ABSOLUTE AGE-DATING OF HONG KONG VOLCANIC AND PLUTONIC ROCKS, SUPERFICIAL DEPOSITS, AND FAULTS

GEO REPORT No. 118

R.J. Sewell & S.D.G. Campbell

GEOTECHNICAL ENGINEERING OFFICE

CIVIL ENGINEERING DEPARTMENT

THE GOVERNMENT OF THE HONG KONG SPECIAL ADMINISTRATIVE REGION

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Prepared by:

Geotechnical Engineering Office,
Civil Engineering Department,
Civil Engineering Building,
101 Princess Margaret Road,
Homantin, Kowloon,
Hong Kong.

PREFACE

In keeping with our policy of releasing information which may be of general interest to the geotechnical profession and the public, we make available selected internal reports in a series of publications termed the GEO Report series. A charge is made to cover the cost of printing.

The Geotechnical Engineering Office also publishes guidance documents as GEO Publications. These publications and the GEO Reports may be obtained from the Government's Information Services Department. Information on how to purchase these documents is given on the last page of this report.

R.K.S. Chan
Head, Geotechnical Engineering Office
October 2001

FOREWORD

This report outlines the various techniques which have been used over the past thirty years to date radiometrically Hong Kong's volcanic and plutonic rocks, superficial deposits, and faults. The results of these absolute age-dating studies are briefly summarized and then evaluated in terms of their effectiveness in improving our understanding of the geology. Recommendations are given for future work. This report was written by Dr R.J. Sewell and Dr S.D.G. Campbell of the Hong Kong Geological Survey in the Planning Division.

Helpful comments were provided by GEO colleagues including Dr C.J.N. Fletcher, Dr R. Shaw, Mr K.W. Lai and Mr J.P. King.

(R.P. Martin)
Chief Geotechnical Engineer/Planning

ABSTRACT

Over the past thirty years, with improvements in analytical techniques, absolute age-dating precisions have improved dramatically. As a result, absolute age-dating is now being used routinely to solve complex geological problems.

In Hong Kong, major advances in the understanding of geological relationships, particularly with regard to the volcanic and plutonic rocks have been achieved using age-dating. Radiometric dating has proved to be an effective tool for refining the existing geological maps and has complemented other analytical techniques including geochemistry, mineralogy and petrography, and seismic interpretation and borehole geophysics.

Recent developments in luminescence dating have enabled the dating of superficial deposits in Hong Kong. Refinements to the radiocarbon age-dating technique and the development of cosmogenic isotope techniques to date very young surfaces, also hold promise for dating colluvium. The use of these dating techniques, therefore, could have very significant applications in risk management strategy for natural terrain in Hong Kong.

Several outstanding structural problems still remain in Hong Kong, particularly with regard to the last age of movement on major faults and characterisation of the regional stress regime. These problems could be readily resolved by precise dating of the mafic and intermediate dykes, and the dating of fault-related materials.

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1. INTRODUCTION

Since the pioneering work on natural radioactivity by Rutherford and Soddy (1903), it has been recognised that the rates of radioactive decay can be used for measuring geological time. Thus, radiogenic isotopes have been used historically to determine the absolute age of igneous rocks and minerals, and inevitably the age of the earth. Three isotopic systems are now routinely used in age determinations of igneous rocks. These are the K–Ar, Rb–Sr, and U–Pb systems. Radiogenic isotopes are also used for dating superficial deposits, the most common method being radiocarbon dating. More recently, uranium-series and luminescence dating techniques have been applied to these relatively young deposits and several new radiometric techniques are currently under development. Luminescence and other radiometric techniques are also being applied to the dating of fault movements. These age-dating techniques provide a valuable and quantitative alternative to the traditional approach of using fossils to date geological strata and tectonic events.

The geology of Hong Kong is highly variable with a great diversity of rock types, superficial deposits and geological structures which have evolved during some 400 million years of geological time. As geological mapping techniques have improved and the demand for accurate geological information has increased, the relationships between these different rock units and superficial deposits have become increasingly important to a complete understanding of the geology. Since fossils are relatively rare in the predominantly volcanic record of Hong Kong and, in most instances, provide rather imprecise ages, absolute age-dating using isotopic techniques has played a key role in deciphering the geological history. Isotopic dating of rocks and superficial deposits in Hong Kong has also been of practical benefit in a variety of ways.

Knowledge of the absolute ages of volcanic and granitic rocks has been successfully used:

(a) in stratigraphic correlation, both locally and with neighbouring Guangdong, hence assisting geological map production on a variety of scales,

(b) as a rational basis for grouping stratigraphic formations,

(c) as an aid to identifying major geological structures, notably faults and fault zones, but also unconformities, and

(d) for correlating extrusive volcanic rocks and their intrusive equivalents, which can have implications for interpreting various features, such as hydrothermal alteration.

Absolute age determination of superficial deposits has proved to be of considerable value in:

(a) interpreting and correlating the stratigraphy of offshore superficial deposits, with implications for future exploitation of offshore resources,

(b) determining the age of colluvium onshore and so providing a basis for assessing the frequency of very large volume landslides within the context of Quantitative Risk Assessment (QRA), and

(c) dating relationships between various types of superficial deposits within known fault zones as a basis for assessing the possibility of recent fault activity, and for interpreting the significance of microseismic activity recently identified by the Hong Kong Observatory on a regular and widespread basis within Hong Kong.

In addition, absolute age determination has also been applied to dating fault gouges, and hence the most recent significant movement of faults, and may have future application in weathering studies, including for example the rates of accumulation of geotechnically problematic kaolinitic clays.

2. AGE-DATING TECHNIQUES FOR VOLCANIC AND PLUTONIC ROCKS IN HONG KONG

Three isotopic age-dating techniques have generally been used for dating Hong Kong's volcanic and plutonic rocks. These are the potassium–argon (K–Ar), rubidium–strontium (Rb–Sr) and uranium–lead (U–Pb) techniques, each of which is based on dating the crystallisation age of constituent minerals. A slight modification of the K–Ar technique, known as the Ar–Ar technique, has also been used.

2.1 K–Ar Whole-rock and Mineral Age-dating

2.1.1 Methodology

The potassium–argon (K–Ar) method can be used to date rocks ranging in age from 4,600 million years to as young as 30,000 years. The principal isotopes used are the parent isotope ^{40}K, which has a half-life of 11,900 million years, and the daughter isotope ^{40}Ar. The K–Ar dating method can be used on whole-rocks, but is generally more effective on separates of K-rich minerals such as biotite, muscovite, and hornblende. Problems can sometimes arise because of the diffusive loss of ^{40}Ar at temperatures below the blocking temperature which varies from mineral to mineral (e.g. biotite 300 ± 50°C, muscovite 350 ± 50°C, and hornblende 500 ± 50°C). The potassium and argon measurements are also undertaken on separate sub-samples, which introduces potential errors from sample discrepancies. Because of these difficulties, K–Ar age-dating is now less widely used in favour of Ar–Ar age-dating which is a modification of the K–Ar method (see below).

2.1.2 Results

Radiometric dating was first applied to dating Hong Kong igneous rocks and minerals by Chandy & Snelling (*in* Allen & Stephens, 1971) during a geological survey of the Territory commissioned by the Hong Kong Government. They used the K–Ar and Rb–Sr isotopic systems. K–Ar mineral ages were obtained on biotites from eight granites and one volcanic unit while whole-rock dating methods were applied to four mafic and intermediate dykes (Table 1). The ages obtained varied from 154 to 117 million years for the volcanic and granite rocks and 56 to 76 million years for the dykes. Most of the quoted ages had typical errors of ± 3 million years. The most important conclusion drawn from these early dating studies was that the igneous rocks of Hong Kong are mostly of Middle Jurassic to Late Cretaceous age.

2.2 Rb–Sr Whole-rock Age-dating

2.2.1 Methodology

The rubidium–strontium (Rb–Sr) method relies on the decay of ^{87}Rb to the daughter isotope ^{87}Sr and has a half-life of 48,800 million years. It is rarely used for rocks younger than 20 million years. Providing the rock being dated has remained a closed system with respect to Rb and Sr, the dating of a "whole rock" sample of an igneous rock gives the age of crystallisation. Generally, a minimum of eight whole-rock samples are analysed and the age is calculated from the slope of line through data points on a plot of ^{87}Rb/^{86}Sr versus ^{87}Sr/^{86}Sr (known as an isochron plot). This relies on the samples having variable Rb:Sr ratios. One problem, now increasingly recognised using Rb–Sr systematics, is that of resetting of the isotopic system to zero under conditions of low grade metamorphism (e.g. Evans, 1995). Hence, ages obtained may be related to post-emplacement metamorphism of the rock rather than emplacement itself.

2.2.2 Results

Chandy & Snelling (*op. cit.*) were also the first workers to use the Rb–Sr method for dating igneous rocks in Hong Kong. Rb–Sr whole-rock age determinations were made on two volcanic and nine intrusive samples (Table 2). Attempts to construct an isochron for the intrusive rocks were not very successful. A scatter of points about the line of best fit gave an average age of 133 ± 7 million years which was generally consistent with the K–Ar data but rather imprecise. The two samples of volcanic rocks also gave ambiguous results due to their very similar Rb:Sr ratios.

The difficulties encountered by Chandy & Snelling in dating the igneous rocks of Hong Kong can be partly explained by the lack of detailed knowledge of the intrusive and extrusive units. At the time, the intrusive rocks of Hong Kong had been grouped into seven major units but field relationships were not well understood. Detailed geological remapping of Hong Kong at 1:20,000-scale undertaken by the Hong Kong Geological Survey (HKGS) between 1982 and 1991, combined with petrography and whole-rock geochemistry, later revealed several new volcanic and intrusive units, highlighting the need for more accurate age information. By the late 1980's, Rb–Sr isotope measurement techniques had improved considerably and a comprehensive dating programme using the whole-rock method was initiated (see Appendix 1). The dating programme was undertaken for the HKGS over a period of three years from 1989 to 1992 by the NERC Isotope Geosciences Laboratory, UK, and returned much more precise ages than the earlier work (Table 2). However, owing to problems in obtaining fresh material, several intrusive units could not be dated and most of the volcanic units remained undated. The results of the Rb–Sr whole-rock dating programme suggested that the volcanic and plutonic rocks of Hong Kong ranged in age from approximately 155 to 136 million years (Sewell *et al*. 1992). However, the relatively large errors on some units meant that separate pulses or phases of plutonic–volcanic activity could still not be reliably identified. As a result, it was considered that the application of Rb–Sr age-dating had reached the limits of its usefulness and an alternative, more precise technique was needed.

2.3 U–Pb Single Zircon Age-dating

2.3.1 Methodology

The uranium–lead (U–Pb) single zircon dating method is a relatively new technique which enables a precise magmatic age to be obtained from one rock sample with a good zircon population. It is based on the decay of ^{238}U and ^{235}U to ^{206}Pb and ^{207}Pb which have half-lifes of 4,467 and 704 million years respectively. The U–Pb dating method is particularly useful for rocks over 100 million years old and is the preferred method for dating Precambrian rocks. This is because zircons are highly resistant to alteration and dissolution. Hence, the technique is suitable even for rocks that have undergone significant alteration as a result of hydrothermal alteration or metamorphism. They can also be used to date highly weathered rocks. An added benefit of the single zircon age-dating method is that the zircons may preserve a record of previous tectonothermal events. “Inherited” zircons may give valuable information on the nature of the source rocks, particularly at deep crustal levels, which may have implications for the location of major, deep-seated faults in Hong Kong. However, on the basis of previous Rb–Sr dating, its use on rocks as young as those in Hong Kong would be extending the technique to its analytical limits.

2.3.2 Results

In 1995, an attempt was made by the HKGS, in collaboration with the Royal Ontario Museum (ROM), Toronto, Canada, to date the oldest intrusive units of Hong Kong using the U–Pb single zircon dating method. The Royal Ontario Museum in Toronto is the recognised world leader in the field of single zircon U–Pb geochronology after pioneering the technique in the early 1980’s. Several rock units dated earlier by the Rb–Sr technique were re-analysed as a check on precision and accuracy. The U–Pb results gave very precise ages of between 164 and 140 million years with errors in the order of only ± 200,000 years (Table 2). They also revealed that the Rb–Sr whole-rock ages were commonly 3-4 million years younger than the true crystallisation age of the rocks and that a K–Ar date for a volcanic rock obtained by Chandy & Snelling (op. cit.) was at least 10 millions years younger than the probable eruption age. Owing to the impressively high level of precision achieved, many previously undated volcanic and plutonic units were analysed using the U–Pb single zircon method (see Appendix 2). This revealed a complex history of Mesozoic plutonic–volcanic activity which can now be divided into four main episodes (Table 3, Davis *et al*. 1997, Campbell & Sewell 1997) separated by unconformities. These episodes now form the basis of a revised group stratigraphy and granite classification in Hong Kong (Campbell & Sewell, 1998). Furthermore, the new U–Pb ages, together with existing whole-rock geochemical data, have permitted several stratigraphic correlations to be made between isolated areas of volcanic rocks. This has enabled significant improvements to be made to the existing 1:20,000-scale geological maps of Hong Kong and the significance of some major geological faults to be fully realised.

2.4 Ar–Ar Mineral Age-dating

2.4.1 Methodology

Although the U–Pb single zircon dating technique can give very precise crystallisation ages, it can only be applied to rocks containing zircon. This effectively rules out rocks of basic to intermediate composition, including basalts and andesites, which do not normally contain zircon. In recent years a modification of the K–Ar dating technique has been developed which produces substantially greater precision. This is achieved by irradiating a potassium bearing mineral in a nuclear reactor to convert ^{40}K into ^{39}Ar. Since both ^{39}Ar and ^{40}Ar are gasses, they are more easily and accurately measured by mass spectrometry. Step heating of the irradiated sample during analysis has been greatly improved by the introduction of a continuous laser ablation technique.

2.4.2 Results

In 1993, a pilot dating programme was commenced to date mafic dykes of Hong Kong using the Ar–Ar dating technique in collaboration with the University of Taiwan. However, the results of this study were ambiguous and have since proven to be inconsistent with recent U–Pb dating (Table 4). In one instance, an Ar–Ar age turned out to be considerably younger than the U–Pb age of apparently coeval material. This may reflect the greater susceptibility to resetting of the Ar–Ar system at temperatures above *c.* 350°C than the U–Pb system which has a blocking temperature of *c.* 700°C.

3. AGE-DATING TECHNIQUES FOR SUPERFICIAL DEPOSITS IN HONG KONG

Various techniques have been applied to the dating of superficial deposits in Hong Kong. Radiocarbon dating has been the most widely used technique, and more recently, uranium–series dating, and luminescence dating have proved useful. In the offshore areas, the comprehensive seismic coverage combined with borehole controls have provided an ideal basis for dating key stratigraphical horizons. Attention is currently turning to the dating of onshore superficial deposits. In particular, there is a need to date colluvium to provide a timescale relevant to the Natural Terrain Landslide Study (NTLS) and periodicity information for GEO's current efforts focused on Quantitative Risk Assessment (QRA) for natural terrain.

3.1 Radiocarbon Dating

3.1.1 Methodology

Radiocarbon dating is commonly used to date organic materials. The method is based on the assumption that the isotope ratio of carbon cells of living things is identical to that in the air because of the balance between photosynthesis and respiration. Atoms of the radioisotope ^{14}C mix with other carbon isotopes in the atmosphere and hydrosphere making up a steady state concentration. The carbon is then incorporated into plant and animal tissue and the ^{14}C subsequently decays to ^{14}N. The ^{14}C isotope has a half-life of 5730 years. Owing to the relatively short half-life of ^{14}C, radiocarbon dating is only effective in dating material younger than 40,000 years.

3.1.2 Results

Radiocarbon dating was first used to date the superficial deposits of Hong Kong during archaeological investigations in the late 1970's (Kendall, 1975). Since then, numerous dates have been obtained, mainly by the HKGS and by Hong Kong's archaeologists, from material incorporated in Pleistocene and Holocene deposits (Table 5). However, there have been suggestions that radiocarbon-based ages in pre-Holocene sediments in Hong Kong are biased towards younger ages than their actual ages (e.g., Yim *et al*. 1990). This age bias problem is not restricted to Hong Kong, and elsewhere, various explanations have been proposed (e.g., due to the material being coated with thin layers of younger organic matter).

(a) Hang Hau Formation. Early efforts to date the Hang Hau Formation by Meacham (1978) produced dates of 6,520 ± 130 yrs BP at Admiralty and 6,580 ± 130 BP at Prince Edward. An age of 8,080 ± 130 yrs BP was also reported by Strange & Shaw (1986) from near the base of the formation in a borehole at Junk Bay (JBS1/1A). Further dating, as part of HKGS offshore mapping in the northwest New Territories (Langford *et al*., 1989) and central southern waters of Hong Kong (Fyfe *et al*., 1997), confirmed the Holocene age of the entire formation.

(b) Sham Wat Formation. Three dates have been obtained from the recently defined Sham Wat Formation and these range from 19,580 ± 320 to > 43,700 yrs BP (Langford *et al*., 1995).

(c) Waglan Formation. The formation, which is restricted to the southeastern waters of Hong Kong, has yielded radiocarbon ages of *c*.30,000 yrs BP and > 40,000 yrs BP. However, Fyfe *et al*. (1997) argue that ages of < 40,000 yrs BP reflect contamination by more recent carbon.

(d) Chek Lap Kok Formation. The initial attempt to date the Chek Lap Kok Formation by Kendall (1975) at High Island gave one age of 36,000 yrs BP, and two others > 40,000 yrs BP, the limit of the technique. RMP Encon (1982) subsequently reported ages from Chek Lap Kok itself, of between 16,420 ± 660 and 36,480 yrs BP. Whiteside (1984) obtained a date within the same range (23,270 ± 720 yrs BP) near Sha Tin while Strange & Shaw (1986) confirmed that a wood fragment at the base of the formation was > 40,000 yrs BP.

With the development of work associated with the new airport at Chek Lap Kok, and other elements of the Port and Airport Development Strategy (PADS), considerably more radiocarbon dating was undertaken to provide stratigraphic refinement. These dates, reported in HKGS Memoir 6 (Langford *et al.*, 1995), ranged between 16,420 ± 660 and > 41,600 yrs BP).

(e) Onshore alluvial and other deposits. Meacham (1978) reported a radiocarbon age of 6,600 yrs BP for an alluvial deposit on Lamma. For beach deposits on Lung Kwu Chau and in the Tuen Mun Valley, he also obtained ages of 5,800 ± 500 yrs BP and 1,370 ± 100 yrs BP respectively, although the latter was *c*.2,000 years younger than the expected age based on other archaeological evidence.

A more extensive suite of radiocarbon dates was undertaken during HKGS mapping in the NE New Territories (Langford *et al.*, 1989). Holocene alluvium was dated at 1,510 ± 70 and 1,630 ± 70 yrs BP late. In the Yuen Long area, Pleistocene organic clays, interbedded with alluvium, were dated at between 16,289 ± 831 and 33,575 ± 3,186 yrs BP. Pleistocene alluvium from near Fanling has also been dated at 22,780 ± 530 yrs BP (Lai *et al.*, 1996) as was organic mud nearby at 10,160 ± 34 yrs BP.

3.2 Uranium-series Dating

3.2.1 Methodology

Uranium-series dating is based on the measurement of the relative abundance of the radioactive products of ^{238}U and ^{235}U (Schwarz & Blackwell, 1985). The technique is dependent on separation of the daughter products during sedimentary processes. Where this separation accompanies the formation of natural materials, such as bone, shell, or carbonate exoskeletons, measurements of the relative abundance of the daughter radioisotopes provide an age for the sediment.

3.2.2 Results

In Hong Kong, the technique has been used to date oyster shells found in the Chek Lap Kok Formation (Yim *et al.*, 1990; Owen *et al.*, 1998). A uranium-series date of 248,000 ± (12,000–16,000) years was obtained from an oyster shell within the Chek Lap Kok Formation in a borehole from the northern part of the East Lamma Channel (Owen *et al.*, 1998).

3.3 Thermoluminescence (TL) and Optically-stimulated Luminescence (OSL) Dating

3.3.1 Methodology

Luminescence age-dating techniques rely on the capacity of mineral grains such as quartz and feldspar to trap electrons, which are the product of natural radiation in a rock (Dreimanis *et al*. 1985). When these electrons are subsequently heated (TL) or stimulated by light (OSL) in a laboratory, the energy released in the form of light can be measured. Luminescence techniques have been applied to dating quartz and feldspar grains which have been bleached by sunlight and subsequently buried. The technique has been successfully applied to dating sediments between 1,000 and 1,000,000 years old. This age range extends well beyond the maximum limit of radiocarbon dating so is ideal for dating Pleistocene as well as most Holocene sediments, providing the sand grains have been fully bleached on exposure to sunlight.

3.3.2 Results

In Hong Kong, luminescence techniques have been applied to dating quartz grains in landslide debris and, more recently, offshore marine sediments (Owen *et al*., 1998). In the absence of shell material, the luminescence techniques provide the only method to date the sediments in deep offshore boreholes. Radiocarbon dating of the Chek Lap Kok Formation has commonly yielded ages of > 40,000 BP which is the maximum limit achievable with this technique. Therefore, OSL and TL dating have enabled older Pleistocene deposits in the Chek Lap Kok Formation and its onshore equivalents to be dated. Sediments in the deep offshore boreholes are likely to be considerably older than 40,000 years and therefore, well beyond the limit of radiocarbon dating.

(a) Offshore superficial deposits. The Chek Lap Kok Formation has yielded an OSL date of 80,000 ± 9,000 yrs BP (Owen *et al*., 1995) and a TL date of 78,000 ± 8500 yrs BP.

(b) Onshore colluvium and alluvium. OSL dates were reported by Lai *et al*. (1996) for older Pleistocene alluvium from near Fanling (range 84,700 ± 16,300 to 157,500 ± 36,300 yrs BP). A synthesis of available OSL dates for an alluvial sequence near Yuen Long has recently been published by Lai (1998), while two OSL dates from colluvium on Hong Kong Island (196,000 ± 13,000 yrs BP) and in Sai Kung (38,000 ± 4,000 yrs BP) have been reported by Duller & Wintle (1996).

(c) Landslide studies. During GEO's forensic investigation of the Shum Wan Landslide, near Aberdeen, in 1995, TL dating of the colluvium present on the slope prior to the landslide was undertaken. This indicated that the colluvium was between 34,800 and 48,200 years old.

Recently, as part of the NTLS being undertaken principally by the Planning and Terrain Evaluation Section of the Planning Division, a large colluvium lobe near Sham Wat in northeast Lantau Island has been dated using TL. Provisional dates are 1,500 years BP for the top of the lobe and 2,300 yrs BP from near the base[1]. These dates were obtained using numerous very small samples to identify the youngest, i.e. the most recent, age of exposure to light. This was necessary as the samples were poorly bleached suggesting differential exposure to light of individual quartz grains. These results are potentially very significant with respect to Quantitative Risk Assessment in this and similar areas of natural terrain that are being impinged on by development in Hong Kong.

4. AGE-DATING TECHNIQUES FOR FAULT MOVEMENTS IN HONG KONG

Thermoluminescence dating can generally be applied to the dating of fault movements (e.g. Ji & Gao 1988, Hutton *et al*. 1994) in four ways:

(1) dating fault gouge,

(2) dating sediments that are faulted, i.e. the depositional age of the sediments constrains the maximum possible age of fault movement,

(3) dating colluvial deposits formed adjacent to faults scarps, i.e. yielding the minimum age of vertical fault displacement, and

(4) dating sediments that unconformably overlie a fault zone, but are themselves undisturbed, so that a minimum age of movement is determined.

4.1 Thermoluminescence (TL) Dating

4.1.1 Methodology

Although the basis of the technique for dating fault gouge has been widely researched in China, few papers are readily available. Consequently, the technique has yet to be used widely outside mainland China. Research at the Institute of Geology in Beijing has shown that increases in confining pressure have only a modest influence on reducing the TL signal but increases of temperature do. For example, at 270° and a confining pressure of 300 MPa, the TL signal reduces to less than 1% of its original. However, at 500 MPa, a temperature of 370° is required to obtain a similar decrease in the TL signal. The TL signal is also affected by changes in strain rate. For example, at only 10 MPa, a strain rate of about 50 cm/sec

[1] Note added in proof: Using the dose distribution method, the last significant transport event at the Sham Wat Debris Lobe is considered to have occurred within the last 10,000 years, possibly as recently as 1,500 years ago (King, J.P. (2001). Luminescence Dating of Colluvium and Landslide Deposits in Hong Kong. Technical Note No. 1/2001, Geotechnical Engineering Office, 65 p.).

would reduce the TL signal to zero. On the basis of this, Ji *et al*. (1994) have concluded that frictional heating is the main cause of the reduction in the TL signal and as such, the technique has a logical basis for dating fault movements that generate significant frictional heating.

The TL dating metholodogy of sediments that constrain maximum and minimum ages of fault displacements is as already described above (3.3.1).

4.1.2 Results

Ding & Lai (1997) recently published the results of TL dating of samples collected in Hong Kong from fault gouges from various faults, and alluvial sediments overlying fault zones, or whose distribution was controlled by faults.

Nineteen samples were obtained from faults of both NE and NW trends. These yielded TL dates ranging between 33,300 ± 2,700 and 278,700 ± 23,100 yrs. BP (Table 5). One fault was sampled at three different localities to determine the reproducibility of the results and produced encouragingly similar ages.

The data cluster into three main groupings suggesting there have been three phases of comparatively recent fault activity in Hong Kong: approximately at 100 000, 190,000 and 270,000 yrs BP. TL dating of alluvial sediments also indicates fault activity in the Late Pleistocene.

TL dating, in combination with radiocarbon dating of alluvial sediments considered to constrain fault-controlled river capture, suggest that a NW-trending fault that crosses the Lam Tsuen Valley was active between 84,700 ± 16,300 yrs and 23,950 ± 5,300 yrs BP.

5. EVALUATION OF RESULTS

Major advances in the understanding of geological relationships, particularly with regard to the volcanic and plutonic rocks which make up almost three quarters of the rocks of Hong Kong, can be directly linked with improved age-dating. From the earliest dating attempts to the present day, the precision of the ages obtained has increased by several fold such that it is now possible, in some cases, to identify major volcanic–plutonic episodes of less than one million years duration. The benefit of such well-constrained ages is that it enables accurate predictions of stratigraphy and structure to be made across the territory.

The absolute ages which have been obtained using radiometric techniques have solved many difficult stratigraphic problems. For example, the Lai Chi Chong Formation in Tolo Channel contains a variety of rocks which do not easily relate to any other volcanic sequence. Precise age-dating suggests that it actually consists of two formations separated by a major unconformity. Similarly, in the Tai O area of southwestern Lantau Island, the sedimentary sequence was thought to be of Carboniferous age based on apparent lithological similarities with the Lok Ma Chau Formation of the northwestern New Territories. Radiometric dating has since shown that the sequence is of Middle Jurassic age and is similar in age to the Lai Chi Chong Formation of Tolo Channel. This information is likely to have important implications for the interpretation of the highly complex structure of the North Lantau area, including Tung Chung. There, significant geotechnical problems are being encountered as a result of unforseen areas of deep weathering, alteration of the rocks and fault-bounded cavernous marble. Precise age-dating of the volcanic and plutonic rocks of the central New Territories and Lantau Island, have also revealed the existence of a complete section through the upper crust which exposes the system of faults and vents which fed the Lantau caldera.

There are presently several outstanding structural and stratigraphic problems in Hong Kong that could be readily resolved by absolute age-dating methods. These include precise dating of the mafic and intermediate dykes and the dating of fault-related materials. The mafic and intermediate dykes of Hong Kong have various orientations and may represent several separate phases of emplacement. Knowledge of the ages of these dykes is fundamental to an understanding of fault systems in Hong Kong because many dyke orientations lie parallel to, or are closely-aligned with, major faults. The dykes, therefore, may be sensitive indicators of stress regimes. Knowledge of their emplacement age would provide useful information on the orientation of the operative stress field. Coincident with the need for stress field information, is the need for more direct age information on the major fault movements and of related regional deformation in general. The Ar–Ar technique is continually under development and recent reports have shown the potential to date fault materials as young as 5,000 years old. This may have important application to the characterisation of active faults in Hong Kong, some of which are considered to have last moved less than 100,000 years ago (Ding & Lai, 1997). The technique is also likely to provide valuable constraints on considerably older fault movements and deformational events.

Radiometric age-dating results have produced major advances in understanding of the superficial deposits of Hong Kong. Specifically, radiocarbon dating and luminescence dating helped to constrain the ages of the Sham Wat and Waglan formations, and so have enabled their relationships with the Chek Lap Kok and Hang Hau formations to be confirmed. However, the seismic data have also highlighted the need for more precise age information particularly in deep offshore boreholes where the sediments are known to be considerably older than 40,000 years.

Initial findings from the luminescence techniques suggest they may be very suitable for dating ancient large-scale landslides. Dating of very young surfaces is providing valuable information for landslide hazard assessment in natural terrain, and could provide reliable constraints for return periods of major natural slope failures in Hong Kong. However, other age dating techniques currently at an early stage of development, such as cosmogenic beryllium-10 (Be^{10}) dating of exposed surfaces (e.g. boulders and the main scarps of landslides) could also be used to provide independent constraints on these events. The effective age range of this technique is approximately 20,000 to 700,000 yrs.

6. CONCLUSIONS

The main conclusions of this report are:

(a) Absolute age-dating of volcanic and plutonic rocks, and superficial deposits provides a very effective means of solving complex stratigraphic and structural problems.

(b) Radiometric dating has proven to be an extremely useful tool for refining the existing geological maps of Hong Kong and complements other analytical techniques including geochemistry, mineralogy and petrography, and seismic interpretation and borehole geophysics. As a result, major modifications to the existing 1:20,000-scale geological maps of Hong Kong have become possible. These are incorporated in the 1:100,000-scale geological map of Hong Kong recently compiled by the HKGS.

(c) The recent major advances in understanding of the stratigraphy of Hong Kong can be directly related to absolute age-dating, especially U–Pb high precision dating of zircon crystals within key stratigraphic volcanic and plutonic rocks.

(d) Due to recent developments in TL dating, precise constraints on the ages of superficial deposits and most importantly of colluvium, are now being achieved. These dates will have very significant implications in risk management strategy for natural terrain in Hong Kong.

7. RECOMMENDATIONS

It is recommended that:

(a) The application of thermoluminescence dating of colluvium should be extended, building on early encouraging and potentially highly significant results. A further suite of TL dates should be obtained from the Sham Wat colluvium lobe to prove the consistency of the data and therefore, the reliability and potentially wider applicability of the technique for colluvium.

(b) A pilot study to investigate the application of the Ar–Ar method to dating of fault material should be initiated. This should include samples from faults intersected in on-going tunnelling projects in Hong Kong (e.g. Strategic Sewage Disposal Scheme).

(c) Further U–Pb single zircon age-dating should be undertaken to resolve outstanding problems regarding the correlation of volcanic and plutonic units. In particular, the duration of recently inferred major unconformities with the volcanic sequence should be firmly established.

(d) A programme to establish the precise ages of mafic and intermediate dykes in Hong Kong should be undertaken using the Ar–Ar method.

(e) Currently, some offshore sediments are being dated using single grain luminescence techniques. These studies should be continued.

(f) New techniques for the radiometric dating of very young surfaces should be investigated. For example, cosmogenic Be^{10} has been used to date exposure ages of outcrops and boulders. This technique could have potential application in Hong Kong in dating the emplacement of boulders on the tops of colluvium lobes, boulders in talus deposits, individual very large boulders, and the main scarps of landslide scars.

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Table 1 - Summary of K–Ar Ages Obtained by Chandy & Snelling (*in* Allen & Stephens, 1971) and Comparison With U–Pb Ages Obtained by Davis *et al.* (1997)

Sample No.	**Analysed Material**	**Old Nomenclature**	**K–Ar (Ma)**	**New Nomenclature**	**U–Pb (Ma)**
HK460	Biotite	Repulse Bay Fm	154 ±4	Shing Mun Fm	undated
HK222	Biotite	Tai Po Granodiorite	134 ±2	Tai Po Granodiorite	164.6 ±0.5
HK739	Biotite	Sung Kong Granite	130 ±3	Lantau Granite	161.5 ±0.2
HK443	Biotite	Sung Kong Grantie	134 ±3	Po Toi Granite	undated
HK190	Biotite	D'Aguilar Monzonite	135 ±3	D'Aguilar Monzonite	140.7 ±0.2
4221E	Biotite	D'Aguilar Monzonite	143 ±4	D'Aguilar Monzonite	"
HK387	Biotite	D'Aguilar Monzonite	143 ±3	D'Aguilar Monzonite	"
HK518	Biotite	Hong Kong Granite	117 ±3	Sth Lamma Granite	undated
4421A	Biotite	Cheung Chau Granite	134 ±4	Kowloon Granite	140.4 ±0.2
HK266	Whole rock	Dolerite	76 ±2	Mafic Dyke	undated
HK304	Whole rock	Dolerite	62 ±2	Mafic Dyke	undated
HK871	Whole rock	Dolerite	57 ±2	Mafic Dyke	undated
6	Whole rock	Dolerite	63 ±6	Mafic Dyke	undated
HK167	Whole rock	Schist	92 ±2	Tuen Mun Formation	undated

Table 2 - Summary of Rb–Sr Ages Obtained by Chandy & Snelling (*in* Allen & Stephens, 1971), Sewell *et al.* (1992), and Darbyshire, D.P.F. (GEO, Unpublished Data), and Comparison With U–Pb Ages Obtained by Davis *et al.* (1997)

Reference	**Analysed Material**	**Old Nomenclature**	**Rb–Sr (Ma)**	**New Nomenclature**	**U–Pb (Ma)**
Chandy & Snelling 1971	whole rock	Phase 1–3 (7 samples)	163 ±35	Lamma Suite	c.164–159
	whole rock	Phase 4 (2 samples)	140 ±7	Lion Rock Suite	c.140
Sewell *et al.* 1992, Darbyshire, Unpub. data	whole rock	Tai Lam Pluton	155 ±6	Tai Lam Granite	159.3 ±0.3
	whole rock	Tsing Shan Pluton	152 ±3	Tsing Shan Granite	159.6 ±0.5
	whole rock	Sha Tin Pluton	148 ±9	Sha Tin Granite	146.2 ±0.2
	whole rock	D'Aguilar Syenite	147 ±8	D'Aguilar Monzonite	140.7 ±0.2
	whole rock	Lantau Rhyolite	144 ±2	Lantau Formation	146.6 ±0.2
	whole rock	Tong Fuk Syenite	144 ±6	Tong Fuk Monzonite	140.4 ±0.3
	whole rock	Kowloon Pluton	138 ±1	Kowloon Granite	140.4 ±0.2
	whole rock	Mt Butler Pluton	136 ±1	Mount Butler Granite	undated
	whole rock	Kwun Tong Pluton	136 ±1	Mount Butler Granite	undated

Table 3 - Summary of U-Pb Age Data Obtained by Davis et al. (1997) and Davis, D.W. (GEO, Unpublished Data)

VOLCANIC ROCKS				GRANITOID ROCKS			
Previous Group Nomenclature	**Revised Group Nomenclature**	**Formation (new formations in bold)**	**U-Pb Age (Ma)**	**Previous Suite Nomenclature**	**Revised Suite Nomenclature**	**Intrusion (new nomenclature in bold)**	**U-Pb Age (Ma)**
REPULSE BAY VOLCANIC GROUP	KAU SAI CHAU VOLCANIC GROUP	High Island	140.9 ± 0.2	LION ROCK SUITE	LION ROCK SUITE	Kowloon Granite	140.4 ±0.2
		Clear Water Bay	140.7 ± 0.2			Tong Fuk Quartz Monzonite	140.4 ± 0.3
		Pan Long Wan				Cape D'Aguilar Quartz Monzonite	140.6 ± 0.3
		Mang Kung Uk					140.7 ± 0.4
	REPULSE BAY VOLCANIC GROUP	Che Kwu Shan	142.5 ± 0.3		CHEUNG CHAU SUITE		
		Ap Lei Chau	142.7 ± 0.2				
		Ngo Mei Chau	<143.7 ± 0.1				
		Mount Davis				Chi Ma Wan Granite	<143.7 ± 0.2
		Long Harbour	142.7 ± 0.2				
			142.8 ± 0.2				
		Lai Chi Chong (revised)					
	LANTAU VOLCANIC GROUP				KWAI CHUNG SUITE	Sha Tin Granite	146.2 ± 0.2
		Undifferentiated	146.6 ± 0.2			East Lantau Rhyolite	146.3 ± 0.3
						East Lantau Rhyodacite	146.5 ± 0.2
						Needle Hill Granite	146.4 ± 0.2
TSUEN WAN VOLCANIC GROUP	TSUEN WAN VOLCANIC GROUP	Sai Lau Kong	164.1 ± 0.4	LAMMA SUITE	LAMMA SUITE	Tai Lam Granite	159.3 ± 0.3
		Tai Mo Shan	<164.6 ± 0.7			Tsing Shan Granite	<159.6 ± 0.5
		Shing Mun	164.4 ± 0.4			Chek Lap Kok Granite	160.4 ± 0.3
			164.7 ± 0.4			Lantau Granite	161.5 ± 0.2
		Yim Tin Tsai	164.5 ± 0.2			Tai Po Granodiorite	<164.6 ± 0.5
						Deep Bay Granite	<236.3 ± 0.8

Table 4 - Summary of Ar–Ar Ages Obtained by Lee, Chi-Yu (University of Taiwan, Unpublished Data)

Sample No.	**Analysed Material**	**Field Character**	**Location**	**Host Rock**	**Ar–Ar (Ma)**
HK10981	biotite	1 m mafic dyke	Ma Wan	Tai Lam Granite	84.3 ±2.1
HK11736	biotite	inclusion	Tsing Chau Tsai	East Lantau Rhyolite	98.8 ±2.4
HK11733	biotite	1 m mafic dyke	Tsing Chau Tsai	Tai Lam Granite	71.6 ±1.8
HK9728	biotite	1 m mafic dyke	High Island Dam	High Island Formation	98.5 ±2.4
HK10118	biotite	inclusion	Lamma Quarry	D'Aguilar Monzonite	109.8 ±2.7
HK11612	biotite	1 m mafic dyke	Stanley Peninsula	D'Aguilar Monzonite	135.0 ±3.3
HK10266	biotite	0.5 m mafic dyke	Chek Lap Kok	Chek Lap Kok Granite	94.5 ±2.7
HK3838	biotite	0.5 m mafic dyke	Po Toi Island	Po Toi Granite	89.1 ±2.2
HK11022	biotite	1 m mafic dyke	Tsing Yi	Tai Po Granodiorite	88.0 ±2.2
HK11604	biotite	2 m mafic dyke	Mo Tat Wan	Lantau Granite	undated

Table 5 - Thermoluminescence Dates from Hong Kong Faults (after Ding & Lai, 1997)

Sample	Location	Coordinates		TL age (years BP)	Fault trend
		Easting	Northing		
1	Tuen Mun	13160	25540	265,500 ± 21,000	NE
2	Lamma Is.	33140	07860	177,700 ± 15,100	NW
3	Yuen Long	21000	29420	105,100 ± 8,700	NW
4	Yuen Long	21700	30160	94,700 ± 8,100	NE
5	Yuen Long	23560	25940	91,100 ± 7,500	NW
6	Ma Wan	24650	23700	93,900 ± 7,900	NW
7	Cheung Shan	12430	11740	101,000 ± 8,600	NW
8	Tsing Yi	26360	23760	222,260 ± 17,800	NW
9	Tui Mun Chau	50160	44660	196,100 ± 16,900	NW
10	Yam O	19700	20720	33,300 ± 2,700	NW
11	Yam O	19600	20720	82,000 ± 6,800	NE
12	Penny's Bay	21380	21240	147,500 ± 11,800	NW
13	Shek Pik	05240	11060	278,700 ± 23,100	NW
14a	Kat O Chau	50400	45450	190,600 ± 15,800	NW
14b	Kat O Chau	50400	45450	201,800 ± 16,100	NW
14c	Kat O Chau	50400	45450	177,500 ± 13,300	NW
15	Ngo Mei Chau	49500	43900	254,500 ± 20,400	NW
16	Sai Kung	51780	28660	118,700 ± 9,700	NW
17	Ngong Ping	07285	12585	196,800 ± 16,300	NW
18	Pak Sha Chau	52150	44560	188,500 ± 15,400	NW
19	Ma Wan	24580	23860	126,200 ± 10,300	NW

Note: Analysis by Institute of Geology, State Seismological Bureau, Beijing

APPENDIX A

Rb–Sr GEOCHRONOLOGY REPORTS

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THE GEOCHRONOLOGY OF HONG KONG

D.P.F. Darbyshire

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1. INTRODUCTION

The solid geology of the Hong Kong Territory is dominated by Mesozoic volcanic and intrusive igneous rocks. Palaeozoic sedimentary strata form the basement and there are extensive Quaternary superficial deposits, primarily in low lying coastal areas and offshore.

There have been a number of geological surveys of Hong Kong. The earliest, undertaken by Brock, Uglow, Scholfield and Williams between 1923 and 1927 resulted in the publication of a map at 1:84480 (Brock et al, 1936) and several professional papers (Uglow, 1926; Brock and Scholfield, 1926; Williams, 1943 and Williams et al, 1945). A memoir based on this work was later published by Davis (1952) and a detailed description of the geology of the Territory was given by Ruxton (1960). Until recently, the most definitive work was that of Allen and Stephens (1971) who carried out a survey between 1967 and 1969 and published a memoir accompanied by maps at 1:50000 scale. These authors made a lithological classification of the Mesozoic volcanic rocks and recognised four phases of granite emplacement within a single episode of late tectonic intrusive activity.

In 1982 the Hong Kong Government Geotechnical Control Office initiated a new programme of systematic geological mapping of the Territory at the 1:20000 scale. To date maps and memoirs for the following districts have been completed: - Sha Tin (Addison, 1986), Hong Kong Island and Kowloon, (Strange and Shaw, 1986), Western New Territories (Langford et al., 1989) and Sai Kung and Clearwater Bay (Strange et al., 1990). This report describes the results of a geochronological study undertaken during 1989 in support of the Geological Survey Section of the Planning Division of the GCO who are responsible for the mapping programme.

2. SAMPLING AND SAMPLE PREPARATION

The locations of samples, together with their grid co-ordinates, are given in Appendix 1. Specimen sizes ranged from 2 to 10 kilos for the volcanic rocks and 4.5 to 18 kilos for the granitic rocks, depending on grain-size. Sample preparation was carried out at the Open University under the supervision of Mr Ian Chaplin. The rocks were jaw-crushed and split, with representative 100-200 g sub-samples finely ground to give a -200 mesh powder for geochemical and isotopic analysis.

3. ANALYTICAL TECHNIQUES

Concentrations of Rb and Sr as well as Rb/Sr atomic ratio were determined by X-ray fluorescence spectrometry on 20 g pellets pressed to 10 tonnes from -200 mesh whole rock powder. Included with each batch of samples were international reference standards, and appropriate corrections were made for instrumental dead time, background and line interferences (Pankhurst and O'Nions 1973). After chemical separation involving ion exchange procedures, Sr was loaded on tantalum filaments prepared with phosphoric acid. Isotope ratio measurements were made on an automated Micromass-354 mass spectrometer. The analytical data are presented in Table 1.

Errors are quoted throughout as two standard deviations from measured or calculated values. The decay constant used in the age calculation is the value $\lambda^{87} = 1.42 \times 10^{-11}\ a^{-1}$ recommended by the IUGS Subcommission for Geochronology (Steiger and Jager 1977). Analytical uncertainties are estimated to be 0.02% for $^{87}Sr/^{86}Sr$ ratios and 1.0% for $^{87}Rb/^{86}Sr$ ratios. During the period of this analytical work, the average $^{87}Sr/^{86}Sr$ ratio determined for 46 analyses of the NBS-987 Sr-isotopic standard was 0.710204 ± 0.000023.

The $^{87}Rb/^{86}Sr$ - $^{87}Sr/^{86}Sr$ regression lines shown in Figures 1 - 10 have been calculated using a least-squares method based on that described by York (1969). As a measure of "goodness of fit" of the regression lines to the analytical data, the "mean square of weighted deviates" (MSWD) is employed (Brooks et al. 1972). Where the observed value exceeds a limiting or critical value (3.0) the scatter of data cannot be entirely accounted for by experimental and sampling errors. In such cases the data do not satisfy the criteria for an isochron (Faure, 1987), and the values calculated for age and initial Sr-isotope ratio should be viewed with caution. When manifest in this study, the errors have been enhanced by multiplying by the square root of the MSWD following the method of York (1969).

Whole-rock geochemical analyses were carried out by X-ray fluorescence spectrometry (Dr T Brewer, University of Nottingham), using fused beads for major and minor elements, and pressed powder pellets for trace elements.

4. VOLCANIC ROCKS

The Mesozoic volcanic rocks, termed the Repulse Bay Volcanic Group, comprise a complex succession dominated by tuffs. Addison (1986) recognised four formations in the Sha Tin district, each displaying distinctive characteristics. The lithologically uniform Yim Tin Tsai Formation, at the base of the sequence, consists of massive coarse-ash tuffs. This is overlain by the more variable Shing Mun Formation which includes both coarse- and fine-ash tuffs, as well as conglomerate, sandstone, siltstone and mudstone. The boundary between the Shing Mun Formation and the overlying Ap Lei Chau Formations is not clearly defined, but an arbitrary distinction is made where the dominant lithology becomes a persistent uniform fine-ash vitric tuff. The uppermost Tai Mo Shan Formation is a thick and homogeneous sequence of welded ash-lapilli crystal tuffs. A further two formations, the mainly sedimentary Tsing Shan and the Tuen Mun consisting largely of andesitic lavas, have been delineated in the Tuen Mun area of the Western New Territories.

In the Sai Kung and Clear Water Bay district the oldest volcanic rocks are the fine-ash vitric tuffs of the Ap Lei Chau Formation. These are overlain by the eutaxitic Silverstrand Formation which, in turn, is overlain by the Mang Kung Uk Formation, a sequence of well bedded tuffite, breccia, conglomerate, siltstone and sandstone layers with impersistent lavas and fine ash-tuff bands. The Clear Water Bay Formation, consisting of trachydacite and rhyolite lavas, is the next unit in the succession. Capping the stratigraphic sequence is the High Island Formation, which consists of massive, uniform fine-ash welded tuff.

Chandy and Snelling (reported in Allen and Stephens, 1971) obtained a biotite K-Ar age of 154 ± 4 Ma from a sample of tuff. Whilst there is insufficient information regarding the location of the sample to determine its exact position in the succession, it is likely to be from one of the lower units which contain sufficient biotite for K-Ar dating. Two formations of the Repulse Bay Volcanic Group were sampled for Rb-Sr analysis: the Ap Lei Chau and the High Island Formations.

4.1 Ap Lei Chau Formation

Nine samples of Ap Lei Chau were collected, seven from the type locality on the island of Ap Lei Chau. The analytical data are plotted on Figure 1a. One sample (HK 8676) was found to be strongly recrystallised and has been excluded from the regression analysis, which then yields an age of 140 ± 2 Ma with an intercept 0.7068 ± 0.0003. The MSWD of 3.8 reflects the slight scatter of the data points about the line which may not, in the strict sense, be termed an isochron. However it should be noted that the data form a bimodal distribution and there is a marked difference in geochemistry between the two groups. The two low Rb/Sr samples HK 8672 and HK 8674 are depleted in SiO_2, Nb, and Th, and enriched in TiO_2, MgO, CaO, P_2O_5, Ba, Sr and V compared to the remaining six samples. This may be the result of the accumulation of mafic minerals in a differentiating magma chamber prior to eruption or the result of the incorporation of more basic material within the magma. Omission of these two samples from the regression results in a statistically good isochron (MSWD = 1.7) which yields a younger age of 131 ± 5 Ma and higher initial $^{87}Sr/^{86}Sr$ ratio 0.7094 ± 0.0014 (Figure 1b).

4.2 High Island Formation

Eight samples were analysed for this fine-ash welded tuff, yielding an age of 135 ± 8 Ma and intercept 0.7091 ± 0.0030 (Figure 2). The high MSWD of 5.2 is solely due to sample HK 8663 which plots below the line and omission of this sample from the regression results in an excellent isochron (MSWD = 1.4) However there are no apparent reasons for excluding this sample, geochemically and petrologically it is similar to the rest of the suite.

5. PLUTONIC ROCKS

The Repulse Bay Volcanic Group is intruded by granitoid rocks of Upper Jurassic to Lower Cretaceous age. Granodiorite and coarse-grained granite are the oldest intrusions. Younger plutons include fine-, fine- to medium- and medium-grained granite varieties and, in the Kings Park area of Kowloon, the granites are markedly megacrystic. Quartz syenite forms a small plutonic body on the D'Aguillar Peninsular of Hong Kong Island, a number of sheet like intrusions in the area to the southeast of the Sha Tin valley, and impersistent dykes extending across the region. Also present are minor intrusions of feldsparphyric and quartzphyric rhyolite, aplite or fine-grained granite, dacite, basalt and gabbro, andesite, lampropyre and pegmatite. These principally occur as dykes varying in width from a few centimeters to 200 metres, though more substantial bodies of felsparphyric rhyolite are found in the Sha Tin district. The acidic dykes are considered to be related to the emplacement of the Mesozoic granite whereas the basaltic rocks are thought likely to be Tertiary in age (Allen and Stephens, (1971)).

