.3	1589	0.229	0.02298	6	0.1556	24	0.04910	72	146.49	0.38	146.85	2.09	152.7	24	0.389	4.1
48 2 ZR, FEW INCL	0.020	196	0.63	1.3	4613	0.210	0.02352	8	0.1591	8	0.04906	18	149.89	0.48	149.93	0.68	150.6	8.2	0.692	0.5
HK12003 Lantau Dyke II																				
49 6 ZR, FEW INCL	0.020	271	0.83	1.8	4516	0.271	0.02295	6	0.1552	6	0.04906	14	146.29	0.38	146.53	0.55	150.6	6.7	0.709	2.9
50 5 ZR, INCL	0.020	250	0.71	2.8	2671	0.233	0.02295	8	0.1554	8	0.04912	20	146.26	0.50	146.69	0.73	153.5	9.2	0.676	4.8
51 2 ZR, INCL	0.030	515	0.43	7.9	3049	0.140	0.02405	8	0.1634	7	0.04929	14	153.21	0.54	153.63	0.65	160.1	6.2	0.812	4.3
HK11839 Sha Tin Granite																				
52 7 ZR, FEW INCL	0.060	99	0.69	4.6	1901	0.227	0.02296	6	0.1553	12	0.04906	36	146.34	0.43	146.59	1.04	150.7	16.8	0.344	2.9
53 7 ELONG ZR	0.025	210	0.65	3.5	2221	0.212	0.02295	6	0.1554	10	0.04912	30	146.25	0.33	146.66	0.91	153.4	14.4	0.382	4.7
54 4 ZR, FEW INCL	0.040	65	0.79	1.7	2301	0.258	0.02293	8	0.1552	12	0.04909	34	146.14	0.44	146.47	1.01	151.9	16.1	0.376	3.9
55 1 ZR, ABUND INCL	0.020	188	0.64	1.5	3845	0.209	0.02415	6	0.1642	8	0.04933	20	153.83	0.38	154.35	0.69	162.4	9.2	0.561	5.3
HK8353 Chi Ma Wan Granite																				
56 15 ZR, ABUND INCL	0.070	259	0.56	5.2	5010	0.189	0.02255	6	0.1523	6	0.04897	14	143.72	0.34	143.88	0.40	146.5	4.0	0.658	1.9
57 1 ZR, INCL	0.010	94	0.69	6.1	244	0.228	0.02267	4	0.1539	20	0.04924	64	144.62	0.24	145.38	1.45	157.8	30	0.051	7.5
58 7 ZR, FEW INCL	0.030	273	0.55	1.8	6712	0.180	0.02282	6	0.1542	5	0.04902	12	145.44	0.34	145.63	0.48	148.8	5.8	0.719	2.3
59 15 ZR	0.070	196	0.13	2.5	10 540	0.190	0.03029	8	0.2775	9	0.06645	10	192.36	0.52	248.69	0.70	820.7	3.2	0.870	78
60 1 MONAZITE FRAG	0.002	36 000	9.62	81.8	988	3.301	0.01703	8	0.1149	7	0.04893	20	108.83	0.46	110.40	0.60	144.3	9.2	0.735	25
HK11832 Long Harbour Formation																				
61 1 ZR, INCL	0.060	45	0.60	2.1	1844	0.197	0.02240	4	0.1515	15	0.04905	44	142.80	0.39	143.22	1.28	150.2	21	0.337	5.0
62 4 ZR, FEW INCL	0.060	91	0.59	4.1	1918	0.196	0.02241	6	0.1523	12	0.04930	36	142.87	0.39	143.97	1.04	162.2	16.6	0.399	12
63 6 ELONG ZR, INCL	0.070	94	0.72	3.6	2636	0.234	0.02240	6	0.1513	9	0.04897	26	142.83	0.32	143.03	0.76	146.3	12.1	0.402	2.4
64 7 RND ZR, INCL	0.060	116	0.64	1.6	6460	0.209	0.02241	6	0.1515	6	0.04905	14	142.85	0.39	143.26	0.52	150.1	6.8	0.670	4.9
HK11835 Sai Kung Formation																				
65 1 ZR, INCL	0.030	131	0.66	1.6	3637	0.216	0.02238	6	0.1508	8	0.04888	20	142.71	0.41	142.66	0.70	141.9	9.8	0.591	−0.6
66 2 ZR, INCL	0.050	98	0.59	0.9	7474	0.194	0.02238	6	0.1513	7	0.04903	20	142.65	0.35	143.03	0.65	149.4	9.3	0.578	4.6
67 8 ZR, INCL	0.080	62	0.72	1.5	4653	0.238	0.02239	6	0.1513	6	0.04901	16	142.73	0.33	143.06	0.56	148.4	7.7	0.610	3.9
68 7 ZR, FEW INCL	0.030	202	0.68	1.7	5266	0.242	0.02254	6	0.1558	6	0.05013	16	143.66	0.33	146.98	0.55	200.9	6.9	0.667	29
HK11840 Ap Lei Chau Formation																				
69 1 ZR	0.012	190	0.54	2.5	1315	0.177	0.02239	6	0.1512	17	0.04900	52	142.72	0.36	143.01	1.46	147.7	25	0.256	3.4
70 7 ZR, INCL	0.050	99	0.62	2.0	3555	0.205	0.02239	4	0.1515	7	0.04909	20	142.72	0.30	143.24	0.64	152.0	9.5	0.520	6.2
71 8 ZR, FEW INCL	0.020	237	0.06	0.8	20 115	0.118	0.05350	26	0.8497	42	0.11519	16	335.96	1.54	624.46	2.30	1882.9	2.5	0.958	84

