Geological Society of Malaysia Annual Geological Conference 2001
June 2–3 2001, Pangkor Island, Perak Darul Ridzuan, Malaysia

Preliminary uranium series dates on speleothem in the Kinta Valley and its significance in the karst landscape evolution

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Abstract: Uranium series dating technique has been used in dating cave materials and give estimation of up to 500 ka. The ^{230}Th / ^{234}U method has been proven to be the most versatile and useful of all the uranium series methods and has been applied to a wide range of materials including speleothems in which the optimal range being around 350 ka using the alpha spectrometer and 500 ka for mass spectrometer. This technique has been used in dating speleothem samples from Kinta Valley caves. The preliminary ages obtained show some indications that it can be correlated to the rate of denudation in this area. These ages when combined with the rate of denudation and studies of slope processes will help in better understanding the evolution of karst landscape.

Abstrak: Teknik siri uranium telah digunakan dalam penentuan umur bahan-bahan enapan gua dan anggaran umur sehingga 500 ribu tahun diberi. Kaedah ^{230}Th / ^{234}U telah dibuktikan yang paling versatil dan berguna dalam semua kaedah siri uranium dan telah diaplikasikan kepada pelbagai bahan termasuk speleothem di mana julat optimum adalah sekitar 350 ribu tahun menggunakan alpha spektrometer dan 500 ribu tahun menggunakan mass spektrometer. Teknik ini telah digunakan dalam menentukan umur speleotherm dari gua-gua di Lembah Kinta. Keputusan awal menunjukkan umur-umur yang didapati memberi tanda yang ianya boleh digunakan untuk korelasi dengan kadar denudasi di kawasan ini. Umur-umur ini bila digabungkan dengan kadar denudasi dan kajian proses cerun boleh menolong dalam memahami evolusi landskap karst.

INTRODUCTION

Uranium series dating methods have been of great importance in Quaternary geology. This technique is not only applicable to a wide range of geological materials but it also can provide reliable dates of up to 500,000 years in age. Many caves contain layers or concretions of inorganically precipitated calcium carbonate or speleothem as cave floor material or as stalactites and stalagmites. These precipitates can, in many instances, be dated by measurements of the disequilibrium between the isotopes of uranium and their various radioisotopic daughters, over the time range from about 5,000 to 500,000 years (Schwarcz, 1980)

The ^{230}Th / ^{234}U method has been proven to be the most versatile and useful of all the uranium series methods and has been applied to a wide range of materials including speleothems in which the optimal range being around 350 ka using the alpha spectrometer and 500 ka for Mass Spectrometry (Smart, 1991).

The uranium series age determination of the speleothems collected from the limestone hills of the Kinta Valley was carried out to bracket some crucial dates in the formation of the karstic features.

GENERAL PRINCIPLES

When $CaCO_3$ is precipitated from natural waters, uranium ions that are present in solution are co-precipitated with the calcium ions and are trapped in the carbonate crystal lattice. Fission track studies of such precipitates show that the uranium is homogeneously distributed throughout the calcite crystal and not preferentially bound to crystal interfaces or are entrapped in the detritus.

Uranium is readily oxidised from the 4+ state, in which it is found as primary U-minerals (such as uraninite, absite, pitchblende and davidite) in igneous rocks, to the 6+ state in the form of the soluble uranyl ion $(UO_2)^{2+}$ (Langmuir, 1978). The oxidized U^{6+} state is the usual form in carbonate rocks. This ion is readily soluble, and frequently forms anion complexes in natural waters with carbonate and phosphate (Smart, 1991).

Whereas uranium is readily transported in groundwaters, thorium and protactinium are quickly hydrolyzed on dissolution of their primary host rock (e.g. limestone) and trapped in clay minerals and hydroxides in the soil; both these elements are present in negligible concentrations in groundwaters. Therefore calcareous deposits that are formed by precipitation from solutions (for example speleothems) can contain uranium but are free of its long-lived daughter isotopes, ^{230}Th ($t_{1/2}$ = 75,200 y) and ^{231}Pa ($t_{1/2}$ = 32,500 y).

