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**URANIUM SERIES DISEQUILIBRIUM STUDIES OF  
DRILLCORE KM3 FROM THE KAMLUNGE TEST-SITE,  
NORTHERN SWEDEN**

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**Luleå, Sweden 1984-03-30**

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THE KAMLUNGE TEST-SITE, NORTHERN SWEDEN

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Abstract

Studies of the uranium decay series ( $^{238}\text{U} - ^{234}\text{U} - ^{230}\text{Th}$ ) have been carried out on samples from unaltered bedrock and highly altered fracture/crush zones from drillcore Km3 (Kamlunge test-site). The fracture zones are characterised by abundant iron-oxide coatings (hemite and hydroxy iron-oxides) resulting from the passage of hydrothermal solutions coeval with the Lina granite intrusion. Enrichments of uranium and thorium, thought to be due to co-precipitation (or preferential sorption) processes together with the iron-oxides, are also present.

The isotopic results show that out of a total of twelve rock samples measured, six indicate isotopic disequilibrium mostly due to unequal depletions of  $^{234}\text{U}$  and  $^{238}\text{U}$ ; one near-surface sample indicated some minor assimilation of uranium. The major fracture zones generally indicate removal of total uranium. This has resulted from interaction with groundwaters which are still marginally oxidising, even at depths of 450 m.

Isotopic disequilibrium has occurred within recent geological times, i.e. during the last 0.5 Ma as imposed by the half-lives of  $^{234}\text{U}$  and  $^{230}\text{Th}$ . In terms of radioactive disposal considerations, the results are important in that (1) the investigated bedrock environment (100-600 m) is generally reducing, however (2) there is some evidence to indicate that rock/water interactions leading to the removal of total uranium have resulted from the presence of less reducing groundwaters within those large-scale fracture/crush zones which intersect the bedrock surface.

## 1. Introduction

The Kamlunge test-site is situated in northern Sweden about 35 Km from the Baltic Sea coast (Fig. 1). It represents one of several sites in Sweden which have recently been investigated as potential repositories for radioactive waste disposal (Ahlbom et al, 1980; Tirèn et al, 1981; Albino et al, 1982; Carlsten et al, 1982). In common with the other areas, Kamlunge represents a crystalline rock environment which is Precambrian in age. It has been investigated in detail, both geologically (Albino et al, 1983) and hydrologically (Danielson, 1983), this being facilitated by the diamond drilling of 16 drillholes (down to a maximum depth of 650 m) complemented by 22 percussion drillholes (down to a maximum depth of 150 m). Ground-water sampling was carried out at various levels from four holes; surface-water sampling from lakes, streams and springs was carried out to evaluate the recharge environment.

This present paper describes part of a larger programme of study which involves uranium series disequilibrium studies of both surface and groundwaters, together with the geological bedrock through which the waters permeate. Presented here are some preliminary results from drillcore Km3.

Uranium series disequilibrium studies have now become a fairly standard investigative method within the field of geochemistry. Pioneered by Cherdynstev (e.g. 1955, 1971) the methods have been subsequently improved and applied by many workers to a wide range of geological problems; see, for example, Rosholt (1959); Thurber (1962); Rosholt et al (1963); Koide and Goldberg (1965); Rosholt

et al (1966); Kigoshi (1971); Kronfeld (1974); Osmond and Cowart (1976); Fleischer and Raabe (1978); Ivanovich and Harmon (1982), and Rosholt (1983).

For crystalline rocks, such as those described in this paper, the uranium series disequilibrium system has been used as a sensitive indicator of recent uranium mobility during the last 0.5 Ma (Zielinski et al, 1981; Schwarcz et al, 1982; Smellie, 1982; Rosholt, 1983). To the extent that the uranium series disequilibrium is a product of rock/water interaction, these measurements may help to evaluate the effective permeability of unfractured and macroscopically-fresh rocks, and they can be used to assess geologically recent uranium mobility in 'sealed' fracture zones.

## 2. Geological Setting

The regional geology of the area (Fig. 1) has been described generally by Ödman (1957) and Lundqvist (1979), and in more detail by Albino et al (1983). The region is characterised by metamorphic and migmatitic rocks which are Precambrian in age; the region is regarded as having been relatively stable for long periods of geological time. Briefly, the oldest rocks in the area are basement Archean granite gneisses. In Finland and further north in Sweden, similar basement rocks reveal ages ranging from 2600-2800 Ma (Welin et al, 1971; Perttunen, 1980). Overlying and disconformable with the Archean basement are the younger Svecokarelian rock groups. The Svecokarelian is initially represented by metasediments and metavolcanics. These are



followed by the Haparanda series of deep intrusives comprising granodiorite and gabbro which have been dated by Rb-Sr to around 1840 Ma (Welin et al, 1970). The earlier metasediments and metavolcanics are thus considered to be within the range of 1900-2500 Ma. Metamorphism in the region culminated during the Svecokarelian epoch at approximately 1800 Ma resulting in widespread migmatitisation. Coeval with metamorphism, and forming large-scale intrusions in the region, is the Lina granite which indicates a range of Rb-Sr ages from 1565-1800 Ma (Welin et al, 1970).