Table 1. *Cont.*

Fraction analysed	Weight (mg)	U (ppm)	Th/U	Pbcom (pg)	$^{206}Pb/^{204}Pb$*	$^{208}Pb/^{206}Pb$†	$^{206}Pb/^{238}U$†	2σ	$^{207}Pb/^{235}U$†	2σ	$^{207}Pb/^{206}Pb$†	2σ	$^{206}Pb/^{238}U$‡ age (Ma)	2σ	$^{207}Pb/^{235}U$‡ age (Ma)	2σ	$^{207}Pb/^{206}Pb$‡ age (Ma)	2σ	Corr. coef.	Disc. (%)
HK11836 Che Kwu Shan Formation																				
72 7 ZR, FEW INCL	0.025	127	0.51	1.1	4287	0.166	0.02236	8	0.1510	8	0.04897	20	142.56	0.46	142.79	0.69	146.6	9.8	0.583	2.8
73 7 ZR, ABUND INCL	0.060	118	0.64	3.7	2733	0.208	0.02231	14	0.1508	12	0.04901	24	142.25	0.91	142.58	1.10	148.2	11.7	0.796	4.0
74 1 ZR, ABUND INCL	0.018	127	0.76	1.1	2980	0.251	0.02237	8	0.1515	11	0.04911	30	142.61	0.52	143.21	0.97	153.1	14.2	0.551	7.0
75 1 ZR, INCL	0.020	249	0.52	9.6	781	0.172	0.02298	6	0.1556	27	0.04912	84	146.44	0.40	146.86	2.36	153.7	40	0.181	4.8
HK11834 Clear Water Bay Formation																				
76 10 ZR, FEW INCL	0.015	326	0.58	0.7	9419	0.197	0.02206	4	0.1487	5	0.04890	12	140.68	0.31	140.80	0.45	143.0	5.6	0.716	1.6
77 4 ZR, INCL	0.015	255	0.69	6.8	821	0.234	0.02209	6	0.1490	24	0.04891	80	140.85	0.34	140.99	2.16	143.4	38	0.156	1.8
78 10 ZR, INCL	0.030	185	0.67	1.4	5541	0.221	0.02205	6	0.1488	6	0.04895	14	140.61	0.35	140.87	0.49	145.2	6.5	0.673	3.2
79 17 ZR, FEW INCL	0.030	164	0.69	0.8	8561	0.227	0.02207	6	0.1489	5	0.04892	12	140.73	0.36	140.92	0.45	144.1	5.6	0.704	2.8
HK11042 Kowloon Granite																				
80 1 ZR	0.008	255	0.61	1.5	1944	0.202	0.02204	6	0.1492	10	0.04911	30	140.53	0.41	141.23	0.91	153.2	13.8	0.522	8.3
81 1 ZR, FEW INCL	0.006	277	0.66	0.5	4629	0.215	0.02199	8	0.1483	8	0.04892	24	140.20	0.50	140.41	0.73	143.9	11.5	0.492	2.6
82 1 ZR, ABUND INCL	0.004	272	0.65	1.1	1444	0.213	0.02200	10	0.1485	18	0.04894	60	140.29	0.61	140.55	1.62	145.1	28	0.250	3.3
83 1 ZR, CRACKS	0.008	233	0.54	1.0	2547	0.179	0.02203	6	0.1491	12	0.04909	36	140.49	0.37	141.14	1.05	152.1	16.9	0.431	7.7
NHK12001 High Island Formation																				
84 7 ZR, FEW INCL	0.015	897	0.49	7.7	2492	0.161	0.02210	6	0.1494	6	0.04901	16	140.92	0.35	141.35	0.55	148.5	7.2	0.681	5.1
85 4 ZR, ABUND INCL	0.020	672	0.63	5.9	3252	0.208	0.02212	8	0.1492	11	0.04892	30	141.03	0.44	141.20	0.94	144.1	13.9	0.558	2.2
86 6 ZR, INCL	0.020	678	0.58	4.4	4348	0.191	0.02209	6	0.1492	5	0.04898	10	140.88	0.40	141.22	0.45	146.9	4.9	0.786	4.1
HK8758 Tong Fuk Quartz Syenite																				
87 1 ZR, NO INCL	0.011	73	0.75	0.6	2026	0.256	0.02199	12	0.1503	21	0.04958	66	140.22	0.73	142.20	1.8	175.4	31	0.319	20
88 1 ZR, INCL	0.011	36	0.79	1.1	561	0.233	0.02198	14	0.1471	46	0.04853	148	140.16	0.93	139.34	4.1	125.4	71	0.222	− 12
89 1 ZR, INCL	0.010	59	0.69	2.2	419	0.227	0.02204	8	0.1494	57	0.04918	184	140.53	0.50	141.35	5.0	155.1	86	0.196	9.5
90 1 ZR, INCL	0.005	156	0.64	2.5	466	0.212	0.02204	12	0.1493	58	0.04912	184	140.52	0.75	141.26	5.1	153.8	87	0.305	8.7

