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CONTACT ZONES AND HYDROTHERMAL SYSTEMS AS ANALOGUES TO REPOSITORY CONDITIONS

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Contact Zones and Hydrothermal Systems as Analogues to Repository Conditions

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Abstract

Radioactive waste isolation efforts in the U.S. are currently focused on examining basalt, tuff, salt, and crystalline rock as candidate rock types to encompass waste repositories. As analogues to near-field conditions, the distributions of radio- and trace-elements have been examined across contacts between these rocks and dikes and stocks that have intruded them. The intensive study of the Stripa quartz monzonite has also offered the opportunity to observe the distribution of uranium and its daughters in groundwater and its relationship to U associated with fracture-filling and alteration minerals.

Investigations of intrusive contact zones to date have included 1) a Tertiary stock into Precambrian gneiss, 2) a stock into ash flow tuff, (3) a rhyodacite dike into Columbia River basalt, and 4) a kimberlite dike into salt. With respect to temperature and pressure, these contact zones may be considered "worst-case scenario" analogues. Results indicate that there has been no appreciable migration of radioelements from the more radioactive intrusives into the less radioactive country rocks, either in response to the intrusions or in the fracture-controlled hydrological systems that developed following emplacement. In many cases, the radioelements are locked up in accessory minerals, suggesting that artificial analogues to these would make ideal waste forms.

Emphasis should now shift to examination of active hydrothermal systems, studying the distribution of key elements in water, fractures, and alteration minerals under pressure and temperature conditions most similar to those expected in the near-field environment of a repository.

INTRODUCTION

Evidence for natural occurrences in candidate rock types can help to predict the long-term performance of nuclear waste repositories. Investigations of natural analogues are significant in determining the capability of radioelements to migrate into and through the near-field rock and into the hydrologic systems encompassing the repositories.

Occurrences reported here include those where intrusive rocks with relatively high concentrations of radioelements are in contact with some host-rock types presently considered candidates for repositories: plutonic rock and high-grade metamorphics, tuff, basalt, and salt. The conditions of intrusion have generally resulted in temperatures considerably higher than those expected in a repository. However, at stages in their cooling history the temperatures in intrusive-contact zones reach the range expected in the near-field, and during and following cooling, hydrologic systems are established that last for periods comparable to those of concern for repository environments.

Also of concern is the movement of radioelements and changes in mineralogy of near-field rock in response to the thermal-hydrologic effects of the introduction of the radioactive waste. A geologic analogue of this type has been investigated at Stripa, Sweden by mineralogic and radioelement measurements of the quartz monzonite following full-scale heater tests. Investigations of present-day active hydrothermal systems, where temperatures (100 to over 250°C) are similar to those expected in rock close to the waste canisters, will also provide appraisals of radioelement movement and the effects of alteration mineralogy.

In this paper we describe analogue investigations of intrusive - country rock contact zones of contrasting character: one where there was no apparent hydrothermal system in response to the intrusion, and the other where a strong circulating hydrothermal system accompanied intrusion. Studies of contacts between relatively radioactive dikes cutting basalt and salt are briefly described, as are results of mineralogical and radioelement investigations of the Stripa pluton and preliminary findings at a present-day circulating hydrothermal system in basalt.

The Eldora Stock-Idaho Springs Formation Contact Zone: a Conductive Thermal Regime

Samples were obtained from the contact zone between the 58-million-year-old Eldora Stock and Precambrian gneiss of the Idaho Springs Formation, Colorado, where previous geochronologic, mineralogic, geochemical and heat-flow modeling studies were well documented (Hart et al., 1968). The samples were collected from the stock and from the Idaho Springs Formation at the contact and at increasing distances to 7.5 km from the contact, (Figure 1) following a traverse essentially identical to that used by Hart et al. (1968).

The fresh stock rocks range in composition from monzonite to granodiorite. As described by Hart et al. (1968), the stock crystallized from a magma temperature of 780°C and the rocks now exposed were probably never at depths greater than 1 km. The Idaho Springs Formation consists predominantly of alternating felsic- and mafic rich plagioclase-hornblende gneiss with occasional secretion pegmatites. Its age is 1.5-1.6 billion years, and the rocks were regionally metamorphosed approximately 1.4 billion years ago, at which time the pegmatites were injected. These "sweat" pegmatites filled the fractures and formed the veinlets that appear in the gneiss. Elemental variations due to pre-stock emplacement thermal events in the gneiss must then be carefully deciphered before attempting to interpret the stock-induced effects at 58 million years ago.

Samples from the stock, and of felsic, mafic and pegmatitic phases of the Idaho Springs Formation, were taken along the aforementioned traverse and from another site near Antelope Creek, Colorado (southwest portion of Figure 1). Splits of the samples were used for thin section preparation, laboratory gamma spectrometry, fission-track radiography, Rb-Sr and K-Ar geochronology, neutron activation analysis (NAA), and for stable oxygen isotopic analysis.