The plutonic igneous rocks of the Territory have been classified according to Streckeisen (1974) and further subdivided on the basis of grain size (Strange, 1985). The need to convey clear lithological information for engineering purposes led to a modification of the 5 mm and 1 mm dividers used by Allen and Stephens (1971) and to the adoption of the boundaries used in engineering practice (BSI, 1981). Coarse-grained rocks are taken to be those with a grain size exceeding 6 mm, with medium-grained rocks between 6 mm and 2 mm, and fine-grained rocks less than 2 mm. Where the grain size clearly straddles a class boundary a hybrid term is used, for example fine- to medium-grained granite.

5.1 Granodiorite

The granodiorite includes fine-, medium- and coarse-grained varieties. It is particularly susceptible to chemical weathering and this severely restricted collection of samples for isotope studies. Four samples were obtained, three from boreholes drilled for the Route 3 feasibility study in Tsuen Wan, and one from a public housing estate construction site on north Tsing Yi. The samples display evidence of recrystallisation and the Rb-Sr data do not define a linear array. Samples HK 8740 and 8741 are depleted in SiO_2, K_2O, and MnO with enriched TiO_2, MgO and CaO compared to samples HK 8742 and 8743. Chandy and Snelling (reported in Allen and Stephens, 1971) obtained a K-Ar age of 134 ± 2 Ma on biotite separated from a sample of granodiorite from Stanley Peninsular. Since they obtained similar dates for the later granitic intrusions, this result is clearly a minimum estimate for the age of intrusion of the granodiorite.

5.2 Coarse-grained Granite

Coarse-grained granite forms a large oval outcrop along the Sha Tin valley; it is also found on central and eastern Lamma Island, on the Po Toi Island Group, on the hillslopes southeast of Tuen Mun, on the peninsula east of Lung Chue To and in a number of localities on Lantau Island. In some areas, the original texture of the rock appears to have been partially recrystallised to produce two-phase variants similar to those described by Cobbing et al (1986) in the granites of the Southeast Asia Tin Belt. Chandy and Snelling (reported in Allen and Stephens, 1971) obtained biotite K-Ar ages of 130 ± 3 Ma and 134 ± 3 Ma from samples of coarse-grained granite from Lantau Island and Po Toi Island, respectively.

A generally uniform coarse-grained granite with grey to pink alkali feldspar phenocrysts forms the core of a complex pluton in the Sha Tin area. Seven samples were collected for Rb-Sr analysis. The data do not define a linear array. Four of the samples appear to have suffered some textural modification and regressing only this group (HK 8694-7) yields an excellent isochron (MSWD = 0.1) giving an age of 148 ± 9 Ma and an initial $^{87}Sr/^{86}Sr$ ratio of 0.7060 ± 0.0006 (Figure 3).

5.3 Medium-grained Granite

Medium-grained granites are of widespread occurrence, forming major outcrops around Kowloon, northern Hong Kong Island, Sha Tin, East Lantau Island and in the Western New Territories. In some areas the medium-grained granite is related to the coarse-grained granite, for example the markedly inequigranular megacrystic granite which occurs exclusively on Lamma Island and the microcrystic granite at Tuen Mun which has suffered severe textural modification. In the Sha Tin district the medium-grained granite intrudes and forms a concentric shell around the coarse-grained granite. On Needle Hill, northwest of the Sha Tin valley the medium-grained granite is intercalated with fine-grained granite, the absence of chilling and the close chemical similarities suggesting that they are coeval. However, to the southeast of the Sha Tin valley there are outcrops of fine-grained granite which are clearly younger than the medium-granite granite.

The equigranular medium-grained granite is the most uniform of all the mapped granite types, with no significant variation between samples collected several kilometres apart. The outcrops on Kowloon, Stonecutters Island and northern Hong Kong Island appear to form an almost circular pluton approximately 10 km in diameter. Later intrusions of fine- and fine- to medium-grained granites have interrupted the original plutonic boundaries and therefore the relationship of the smaller medium-grained intrusions which occur at Stanley and Shek-O is unclear. A similar problem exists with the granites on Lantau and Cheung Chau and it was hoped that this Rb-Sr study might resolve some of these difficulties.

Eleven samples of Hong Kong and Kowloon medium-grained granite were collected and the analytical data are plotted on Figure 4. The MSWD of 5.9 indicates a slight degree of scatter of the data points about the regression line which yields an age of 139 ± 2 Ma and initial Sr isotope ratio of 0.7076 ± 0.0003. There is no obvious reason for the omission of any data points and no differences are observed between the samples from Kowloon and from Hong Kong Island. Therefore the figure of 139 ± 2 Ma is considered to be the best estimate for the age of the medium-grained granite in this district. A small number of samples were collected from the medium-grained granite plutons at Shek-O on southern Hong Kong Island, on east Lantau Island, from Cheung Chau Island and from the Sha Tin district. The isotope ratios of the Lantau samples (HK 8710-1, Table 1) are very similar to those of the Kowloon granite, however inclusion of these samples in the regression results in an increased MSWD and larger errors on the age and intercept. It would appear that the Lantau granite and the Kowloon granite are either different phases of the same intrusion or separate intrusions. A sample HK 8712 taken from a borehole through the Cheung Chau granite is much more radiogenic (Table 1). Model age calculations, assuming an initial Sr isotope ratio of 0.71, indicate an age of c. 150 Ma.

Data from the Shek-O pluton is equivocal, one of the three samples analysed (HK 8720) has suffered textural modification and is considerably more enriched in ^{87}Sr than the others. Therefore the Rb-Sr data plot with a two-point distribution on an isochron diagram (Figure 5). The age and initial Sr-isotope ratio are statistically the same as those of the Hong Kong and Kowloon granite so that plotting all the samples together yields a regression line with the same parameters but slightly reduced MSWD (4.6). However the Shek-O samples also display some similarities to the fine-grained granite which outcrops on Mount Butler. Inclusion of the data points on that isochron (se below) makes no difference to the age or MSWD, but reduces the errors on the initial ratio (0.7086 ± 0.0005).

The Rb-Sr data for samples of medium-grained granite from the Sha Tin district (HK 8689, 8691-2; Table 1) do not define an isochron. The MSWD of 45 indicates considerable scatter of the three data points about the regression line. The low strontium concentrations and elevated ^{87}Sr/^{86}Sr ratios are comparable with those of fine-grained granite elsewhere in the Territory.

5.4 Fine-grained Granite

The fine-grained granite is commonly associated with the fine- to medium-grained granite and both may be megacrystic. In the Western New Territories, fine-grained granite forms the bulk of the granite outcrop and an exclusive feature of the Tsing Shan and Tai Lam outcrops is the presence of mylonite or schist bands. These are generally only a few centimetres wide and often occur close to the contacts between the two granites. The fine-grained granite intrudes the coarse-grained granite in the Sha Tin valley and around To Shek and Sha Tin Wai it intrudes, and includes xenoliths of, medium-grained granite. Fine-grained and fine- to medium-grained granites intrude the eastern part of the medium-grained Kowloon - Hong Kong pluton, cropping out in the Kwung Tong - Anderson Road area of East Kowloon and over Braemar Hill and Mount Butler on Hong Kong Island. The rock is equigranular, either light grey or pink in colour, and has a chemical character that is similar to the medium-grained granite. A small body of megacrystic fine- and fine- to medium-grained granite intrudes the medium-grained granite in the Kings Park area of Kowloon.

Four samples were collected from the Mount Butler Quarry and one from Jardine's Lookout and the analytical data define an excellent isochron (MSWD = 2.2 : Figure 6) giving an age of 136 ± 1 Ma and an initial $^{87}Sr/^{86}Sr$ ratio 0.7084 ± 0.0010. A further five samples of fine-grained granite were collected from the Anderson Road quarries, one from the Lam Tin estate, and three of fine- to medium-grained granite were obtained from Sai Tso Wan. When plotted the Rb-Sr data show a slight scatter about the regression line which gives an age of 137 ± 1 Ma. One of the samples (HK 8728) was from an outcrop where there was extensive veining; and omitting this from the regression results in a good isochron (MSWD = 1.4, Figure 7) yielding an age of 136 ± 1 Ma and an initial $^{87}Sr/^{86}Sr$ ratio of 0.7092 ± 0.0006, MSWD = 0.4).

Since the Rb-Sr isochron ages for the Hong Kong Island and east Kowloon samples are the same and the initial ratios overlap within the errors it is reasonable to combine the data for these two samples suites which then yield an excellent twelve- point isochron (MSWD 1.2) giving an age of 136 ± 1 Ma and an initial $^{87}Sr/^{86}Sr$ ratio of 0.7091 ± 0.0005 (Figure 8).

The samples of megacrystic granite (HK 8718-9) from the Kings Park area of Kowloon have much lower $^{87}Rb/^{86}Sr$ ratios than the other fine- and fine- to medium-grained granite samples. Furthermore they are enriched in TiO_2, CaO, MgO, K_2O, P_2O_5, Nb, Sr, V and Zr and depleted in SiO_2, Na_2O and Y. In general there would seem to be greater affinity with the medium-grained granite samples from that part of Kowloon than with the fine-grained granite samples. The boundary between the Kings Park megacrystic rocks and the equigranular medium-grained Kowloon granite has not been seen. It may be that these are two phases of the same intrusion.

5.5 Quartz Syenite

Quartz syenite forms small plutons at Stanley and on the D'Aguillar Peninsula of Hong Kong Island and a number of small intrusive bodies in northern and eastern Lamma Island, and on Lantau Island. It occurs as impersistent dykes which intrude both granite and volcanic rocks in the Aberdeen area; and sheet-like bodies parallel pre-existing intrusive units or faults in the Sha Tin valley. There appear to have been several phases of intrusion of quartz syenite, but the plutons on southern Hong Kong Island pre-date the medium-grained granite in which large xenolith blocks of quartz syenite have been found.

Nine samples were collected from the outcrop on the D'Aguillar Peninsula and one from a syenitic dyke in northern Kowloon. The Rb-Sr data from the Cape D'Aguillar syenites yield an isochron age of 147 ± 8 Ma with an initial $^{87}Sr/^{86}Sr$ ratio of 0.7068 ± 0.0003 (Figure 9). Although the MSWD of 0.3 indicates an excellent fit of the data points to the isochron, it can be seen that there is essentially a bimodal distribution with eight of the samples forming a single cluster. All of the samples analysed display signs of textural modification; the finer grained high Rb/Sr sample (HK 8688) perhaps more so than the rest. However if this data point is omitted from the regression there is such a limited range of Rb-Sr ratios that the resultant errors are high and hence the age and initial Sr isotope ratio not very useful. Chandy and Snelling (reported in Allen and Stephens, 1971) obtained K-Ar ages of 143 ± 3 Ma, 143 ± 4 Ma and 135 ± 3 Ma for biotites separated from samples of syenite from the D'Aguillar Peninsula. The Rb-Sr isochron age would appear therefore to be a reasonable estimate for the age of intrusion of the quartz syenite pluton at Cape D'Aguillar.

It is worth noting that inclusion of the syenitic dyke sample (HK 8684), from the Tai Po Road Kowloon, in the regression also results in an isochron giving the same age and intercept within error (153 ± 2 Ma, 0.7066 ± 0.0001, MSWD = 0.5). This rock has a higher SiO_2 content and is depleted in the remaining major elements compared to the D'Aguillar syenites, it is even finer grained and perhaps suffering further modification by granitic fluids.

5.6 <u>Feldsparphyric Rhyolite</u>

Feldsparphyric rhyolite occurs mainly as dykes which intrude both granodiorite and granite intrusions and tuffs of the Repluse Bay Volcanic Group. The rock contains abundant, large pink or grey, feldspar megacrysts set in a fine, often aphanitic, greenish grey to dark grey groundmass. Field evidence indicates that some of the dykes are composite intrusions with several phases of fluid injection. Around Tsing Yi and Ma Wan in the Western New Territories, the feldsparphyric rhyolite appears to be an early phase of an intrusion of fine-grained granite.

Eight samples were collected from the ENE trending dyke swarm on Lantau island, but unfortunately it proved impossible to sample a single continuous dyke. When plotted (Figure 10) the analyses do not define an isochron. The sample (HK 8732) from Penny's Bay displays a markedly different geochemistry to the remainder of the suite, it is depleted in $A1_2O_3$, TiO_2, MgO, CaO, Ba, Ce, SrV and Zr. The outcrop samples were very weathered and this rock was taken from a large stock pile nearby. If this sample is omitted from the regression analysis the data form a bimodal distribution on the isochron plot which then yields a much older age of 154 ± 6 Ma (MSWD = 2.5). However as the dykes are considered to form part of a large swarm which extends from Lantau through Tsing Yi into the Sha Tin district, and which have been found cutting all major plutonic rock types, such an old age is clearly untenable. Broken and rounded feldspar megacrysts have been observed in some dykes suggesting that they may have crystallized elsewhere and been transported by the liquid groundmass fluids. Such inherited isotope systematics could result in an older age. Alternatively, the several phases of fluid injection in a multiple intrusion may have differing initial $^{87}Sr/^{86}Sr$ ratios and a composite isochron would result in an erroneous age.

6. DISCUSSION

Emplacement of the granitoids in the Hong Kong territory occurred over a period of approximately 20 million years during the late Jurassic to Early Cretaceous (Table 2). These plutons intrude rocks of the Repluse Bay Volcanic Group and, therefore, the ages obtains for the Ap Lei Chau and High Island Formations would appear to be too young. While any Rb-Sr whole-rock system can be reset, regardless of rock type, fine-grained acid volcanics may be particularly susceptible to open-system behaviour. Farquharson and Richards (1973), in a study of the Mount Isa Tuff beds, suggested that the poor resistance of acid pyroclastics to resetting may be due to metastable disordered structures in the feldspars resulting from rapid cooling. Subsequent structural re-ordering, either gradually or in response to a tectonic or thermal event, could provide a mechanism for isotopic redistribution. Large scale remobilization of Sr and Rb would occur if sufficient water were present.

Priem et al (1978) describe the resetting of water-laid tuffs from the Megacryst Tuff Formation of Aljustrel, Portugal. While the isochron fit is statistically excellent the age of 308 ± 8 Ma is too young sicne stratigraphically the tuffs are post Famennian and pre-late Dinantian (c. 350 Ma). In the Lachlan Fold Belt of Australia hydrothermal alteration of the volcanics is generally accompanied by the loss of Ca and Sr and addition of Na (Wyborne et al, 1981). Since a similar pattern may be observed in the Ap Lei Chau samples the anomalously young Rb-Sr isochron age (131 ± 5 Ma) could be interpretated as dating not extrusion but a subsequent hydrothermal event. Both age and initial ratio overlap within error with those of the fine-grained granite. Oxygen isotope data would be required to test this hypothesis.

The High Island Formation is the youngest unit within the succession in the Sai Kung and Clearwater Bay district. Although 137 ± 4 Ma may be accepted as a reasonable estimate for the age of extrusion, it is equally possible that this age has also been reset.

For the plutonic rocks, initial Sr-isotope ratios exhibit an inverse correlation with calculated ages. The sequence of emplacement correlates with that deduced form the field observation. Although the ages of the medium-grained and fine-grained granites overlap within error, there is a statistical difference in the initial ratios. The textural modification suffered by samples of coarse-grained granite from Sha Tin is more likely to be the result of a reaction with infiltrating syentic fluids than to reactions with the fine-grained granite which has a significantly higher initial Sr-isotope ratio.

Hong Kong lies within the East China Volcanic Province which is considered to have been an active volcano-plutonic arc during the Late Jurassic to Cretaceous Yenshanian cycle (Hutchison, 1989). Yenshanian granitoids are widely distributed and appear to have been intruded in at least two phases. The early phase c. 190 - 140 Ma are predominantly of biotite granite, often with a late-stage, two-mica granite. The later phase plutons are more varied in composition, comprising granite, miarolitic potash-granite, granodiorite and diorite, and have yielded ages ranging from 135 - 70 Ma (Yang et al, 1986).

There are a number of references in the literature to isotopic age determination of granites in southern China. However, these data usually appear on maps showing the distribution of ages within a particular province. These is often mention of the isotopic technique employed, and only very rarely are the errors quoted. Consequently it is impossible to assess the quality of the data whether or not the ages represent reasonable estimates of the time of intrusion. Jahn et al, (1976) published Rb-Sr data for three areas in the coastal region of southeastern China and one in the Taiwan Strait. However, the samples (which were not originally collected for geochronology) ranged in size from 1 in^3 to hand-specimen size. Despite the care in separating and analyzing whole rock and mineral fractions only limited conclusions may be drawn from the data.

There have been several classifications of the Yenshanian granites on the basis of geological setting and probable source materials. In 1920, Weng proposed division into two groups: a granodioritic type of deep origin associated with iron and copper mineralisation (exemplified by the intrusions in the middle to lower Yangzi Valley); and a grantic type (such as the intrusions of the Nanling region) geneticaly related to tin and tungsten mineralisation. These were later renamed “Yangzi” and “Hong Kong” types respectively by Xie Jiaron (reported in Yang et al, 1986). Xu et al, (1982) divided the granites on the basis of a scheme in which there are two genetic series labelled “transformation” and “syntexis”. These two groups are broadly comparable to the “llmenite - Magnetite” classification of Ishihara (1977) and the “S- and I-types” of Chappell and White (1974). Wang Lianku et al (1982) proposed a similar grouping, “Series I” (Nanling) formed mainly through anatexis of crustal materials and “Series II” (Yangzi) derived primarily form the mantle or lower crust. However they note certain differences in the $^{87}Sr/^{86}Sr$, $^{18}O/^{16}O$ and $^{34}S/^{32}S$ values of their two granitoid series compared with other classifications.

The ages of the Hong Kong granites place them on the boundary between the early and late Yenshanian phases of granitoid emplacement in southeastern China. The geochemistry and the initial Sr-isotope ratio of the Sha Tin coarse-grained granite indicates that it has an “I-type” character. The fine-grained granites, however, display “S-type” characteristics, and the close similarity of the medium-grained granites suggested the same classification. However, the range of initial Sr-isotope ratios would place all the Hong Kong granites in the Series II of Yangxi Series of Wang Liankui et al. (1982). The granites may form a single continuous sequence and it is anticipated that, with a study of the Nd-and O-isotope systematics of these rocks, their petrogenesis may be further elucidated.

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Table 1 - Rb–Sr Data (Sheet 1 of 3)

Sample No.	Rb ppm	Sr ppm	87Rb/86Sr	87Sr/86Sr
Ap Lei Chau Formation				
HK 8669	255	31.3	23.71	0.753854
HK 8670	252	31.0	23.65	0.753726
HK 8671	252	35.9	20.42	0.747123
HK 8672	229	138	4.817	0.716478
HK 8673	258	33.2	22.63	0.751434
HK 8674	216	36.6	17.17	0.741623
HK 8675	183	211	2.510	0.711653
HK 8676	269	41.9	18.66	0.745312
HK 8677	265	33.0	23.35	0.753029
High Island Formation				
HK 8661	241	25.7	27.39	0.762104
HK 8661	245	28.0	25.45	0.758422
HK 8661	241	25.2	27.88	0.761364
HK 8664	231	25.0	26.95	0.760539
HK 8665	237	29.9	23.07	0.753734
HK 8666	233	34.8	19.46	0.746360
HK 8667	251	25.2	29.04	0.765122
HK 8668	250	24.5	29.75	0.766378
Granodiorite				
HK 8740	283	222	3.705	0.724078
HK 8741	274	318	3.500	0.721034
HK 8742	249	248	2.913	0.719428
HK 8743	214	277	2.237	0.717553
Sha Tin coarse-grained granite				
HK 8690	223	115	5.608	0.720231
HK 8693	233	83.6	8.079	0.723964
HK 8694	231	143	4.681	0.715796
HK 8695	230	133	5.002	0.716503
HK 8696	224	155	4.188	0.714817
HK 8697	228	108	6.138	0.718916
HK 8698	180	83.5	6.260	0.720411
Hong Kong & Kowloon Medium grained granite				
HK 8699	261	26.8	28.36	0.763453
HK 8700	232	40.9	16.48	0.740535
HK 8701	231	30.4	22.09	0.751110
HK 8702	259	76.0	9.862	0.726835
HK 8703	266	170	4.540	0.716422
HK 8704	241	127	5.489	0.718165
HK 8705	210	54.9	11.10	0.729919
HK 8706	236	35.2	19.47	0.746190
HK 8707	283	54.2	12.51	0.732425
HK 8708	197	108	5.258	0.718191

Table 1 - Rb–Sr Data (Sheet 2 of 3)

Sample No.	Rb ppm	Sr ppm	87Rb/86Sr	87Sr/86Sr
HK 8709	206	103	5.811	0.719491
Lantau medium-grained granite				
HK 8710	274	84.3	9.437	0.725707
HK 8711	270	83.4	9.403	0.725740
Cheung Chau medium-grained granite				
HK 8712	324	13.5	70.48	0.860731
Shek-O medium -grained grainite				
HK 8720	400	9.3	127.1	0.957725
HK 8721	276	31.9	25.12	0.757346
HK 8722	290	30.3	27.93	0.763043
Sha Tin medium Grained granite				
HK 8689	328	21.7	44.12	0.799585
HK 8691	417	14.1	86.95	0.888179
HK 8692	529	10.1	157.2	1.055053
Mount Butler fine-grained granite				
HK 8713	311	25.1	36.13	0.778365
HK 8714	392	6.14	192	1.083850
HK 8715	419	6.66	187.7	1.069672
HK 8716	360	12.7	83.19	0.869777
HK 8717	412	7.94	154.8	1.006707
East Kowloon fine-grained granite				
HK 8723	353	28.8	35.70	0.778246
HK 8724	300	32.8	26.56	0.760447
HK 8725	348	26.1	38.85	0.784273
HK 8726	426	6.53	195.9	1.083587
HK 8727	454	7.26	238.7	1.169862
HK 8728	447	5.58	242.8	1.189026
East Kowloon fine- to medium-grained granite				
HK 8729	446	8.66	153.4	1.007870
HK 8730	454	7.26	187.2	1.070721
HK 8731	436	8.39	154.9	1.009654
Kings Park megacrystic fine-grained granite				
HK 8718A	249	162	4.450	0.715839
HK 8718B	250	165	4.390	0.715771
HK 8719	231	200	3.338	0.713882

Table 1 - Rb–Sr Data (Sheet 3 of 3)

Sample No.	Rb ppm	Sr ppm	87Rb/86Sr	87Sr/86Sr
Cape D'Aguillar Syenites				
HK 8678	163	201	2.350	0.711737
HK 8679	166	190	2.519	0.712011
HK 8680	154	175	2.551	0.712116
HK 8681	165	201	2.376	0.711782
HK 8682	165	190	2.521	0.712058
HK 8683	164	185	2.564	0.712064
HK 8685	168	196	2.488	0.711984
HK 8686	166	202	2.391	0.711817
HK 8687	159	192	2.401	0.711784
HK 8688	173	125	4.019	0.715195
Tai Po Road syenite dyke				
HK 8684	231	53.2	12.60	0.734007
Feldsparphyric Rhyolite				
HK 8732	253	49.9	14.70	0.737700
HK 8733	236	156	4.395	0.717772
HK 8734	217	159	3.936	0.716514
HK 8735	220	159	4.013	0.717085
HK 8736	191	205	2.703	0.714047
HK 8737	183	203	2.616	0.713863
HK 8738	188	196	2.780	0.714158
HK 8739	186	202	2.674	0.714029

Table 2 - Results of Rb–Sr Isochron Plots

Suite	HK Samples	Age ± Error Ma	Initial 87Sr/86Sr ratio	MSWD
Repulse Bay Volcanic Group				
High Island Formation	8661-2; 8664-8	135 ± 8	0.7091 ± 0.0030	5.2
Ap Lei Chau Formation	8669-8676; 8677	140 ± 2	0.7068 ± 0.0003	3.8
	8669-71; 3; 4; 7	131 ± 5	0.7094 ± 0.0014	1.7
Plutonic Rocks				
Sha Tin Gc	8694-7	148 ± 9	0.7060 ± 0.0006	0.1
Cape D'Aguillar Qs	8678-83; 8685-8	147 ± 8	0.7068 ± 0.0003	0.3
Hong Kong & Kowloon Gm	8699-8709	139 ± 2	0.7076 ± 0.0003	5.9
Mount Butler Gf	8713-17	136 ± 1	0.7084 ± 0.0010	2.2
East Kowloon Gf and Gf-m	8723-7; 8729-31	136 ± 1	0.7092 ± 0.0006	1.4
Mt Butler & E Kowloon Gf	8713-7; 8723-7; 8729-31	136 ± 1	0.7091 ± 0.0005	1.6

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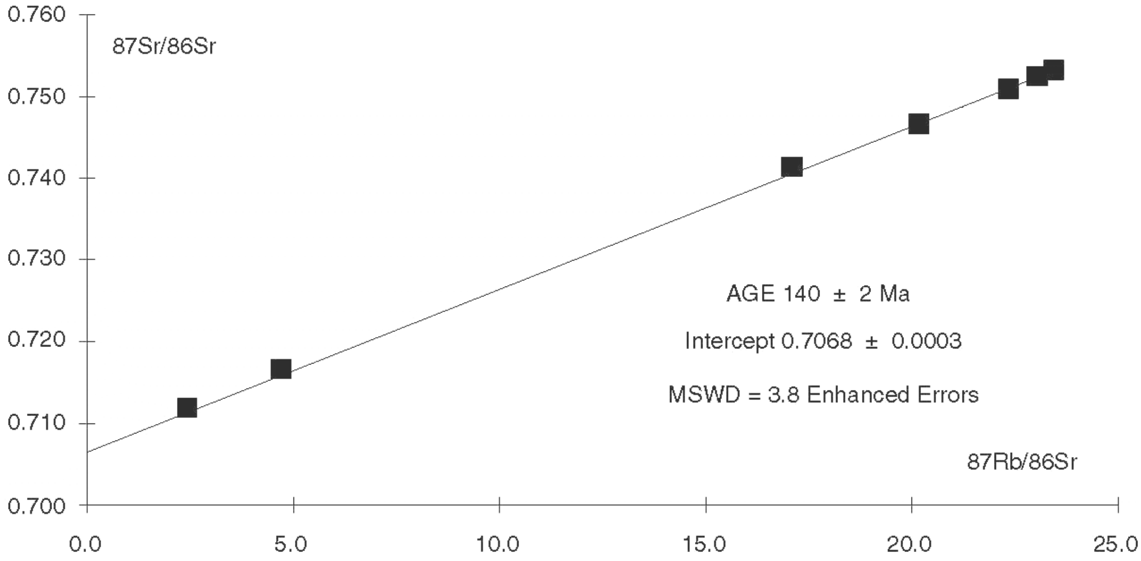


Figure 1a - Ap Lei Chau Formation

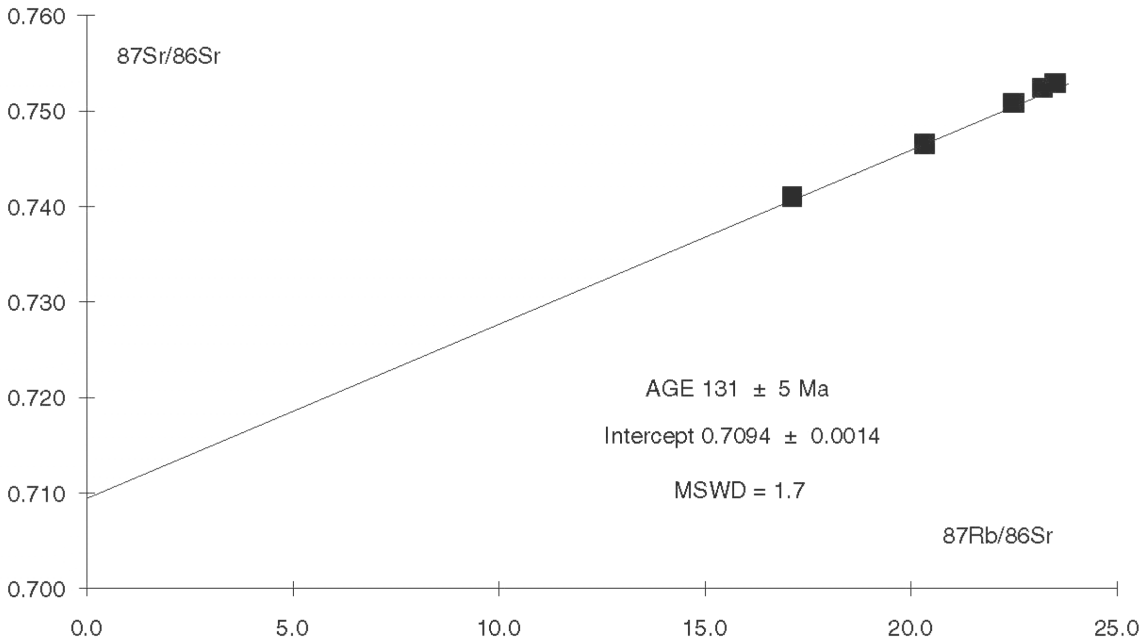


Figure 1b - Ap Lei Chau Formation

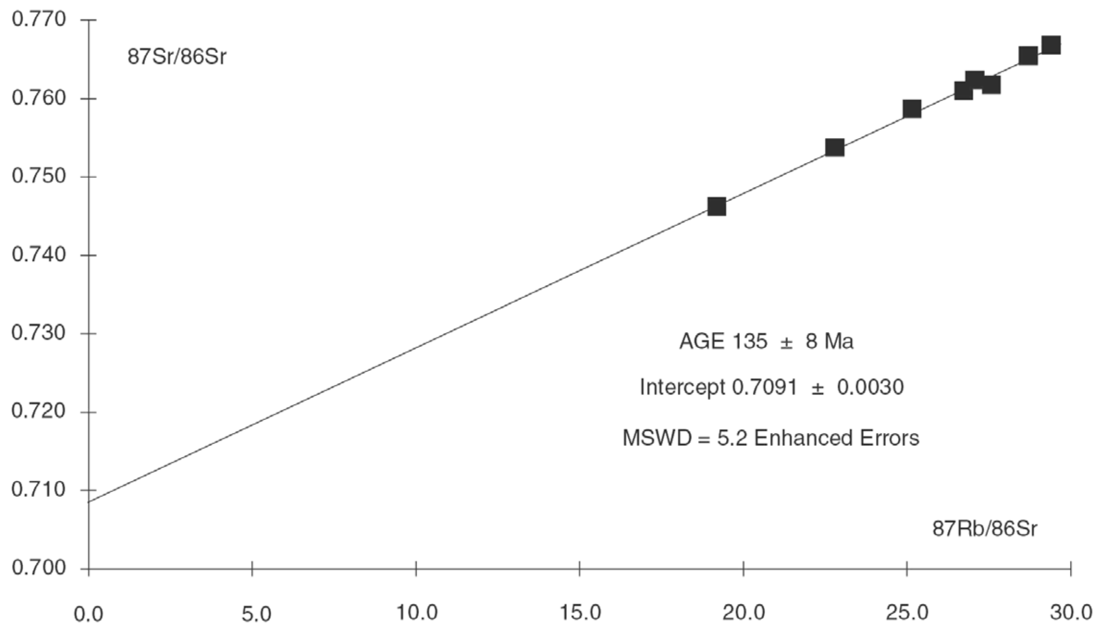


Figure 2 - High Island Formation

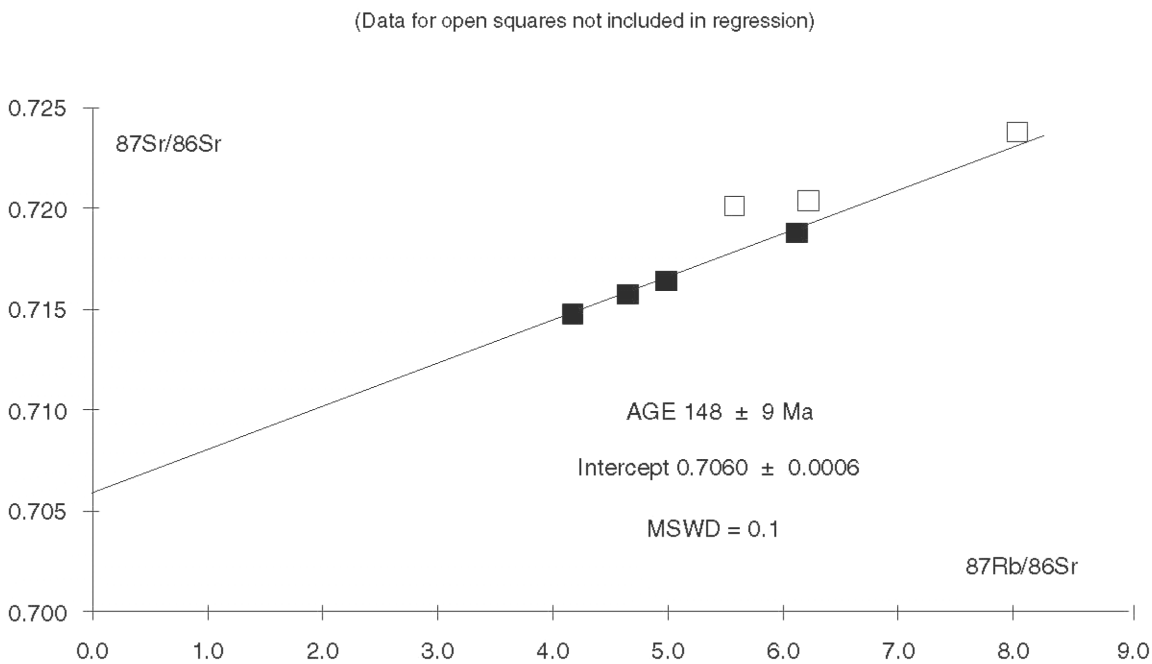


Figure 3 - Sha Tin Coarse-grained Granite

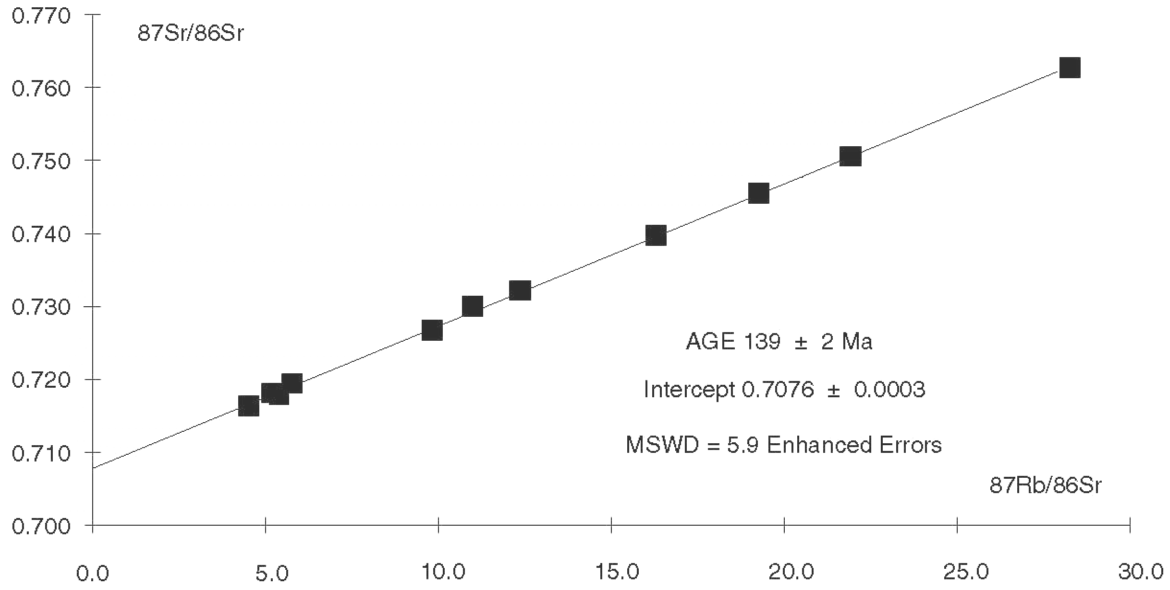


Figure 4 - Hong Kong and Kowloon Medium-grained Granite

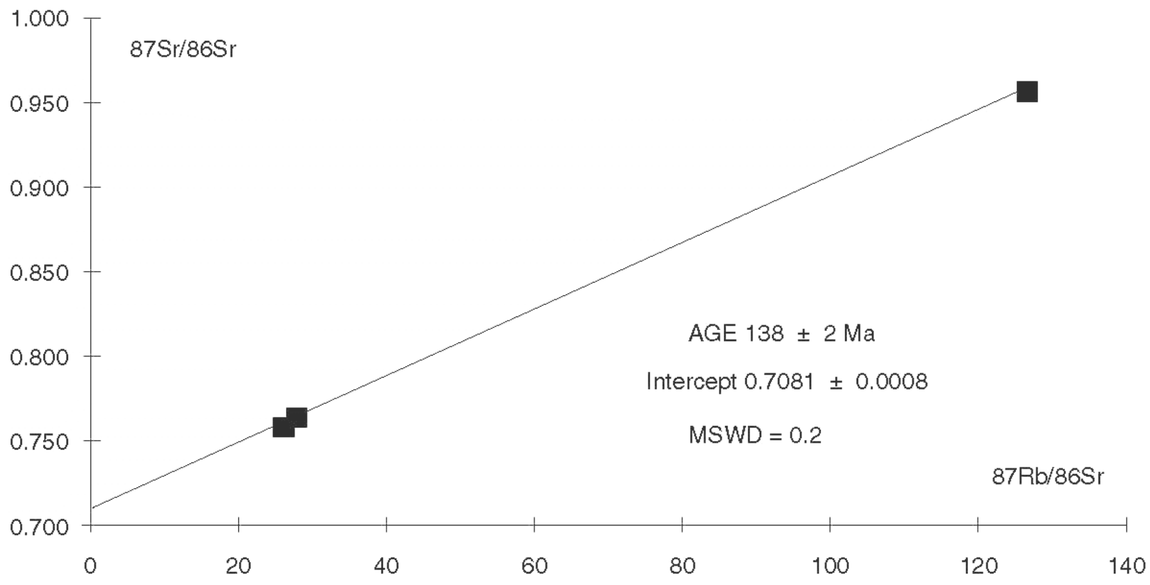


Figure 5 - Shek O Medium-grained Granite

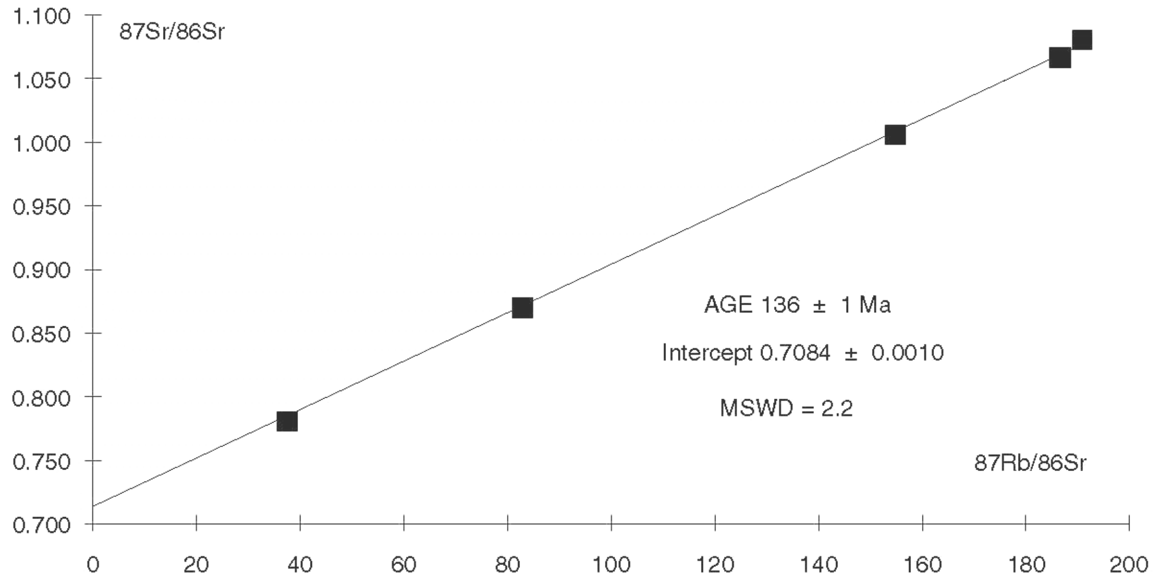


Figure 6 - Mount Butler Fine-grained Granite

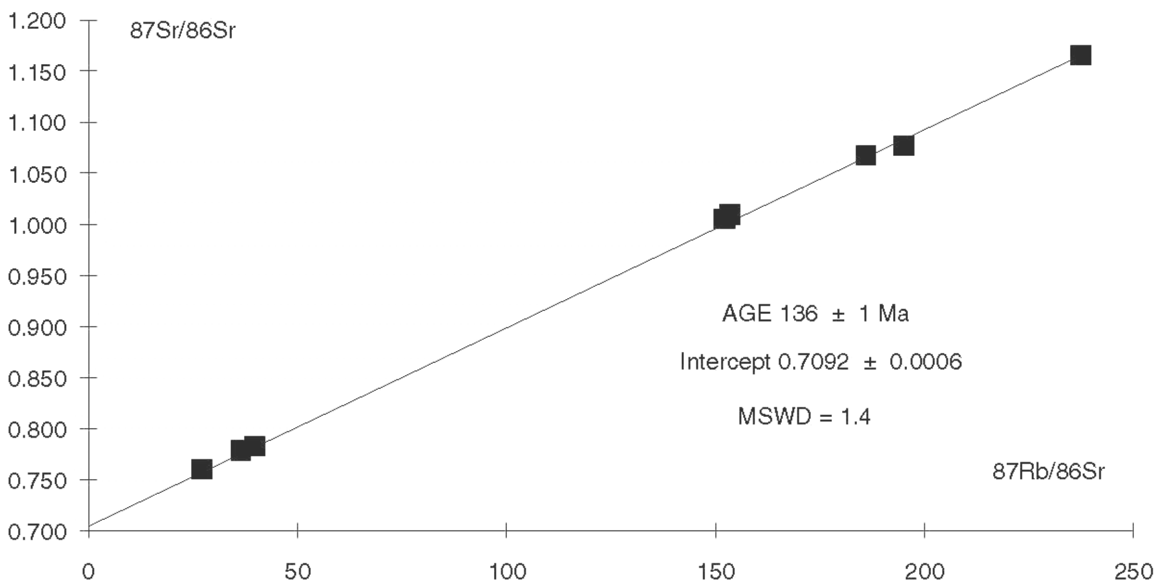
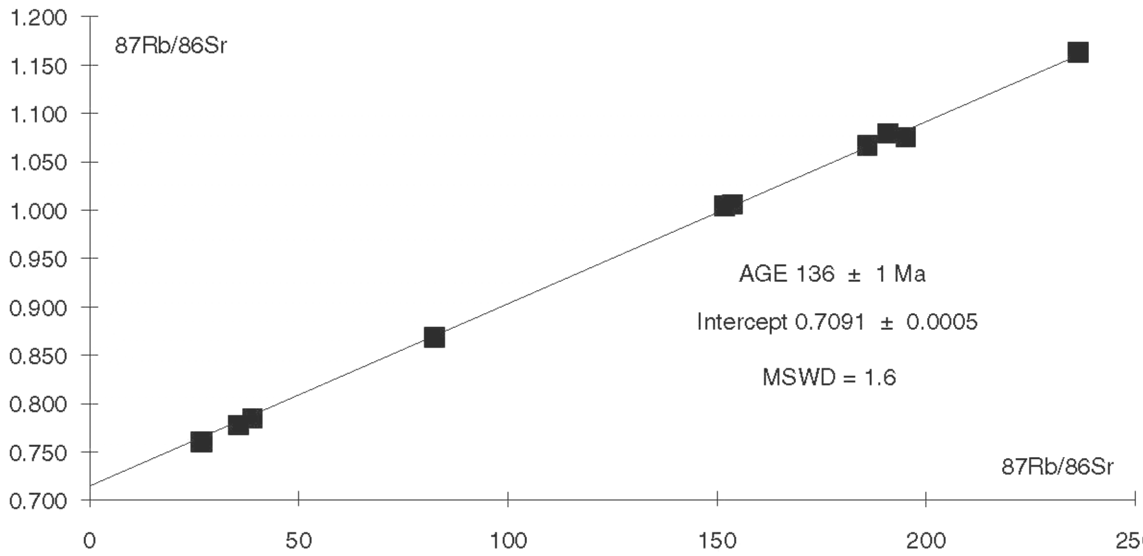


Figure 7 - East Kowloon Fine-grained Granite



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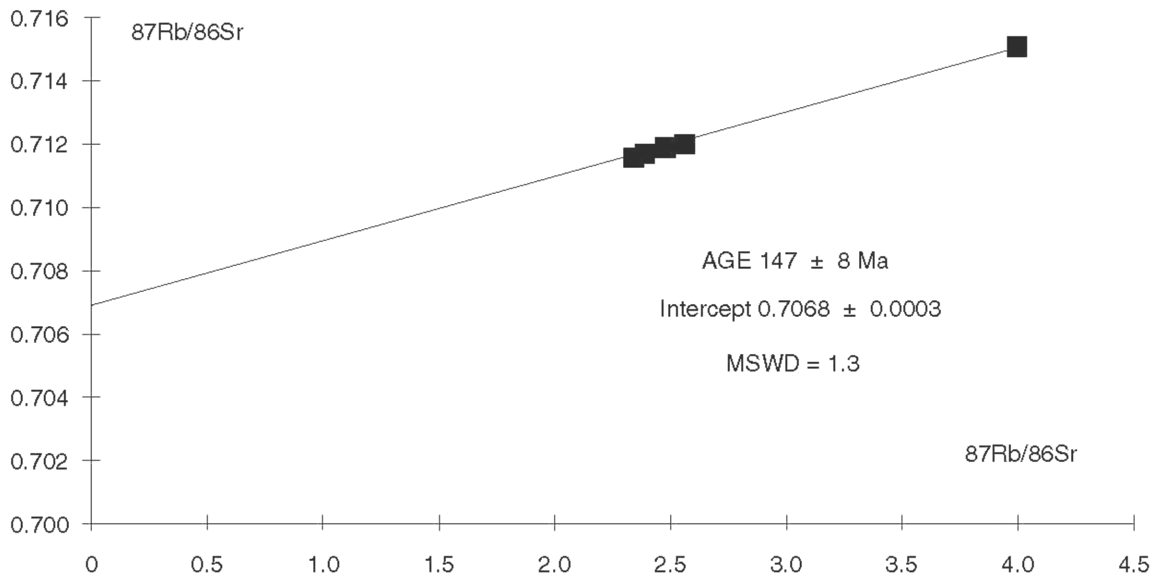