With regards to the U-isotopes, the activity ratio of ^{234}U/^{238}U is generally found to be greater than unity in groundwaters due to the tendency of ^{234}U to be selectively leached from rocks during incipient weathering (Cherdyntsev, 1971). Because of this, therefore the ^{234}U/^{238}U ratio in precipitated carbonate is initially >1.0. With the passage of time after deposition, the decay of excess ^{234}U, into secular equilibrium with ^{238}U will then produce ^{231}

Pa, ^{230}Th daughter isotopes.

At the time of the formation, speleothems can contain traces (about 1 ppm) of uranium but are devoid of the daughter isotopes ^{230}Th and ^{231}Pa. Any content of the ^{230}Th and ^{231}Pa that are found subsequently in the speleothem is due to the decay of the ^{234}U with time. Thus the age of the speleothem deposit can be determined from the content of these daughter isotopes that are in secular equilibrium with the uranium. The age of the speleothem sample can be calculated based on the equation below (Ivanovich and Harmon, 1992):

$$230Th/234U = 1 - e^{-\lambda 230t}/(234U/238U) + \{1-1/(234U/238U)\}\ \lambda 230/(\lambda 230 - \lambda 234)\{1 - e^{-(\lambda 230-\lambda 234)t}\}$$

where λ denotes decay constant of a given isotope. The ^{230}Th half-life is of 75.38 ka, giving the $^{230}Th/^{234}U$ method a potential range of 350 ka. Note that a correction is applied for the presence of ^{238}U, which may maintain the activity of ^{234}U, affecting $^{230}Th/^{234}U$ ratio.

Detrital contaminants in the deposit may contribute ^{230}Th and ^{231}Pa as well as uranium all of which could be leached from old detrital clay particles. Other sources of error include leaching of U or Th from late recrystalization and cementation of the deposit by later generations of carbonates. Methods are proposed to correct these errors.

METHODOLOGY

Thompson (1973 in Farrant, 1995) was the first to demonstrate the validity of the $^{230}Th/^{234}U$ method and since then, the technique had been applied to many problems in the earth sciences. The chief dating method that uses the decay of excess ^{234}U to ^{230}Th has a normal limit of 350 ka (or approximately ten times the ^{14}C range) by the standard method of counting the α disintegration of the these isotopes (Ivanovich and Harmon, 1992). Substitution of atom counting by mass spectrometry may permit the extension of the detemination limit (Ford and Williams, 1989). Developments in mass spectrometric U-series techniques has enabled the age to be extended to about 500 ka with considerable increase in precision (Li *et al.*, 1989). Age determinations using the U-series methodology that have been published for sites in Europe and Asia, that have a range between 400,000 years to 12,000 years B.P are consistent with estimates based on archeological and geological evidence (Schwarcz, 1980)

The dating of speleothem by the Th/U disequilibrium method is now routine and is the method used here. This was carried out in the Soil Laboratory of the Department of Geographical Sciences, University of Bristol during September to December, 2000.

SAMPLE SELECTION AND COLLECTION

Speleothem samples from various parts of the Sungai Perak Basin were used in this study. Where possible, speleothem samples were collected where they would provide a good age constraint on the cave. In practice this meant sampling the basal portion (where possible) of the oldest speleothem in the cave. Although it is impossible to always pick the oldest speleothem, often a good idea can be obtained based on the physical condition (a compact spleothem is preferred), stratigraphic position and geomorphic location. However, where possible clean, non-porous uncontaminated insitu speleothem was collected. In order not to cause unnecessary damage to the cave environment, wherever possible, only broken, damaged and unaesthetic speleothem specimens were taken. A minimum of 500 g per sample of the speleothem was collected using hammers and chisels. For large size speleothem growth in the caves, a portable light weight corer was used to core to depths of 20 cm. The cored holes are sealed with the drilled powder and white cement. Generally the speleothems are rather fragile and using this method the 25 mm diameter cores are usually rather broken and the longest core is only about 10 cm long. For samples that are obtained using the corer about 30 cm aggregate core length is collected per sample and this give weights ranging from 200 to 300 gram per sample. All these speleothem samples were packed and hand-carried from Kuala Lumpur International Airport to the University of Bristol.