Indicated in Fig. 1 is the location of the Kamlunge area. Topographically, the area forms a plateau with its highest point some 175.2 m above sea-level; ice-movement has imposed a dominant NNW-SSE orientation on the local topographic features. The plateau may be described as a horst-type feature, bounded on three sides by large-scale regional lineaments which are presumed to be near vertical in orientation. Outcrop exposure is generally good, otherwise a thin to moderate moraine cover is usual (approx. 5-10 m).

The oldest rocks exposed at the Kamlunge test-site area are the above-mentioned metasediments and metavolcanics. These are present as quartzitic gneiss, biotite gneiss and amphibolite which are later intruded by granodiorite and gabbro of the Haparanda series. The Lina granite, with widespread pegmatitic activity, intrudes all older rock types.

Large-scale lineaments measured in an area of approximately 600 km<sup>2</sup> around Kamlunge revealed three main groups characterised by orientation. The most important group was orientated parallel to the dominant ice-

movement direction (N40W-S40E); the remaining more minor trends were N10E-S10W and N30E-S30W respectively. Detailed fault and joint patterns have been measured from the exposed bedrock at the Kamlunge test-site. Major crush zones have been indicated by different geophysical methods, and have suggested the presence of seven zones ranging in width from less than 5 m to 15 m which traverse the test-site area. Several of these have subsequently been confirmed from the drilling programme.

### 3. Description of Drillcore Km3

Drillcore Km3 was chosen for examination because it intersects two of the major fracture/crush zones and one minor crush zone revealed at the bedrock surface by geophysical investigations. In addition, the intersection points were sampled for groundwaters thus providing a suitable opportunity to directly relate the water chemistry with the fracture mineral chemistry within the bedrock.

Drillcore Km3 (Fig. 2) is 700.15 m long and represents a vertical depth of 555 m. In terms of rock composition, 42.9% of the intersected bedrock is composed of granodiorite, 25.3% granite/pegmatite, 22.2% amphibolite and 9.6% biotite gneiss. With regard to fracture density, granodiorite recorded 4.94 fractures/metre, granite 4.76, amphibolite 4.32, and biotite gneiss 3.54. In general, pegmatite horizons are most fractured. Effective porosity measurements of individual rock units (S. Sehlstedt, 1983, per. commun.) show a generally low porosity (<0.3%). However, significant differences do exist between the different rock units, for example, amphibolite (mean 0.26%) records slightly higher

values than biotite gneiss (mean 0.23%) and granite/pegmatite (mean 0.22%) but significantly higher than granodiorite (mean 0.13%).

#### Rock composition

The upper 400 m of the drillcore (Fig. 2) is dominated by massive, often foliated, granodiorite. In handspecimen it is generally porphyritic in texture, grey in colour and fine- to medium-grained, consisting of large plagioclase grains (2-5 mm) set in a biotite-rich matrix. Microscopically, the rock is composed of 20-25% mafic constituents (mainly biotite and hornblende) together with quartz, plagioclase and potassium feldspar (mostly microcline). Subordinate amounts of epidote (clinozoisite), sphene, apatite, magnetite and pyrite are also present with accessory zircon. The unaltered rock shows little microscopic evidence of alteration apart from some minor sericitisation of the feldspars and some chlorite from biotite breakdown. Below 400 m and down to 660 m, the main rock type is amphibolite (metavolcanic) which is mainly fine-grained, often foliated and dark-green in colour. Microscopically, the rock is equigranular with up to 50% mafic phases. The main mineral phases are quartz, plagioclase, hornblende and biotite with subsidiary amounts of sphene and magnetite; accessory apatite and epidote (clinozoisite) are also present. Epidote is of local importance occurring as bands and vein infillings. Within the amphibolite are horizons or schlieren of coarse-grained material rich in quartz, plagioclase, potassium feldspar (microcline now partly albitised) and biotite with accessory amounts of zircon and apatite. Below 660 m strongly foliated biotite gneiss occurs which is dark-grey in colour and fine- to medium-grained in texture. Microscopically, the

main constituents are quartz, plagioclase, potassium feldspar and biotite ± amphibole (hornblende) with subordinate epidote (clinozoisite) and magnetite; apatite occurs in accessory amounts. Localised areas are rich in epidote and/or quartz and feldspar.

Occurring within all rock-types are intrusive horizons of medium- to coarse-grained pegmatite/granite. Granite horizons with pegmatite veins can be up to 10 m in thickness; the pegmatites are generally 1-2 m in thickness. The granite is commonly red in colour characterised by quartz, potassium feldspar (microcline), plagioclase with subordinate biotite and accessory amounts of zircon, apatite, sphene, magnetite and allanite. The pegmatite, both red and grey varieties, tends to be typically coarse-grained and composed dominantly of potassium feldspar (mostly microcline) and quartz with subsidiary plagioclase, muscovite and biotite and minor amounts of magnetite. Uranothorite has also been observed.