Figure 9 - Cape D'Aguillar Syenites

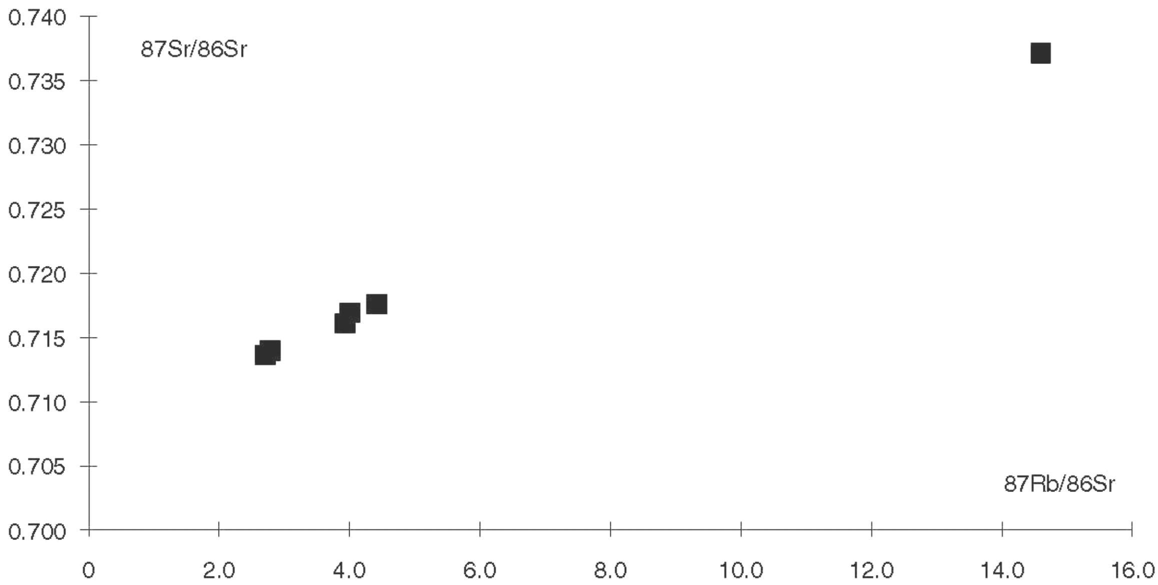

Figure 10 - Feldsparphyric Rhyolites

APPENDIX

H.K. No.	Locality	Rock type	H K Metric Grid East	North
8661	High Island Dam West	Tuff High Island Formation	52950	26400
8662	High Island Dam West	Tuff High Island Formation	52750	26330
8663	High Island Dam West	Tuff High Island Formation	56760	25050
8664	High Island Dam West	Tuff High Island Formation	56800	25010
8665	High Island Dam West	Tuff High Island Formation	56630	25020
8666	High Island Dam West	Tuff High Island Formation	56620	24590
8667	High Island Sai Wan Road	Tuff High Island Formation	54670	28060
8668	High Island Sai Wan Road	Tuff High Island Formation	54650	28140
8669	Ap Lei Chau Lee Nam Road	Tuff Ap Lei Chau Formation	33330	11250
8670	Green Island Cement Works	Tuff Ap Lei Chau Formation	33790	11140
8671	Green Island Cement Works	Tuff Ap Lei Chau Formation	33920	10990
8672	Ap Lei Chau Lei Tung Estate	Tuff Ap Lei Chau Formation	34210	11400
8673	Ap Lei Chau Lei Tung Estate	Tuff Ap Lei Chau Formation	33970	11360
8674	Ap Lei Chau Lei Tung Estate	Tuff Ap Lei Chau Formation	33900	11400
8675	Ap Lei Chau Lei Tung Estate	Tuff Ap Lei Chau Formation	34210	11520
8676	Ocean Park entrance	Tuff Ap Lei Chau Formation	35030	11070
8677	Nam Long Shan Road	Tuff Ap Lei Chau Formation	35370	11020
8678	Cape D'Aguillar Road	Syenite	43672	08268
8679	Cape D'Aguillar Road	Syenite	43230	08860
8680	Cape D'Aguillar Road	Syenite	43240	08710
8681	Cape D'Aguillar Road	Syenite	43290	07910
8682	Cape D'Aguillar Road	Syenite	43560	07910
8683	Cape D'Aguillar Road	Syenite	43630	08320
8684	Tai Po Road	Syenite dyke	33990	22790
8685	Cape D'Aguillar Road	Syenite	43720	08420
8686	Cape D'Aguillar Road	Syenite	43790	08540
8687	Cape D'Aguillar Road	Syenite	43710	08570
8688	Cape D'Aguillar Road	Syenite	43290	08050
8689	Tate Cairn Tunnel N Entrance	Medium grained granite Sha Tin	35150	27840
8690	Pak Tin	Coarse grained granite Sha Tin	36280	26710
8691	Tate Cairn Tunnel	Medium grained granite Sha Tin	39980	26520
8692	Ngau Pei Sha	Medium grained granite Sha Tin	40020	26480
8693	Ka Tin Court	Coarse grained granite Sha Tin	36000	24600
8694	San Tin Wai Estate	Coarse grained granite Sha Tin	37120	25820
8695	San Tin Wai Estate	Coarse grained granite Sha Tin	37260	25700
8696	San Tin Wai Estate	Coarse grained granite Sha Tin	37400	25680
8697	Lion Rock Tunnel	Coarse grained granite Sha Tin	37650	25910
8698	Tai Po Road	Coarse grained granite Sha Tin	33570	22890
8699	Diamond Hill Quarry	Medium grained granite	39100	22720
8700	Diamond Hill Quarry	Medium grained granite	39140	22770
8701	Diamond Hill Quarry	Medium grained granite	39160	22730
8702	Tai Wan Road Hung Hom	Medium grained granite	37620	18800
8703	Ko Shan Park	Medium grained granite	37080	19530
8704	Ko Shan Park	Medium grained granite	37080	19470

APPENDIX

H.K. No.	Locality	Rock type	H K Metric Grid East	North
8705	Tate Cairn Tunnel S Entrance	Medium grained granite	38800	22770
8706	Tai Hang Road	Medium grained granite	37870	14850
8707	Tai Hang Road	Medium grained granite	37840	14940
8708	Princess Margaret Road	Medium grained granite	36500	19760
8709	Pak Tin Estate	Medium grained granite	34930	22090
8710	Tai Long Wan Lantau Island	Medium grained granite	18000	08780
8711	Tai Long Wan Lantau Island	Medium grained granite	17990	08800
8712	Cheung Chau	Medium grained granite	20624	07338
8713	Jardines lookout	Fine grained granite Mount Butler	37950	14150
8714	Mount Butler Quarry	Fine grained granite Mount Butler	39070	14410
8715	Mount Butler Quarry	Fine grained granite Mount Butler	38980	14490
8716	Mount Butler Quarry	Fine grained granite Mount Butler	38900	14480
8717	Mount Butler Quarry	Fine grained granite Mount Butler	38920	14440
8718	Gasgoigne Road Kowloon	Megacrystic Fine grained granite	36930	18740
8719	Nathan Road Kowloon	Megacrystic Fine grained granite	35730	18790
8720	Shek-O Quarry	Medium grained granite Shek-O	42780	09220
8721	Shek-O Quarry	Medium grained granite Shek-O	42720	09290
8722	Shek-O Quarry	Medium grained granite Shek-O	42890	09290
8723	Pioneer Quarry	Fine grained granite	42730	20210
8724	Pioneer Quarry	Fine grained granite	42720	20190
8725	Pioneer Quarry	Fine grained granite	42710	20200
8726	Kai Wah Quarry	Fine grained granite	42440	20370
8727	Kai Wah Quarry	Fine grained granite	42470	20360
8728	Lam Tin Estate	Fine grained granite	42570	19210
8729	Sai Tso Wan	Fine - medium grained granite	41580	18680
8730	EHC site	Fine - medium grained granite	41950	18130
8731	EHC site	Fine - medium grained granite	41900	18050
8732	Penny's Bay Lantau Island	Feldsparphyric rhyolite	22110	20800
8733	Penny's Bay Lantau Island	Feldsparphyric rhyolite	22150	20740
8734	Discovery Bay Lantau Island	Feldsparphyric rhyolite	19370	16540
8735	Discovery Bay Lantau Island	Feldsparphyric rhyolite	19350	16560
8736	Mei Tei Wan N Lantau Island	Feldsparphyric rhyolite	20550	17460
8737	Mei Tei Wan N Lantau Island	Feldsparphyric rhyolite	20480	17480
8738	Mei Tei Wan E Lantau Island	Feldsparphyric rhyolite	20660	17290
8739	Mei Tei Wan W Lantau Island	Feldsparphyric rhyolite	20310	17230
8740	Site 3 Bhole 12 19.7-20.6 metres	Granodiorite	24915	27840
8741	Site 3 Bhole 12 42.4-43 metres	Granodiorite	24915	27840
8742	Site 3 Bhole 14 33.1-33.8 metres	Granodiorite	24740	28955
8743	Tsing Yi N	Granodiorite	28400	24200

THE GEOCHRONOLOGY OF HONG KONG - PART II

D.P.F. Darbyshire

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1. INTRODUCTION

The Territory of Hong Kong is situated on the southern coast of China at the mouth of the Pearl River and encompasses a portion of mainland China (Kowloon and the New Territories), two large islands (Hong Kong and Lantau) and several dozen smaller islands. The solid geology of the Territory is dominated by Mesozoic volcanic and intrusive igneous rocks. Palaeozoic sedimentary strata form the basement and there are extensive Quaternary superficial deposits, primarily in low lying coastal areas and offshore.

There have been a number of geological surveys of Hong Kong. The earliest, undertaken by Brock, Uglow, Scholfield and Williams between 1923 and 1927 resulted in the publication of a map at 1:84480 (Brock et al, 1936) and several professional papers (Uglow, 1926; Brock and Schofield, 1926; Williams, 1943 and Williams et al., 1945). A memoir based on this work was later published by Davis (1952) and a detailed description of the geology of the Territory was given by Ruxton (1960). Until recently, the most definitive work was that of Allen and Stephens (1971) who carried out a survey between 1967 and 1969 and published a memoir accompanied by maps at 1:50000 scale. These authors made a lithological classification of the Mesozoic volcanic rocks and recognised four phases of granite emplacement within a single episode of late tectonic intrusive activity.

In 1982 the Hong kong Government Geotechnical Control Office initiated a new programme of systematic geological mapping of the Territory at the 1:20000 scale. To date maps and memoirs for the following districts have been completed: - Sha Tin (Addison, 1986), Hong Kong Island and Kowloon (Strange and Shaw, 1986), Western New Territories (Langford et al., 1989) and Sai Kung and Clearwater Bay (Strange et al., 1990). A geochronological study commenced in 1989 in support of the Geological Survey Section of the Planning Division of the GCO who are responsible for the mapping programme. The Rb-Sr data from the first phase (1989-1990) were documented in the NERC Isotope Geosciences Laboratory Report (Darbyshire, 1990) and the ages for the granites were published in Sewell et al. (1992). This report describes the results obtained during 1991-1993 and concentrates on plutonic rocks from the Western New Territories and the island of Lantau.

2. SAMPLING AND SAMPLE PREPARATION

Sampling was undertaken by the staff of the Geological Survey of Hong Kong following the guidelines given by the author during the first phase of the project. Specimens ranged from 6 to 20 kilos in weight, depending on grain-size. A limited number of the rocks were pre-crushed in Hong Kong, but the majority were shipped to the UK for sample preparation 34 of the samples were jaw-crushed and split at the Open University under the supervision of Mr John Holbrook. Representative 100-200 g sub-samples were then finely ground to give a -200 mesh powder for geochemical and isotope analysis. The remaining 15 samples were similarly prepared in the NIGL processing laboratories by Mr Mark Allen and staff of the British Geological Survey.

3. ANALYTICAL TECHNIQUES

Concentrations of Rb and Sr as well as Rb/Sr ratio were determined by X-ray fluorescence spectrometry (Analytical Geochemistry Group, British Geological Survey) on 20 g pellets pressed to 10 tonnes from -200 mesh whole rock powder. Included with each batch of samples were international reference standards, and appropriate corrections were made for instrumental dead time, background and line interferences (Pankhurst and O'Nions, 1973). After chemical separation involving ion exchange procedures, Sr was loaded on single tantalum filaments prepared with phosphoric acid. Isotope ratio measurements were made on an automated Finnegan-MAT 262 mass spectrometer. The analytical data are presented in Table 1.

Errors are quoted throughout as two standard deviations from measured or calculated values. The decay constant used in the age calculation is the value $\lambda^{87} = 1.42 \times 10^{-11}\ a^{-1}$ recommended by the IUGS Subcommission for Geochronology (Steiger and Jager, 1977). Analytical uncertainties are estimated to be 0.01% for $^{87}Sr/^{86}Sr$ ratios and 1.0% for $^{87}Rb/^{86}Sr$ ratios. During the period of this analytical work (1991-1993) the average $^{87}Sr/^{86}Sr$ ratio determined for 479 analyses of the NBS-987 Sr-isotopic standard was 0.710233 ± 0.000025.

The $^{87}Rb/^{86}Sr$ – $^{87}Sr/^{86}Sr$ regression lines shown in Figures 1 - 6 have been calculated using a least-squares method based on that described by York (1969). As a measure of "goodness of fit" of the regression lines to the analytical data, the "mean square of weighted deviates" (MSWD) is employed (Brooks et al., 1972). Where the observed value exceeds a limiting or critical value (3.0) the scatter of data cannot be entirely accounted for by experimental and sampling errors. In such cases the data do not satisfy the criteria for an isochron (Faure, 1986), and the values calculated for age and initial Sr-isotope ratio should be viewed with caution. When manifest in this study, the errors have been enhanced by multiplying by the square root of the MSWD following the method of York (1969).

Whole-rock geochemical analyses were carried out by X-ray fluorescence spectrometry (Dr T Brewer, University of Nottingham), using fused beads for major and minor elements, and pressed powder pellets for trace elements.

4. CLASSIFICATION AND NOMENCLATURE FOR HONG KONG GRANITES

The granites of Hong Kong may be grouped into two suites on the basis of petrographic, geochemical and geochronological criteria (Sewell et al., 1992). The Lamma suite comprises the Tai Po granodiorite and the Sung Kong granite which are the oldest and most primitive units in the Territory. The rocks, which are characterised by high CaO (1.4-2.7%) and low Nb and Y contents, occur as isolated outcrops throughout much of the central and southern parts of the Territory. The Lion Rock suite is dominated by relatively undeformed monzogranite with subordinate quartz syenite and has been further subdivided into three groups. The Tai Lam and Tsing Shan plutons represent the oldest subgroup. The coarse-grained lithologies together with those of the Lamma suite are interpreted as synorogenic I-types. Fine-to medium-grained granites are predominantly fluorite-bearing and display a distinctive A-type signature. Subground II comprises the Lantau and Sha Tin granite plutons together with several bodies of quartz syenite. The rocks display a wide range of compositions (63-77% SiO_2) and are characterised by highly variable trace element abundances. The granites of subgroup III include the equigranular Kowloon, Chi Ma Wan, S Lamma and Stanley plutons and the fine-grained leucogranites of Mount Butler and Kwun Tong. They are moderately to highly evolved (72.5-77.9% SiO_2) with the silica-rich compositions showing a marked enrichment in Y, Nb and Rb and depletion in Ba and Sr. Granites of subgroups II and III are interpreted as late-orogenic to post-orogenic, fractionated I-types.

5. RESULTS

5.1 Lion Rock Suite Subgroup I – Tai Lam Granites

The chemical and petrographic evidence suggests that the Tai Lam pluton is a composite intrusive body with a fine-to medium-grained granite intruding a coarse-grained central core (Sewell et al., 1992). Rb-Sr data for six samples of foliated coarse-grained granite are plotted in Figure 1. The MSWD of 23.5 indicates the large degree of scatter of the data points about the regression line and therefore the age of 158 ± 7 Ma should be viewed with some caution. The Sr-isotope systematics have undoubtedly been disturbed by the subsequent intrusion.

Six samples of fine to medium-grained granite were analysed, yielding an age of 155 ± 6 Ma and an initial $^{87}Sr/^{86}Sr$ ratio of 0.71065 ± 0.00597 (Figure 2). The high MSWD of 4.7 is solely due to one sample (HK8750) and omission of this data point from the regression results in a statistically good isochron (MSWD = 1.0) with the same parameters. However there is no apparent reason for excluding this sample.

The analytical data for six samples of fine-grained granite do not define a linear array. The elevated $^{87}Rb/^{86}Sr$ ratios (194 - 360) reflect the highly evolved nature of these rocks which are characterised by flat REE profiles with pronounced negative europium anomalies.

5.2 Lion Rock Suite Subgroup I – Tsing Shan Granites

The Tsing Shan granites exhibit a range of lithologies from coarse-, coarse to medium-, and medium to fine-grained granite, however these are all viewed as texural variations of the same pluton. Twelve samples were analysed and the data, which are plotted in Figure 3, yield an age of 152 ± 3 Ma with intercept 0.71438 ± 0.00108. The MSWD of 11.9 reflects some disturbance to the Sr-isotope systematics, although the scatter is exhibited by only four data points (HK 9747, HK 10065, HK 10068-9).

5.3 Lion Rock Suite Subgroup II – Lantau Syenites

Isolated plutonic bodies of syenite outcrop along the margin of the Lantau caldera on Lantau island. Petrological and geochemical data suggest two main groups, Pui O and Tong Fuk, although field relations between them are not always well defined. The Pui O syenites display similar characteristics to those of the syenite and syenogranite dykes that trend NNE through Hong Kong Island. Rb-Sr data for three samples of the Pui O group yield an isochron age of 146 ± 8 Ma with initial $^{87}Sr/^{86}Sr$ ratio 0.70687 ± 0.00022 (MSWD = 1.5 Figure 4). However, in view of the limited data set, these results must be regarded as provisional.

In general the Tong Fuk group of syenites are slightly more evolved than the Pui O. Four samples were collected from the main outcrop at Tong Fuk, two from a separate syenite pod nearby and one from the other side of Lantau almost due north of Tong Fuk. A further sample from a boulder dump at Pui O was found to be more compatible both geochemically and petrographically with the Tong Fuk suite. The Rb-Sr data yield an age of 144 ± 6 Ma and intercept 0.70717 ± 0.00019 (Figure 5). The MSWD of 4.1 suggests that either the Tong Fuk samples have suffered some disturbance of the Sr-isotope systematics or there have been several phases of intrusion of syenite. HK 11057 plots above the regression line and omission of this sample results in an isochron age of 145 ± 3 Ma (0.70712 ± 0.00010, MSWD 3.0). However there would appear to be no valid petrological, geochemical or geographic reasons for excluding this sample.

5.4 Lion Rock Suite Subgroup III – Chi Ma Wan

The isotope ratios determined on the sample from the Chi Ma Wan granite (HK 8353) are very similar to those obtained for the two samples collected during the 1990 study (HK 8710 - HK 8711). Therefore there is insufficient spread in the data to yield a well defined age.

5.5 Lantau Rhyolite

The analytical data for six samples of rhyolite lava from Lantau are plotted in Figure 6 and yield an age of 144 ± 2 Ma with intercept 0.70858 ± 0.00019. The MSWD of 5.3 indicates disturbance of the Sr-isotope systematics and therefore the age should be regarded as a minimum. Although it is widely accepted that fine-grained acid volcanic rocks may be susceptible to open system behaviour, there is some controversy over whether this applies to rhyolite lavas. Gale et al. (1979) cited a number of statistically good Rb-Sr isochrons for felsic lava flows and argued that these reliably dated their extrusion. Evans (1989) and Asmeron et al. (1991) have demonstrated that Rb-Sr ages of volcanic rocks, even lava flows with SiO_2 contents as low as 57 wt % are susceptible to complete resetting by large scale pervasive fluid movement. Some of the specimens of lava from Lantau display evidence of alteration and this together with the high initial $^{87}Sr/^{86}Sr$ ratio strongly suggest that the Rb-Sr age is not dating extrusion. The degree of scatter of the data points indicate that the Rb-Sr systematics have not been coherently reset. Therefore it would not be prudent to interpret the age as a reliable indication of the time of low grade metamorphism.

6. DISCUSSION

The earlier Rb-Sr study (Darbyshire, 1991) established the age of selected granites in subgroups II and III of the Lion Rock Suite as middle Yenshanian (150 - 135 Ma). Yenshanian granitoids are widely distributed in southeastern China and are considered to have been emplaced in two main phases 190 - 140 Ma and 135 - 70 Ma (Yang et al., 1986). However the intrusion of the Hong Kong granites between the early and late phases suggested that plutonism in southern China was continuous from Early Jurassic to Late Cretaceous.

The ages documented in this report for the Tai Lam and Tsing Shan granites support their classification in the oldest subgroup of the Lion Rock Suite. The scatter displayed by the analytical data on the regression lines indicates that the rocks have not behaved as closed systems with respect to Rb and Sr. Therefore the ages should be regarded as minimum estimates of the timing of emplacement. The syenites from Lantau have yielded similar ages and initial ratios although there is some uncertainty attached to both results. However comparable ages have been obtained for the D'Aguillar syenite (147 ± 8 Ma, 0.7068 ± 0.0003) and for the Sha Tin pluton (148 ± 9 Ma, 0.7060 ± 0.0006) which are also classified in subgroup II (Sewell et al., 1992).

Emplacement of the Lion Rock Suite of granites occurred over a period of at least 25 million years during the Middle to Late Jurassic. Ages for the earlier plutonic bodies of the Lamma Suite, the Tai Po Granodiorite and the Sung Kong Granite, have still to be established. There would appear to be no evidence for granite magmatism in the Territory of Hong Kong during the Cretaceous.

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Table 1 - Rb–Sr Data (Sheet 1 of 2)

Sample	Rb ppm	Sr ppm	87Rb/86Sr	87Sr/86Sr
Tai Lam coarse-grained granite				
HK 2416	218	139	4.523	0.722333
HK 6260	265	38.6	20.01	0.756533
HK 7260	233	133	5.085	0.722858
HK 8511	209	141	4.284	0.721689
HK 8512	233	155	4.343	0.721365
HK 8514	283	39.3	20.97	0.759094
Tai Lam fine-to medium-grained granite				
HK 8747	524	15.0	103.5	0.936896
HK 8749	513	19.0	79.68	0.885908
HK 8750	494	19.5	74.70	0.878534
HK 8751	531	20.7	75.42	0.876532
HK 10403	451	25.8	51.21	0.823279
HK 10488	549	15.8	102.5	0.937619
Tai Lam fine-grained granite				
HK 3178	621	6.31	304.2	1.399117
HK 8744	604	8.73	209.6	1.199412
HK 8745	651	5.65	360.3	1.524684
HK 8746	553	8.61	193.9	1.140463
HK 8753	645	8.38	235.0	1.270525
HK 8755	598	5.80	318.0	1.393761
Ma Wan granite				
HK 10482	416	23.7	51.23	0.824290
Tsing Shan granites				
HK 9715	464	19.2	70.94	0.868356
HK 9747	357	40.4	25.69	0.768877
HK 9748	349	36.5	27.84	0.775358
HK 10065	346	31.3	32.24	0.786060
HK 10066	365	35.6	29.82	0.777968
HK 10068	410	24.1	49.71	0.819194
HK 10069	329	29.6	32.43	0.786547
HK 10071	413	29.9	40.31	0.801641
HK 10072	379	25.1	44.15	0.810151
HK 10074	264	71.4	10.74	0.737732
HK 10344	268	41.3	18.89	0.754989
HK 11060	513	19.0	79.58	0.887076
Pui O syenite, Lantau				
HK 11054	188	294	1.852	0.710757
HK 11056	196	213	2.667	0.712401
HK 11058	178	320	1.608	0.710183

Table 1 - Rb–Sr Data (Sheet 2 of 2)

Sample	Rb ppm	Sr ppm	87Rb/86Sr	87Sr/86Sr
Tong Fuk syenite, Lantau				
HK 8756	195	259	2.180	0.711696
HK 8757	202	252	2.313	0.711924
HK 8759	198	271	2.112	0.711491
HK 8941	136	235	1.678	0.710628
HK 10061	135	266	1.469	0.710042
HK 10067	177	281	1.824	0.710867
HK 11055	237	159	4.318	0.715963
HK 11057	143	256	1.613	0.710581
Lantau rhyolite lava				
HK 9907	292	41.8	20.30	0.749520
HK 9916	176	191	2.656	0.714018
HK 10062	226	60.5	10.82	0.730842
HK 10063	184	196	2.718	0.714203
HK 10891	228	136	4.855	0.718388
HK 11052	354	34.4	29.99	0.770695
Chi Ma Wan granite				
HK 8353	294	92.1	9.264	0.725400
HK 8710	274	84.3	9.437	0.725707
HK 8711	270	83.4	9.403	0.725740

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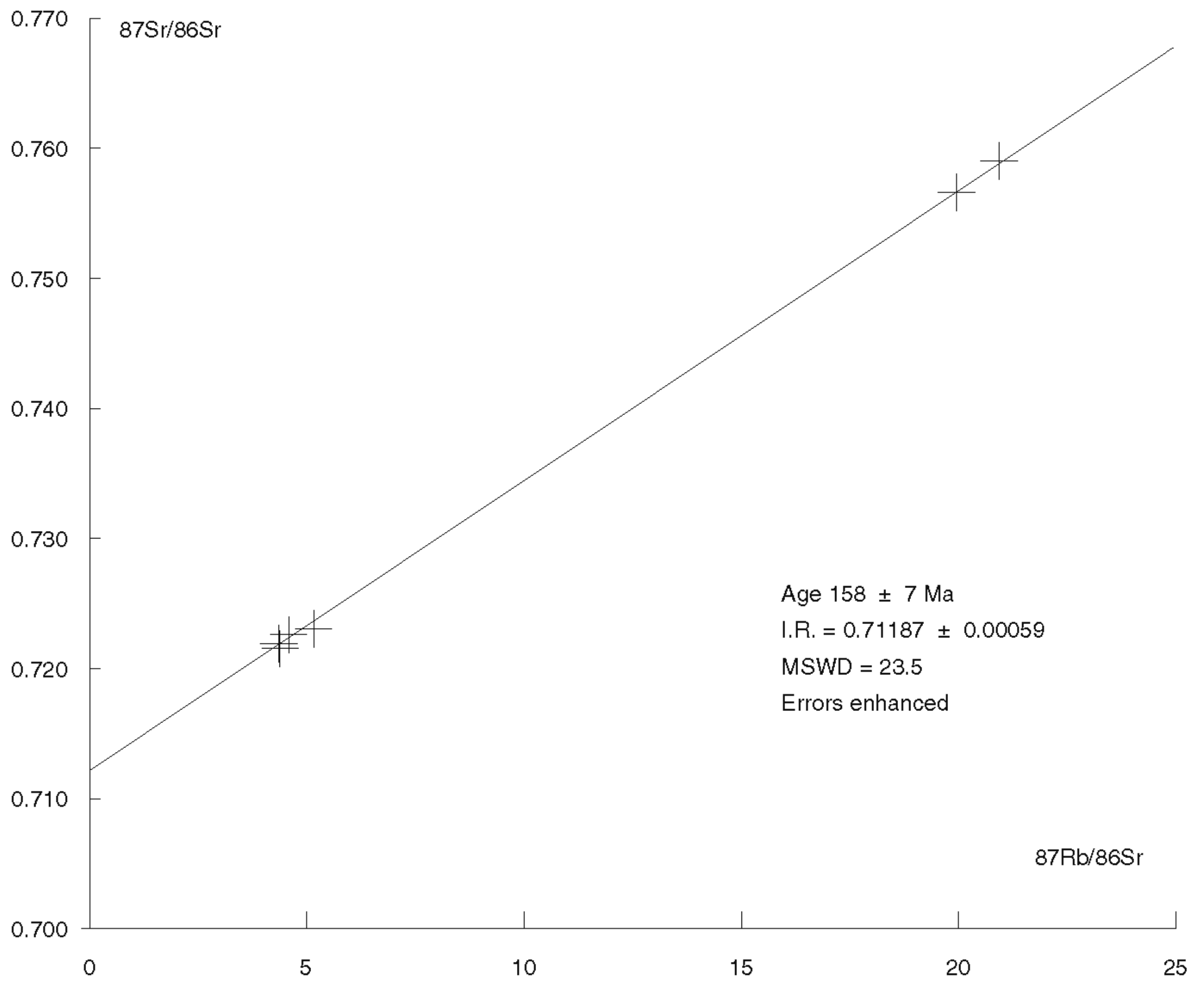

Figure 1 - Tai Lam Coarse-grained Granite

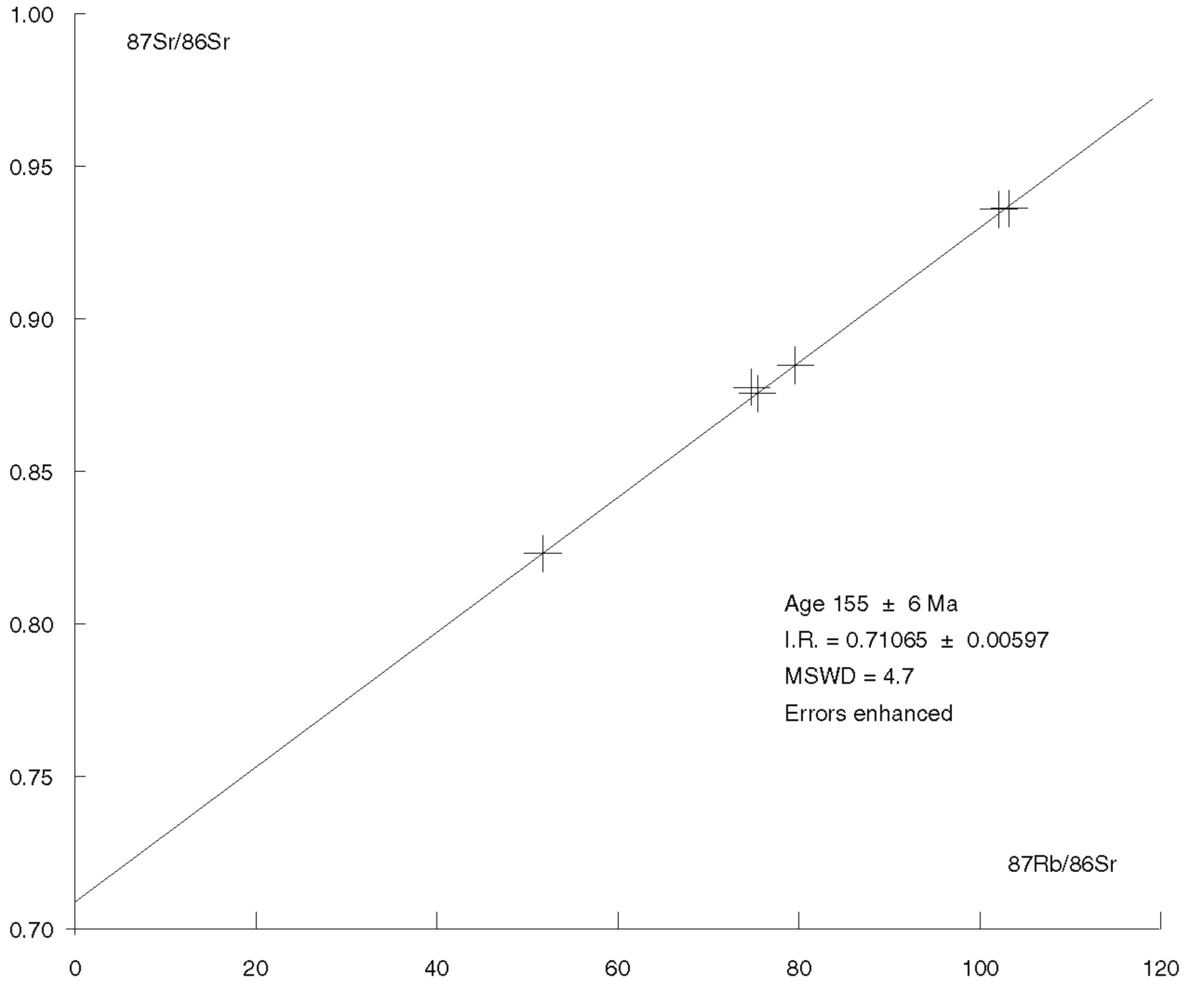

Figure 2 - Tai Lam Fine- to Medium-grained Granite

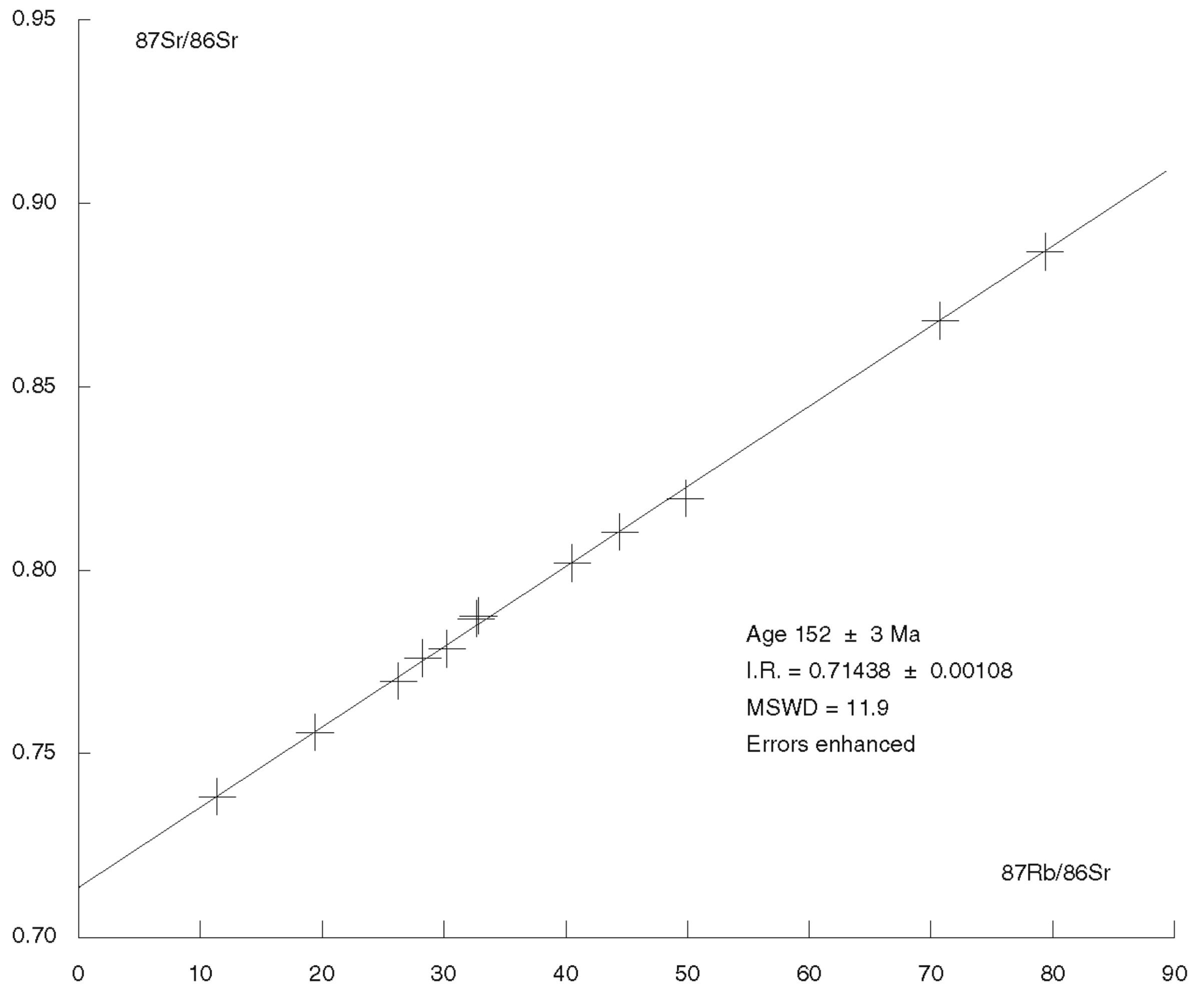

Figure 3 - Tsing Shan Granites

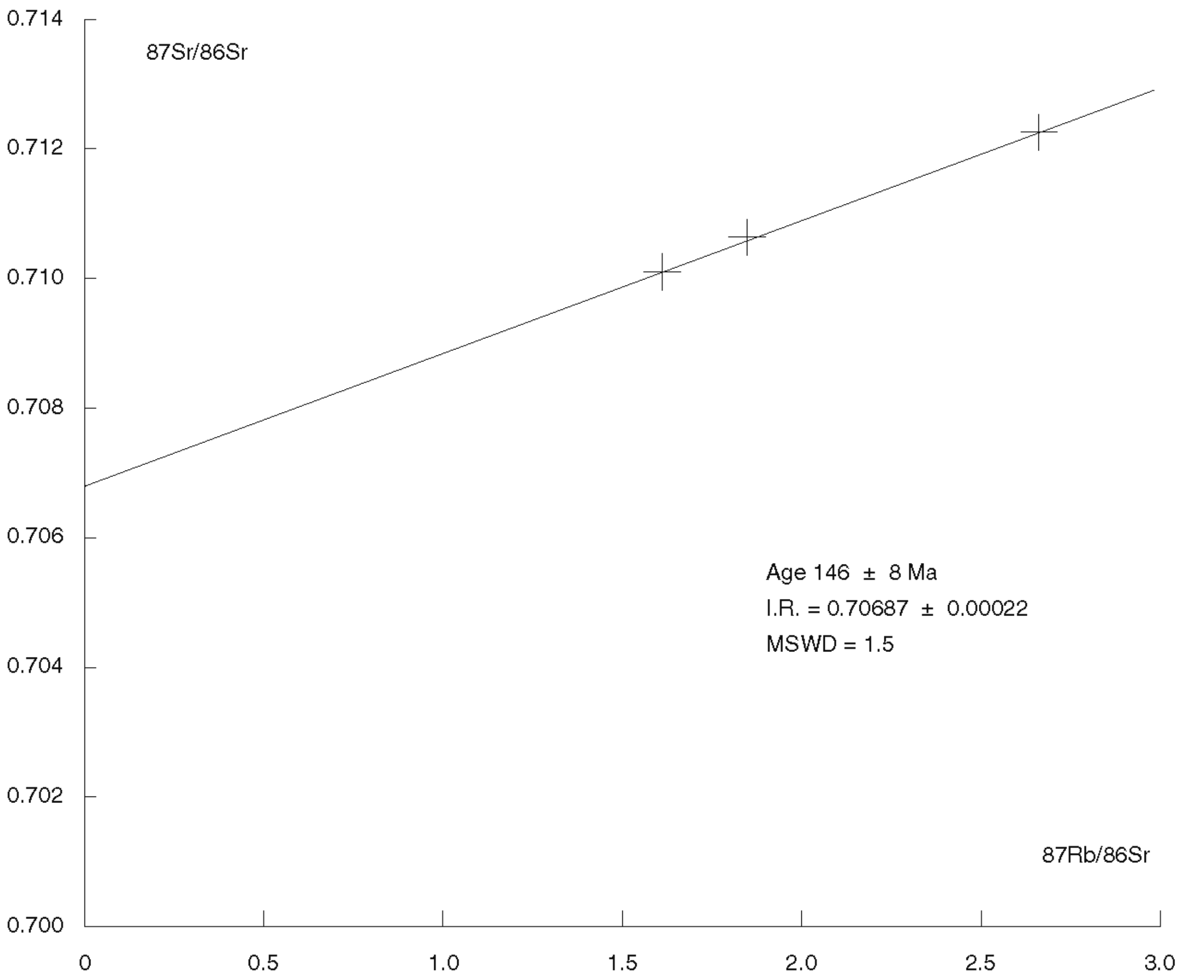

Figure 4 - Pui O Syenites, Lantau

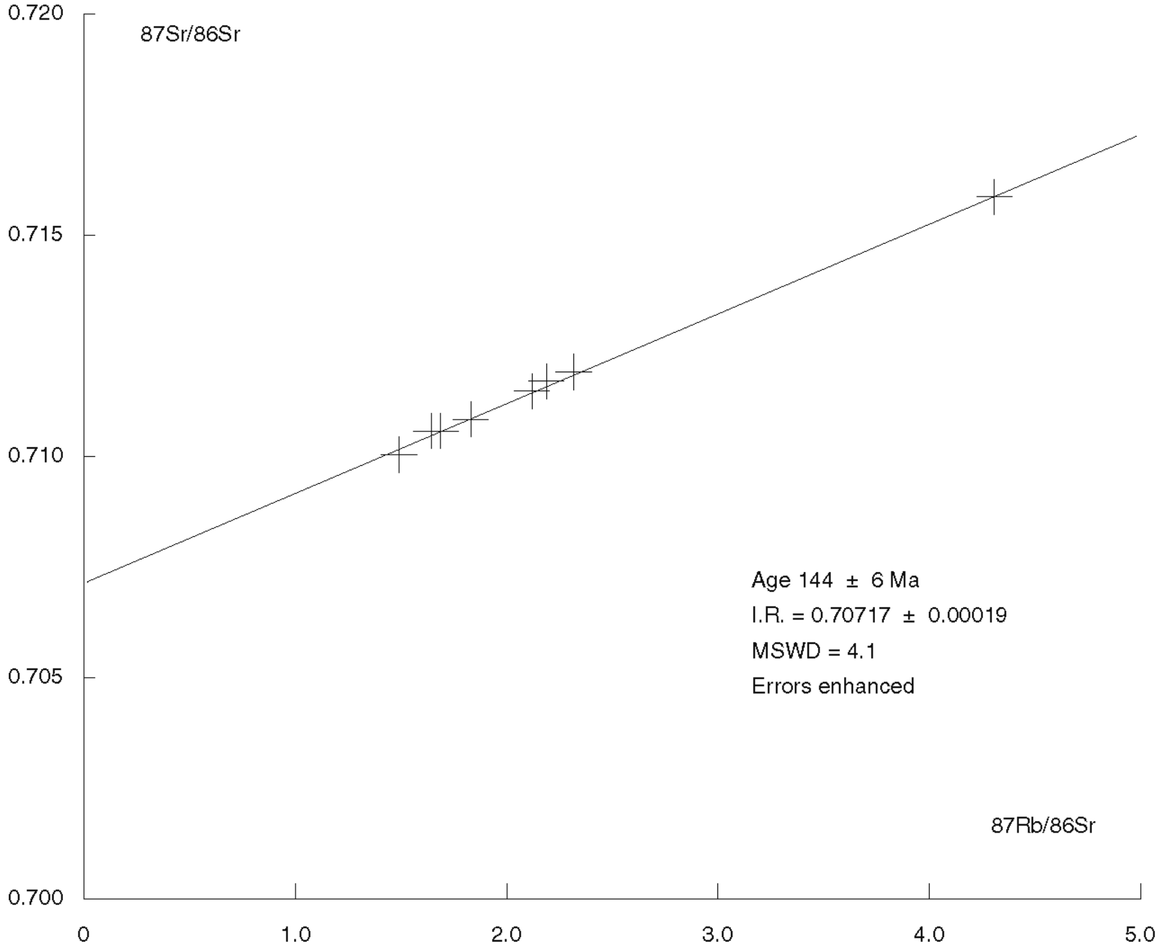

Figure 5 - Tong Fuk Syenites, Lantau

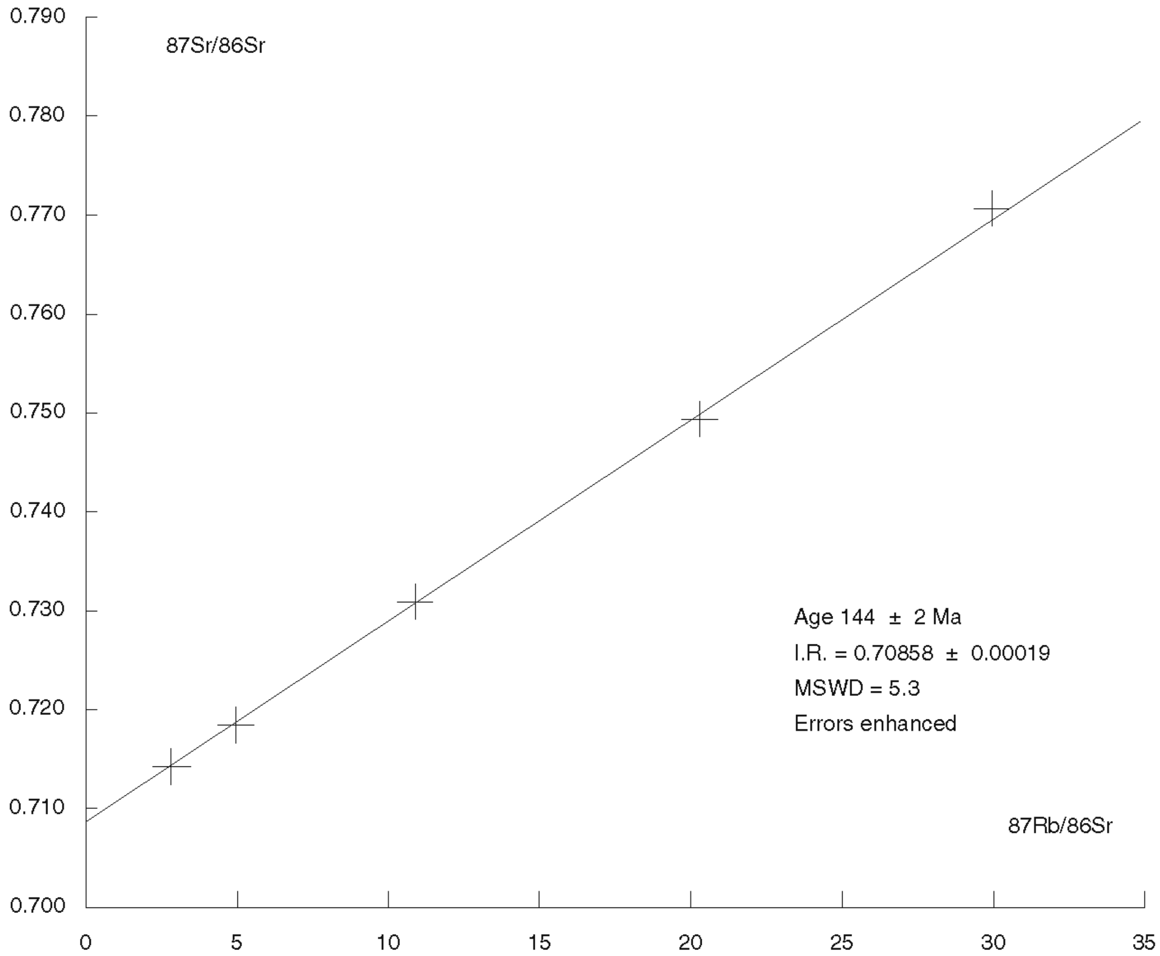

Figure 6 - Lantau Rhyolite

APPENDIX B

U-Pb GEOCHRONOLOGY REPORTS

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U-PB GEOCHRONOLOGY OF PLUTONIC AND VOLCANIC ROCKS IN HONG KONG PHASE 1

JULY 1, 1996

D. W. DAVIS, Y. AMELIN, F. CORFU AND Y. Y. KWOK
GEOLOGY DEPT.
ROYAL ONTARIO MUSEUM
100 QUEEN'S PARK
TORONTO, ONTARIO
M5S 2C6

1. SAMPLES

1) HK8754 Tai Lam granite
2) HK8758 Lan Tau quartz syenite
3) HK10277 Tsing Shan granite
4) HK11025 Tai Po granodiorite
5) HK11042 Kings Park granite
6) HK11640 Borehole S-type granite
7) HK11821 Yim Tin Tsai crystal tuff
8) HK11822 Lantau granite

2. ANALYTICAL METHODS

Sample crushing was with a jaw crusher followed by a disk mill. Samples were 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 to be usually accurate to about ± 30%. This affects only U concentrations, not age information, which depends on isotopic ratio measurements (Table 1).

Zircon was dissolved using HF in teflon bombs at 200°C, after being washed in HNO_3. Monazite was dissolved in 6N HCl in a savillex capsule. ^{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.

3. RESULTS

All samples yielded zircon, in varying abundance. Zircon populations are generally quite fresh due to the young age and generally low U concentrations, although in some rocks many of the zircons are highly fractured. Crack-free zircons without evidence of cores or alteration were selected for abrasion.

Most of the zircon populations show similar characteristics. Exceptions are noted below. Zircon crystals are generally colourless, euhedral, doubly-terminated prisms of varying length. Low-order crystal faces are well-developed and most grains have an abundance of inclusions, including amorphous melt inclusions, apatite rods and sulphide inclusions.

Because of depletion of the shorter half-life ^{235}U isotope, there is much less ^{207}Pb than ^{206}Pb for relatively young samples. For Mesozoic and younger samples, ^{206}Pb/^{238}U ages are much more precise and reliable than ^{207}Pb/^{235}U ages, and ^{207}Pb/^{206}Pb ages are quite imprecise because the concordia curve is nearly parallel to a line through the origin. Therefore, ages for these samples are calculated as ^{206}Pb/^{238}U ages. ^{206}Pb/^{238}U ages are sensitive to secondary Pb loss, but 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).

Slight to moderate amounts of inheritance are present in many of the samples, probably due to the presence of xenocrysts or invisible cores. Because of the low U concentrations of most of the grains, single grain dating could only be carried out on exceptionally large crystals. Most fractions consisted of several grains. The probability of accidentally including an inherited zircon increases with the number of grains picked. Therefore, in most cases 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. This probably accounts for common Pb values in many of the samples that are several picograms higher than normal lab blanks (0.5 - 2 pg). This small amount of extra common Pb has a negligible effect on the ^{206}Pb/^{238}U age precision. Common Pb corrections are made assuming an isotopic composition similar to laboratory blank. For these young samples, this is effectively the same as the Stacey and Kramers (1975) value, which represents a crustal average. Concordia values in Table 1 are corrected for fractionation, blank and spike. ^{206}Pb/^{204}Pb values are corrected for fractionation and spike.

The plotted data (Figs. 1-8), as well as the ages in Tables 1 and 2, are corrected for ^{230}Th disequilibrium, assuming a Th/U ratio in the magma of 4.2, the terrestrial average. This increases ^{206}Pb/^{238}U ages by about 0.09 Ma in all of the zircon samples. The concordia coordinates in Table 1 are quoted as measured values, uncorrected for assumed disequilibrium. Th/U is calculated from the measured ^{208}Pb/^{206}Pb ratio and ^{207}Pb/^{206}Pb age.

Ages, errors and probabilities of fit are calculated from the Davis (1982) program, modified for ^{206}Pb/^{238}U data. U decay constants are from Jaffey et al. (1971). A summary of age results is given in Table 2. 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. Errors are quoted at the 95% confidence level in the text and

Table 2. Errors in Table 1 are quoted as 1σ. Error ellipses are given at 2σ on figures 1 to 8. Detailed results of mass spectrometer outputs and data reduction are included in disk and photocopy form with this report.