Samples for analysis were prepared in the Soil Laboratory of the Department of Geographical Sciences, University of Bristol. In the laboratory these samples were cleaned and cut with a rock saw to select the best portion for the analysis. Some samples needed to be crushed and handpicked to obtain the cleanest material. The procedure of further sample preparation in the laboratory is listed in Appendix 1.

SAMPLE LOCATION AND SIGNIFICANCE

Out of the 21 samples of speleothem from Kinta Valley and Lenggong area that were brought over to the University of Bristol, only 14 samples were considered suitable for testing. Samples of the speleothems were collected according to their geological and geomorphological significance. These speleothems are mainly found in the cave systems of the limestone hills. The caves and the containing speleothems were mapped prior to any sampling. Where possible, samples were collected from where the stratigraphic relationship between the geomorphological process such as cave formation and notching and the speleothem could be determined. Where there are more then one deposition period of the speleothems, the stratigraphic relation between individual speleothems are determined and demarcated on the maps. However in some cave systems, the stratigraphy could not be readily determined. The sites where the speleothems were collected for the uranium series age determination are as follows:

1. Naga Mas Cave, Gunung Lanno, Kepayang.

2. Kek Lok Tong temple cave, Gunung Rapat.
3. Gua Badak cave, Lengong, Upper Perak.
4. Highway Entrance to Crystal Cave (Gua Kandu), Gunung Mesah.

THE IMPORTANCE AND SIGNIFICANCE OF THE RADIOMETRIC DATES OF CAVE MATERIALS TO THE LANDSCAPE DEVELOPMENT – DISCUSSION

Smart (1986) in his study on the geomorphology of the karst topography in western Guizhou, China has suggested that dating of speleothems may permit estimates of rate of evolution, assist in the studies of slope processes and, therefore arrive at a better understanding of its topographic evolution. He also suggested such studies can also be done in the Kinta Valley limestone hills which appeared to be affected by similar geomorphologic processes as in Guizhou (Smart, 2000. pers. comm.). Ford and Williams (1989) stated that radiometric dates can be used to determine mean rates of growth of stalagmites and flowstones. More fundamentally, these ages represent the minimum ages for the cutting of the vadose trenches (cave system) or draining of the phreatic passages that they now occupy.

PROBLEMS IN DATING SPELEOTHEM IN TROPICAL CAVES

Certain assumptions and criteria were made for the purpose of interpreting the date of formation of the speleothems based on its Th and U isotopic contents. These are as follows:

1. There should be no ^{230}Th incorporated in the crystal lattice on deposition. Most non-authigenic ^{230}Th is introduced bonded to the detrital mineral grain surfaces, and is accompanied by ^{232}Th. This long-lived isotope can therefore be used to monitor the degree of non-authigenic (or detrital) thorium contamination. Correction for non-authigenic ^{230}Th is generally needed if the $^{230}Th/^{232}U$ ratio is less than 20.
2. The system should remain closed to the migration of uranium and thorium after deposition. This may be indicated by an anomalous $^{230}Th/^{234}U$ ratio (>1), by a positive correlation between the uranium concentration and $^{2324}U/^{238}U$ for coeval samples, and by lack of agreement with $^{231}Pa/^{235}U$ ages on the same samples. There may also be gross physical evidence of recrystallization, solution, secondary precipitation or high porosity.