Abbreviations: Number of grains analysed is at beginning, ZR, zircon; INCL, inclusions; RND, rounded; ELONG, elongate; ABUND, abundant; FRAG, fragment; CK, cracked; BR, brown. Th/U is calculated from measured $^{206}Pb/^{208}Pb$ and $^{207}Pb/^{206}Pb$ age.

Pbcom is total measured common Pb assuming all common Pb has the isotopic composition of laboratory blank: $^{206}Pb/^{204}Pb = 18.221$; $^{207}Pb/^{204}Pb = 15.612$; $^{208}Pb/^{204}/Pb = 39.360$.

*Corrected for fractionation and spike.

†Corrected for common Pb assuming laboratory blank composition.

‡Corrected for ^{230}Th disequilibrium assuming a magmatic Th/U of 4.2.

%Disc. is percent discordance for the given $^{207}Pb/^{206}Pb$ age.

U decay constants are from Jaffey *et al.* (1971).

2 sigma errors represent uncertainties in the last significant digits.

Table 2. *Brief descriptions and summary of ages from analysed Hong Kong rocks*

Formation/pluton	Sample No.	Description	U-Pb (U-Pb inherit) ages (Ma) (this study)	Probability of fit (%)	Rb-Sr ages (Ma) (Sewell et al. 1992; Darbyshire, unpub. data)
Deep Bay Granite	HK11640	Two-mica leucogranite	<236.3 ± 0.8 (507 ± 70, 1269 ± 7)	—	—
Period 1					
Tai Mo Shan Formation	HK11837	Coarse ash crystal tuff	<164.5 ± 0.7 (1872 ± 3)	—	—
Tai Po Granodiorite	HK11025	Porphyritic granodiorite	164.6 ± 0.2 (1134 ± 64)	58	—
Yim Tin Tsai Formation	HK11821	Coarse ash crystal tuff	164.5 ± 0.2 (2719 ± 4)	41	—
Lantau Granite	HK11822	Porphyritic monzogranite	161.5 ± 0.2 (713 ± 61)	62	—
Chek Lap Kok Granite	HK10058	Leucogranite	160.4 ± 0.3	72	—
Tsing Shan Granite	HK10277	Biotite monzogranite	<159.6 ± 0.5	—	152 ± 3
Tai Lam Granite	HK8754	Biotite monzogranite	159.3 ± 0.3	61	158 ± 7, 155 ± 6
Period 2					
Lantau Formation	HK11052	Fine ash crystal tuff	146.6 ± 0.2	17	144 ± 2
Lantau Dyke I	HK11831	Feldspar porphyry	146.5 ± 0.2 (149.5 ± 0.4)	79	—
Needle Hill Granite	HK11838	Porphyritic leucogranite	146.4 ± 0.2 (150.0 ± 0.5)	72	—
Lantau Dyke II	HK12003	Quartz porphyry	146.3 ± 0.3 (153.2 ± 0.5)	92	—
Sha Tin Granite	HK11839	Biotite monzogranite	146.2 ± 0.2 (153.8 ± 0.4)	81	148 ± 9
Period 3					
Chi Ma Wan Granite	HK8353	Biotite monzogranite	<143.7 ± 0.3 (1845 ± 15)	—	—
Long Harbour Formation	HK11832	Coarse ash crystal tuff	142.8 ± 0.2	99	—
Sai Kung Formation	HK11835	Coarse ash crystal tuff	142.7 ± 0.2 (3000 ± 700)	94	—
Ap Lei Chau Formation	HK11840	Fine ash vitric tuff	142.7 ± 0.2 (2427 ± 5)	100	140 ± 2 or 131 ± 5