Rb-Sr, K-Ar, U, and Th-Pb radiometric ages and other data (Simmons and Hedge, 1978; Hart et al., 1968) allow heat models for the Eldora stock to be calculated. The stock is considered to have steep-to-vertical sides; the heat distribution about the stock was fairly uniform based on radiogenic Ar, Sr and Pb behavior in minerals, and the isotherm corresponding to the orthoclase-microcline transition (a maximum of 400°C) is considered to be 300-800 m from the contact. The model advocated is that of a "brick" with large vertical extent downwards, its thickness equal to the average E-W outcrop extent of the stock and its length equal to the average N-S extent of the stock. The model is based on the assumption that cooling was solely by conduction and best explains the isotopic variations as a function of distance from the contact.

The loss of radiogenic ^{40}Ar from minerals as a function of distance in the gneiss from the contact was well documented by Hart et al. (1968), who also related estimated temperatures and

apparent radiometric ages to distance from the contact. These apparent whole-rock ages were corroborated by K-Ar determinations on biotite, hornblende and feldspar from varying distances, and it was confirmed that the ages of minerals from various whole-rock samples are more thoroughly reset near the contact than away from it (Brookins et al., 1981). In addition, Rb-Sr whole-rock ages were determined on samples obtained at, near, and removed from the contact. The whole-rock isochron age is 1.5±0.1 billion years, in close agreement with earlier work by Simmons and Hedge (1978). The Rb and Sr analyses also indicated that there was no gain of these elements in the Idaho Springs Formation from the Eldora stock except possibly within the 1-to-3 m contact zone where some mixing of magmatic fluids with the metamorphic rocks occurred.

To further investigate the matter of closed versus open system conditions, as well as to address the problem of conductive versus convective cooling, trace element and stable isotopic analyses of the samples used for Rb-Sr whole-rock geochronology were carried out. The rare earth/chondrite ratio versus rare-earth atomic number distribution plot is shown in Figure 2. Samples 1a and 1b are from stock material and samples 2 and 3 from stock-plus-metamorphic rocks in the 1-to 3 m contact zone. These four curves are all similar and show pronounced enrichment of the light rare earth elements (LREE). Curves 5a and 6a are from mafic units of the Idaho Springs Formation, whereas curves 5b, 6b-1 and 6b-2 are from felsic units. The LREE are depleted in the mafic units but enriched in the felsic units; this behavior is noted not only in these samples taken 20-to-25 m from the contact (nos. 5, 6), but also in samples taken 2.5 km from the contact. It is apparent that some REE partitioning between mafic and felsic rocks took place during the Precambrian regional metamorphism, with open system conditions prevailing, as evidenced by the formation of secretion pegmatites.

The stable oxygen isotopic data (Figure 3) show a distinct contrast between the Eldora stock and the Idaho Springs Formation. Del ^{18}O values for the stock and stock-metamorphic mixes (in the contact zone) are confined to a relatively narrow range (+ 8.0-9.0 o/oo) compared with those of the Idaho Springs Formation (+ 7.5-11.5 o/oo). This indicates essentially closed system conditions for oxygen in the intruded rocks and no exchange of oxygen between the stock and the Idaho Springs Formation. In turn, this implies a lack of hydrothermal convective cooling, usually accompanied by hydrothermal solutions, (Parmentier and Schedl, 1981) and cooling by conduction appears most likely.

The location and abundance of uranium near and away from the contact were determined by fission-track radiography and gamma spectrometry (Flexser and Wollenberg, 1981). It was found that the occurrence of uranium is controlled predominantly by primary accessory minerals, both in the stock and in the Idaho Springs Formation: zircon, sphene, monazite, allanite, opaque minerals, and an unidentified highly uraniferous mineral present only in

the Eldora intrusive (Figure 4.) Secondary migration of uranium due to the intrusion of the stock has occurred, but on a small scale and only within a few meters of the contact. There is no indication of systematic enrichment or depletion in uranium, in either country rock or stock, as a function of distance from the contact. Mirgration of uranium is probably due to local redistribution from the accessory minerals by diffusion; there is no evidence to suggest that transport of uranium by circulating hydrothermal solutions in fractures played a significant role.

In summary, at the time of intrusion of the Eldora Stock and following its intrusion, the rocks of the Idaho Springs Formation were of low porosity and permeability, and the numerous fracture fillings and veinlets are prestock in age. In the 0.3m zone at the contact, there was mixing of some fluids from the Eldora stock due to infiltration into cracked and deformed parts of the Idaho Springs Formation accompanying emplacement. With the exception of this zone, closed system conditions, over the 10^5 to 10^6 years of stock crystallization and cooling, are demonstrated by the geochemical data. The data also indicate that subsequent to intrusion and cooling of the stock, there has been no appreciable migration or redistribution of elements within the gneiss over the zone investigated.

The Alamosa River Stock - La Jara Tuff Contact Zone: A Convective Thermal Regime

In contrast to the Eldora occurrence, the presence of strong hydrothermal circulation in tuffaceous rock in response to the intrusion of the Alamosa river stock near Platoro, Colorado was evident from oxygen isotope ratios measured by Williams (1980) on samples collected over a broad region. Based on this evidence, the contact zone and areas away from the contact between the stock and the intruded rocks -- the La Jara member of the Treasure Mountain tuff, and the Summitville andesite -- were investigated, primarily to determine if radioelements and fission-product- analogue trace elements moved from the monzonite into the tuff or andesite, or moved within the tuff, in response to the circulating hydrothermal system.