3.1 HK8754 Tai Lam Granite

Zircon is moderately abundant but the grains are commonly highly fractured. Three multigrain fractions of uncracked grains give overlapping data points (61% probability of fit) and define an age of 159.3 ± 0.3 Ma (Fig. 1).

3.2 HK8758 Lantau Quartz Syenite

This sample yielded abundant, fresh zircon. Analyses of four single grains agree within error (Fig. 2) and define an age of 140.4 ± 0.3 Ma (83% probability of fit).

3.3 HK10277 Tsing Shan Granite

Zircon is moderately abundant but the grains are mostly small and generally highly fractured. Because of the small size of the crystals, fractions consisting of many grains had to be analysed. Three data points cluster near concordia with an average age of 159.9 ± 0.2 Ma, but with a probability of fit of only 8% (Fig. 3). This age is probably close to the true age of the sample because the lack of fit is only marginal, but the error cannot be considered reliable. The age of the youngest data point 159.6 ± 0.5 Ma should give the closest approximation to the age of the rock and is at least an older limit. One error ellipse, affected by inheritance, is very large because of the high proportion of common Pb in the analysis. Two other, more precise, points are also affected by inheritance from Precambrian sources. Unlike some of the 140-150 Ma samples in the Phase 1 report, the ca. 160 Ma samples in this report do not show evidence of scatter along concordia due to inheritance from slightly older sources. This suggests again that the concordant data point is likely close to the age of the sample.

3.4 HK11025 Tai Po Granodiorite

This sample yielded abundant fresh zircon with typical euhedral, stubby to elongate morphology and abundant melt inclusions. Three data points overlap within error (Fig. 4A) and define an age of 164.6 ± 0.2 Ma (58% probability of fit). A fourth multigrain data point shows an average inheritance age of 1136 Ma (Fig. 4B).

3.5 HK11042 Kings Park Granite

Zircon is moderately abundant in this rock but the grains are mostly brownish and highly fractured. Four single-grain fractions give overlapping data points (Fig. 5) with an age of 140.4 ± 0.2 Ma (71% probability of fit).

3.6 HK11640 Borehole S-type Granite

This sample yielded a moderate amount of zircon. Grains are generally small, stubby to elongate and multifacetted with sharp terminations. Typical zircon morphologies in this rock are distinct from the other Hong Kong samples that have been analysed, where the grains are generally prismatic with well developed [110] and [100] crystal faces. Zircons from this sample also have relatively few inclusions. This sample showed persistant inheritance with average ages of 507 Ma and 1269 Ma in two multi-grain fractions (Figs 6A and 6B). Two zircon data points plot near each other on concordia but are slightly outside of error (Fig. 6A).

A small amount of monazite was recovered and analysed, giving a data point with an age of 236.3 ± 0.8 Ma, in agreement with one of the concordant zircon data points. This data point is corrected for excess ^{206}Pb derived from decay of excess ^{230}Th. Uncertainty in this correction can be a problem for young monazite because of its typically high Th/U ratios. Fortunately, this monazite fraction shows a relatively low Th/U ratio of 9.7, so the total correction to the $^{206}Pb/^{238}U$ age is only 160 Ka. Two other near-concordant zircon data points plot distinctly below the zircon-monazite cluster, the youngest showing an age of 229 Ma. Assuming there has been no secondary Pb loss or contamination from a younger source, either in the lab or from a cross-cutting unit, this should be taken as an older age limit on the sample. However, the monazite age is here considered to be the most reliable estimate for granite crystallization for a number of reasons. First, there is the near agreement with two zircon data points (8% probability of fit). Second, although inheritance has been previously documented in monazite, but it is thought to be less common than in zircon. Third, a previous report by Y. Chen on this sample gave three $^{206}Pb/^{238}U$ ages in agreement at 236 Ma. Although the reliability of these results is uncertain, $^{206}Pb/^{238}U$ ages are difficult to bias significantly through analytical error. This fact and the agreement with the cluster found in the repeat study strongly suggests that the age of the rock is close to 236 Ma. In this case, the younger data points may be recording contamination or secondary Pb loss.

3.7 HK11821 Yim Tin Tsai Crystal Tuff

Zircon is moderately abundant in this sample, but generally cracked. Three single grain fractions give overlapping, concordant data points (Fig. 7A) with an age of 164.5 ± 0.2 Ma (41% probability of fit). A fourth single grain is affected by inheritance from a 2719 Ma, late Archean source (Fig. 7B).

3.8 HK11822 Lantau Granite

Zircon is abundant in this rock, although commonly cracked with a small proportion of fresh grains. Three multi-grain fractions overlap near concordia (Fig. 8A) and define an age of 161.5 ± 0.2 Ma (62% probability of fit). A fourth multigrain fraction shows inheritance from a source or sources with an average age of 714 Ma (Fig. 8B).

4. DISCUSSION

Sample HK8758 appears to be coeval with HK11042 at 140.2 Ma. HK11025 and HK11821 are also the same age, within error, at 164.5 Ma. HK10277 may also be coeval with HK8754 at 159.3 Ma, if the youngest zircon in HK10277 is unaffected by inheritance.

As discussed in the Phase 1 report, although the relationship between zircon morphology and tectonic environment is not well established, a predominance of low order crystal faces and abundant melt inclusions are commonly found in zircon populations in rocks from rift environments, whereas zircons from calc-alkaline felsic rocks tend to show a multifacetted morphology similar to that found in HK11640. The common occurrence of inheritance in many of the rocks also indicates that they were erupted on or through older crust containing a wide variety of age components, either as igneous or detrital material.

Precise data points in this study, as well as the Phase 2 study, generally lie slightly to the right of or below the concordia curve. The presence of residual inheritance 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 200 Ka. The same consistency argues against a cause due to analytical error, or incorrect choice of common Pb isotopic composition, since the samples were measured under a variety of conditions, including measurements on two mass spectrometers with two data acquisition programs, and the analyses have a wide range 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 data point to the right (231-protactinium has a 32,000 yr 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 $^{206}Pb/^{238}U$ ages.

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Table 1 - U-Pb Isotopic Data on Abraded Zircon and Monazite from Hong Kong Rocks - Phase 1 Report (Sheet 1 of 3)

	Fraction Analysed	**Weight (mg)**	**U (ppm)**	**Th/U**	**Pbcom (pg)**	**206Pb/ 204Pb**	**206Pb/ 238U**	**207Pb/ 235U**	**206/238 Age (Ma)**	**1 sig**	**207/235 Age (Ma)**	**1 sig**	**207/206 Age (Ma)**	**1 sig**	**Disc. (%)**
	HK8754 TAI LAM GRANITE														
1	2 ZR, MELT & ROD INCL	0.015	270	0.39	1.4	4608	0.024979	0.17008	159.14	0.22	159.49	0.35	164.6	4.3	3.4
2	9 ZR, MELT & ROD INCL	0.030	259	0.48	1.3	9783	0.025023	0.17033	159.42	0.30	159.70	0.32	164.0	2.3	2.8
3	5 ELONG ZR, INCL	0.030	221	0.53	1.9	5736	0.025025	0.17022	159.43	0.23	159.61	0.26	162.3	2.2	1.8
	HK8758 LAN TAU QUARTZ SYENITE														
4	1 ZR, CLR, NO INCL	0.011	73	0.75	0.6	2026	0.021980	0.15033	140.22	0.36	142.20	0.92	175.4	15	20
5	1 ZR, CLR, MELT INCL	0.011	36	0.79	1.1	561	0.021970	0.14709	140.16	0.47	139.34	2.0	125.4	36	-12
6	1 ZR CLR, MELT INCL	0.010	59	0.69	2.2	419	0.022030	0.14937	140.53	0.25	141.35	2.5	155.1	43	9.5
7	1 ZR, CLR, INCL	0.005	156	0.64	2.5	466	0.022020	0.14926	140.52	0.38	141.26	2.6	153.8	43	8.7
	HK10277 TSING SHAN GRANITE														
8	14 ZR, CLR	0.004	626	0.55	0.5	7632	0.025046	0.17055	159.56	0.23	159.90	0.39	165.0	5.0	3.3
9	13 ZR	0.012	556	0.51	0.7	15519	0.025090	0.17174	159.84	0.23	160.93	0.30	177.0	2.7	9.8
10	14 ZR, INCL	0.009	398	0.60	1.1	5418	0.025148	0.17165	160.20	0.18	160.85	0.36	170.4	4.6	6.1
11	18 ZR	0.008	632	0.45	0.7	11510	0.025405	0.17709	161.82	0.18	165.55	0.26	219.3	2.5	27
12	6 ZR	0.006	413	0.44	2.0	2085	0.025965	0.18013	165.34	0.17	168.17	0.51	208.3	7.1	21
13	13 ZR	0.005	462	0.45	13.2	314	0.026259	0.18338	167.19	0.28	170.96	3.3	223.5	48	26
	HK11025 TAI PO GRANODIORITE														
14	4 ELONG, MELT INCL	0.040	121	0.58	12.5	657	0.025847	0.17663	164.60	0.19	165.16	0.84	173.3	12	5.1
15	3 ELONG, MELT INCL	0.040	100	0.63	3.1	2168	0.025859	0.17635	164.67	0.19	164.91	0.36	168.4	4.4	2.2
16	7 NEEDLES	0.025	103	0.74	1.8	2338	0.025813	0.17634	164.38	0.21	164.91	0.41	172.6	5.2	4.8
17	2 ZR, ROD & DARK INCL	0.040	135	0.31	3.4	2895	0.028547	0.20646	181.50	0.33	190.58	0.39	304.1	4.1	41

Table 1 - U-Pb Isotopic Data on Abraded Zircon and Monazite from Hong Kong Rocks - Phase 1 Report (Sheet 2 of 3)

	Fraction Analysed	**Weight (mg)**	**U (ppm)**	**Th/U**	**Pbcom (pg)**	**206Pb/ 204Pb**	**206Pb/ 238U**	**207Pb/ 235U**	**206/238 Age (Ma)**	**1 sig**	**207/235 Age (Ma)**	**1 sig**	**207/206 Age (Ma)**	**1 sig**	**Disc. (%)**
	HK11042 KINGS PARK GRANITE														
18	1 ZR	0.008	255	0.61	1.5	1944	0.022024	0.14923	140.53	0.21	141.23	0.46	153.20	6.9	8.3
19	1 ZR, FEW INCL	0.006	277	0.66	0.5	4629	0.021970	0.14830	140.20	0.25	140.41	0.36	143.9	5.8	2.6
20	1 ZR, ABUND INCL	0.004	272	0.65	1.1	1444	0.021990	0.14846	140.29	0.31	140.55	0.81	145.1	14	3.3
21	1 ZR, CRACKS	0.008	233	0.54	1.0	2547	0.022018	0.14913	140.49	0.19	141.14	0.53	152.10	8.5	7.7
	HK11640 BOREHOLE S-TYPE GRANITE														
22	1 MONAZITE	0.001	1850	9.74	1.1	4055	0.03736	0.26154	236.30	0.40	235.91	0.80	232.0	7.5	-1.9
23	13 ZR	0.005	616	0.71	0.8	9831	0.03740	0.26325	236.79	0.43	237.29	0.50	242.2	3.2	2.3
24	3 NEEDLES	0.001	484	0.80	2.0	606	0.03753	0.26318	237.60	0.41	237.23	2.30	233.6	24	-1.8
25	18 ZR	0.006	431	0.63	2.3	2716	0.03665	0.25981	232.14	0.30	234.52	0.70	258.4	6.8	10
26	7 ZR, INCL	0.004	815	0.51	4.8	1589	0.03608	0.25434	228.57	0.30	230.09	0.92	245.7	9.7	7.1
27	4 ZR, INCL	0.017	405	1.58	1.4	13187	0.04046	0.28920	255.75	0.28	257.93	0.35	277.8	2.3	8.1
28	11 ZR TIPS	0.007	290	0.27	1.5	6680	0.07620	0.74257	473.51	0.59	563.91	0.73	947.6	2.0	52
	HK11821 YIM TIN TSAI CRYSTAL TUFF														
29	1 ZR, MELT INCL	0.015	81	0.54	0.9	2150	0.025859	0.17670	164.67	0.21	165.21	0.41	173.0	5.5	4.9
30	1 ZR, MELT INCL	0.015	151	0.93	1.5	2507	0.025821	0.17561	164.42	0.23	164.28	0.40	162.2	5.4	-1.4
31	1 AB ZR, MELT INCL	0.005	139	0.54	2.3	520	0.025787	0.17725	164.22	0.27	165.69	1.67	186.8	24	12
32	1 AB ZR, ABUND INCL	0.030	162	0.12	1.9	28246	0.174970	4.17393	1039.4	1.5	1668.9	1.2	2587.0	1.6	65
	HK11822 LANTAU GRANITE														
33	5 ELONG, MELT INCL	0.013	498	0.37	1.5	6966	0.025358	0.17282	161.52	0.20	161.86	0.25	166.8	2.6	3.2
34	2 ZR, MELT INCL	0.011	447	0.37	2.3	3478	0.025341	0.17272	161.42	0.19	161.78	0.29	167.0	3.3	3.4
35	2 ELONG, MELT INCL	0.014	465	0.38	1.7	6424	0.025380	0.17307	161.66	0.16	162.08	0.22	168.3	2.1	4.0

Table 1 - U-Pb Isotopic Data on Abraded Zircon and Monazite from Hong Kong Rocks - Phase 1 Report (Sheet 3 of 3)

	Fraction Analysed	**Weight (mg)**	**U (ppm)**	**Th/U**	**Pbcom (pg)**	**206Pb/ 204Pb**	**206Pb/ 238U**	**207Pb/ 235U**	**206/238 Age (Ma)**	**1 sig**	**207/235 Age (Ma)**	**1 sig**	**207/206 Age (Ma)**	**1 sig**	**Disc. (%)**
36	4 ZR. MELT & DARK INCL	0.011	405	0.43	1.9	4203	0.027802	0.19501	176.87	0.23	180.89	0.30	233.8	2.9	25

Footnotes to Table 1:
Weights are based on visual estimates.
Th/U is calculated from measured 206Pb/208Pb and 207Pb/206Pb age.
Pbcom is total measured common Pb assuming all common Pb has the isotopic composition of laboratory blank:
]206/204 - 18.221; 207/204 - 15.612; 208/204 - 39.360.
206/204 are measured values corrected for fractionation and spike.
206Pb/238U and 207Pb/235U ratios are corrected for common Pb assuming laboratory blank composition..
206Pb/238U age, 207Pb/235U age and 207Pb/206Pb age are corrected for 230Th disequilibrium assuming a magmatic Th/U of 4.2.
%Disc. is percent discordance for the given 207Pb/206Pb age.

Table 2 - Summary of Ages from Hong Kong Samples

SAMPLE	**206Pb/238U Age (Ma)**	**Probability of Fit (%)**	**Number of Points**	**Inheritance (Ma)**
HK8754	159.3 ± 0.3	61	3	none
HK8758	140.4 ± 0.3	83	4	none
HK10277	less than 159.6 ± 0.5	-	1	1050, 2200
HK11025	164.6 ± 0.2	58	3	1136
HK11042	140.4 ± 0.2	71	4	none
HK11640	less than 236.3 ± 0.8	-	1	507, 1269
HK11821	164.5 ± 0.2	41	3	2719
HK11822	161.5 ± 0.2	62	3	714

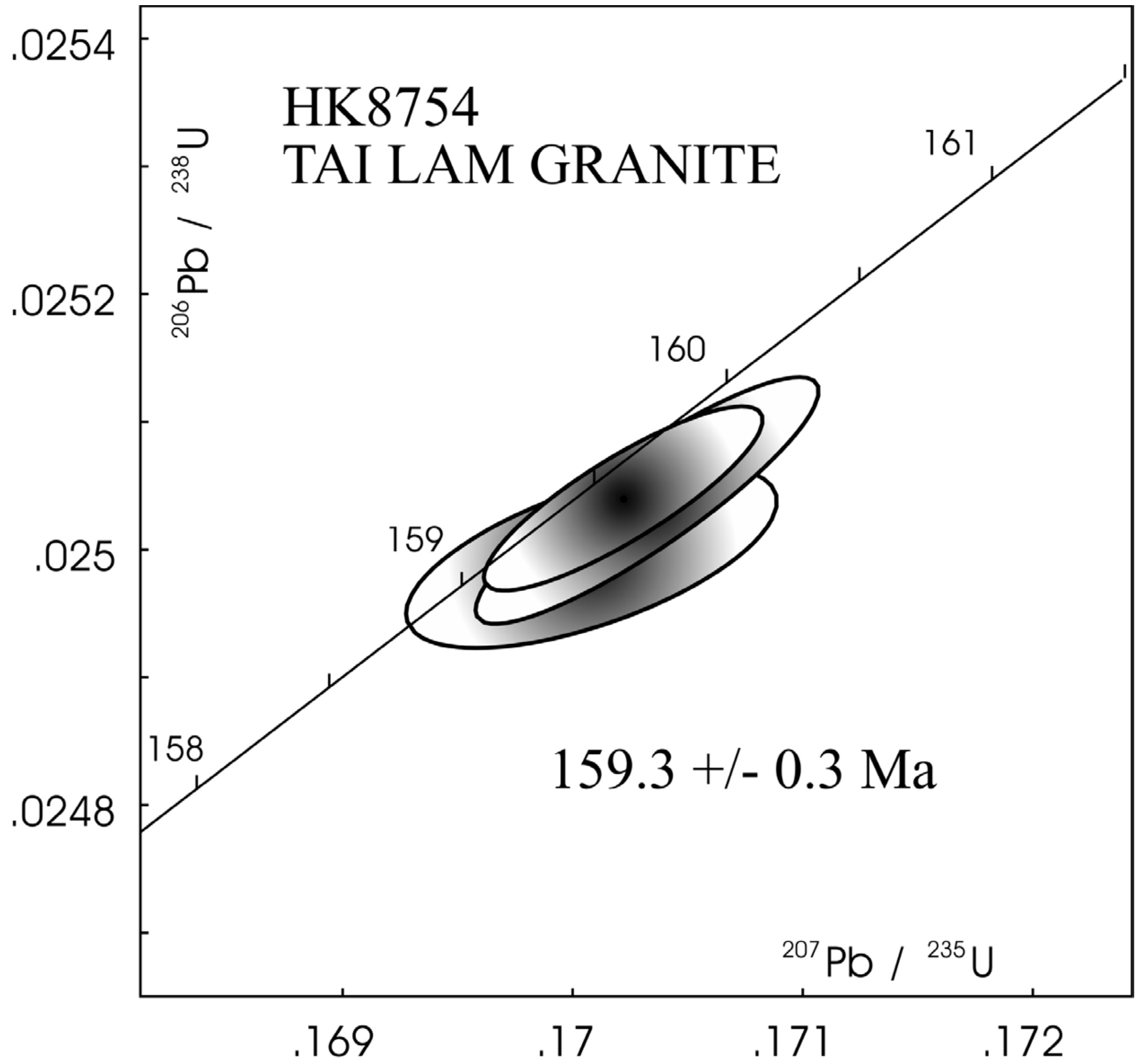
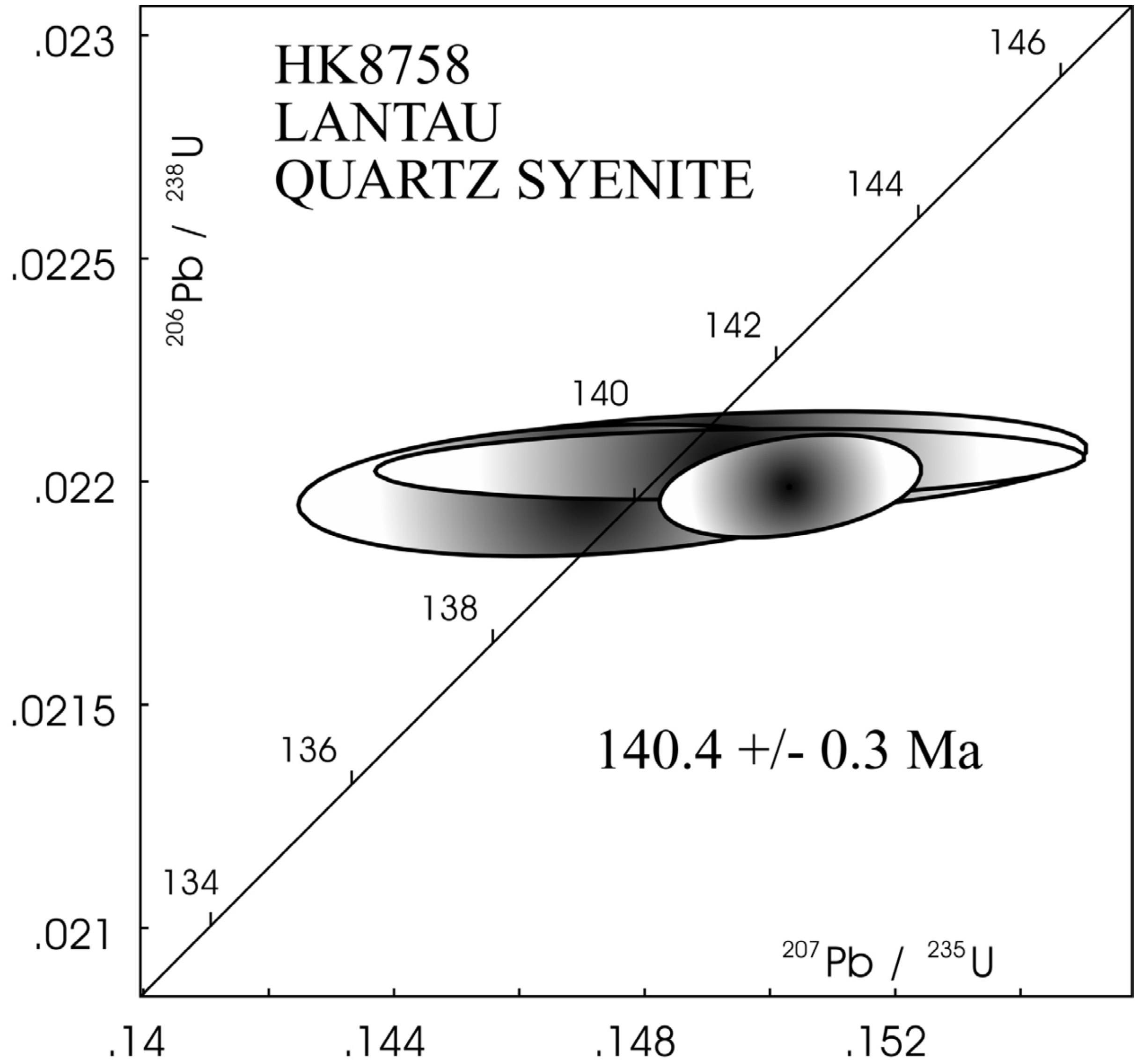
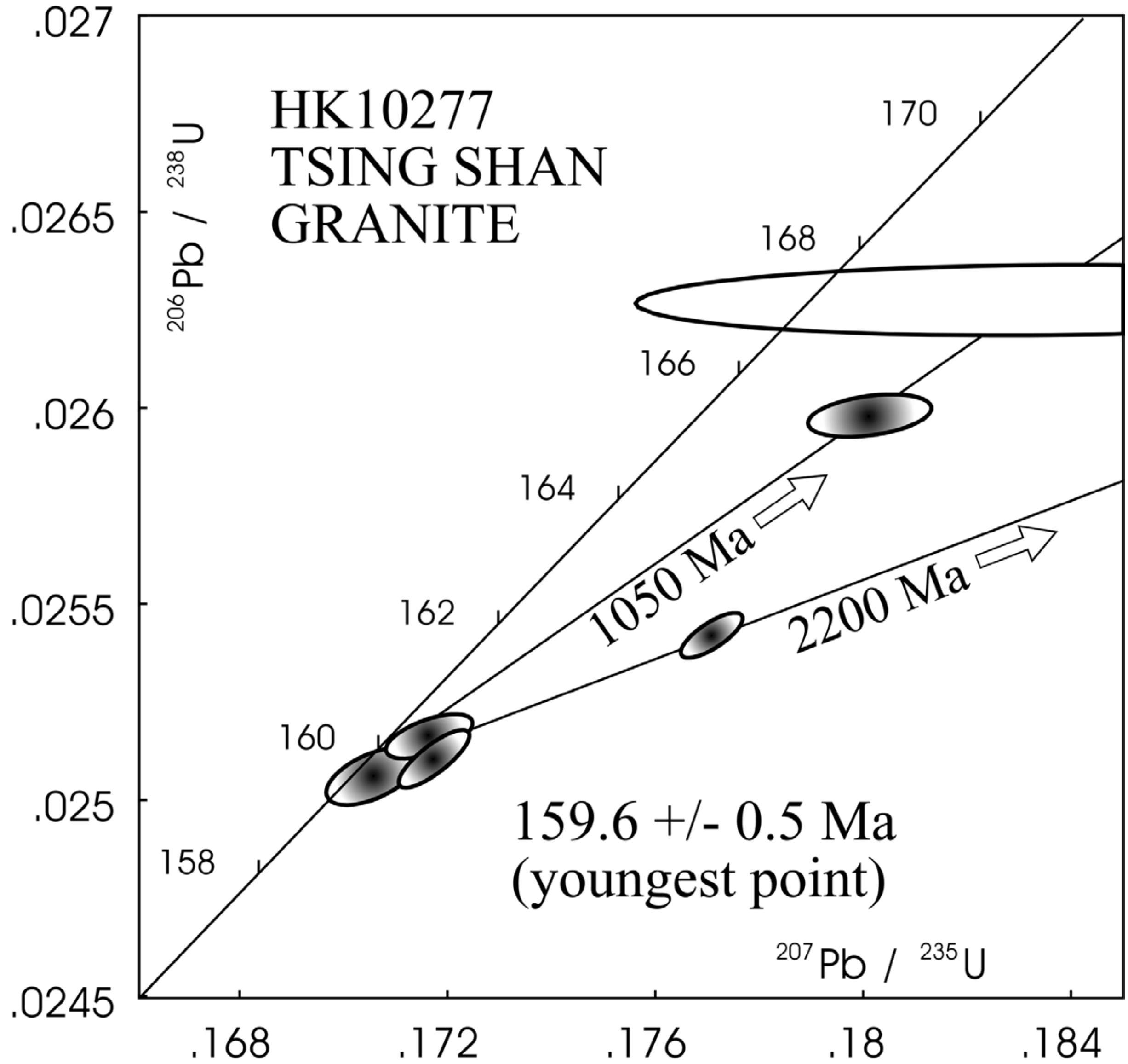

HK8754
TAI LAM GRANITE
159.3 +/- 0.3 Ma
.0254
.0252
.025
.0248
^{206}Pb / ^{238}U
^{207}Pb / ^{235}U
.169
.17
.171
.172
158
159
160
161

Figure 1



HK8758
LANTAU
QUARTZ SYENITE
140.4 +/- 0.3 Ma
146
144
142
140
138
136
134
.023
.0225
.022
.0215
.021
^{206}Pb / ^{238}U
^{207}Pb / ^{235}U
.14
.144
.148
.152

Figure 2



HK10277
TSING SHAN
GRANITE
^{206}Pb / ^{238}U
^{207}Pb / ^{235}U
.027
.0265
.026
.0255
.025
.0245
.168
.172
.176
.18
.184
170
168
166
164
162
160
158
1050 Ma
2200 Ma
159.6 +/- 0.5 Ma
(youngest point)

Figure 3

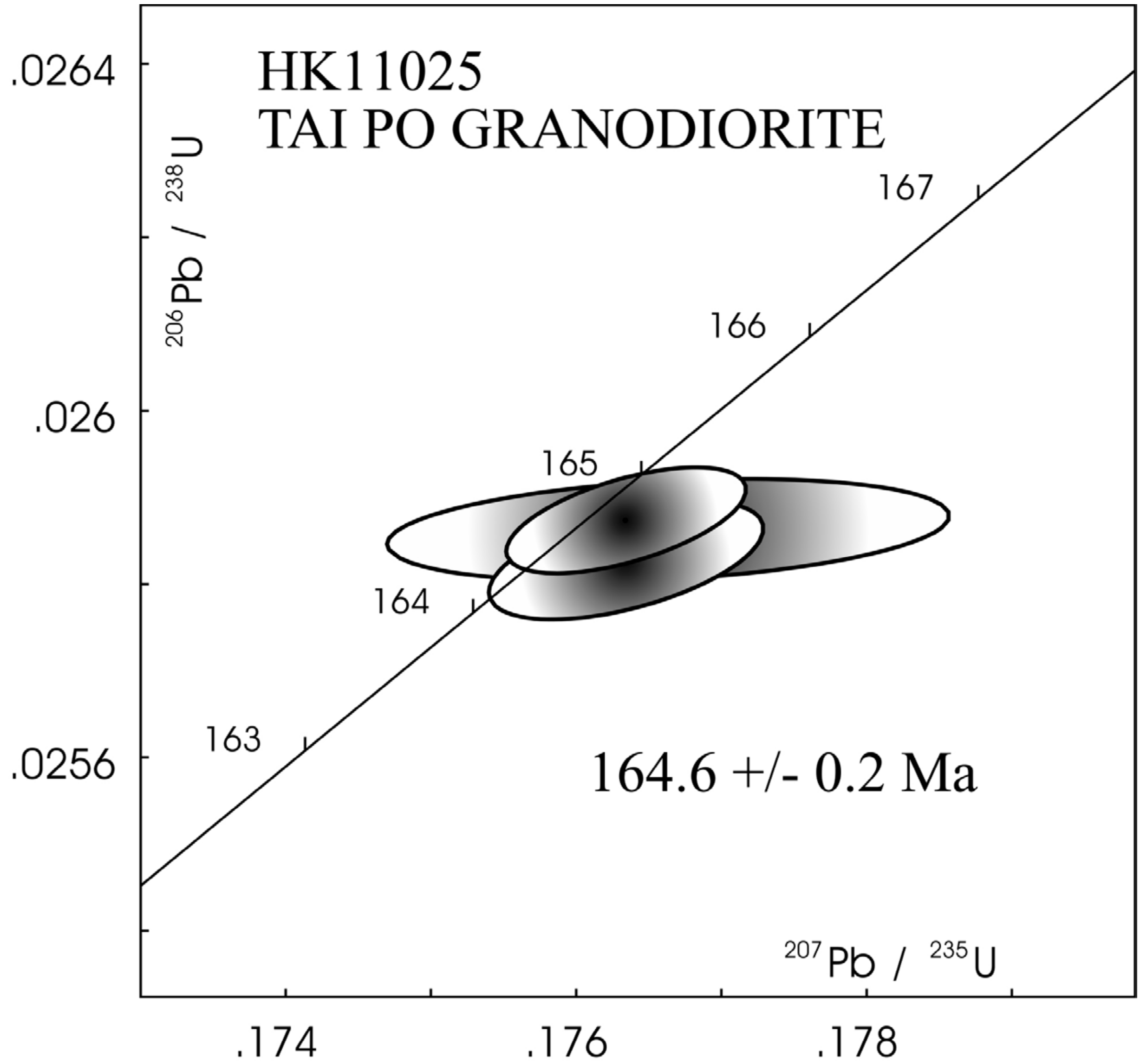

HK11025
TAI PO GRANODIORITE
164.6 +/- 0.2 Ma
167
166
165
164
163
.0264
.026
.0256
^{206}Pb / ^{238}U
^{207}Pb / ^{235}U
.174
.176
.178

Figure 4A

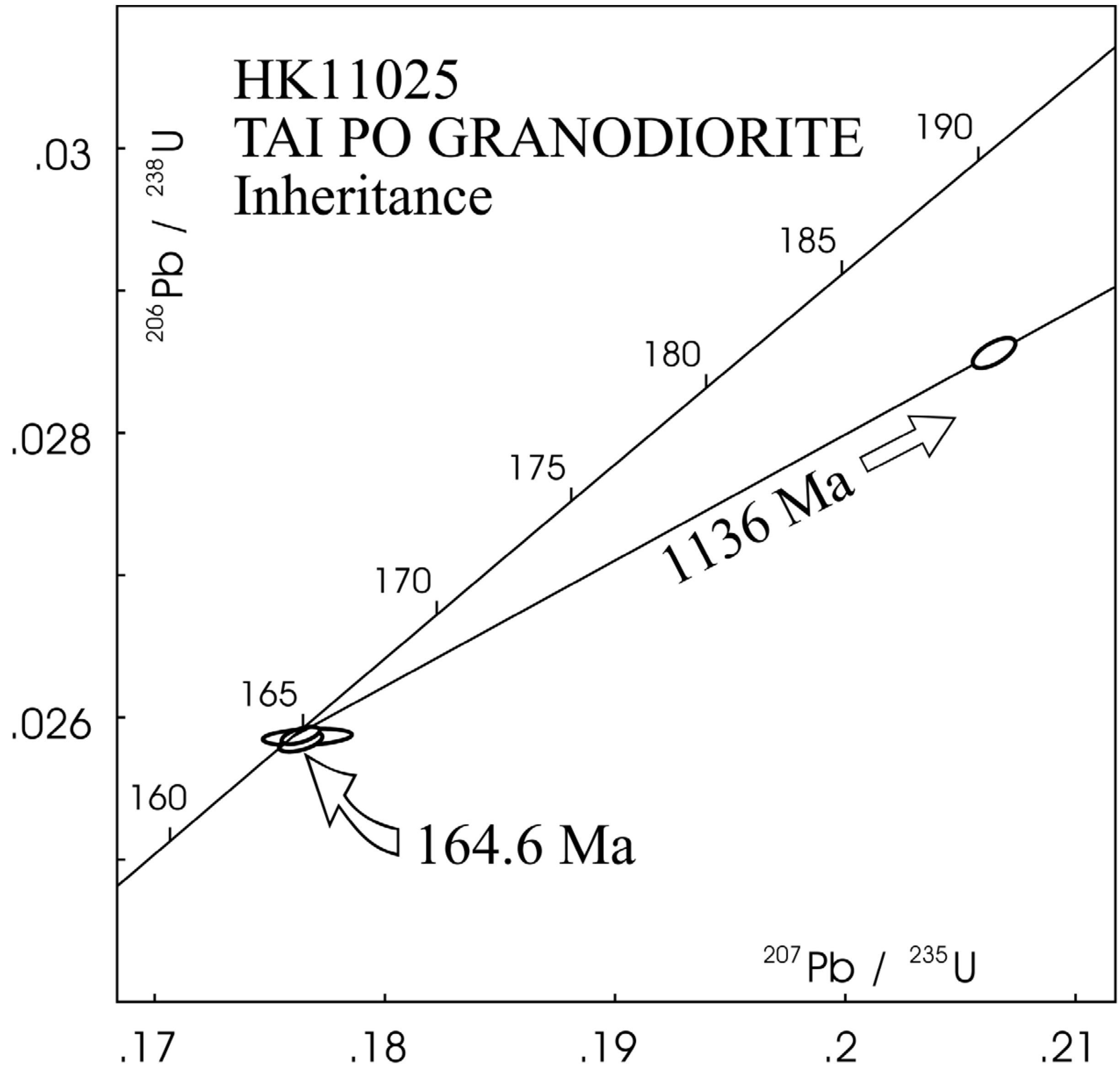

HK11025
TAI PO GRANODIORITE
Inheritance
190
185
180
175
170
165
160
1136 Ma
164.6 Ma
.03
.028
.026
206Pb / 238U
207Pb / 235U
.17
.18
.19
.2
.21

Figure 4B

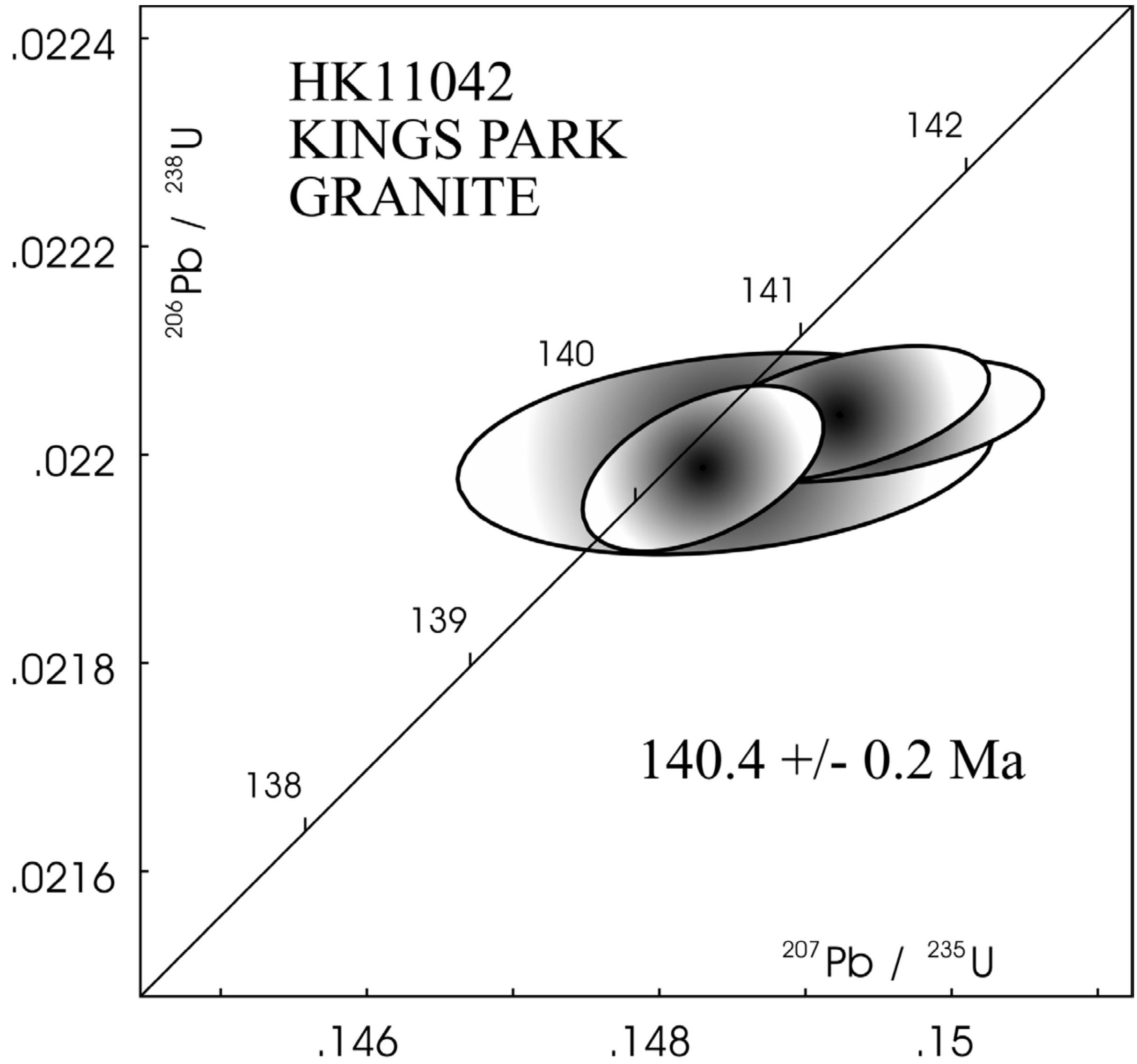

.0224
.0222
.022
.0218
.0216
^{206}Pb / ^{238}U
HK11042
KINGS PARK
GRANITE
142
141
140
139
138
140.4 +/- 0.2 Ma
^{207}Pb / ^{235}U
.146
.148
.15

Figure 5

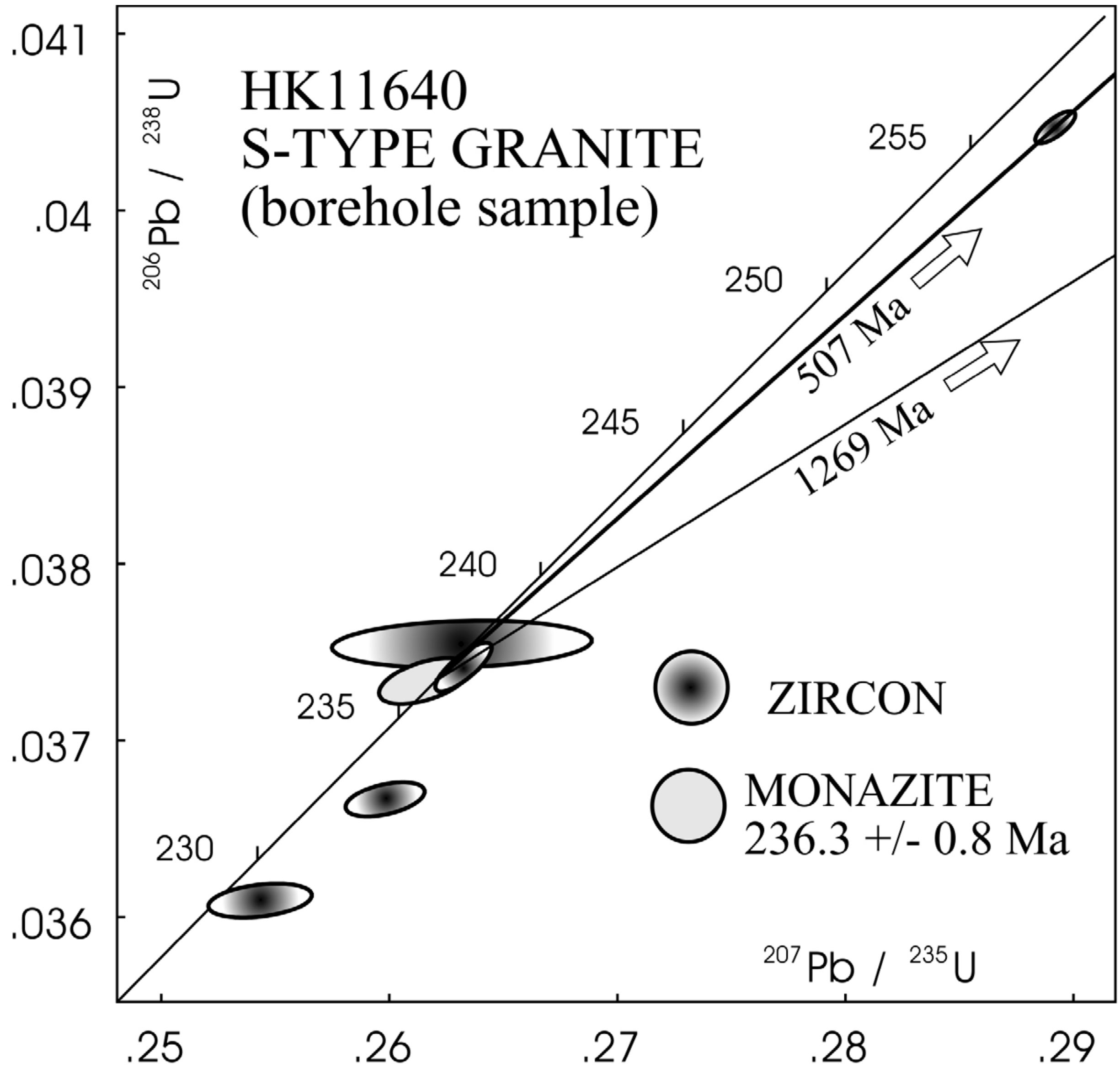

.041
.04
.039
.038
.037
.036
^{206}Pb / ^{238}U
HK11640
S-TYPE GRANITE
(borehole sample)
255
250
245
240
235
230
507 Ma
1269 Ma
ZIRCON
MONAZITE
236.3 +/- 0.8 Ma
^{207}Pb / ^{235}U
.25
.26
.27
.28
.29

Figure 6A

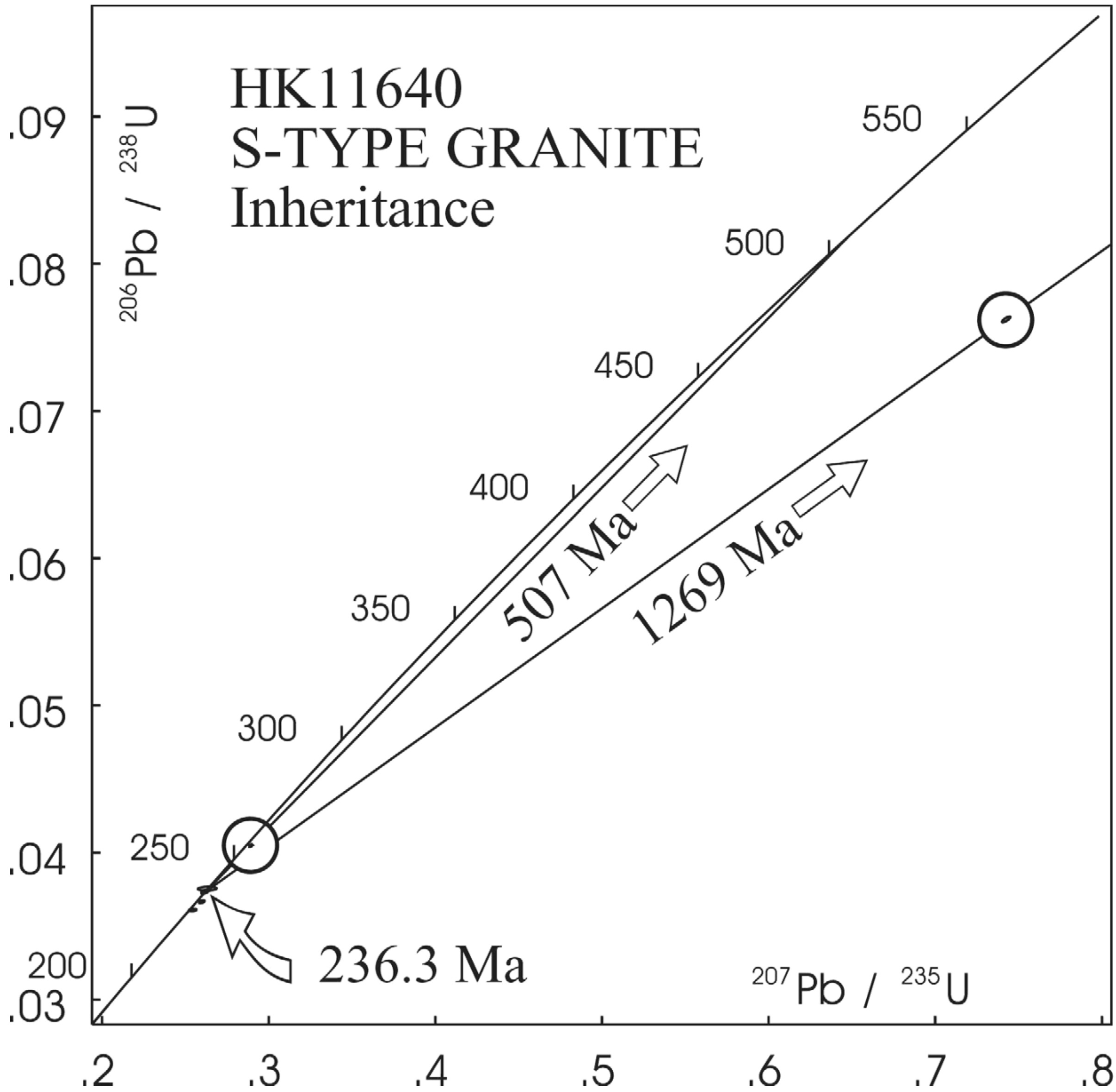

HK11640
S-TYPE GRANITE
Inheritance
.09
.08
.07
.06
.05
.04
.03
^{206}Pb / ^{238}U
550
500
450
400
350
300
250
200
507 Ma
1269 Ma
236.3 Ma
^{207}Pb / ^{235}U
.2
.3
.4
.5
.6
.7
.8