Che Kwu Shan Formation	HK11836	Fine ash vitric tuff	142.5 ± 0.3 (146.4 ± 0.4)	78	—
Period 4					
Clear Water Bay Formation	HK11834	Coarse ash crystal tuff	140.7 ± 0.2	79	—
Kowloon Granite	HK11042	Biotite monzogranite	140.4 ± 0.2	71	138 ± 1
High Island Formation	HK12001	Fine ash vitric tuff	140.9 ± 0.2	88	137 ± 4
Tong Fuk Qtz Monzonite	HK8758	Porphyritic quartz monzonite	140.4 ± 0.3	83	—

monazite was recovered and a single grain was analysed, giving a concordant datum point with a $^{206}Pb/^{238}U$ age of 236.3 ± 0.8 Ma, in approximate agreement with the two concordant zircon data points. Its Th/U value is rather low for monazite, resulting in a $^{206}Pb/^{238}U$ age correction of only 0.14 Ma. Therefore, its $^{206}Pb/^{238}U$ ratio is considered to give a more reliable age than the less radiogenic $^{207}Pb/^{235}U$ ratio. Since monazite is less likely to contain inheritance than zircon, the age of this grain is considered to give the most accurate estimate for the crystallization age of the Deep Bay pluton. Upper concordia intercepts between 236.3 ± 0.8 Ma and the two older discordant zircon data points are 507 ± 70 Ma and 1269 ± 7 Ma. These may represent mixed ages of inheritance because the samples were multi-grain fractions.

Mid-Jurassic–Early Cretaceous magmatism

Zircon morphologies in these rocks are distinct from those in the Triassic granitoid with grains being typically prismatic and showing well-developed [110] and [100] crystal faces. The samples are divided into four periods according to the grouping of their ages.

Period 1. Granitoid rocks and volcanic formations of the earliest period were emplaced between 164.5 ± 0.7 Ma and 159.3 ± 0.3 Ma (Fig. 3b–h). Ages for the three oldest analysed samples are clustered around 164.5 ± 0.2 Ma (Period 1A), although one of these ages, from HK11837 (Fig. 3b), is based on only one concordant data point. Ages for the younger samples reveal apparently distinct events at 161.5 ± 0.2 Ma, 160.4 ± 0.3 Ma and 159.3 ± 0.3 Ma, based on $^{206}Pb/^{238}U$ ages (see Discussion). These younger rocks, from three individual plutons, may represent a separate period of intrusive activity and are tentatively assigned to Period 1B. A fourth pluton, HK10277 (Fig. 3g), yielded three data points clustering near concordia with an average age of 159.9 ± 0.2 Ma, but with a probability of fit of only 8%. The age of the youngest datum point (159.6 ± 0.5 Ma) is to probably the closest approximation to the age of this pluton.