The Alamosa River stock, of monzonitic composition, was emplaced at 29.1 ± 1.2 MYBP into predominantly andesitic volcanics forming and filling caldera structures (Lipman, 1975). The La Jara is predominantly a densely welded and devitrified ash flow tuff primarily of phenocryst rich quartz latite, ejected by an explosive event at 29.8 ± 1.2 MYBP.

Based on analyses of oxygen isotope ratios in 260 minerals and whole rock samples from the Alamosa River stock region, Williams (1980) suggested that the heat from the stock and other small intrusions, which range in age from 28 to 22.8 MY (Lipman, 1975), initiated extensive hydrothermal circulation. A roughly concentric aureole of $\delta^{18}O$ depletion was noted around the south and east margins of the stock, with depletion enhanced along two

major faults, attesting to the importance of fracture permeability in the circulation of this system. Temperatures of the hydrothermal system were estimated by Williams (1980) to have been in the range 250-370°C.

For our studies, samples from the Alamosa River stock area were collected at several locations as shown in Figure 5. A detailed traverse was made across the intrusive-tuff contact, as well as regional traverses in the tuff and in the andesite away from the stock, and samples were analyzed by neutron activation and fission-track methods to determine the distribution of radio- and trace elements.

Thin-section petrography shows that alteration of the tuff related to the monzonite contact has affected both the phenocrysts and the interstitial matrix. The progression of alteration starts within 60m of the contact with the development of calcite, intergrown with the fine quartz-feldspar mosaic of the matrix. Within 40 m of the contact chlorite and sericite appear in the matrix, as well as stringers and over-growths of quartz which increase in abundance and coarseness toward the contact. Epidote also becomes a common matrix alteration within 12 m of the contact. Phenocryst alteration in the tuff more than 60m from the contact is mainly confined to biotite, which is partly altered to fine opaque grains and sphene. Closer to the contact, pyroxene grains are altered to an opaque mineral, probably magnetite, and within 30 m of the contact biotite grains have been reduced to mere streaks of fine opaque grains, with associated epidote and sphene.

The distribution of uranium in rocks of this contact zone, represented by a traverse at Telluride Mountain (Figure 5), was examined by fission-track radiography. Uranium in the monzonite is mainly confined to minute accessory grains (probably zircon) which occur most typically in grains of potassium feldspar. Uranium also occurs, though more rarely, with altered mafic grains in monzonite close to the contact, and is probably associated there with very fine sphene. In contrast to the monzonite, the tuff rarely contains uranium-bearing accessory grains. Instead, U in the tuff usually occurs in low concentrations in the fine feldspar-quartz intergrowth comprising the matrix between phenocryst grains. The actual contact between monzonite and tuff, identifiable in thin sections, is marked by a dense intergrowth of epidote and lesser sphene. Uranium is often associated there with sphene, but is otherwise absent from the contact. The contact is also cut by fine hematite-filled fractures extending into adjacent tuff and monzonite. Uranium does not appear to be associated with these fractures within the immediate contact zone or on either side of the contact.

Results of neutron activation analyses of some trace elements in samples of monzonite and tuff from the meter-scale traverse across the contact at Telluride Mountain comprise Figure 6. Strong contrasts between monzonite and tuff are evident, with higher contents of Cs, Rb, Sc, V, Fe, Th, U and Co in the monzonite. On the 10-meter scale of sampling, there are

suggestions of gradients in Cs, Th and Co in the tuff, with abundances of these elements increasing towards the contact. In general, the elements studied with the exception of Cs, Th and Co, show no evidence for migration between the stock and intruded rocks. These observations, together with petrographic investigation (Wollenberg et al., 1983), indicate that elemental distributions in the rocks appear to be mineralogically controlled, and local whole-rock chemical variations reflect mineralogical variations. On a broader scale, analyses of samples from a regional traverse (Figure 7), extending several kilometers from the contact, indicate that there are no apparent chemical gradients to match the regional gradients in whole-rock $\delta^{18}O$ in the La Jara tuff.

The effects of alteration on trace element abundances were investigated. Strongly altered tuff is enriched in Cs, Sr, and Rb and depleted in La and Fe, relative to the less altered tuff. Alteration effects are less apparent in the monzonite, though altered samples are high in Th and relatively low in La and Fe. The general high degree of correlation between U and Th, (Figure 8) irrespective of degree of alteration and distance from the contact, contrasts with the lack of correlations between Th and both Sr and Cs. Weak correlations with Th hold (in all but the strongly altered samples) for Rb and La, and for Fe in tuff and monzonite. These observations suggest that Sr and Cs were relatively mobile in response to alteration, while La, Rb, and Fe were less affected, and U and Th were essentially unaffected by alteration, and thus were relatively immobile.