The ideal material for dating is a deposit consisting of intimately intergrown coarse crystals of $CaCO_3$, with no intergranular porosity or permeability, and free of any impurities such as detritus, organic matter and bone fragments. Many speleothem deposits fail to meet these requirements in a number of ways such as the following.

Porosity

Speleothem materials range from compact to highly porous. In general, stalactites are far more porous then stalagmites. High porosity in speleothem samples allow solution to percolate through and deposit the carbonates during various periods of time and thus will give rise to problems of mixed ages, which is detected only as an average. Samples for dating should therefore be collected only from those layers which appear not to have had much initial porosity, and whose crystals are now densely packed.

Some materials especially the stalactite (G.Rapat) and the cave floor material (e.g. from G. Lanno) are very light and porous and had to be discarded.

Impurities

Many spring-deposited travertines are precipitated by the action of plants which extract HCO_3 ions, from the spring water leading to carbonate precipitation. The plant material is then deposited together with the carbonate minerals. The main source of detrital contamination in speleothem is, of course, the same source that leads to deposition in the caves. Samples from Naga Mas contain reddish clay material and organic matters such as small roots. The cave floor from Gua Mesah contains algae and mud. Whereas in G. Rapat, layers of iron were found in the stalagmite and the cave floor. The non-carbonate component is probably a mixture of silicates and oxides and can contain uranium and thorium in the form of traces of U and Th minerals and as a trace element incorporated in the common clastic minerals. In order to avoid this type of contamination, some of the samples were chipped and handpicked to obtain the cleanest material.

Recrystallization and Secondary Overgrowths

Th and U will be at least partly mobilised during recrystallization while secondary, pore filling overgrowths will behave isotopically like newly deposited travertine (Schwarcz, 1980). Thus such ages can be said to have been reset and are definitely younger then the age when the host speleothem materials were deposited.

RESULTS OF THE PRELIMINARY AGE DETERMINATION

Table 1 shows the preliminary computed ages of the speleothems that were analyzed for their alpha radioactivity for U and Th as outlined in the earlier sections. The ages are not yet fully corrected for errors. Some samples need to be counted longer in the spectrometer and this is being done in the laboratory in Bristol at the time of writing of this paper. Nevertheless, any correction for errors that are to be applied will probably consist of minor alterations to the values.

Naga Mas Cave, Gunung Lanno, Kepayang

Eight (8) samples were collected from Naga Mas which is a small cave situated at about 30 m above the ground in the G. Lanno limestone hill complex. Up to this stage only 4 ages could be obtained. A few more results may be available in one or two months time. The most interesting feature in the Naga Mas cave is the presence of an almost whole skeleton of a large vertebrate mammal exposed on the cave roof that is composed of speleothem material. In this sense, the present Naga Mas cave is a second-generation cave. Based on the mapping of the cave and the material found inside, it is interpreted that a cave (the first generation) had developed some time back in the geologic past. The original or first generation cave cavity was probably larger then the present second generation cavity. The excavation of this original cave cavity probably occurred when the surrounding areas were at about 30 m above the present general level. Works by some researchers in Malaysia have given some ideas of approximate denudation rate in the country. In the case of Naga Mas, assuming an average denudation rate of 0.1 mm per year for that of the Kinta Valley (Krahenbuhl, 1991), then the time when the alluvial plain was at the same level as the cave opening floor height is about 300,000 years.

Observation of cave formation in the Kinta Valley indicates that speleothem development seen in a cave is temporary and these will collapse and become part of the cave floor material as the cave enlarges through further solution. Based on observation of Naga Mas, a lot of speleothem material had collapsed and was incorporated to become part of the cave floor.

It is also interpreted that after the first generation cave was fully developed, there probably was a change of climate when vadose cave solution became replaced by predominantly deposition of flowstone, cave floor cementation, stalactite and stalagmite formation. There is a general built-up of these speleothem material especially at the side walls and on the floor of the first generation cave. That was also during the time when the large vertebrate mammal had died inside the cave and its skeleton became encased by the speleothem material and was thus preserved. The age of 228 ± 40 ka is quite consistent with the interpreted cave history.