Inherited zircons were detected in at least five of the analysed samples. Projection of lines from the best fit ages for concordant data points through these older discordant points yields upper concordia intercept ages of 1134 ± 64 Ma, 2719 ± 4 Ma and 713 ± 61 Ma for HK11025, HK11821 and HK11822, respectively. Upper intercepts through discordant zircons from HK11837 and HK10277 are much less precise because the data points only show small amounts of inheritance. Assuming that the age estimates of these samples are correct, the spread of older data points could be accounted for by a range of inheritance ages from about 1000 Ma to 3000 Ma (see reference Pb-loss lines in Fig. 3b and g) although the older age limit on this estimate is very uncertain. As with the Triassic sample, since many of the inherited fractions contain several grains, some of the upper intercept ages may represent averages of different older components.

Analysis of one pink, rounded zircon from the Tai Mo Shan Formation (HK11837), which was clearly a xenocryst, gave a concordant datum point with an age of 1872 ± 3 Ma (Fig. 3b). Its concordancy indicates that it was isotopically undisturbed by the emplacement of its much younger host rock.

Period 2. For samples from Periods 2 to 4, combined plots of U–Pb data thought to be unaffected by inheritance reveal clusters of data points with internally unresolvable ages (Fig. 4). Data from five rocks in Period 2 are clustered between 146.6 ± 0.2 Ma and 146.2 ± 0.2 Ma (Fig. 5a–e). The average

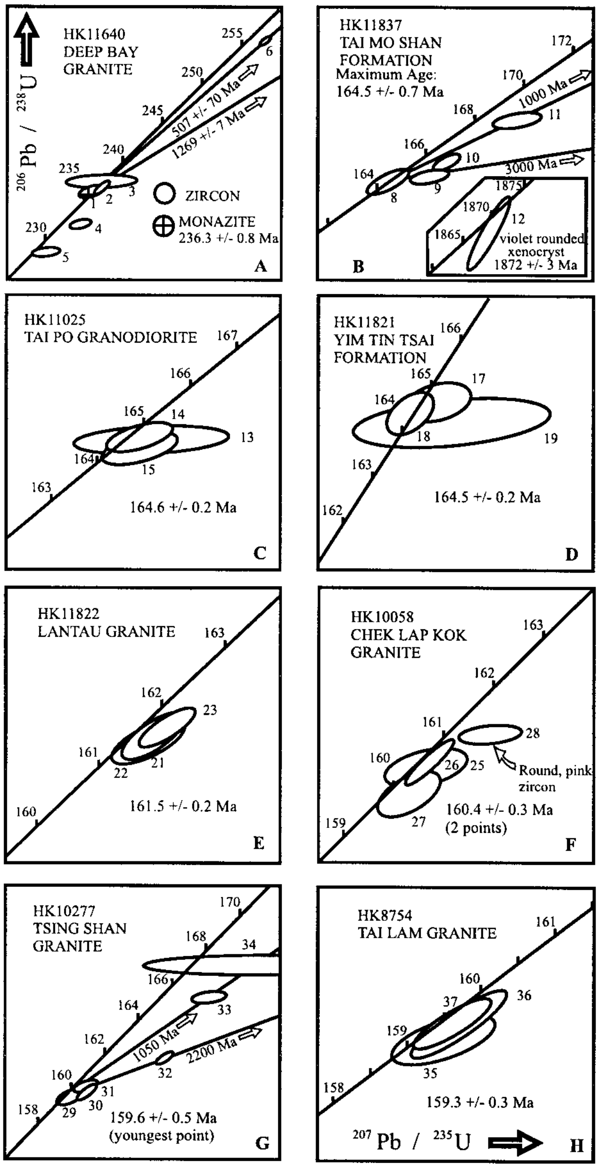

Fig. 3. (**a**) U–Pb concordia plot for the Triassic Deep Bay Granite. Discordia lines with upper intercept ages are regressed through data points affected by inheritance. (**b–h**) Concordia plots for Jurassic rocks of Period 1. Discordia lines with upper intercept ages shown in (**b**) and (**g**) are reference lines.

^{206}Pb/^{238}U age is 146.4 ± 0.1 Ma with a 43% probability of fit. Inherited components in the analysed samples consistently give concordant or near-concordant data with ages ranging from 153.8 ± 0.4 Ma to 149.5 ± 0.4 Ma suggesting that they may have been derived from the *c.* 160 Ma rocks of Period 1.