#### Alteration features of the fracture/crush zones

Drillhole Km3 intersects several open fracture/crush zones; of these, Zones 2, 3 and 4 (Fig. 2) can be correlated to the bedrock surface. These zones are observed as irregular thicknesses of crushed rock together with moderately to highly fractured rock. Losses of drillcore material within the crush zones are quite common. These zones exhibit some common features of alteration which can be generally summarised as follows:-

- (a) Moderate to strong alteration of feldspar to sericite; complete pseudomorphing is not uncommon.

- (b) Breakdown of biotite ± hornblende to chlorite; pseudomorphing partly by calcite is also observed.
- (c) Martitisation of magnetite to hematite.
- (d) Strong Fe<sup>3+</sup> (hematite + hydrous iron-oxides) penetration along fractures and within the adjacent rock matrix forming impregnations and coatings.
- (e) Stringers and small concentrations of anatase/leucosene as end-products of magnetite and biotite breakdown.
- (f) Late-stage veinlets and fracture infillings of mostly calcite and chlorite with minor amounts of quartz ± zeolite.

Common to all rock-types is the presence of fractures containing iron-oxide in the form of hematite and hydrous iron-oxides. According to Tullborg and Svensson (written commun. 1983) the greatest percentage of iron-oxide fractures occur in the granite/pegmatite (70%), followed by quartz/biotite gneiss (25%), granodiorite (3%) and amphibolite (2%). The iron-oxides are present as coatings along the fracture margins and around matrix minerals and their pseudomorphs. Hematite also occurs as a fracture/vein infilling constituent and as an impregnation within the rock matrix peripheral to the fractures. Especially in the amphibolite, hematite-rich fractures occur in association with hydrothermal phases such as epidote. Some of these iron-oxide concentrations are considered by the author to be the result of hydrothermal activity probably in association with the intrusion of the Lina granite which dominates the region (Fig. 1).

Later veinlets of calcite ± chlorite devoid of iron-oxide occur parallel and obliquely to the earlier iron-oxide dominated fracture patterns.

#### 4. Sampling Procedures and Analysis

Rock specimens for uranium series disequilibrium studies were selected as follows: (a) representative macroscopically fresh samples from all rock-types at varying depths, (b) fractured samples, especially from the more major fracture/crush zones which extend to the bedrock surface, and (c) fractured samples from those horizons sampled for groundwater.

Samples consisted of approximately 30 cm lengths of drillcore, and for the major fracture zones up to three specimens were selected (centre of fracture/crush zone, margin of zone and one from just within the adjacent unaltered bedrock). Location of the samples are shown in Fig. 2. Points chosen for groundwater sampling were based on detailed drillcore mapping and correlation with hydraulic conductivity measurements carried out every 25 m along the drillcore (Fig. 2); lengths of promising potential were subsequently tested every 5 m (Danielson, 1983). From Fig. 2 it can be seen that the points of highest hydraulic conductivity not surprisingly coincide with the major fracture/crush zones. The generally high conductivity values for the upper 150 m is fairly typical for the Swedish bedrock. This is due to a high concentration of tensional joints/fractures resulting from adjustments subsequent to the removal of the ice overburden in recent Pleistocene times.

From each rock sample a thin slice was first removed from the length of the drillcore piece for mineralogical and fission-track studies. The remainder was crushed and portions sent for isotopic analysis using high resolution alpha spectrometry at the Department of Radiation Physics, University of Lund, Lund, Sweden, and the USGS in Denver, USA.

At Denver, details of sample preparation are according to Rosholt (1980, 1983). The quoted errors (Table 1), better than  $\pm 2\%$  for the  $^{234}\text{U}/^{238}\text{U}$  ratio and  $\pm 3\%$  for the  $^{230}\text{Th}/^{234}\text{U}$  and  $^{230}\text{Th}/^{238}\text{U}$  ratios, are due to counting statistics only. At Lund, general details of sample preparation are outlined by Duniec et al (in preparation). Errors ( $2\sigma$ ) for the ratios  $^{234}\text{U}/^{238}\text{U}$ ,  $^{230}\text{Th}/^{234}\text{U}$  and  $^{230}\text{Th}/^{238}\text{U}$  are presented in Table 1.

The remaining drillcore portions were analysed for uranium (delayed neutron activation) and thorium (sealed-can gamma spectrometry). Fission-track analyses according to the method of Kleeman and Lovering (1967) were carried out on polished sections from all samples to assess the location and distribution of uranium.