Oxygen isotope data, obtained for samples from the Telluride Mountain traverse show a broad variation of $\delta^{18}O$ values of the tuff, ranging from + 0.8 o/oo to 3.6 o/oo in the zone within 60 m of the contact. Values in the monzonite within 10 m of the contact are +2 o/oo. The general degree of depletion in the monzonite and in the tuff is consistent with previous data (Williams, 1980). However, the $\delta^{18}O$ depletion does not, on the scale examined in the Telluride Mountain traverse, show any consistent gradient away from the intrusive in the tuff. Local fracture permeability variations appear to control the variations observations observed in the $\delta^{18}O$ depletion of any specific sample. Although rock samples from the Telluride Mountain traverse are quite variable in $\delta^{18}O$, they are all significantly depleted relative to normal igneous rock. Water-rock mass ratios greater than 0.1 are implied for even the least $\delta^{18}O$-depleted samples. The samples lowest in $\delta^{18}O$ indicate water/rock values greater than 0.3.

In summary, at Platoro:

- o A strong convective hydrothermal system accompanied intrusion of Alamosa River Stock.

- The distributions of U, Th, REE, V, K, and Ti in the monzonite and tuff are apparently unaffected by the intrusion or are the result of complete homogenization by the hydrothermal circulation. This is true also for Rb, Sr, and other elements, although for some of these elements there is no strong chemical gradient between the rocks. U and Th are essentially immobile with alteration, in comparison with other trace elements.

- Within ten meters of the contact, some elements show evidence for contact zone mobility.

- Both monzonite and tuff have essentially retained their bulk chemistry during and after intrusion.

A Rhyodacite Dike Basalt Contact Zone

A contact zone between a rhyodacite dike and the Wanapum Basalt of the Grande Ronde Formation is exposed in a quarry on the Hood River, Oregon. Investigation of this contact showed that chemical gradients between the dike and the basalt are pronounced, permitting assessment of element migration during intrusion of the dike as well as during and after its cooling. In this study, radioelement contents and Sr isotope ratios were determined from a sampling traverse encompassing the dike and extending several meters into the basalt. If chemical and/or isotopic exchange has occurred between such contrasting rock types, mixing should be apparent in analyses of these samples.

The distributions of radioelement contents and Sr isotope ratios are plotted in Figure 9. The sharp contrast between the uranium and thorium contents of the rhyodacite and the basalt is evident, as is the strong contrast in $^{87}Sr/^{86}Sr$. Uranium in the rhyodacite averages 4.3 ppm; thorium, 13.2 ppm; potassium, 3.1%; and $^{87}Sr/^{86}Sr$ 0.7041. Corresponding average values for basalt are: U, 1.05 ppm: Th, 3.95 ppm; K, 0.9%, and $^{87}Sr/^{86}Sr$, 0.7052. These data argue against any transfer of radioelements or Sr from one rock into the other, either during intrusion of the dike or through fractures formed in the basalt after the dike had cooled.

It is concluded from this occurrence that

- The strontium isotopic characteristics of both the intrusive and intruded rocks are preserved. There is no evidence for Sr isotpic disturbance or redistribution due to the emplacement of the rhyodacite dike in the Wanapum Basalt.

- The distribution of radioelements, with pronounced gradients in U, Th, and K between the rhyodacite and

basalt, shows that no radioelements have been transferred across the contact.

- Consideration of the rhyodacite as a heat engine, and therefore as an analogue for buried radioactive waste in basalt, indicates that radionuclide migration into the host rock is unlikely under the conditions of dike intrusion.

Contacts Between Dikes and Bedded Salt

The migration of radio- and trace elements into salt in response to intrusion of a dike and over long time periods following its cooling may be analogous to migration of radionuclides in the near-field of a breached canister in a salt repository. Investigation of the abundance and contents of fluid inclusions in the salt may also be definitive in assessing the thermal and chemical effects of the dike. Potential analogue occurrences include a lamprophyre dike cutting the evaporite sequence of the Delaware Basin in southeastern New Mexico, a basaltic dike transecting salt of the Zechstein, West Germany, and Permain kimberlitic dikes cutting upper Silurian salt beds of Salina Basin in northwestern New York.

Gamma spectrometric measurements of a set of samples obtained of the basaltic dike, of Miocene age, and salt of the Zechstein indicated appreciable radioelement contents of the dike (U = 2.1 ppm, Th = 7.6 ppm), while radioelement contents of the salt at and away from the contact are below detectability limits. A similar situation was observed in a set of samples of kimberlite dikes (U = 1.5-1.9 ppm, Th = 11.7-12.6 ppm) and salt obtained from underground exposure at the Cayuga mine, New York. Preliminary investigation of fluid inclusions in salt samples from the Cayuga mine by D. K. Smith (1983) indicates that their homogenization temperatures exceeded 380°C.

The Cayuga set remains to be examined in more detail petrographically, and selected samples of salt and dike analyzed for trace elements. Examination of fluid inclusions, their abundance, configuration, and analyses of their contents are also required.

Preliminary data then suggest that U and Th have not migrated appreciably from the dikes into salt, either in response to injection of the dikes or over the tens to hundreds of millions of years subsequent to their cooling.

Investigations at Stripa, Sweden

At the Stripa experimental facility in an inactive iron mine in central Sweden (Witherspoon et al., 1981) radiogeologic studies included gamma-spectrometric surveys on the surface and underground of the U, Th and K contents of the quartz monzonite

pluton encompassing the experiments, high-grade metamorphic rocks surrounding the pluton, and neighboring larger granitic plutons (Wollenberg et al., 1982). A geological cross section through the experimental workings comprises Figure 10.