Eventually, the original first generation cave cavity was filled or almost fully filled by speleothems (flowstone, stalagmite, collapsed stalactite and other secondary carbonate material). It appeared that the filling of the first generation cave must have taken some time and the age of 119 ± 15 ka (NM 4) and 130, ± 27 ka (NM 3) through to 228 ± 40 ka are indicative of this.

It appeared that after a lapse of geological time a second vadose solution cave was excavated inside the first generation speleothem-filled cave. It is believed that the original cavity was not fully filled and the dissolution of this second generation cave must have taken place starting with the partially filled fractures. This stage of cave development can probably correlated with another change of climate probably from a drier to a wetter condition. The young stalagmite (NM 7) on the present cave floor gave an age of 19 ± 2 ka.

Gua Badak, Lengong, Upper Perak

The sample is a stalagmite from the central chamber in Gua Badak C, Lenggong in where a rich collection of fossil teeth and bones of vertebrate mammals were found (Ros and Yeap, 2000). This sample of the stalagmite was cut and sectioned. LBC-SM-9/00 (a) is composed of the core while LBC-SM-9/00 represents the outer parts of the stalagmite. The preliminary age of the former is 46.5 ± 15.5 ka and the latter is 52.2 ± 9.5 ka. These two ages must be taken to be consistent to indicate that the age of the stalagmite is not younger then 30 ka and not older then 60 ka.

In the case of Lenggong, Zuraina and Tjia (1988) and Tjia (1993) are of the opinion that the palaeolithic tool workshop at Kota Tampan was active at around 30,000 years ago. They based this on the premise that Kota Tampan "workshop" site was at shore of a natural lake that was formed due to several landslides which blocked the Sungai Perak prior to 30,000 years ago. The age was derived from the acid volcanic ash associated with the stone tools. Ros and Yeap (2000) had related the preservation of the large vertebrate fossil bones and teeth to the time when the Tampanian community was thriving in the area of Lenggong and Kota Tampan. They are of the opinion that the preservation of these fossil bones and teeth in the Gua Badak C cave took place prior to the 30, 000 years ago and probably prior to the blockage of the Sungai Perak basin by several land slides as postulated by Tjia (1993).

The age of the stalagmite in the Gua Badak C is consistent with the postulated time when the Tampanian community was thriving in the Lenggong area which was probably a grass land supporting a large population of large vertebrates. As Ros and Yeap (2000) had postulated, the mass catastrophic death of the preservation of the large vertebrate fossils in the Badak C cave during this time frame is also supported by the age of the stalagmite (not younger then 30 ka and not older then 60 ka) in the said cave.

Kek Lok Tong, Gunung Rapat

Three samples were from Kek Look Tong where KLT1-KLT2 are younger then KLT3. These samples happen to be the cleanest and are composed of a dense form of calcite. KLT1 and KLT2 were cored out of a large flowstone which had been broken and showed clear stratigraphic sequence where KLT1 is older then KLT2. Whereas KLT3 is milky white dense cave floor material deposited at about 5 m above the general ground level and about 0.5 m above the lowest cemented floor level of Kek Lok Tong. Field evidence does not allow the interpretation of the stratigraphic relationship between KLT1 / KLT2 and KLT3

The lowest level floor of the Kek Look Tong, is about 5 m above the general land surface of the surrounding area.

Table 1. Preliminary U-Th radioactivity age determination of speleothem from some caves in the Sungai Perak basin.