Water samples, normally 5 litres in volume, were collected from surface and near-surface localities in the vicinity of borehole Km3; groundwater samples were collected at depths of approximately 122 m and 444 m from the borehole (Fig. 2). All samples were immediately filtered ( $0.45\ \mu\text{m}$  pore diameter) and treated with sufficient hydrochloric acid to attain a pH of 1.0. Uranium recovery and analysis were carried out at the University of Lund.

## 5. Results and Discussion

### Radioelement distribution in the Km3 bedrock profile

The results are presented in Table 1. Uranium concentrations within the three fracture zones (ranging from 2.3-9.7 ppm U) show a significant departure from the typical background values of the petrographically unaltered host bedrock (ranging from 0.7 - 1.9 ppm U); this is especially

marked within the fracture/crush zones located at the 122 m and 336 m levels (Fig. 2). Fission-track studies show that the background activity recorded for the unaltered bedrock samples are due to low uranium concentrations (10-30 ppm) associated mostly with subordinate to accessory amounts of zircon, apatite, epidote and sometimes magnetite. Within the altered fracture zones, uranium (<5-30 ppm) is associated with iron-oxides and very small anatase/leucoxene aggregates. No significant uranium is associated with later stage calcite and chlorite ( $\pm$  zeolite) infillings.

Increases of thorium within the fracture zones (especially marked in samples Km3F and Km3G which show contents of 83.6 and 312 ppm Th respectively) generally correlate with uranium suggesting that both uranium and thorium have accumulated by sorption or co-precipitation with iron-oxide. In contrast, Gascoyne (1982) records a preferential sorption or co-precipitation of uranium (rather than thorium) in hematized fractures from the Eye-Dashwa Lakes pluton near Atikokan, NW Ontario, Canada.

If the observed enrichment of thorium within the fracture/crush zones (Zones 2 and 3; Fig. 2) relative to the host-rock background values is the result of rock/water interaction, this is surprising considering thorium's generally assumed immobility in groundwater. Thorium isotopic data (not included in Table 1) show that detectable amounts of the principle thorium isotopes  $^{232}\text{Th}$ , and  $^{230}\text{Th}$  (from the decay of  $^{234}\text{U}$ ), are present in all the measured samples. However, the content of  $^{232}\text{Th}$  (and its corresponding decay daughter  $^{228}\text{Th}$ ) is anomalously high in the



two lower fracture zones (Zones 2 and 3; Fig. 2) and in the pegmatite samples (Km3E and Km3L). In contrast, the dominant thorium isotope in the upper fracture zone (122 m level) is  $^{230}\text{Th}$  (i.e. one of the  $^{238}\text{U}$  decay daughters). This similarity between Zones 2 and 3 and the two pegmatite horizons suggests that the  $^{232}\text{Th}$  (and  $^{228}\text{Th}$ ) is of primary hydrothermal origin (as a co-precipitation with iron-oxide and uranium) which accompanied the intrusion of the Lina granite.

Within the limits of analytical error, the  $^{234}\text{U}/^{238}\text{U}$ ,  $^{230}\text{Th}/^{238}\text{U}$  and  $^{230}\text{Th}/^{234}\text{U}$  activity ratios indicate equilibrium or near-equilibrium in six out of a total of twelve analysed samples (Table 1). For the two inter-laboratory analysed samples not in agreement, i.e. Km3C and Km3I, the Denver laboratory values are preferred because of their greater precision. Isotopic equilibrium indicates that little or no migration of the isotopes has occurred in these six samples over a period of at least 1.25 Ma, as required by the half-lives in the decay sequence  $^{238}\text{U}$ - $^{234}\text{U}$ - $^{230}\text{Th}$ . Of the remaining six samples recording disequilibrium, unequal depletions of  $^{234}\text{U}$  and  $^{238}\text{U}$  rather than additions of  $^{230}\text{Th}$  which is generally assumed to be immobile in natural waters, would mostly account for the observed deviations. Disequilibrium in the  $^{230}\text{Th}/^{234}\text{U}$  system, which is evident in five out of the six samples, indicates a disturbance within the last 0.35 Ma.

Isotopic equilibrium is indicated in three granodiorite samples (Km3B, Km3C and Km3D), two of which (Km3B, Km3C) represent the upper fracture zone at the 122 m level. This contrasts with the uppermost granodiorite

sample (Km3A) at 33.40 m which contains excess  $^{234}\text{U}$  and the fracture/crush zone at the 336 m level (Km3F, Km3G; Zone 2) which indicates depletions of  $^{234}\text{U}$  and  $^{238}\text{U}$ . At deeper levels, within the amphibolite rock-type, the two petrographically-fresh samples (Km3H and Km3K) exhibit isotopic equilibrium. Samples Km3I and Km3J, representing the major fracture/crush zone at level 444 m (Zone 3), show a loss of total uranium.