Sampling at Stripa over a vertical extent of nearly 900m was afforded by continuously-cored inclined holes drilled from the surface, excellent access to underground workings, and core from a vertical hole drilled underground from a depth of 410 to 899 m (Figure 10). The abundances of U, Th, and K were measured by laboratory gamma spectrometry of core and hand specimens and by field measurements, on the surface and underground, using a portable gamma-ray spectrometer. The field gamma spectral measurements were calibrated by the laboratory analyses, permitting calculations of radioelement concentrations from field counting rates. Laboratory analyses indicated that the daughter products in the U and Th decay series were in secular equilibrium with their parents in the granitic rocks studied.

The Stripa quartz monzonite is unique in its radioelement content, both in the abundance of radioelements and in their ratios, as summarized in Table 1. The relatively high U contents of the quartz monzonite contrast with those of the other granitic rocks in the region and with the neighboring metamorphic rocks. The Th/U ratio of the Stripa quartz monzonite ($\sim$1) is considerably lower than in the other plutons (2.4), leptite (3.8), and regional metamorphic rocks (2.6), and is considerably lower than the average for granitic rocks in general. The relatively low Th/U ratio in the quartz monzonite suggests that U and Th are not in their usual association with accessory minerals, a fact confirmed by alpha- and fission-tract radiography (Wollenberg et al., 1982).

Table 1. Mean radioelement contents of rocks in the Stripa region

Rock	U(ppm)	Th(ppm)	K(%)	Th/U
STRIPA QUARTZ MONZONITE				
SURFACE	27	33	4.6	1.1
UNDERGROUND	37	29	3.9	0.8
LEPTITE				
SURFACE	3.3	12	3.1	3.6
UNDERGROUND	5.4	18	2.8	3.9
REGIONAL GRANITIC ROCKS	18	27	5.2	2.4
REGIONAL METAMORPHIC ROCKS	6.1	15	2.5	2.6

Inspection of the plot of U and Th versus depth in the quartz monzonite (Figure 11) indicates that U is depleted in surface exposures relative to its abundance underground. However, U in groundwater (also shown in Figure 11) increases markedly to a depth of 150 -200 m, then decreases steadily with depth in samples from the deep vertical drill hole. An explanation for these distributions based on fission track radiographic observations, is that at depth in the Stripa quartz monzonite, U is primarily associated with fracture-filling chlorite and not with accessory minerals. Andrews et al., (1982) suggest that at Stripa, U may be deposited with frature calcite, though this occurrence has not been confirmed by radiography. The association of U with fracture minerals indicates that U has been, and may still be relatively mobile. It may be removed from near-surface rock where slightly acidic and oxidizing conditions prevail (as reported by Andrews et al. (1982)), and transported in fractures by groundwater to deeper zones where more reducing conditions favor its concentration in fracture-filling material. The gradational increase in U with depth in the rock below 410 m, shown in Figure 11, then might result from redistribution and concentration in fracture filling material by the groundwater system. The concomitant increase in Th with depth may also be explained by its association with U in fracture minerals. Thorium-rich accessory minerals are very rare in the Stripa quartz monzonite, compared with the other plutons in the region and with granitic rocks in general.

The mobility of uranium in the Stripa quartz monzonite is also demonstrated by results of examination of core from "drillback" holes (Figure 12), drilled through the walls of a hole that contained an electric heater to simulate the thermal effects of the introduction of radioactive waste (Flexser et al. 1982). The effects of in situ heating of the monzonite were studied with respect to petrologic alterations and mechanical damage to the rock. The suite of core samples was examined in thin sections, by alpha radiography, gamma spectrometry, x-ray diffraction, and by electron microprobe. Mineralogic alterations in the rock adjacent to the heater were most pronounced in chlorite, which showed a marked change in color associated with proximity to fractures as well as to the heater hole. Structural changes in chlorite included decrease in the dimensions of the unit cell, a change to hexagonal or pseudo-hexagonal symmetry, and possibly disorder in layer stacking perpendicular to the c-axis. Intergrowth of fine hematite with chlorite also occurred.

Chlorite from within 5 cm of the heater hole contained slightly less SiO_2 and MgO and more FeO than chlorite in the unheated rock. Muscovite in the heated rock showed faint color changes associated with heating but was structurally unaltered. Muscovite near the heater hole was generally consistent in chemical composition, although it showed some variability at grain margins and in fracture fillings.

The distribution of uranim and thorium in the heated rock was studied by alpha radiography, which provided qualitiative evidence for the addition of U or Th to sites of disseminated acculations of these elements in samples near the heater hole. These accumulations occurred in fractures, cleavage planes, and grain boundaries. Sources of the added U or Th were not positively identified, but gamma-spectral analyses suggested depletion of U in rock away from the heater and its migration toward the heater hole (Figure 13).

Therefore at Stripa, where U occurs predominantly in fracture-filling chlorite, there is evidence for present-day mobility of this element in the groundwater system and in response to a one-year heater test.

Newberry, Oregon: A Present-day Hydrothermal System

A set of samples of andestic basalt, from a hydrothermal regime where temperatures range from 150 to 265°C, was obtained from core from a 950m deep hole drilled by the U.S. Geological Survey in the Newberry Caldera, Oregon (Macleod and Sammel, 1982). Saturated rock at these temperatures may be analogous to conditions in the near-field of a repository, within a few hundred years following emplacement of radioactive waste.