Sample Name (location)	Age	Errors
Naga Mas, Gunung Lanno, Kinta Valley		
NMF (Core near the vertebrate fossil)	**227,890**	-35,435, +55,210
NM3 (Inner layer of flow stone on the lower left wall)	**119,042**	-14,911, +16,992
NM4 (Outer layer of flow stone on the upper left wall)	**130,715**	-22,670, +30,965
NM7 (Young stalagmite on present cave floor)	**19,879**	-2,716, +2,808
Gua Badak C, Lenggong, Upper Sg. Perak Basin		
LBC-SM-9/00 (Gua Badak)	**52,209**	-9,217, +10,284
LBC-SM-9/00 (a) (Gua Badak)	**46,519**	-14,185, +16,854
Kek Lok Tong, Gunung Rapat, Ipoh		
KLT3-9/00 (Collapsed flowstone exposed on the first level cave floor)	**271,369**	-65,743, +221,233
KLT1-9/00 (Collapsed block of flowstone at the entrance)	**113,178**	-15,336, +18,666
Highway Entrance to Crystal Cave (Gua Kandu), G. Mesah		
GM1 (Stalagmite on the cave floor below the deepest incised notch)	**31,716**	-3,052,+3,166

Another cave floor levels towards the west of the entrance is about 3 m to 4 m higher. The Kek Look Tong has a reasonably large main chamber roof which is dome-shaped and measures about 18 m in diameter and is about 17 m high measured from the lower cave floor level. Many small bells or vertical cylinders (from 30 cm to 2 m in diameter) project above the dome. These bells appear to terminate on unfractured limestone rock on the roof indicating that these bells were probably formed as a result of condensation from warmer water that originated from outside the cave (Ford and Williams, 1989). Therefore it is postulated that a former stream must have passed through the cave chamber in the geologic past. When the source of this stream was captured elsewhere outside this Kek Look Tong cave chamber, the supply of warm water stopped and the bells probably stopped developing.

Two very large flowstone columns were located west and north west of the dome-shaped chamber. These probably mark fracture zones where continuous growth of the flowstone or speleothems must have occurred for some time. In front of the entrance to Kek Look Tong, appears to be speleothem located higher than the roof chamber of the Kek Look Tong. While a rock window is located at about 113 m above the general ground level. Based on the over all picture, it appears that the precursor of the present Kek Look Tong is probably very old.

Two preliminary ages of Kek Look Tong are presently available. KLT3-9/00 is quite old at 271 ka while KLT1-9/00 is 113 ka. The stratigraphic relationship of these two are not known. Apparently the precursor of the present Kek Look Tong cave could have been developed prior to 271 ka and it was mainly a vadose cave accompanied by flowstone deposition. KLT2-9/00 is from a collapsed speleothem, that could probably be associated with major chamber enlargement including collapse of some of the flowstone deposit. The 113 ka can thus be correlated to this period of cave formation.

Highway Entrance to Crystal Cave (Gua Kandu), Gunung Mesah

One sample of dense, milky white, crystalline carbonate was collected from remnants of cave floor material at the height of about 2 m from the general ground level. This sample is above the most deeply laterally incised notch on the side of the limestone hill. This location of the sample is at one of the four entrances of the Crystal Cave in G. Mesah (this is known as the highway entrance). The age of 31.7 ka has certain significance. It indicates that the deepest horizontally incised notch that is located on G.Mesah is probably younger then 31.7 ± 3 ka. Ros and Yeap (1999) is of the opinion that the 2.0 m high (above ground level) horizontal deeply incised notch located on G.Mesah and elsewhere in the Kinta Valley probably marks the onset of Holocene when the paleoclimate in Peninsular Malaysia had become relatively wetter. Prior to this it is postulated that Peninsular Malaysia which is part of the Sundaland continent having a drier continental paleo-climate.

The age of 31.7 ± 3 ka appears to lend some weight to this concept that the 1.5 m horizontal notch was formed due to the setting in of the wetter Holocene paleoclimate.

CONCLUSION

Speleothem or cave deposits are important because of their suitability to be used in uranium series dating technique. The uranium series dating method is useful in determining the age of speleothems to up to 500 ka.

The preliminary U-series age of several samples of speleothems are useful to bracketing several events that occurred in the Kinta Valley. They have proven correct for some of the inferences of the geomorphologic events that had been postulated so far by us.