The pegmatite samples (Km3E and Km3L) which are macroscopically fresh but petrographically altered, exhibit both isotopic equilibrium (Km3E) and disequilibrium (Km3L), the latter resulting from depletions of both  $^{234}\text{U}$  and  $^{238}\text{U}$ . This mobilisation of uranium in Km3L is supported by fission-track studies which show significant interstitial uranium present within the rock matrix. In addition, primary uranium- and thorium-bearing phases (e.g. uranothorite) exhibit marked evidence of alteration and leaching.

Microscopically, the three open fracture/crush zones intersected by drillhole Km3 (Fig. 2) show extensive rock/water alteration characteristics. As described above, uranium series disequilibrium is indicated from Zones 2 and 3 (levels 336 m and 444 m respectively) in contrast to the uppermost zone (122 m) which appears to have remained relatively undisturbed for at least 1.25 Ma. It is known through geological investigations that Zones 2 and 3 extend to the bedrock surface; the orientation and extent of the upper zone is unknown. It is therefore reasonable that Zones 2 and 3, both of which are characterised by a strong piezometric pressure (Danielson, 1983), facilitate the downward movement of groundwater. This has resulted in rock/water interaction

and hence isotopic disequilibrium along and peripheral to the fractures. The absence of disequilibrium at the 122 m fracture level is unexpected and may reflect insensitive sampling. Here, in contrast to Zones 2 and 3, the fracture/alteration areas are more confined to narrow zones. Samples most likely include sufficient adjacent bedrock material at isotopic equilibrium to mask any disequilibrium effects resulting from rock/water interaction along these fine fracture channels. Future studies of this type could be improved by the leaching of mineral coatings from fracture mineral separates in order to achieve a better sensitivity of measurement.

#### Uranium chemistry of waters collected from the Km3 bedrock profile

Dissolved uranium contents and  $^{234}\text{U}/^{238}\text{U}$  activity ratios for the sampled waters are presented in Table 1. Tritium values of the collected groundwaters suggest sporadic amounts of near-surface water contamination during sampling from depth. The quoted compositions for the 336 m and 444 m depths are the means for those samples indicating minimum contamination.

The recharge environment is characterised by surface and near-surface waters containing low amounts of dissolved uranium (0.147-0.264 ppb) and activity ratios which indicate isotopic disequilibrium (1.74-1.82). At a depth of 12 m, in the vicinity of borehole Km3, the groundwater collected from a percussion drillhole contained up to 27.3 ppb U (activity ratio 2.53). Groundwaters samples over a period of 22 days from the 122m fracture level, are also rich in dissolved uranium (mean of 18.91 ppb; activity ratio mean of 2.75), especially when compared to the 444 m (Zone 3) fracture level (mean of 3.46 ppb; activity ratio 2.73). The moderately high  $^{234}\text{U}/^{238}\text{U}$  activity ratios indicated by all

the sampled waters thus show a widespread disequilibrium within the hydrological environment due to excess  $^{234}\text{U}$ . The marked decrease in dissolved uranium with depth is mostly a function of changes in the redox potential of the groundwaters as a more reducing environment is increasingly encountered. Such changes in groundwater composition, accompanied by isotopic disequilibrium due to excess  $^{234}\text{U}$ , are well documented in the literature (e.g. Osmond and Cowart, 1976). However, true reducing conditions, which are normally reflected by extremely low uranium contents, namely less than 0.1 ppb and thus significantly lower than the groundwaters sampled at 444 m depth, indicate that at this level, the groundwaters must still be marginally oxidising.

It is proposed that near-surface groundwaters, which will be relatively oxidising in type, are picking up uranium (with preferential chemical etching of  $^{234}\text{U}$  dominating over solid-solution recoil build-up processes) during their descent through the bedrock. As the pegmatite/granite dominates within the Kamlunge area, is usually fractured, and is known to contain labile uranium, the waters soon achieve high (saturation?) levels of dissolved uranium and appreciable amounts of excess  $^{234}\text{U}$  at fairly shallow depths. At deeper levels, exemplified by Zone 3 (444 m), the groundwater is more reducing and the dissolved uranium content has correspondingly decreased. At this level, excess  $^{234}\text{U}$  due to recoil processes, is thought to be increasingly dominant.

With its high mafic content (i.e. high  $\text{Fe}^{2+}$  availability), the amphibolite (and to a lesser extent the biotite gneiss) present within the Kamlunge area will greatly contribute to the reducibility of the groundwater environment.

The observed reduction of the dissolved uranium content in the groundwaters with depth should be reflected by uranium accumulations somewhere within the bedrock during downward movement of the waters. However, only one bedrock sample (Km3A) at a depth of 33.4 m shows significant evidence of uranium assimilation (mostly  $^{234}\text{U}$  recoil gain); the remaining samples not at isotopic equilibrium indicate removal of total uranium. The removal of total uranium is particularly evident at the 336 m level (Zone 2) and less apparent at the 444 m level (Zone 3). This indicates that although the groundwaters within these fracture zones are generally becoming more reducing with increasing depth, and subsequently removing less total uranium, even at the 608 m level, as evidenced by the pegmatite sample Km3L, the groundwaters appear to be still sufficiently oxidising to remove  $^{238}\text{U}$  and  $^{234}\text{U}$ .