Figure 6B

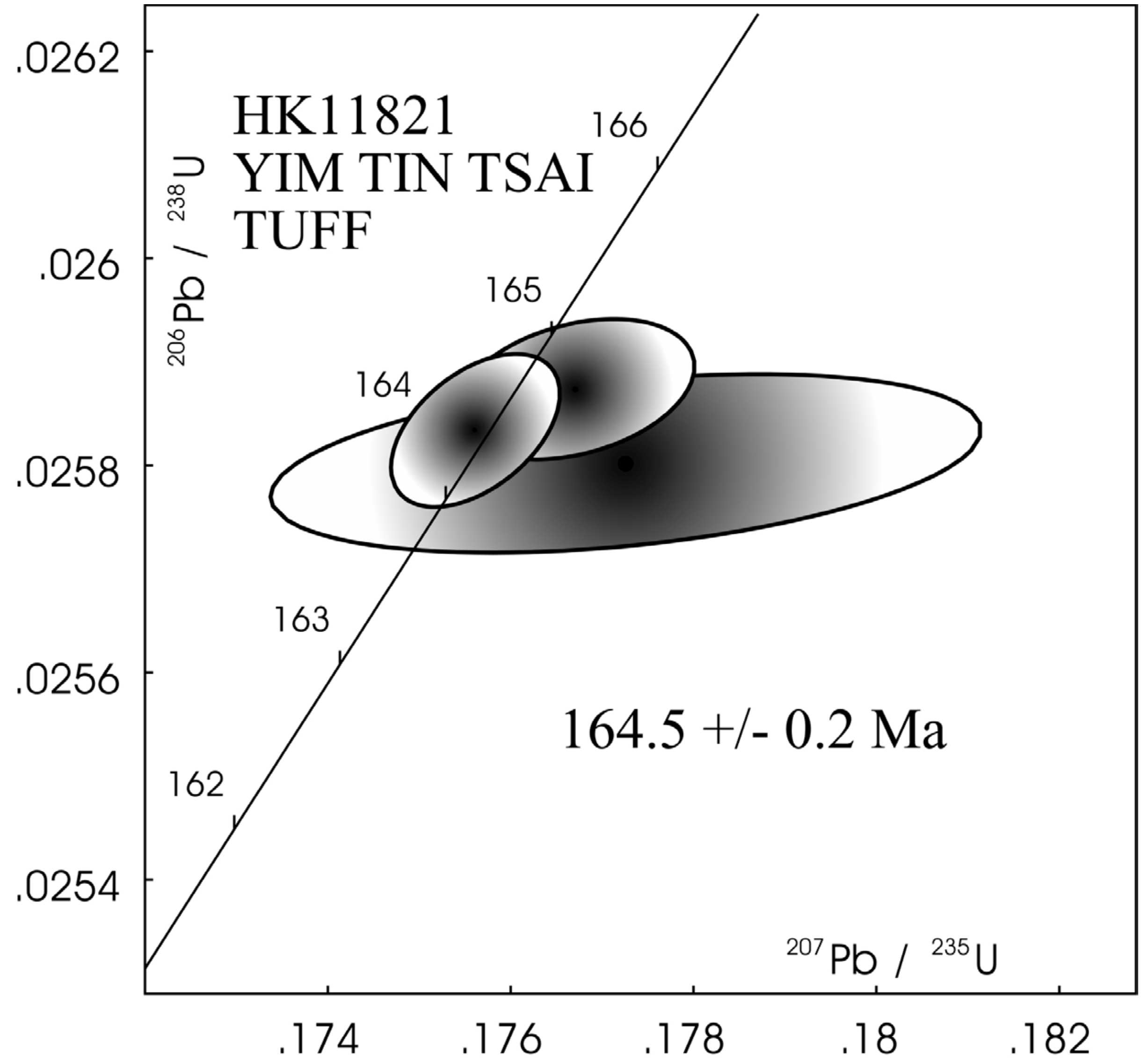

HK11821
YIM TIN TSAI
TUFF
164.5 +/- 0.2 Ma
.0262
.026
.0258
.0256
.0254
166
165
164
163
162
.174
.176
.178
.18
.182
206Pb / 238U
207Pb / 235U

Figure 7A

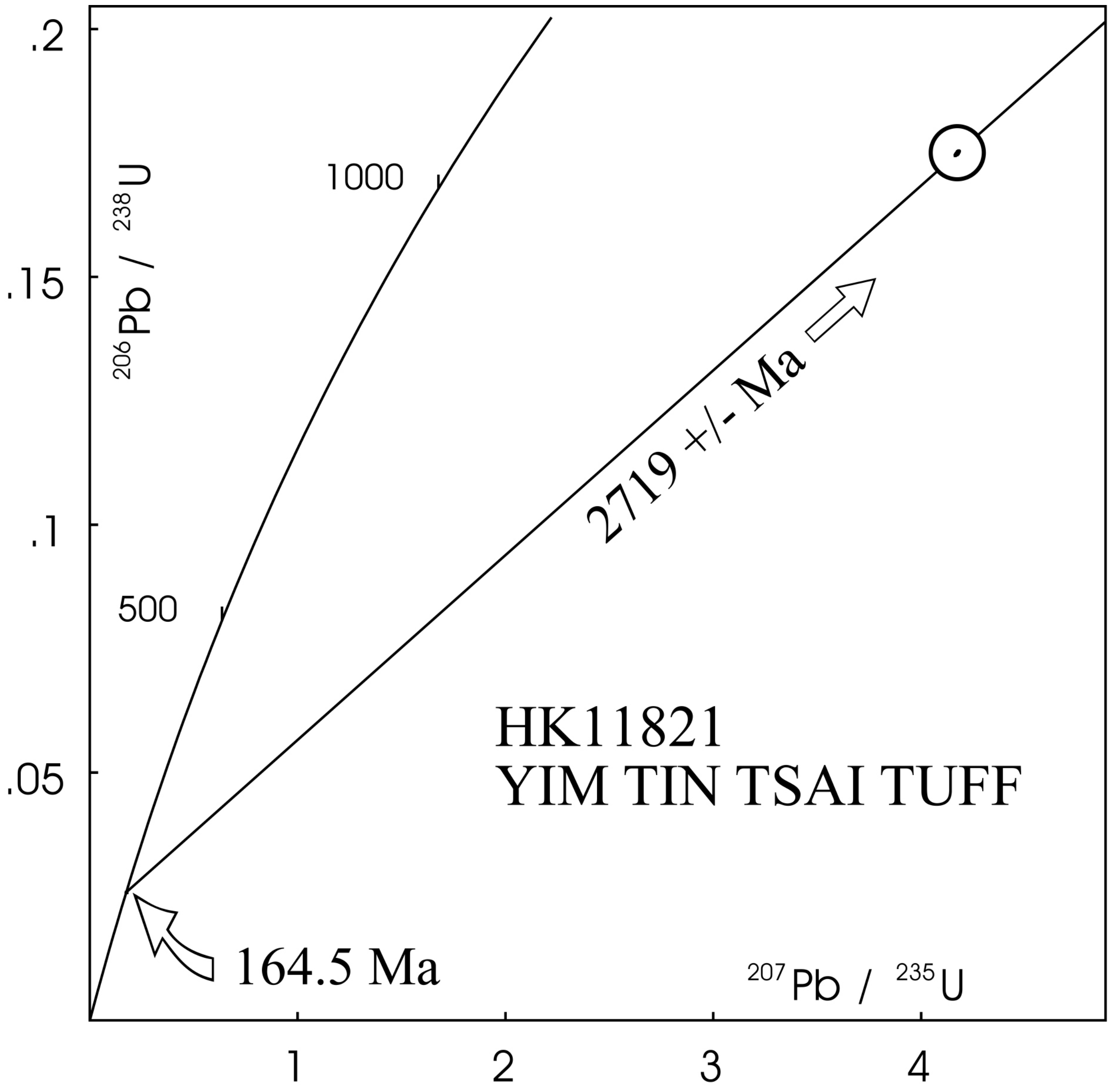

.2
.15
.1
.05
206Pb / 238U
1000
500
2719 +/- Ma
HK11821
YIM TIN TSAI TUFF
164.5 Ma
207Pb / 235U
1
2
3
4

Figure 7B

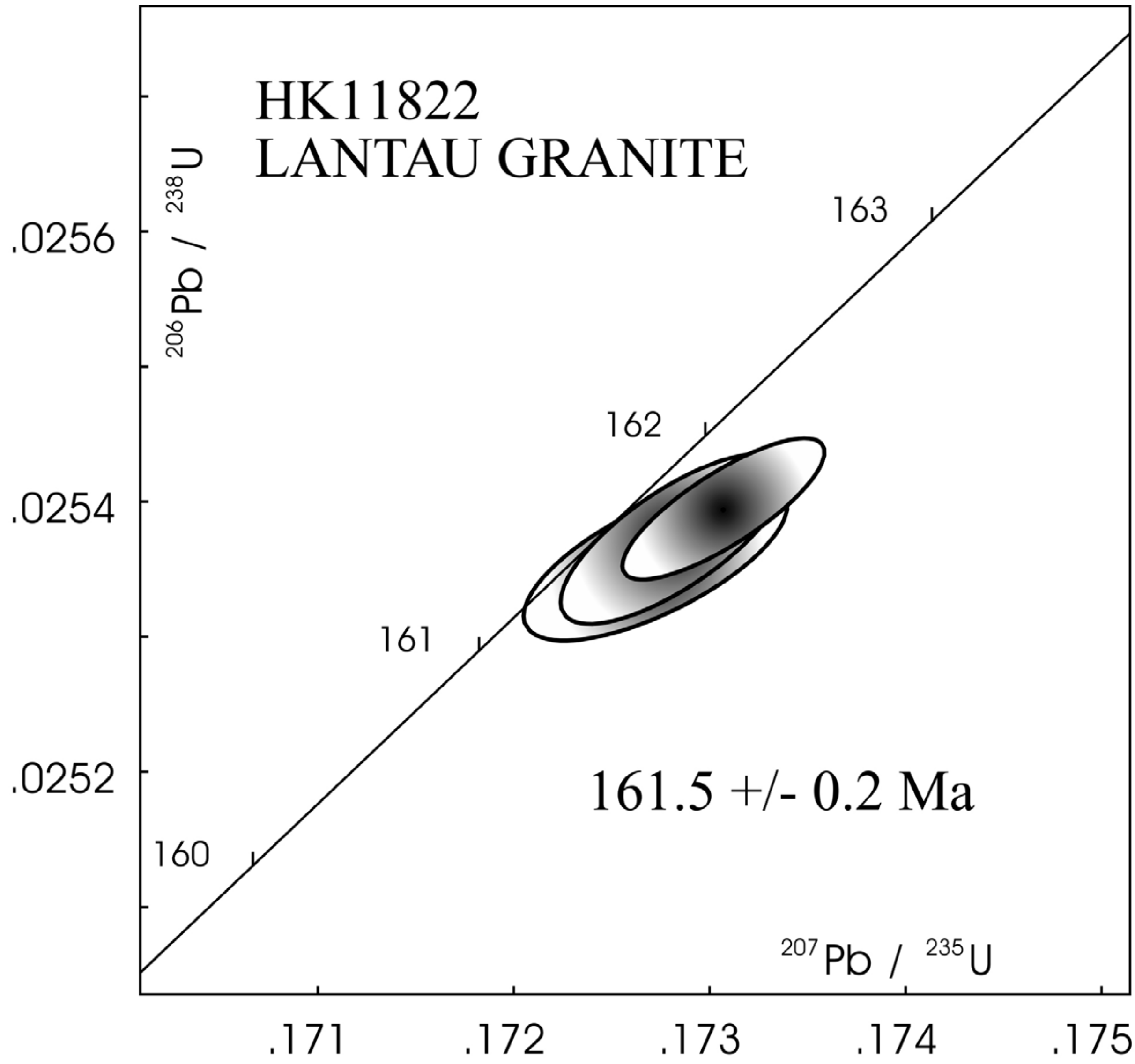

HK11822
LANTAU GRANITE
.0256
.0254
.0252
206Pb / 238U
163
162
161
160
161.5 +/- 0.2 Ma
207Pb / 235U
.171
.172
.173
.174
.175

Figure 8A

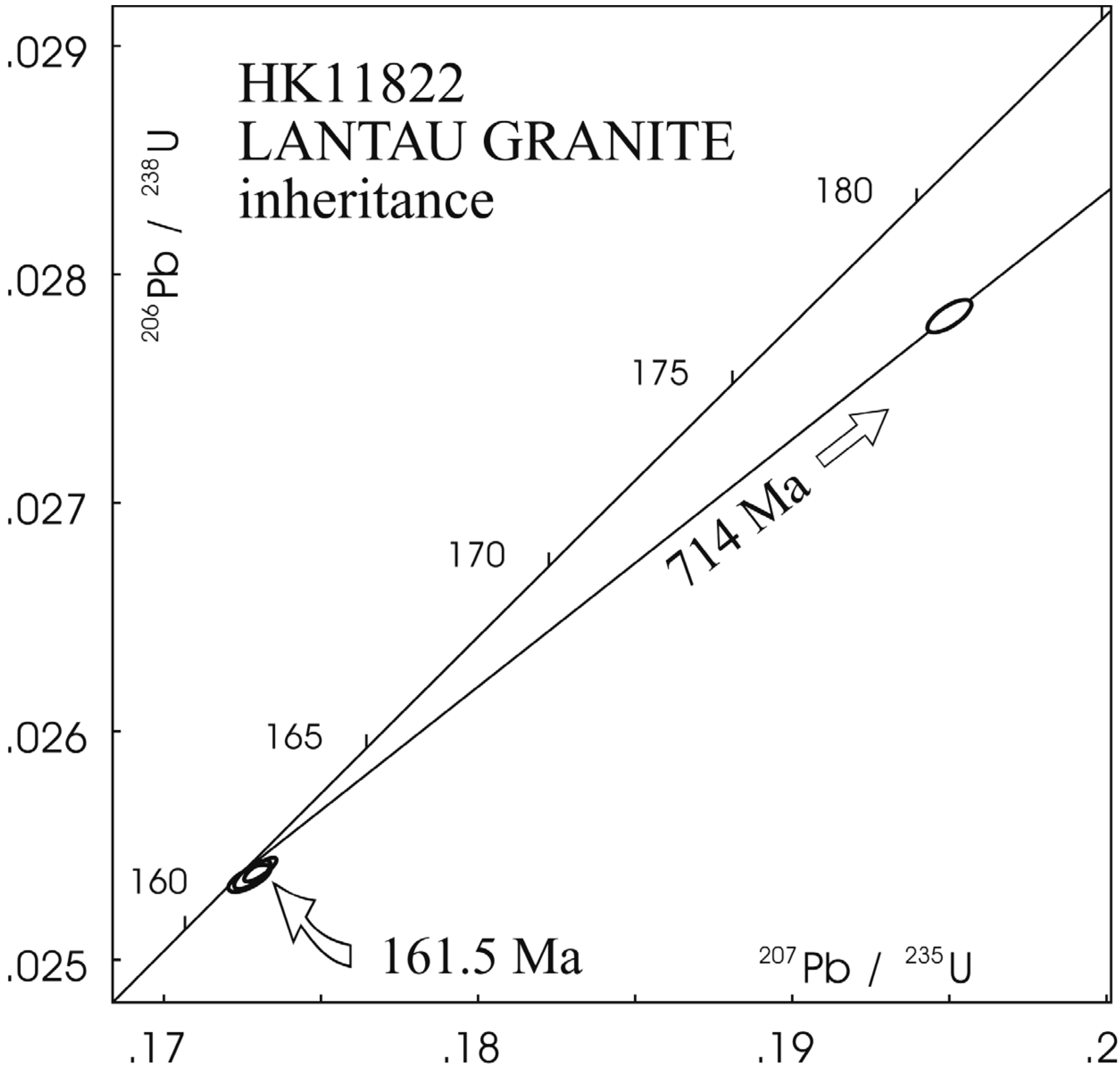

HK11822
LANTAU GRANITE
inheritance
^{206}Pb / ^{238}U
^{207}Pb / ^{235}U
.029
.028
.027
.026
.025
.17
.18
.19
.2
160
165
170
175
180
161.5 Ma
714 Ma

Figure 8B

U-PB GEOCHRONOLOGY OF ZIRCON FROM PLUTONIC AND VOLCANIC ROCKS IN HONG KONG PHASE 2

JULY 10, 1996

DONALD W. DAVIS
GEOLOGY DEPT.
ROYAL ONTARIO MUSEUM
100 QUEEN'S PARK
TORONTO, ONTARIO
M5S 2C6

1. SAMPLES

Twelve samples were received for U-Pb geochronology and are listed below. Descriptions are based on examination of hand samples.

1) HK8353 Chi Ma Wan Pluton (biotite-granitoid)
2) HK10058 Chek Lap Kok Pluton (leuco-granitoid)
3) HK11052 Lantau Formation (quartz-porphyry rhyolite)
4) HK11831 Lantau Dike (felsic porphyry)
5) HK11832 Long Harbour Formation (quartz-feldspar porphyry)
6) HK11834 Clearwater Bay Formation (dark fine-grained feldspar porphyry)
7) HK11835 Sai Kung Formation (grey quartz-feldspar porphyry)
8) HK11836 Silverstrand Formation (quartz-porphyry rhyolite)
9) HK11837 Tai Mo Shan Formation (quartz-feldspar porphyry)
10) HK11838 Needle Hill Pluton (pink altered granitoid)
11) HK11839 Sha Tin Formation (biotite-amphibole granitoid)
12) HK11840 Ap Lei Chau Formation (grey fine-grained rhyolite/dacite)
13) HK12001 (quartz-feldspar porphyry, small reddish feldspar)
14) HK12003 (quartz-feldspar porphyry, phenocrysts up to 1 cm)

2. ANALYTICAL METHODS

Sample crushing was with a jaw crusher followed by a disk mill. Samples were 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 to be usually accurate to about ± 30%. This affects only U concentrations, not age information, which depends on isotopic ratio measurements (Table 1).

Zircon was dissolved using HF in teflon bombs at 200ºC, 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.

3. RESULTS

All samples yielded zircon, in varying abundance. Zircon populations are generally quite fresh due to the young age and generally low U concentrations, so a high proportion of the grains could be analysed. Crack-free zircons without evidence of cores or alteration were selected for abrasion.

Most of the zircon populations show similar characteristics. Exceptions are noted below. Zircon crystals are generally colourless, euhedral, doubly-terminated prisms of varying length. Low-order crystal faces are well-developed and most grains have an abundance of inclusions, including amorphous melt inclusions, apatite rods and sulphide inclusions (Plate 1).

Because of depletion of the shorter half-life ^{235}U isotope, there is much less ^{207}Pb than ^{206}Pb for relatively young samples. For Mesozoic and younger samples, $^{206}Pb/^{238}U$ ages are much more precise and reliable than $^{207}Pb/^{235}U$ ages, and $^{207}Pb/^{206}Pb$ ages are quite imprecise because the concordia curve is nearly parallel to a line through the origin. Therefore, ages for these samples are calculated as $^{206}Pb/^{238}U$ ages. $^{206}Pb/^{238}U$ ages are sensitive to secondary Pb loss, but 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).

Slight to moderate amounts of inheritance are present in many of the samples, probably due to the presence of xenocrysts or invisible cores. The probability of accidentally including an inherited zircon increases with the number of grains picked for a fraction. Because of the low U concentrations of most of the grains, single grain dating could only be carried out on exceptionally large crystals and most 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. This probably accounts for common Pb values in many of the samples that are sveral picograms higher than normal lab blanks (0.5 - 2 pg). This small amount of extra common Pb has a negligible effect on the $^{206}Pb/^{238}U$ age precision. Common Pb corrections are made assuming an isotopic composition similar to laboratory blank. For these young samples, this is effectively the same as the Stacey and Kramers (1975) value, which represents a crustal average. Concordia coordinates and ages in Table 1 are corrected for fractionation, blank and spike. $^{206}Pb/^{204}Pb$ values are corrected for fractionation and spike.

The plotted data, as well as the ages in Tables 1 and 2, 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. The concordia coordinates in Table 1 are quoted as measured values, uncorrected for assumed disequilibrium. Th/U is calculated from the measured $^{208}Pb/^{206}Pb$ ratio and $^{207}Pb/^{206}Pb$ age.

Ages, errors and probabilities of fit are calculated from the Davis (1982) program, modified for fitting $^{206}Pb/^{238}U$ data. U decay constants are from Jaffey et al. (1971). A summary of results is given in Table 2. 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. Errors are quoted at the 95% confidence level in the text and Table 2. Errors in Table 1 are quoted as 1σ. Error ellipses are given at 2σ on figures 1 to 15. Detailed results of mass spectrometer outputs and data reduction are included in disk and photocopy form with this report.

3.1 HK8353 Chi Ma Wan Pluton

This granitoid rock contains abundant zircon and some molybdenite. The zircon typically contains large melt inclusions and rare opaque inclusions. Analysis of 3 fractions with inclusions produced concordant data points, but the ages of the points disagree (Fig. 1A). This probably indicates that invisible cores of mid-Phanerozoic age are present in the zircons. The youngest data point gives an age of 143.7 ± 0.3 Ma, which can be considered an older age constraint on on crystallization of the rock. One fraction of monazite gave a data point (corrected for ^{230}Th disequilibrium) with a $^{206}Pb/^{238}U$ age of 108.8 ± 0.5 Ma (Fig. 1B). ^{230}Th disequilibrium correction for this data point is small (0.14 Ma) because of the low (relative to values typical of monazite) Th/U ratio. This fraction may be affected by secondary Pb loss because of its high U concentration (Table 1), so the age is probably a minimum estimate for the rock. The $^{207}Pb/^{206}Pb$ age of 144 ± 5 Ma agrees with the $^{206}Pb/^{238}U$ ages of the younger data points, suggesting that these are probably close to the age of crystallization. A multigrain fraction, which contained inclusion-free zircons, is strongly affected by inheritance (Fig. 1C). The line through this data point and 143.7 Ma has an upper concordia intercept close to 1870 Ma, the age obtained from a xenocryst in HK11837 (see below).

3.2 HK10058 Chek Lap Kok Pluton

Zircon from this leuco-granitoid rock is sparse and fine grained. The crystals have an unusual appearance, consisting of brownish to colourless grains and fragments. Many examples of colourless, rounded zircon overgrown by brown zircon mantles can be seen (Plate 2). Two analyses of the brown euhedral zircon showed an extrordinarily high U concentration, which allowed measurement of precise ages on very small fractions. Analysis of a fraction of colourless euhedral zircon with melt inclusions gives a data point that agrees with one data point from the brown zircon. The other data point is slightly younger and is from a fraction that contained cracked grains. This may be affected by slight secondary Pb loss. The two data points that agree define an age of 160.4 ± 0.3 Ma (72% probability of fit), which is considered the best estimate for crystallization of the rock. A fourth analysis from a pinkish, rounded zircon, probably a core, produced a slightly older data point (Fig. 2).

3.3 HK11052 Lantau Formation

This greenish quartz-phyric rhyolite contains abundant zircon, as well as rare grains of red rutile. Data points from three zircon fractions are concordant and define an age of 146.6 ± 0.2 Ma (17% probability of fit). The relatively low probability of fit may result from too small estimates of analytical error, or slight inheritance may have affected at least one of the data points.

3.4 HK11831 Lantau Dike

This K-feldspar-amphibole porphyry contains abundant zircon and a small amount of molybdenite. Three zircon fractions gave concordant data points defining an age of 146.5 ± 0.2 Ma (79% probability of fit). A fourth concordant data point, from a fraction of inclusion-free zircons, is distinctly older, with an age of 149.5 ± 0.4 Ma (Fig. 4). Inheritance in dikes is not unusual since they occasionally entrain fragments of wall rock. Fine-grained dolerite-like inclusions were seen in hand specimen and two rounded frosted zircons, which may be xenocrysts, were seen during picking. The age of the inherited component is likely mid-Phanerozoic, since the older data point is concordant.

3.5 HK11832 Long Harbour Formation

This quartz-feldspar porphyry contains abundant phenocrysts, as well as fine-grained felsic and mafic fragments. It yielded abundant euhdral zircon. Rare rounded frosted, colourless to pink zircons were also seen, and were avoided during picking. Four zircon fractions gave concordant or near-concordant data points with overlapping $^{206}Pb/^{238}U$ ages (Fig. 5). These define an average age of 142.8 ± 0.2 Ma (99% probability of fit).

3.6 HK11834 Clearwater Bay Formation

This fine-grained feldspar porphyry is quite dark in colour making it appear mafic or intermediate in composition. The sample yielded a small amount of relatively fine, but fresh, zircon. Four fractions gave concordant, overlapping data points that define an age of 140.7 ± 0.2 Ma (79% probability of fit, Fig. 6).

3.7 HK11835 Sai Kung Formation

This medium-grained grey porphyry yielded abundant zircon. Low order crystal faces predominate, but there is incipient development of secondary faces along prism corners and on tips. Three zircon fractions produced concordant overlapping data points with an age of 142.7 ± 0.2 Ma (94% probability of fit). A fourth fraction, consisting of zircon with few inclusions, gave an older, discordant data point. Although this data point is too close to the concordant cluster to precisely define an upper intercept age, the age of the inherited component is clearly Archean. The point fits on a 3000 Ma mixing line with the concordant data points (Fig. 7).

3.8 HK11836 Silverstrand Formation

This greenish quartz-porphyry rhyolite is similar in appearance to HK11052, but yielded only sparse zircon. Rare rounded, frosted pink grains were seen during picking. Four fractions of euhedral, colourless zircons give concordant data points (Fig. 8). Three of the data overlap, defining an age of 142.5 ± 0.3 Ma (78% probability of fit). A fourth fraction gives an older age of 146.4 ± 0.4 Ma. This was a single zircon grain with a cluster of clear inclusions in the middle, which may mark the presence of a recrystallized older core from a mid-Phanerozoic aged rock.

3.9 HK11837 Tai Mo Shan Formation

Abundant zircon was found in this phenocryst-rich porphyry. Rare, violet-pink and colourless, rounded and multi-facetted zircons were seen during picking (Plate 3). A single euhedral zircon produced a concordant data point with an age of 164.5 ± 0.7 Ma, while three other multi-grain fractions of euhedral zircons with melt inclusions gave slightly older discordant data points (Fig. 9A). Analysis of one pink, rounded zircon gave a concordant data point with an age of 1872 ± 3 Ma, confirming that this grain is a Precambrian xenocryst (Fig. 9B). Since there has been negligible resetting of the grain, it was likely incorporated into the porphyry by wall rock contamination, and probably did not originate in the zone of melting from which the porphyry was derived.

The data from the other euhedral fractions show diverse ages of inheritance. These data points lie on separate mixing lines with upper intercept ages of 1000 Ma, 1870 Ma and 3000 Ma. Since the fractions contain several grains, some of the upper intercept ages may represent meaningless averages of different older components. Since these fractions contain only a few grains each, the small degree of inheritance indicates that some of the grains likely contain small cores. If a Precambrian xenocryst were present in any of these fractions, they would probably have showed much older ages beacuse very old zircons have a relatively high radiogenic Pb content and would strongly affect the average age.

3.10 HK11838 Needle Hill Pluton

This granitoid rock yielded relatively sparse zircon, and the grains are generally fine, brownish, and cracked or altered. The rock also appears to have monazite. Four fractions of fresh euhedral zircon were separated and analysed. Three fractions consisting of zircons with abundant melt inclusions produced overlapping, concordant data points that define an age of 146.4 ± 0.2 Ma (72% probability of fit, Fig. 10). A fourth concordant data point, from two grains with few inclusions, gives an older age of 149.9 ± 0.5 Ma.

3.11 HK11839 Sha Tin Pluton

This biotite-amphibole granitoid is mineralogically similar to HK11831. It also yielded abundant zircon, with a similar age pattern. Three fractions produced concordant overlapping data apoints with an age of 146.2 ± 0.2 Ma (81% probability of fit, Fig. 11A). A single-grain fraction produced an older near-concordant data point with an age of

153.8 ± 0.4 Ma (Fig. 11B).

3.12 HK11840 Ap Lei Chau Formation

This fine-grained felsic rock yielded only a small amount of zircon, but a high proportion of it is fresh. Two fractions produced concordant, overlapping data points, defining an age of 142.7 ± 0.2 Ma (100% probability of fit, Fig. 12A). A third, multigrain fraction produced a much older discordant data point (Fig. 12B). This point, along with the concordant points, defines a line with an upper concordia intercept age of 2426 Ma. It is likely that at least one of the zircons in this fraction was an Archean xenocryst or contained a large core.

3.13 HK12001

This quartz-feldspar porphyry yielded a small amount of relatively small euhedral stubby reddish zircons. Three fractions gave overlapping near-concordant data points, defining an age of 140.9 ± 0.2 Ma (88% probability of fit, Fig. 13).

3.14 HK12003

This porphyry yielded abundant zircon with typical euhedral, stubby to elongate morphology. Two data points overlap near concordia and define an age of 146.3 ± 0.3 Ma (92% probability of fit, Fig. 14). A third, near concordant data point is older, with an age of 153.2 ± 0.5 Ma.

4. DISCUSSION

As mentioned above, zircon populations from most of the samples show similar characteristics that include low-order crystal faces and an abundance of inclusions (Plate 1 and 2). Although possible relationships between zircon morphology and tectonic environment have never been systematically studied, the features of these zircons are similar for zircons from rift environments, such as the North American Midcontinent Rift (Davis and Green submitted). In contrast, zircons from calc-alkaline felsic rocks that crystallized in arc environments generally show stronger development of high order crystal faces (multifacetted) and have fewer inclusions.

Combining U-Pb results that are thought to be unaffected by inheritance (Fig. 15) shows a distinct clustering from different rocks with mutually unresolvable ages. The oldest cluster contains five rocks that together define an age of 146.4 ± 0.1 Ma with a 43% probability of fit. A younger cluster containing four rocks defines an age of 142.7 ± 0.1 Ma with a 98% probability of fit. The youngest cluster has two rocks defining an age of 140.8 ± 0.1 Ma (72% probability of fit).

Two rocks from the Phase 1 project, HK8758 and HK11042, gave ages of 140.4 ± 0.2 Ma and are close to, but probably a few hundred thousand years younger than, the youngest rocks in this study. The majority of the rocks dated in the Phase 1 project were ca. 160 Ma in age. The two oldest agreed at about 164.5 ± 0.2 Ma and may be the same age as HK11837, which had only one concordant data point at this age. Other events at 159.3 ± 0.3 Ma (HK8754), 160.4 ± 0.3 Ma (HK11058) and 161.5 ± 0.2 Ma (HK11822) are close to each other but analytically distinct in age.

None of the ca. 160 Ma rocks show evidence of concordant data points affected by inheritance, strongly suggesting that the concordant inheritance affecting the ca. 140-150 Ma rocks is derived from the ca. 160 Ma rocks. This provides evidence in support of the validity of ages based on single concordant data points from the ca. 160 Ma suite (i.e. HK11837 and HK10277). HK11640 gives a most probable age estimate of 236 ± 1 Ma and seems to represent a still older S-type granite-forming event. Precambrian inheritance affects both younger and older suites of rocks and shows a wide range of ages back to 3000 Ma. This is likely due to both xenocrysts and invisible cores derived from older rocks. Some of the samples contain pink, rounded xenocrysts, one of which was concordant at 1872 Ma. The only sample with obvious core-overgrowth relationships (HK10058) showed only minimal inheritance (probably Precambrian) from an analysed core. These older ages likely reflect ages of basement rocks, possibly including detrital zircons from underlying sediments.

Precise data points in this study, as well as in the Phase 1 study, generally lie slightly to the right of or below the concordia curve. The presence of residual inheritance 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. 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 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 data point to the right (231-protactinium has a 32,000 yr 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 $^{206}Pb/^{238}U$ ages.

5. REFERENCES

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Table 1 - U-Pb Isotopic Data on Abraded Zircon and Monazite from Hong Kong Rocks - Phase 2 (Sheet 1 of 4)

	Fraction Analysed	Weight (mg)	U (ppm)	Th/U	Pbcom (pg)	206Pb/204Pb	206Pb/238U	207Pb/235U	206/238 Age (Ma)	1 sig	207/235 Age (Ma)	1 sig	207/206 Age (Ma)	1 sig	Disc. (%)	Th (ppm)
	HK8353 CHI MA WAN PLUTON															
1	15 ZR, ABUND INCL	0.070	259	0.56	5.2	5010	0.022534	0.15226	143.72	0.17	143.88	0.20	146.5	2.0	1.9	145.48
2	1 ZR, MELT INCL	0.010	94	0.69	6.1	244	0.022673	0.15393	144.62	0.12	145.38	1.45	157.8	22	7.5	64.76
3	7 ZR, FEW INCL	0.030	273	0.55	1.8	6712	0.022803	0.15422	145.44	0.17	145.63	0.24	148.8	2.9	2.3	150.22
4	15 ZR	0.070	196	0.13	2.5	10540	0.030273	0.27753	192.36	0.26	248.69	0.35	820.7	1.6	78	26.27
5	1 MONAZITE FRAG	0.002	36000	9.62	81.8	988	0.01705	0.11486	108.83	0.23	110.40	0.29	144.3	4.6	25	346470.43
	HK10058 CHEK LAP KOK PLUTON															
6	1 ZR, ABUND MELT INCL	0.008	362	0.44	1.5	3066	0.025178	0.17142	160.39	0.20	160.65	0.41	164.4	5.8	2.5	161.05
7	1 BR MANTLE FRAG	0.003	6206	0.27	1.3	22409	0.025194	0.17149	160.50	0.23	160.72	0.24	163.9	1.5	2.1	1659.51
8	1 BR CK FRAG	0.001	3779	0.23	1.0	6307	0.025112	0.17116	159.98	0.24	160.42	0.29	166.9	3.5	4.2	851.96
9	1 PINK CORE, NO INCL	0.002	1133	0.92	2.9	1277	0.025288	0.17290	161.06	0.09	161.93	0.31	174.8	4.1	7.8	1039.45
	HK11052 LANTAU FORMATION															
10	2 ZR, ABUND MELT INCL	0.020	131	0.71	3.2	1211	0.022954	0.15585	146.39	0.18	147.06	0.82	157.9	13	7.4	93.82
11	7 ZR, NO INCL	0.020	166	0.71	5.5	913	0.023001	0.15562	146.68	0.18	146.86	1.04	149.8	17	2.1	118.04
12	12 ZR, ABUND INCL	0.060	97	0.68	2.5	3503	0.023032	0.15600	146.88	0.19	147.20	0.33	152.3	4.8	3.6	65.54
	HK11831 LANTAU DIKE															
13	3 ZR, ABUND INCL	0.040	114	0.62	3.6	1908	0.022965	0.15556	146.46	0.20	146.81	0.51	152.5	8.3	4.0	70.55
14	6 ZR, FEW INCL	0.040	76	0.66	1.2	3821	0.022956	0.15549	146.40	0.18	146.75	0.33	152.4	4.6	4.0	50.28
15	9 ZR, MELT & ROD INCL	0.070	64	0.71	3.3	2020	0.022982	0.15591	146.56	0.15	147.12	0.52	156.0	8.3	6.1	45.86
16	8 AB ZR, NO INCL	0.040	106	0.68	1.7	3839	0.023448	0.15908	149.50	0.22	149.90	0.36	156.2	4.7	4.4	72.10

Table 1 - U-Pb Isotopic Data on Abraded Zircon and Monazite from Hong Kong Rocks - Phase 2 (Sheet 2 of 4)

	Fraction Analysed	Weight (mg)	U (ppm)	Th/U	Pbcom (pg)	206Pb 204Pb	206Pb 238U	207Pb 235U	206/238 Age (Ma)	1 sig	207/235 Age (Ma)	1 sig	207/206 Age (Ma)	1 sig	Disc. (%)	Th (ppm)
	HK11832 LONG HARBOUR FORMATION															
17	1 ZR, MELT INCL	0.060	45	0.60	2.1	1844	0.022385	0.15149	142.80	0.15	143.22	0.64	150.2	11	5.0	26.82
18	4 ZR, FEW INCL	0.060	91	0.59	4.1	1918	0.022395	0.15234	142.87	0.20	143.97	0.52	162.2	8.3	12	53.65
19	6 EL ZR, INCL	0.070	94	0.72	3.6	2636	0.022390	0.15127	142.83	0.16	143.03	0.38	146.3	6.1	2.4	67.06
20	7 RND ZR, FEW INCL	0.060	116	0.64	1.6	6460	0.022393	0.15153	142.85	0.20	143.26	0.26	150.1	3.4	4.9	74.08
	HK11834 CLEARWATER BAY FORMATION															
21	10 ZR, FEW INCL	0.015	326	0.58	0.7	9419	0.022048	0.14875	140.68	0.16	140.80	0.22	143.0	2.8	1.6	190.39
22	4 ZR, ROD INCL	0.015	255	0.69	6.8	821	0.022075	0.14896	140.85	0.17	140.99	1.08	143.4	19	1.8	177.06
23	10 ZR, ROD INCL	0.030	185	0.67	1.4	5541	0.022038	0.14882	140.61	0.18	140.87	0.25	145.2	3.2	3.2	124.49
24	17 ZR, FEW ROD INCL	0.030	164	0.69	0.8	8561	0.022056	0.14887	140.73	0.18	140.92	0.22	144.1	2.4	2.8	114.10
	HK11835 SAI KUNG FORMATION															
25	1 ZR, ROD INCL	0.030	131	0.66	1.6	3637	0.022370	0.15085	142.71	0.21	142.66	0.35	141.9	4.9	-0.6	86.33
26	2 ZR, OPAQUE INCL	0.050	98	0.59	0.9	7474	0.022361	0.15127	142.65	0.18	143.03	0.32	149.4	4.6	4.6	57.88
27	8 ZR, MELT INCL	0.080	62	0.72	1.5	4653	0.022375	0.15130	142.73	0.17	143.06	0.28	148.4	3.8	3.9	45.00
28	7 AB ZR, FEW ROD INCL	0.030	202	0.68	1.7	5266	0.022522	0.15576	143.66	0.17	146.98	0.27	200.9	3.5	29	136.86
29	7 ZR, FEW MELT INCL	0.025	127	0.51	1.1	4287	0.022346	0.15099	142.56	0.23	142.79	0.35	146.6	4.9	2.8	64.42
30	7 ZR, ABUND INCL	0.060	118	0.64	3.7	2733	0.022297	0.15076	142.25	0.45	142.58	0.55	148.2	5.8	4.0	75.16
31	1 ZR, ABUND INCL	0.018	127	0.76	1.1	2980	0.022355	0.15147	142.61	0.26	143.21	0.49	153.1	7.1	7.0	97.37

Table 1 - U-Pb Isotopic Data on Abraded Zircon and Monazite from Hong Kong Rocks - Phase 2 (Sheet 3 of 4)

	Fraction Analysed	Weight (mg)	U (ppm)	Th/U	Pbcom (pg)	206Pb/204Pb	206Pb/238U	207Pb/235U	206/238 Age (Ma)	1 sig	207/235 Age (Ma)	1 sig	207/206 Age (Ma)	1 sig	Disc. (%)	Th (ppm)
	HK11836 SILVERSTRAND FORMATION															
32	1 AB ZR, INCL IN CENTRE	0.020	249	0.52	9.6	781	0.022962	0.15562	146.44	0.20	146.86	1.18	153.7	20	4.8	130.86
	HK11837 TAI MO SHAN FORMATION															
33	1 ZR, MELT INCL	0.025	202	0.59	1.2	7143	0.025830	0.17581	164.49	0.36	164.45	0.43	163.9	4.4	-0.3	118.66
34	8 ZR, MELT INCL	0.040	175	0.60	3.8	3091	0.025876	0.17778	164.78	0.21	166.15	0.39	185.7	5.2	11	105.24
35	5 ZR, MELT INCL	0.050	258	0.54	3.2	6756	0.026011	0.17859	165.63	0.24	166.85	0.28	184.2	3.1	10	139.11
36	2 ZR, MELT INCL	0.030	158	0.52	1.6	5004	0.026398	0.18192	168.06	0.23	169.71	0.49	192.9	6.4	13	82.61
37	1 PINK RND ZR	0.003	304	0.28	1.1	17274	0.335870	5.3023	1866.8	3.30	1869.2	1.7	1872.0	1.5	0.3	85.4
	HK11838 NEEDLE HILL PLUTON															
38	9 ZR, ABUND INCL	0.030	230	0.66	1.9	5491	0.022942	0.15540	146.31	0.16	146.67	0.25	152.5	3.2	4.1	152.25
39	1 ZR, ABUND INCL	0.020	161	0.86	4.3	1125	0.022966	0.15584	146.46	0.17	147.06	0.84	156.7	13.9	6.6	137.86
40	1 ZR, ABUND INCL	0.015	162	0.70	2.3	1589	0.022970	0.15561	146.49	0.19	146.85	1.05	152.7	16.9	4.1	113.04
41	2 ZR, FEW INCL	0.020	196	0.63	1.3	4613	0.023510	0.15912	149.89	0.24	149.93	0.34	150.6	4.1	0.5	124.12
	HK11839 SHA TIN PLUTON															
42	7 ZR, FEW INCL	0.060	99	0.69	4.6	1901	0.022947	0.15531	146.34	0.21	146.59	0.52	150.7	8.4	2.9	68.40
43	7 ELONG ZR	0.025	210	0.65	3.5	2221	0.022931	0.15539	146.25	0.17	146.66	0.45	153.4	7.2	4.7	135.73
44	4 ZR, FEW INCL	0.040	65	0.79	1.7	2301	0.022915	0.15518	146.14	0.22	146.47	0.51	151.9	8.0	3.9	51.37
45	1 ZR, ABUND INCL	0.020	188	0.64	1.5	3845	0.024135	0.16417	153.83	0.19	154.35	0.34	162.4	4.6	5.3	120.00

Table 1 - U-Pb Isotopic Data on Abraded Zircon and Monazite from Hong Kong Rocks - Phase 2 (Sheet 4 of 4)

	Fraction Analysed	Weight (mg)	U (ppm)	Th/U	Pbcom (pg)	206Pb / 204Pb	206Pb / 238U	207Pb / 235U	206/238 Age (Ma)	1 sig	207/235 Age (Ma)	1 sig	207/206 Age (Ma)	1 sig	Disc. (%)	Th (ppm)
	HK11840 AP LEI CHAU FORMATION															
46	1 ZR	0.012	190	0.54	2.5	1315	0.022372	0.15124	142.72	0.18	143.01	0.73	147.7	12.3	3.4	102.58
47	7 ZR, MELT INCL	0.050	99	0.62	2.0	3555	0.022372	0.15151	142.72	0.15	143.24	0.32	152.0	4.8	6.2	61.72
48	8 ZR, FEW INCL	0.020	237	0.06	0.8	20115	0.053481	0.84966	335.96	0.77	624.46	1.15	1882.9	1.3	84	14.80
	HK12001															
49	7 ZR, FEW INCL	0.015	897	0.49	7.7	2492	0.02209	0.14936	140.92	0.18	141.35	0.28	148.5	3.6	5.1	441.10
50	4 ZR, ABUND INCL	0.020	672	0.63	5.9	3252	0.02210	0.14920	141.03	0.22	141.20	0.47	144.1	6.9	2.2	425.93
51	6 ZR, INCL	0.020	678	0.58	4.4	4348	0.02208	0.14922	140.88	0.20	141.22	0.23	146.9	2.5	4.1	394.38
	HK12003															
52	6 ZR, FEW INCL	0.020	271	0.83	1.8	4516	0.02294	0.15525	146.29	0.19	146.53	0.28	150.6	3.3	2.9	223.79
53	5 ZR, INCL	0.020	250	0.71	2.8	2671	0.02293	0.15542	146.26	0.25	146.69	0.37	153.5	4.6	4.8	177.52
54	2 ZR, INCL	0.030	515	0.43	7.9	3049	0.02404	0.16335	153.21	0.27	153.63	0.33	160.1	3.1	4.3	219.60

Table 2 - Summary of Ages from Hong Kong Samples - Phase 2

SAMPLE	206Pb/238U Age (Ma)	Probability Of Fit (%)	Number of Points	Inheritance (Ma)
HK8353	less than 143.7 ± 0.3	-	1	>145, ~1870
HK10058	160.4 ± 0.3	72	2	Slight
HK11052	146.6 ± 0.2	17	3	None
HK11831	146.5 ± 0.2	79	3	>149
HK11832	142.8 ± 0.2	99	4	None
HK11834	140.7 ± 0.2	79	4	None
HK11835	142.7 ± 0.2	94	3	~3000
HK11836	142.5 ± 0.3	78	3	>146
HK11837	less than 164.5 ± 0.7	-	1	1872 ± 3 ~1000, ~3000
HK11838	146.4 ± 0.2	72	3	>150
HK11839	146.2 ± 0.2	81	3	>154
HK11840	142.7 ± 0.2	100	2	2426 Ma
HK12001	140.9 ± 0.2	88	3	None
HK12003	146.3 ± 0.3	92	2	>153