Twenty-four samples from the U.S.G.S. core repository in Vancouver, Washington were selected from the lower 200 m of the hole, encompassing andesitic basalt that exhibits varying degrees of brecciation and alteration. The alteration mineral assemblage in the basalt was preliminarily documented by Keith and Barger (1983) and is shown in Figure 14. The generally straight temperature gradient in the lower portion of the hole suggests conductive thermal conditions, so that the Newberry basalt flows are low-permeability layers that inhibit vertical fluid flow. Some horizontal fluid flow probably occurs along flow-top breccia zones, indicated by the strongly altered brecciated zones in the core.

Preliminary whole-rock gamma spectrometric analyses of U, Th and K in core from the lower 200 m of Newberry 2 are plotted in Figure 15. A general decrease of U and Th with increasing depth in the basalt is evident, and appears to be independent of the degree of alteration. This decrease may be attributed to more prevalent oxidizing conditions at depth, evidenced by the increasing scarcity of sulfide minerals and appearance of sulfates. However, a definitive explanation for this variation awaits detailed petrography to determine more accurately the alteration mineralogy; radiography to determine the mineral association of these elements; and, ultimately, analysis of fluid samples to determine Eh and pH conditions at depth.

Conclusion

In some contact zones between intrusives and gneissic, tuffaceous and basaltic country rock, migration of elements of interest in radioactive waste isolation has been confined to within a few meters of the contacts. The apparent lack of movement of radioelements and absence of appreciable redistriution of them, either in response to the conductive thermal regime at Eldora, Colorado or to the convective hydrothermal system at Platoro, Colorado is attributed primarily to the sites of the radioelements in accessory minerals. In contrast, the apparent mobility of uranium in the groundwater in the Stripa quartz monzonite and in response to a one-year heater experiment at Stripa, is based on the principal locus of U in chloritic fracture-filling material, more readily attackable by the moderately oxidizing groundwater. The apparent depletion of U with depth in basalt at Newberry, Oregon is also probably attributable to oxidizing conditions.

Investigation of present-day active hydrothermal systems, where temperatures approximate those expected in the near-field of a repository, would disclose the distribution of elements in rocks and fluids and the associated mineral assemblages in conditions most analogous to repository environments. Calculation of aqueous chemical species using water-rock equilibration codes, substantiated by such observations, would help define the source terms for prediction of radionuclide transport from waste canisters into and through their encompassing hydrologic systems.

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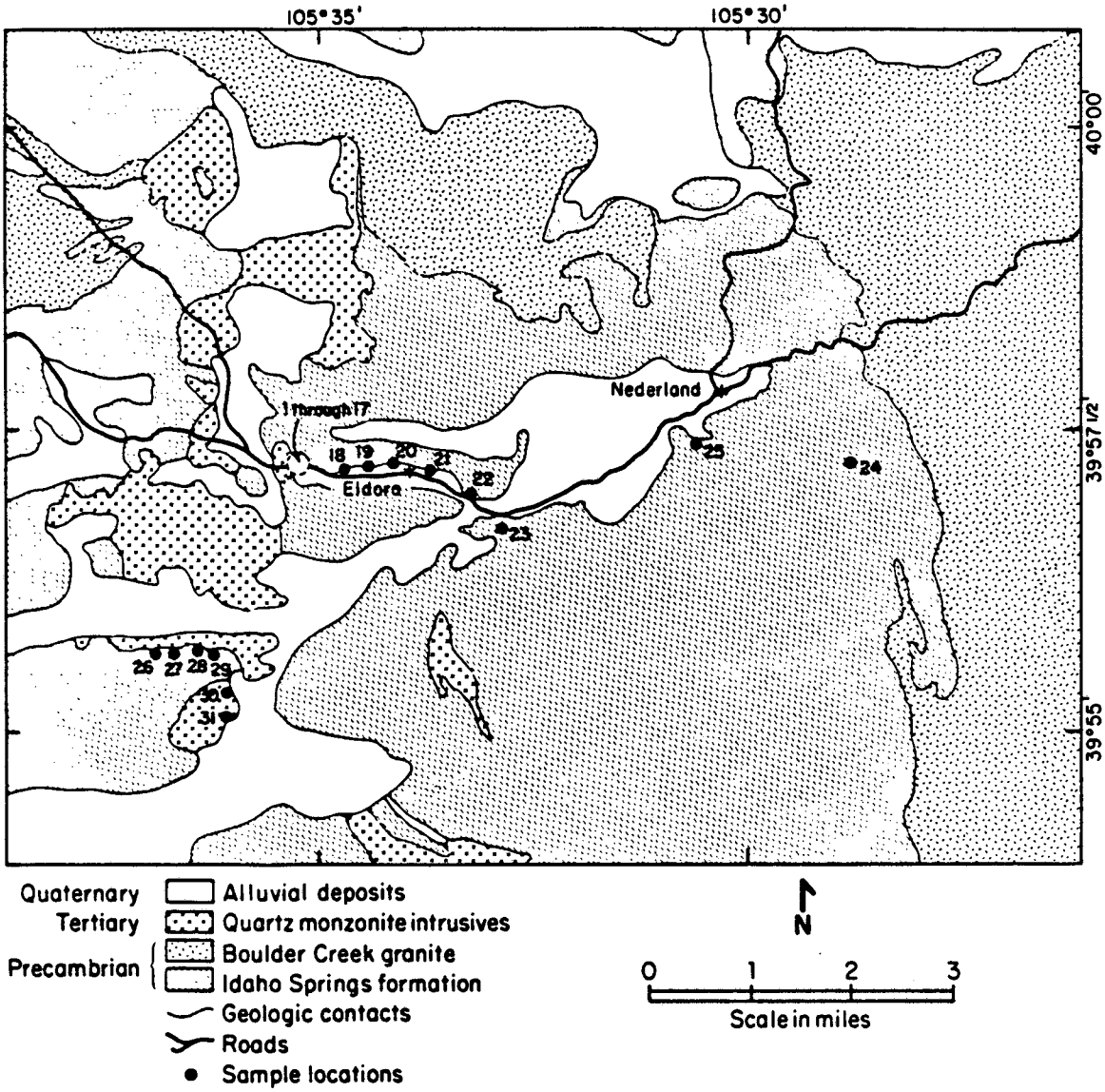