Period 3. A third period of Mid-Jurassic–Early Cretaceous magmatic activity occurred between 142.8 ± 0.2 Ma and 142.5 ± 0.3 Ma (Fig. 6a–f). Four rocks define an average ^{206}Pb/^{238}U age of 142.7 ± 0.1 Ma with a 98% probability of fit (Fig. 4). Three zircon fractions from HK8353 produced concordant data points which did not agree (Fig. 6a), probably due to the presence of invisible cores. The youngest of these data points returned an age of 143.7 ± 0.3 Ma, which is considered an older age constraint on the crystallization of the rock. This may be close to the emplacement age since it

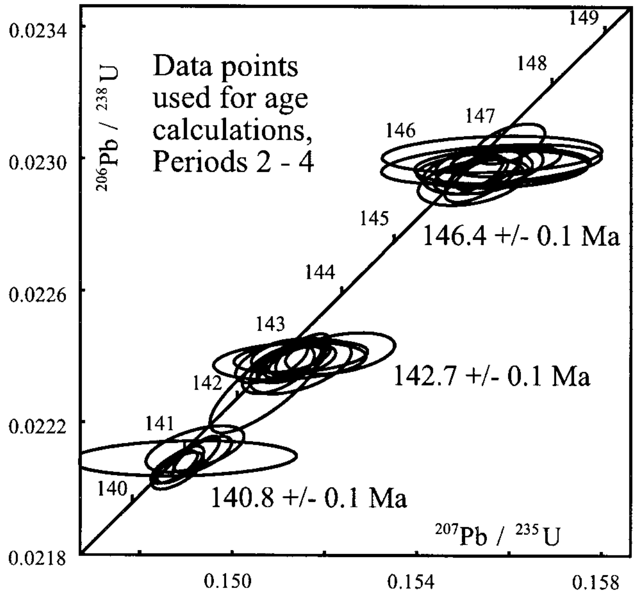

Fig. 4. U–Pb concordia plot showing a summary of data points used in calculating ages of rocks from Periods 2, 3 and 4 along with the average age of each data cluster.

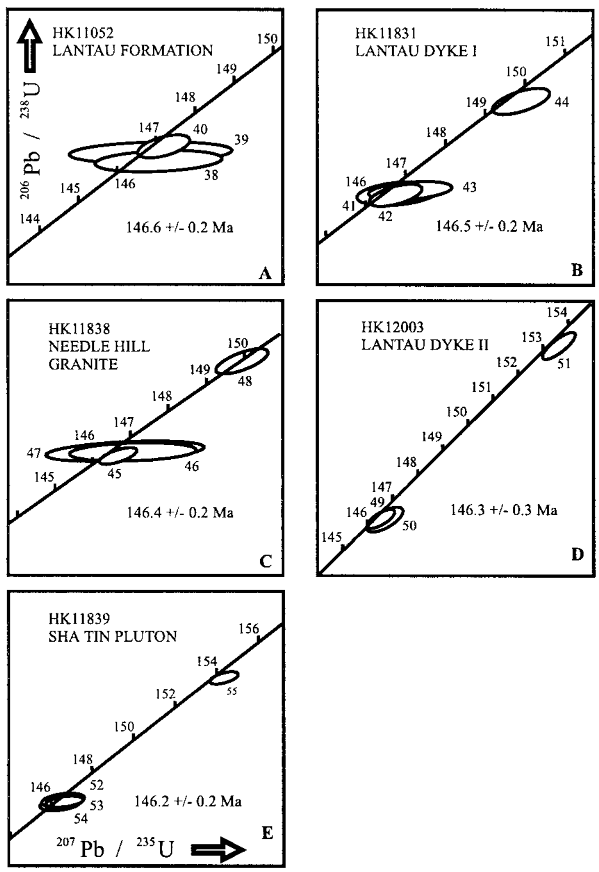

Fig. 5. U–Pb concordia plots for Jurassic magmatism of Period 2.

agrees with the ^{207}Pb/^{206}Pb age of a discordant monazite fraction from this rock (144 ± 9 Ma, Fig. 6b). A multi-grain fraction containing inclusion-free zircons from this rock revealed strong inheritance. The line through this data point