According to secondary uranium accumulation processes as discussed by Osmond et al (1983), the present isotopic disequilibrium data from the fracture zones indicate a mixture of groundwater environments. For example, Km3F (Zone 2; 336 m level) suggests up-flow oxidising conditions whereupon  $^{230}\text{Th}$  exceeds  $^{238}\text{U}$  and  $^{234}\text{U}$ . Similar observations resulting from the leaching and remobilisation of pre-existing accumulations of uranium have been noted by the above authors. In the Kamlunge context, earlier uranium (and thorium) enrichments are a characteristic feature of the fracture zones under investigation, and thus the fractures can be regarded as mineralised in a sub-economic sense. In contrast to Km3F, samples Km3G (Zone 2; 336 m level), Km3I and Km3J (Zone 3; 444 m level) and Km3L from the deepest sampled pegmatite, indicate a non-steady state system which, according to

Osmond et al (1983), reflects an environment characterised by uranium mobilisation events and relatively abrupt changes from precipitation to leaching processes. In such cases,  $^{234}\text{U}$  is in excess of  $^{238}\text{U}$  (reducing down-flow environment) and at the same time deficient in relation to  $^{230}\text{Th}$  (oxidising up-flow environment). The non-steady state processes suggested from the isotopic data is perhaps not so surprising when considering the large-scale extent of these zones (5-15 m wide) and the fact that they extend to the bedrock surface. Groundwater flow is in all probability facilitated by these zones which will intersect minor and more major groundwater flow-paths at various levels as they continue down through the bedrock. This will result in the mixing of groundwater masses of differing origins and chemistries, and may also enable more oxidising groundwater to locally penetrate to greater depths.

## 6. Conclusions

Borehole Km3 exemplifies the complexity of the hydrogeochemical systems prevalent within the bedrock at Kamlunge. Studies of the uranium decay system ( $^{238}\text{U} - ^{234}\text{U} - ^{230}\text{Th}$ ) show that the macroscopically fresh and unfractured bedrock samples generally appear to be either at or near isotopic equilibrium. Notable exceptions include one near-surface granodiorite sample which has experienced some minor assimilation of uranium, and a pegmatite sample at 608 m which has undergone a depletion of total uranium. The most representatively sampled fracture zones (Zones 2 and 3), which have been initially mineralised (uranium and thorium enrichments) by hydrothermal activity during the latter stages

of the Lina granite intrusion, generally indicate depletions of  $^{238}\text{U}$  and  $^{234}\text{U}$ . This has resulted from the interaction of groundwaters still marginally oxidising, even at depths of 444 m (Zone 3).

The rock/water interaction processes giving rise to the isotopic disequilibrium have taken place within geologically recent times, i.e. during the last 0.5 Ma as imposed by the half-lives of  $^{234}\text{U}$  and  $^{230}\text{Th}$ . In terms of radioactive disposal considerations, the results are important in that (1) the investigated bedrock environment (100-600 m) is generally reducing, however (2) there is some evidence to indicate that rock/water interaction processes leading to the removal of total uranium has resulted from the presence of less reducing groundwaters within those high-risk areas, namely the large-scale fracture/crush zones extending from depth to the bedrock surface.

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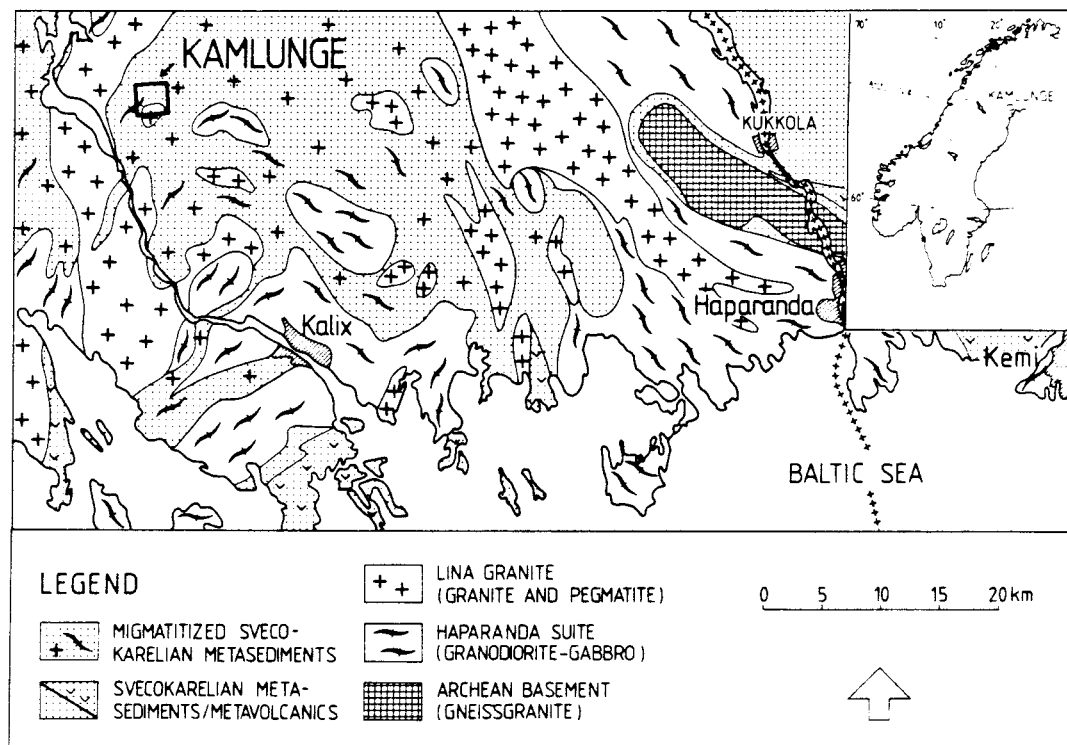