With these absolute ages combined with the estimated rate of denudation, it is possible to obtain better understanding of the evolution of the karst landform.

ACKNOWLEGDMENTS

The authors would like to express thanks to Dr Dave Richards of University of Bristol who has been advising and helping in the lab and with the calculations. Thanks are also due to Prof Tjia for sample NMF - Naga Mas and advises in the field. The laboratory work and some of the field trips were funded by IRPA grant 02-02-02-0015 for 'Geological Resources of Nature Parks for Tourism Development' led by Prof Ibrahim Komoo, LESTARI, Universiti Kebangsaan Malaysia. The rest of the field studies were funded by University of Malaya.

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APPENDIX 1

Sample Dissolution

Between 50-200 g of clean calcite was first dissolved in an excess of 6M HCL, with 10-20 ml of 30% H_2O_2. Once dissolved, the mixture was filtered to remove any acid insoluble residue and 5 mg of iron (as a chloride solution) added with a mixture of uranium (^{236}U) and thorium (^{230}Th) spike and left overnight to equilibrate, while exposed to a strong UV source to destroy any organic matter. The solution was then boiled to remove any peroxide, and diluted. The Fe was co-precipitated by adding 0.88M NH_4OH until a brown precipitate is formed. This was left to settle and the supernatant siphoned off. The Fe that is still present in the supernatant solution was then extracted with HCl equilibrated MIBK. A few drops of $HClO_4$ were added before evaporating the supernatant solution to dryness.

Elution Process

The evaporated sample was taken up in 9 M HCl and the uranium and thorium were then eluted using standard ion exchange columns filled with Dowex AG1X8 anion exchange resin. The columns were first pre-washed with 70 ml 0.1M HCl. The sample solution was then poured through the ion exchange column. The Th that was extracted by the resin was eluted with 40 ml 9M HCl. Any remaining Fe was then removed with 30 ml 7 M HNO_3. Finally the U was eluted from the same resin column using 0.1M HCl. The U solution was then prepared for electro-deposition by adding H_2SO_4 fumed and evaporated and then finally dissolved with $(NH_4)_2SO_4$. This solution is then ready for electroplating using stainless steel planchette at 0.2 amps for 3 hours.

The thorium solution was evaporated to dryness and then dissolved in 7 M HNO_3. This solution was evaporated to dryness. This process of solution in 7M HNO_3 was repeated three times. After the third round, the dried sample was dissolved in 7M HNO_3 then passed through a second set of pre-washed column to further purify the Th. The column was then eluted with 40 ml 2M HCl. It is not necessary to go through the resin column for the U.

Alpha Radioactivity Counting

The thorium that was extracted from the solution was electroplated onto stainless steel planchettes at 0.2 amps for 6 hours. Both the U and Th deposited planchettes were loaded onto the Canberra 7404 alpha spectrometer set to count for the alpha radiation of ^{234}U, ^{236}U, ^{238}U, ^{229}Th, ^{230}Th, and ^{232}Th.

In the routine procedure, a total alpha radioactivity counts of between 5000-30000 is considered acceptable to minimize counting errors, and for correction for any uranium break-through on the thorium spectra and tailing of the uranium spectra.

Computation of the Age

The ages were then calculated from the standard decay equations using a GWBASIC computer program. For samples that had a high concentration of detrital ^{232}Th, standard correction procedures were followed. These assumed an initial $^{230}Th/^{232}Th$ atomic ratio of $4.4 \pm 2.2 \times 10^{-6}$ (method 1, equation 8 from Schwarcz (1980)), which is the value for natural earth material at secular equilibrium, with a crustal $^{232}Th/^{238}U$ value of 3.8. The error in this value is arbitrarily assumed to be 50%. Given a clean spectra and absence of detrital contamination, errors are usually within 5-10%. In case of heavy contamination, the error may become considerably larger and close to the limit of the method.