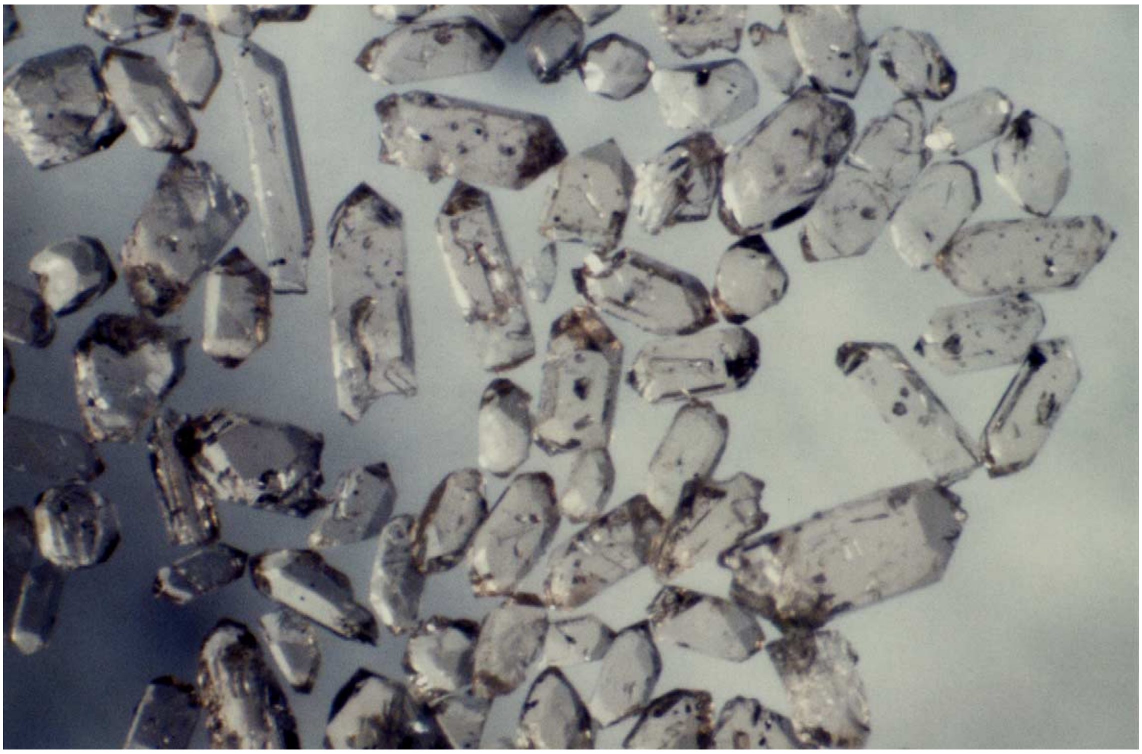


Plate 1

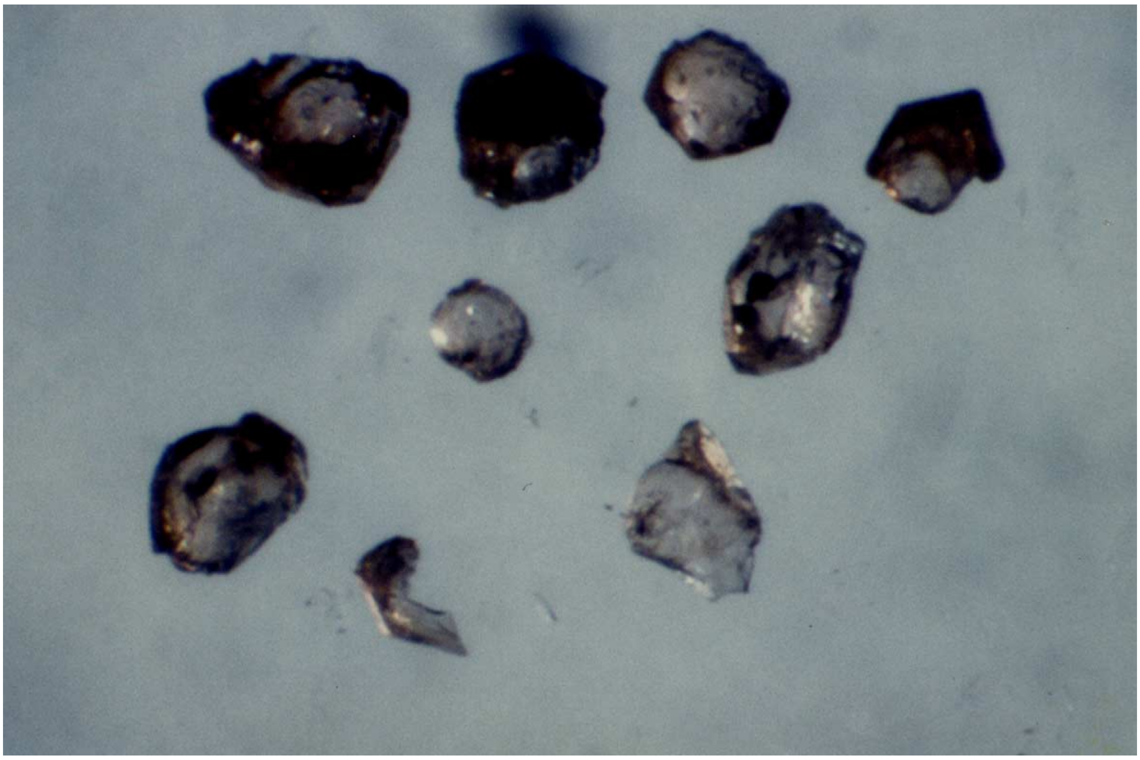


Plate 2

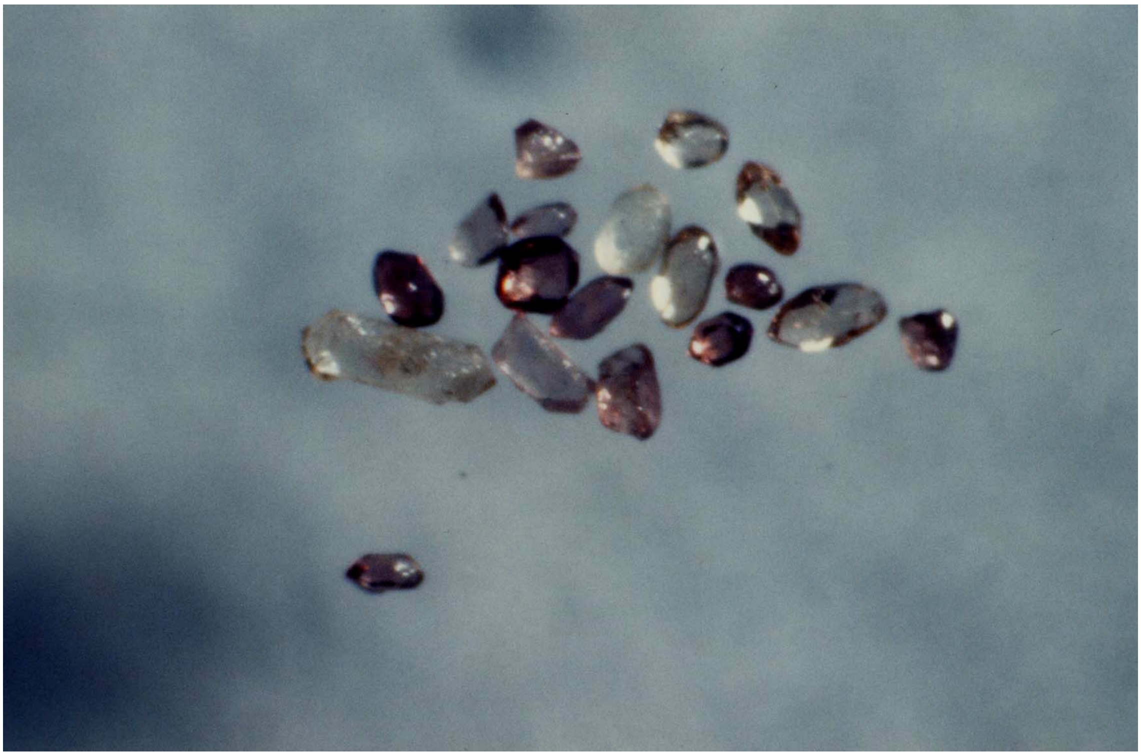
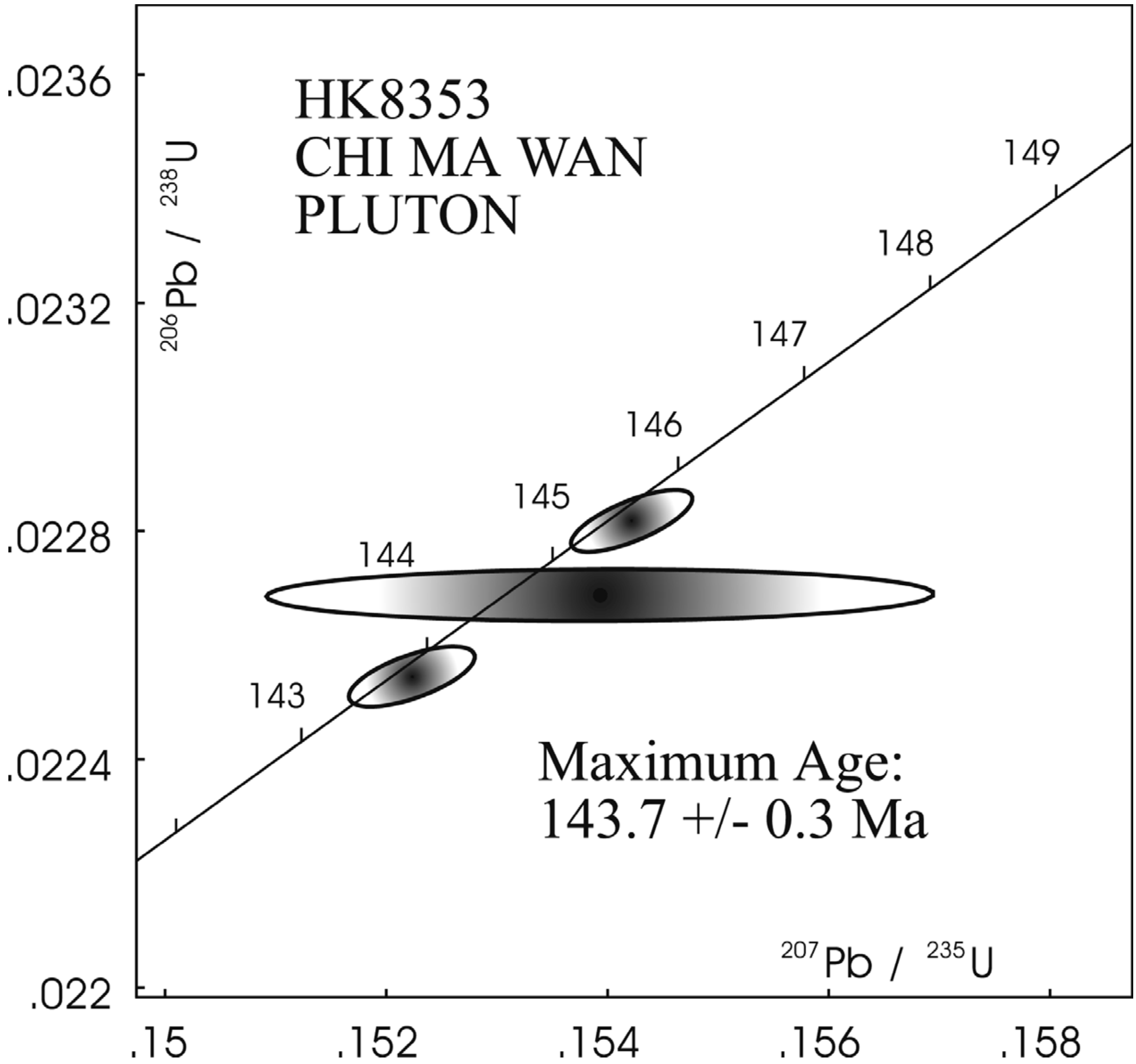
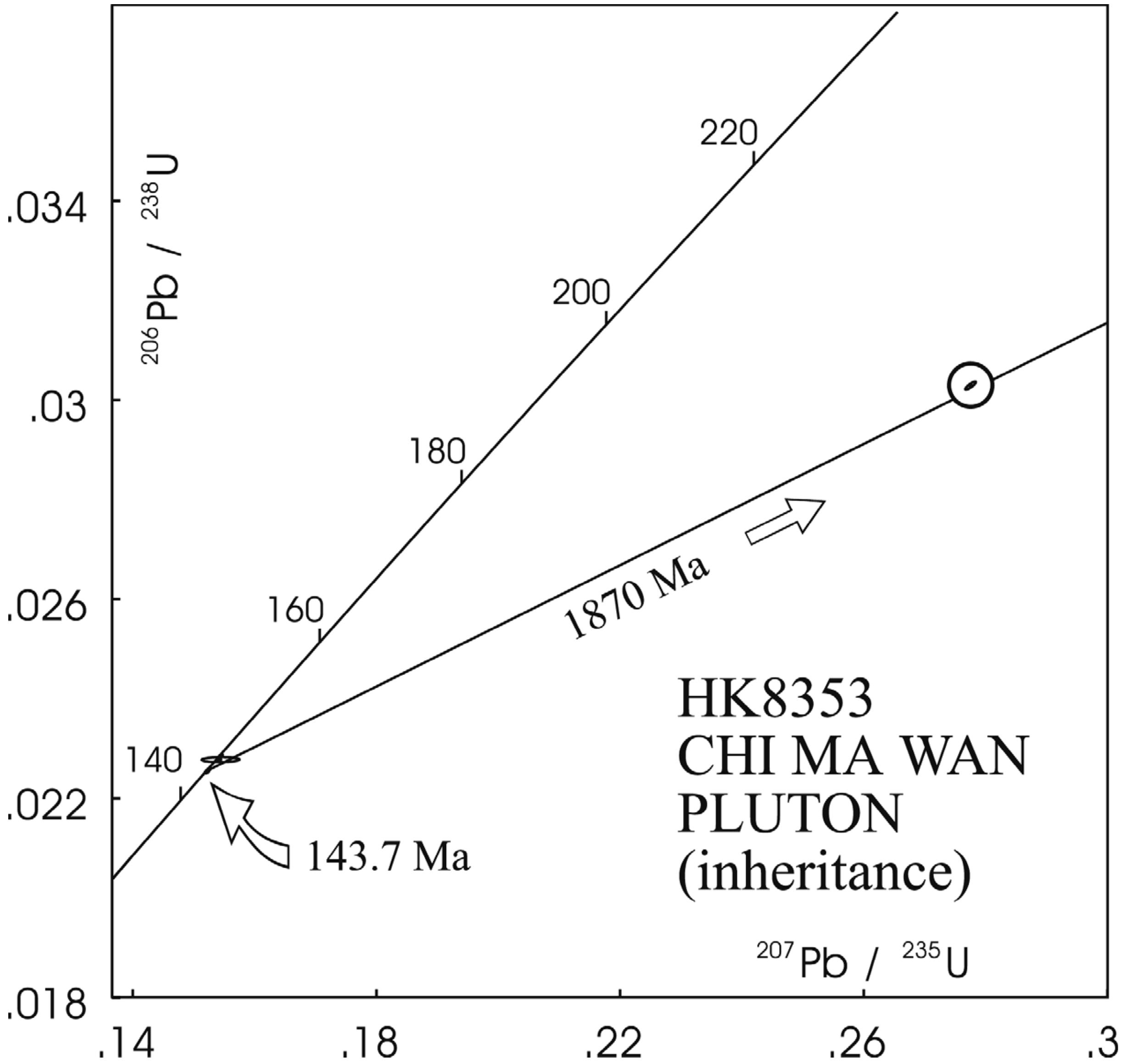


Plate 3



.0236
.0232
.0228
.0224
.022
^{206}Pb / ^{238}U
HK8353
CHI MA WAN
PLUTON
149
148
147
146
145
144
143
Maximum Age:
143.7 +/- 0.3 Ma
^{207}Pb / ^{235}U
.15
.152
.154
.156
.158

Figure 1A



.034
.03
.026
.022
.018
^{206}Pb / ^{238}U
.14
.18
.22
.26
.3
^{207}Pb / ^{235}U
220
200
180
160
140
1870 Ma
143.7 Ma
HK8353
CHI MA WAN
PLUTON
(inheritance)

Figure 1B

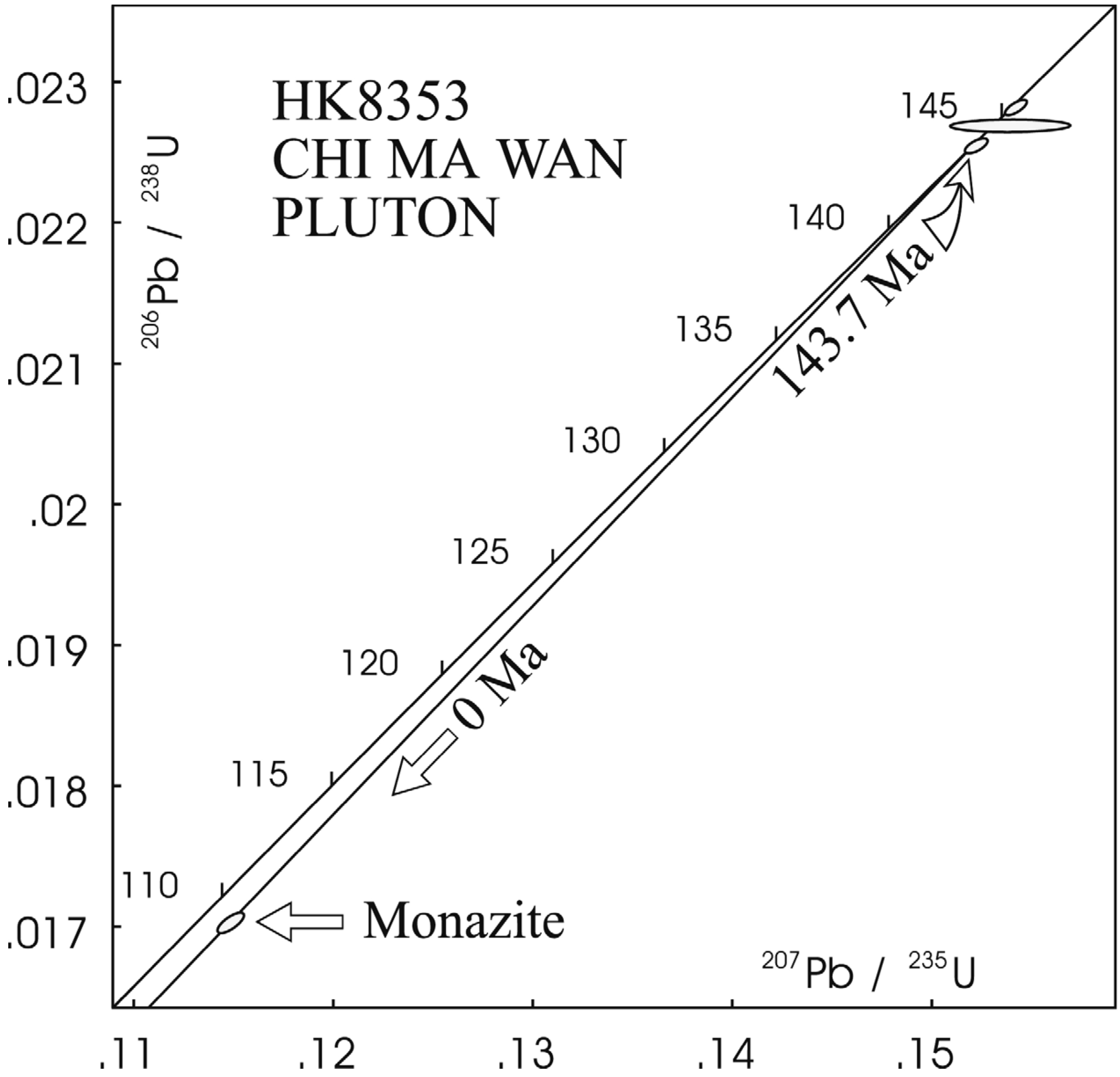

HK8353
CHI MA WAN
PLUTON
.023
.022
.021
.02
.019
.018
.017
^{206}Pb / ^{238}U
145
140
135
130
125
120
115
110
143.7 Ma
0 Ma
Monazite
^{207}Pb / ^{235}U
.11
.12
.13
.14
.15

Figure 1C

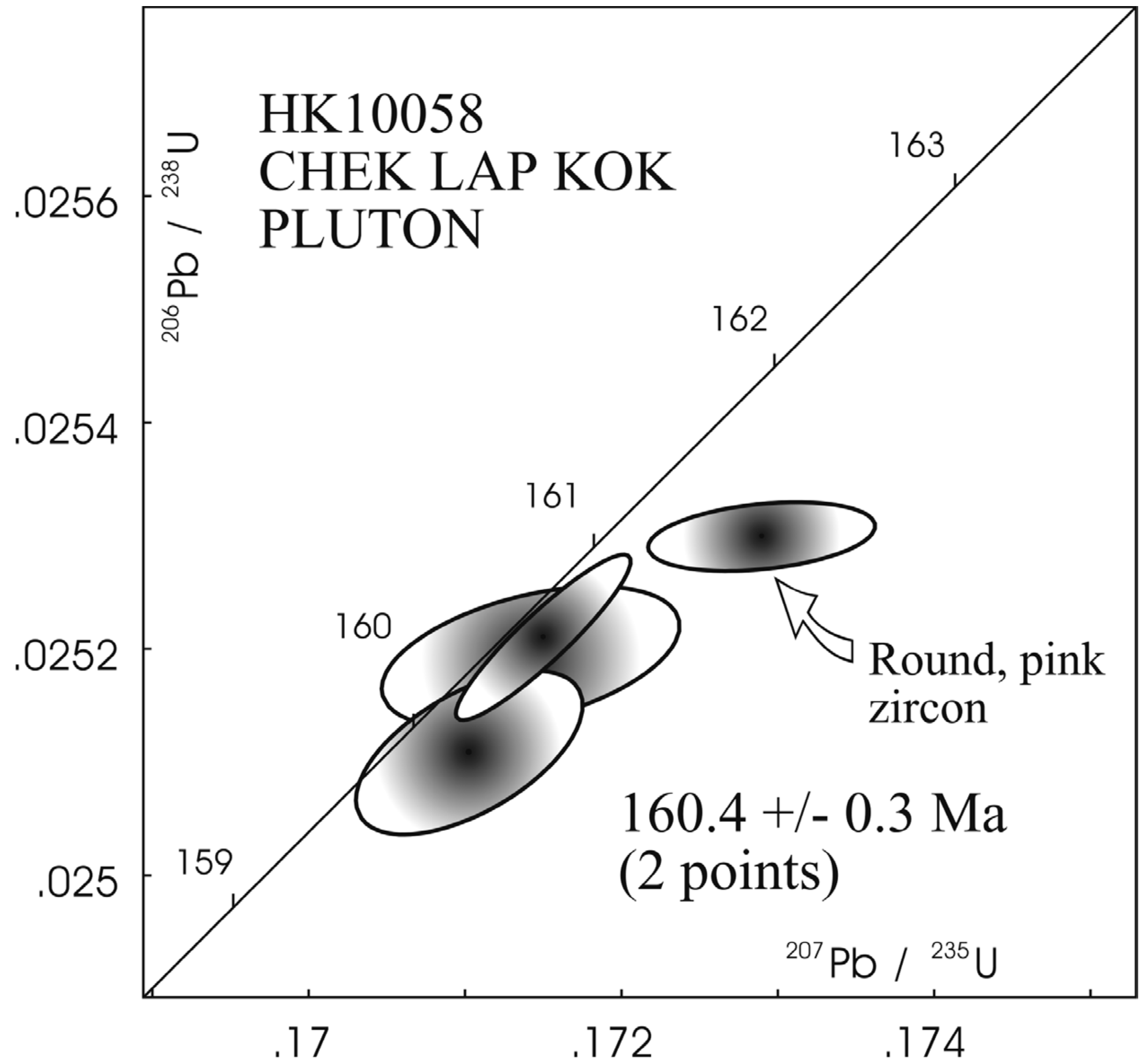

HK10058
CHEK LAP KOK
PLUTON
.0256
.0254
.0252
.025
^{206}Pb / ^{238}U
163
162
161
160
159
Round, pink
zircon
160.4 +/- 0.3 Ma
(2 points)
^{207}Pb / ^{235}U
.17
.172
.174

Figure 2

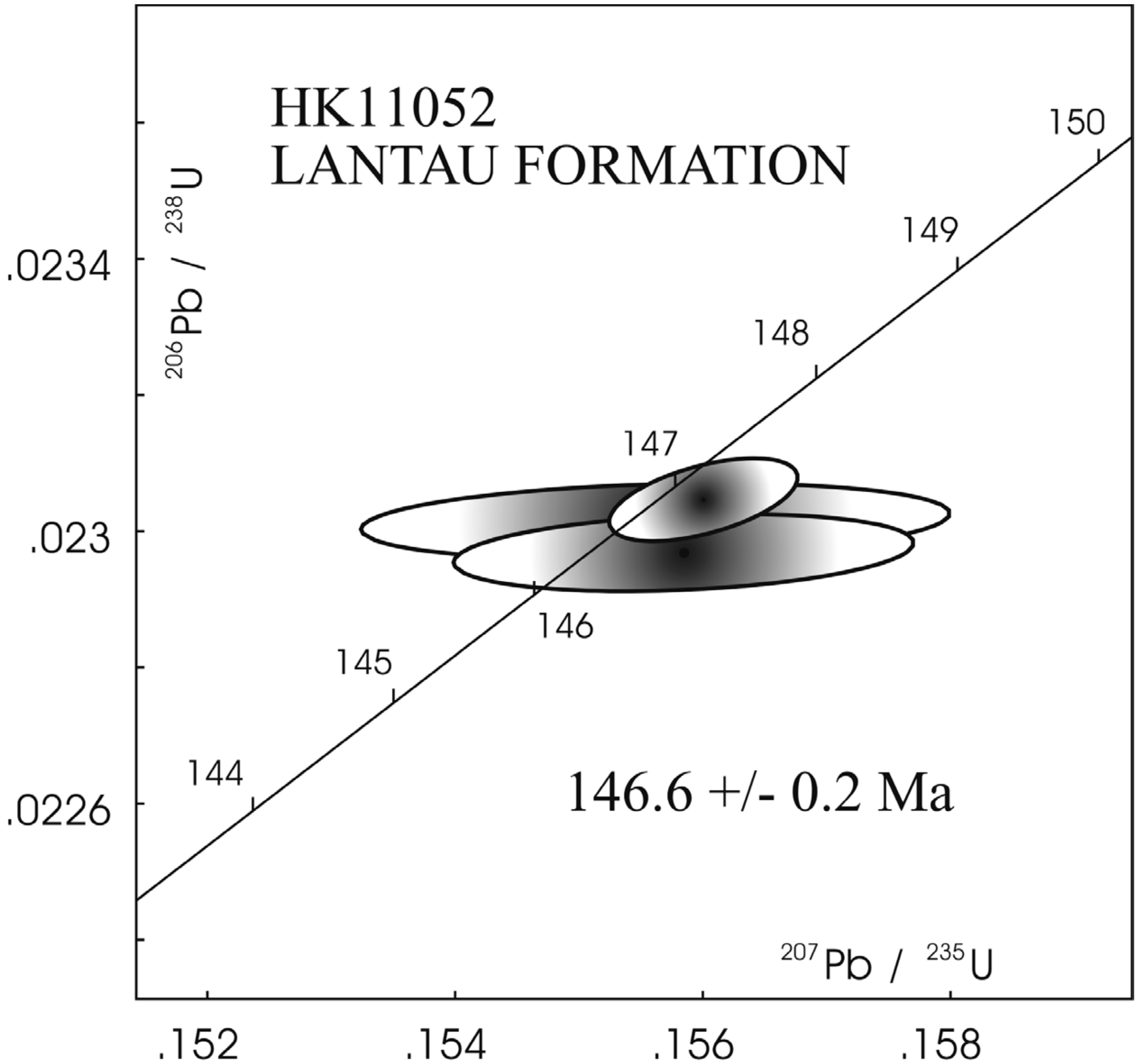

HK11052
LANTAU FORMATION
146.6 +/- 0.2 Ma
150
149
148
147
146
145
144
.0234
.023
.0226
206Pb / 238U
207Pb / 235U
.152
.154
.156
.158

Figure 3

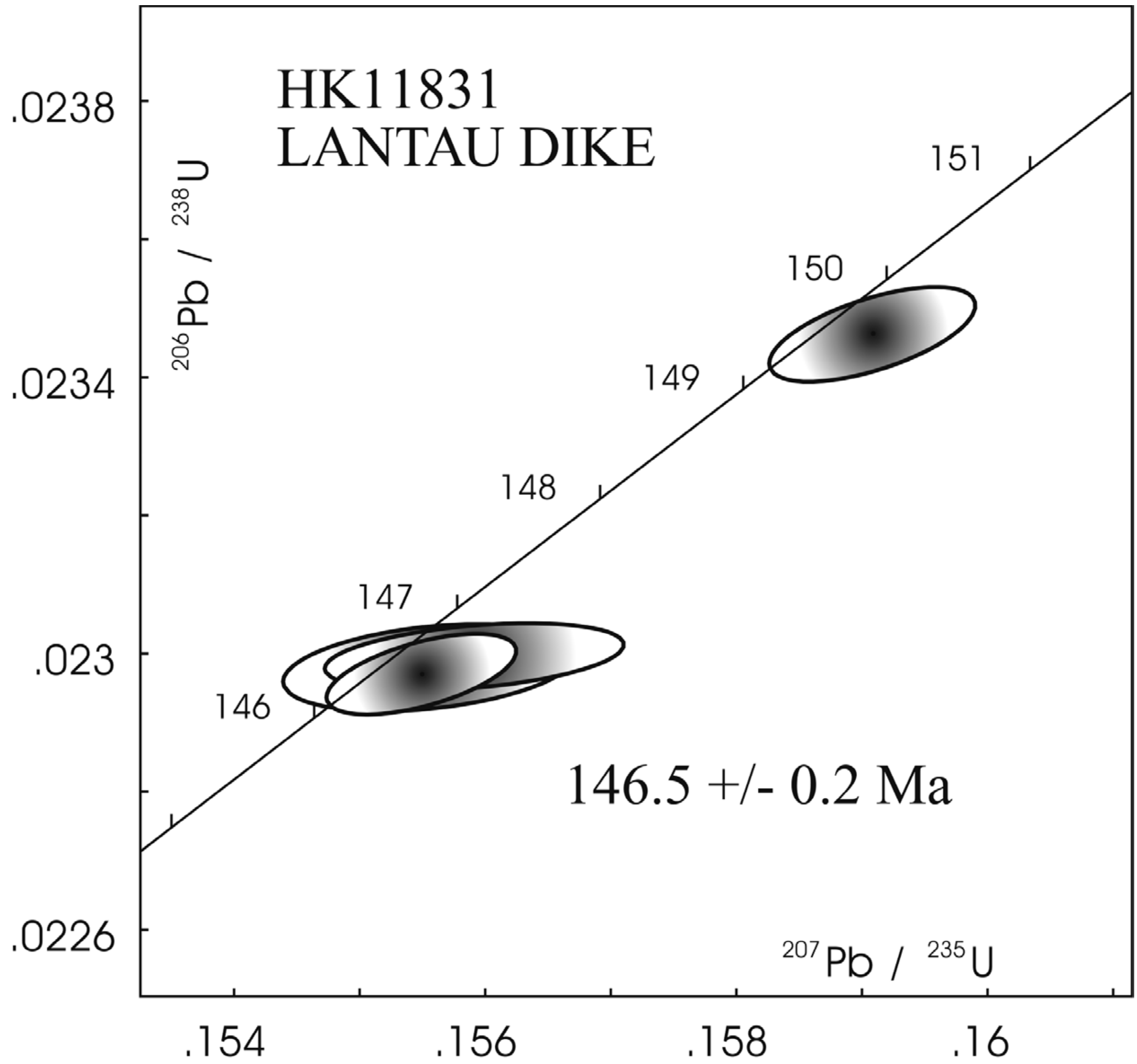

HK11831
LANTAU DIKE
146.5 +/- 0.2 Ma
.0238
.0234
.023
.0226
.154
.156
.158
.16
146
147
148
149
150
151
206Pb / 238U
207Pb / 235U

Figure 4

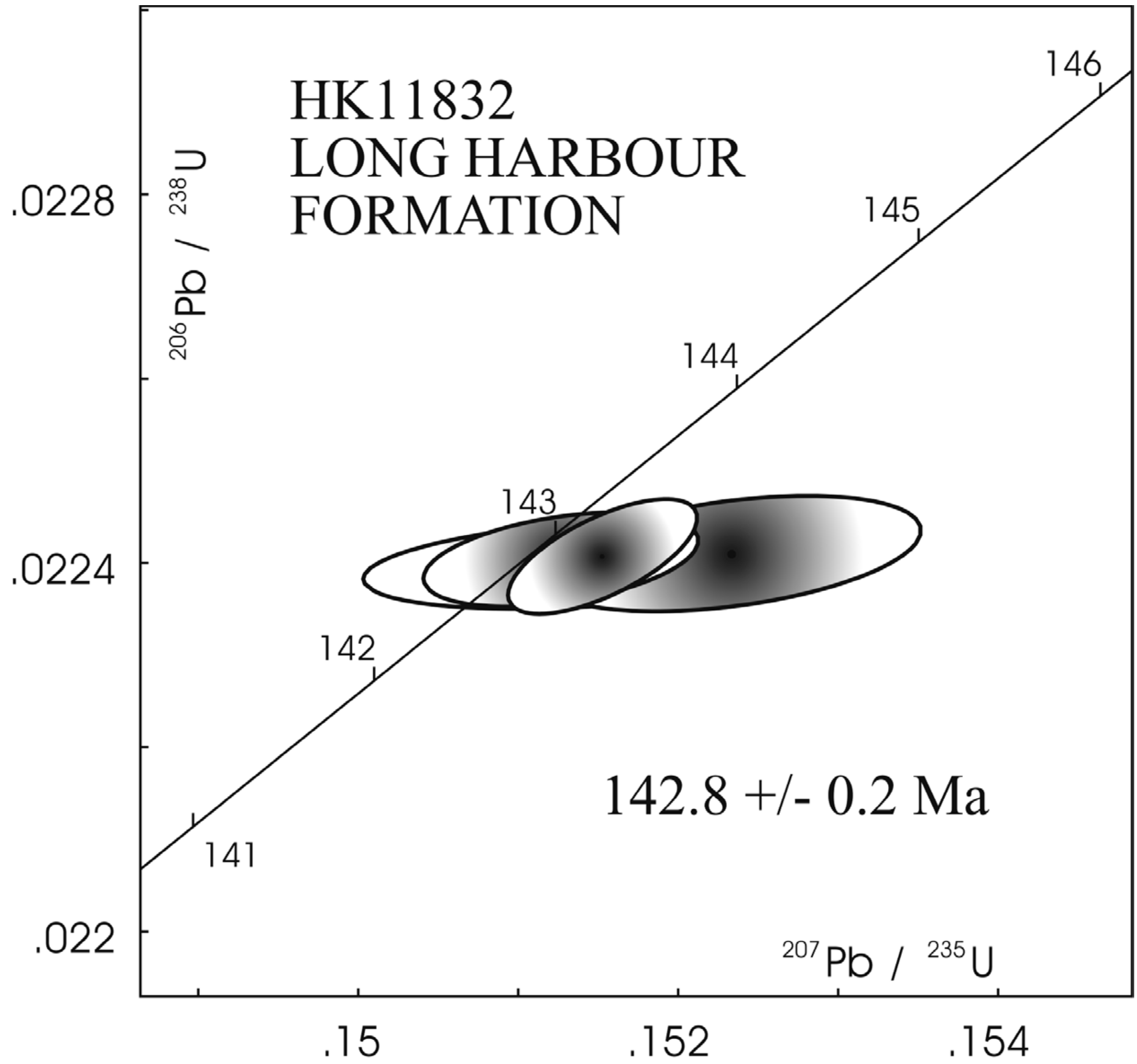

HK11832
LONG HARBOUR
FORMATION
.0228
.0224
.022
^{206}Pb / ^{238}U
146
145
144
143
142
141
142.8 +/- 0.2 Ma
^{207}Pb / ^{235}U
.15
.152
.154

Figure 5

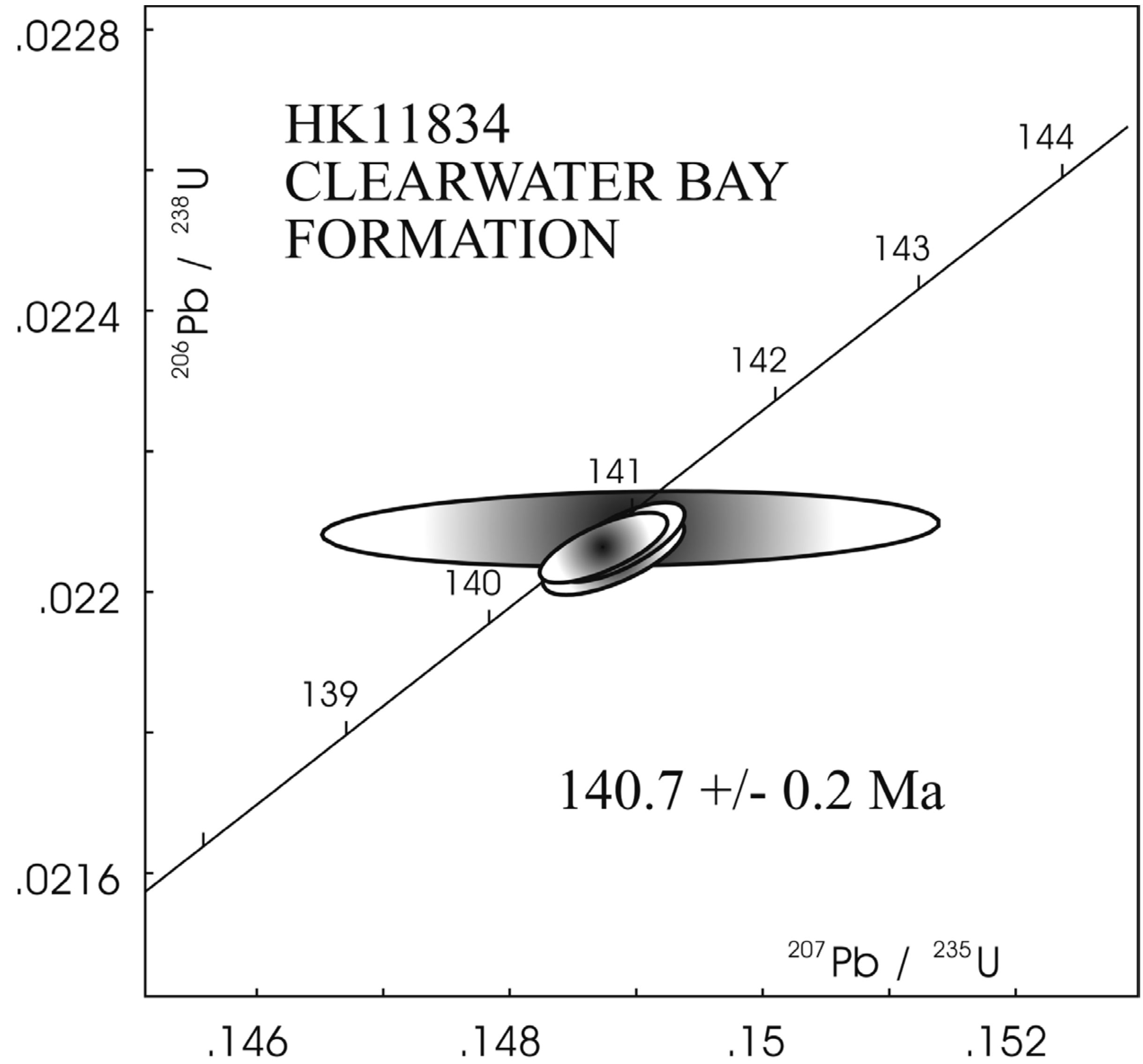

HK11834
CLEARWATER BAY
FORMATION
140.7 +/- 0.2 Ma
.0228
.0224
.022
.0216
206Pb / 238U
207Pb / 235U
.146
.148
.15
.152
139
140
141
142
143
144

Figure 6

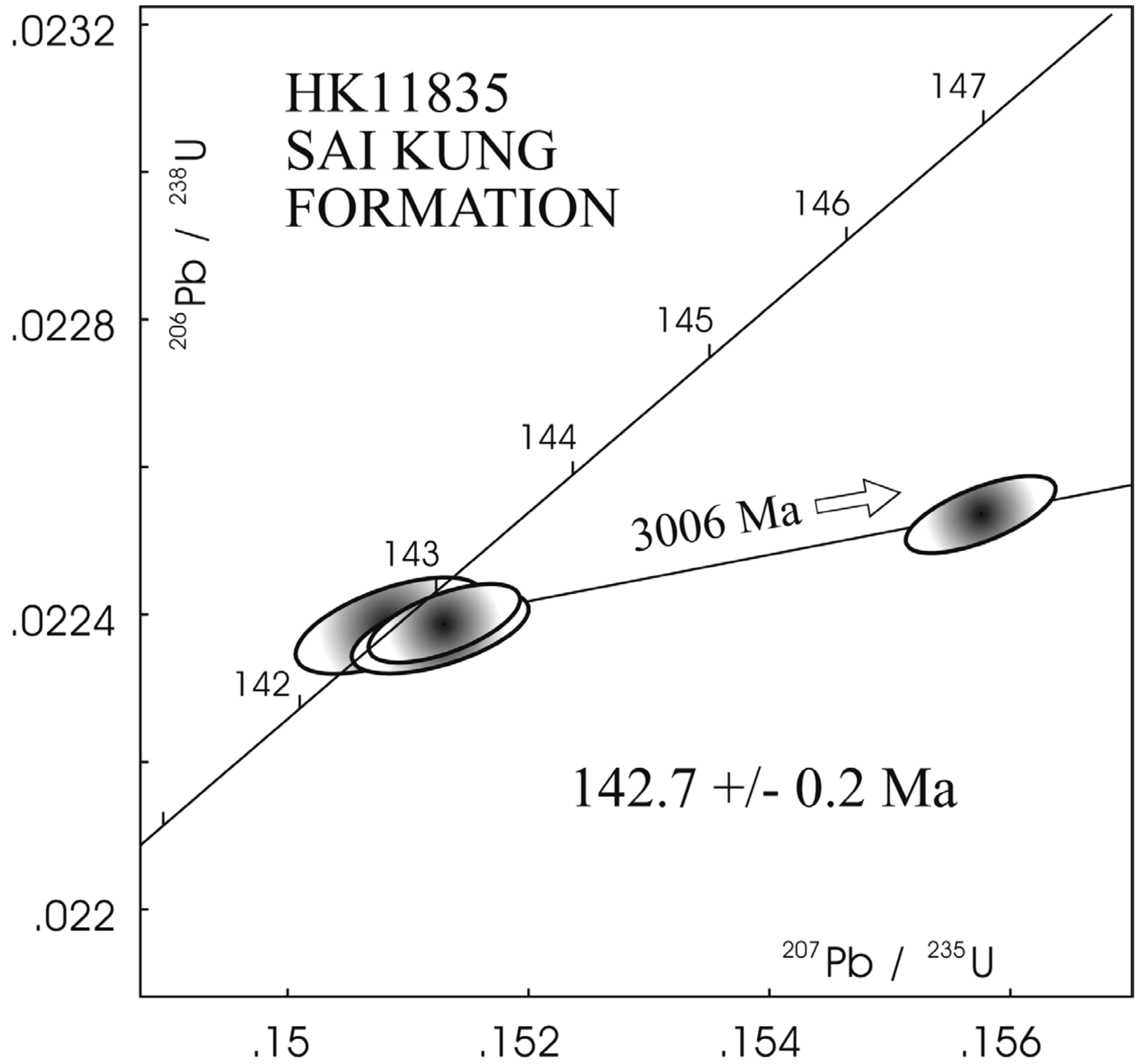

.0232
.0228
.0224
.022
^{206}Pb / ^{238}U
HK11835
SAI KUNG
FORMATION
147
146
145
144
143
142
3006 Ma
142.7 +/- 0.2 Ma
^{207}Pb / ^{235}U
.15
.152
.154
.156

Figure 7

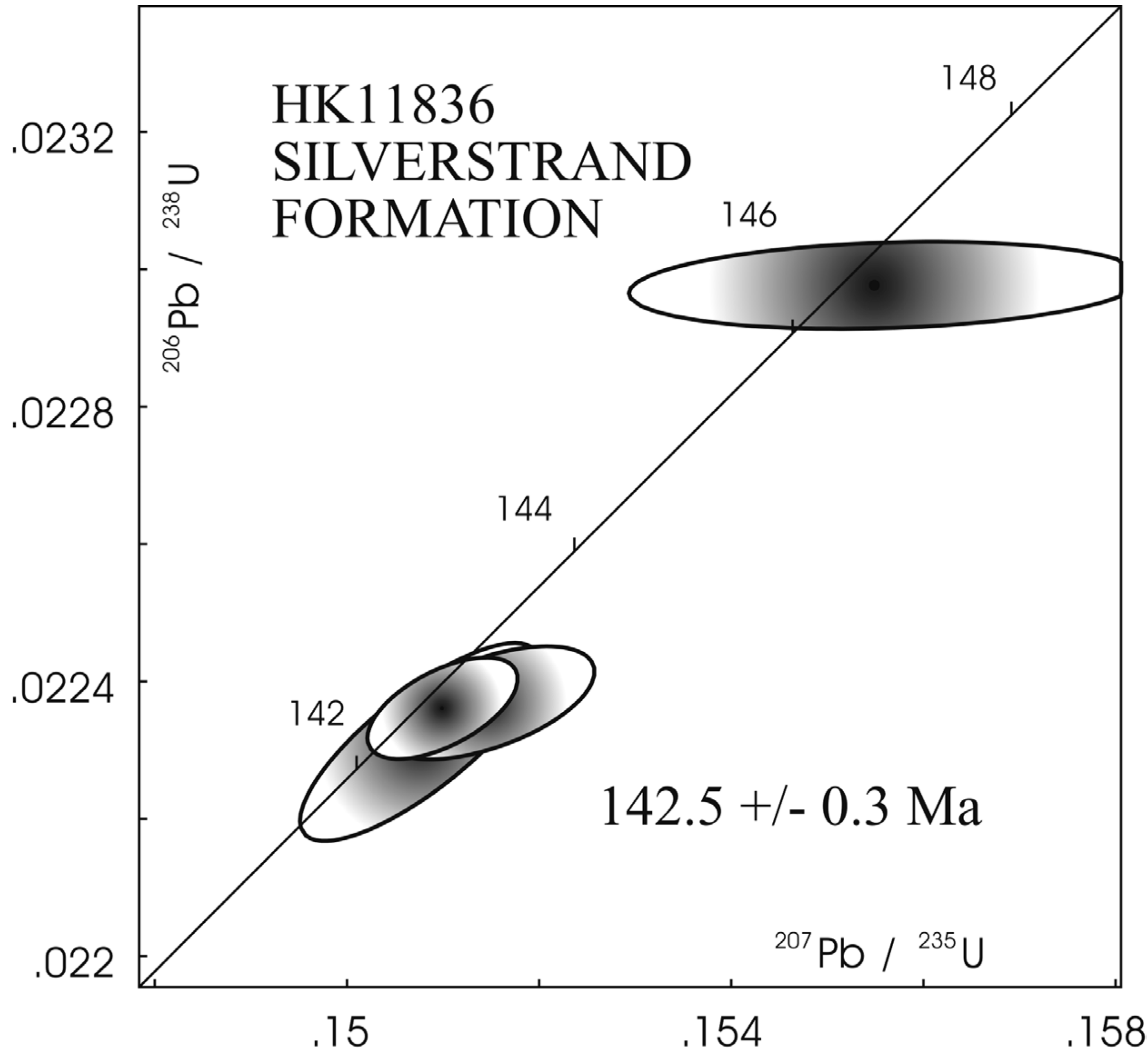

HK11836
SILVERSTRAND
FORMATION
148
146
144
142
142.5 +/- 0.3 Ma
.0232
.0228
.0224
.022
^{206}Pb / ^{238}U
^{207}Pb / ^{235}U
.15
.154
.158

Figure 8

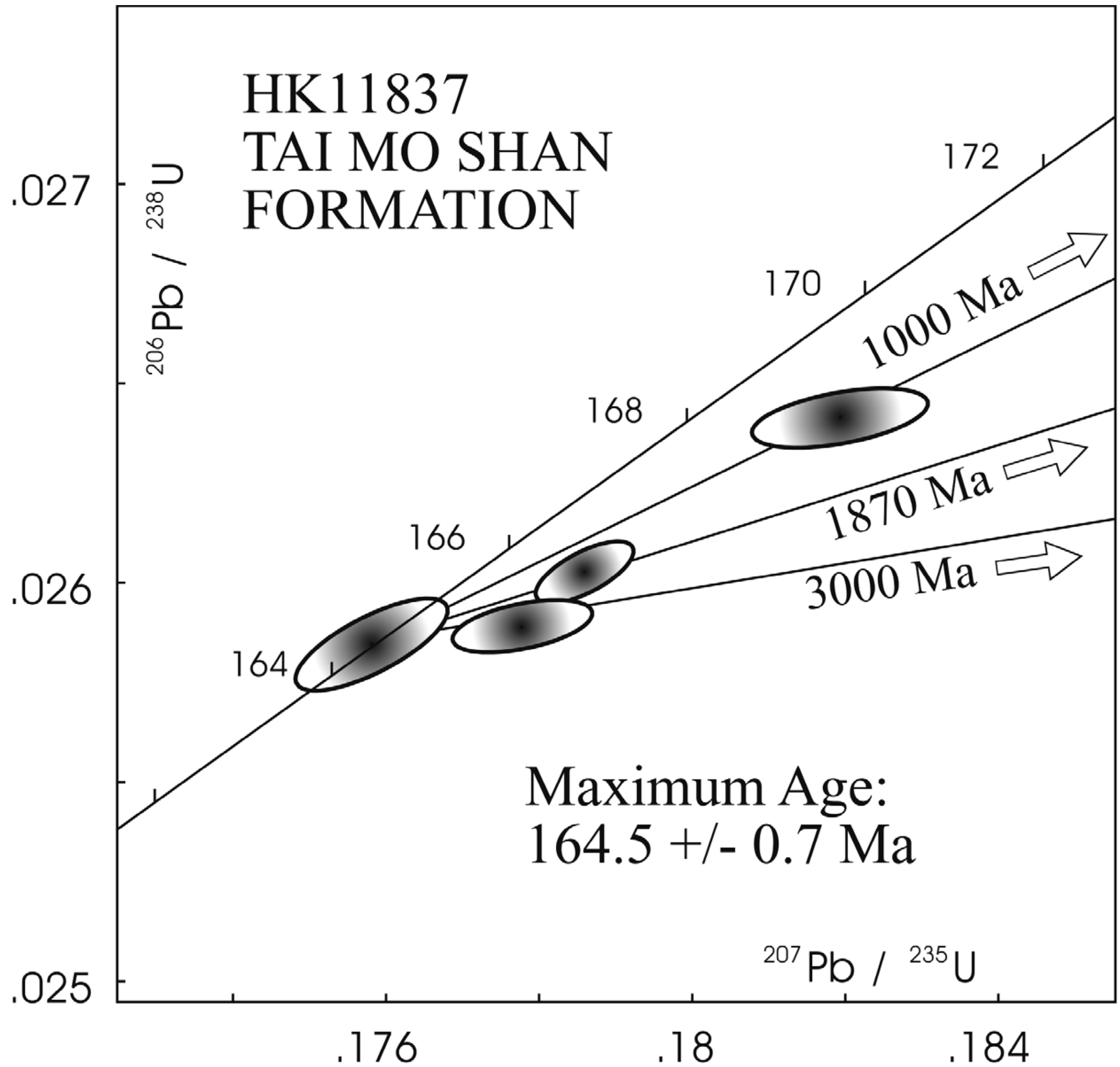

HK11837
TAI MO SHAN
FORMATION
.027
.026
.025
206Pb / 238U
172
170
168
166
164
1000 Ma
1870 Ma
3000 Ma
Maximum Age:
164.5 +/- 0.7 Ma
207Pb / 235U
.176
.18
.184

Figure 9A

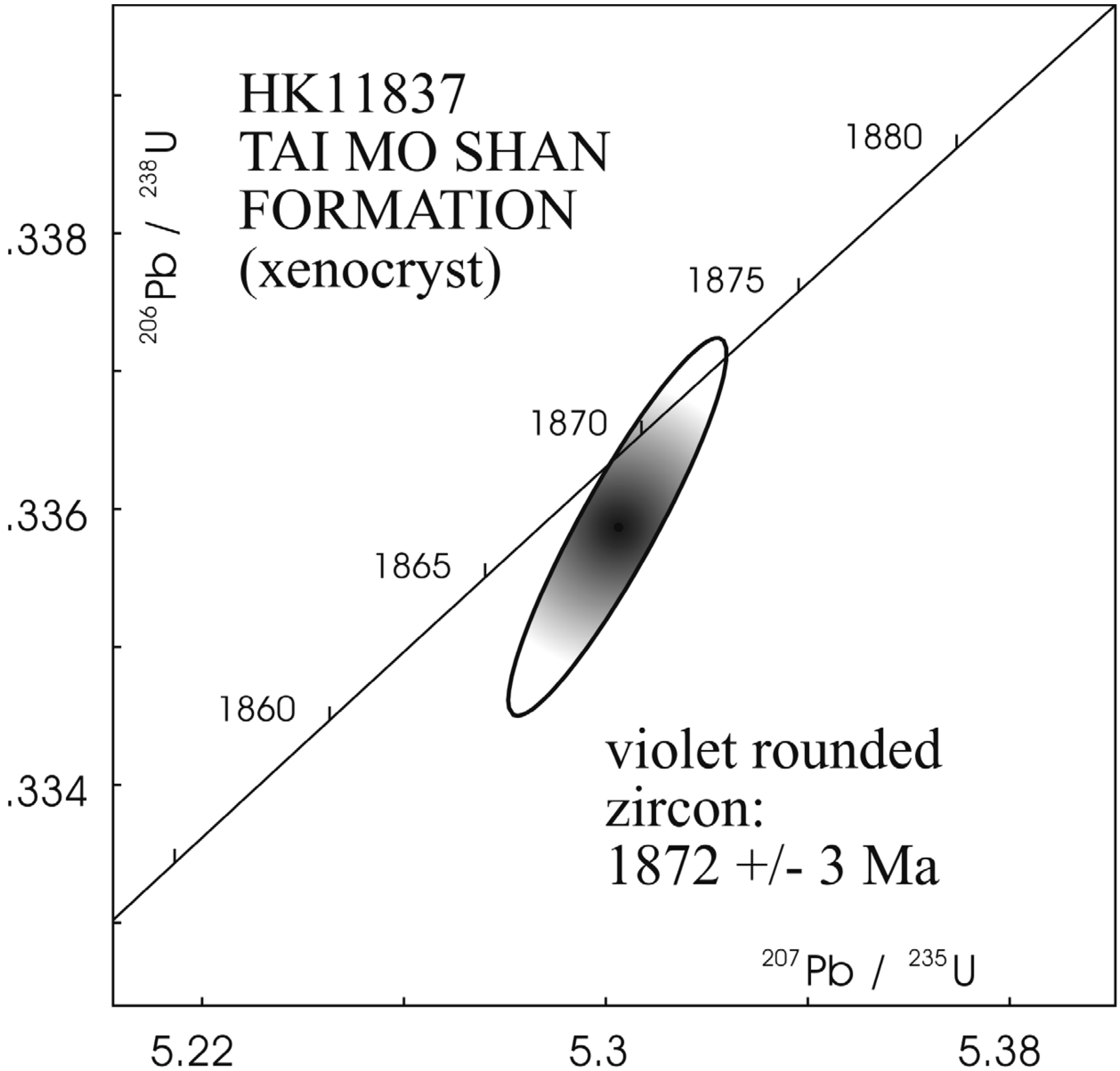

HK11837
TAI MO SHAN
FORMATION
(xenocryst)
1880
1875
1870
1865
1860
.338
.336
.334
206Pb / 238U
violet rounded
zircon:
1872 +/- 3 Ma
207Pb / 235U
5.22
5.3
5.38