Figure 1 - Regional geological setting of the Kamlunge test-site area, northern Sweden. (Modified after Albino et al, 1983).

Figure 2

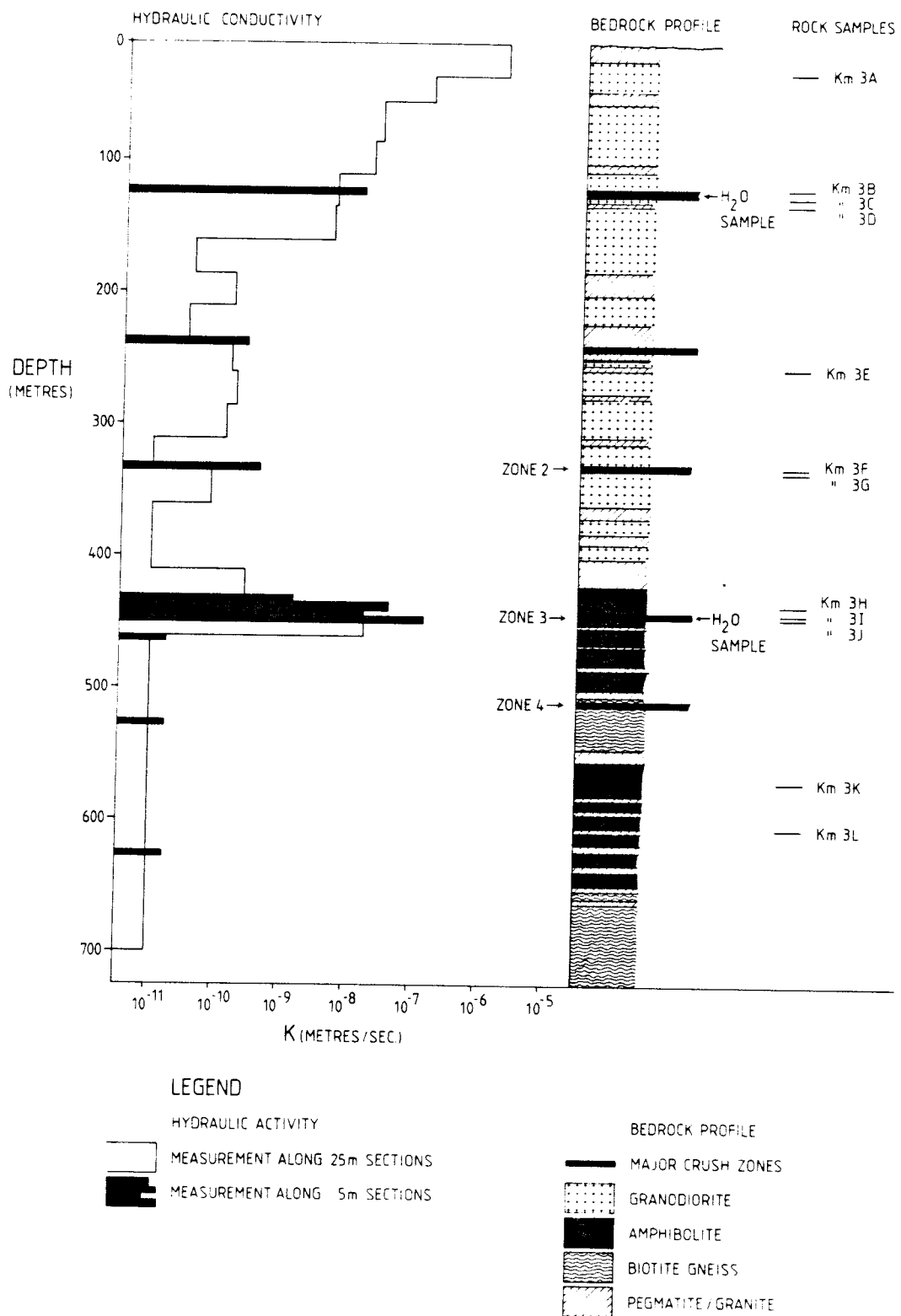


Figure 2 - Some hydrogeological features of drillcore Km3 (Kamlunge test-site) showing specimen locations for rock and groundwater samples.