Figure 1. Simplified geologic map (after Hart, et al., 1968) showing sampling locations in the Eldora Stock-Idaho Springs Formation, Colorado.

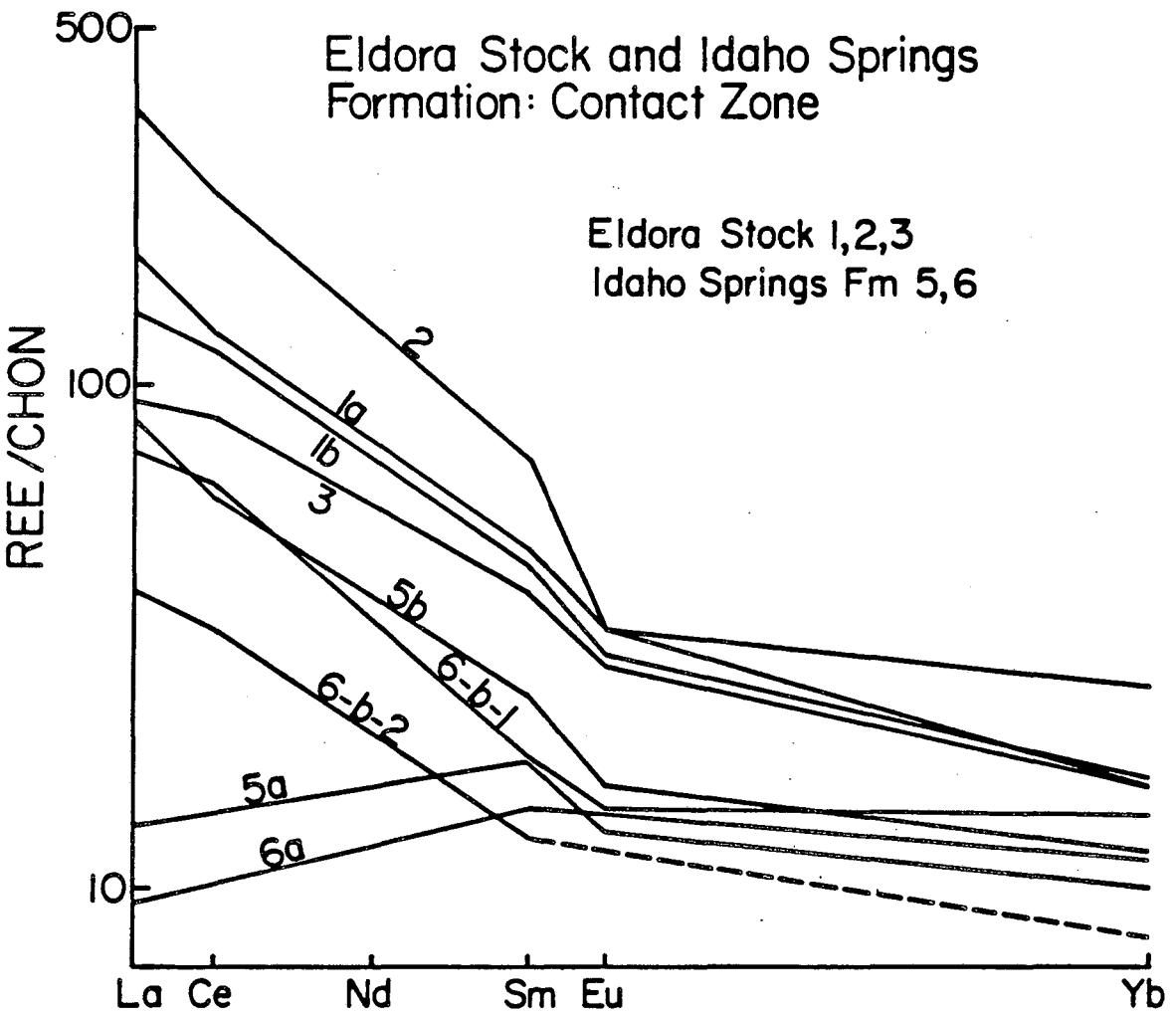


Figure 2. Rare earth element distribution plots for Eldora stock (Nos. 1a, 1b), Idaho Springs Formation (5a, 5b, 6a, 6b), and mixed samples (2, 3).