Figure 9B

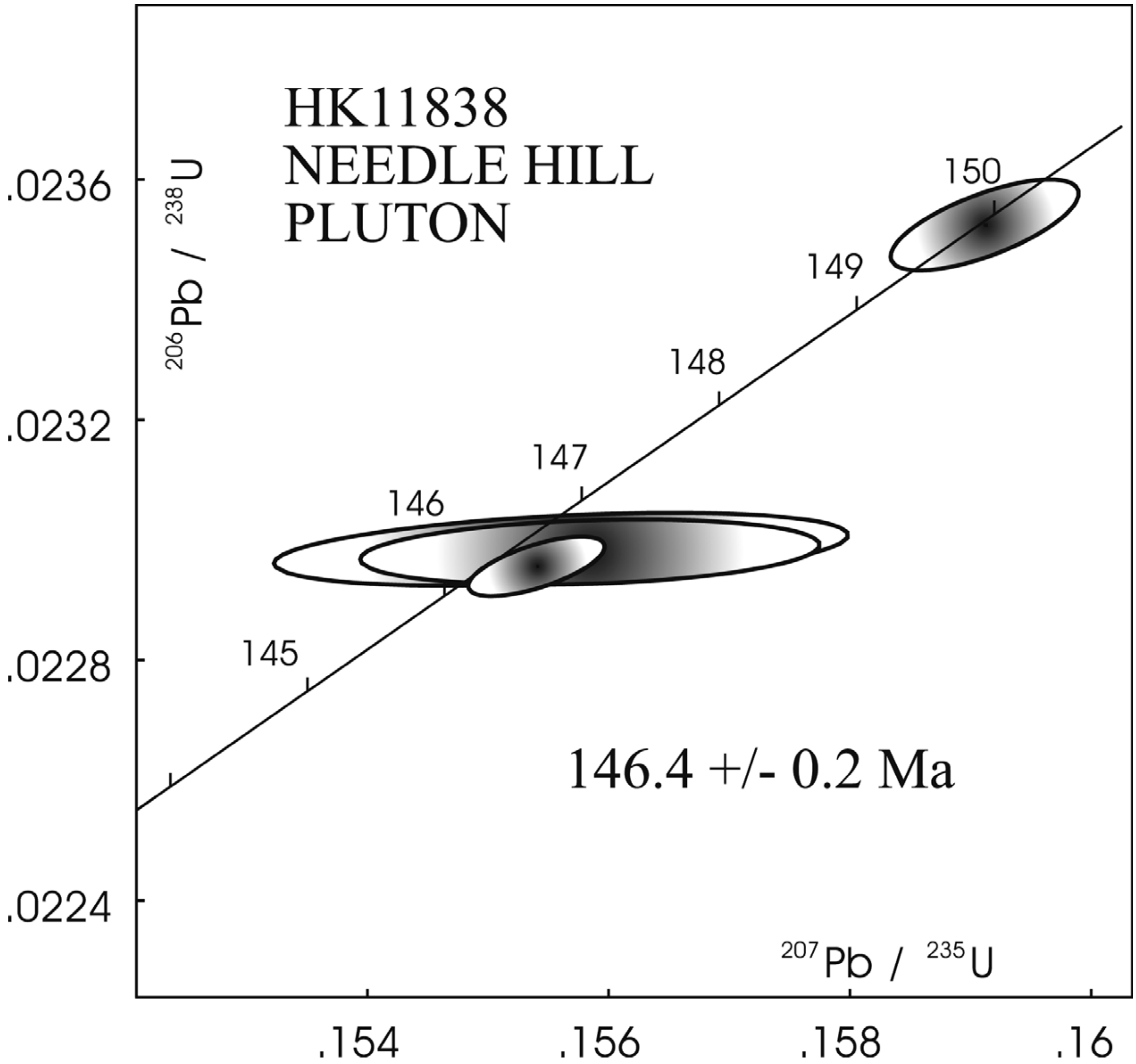

HK11838
NEEDLE HILL
PLUTON
150
149
148
147
146
145
146.4 +/- 0.2 Ma
.0236
.0232
.0228
.0224
206Pb / 238U
207Pb / 235U
.154
.156
.158
.16

Figure 10

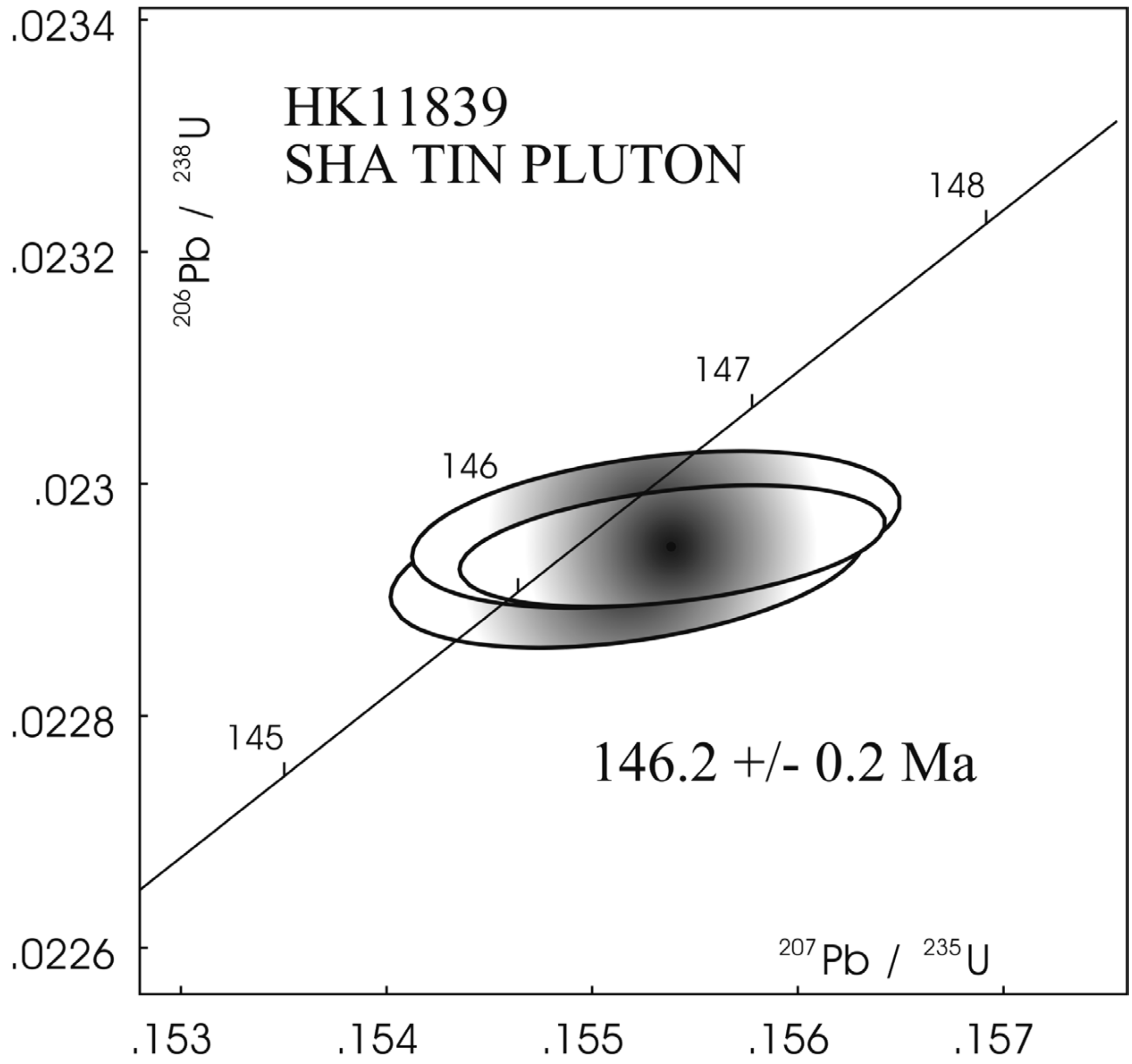

HK11839
SHA TIN PLUTON
146.2 +/- 0.2 Ma
148
147
146
145
.0234
.0232
.023
.0228
.0226
.153
.154
.155
.156
.157
^{206}Pb / ^{238}U
^{207}Pb / ^{235}U

Figure 11A

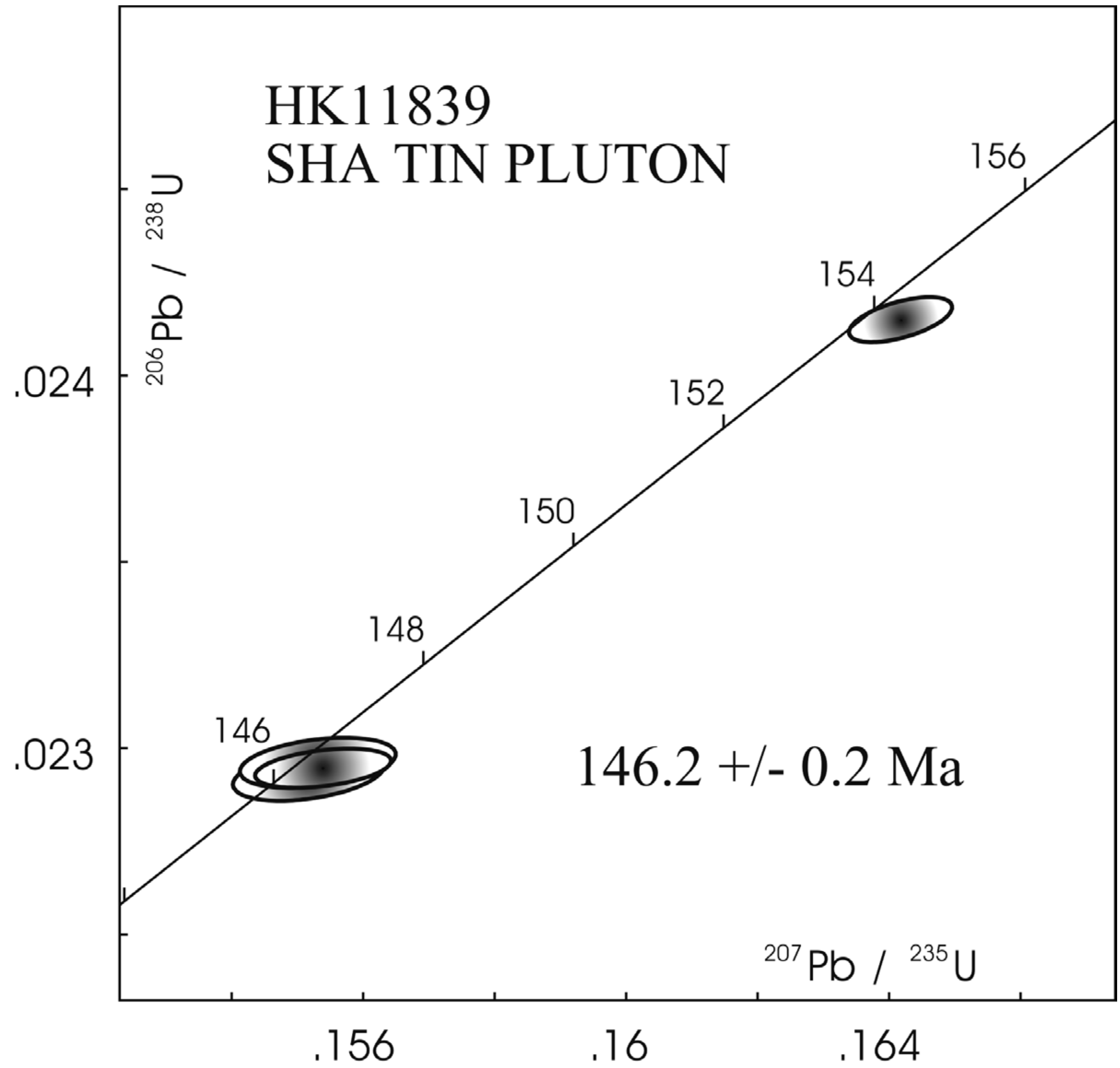
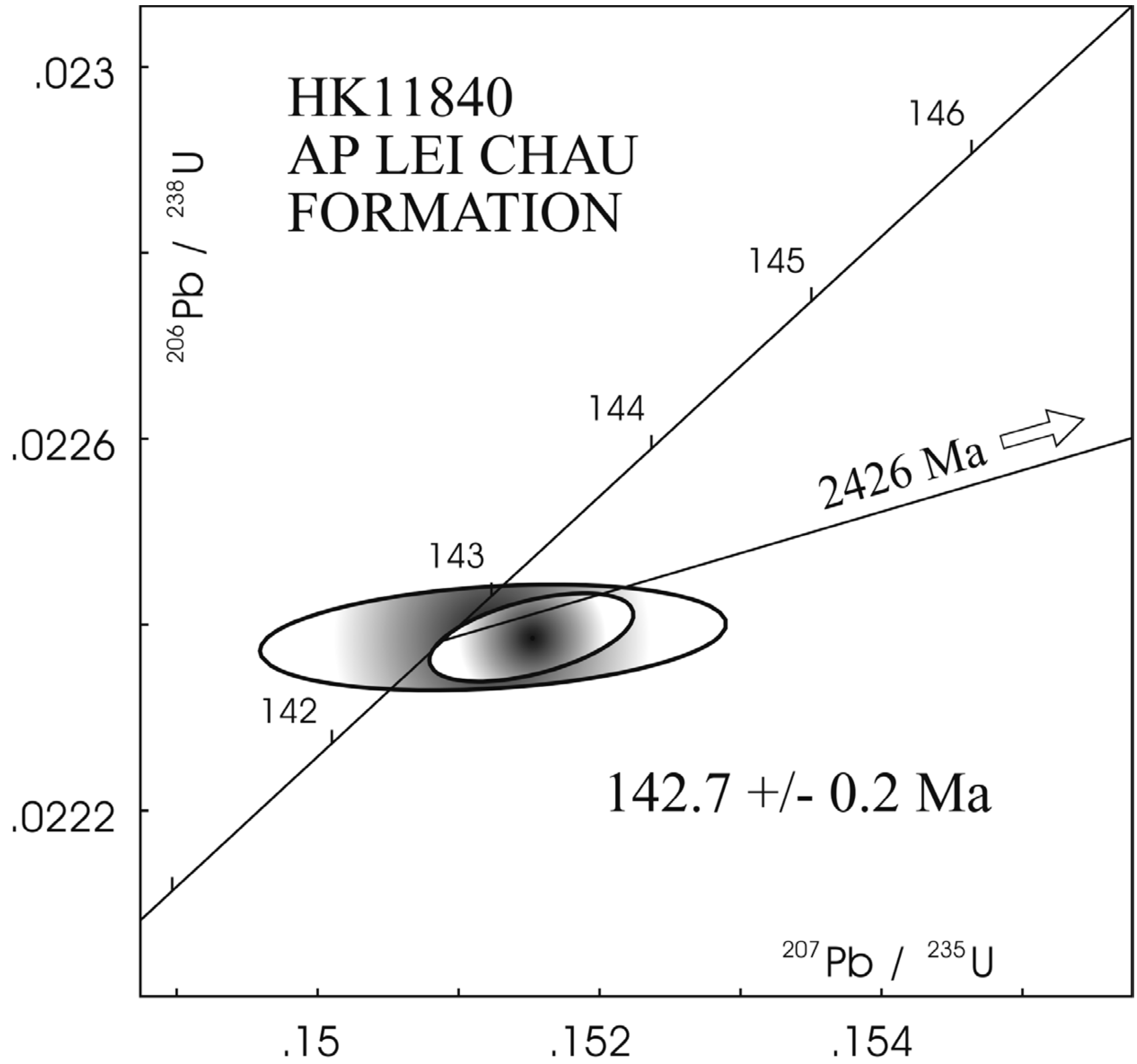

HK11839
SHA TIN PLUTON
146.2 +/- 0.2 Ma
^{206}Pb / ^{238}U
^{207}Pb / ^{235}U
.024
.023
.156
.16
.164
146
148
150
152
154
156

Figure 11B



.023
.0226
.0222
^{206}Pb / ^{238}U
HK11840
AP LEI CHAU
FORMATION
146
145
144
143
142
2426 Ma
142.7 +/- 0.2 Ma
^{207}Pb / ^{235}U
.15
.152
.154

Figure 12A

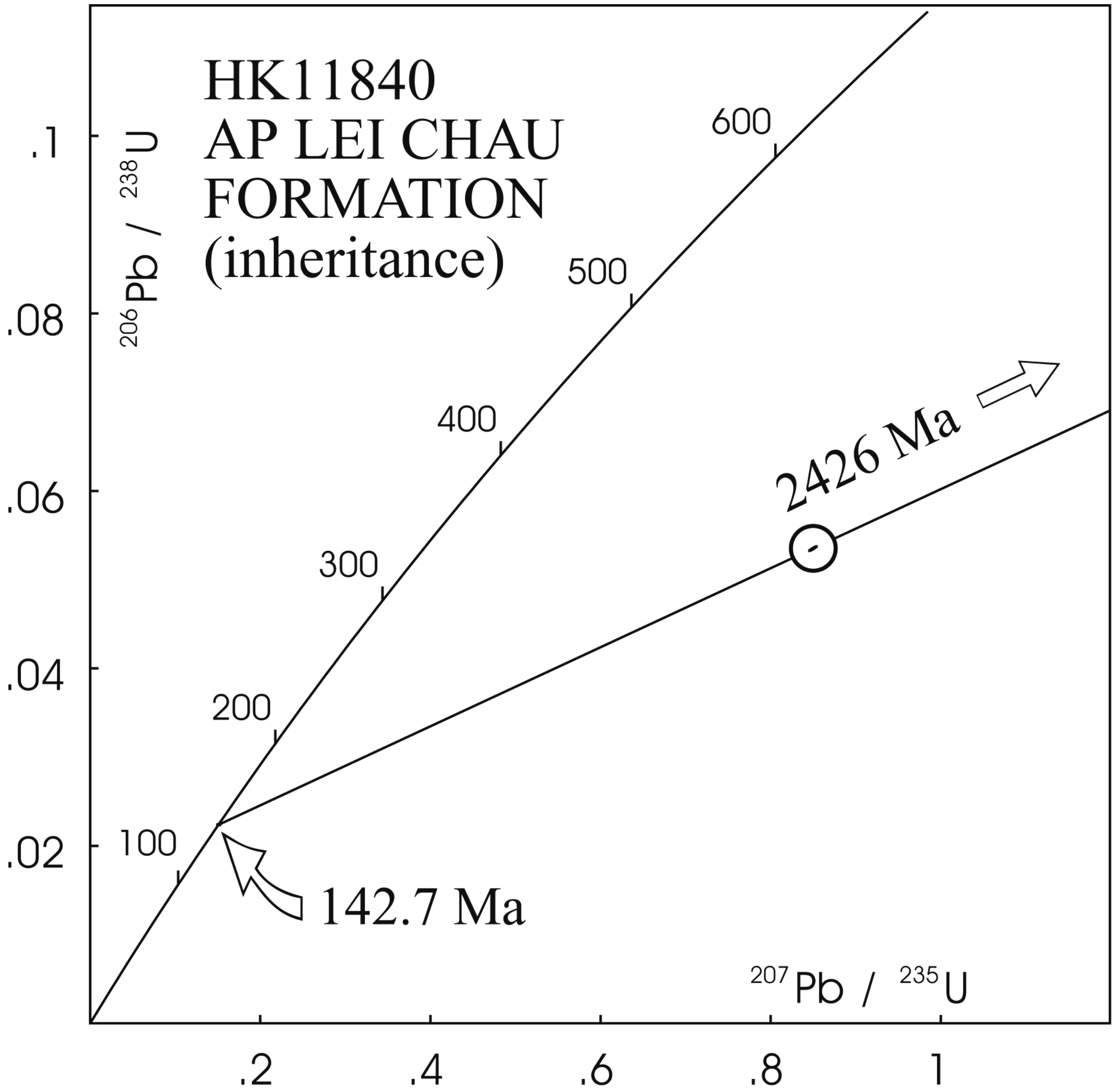

HK11840
AP LEI CHAU
FORMATION
(inheritance)
.1
.08
.06
.04
.02
^{206}Pb / ^{238}U
600
500
400
300
200
100
2426 Ma
142.7 Ma
^{207}Pb / ^{235}U
.2
.4
.6
.8
1

Figure 12B

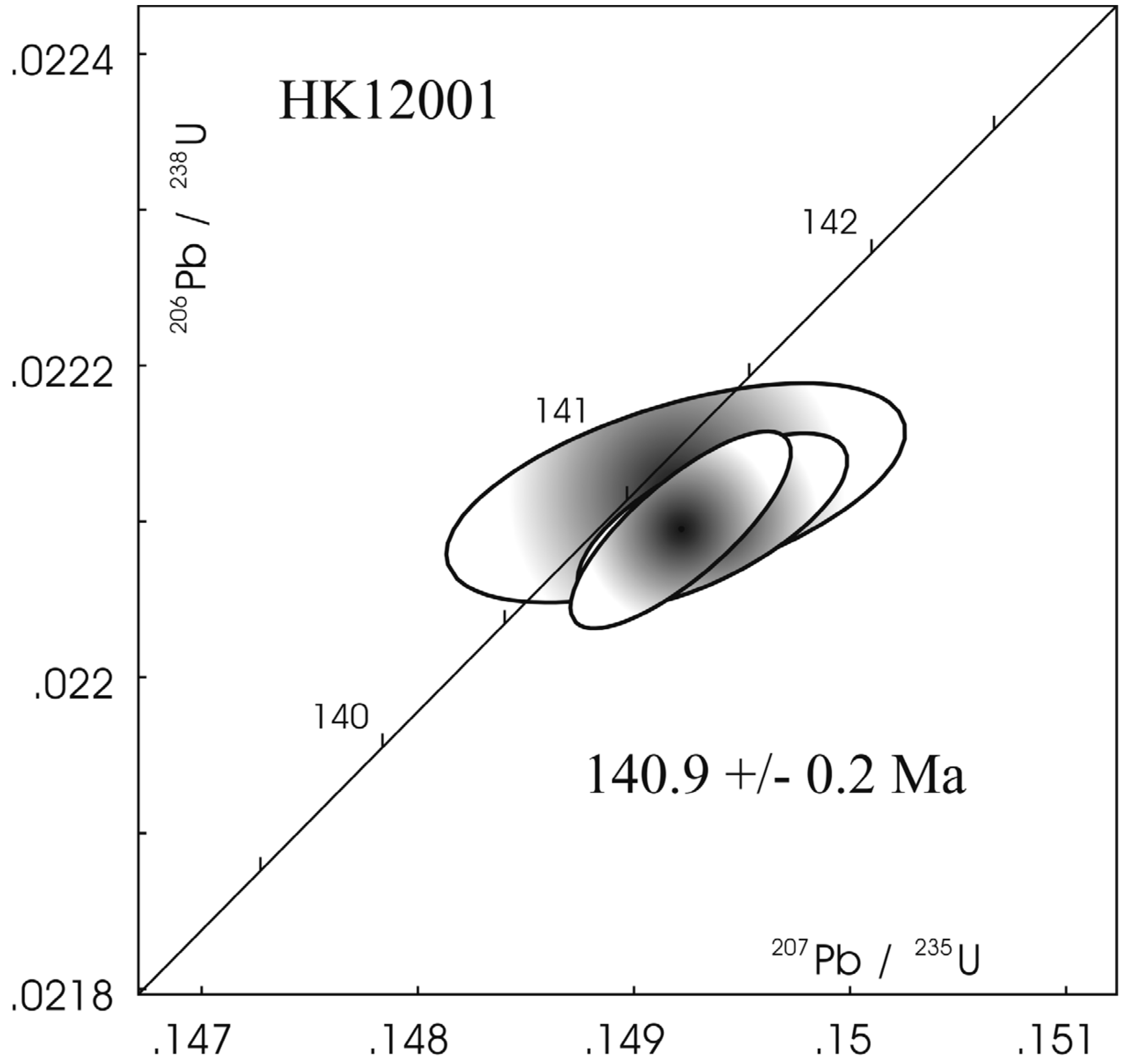

HK12001
^{206}Pb / ^{238}U
.0224
.0222
.022
.0218
142
141
140
140.9 +/- 0.2 Ma
^{207}Pb / ^{235}U
.147
.148
.149
.15
.151

Figure 13

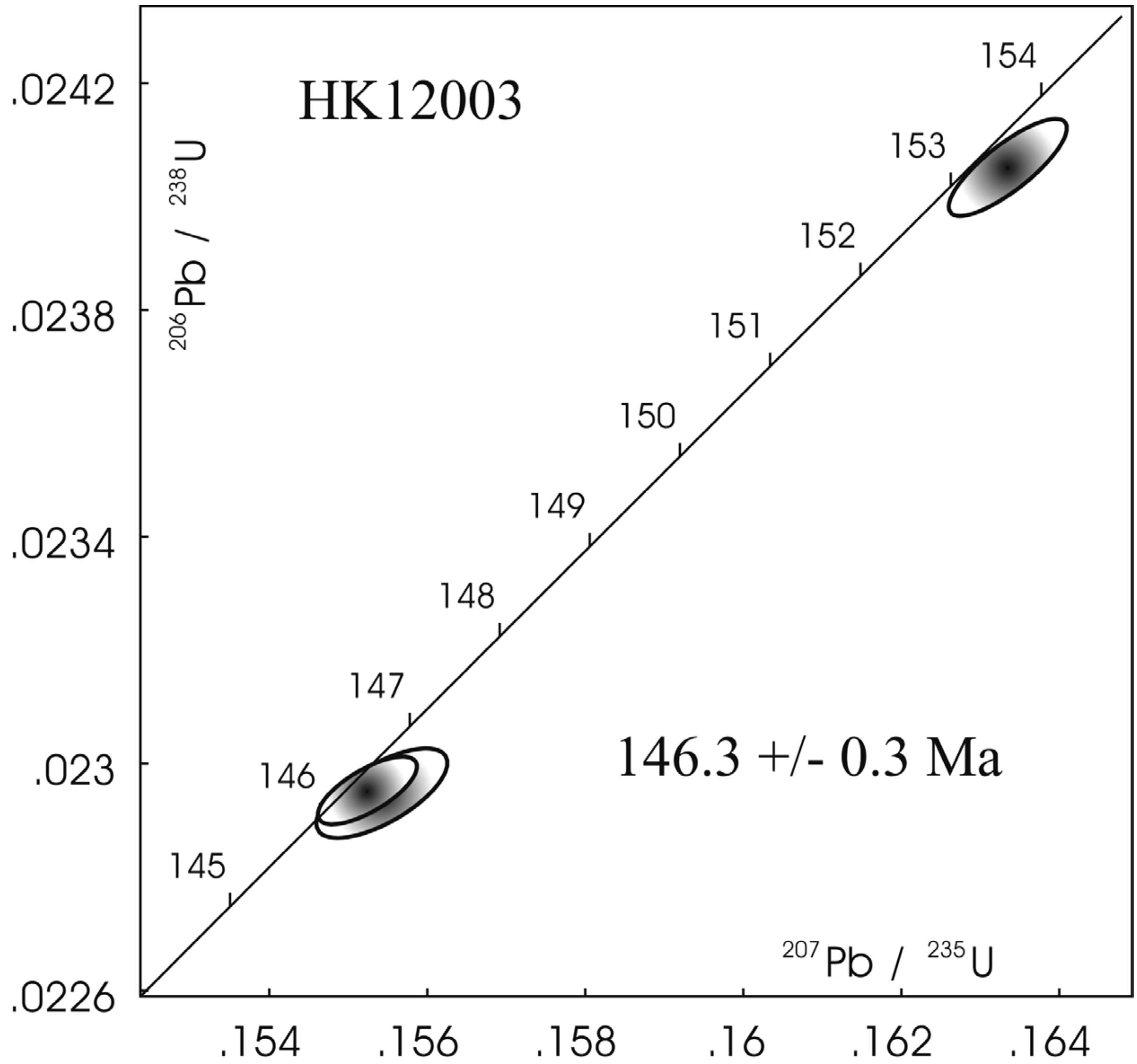

HK12003
146.3 +/- 0.3 Ma
.0242
.0238
.0234
.023
.0226
.154
.156
.158
.16
.162
.164
145
146
147
148
149
150
151
152
153
154
206Pb / 238U
207Pb / 235U

Figure 14

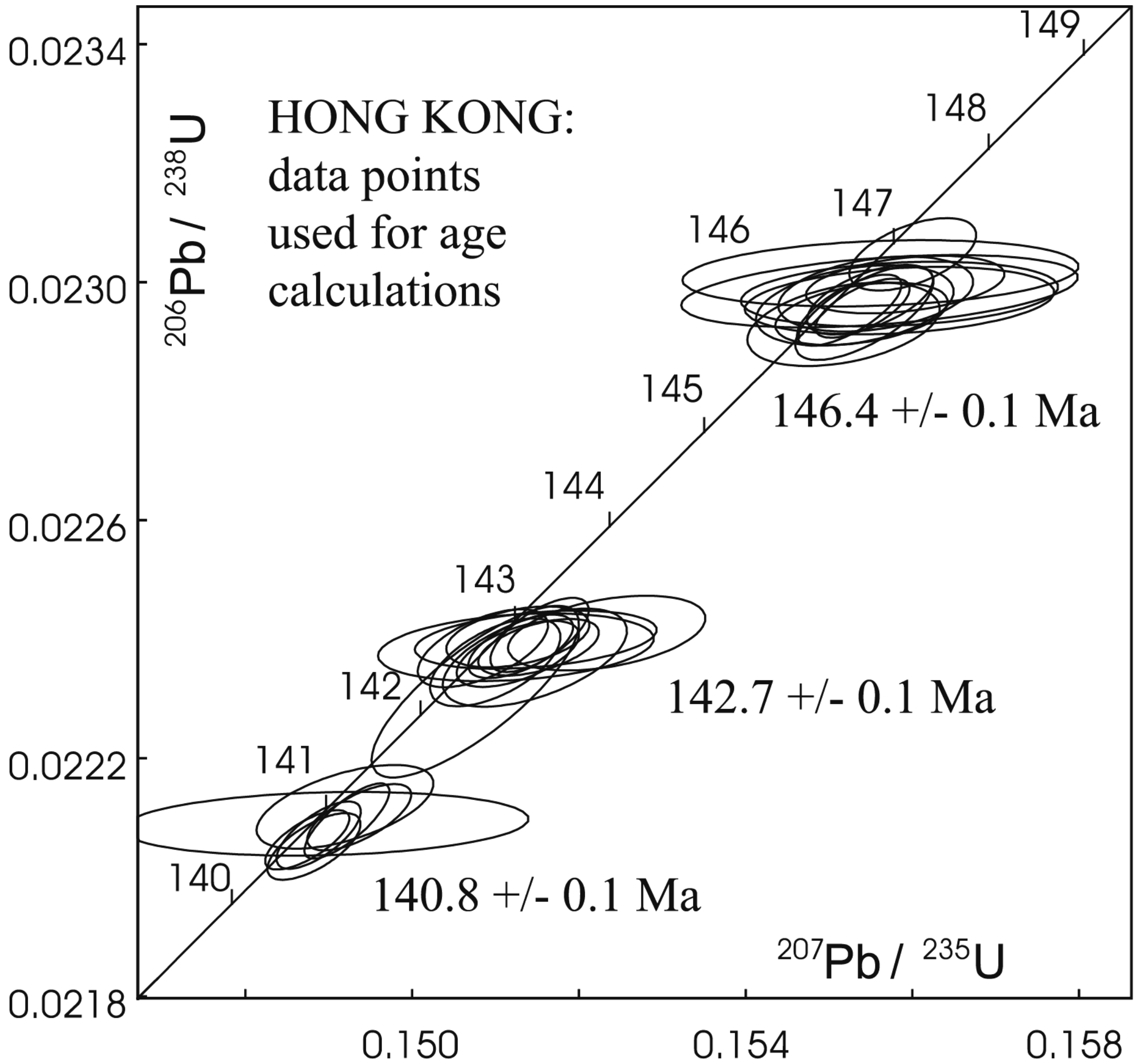

HONG KONG:
data points
used for age
calculations
$^{206}Pb/^{238}U$
$^{207}Pb/^{235}U$
0.0234
0.0230
0.0226
0.0222
0.0218
0.150
0.154
0.158
140
141
142
143
144
145
146
147
148
149
146.4 +/- 0.1 Ma
142.7 +/- 0.1 Ma
140.8 +/- 0.1 Ma

Figure 15

U-PB GEOCHRONOLOGY OF VOLCANIC ROCK HK9015, HONG KONG DECEMBER 3, 1996

DONALD W. DAVIS
EARTH SCIENCE DEPARTMENT
ROYAL ONTARIO MUSEUM
100 QUEEN'S PARK
TORONTO, ONTARIO
CANADA
M5S 2C6

1. SAMPLES

Two samples were processed for extraction of heavy minerals. HK857 was an andesite weighing about 3 kg. This did not yield any zircon. HK9015 was a small sample (about 1 kg) of quartz porphyritic rhoylite with tuffaceous, eutaxitic texture. This yielded a small amount of zircon.

2. ANALYTICAL METHODS

Samples were crushed using a jaw crushed followed by disk milling. The powders were passed over a Wilfley table to concentrate heavy minerals. The concentrate was further processed using density separations with bromoform and methylene iodide, and paramagnetic separations with a Frantz isodynamic separator. Final selection of unaltered, crack-free zircons was by hand picking under a microscope. Exterior crystal surfaces were removed by air abrasion. Weights of mineral fractions were estimated by eye, which is usually accurate to about ± 30%. This affects only U concentrations, not age information, which depends on isotopic ratio measurements and spike calibration.

Zircon was washed in HNO_3, then dissolved using HF in teflon bombs at 200°C. ^{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.

Pb and U were loaded together on Re filaments using silica gel and phosphoric acid and analysed with a VG354 mass spectrometer in single collector mode. All of the measurements were made using a Daly collector with mass dicrimination correction of 0.4%/AMU. The thermal mass discrimination correction is 0.10%/AMU.

3. RESULTS

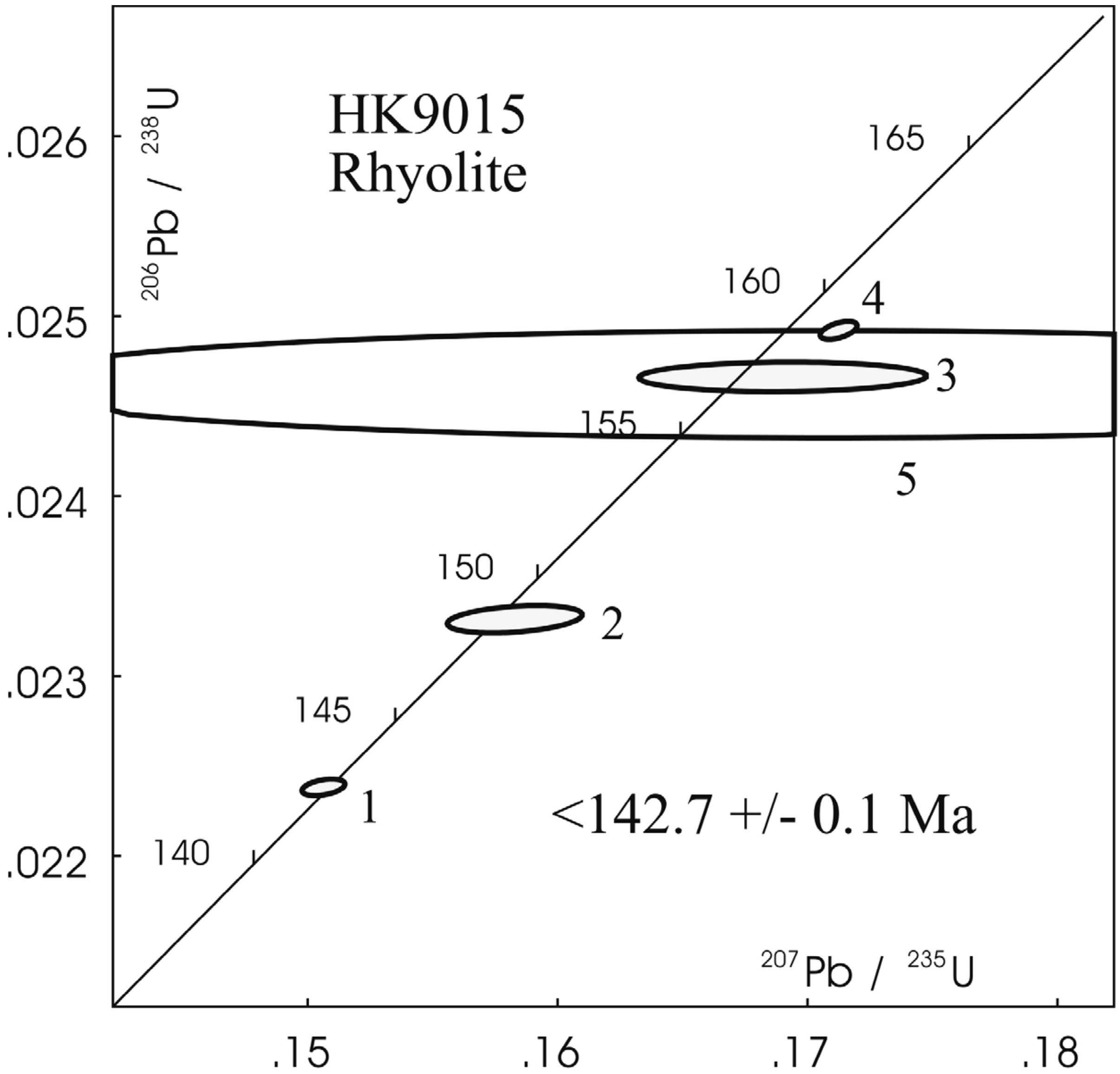
The sample yielded only a few hundred zircon grains, most of which are quite small and cracked. The zircons are typically euhedral with well-developed low-order crystal faces and abundant melt inclusions, as well as small apatite crystals and some small opaque inclusions that appear to be sulphides.

No evidence of cores was seen. Grains were picked to be as transparent and free of cracks as possible, then abraded in order to minimize the possibility of secondary Pb loss. This is unlikely to be significant given the moderate U concentration and young age of the zircons. Fractions were also picked that displayed the typical morphologies and grain characteristics of the population, which are also typical of other rocks analysed from Hong Kong. Rounded and inclusion-free grains were avoided, and fractions were limited to as few grains as possible to minimize the possibility of including xenocrysts or inherited components.

For Mesozoic and younger rocks, $^{206}Pb/^{238}U$ ages are typically much more accurate than $^{207}Pb/^{235}U$ and $^{207}Pb/^{206}Pb$ ages because of the low concentration of ^{235}U and ^{207}Pb isotopes. Ages are corrected for ^{230}Th disequilibrium, using the calculated Th/U ratios of the zircons based on first-order $^{206}Pb/^{238}$ U age estimates and measured $^{208}Pb/^{206}Pb$ ratios, and assuming a Th/U value in the magma of 4.2, the terrestrial average. This increases the $^{206}Pb/^{238}U$ ages by 90 Ka. Errors are plotted as 2 sigma ellipses in the accompanying figure. The figure shows that the zircons contain abundant inheritance, either in the form of xenocrysts or invisible cores. Two of the analyses also show common Pb well above blank levels (typically 0.5 to 2.0 pg). Fraction 5 contained a particularly large amount of common Pb, which greatly increases its $^{207}Pb/^{235}U$ age error beyond the scale of the figure. This may be due to high common Pb inclusions such as galena. Common Pb in excess of blank was corrected assuming an isotopic composition on the Stacey and Kramers growth curve at 143 Ma.

A reliable age estimate cannot be determined from this rock because none of the precise concordant data points overlap within error. The youngest analysis, which is concordant, has a $^{206}Pb/^{238}U$ age of 142.7 ± 0.1 Ma. This is an older age limit for eruption of the rhyolite. Two previous studies on the geochronology of Hong Kong rocks have identified resolvable episodes of igneous activity at 236 Ma, 159-165 Ma, 146 Ma, 143 Ma and 141 Ma, based on analyses of 22 rocks. Therefore, it is likely that sample HK9015 is either 143 Ma or 141 Ma in age, unless there is a still younger undiscovered episode. The other data points are resolvably older, but still almost concordant, indicating that the source of inheritance is Phanerozoic. Inheritance of this kind was found to be common with zircons from the 141-146 Ma episodes in previous studies and likely results from contamination with underlying 159-165 Ma old rocks. These older rocks were also found to contain inheritance but from a wide range of mid-Proterozoic and Archean sources.

No.	Fraction	Weight (mg)	U (ppm)	Th/U	Pbcom (pg)	206Pb/ 204Pb	206Pb/ 238U	207Pb/ 235U	206/238 Age (Ma)	1 sig	207/205 Age (Ma)	1 sig	207/206 Age (Ma)	1 sig	Disc. (%)
1	3 Zircon grains	0.008	415	0.67	1.5	3121.7	0.022382	0.15063	142.69	0.14	142.46	0.38	138.7	6.1	-2.9
2	1 Zircon grain	0.010	246	0.40	2.5	1483.1	0.023316	0.15828	148.58	0.24	149.20	1.18	159.0	19.0	6.7
3	2 Zircon grains	0.010	519	0.66	29.3	296.1	0.024662	0.16901	157.06	0.26	158.56	2.51	181.0	40.0	13.4
4	17 Zircon grains	0.015	477	0.52	3.0	3856.4	0.024921	0.17124	158.68	0.15	160.50	0.32	187.4	4.3	15.5
5	4 Zircon grains	0.014	325	0.68	123.6	76.1	0.024621	0.17081	156.80	0.94	160.12	14.9	209.6	213.0	25.5


HK9015
Rhyolite
<142.7 +/- 0.1 Ma
^{206}Pb / ^{238}U
^{207}Pb / ^{235}U
.026
.025
.024
.023
.022
.15
.16
.17
.18
140
145
150
155
160
165
1
2
3
4
5

U-PB GEOCHRONOLOGY OF ZIRCON FROM PLUTONIC AND VOLCANIC ROCKS IN HONG KONG

JUNE 3, 1998

R. WALTER AND D. W. DAVIS
EARTH SCIENCE DEPT.
ROYAL ONTARIO MUSEUM
100 QUEEN'S PARK
TORONTO, ONTARIO
M5S 2C6

1. SAMPLES

Six samples were received for U-Pb geochronology and are listed below.

1) HK12021 Tuff
2) HK12022 Monzonite
3) HK12023 Quartz monzonite
4) HK12025 Tuff
5) HK12026 Rhyodacite lava
6) X188 Granite

2. ANALYTICAL METHODS

Sample crushing was with a jaw crusher followed by a disk mill. Samples were 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 to be usually accurate to about ± 50%. This affects only U concentrations, not age information, which depends on isotopic ratio measurements (Table 1).

Zircon was dissolved using HF in teflon bombs at 200ºC, 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 analyzed 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.

3. RESULTS

All samples yielded zircon, in varying abundance. Crack-free zircons without evidence of cores or alteration were selected for abrasion.

Most of the zircon populations show similar characteristics. Zircon crystals are generally colourless, euhedral, doubly-terminated prisms of varying length. Low-order crystal faces are generally well-developed and many grains have inclusions, including round or amorphous melt inclusions and apatite rods.

Because of depletion of the shorter half-life ^{235}U isotope, there is much less ^{207}Pb than ^{206}Pb for relatively young samples. For Mesozoic and younger samples, $^{206}Pb/^{238}U$ ages are much more precise and reliable than $^{207}Pb/^{235}U$ ages, and $^{207}Pb/^{206}Pb$ ages are quite imprecise because the concordia curve is nearly parallel to a line through the origin. Therefore, ages for these samples are calculated as $^{206}Pb/^{238}U$ ages. $^{206}Pb/^{238}U$ ages are sensitive to secondary Pb loss, but 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).

Inheritance is present in some of the samples, due to the presence of xenocrysts or invisible cores. Rounded violet-coloured zircons were found in some fractions and are obvious xenocrysts. The probability of accidentally including an inherited zircon increases with the number of grains picked for a fraction. To avoid inheritance, a minimum number of zircons were analyzed in a fraction and 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. Inclusions may account for high common Pb values in some of the samples. Even fairly substantial amounts of common Pb (10's of picrgrams) have only a small effect on the $^{206}Pb/^{238}U$ age precision. Common Pb corrections below 10 pg are made assuming an isotopic composition similar to laboratory blank. Excess common Pb is corrected using the Stacey and Kramers (1975) value, which represents a crustal average. Concordia co-ordinates and ages in Table 1 are corrected for fractionation, blank and spike. $^{206}Pb/^{204}Pb$ values are corrected for fractionation and spike.

The plotted data, as well as the ages in Tables 1 and 2, 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. The concordia co-ordinates in Table 1 are quoted as measured values, uncorrected for assumed disequilibrium. Th/U is calculated from the measured $^{208}Pb/^{206}Pb$ ratio and $^{207}Pb/^{206}Pb$ age.

Ages, errors and probabilities of fit are calculated from the Davis (1982) program, modified for fitting $^{206}Pb/^{238}U$ data. U decay constants are from Jaffey et al. (1971). A summary of results is given in Table 2. 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 or disturbed data. Errors are quoted at the 95% confidence level in the text and Table 2. Errors in Table 1 are quoted as 1σ Error ellipses are given at $2\ \sigma$ on figures 1 to 6. Digital mass spectrometer outputs are included in disk form with this report.

3.1 HK12021 (Fig. 1A, 1B & 1C)

This sample yielded only a small amount of zircon, as stubby euhedral grains, with some development of high order crystal faces. Small melt inclusions are common. A high proportion of the grains are altered. A few rounded violet grains were found. Two of these were analysed to determine the age of the xenocrystic component.

Three fractions of euhedral grains are concordant and define a $^{206}Pb/^{238}U$ age of 164.7 ± 0.3 Ma (Fig. 1A). A fourth euhedral fraction contained an inherited component, probably due to an invisible core. The age of the inheritance is 1081 ± 250 Ma (Fig. 1B). The two violet grains produced slightly discordant analyses with much older $^{207}Pb/^{206}Pb$ ages, 1844 ± 2 Ma and 1878 ± 3 Ma (Fig. 1C). These are minimum ages, but are probably close to the age of the rocks that produced the xenocrysts.

3.2 HK12022 (Fig. 2)

This sample produced abundant zircon as very fresh, euhedral, prismatic grains, many with high order crystal faces. Large amorphous melt inclusions are common in these grains.

Four fractions produced concordant data points that agree within error and define a $^{206}Pb/^{238}U$ age of 140.6 ± 0.3 Ma (Fig. 2). Two of the analyses are much less precise because of the small amount of Pb that they contained as well as, in one case, an unusually high amount of common Pb. The close agreement over such a wide range of radiogenic to common Pb ratios demonstrates that sources of systematic error, such as incorrect common Pb isotopic compositions, are probably minimal.

3.3 HK12023 (Fig. 3)

This sample yielded a small amount of zircon, but the grains are very fresh and morphologically similar to HK12022. Four concordant data points overlap and define a $^{206}Pb/^{238}U$ age of 140.6 ± 0.3 Ma (Fig. 3).