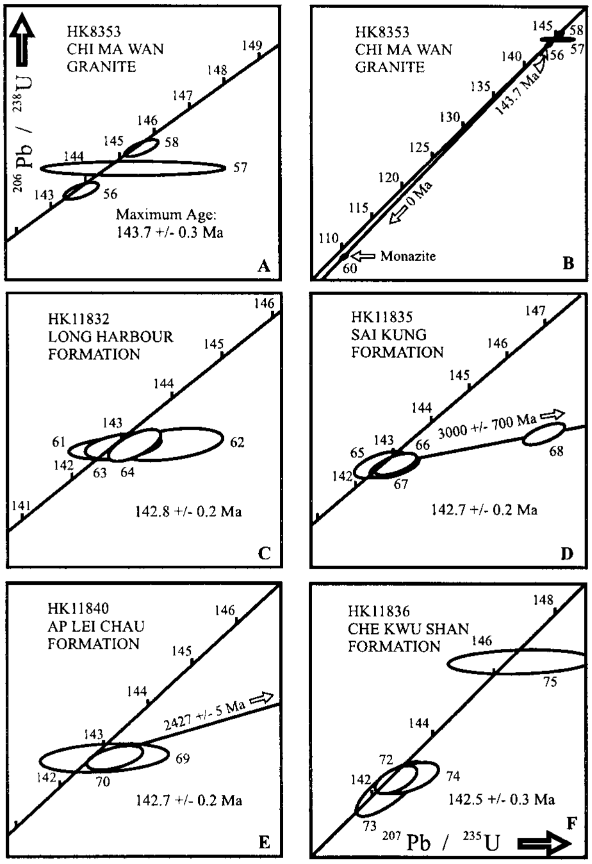

Fig. 6. U–Pb concordia plots for Jurassic magmatism of Period 3. Discordia lines with upper intercept ages in (d) and (e) are regressed through data points affected by inheritance.

and 143.7 Ma has an upper concordia intercept of 1845 ± 15 Ma, close to the xenocryst age from the Tai Mo Shan Formation (see above). Strongly discordant data points from inclusion-free zircon fractions in HK11835 and HK11840 yield upper intercept ages of 3000 ± 700 Ma and 2427 ± 5 Ma, respectively. A single zircon grain from HK11836 with a cluster of clear inclusions returned an older age of 146.4 ± 0.4 Ma. This may be a xenocryst from an underlying Period 2 unit.

Period 4. Four samples from the fourth main period of magmatic activity gave ages between 140.9 ± 0.2 Ma and 140.4 ± 0.2 Ma (Fig. 7a–d) defining an average ^{206}Pb/^{238}U age of 140.8 ± 0.1 Ma with a 72% probability of fit (Fig. 4). None of the analysed fractions appears to have been greatly affected by inheritance and there was no evidence of zircon cores or xenocrysts seen during picking.

Discussion

Precise data points in this study generally lie slightly to the right of, or below the concordia curve. The presence of residual inheritance or secondary Pb loss could produce this effect, but is unlikely because the bias is fairly consistent, producing a difference between ^{206}Pb/^{238}U and ^{207}Pb/^{235}U ages of about 0.2 to 0.3 Ma (e.g. Fig. 4). The same consistency argues against a cause due to analytical error, or incorrect choice of common Pb isotopic composition, since the analyses have a wide range

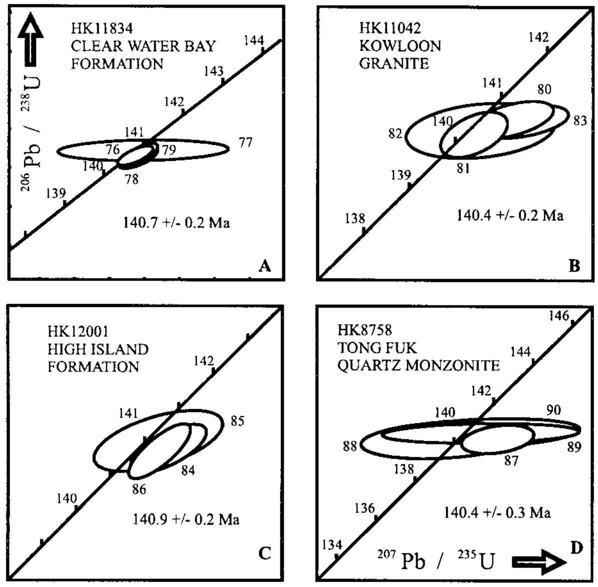

Fig. 7. U–Pb concordia plots for Jurassic magmatism of Period 4.