Uranium and thorium contents and isotopic activity ratios from drillcore material, and uranium contents and activity ratios from associated surface- and ground-waters. Drillcore Km3, Kamlunge test-site, N. Sweden.

Sample	Rock-type	Sample Location	Length along drillcore (metres)	Vertical Depth (metres)	Uranium (ppm)	Thorium (ppm)	Th/U	$^{234}\text{U}/^{238}\text{U}$	$^{230}\text{Th}/^{238}\text{U}$	$^{230}\text{Th}/^{234}\text{U}$	Equilibrium State	Groundwaters	
												U-content (ppb)	$^{234}\text{U}/^{238}\text{U}$
				Surface Water								0.264 ± .068	1.74 ± .34 *
				Spring Water								0.147 ± .036	1.82 ± .32 *
				Borehole 12 m								27.3 ± 4.1	2.53 ± .06 *
Km3A	Granodiorite	Compact bedrock	33.4	29.20	0.9	3.3	3.7	1.140 ± .220	0.922 ± .155	0.810 ± .130 *	-		
Km3B	Granodiorite	Centre of crush zone	121.50	105.50	9.7	4.4	0.5	0.992 ± .080	0.999 ± .097	1.007 ± .098 *	Equilibrium	18.91	2.75 *
Km3C	Granodiorite	80 cm below crush zone	122.80		4.1	3.3	0.8	1.080 ± .128	1.171 ± .148	1.150 ± .145 *	-		
Km3D	Granodiorite	Compact bedrock	126.00	109.00	1.0	2.9	2.9	1.080 ± .350	0.900 ± .270	0.830 ± .240 *	Equilibrium		
Km3E	Pegmatite	Compact bedrock	260.00	222.30	23.1	14.6	0.6	0.933 ± .076	0.969 ± .119	1.039 ± .129 *	Equilibrium		
Km3F	Granodiorite	Margin of crush zone	336.70	286.50	3.4	83.6	24.6	0.943 ± .091	1.611 ± .140	1.709 ± .152 *	-		
Km3G	Granodiorite	Centre of crush zone	336.80		(Zone 2)	9.5	312	32.8	1.033 ± .041	1.510 ± .149	1.462 ± .144 *	-	
Km3H	Amphibolite	Compact bedrock	438.15	369.80	1.9	4.8	2.5	1.050 ± .290	1.040 ± .240	0.990 ± .230 *	Equilibrium		
Km3I	Amphibolite	Centre of crush zone	444.25	375.00	2.3	12.6	5.5	0.983 ± .117	1.090 ± .135	1.110 ± .138 *	Equilibrium	3.46	2.73 *
Km3J	Amphibolite	Centre of crush zone	444.55		(Zone 3)	3.2	13.9	4.3	1.162 ± .149	1.187 ± .179	1.021 ± .150 *		
Km3K	Amphibolite	Compact bedrock	582.30	488.00	0.7	2.9	4.1	1.080 ± .260	0.960 ± .220	0.880 ± .200 *	Equilibrium		
Km3L	Pegmatite	Compact bedrock	608.00	508.50	26.3	12.8	0.5	0.973 ± .020	0.969 ± .030	0.996 ± .030 §	Equilibrium		

\* Analyses by the Department of Radiation Physics, University of Lund, Lund, Sweden.  
 § Analyses by the U.S. Geological Survey, Denver, U.S.A.

Drillcore uranium analyses (delayed neutron activation) were carried out by Studsvik Energiteknik AB, Sweden.  
 Drillcore thorium analyses (sealed-can gamma spectrometry) were carried out by the Danish Atomic Energy Commission Research Establishment, Risø, Denmark.

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Trygve E Eriksen

Royal Institute of Technology

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Hilbert Christensen

Studsvik Energiteknik AB,

Nyköping, Sweden

Erling Bjergbakke

Risø National Laboratory,

Roskilde, Denmark 1984-03-16

TR 84-03

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Hilbert Christensen

Studsvik Energiteknik AB,

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Erling Bjergbakke

Risø National Laboratory

Roskilde, Denmark

1984-07-10

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Luis Moreno

Ivars Neretnieks

The Royal Institute of Technology

Department of Chemical Engineering

Trygve Eriksen

The Royal Institute of Technology

Department of Nuclear Chemistry

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TR 84–05

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Trygve Eriksen

Royal Institute of Technology, Stockholm

Arvid Jacobsson

University of Luleå, Luleå

Sweden 1984-06-28