3.4 HK12025 (Fig. 4A and 4B)

This yielded a moderately large amount of zircon as fresh, euhedral, prismatic grains with abundant melt inclusions. Six single grains were analysed. Five of these produced concordant data points but with a scatter that is slightly outside of error. The oldest concordant analysis is from a grain that was thought to have a core. The other four analyses define an age of 164.4 ± 0.2 Ma but with a marginal 11% probability of fit. The three youngest data are in good agreement and define an age of 164.2 ± 0.3 Ma with a 59% probability of fit (Fig. 4A). This result is least likely to be biased by inheritance and is therefore considered the best estimate for the age of eruption. A rounded violet xenocryst produced an analysis that is near concordia at a Paleoproterozoic age (Fig. 4B). This defines an upper intercept age of 2022 ± 2 Ma with the other data points.

3.5 HK12026 (Fig. 5)

This sample yielded a small amount of zircon as fresh, euhedral prismatic grains, some with well developed high order crystal faces. Four fractions produced concordant overlapping data points that define a $^{206}Pb/^{238}U$ age of 164.1 ± 0.2 Ma (Fig. 5).

3.6 X188 (Fig. 6A and 6B)

This sample yielded very little zircon, of which a high proportion is altered. The zircons are generally euhedral, short prismatic grains, many with well-developed high order crystal faces. Three euhedral fractions produced overlapping concordant data that define a $^{206}Pb/^{238}U$ age of 142.8 ± 0.2 Ma (Fig. 6A). An analysed single zircon grain proved to contain inheritance (Fig. 6B). It defines an upper concordia intercept age of 1091 ± 11 Ma when regressed with the other data.

4. DISCUSSION

Ages measured in the present work correlate with Mid-Jurassic to Cretaceous episodes of igneous activity that were previously defined for the Hong Kong region (Davis et al. 1997). The plutonic samples HK12022 and HK12023 give the same age of 140.6 ± 0.3 Ma. This correlates with the youngest episode of magmatism, which was previously dated on the Clearwater Bay and High Island Formations, and on the Kowloon and Tong Fuk plutons. The 142.8 ± 0.2 Ma age of X188 correlates with the next oldest episode, previously measured on the Long Harbour, Sai Kung, Ap Lei Chau and Che Kwu Shan Formations. The volcanic rocks HK12025 and HK12026 give the same ages within error at 164.2 ± 0.3 and 164.1 ± 0.2 Ma, respectively. The tuff HK12021 is part of the same volcanic episode but appears to be slightly older at 164.7 ± 0.3 Ma. These ages broadly correlate with a 164.5 Ma episode of magmatism previously measured on the Yim Tin Tsai and possibly the Tai Mo Shan formations, as well as on the Tai Po granodiorite.

5. REFERENCES

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Table 1 (Sheet 1 of 2)

No.	Fraction	Weight (mg)	U (ppm)	Th/U	PbCom (pg)	206/204	206/238	207/235	206/238 Age (Ma)	1 sigma	207/235 Age (Ma)	1 sigma	207/206 Age (Ma)	1 sigma	Disc. %
	HK12021	**Tuff**													
1	4 Ab zr	0.010	296	0.56	1.6	3155	0.02584	0.1758	164.43	0.28	164.47	0.46	165.0	6.8	0.4
2	1 Ab zr, incl	0.007	136	0.60	2.0	818	0.02587	0.1773	164.66	0.29	165.75	1.39	181.4	20.9	9.3
3	2 Ab zr, incl	0.016	131	0.41	0.8	4217	0.02592	0.1768	164.99	0.24	165.32	0.45	170.1	6.3	3
4	1 Ab zr, incl	0.007	160	0.48	2.8	757	0.02909	0.2117	184.85	0.37	194.97	1.68	319.3	21.1	42.7
5	1 Ab zr, rnd, violet	0.005	198	0.90	1.5	13945	0.32534	5.0566	1815.76	2.11	1828.86	1.22	1843.8	1.2	1.7
6	1 Ab zr, rnd, violet	0.002	224	0.15	0.8	11832	0.33658	5.3312	1870.20	2.18	1873.89	1.24	1878.0	1.3	0.5
	HK12022	**Monzonite**													
7	3 Ab zr, incl	0.015	100	n.m.	1.5	1480	0.02202	0.1474	140.44	0.21	139.58	0.70	125.0	12.3	-12.5
8	1 Ab zr	0.006	40	0.82	2.6	149.9	0.02205	0.1497	140.61	0.66	141.66	7.08	159.3	127.2	11.9
9	1 Ab zr	0.025	47	0.74	1.6	1050	0.02209	0.1487	140.86	0.24	140.74	0.97	138.8	17.0	-1.5
10	1 Ab zr	0.004	104	0.81	13.7	61.47	0.02224	0.1538	141.81	1.22	145.23	19.79	201.3	206.6	29.9
	HK12023	**Quartz monzonite**													
11	1 Ab zr	0.003	152	0.67	1.9	360	0.02202	0.1487	140.42	0.31	140.79	2.83	147.1	50.2	4.6
12	1 Ab zr, elong	0.008	67	0.67	1.1	699	0.02203	0.1469	140.46	0.26	139.18	1.55	117.5	27.7	-19.7
13	2 Ab zr, incl	0.008	142	0.56	0.7	2378	0.02207	0.1473	140.69	0.22	139.51	0.58	119.5	10.0	-17.9
14	1 Ab zr	0.003	245	0.50	3.9	283	0.02210	0.1497	140.88	0.34	141.67	3.33	154.9	59.4	9.2
	HK12025	**Tuff**													
15	1 Ab zr	0.010	181	0.58	4.0	758	0.02577	0.1756	164.01	0.27	164.26	1.37	167.9	21.1	2.3
16	1 Ab zr, incl	0.010	342	0.61	3.2	1766	0.02581	0.1760	164.30	0.23	164.58	0.63	168.6	9.4	2.6
17	1 Ab zr, elong, incl	0.015	246	0.59	8.3	750	0.02583	0.1759	164.38	0.27	164.53	1.36	166.7	20.8	1.4
18	1 Ab zr, elong, incl	0.020	242	0.54	20.7	405	0.02591	0.1774	164.91	0.26	165.82	1.80	178.9	27.4	7.9
19	1 Ab zr, brn, core?, incl	0.015	350	0.50	50.5	190.4	0.02604	0.1804	165.71	0.38	168.37	4.67	205.8	71.0	19.7
20	1 Ab zr, rnd, violet, crk	0.005	403	0.14	1.2	38192	0.34195	5.8501	1896.06	3.20	1953.86	1.73	2015.7	1.1	6.8

Table 1 (Sheet 2 of 2)

No.	Fraction	Weight (mg)	U (ppm)	Th/U	PbCom (pg)	206/204	206/238	207/235	206/238 Age (Ma)	1 sigma	207/235 Age (Ma)	1 sigma	207/206 Age (Ma)	1 sigma	Disc. %
	HK12026	**Rhyodacite lava**													
21	3 Ab zr, elong	0.008	139.3	0.52	0.7	2603	0.02575	0.1748	163.92	0.21	163.57	0.50	158.5	7.5	-3.5
22	1 Ab zr	0.004	300.8	0.67	1.7	1201	0.02577	0.1763	164.04	0.30	164.86	1.02	176.5	15.3	7.2
23	3 Ab zr	0.015	73	0.60	0.7	2479	0.02582	0.1744	164.31	0.22	163.23	0.62	147.6	9.1	-11.5
24	3 Ab zr, incl	0.012	121.2	0.50	0.6	3863	0.02579	0.1752	164.11	0.31	163.94	0.49	161.4	7.0	-1.7
	X188	**Granite**													
25	4 Ab zr, incl, crk	0.008	426.5	0.58	0.7	7512	0.02239	0.1512	142.75	0.21	143.00	0.34	147.1	5.3	3.0
26	3 Ab zr, incl	0.008	273	0.52	0.8	3869	0.02241	0.1510	142.87	0.21	142.80	0.35	141.7	5.6	-0.8
27	2 Ab zr, incl	0.012	484.6	0.59	1.0	8566	0.02241	0.1511	142.86	0.22	142.86	0.28	142.9	4.5	0.0
28	1 Ab zr	0.005	388.5	0.38	1.1	5752	0.04962	0.4497	312.21	0.48	377.06	0.63	797.6	3.8	62

Table 2 - Summary of Ages from Hong Kong Samples

SAMPLE	206Pb/238U Age (Ma)	Probability of Fit (%)	Number of Points	Inheritance (Ma)
HK12021	164.72 ± 0.28	31	3	1080 , 1880
HK12022	140.64 ± 0.28	44	4	none
HK12023	140.60 ± 0.25	67	4	none
HK12025	164.23 ± 0.27	59	3	2022
HK12026	164.10 ± 0.23	65	4	none
X188	142.82 ± 0.23	90	3	1090

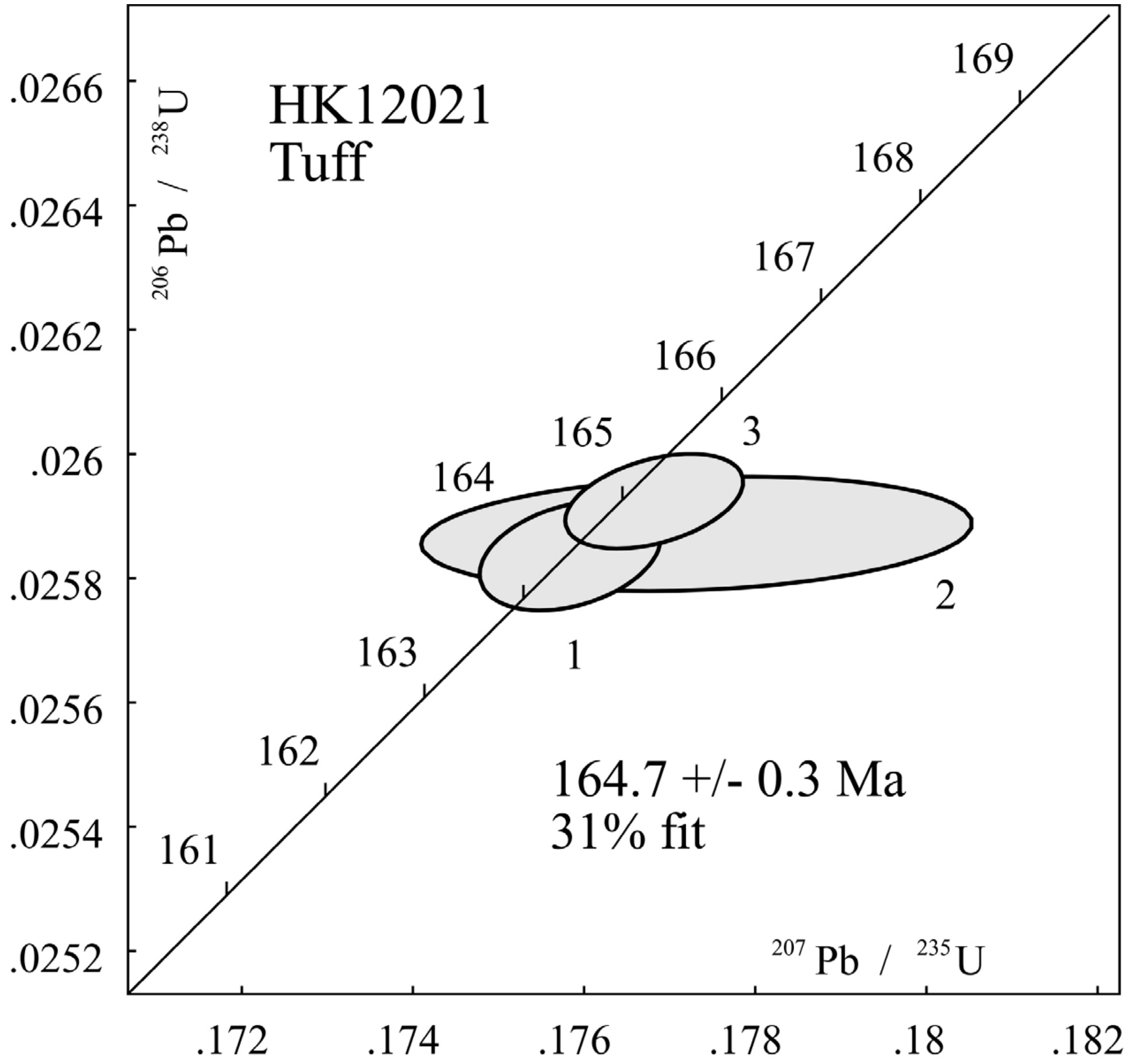

HK12021
Tuff
164.7 +/- 0.3 Ma
31% fit
169
168
167
166
165
164
163
162
161
1
2
3
.0266
.0264
.0262
.026
.0258
.0256
.0254
.0252
.172
.174
.176
.178
.18
.182
206 Pb / 238 U
207 Pb / 235 U

Figure 1A

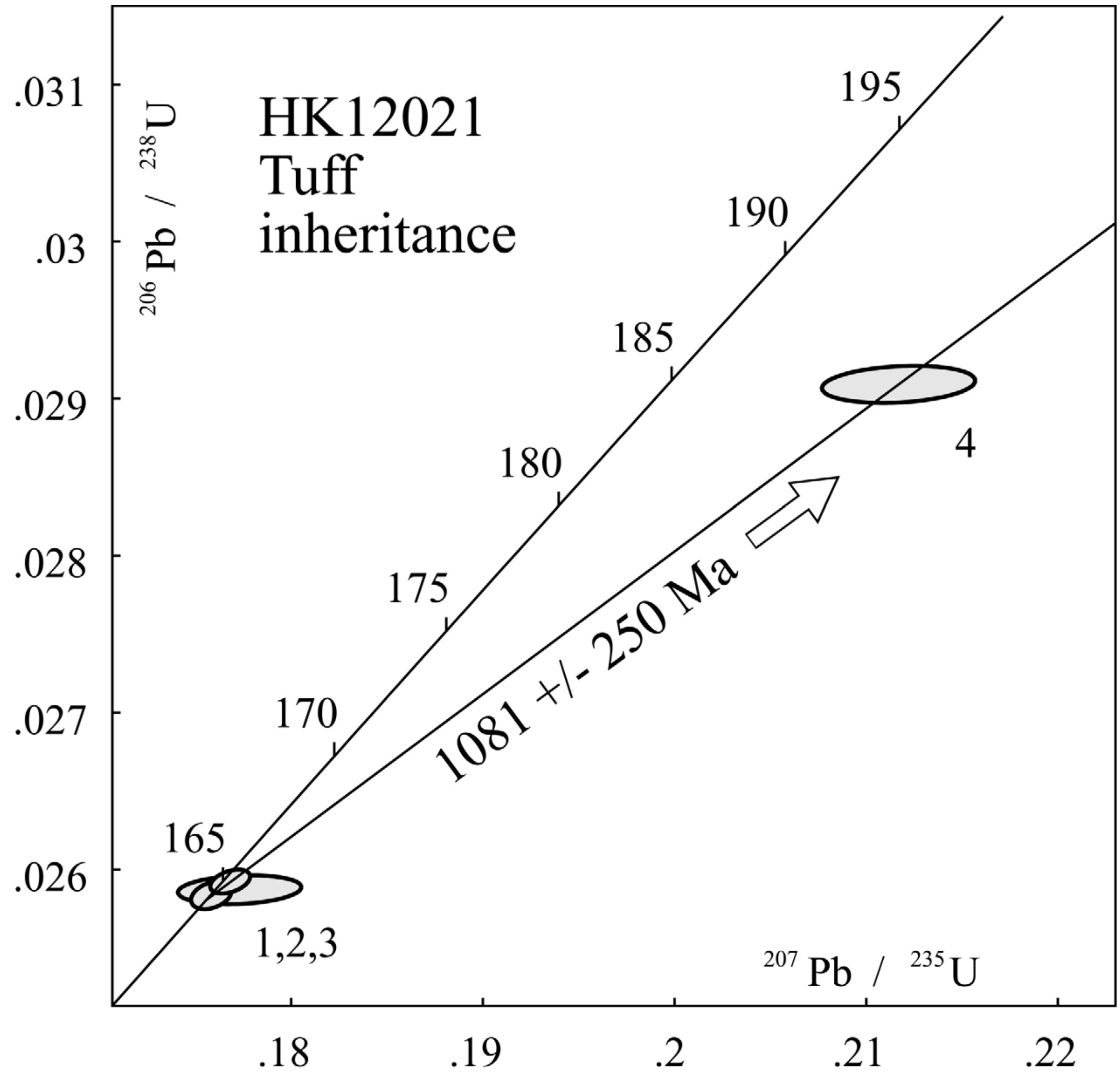

HK12021
Tuff
inheritance
^{206}Pb / ^{238}U
^{207}Pb / ^{235}U
.031
.03
.029
.028
.027
.026
.18
.19
.2
.21
.22
165
170
175
180
185
190
195
1,2,3
4
1081 +/- 250 Ma

Figure 1B

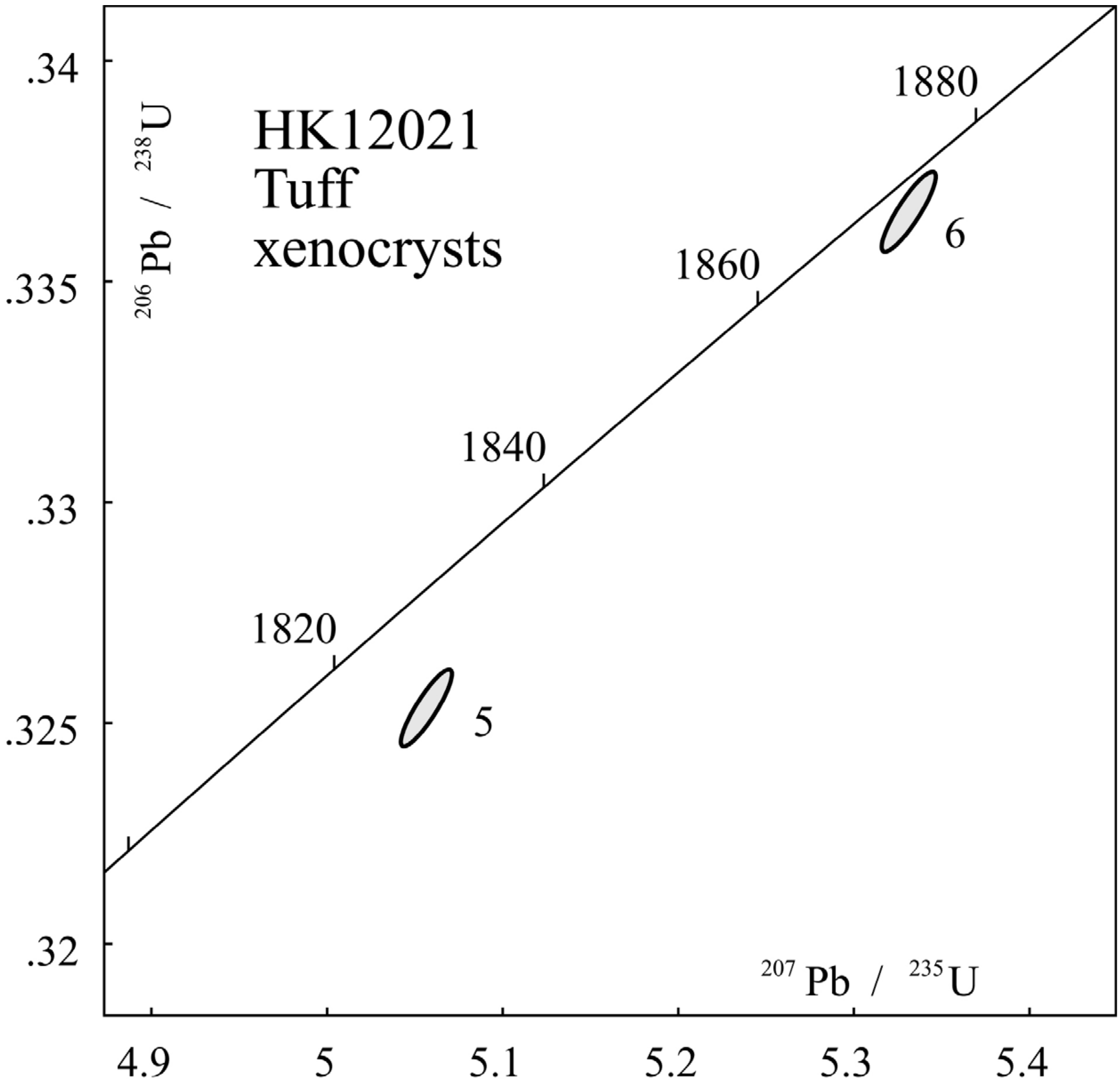

.34
.335
.33
.325
.32
^{206}Pb / ^{238}U
HK12021
Tuff
xenocrysts
1880
1860
1840
1820
6
5
^{207}Pb / ^{235}U
4.9
5
5.1
5.2
5.3
5.4

Figure 1C

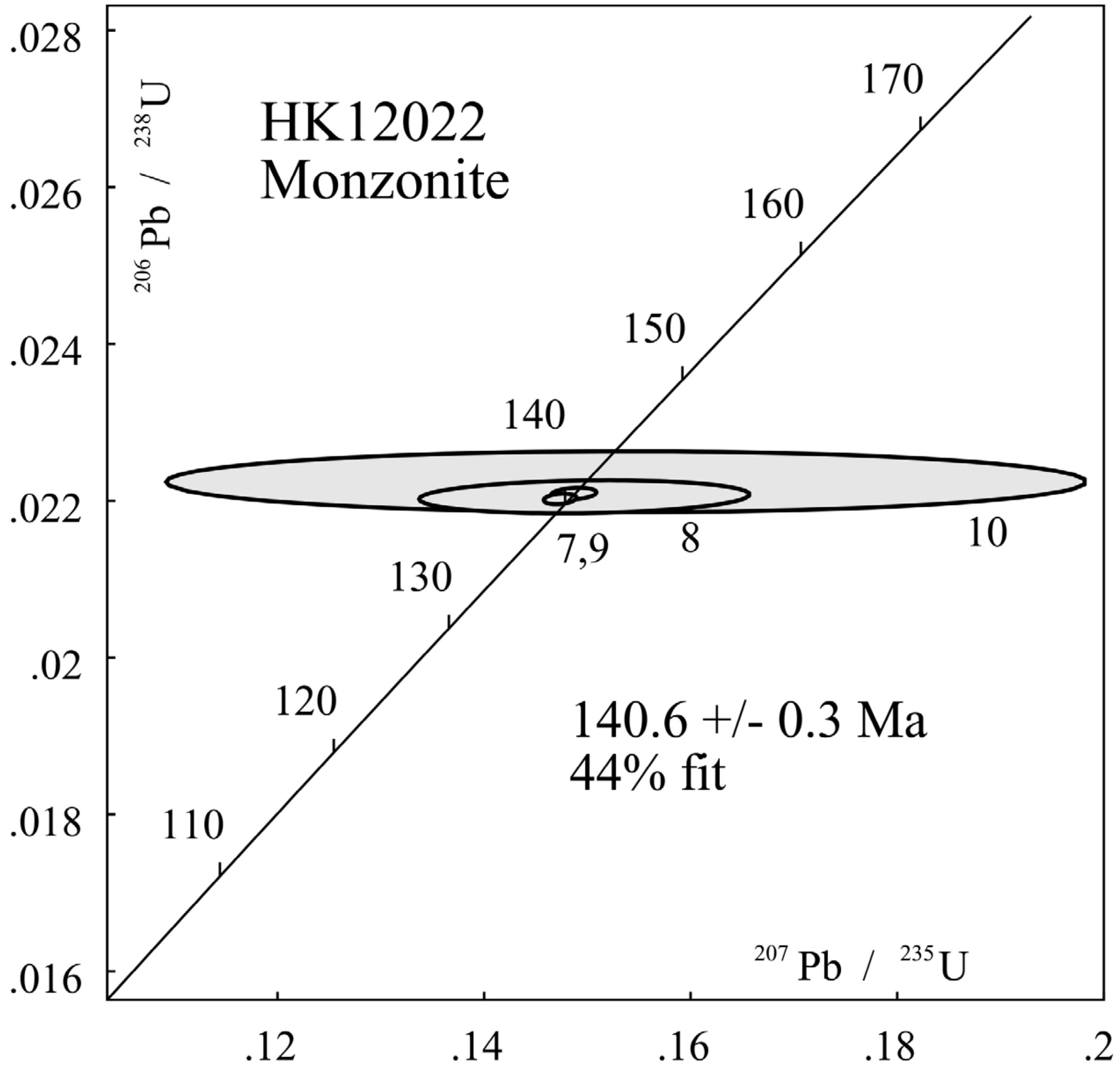

.028
.026
.024
.022
.02
.018
.016
^{206}Pb / ^{238}U
HK12022
Monzonite
170
160
150
140
130
120
110
7,9
8
10
140.6 +/- 0.3 Ma
44% fit
^{207}Pb / ^{235}U
.12
.14
.16
.18
.2

Figure 2

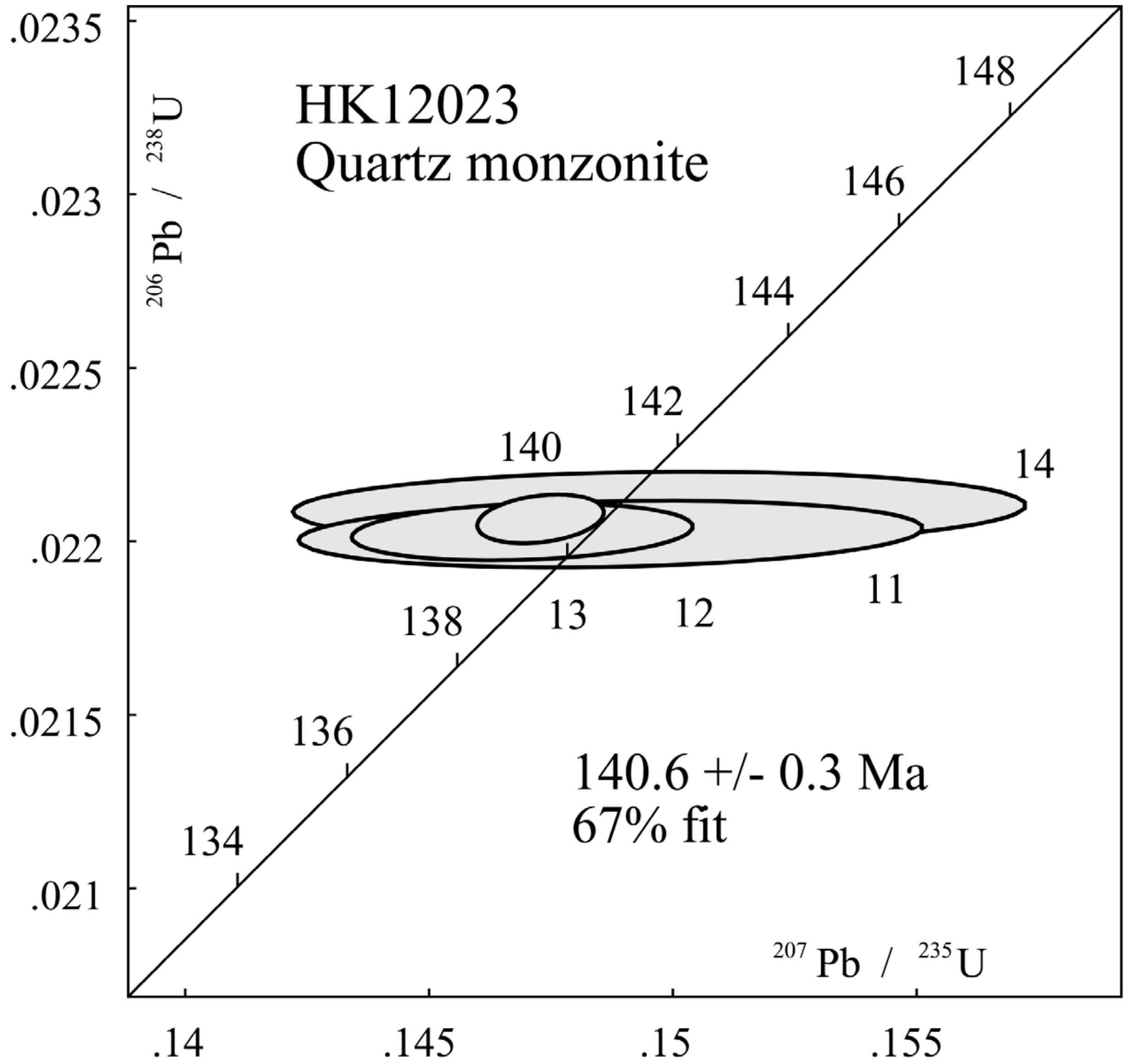

.0235
.023
.0225
.022
.0215
.021
^{206}Pb / ^{238}U
HK12023
Quartz monzonite
148
146
144
142
140
14
11
13
12
138
136
134
140.6 +/- 0.3 Ma
67% fit
^{207}Pb / ^{235}U
.14
.145
.15
.155

Figure 3

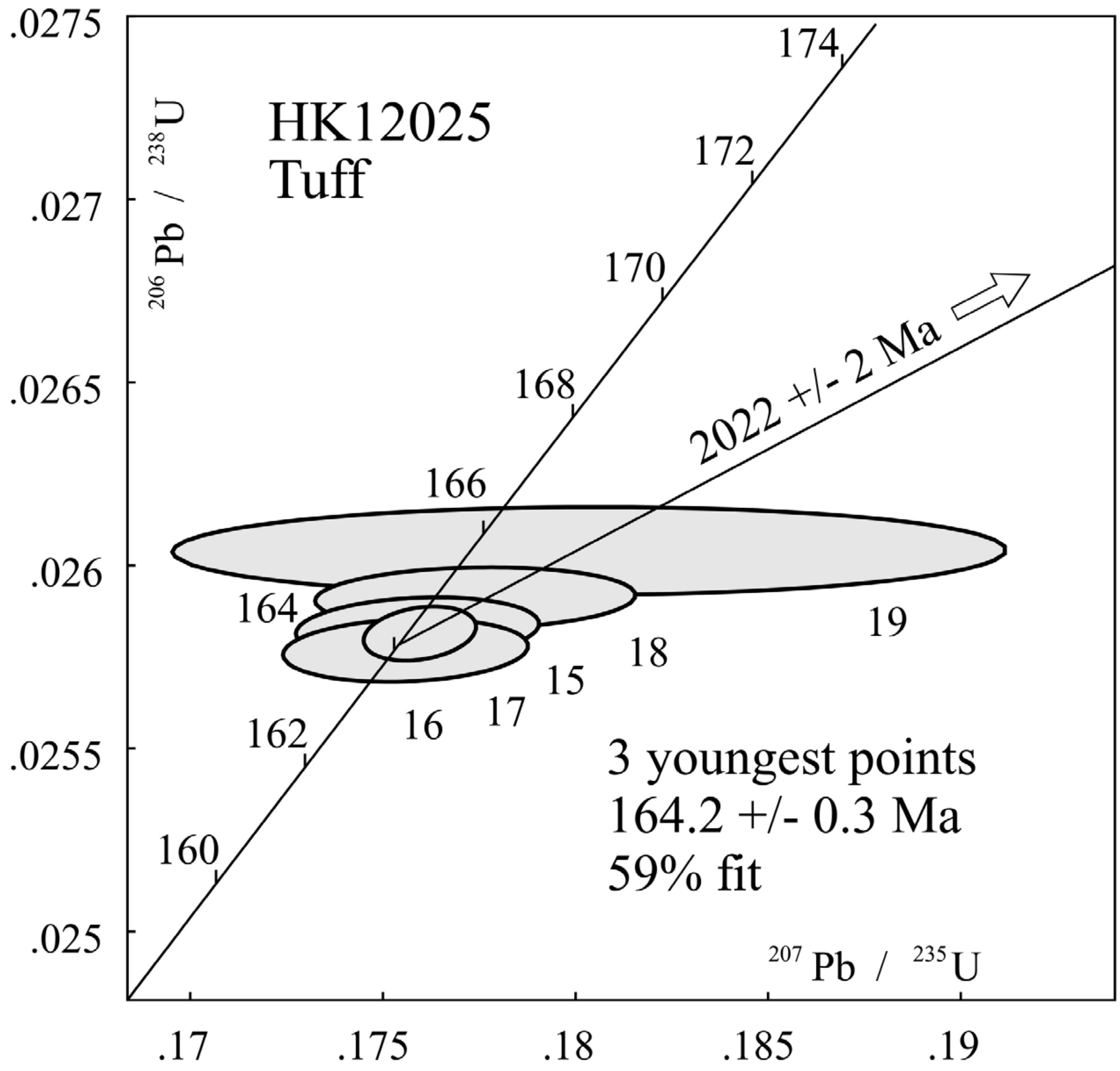

.0275
.027
.0265
.026
.0255
.025
^{206}Pb / ^{238}U
HK12025
Tuff
174
172
170
168
166
164
162
160
2022 +/- 2 Ma
19
18
15
17
16
3 youngest points
164.2 +/- 0.3 Ma
59% fit
^{207}Pb / ^{235}U
.17
.175
.18
.185
.19

Figure 4A

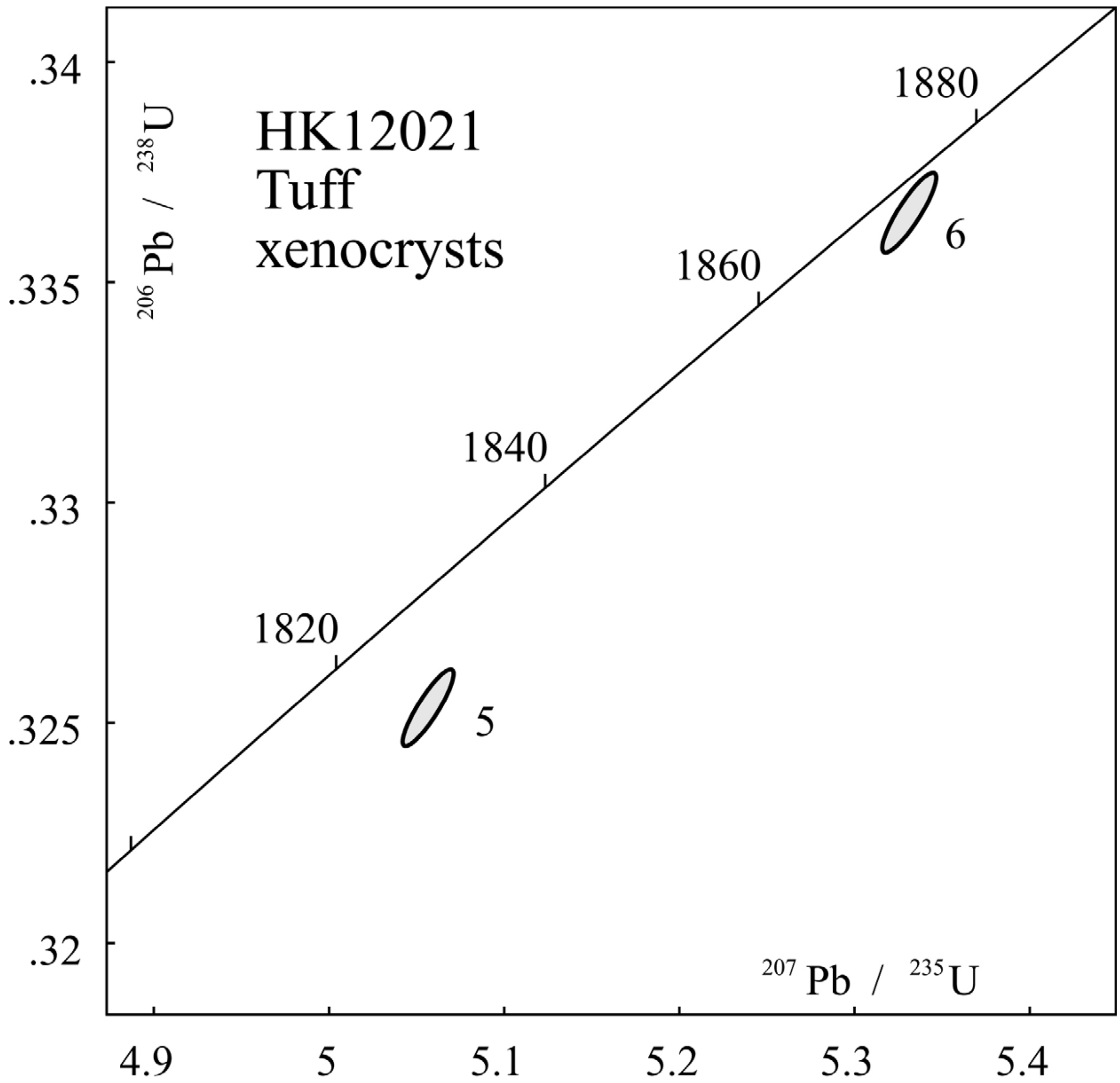

HK12021
Tuff
xenocrysts
1880
1860
1840
1820
6
5
.34
.335
.33
.325
.32
4.9
5
5.1
5.2
5.3
5.4
206Pb / 238U
207Pb / 235U

Figure 4B

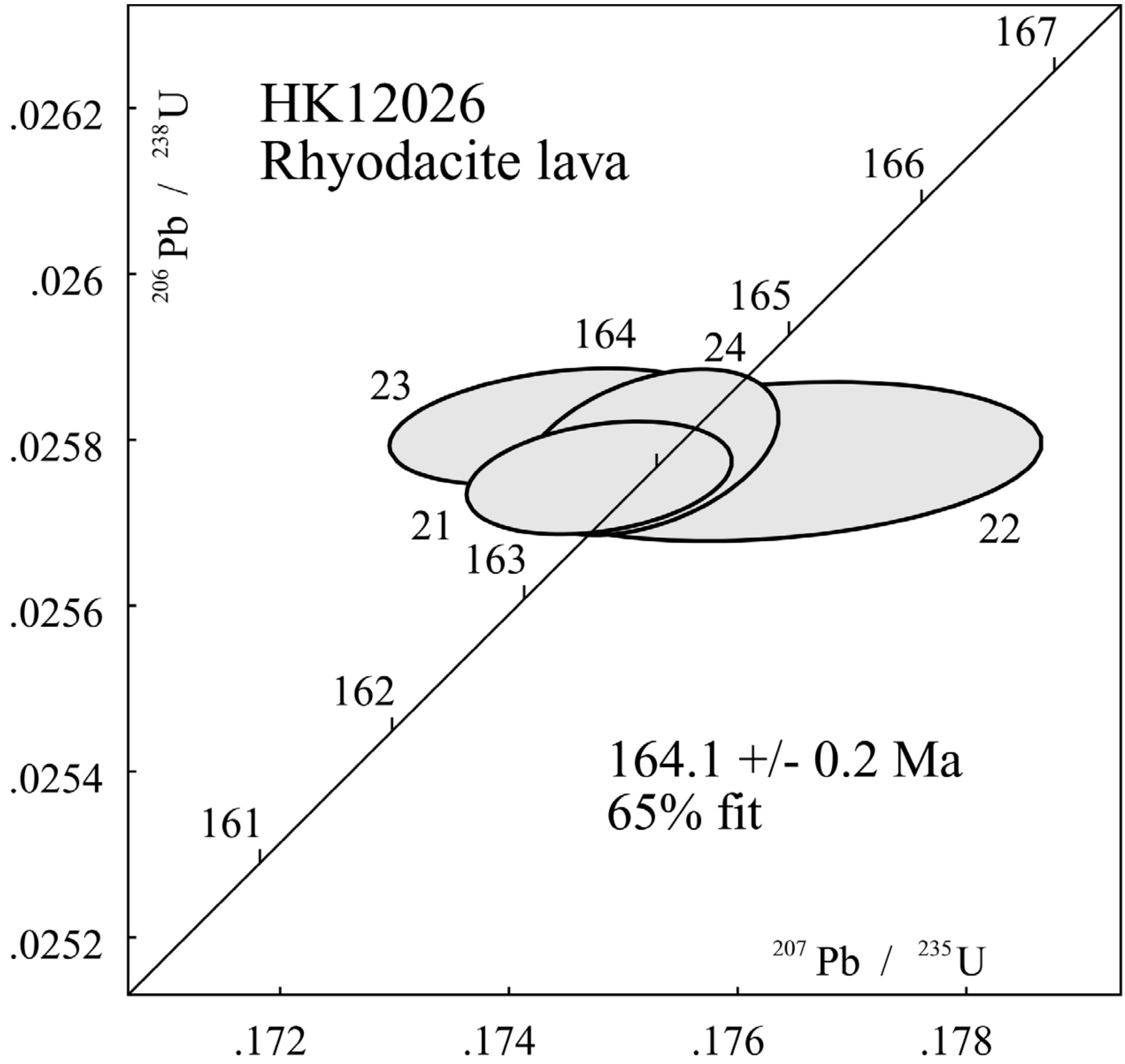

HK12026
Rhyodacite lava
164.1 +/- 0.2 Ma
65% fit
$^{206}Pb / ^{238}U$
$^{207}Pb / ^{235}U$
.0262
.026
.0258
.0256
.0254
.0252
.172
.174
.176
.178
161
162
163
164
165
166
167
21
22
23
24

Figure 5

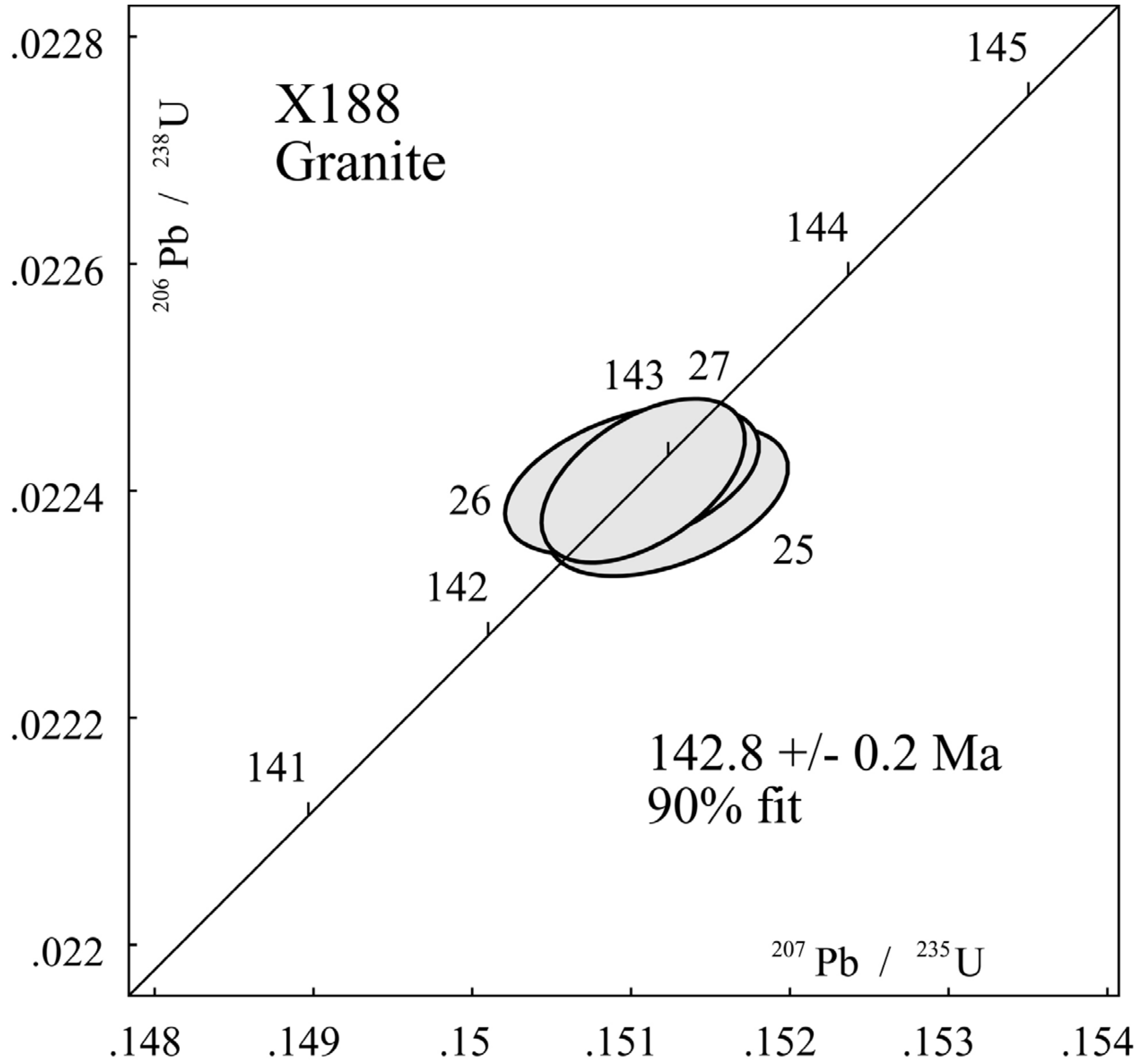
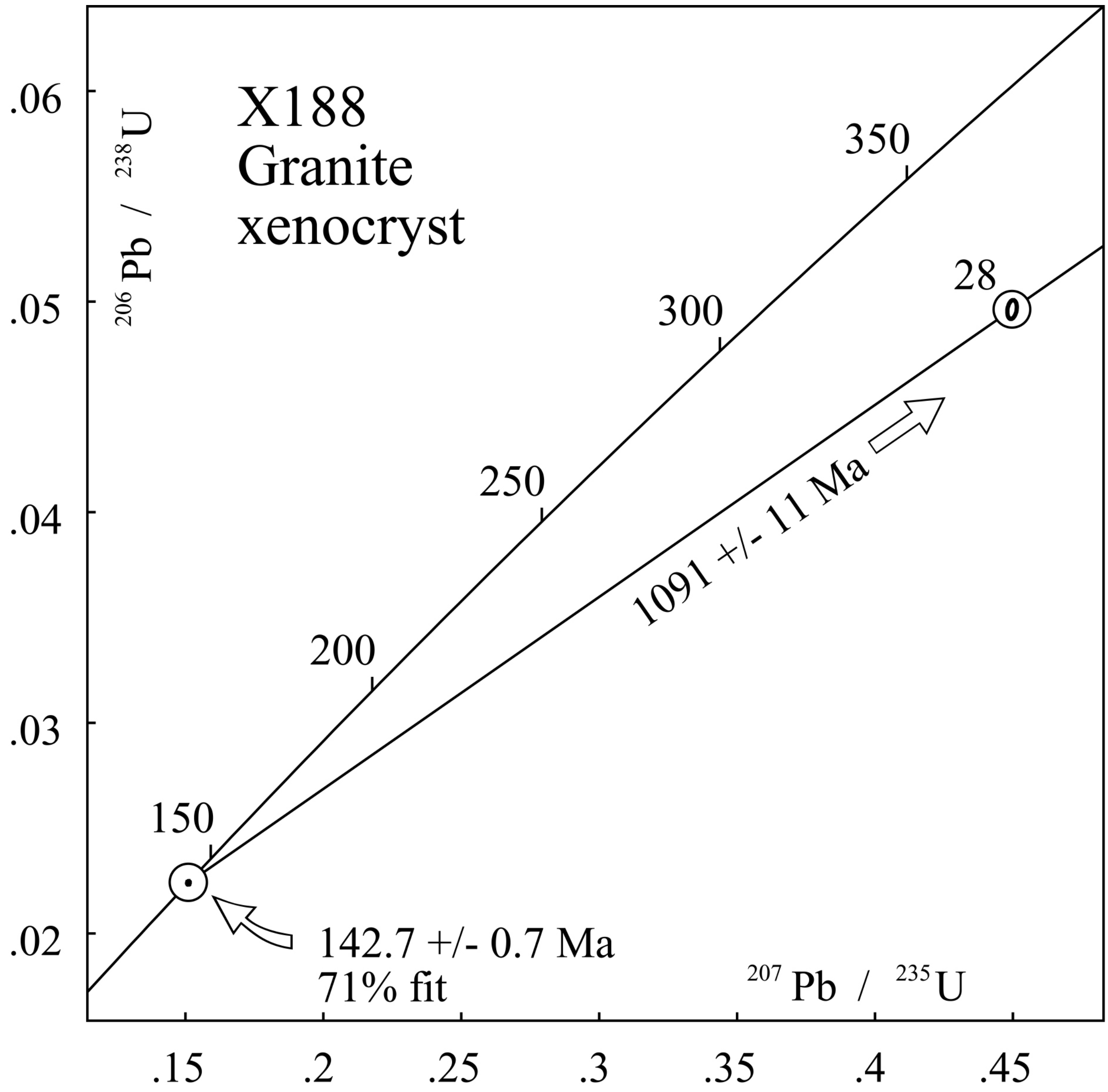

.0228
.0226
.0224
.0222
.022
^{206}Pb / ^{238}U
X188
Granite
145
144
143
27
26
25
142
141
142.8 +/- 0.2 Ma
90% fit
^{207}Pb / ^{235}U
.148
.149
.15
.151
.152
.153
.154

Figure 6A



X188
Granite
xenocryst
$^{206}Pb / ^{238}U$
$^{207}Pb / ^{235}U$
.06
.05
.04
.03
.02
.15
.2
.25
.3
.35
.4
.45
150
200
250
300
350
28
1091 +/- 11 Ma
142.7 +/- 0.7 Ma
71% fit

Figure 6B