of radiogenic to common Pb ratios. The bias is also too great to be accounted for by an error in U decay constants. If it is an isotopic disequilibrium effect, it cannot be due to ^{230}Th depletion since correction for this effect brings the data points closer to concordia and they have been corrected for almost the maximum possible depletion. If zircon crystallized with a much higher ^{231}Pa/U ratio than the magma, this would result in excess ^{207}Pb, pushing the datum point to the right (^{231}Pa has a 32 ka half-life in the ^{235}U decay chain). The partition coefficient of Pa into zircon is unknown, so this cannot be confirmed, although it would have to be quite high to account for the observed effect. This effect would not influence ^{206}Pb/^{238}U ratios, which have been used to calculate ages. Although the ^{206}Pb/^{238}U ages for rocks from Periods 2 to 4 are internally reproducible and give errors on the means of ± 0.1 Ma (Fig. 4), errors of ± 0.3 Ma are considered to be more realistic due to uncertainty in the cause of the data discordance.

Precambrian inheritance unquestionably affects the Triassic granitoid and the granitoids belonging to the first and third periods of Mid-Jurassic–Early Cretaceous magmatism. Although upper intercept ages of partially reset data points from multi-grain fractions may be averages from different aged sources or multiple older Pb-loss events, the youngest and oldest precise upper intercept ages should represent minimum estimates for the age range of the inherited components. Upper intercept ages ranging from early Phanerozoic (507 ± 70 Ma in HK11640) to late Archaean (2719 ± 4 Ma in HK11821) are probably due to a combination of xenocrysts derived from wall-rock contamination, and invisible cores derived from older rocks at the site of melt generation. There are probably also discrete sources of Proterozoic contamination, as seen from the concordant 1872 ± 3 Ma xenocryst in HK11837. Several Jurassic samples contained similar-looking pink, rounded xenocrysts with frosted surfaces suggestive of detrital transport. These may have been derived from sediments that contaminated the magmas during ascent or emplacement.

Zircons from the Triassic granitoid differ in shape and colour from those in the Middle Jurassic–Lower Cretaceous suite. Compositionally, the Triassic granitoid is distinct from the Jurassic granitoids (Sewell & Campbell this issue, table 2), and contrasting Sr–Nd isotope signatures (Darbyshire & Sewell in press) suggest that the two suites had different source rocks.

The U–Pb data presented here confirm the presence of both late Archaean and mid-Proterozoic components in the source regions of Hong Kong felsic magmas. However, some or all of the inherited zircon ages may be derived from detrital zircons in younger underlying sediments. It is also impossible, based on zircon data, to model the degree of older crustal involvement in melting or contamination, or to determine its average age. Zircon inheritance will indicate only whether one or more particular aged sources are likely to have been involved. Although there is no direct correlation between the inherited zircon ages and the Nd model ages described by Darbyshire & Sewell (in press), the strongest evidence for Archaean inheritance occurs in samples from the northwest of Hong Kong (Fig. 2, Table 2). The best evidence for Proterozoic zircon inheritance occurs in samples from both the northwest and southeast of Hong Kong. The nearest exposures of Precambrian basement rocks to Hong Kong are found 2 km north of Hong Kong in Guangdong Province. They consist of gneiss, schist, and quartzite and are thought to be of Neoproterozoic (Sinian) age (Zhen & Wang 1988).

The absence of a significant inherited zircon population in granitoids and volcanic rocks belonging to the youngest period of Mid-Jurassic–Cretaceous magmatism (Period 4) may reflect a general trend toward alkalic (potassic) compositions with time. Magmatic conditions in such magmas generally do not favour preservation of inherited zircon populations due to enhanced zircon solubility in alkaline magmas (Watson & Harrison 1983).

Conclusions

The whole-rock Rb–Sr isochron ages obtained from earlier work (Table 2) provided a useful frame of reference for distinguishing the broad volcanic and plutonic associations. However, the U–Pb zircon ages presented here are much more precise and have considerably improved these earlier interpretations. In addition to establishing the presence of one Triassic granite, four distinct Mid-Jurassic–Lower Cretaceous magmatic events have been identified within the volcano-plutonic sequence of Hong Kong. Inheritance patterns in the U–Pb data accord with earlier conclusions drawn from Sr and Nd isotope studies for involvement of Proterozoic and late Archaean sources in Hong Kong felsic rocks.

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