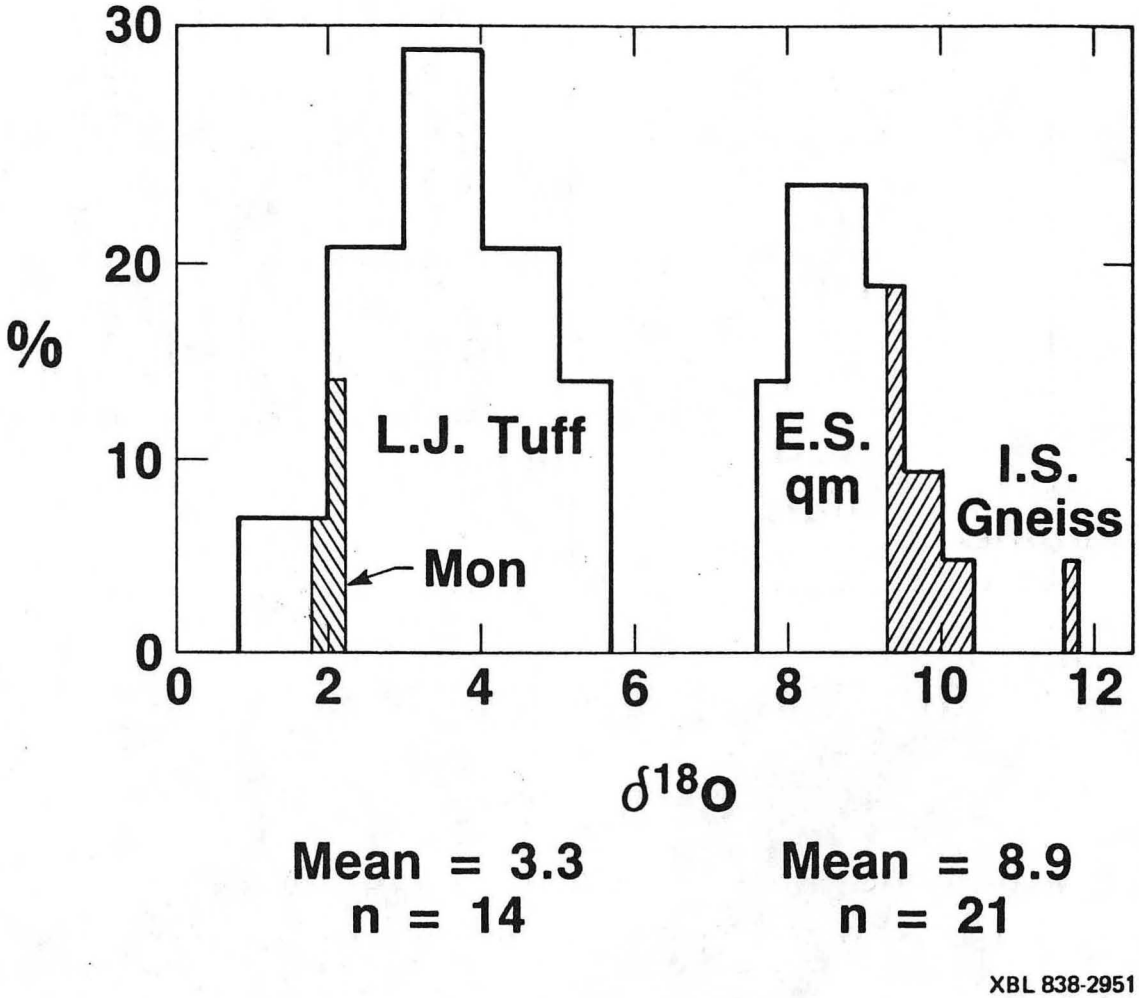
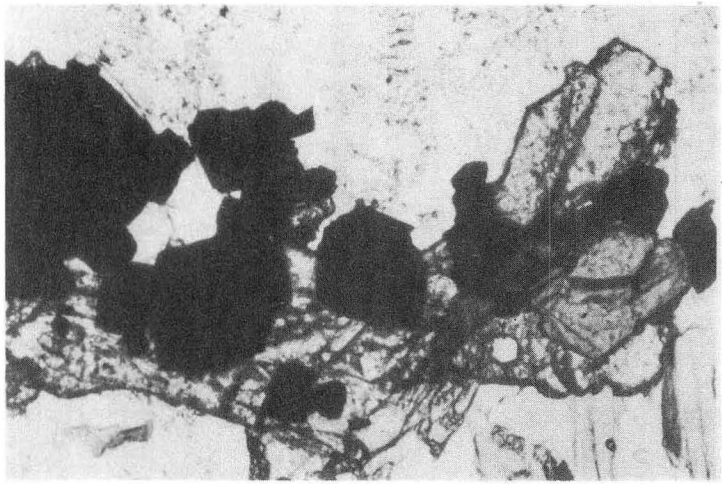
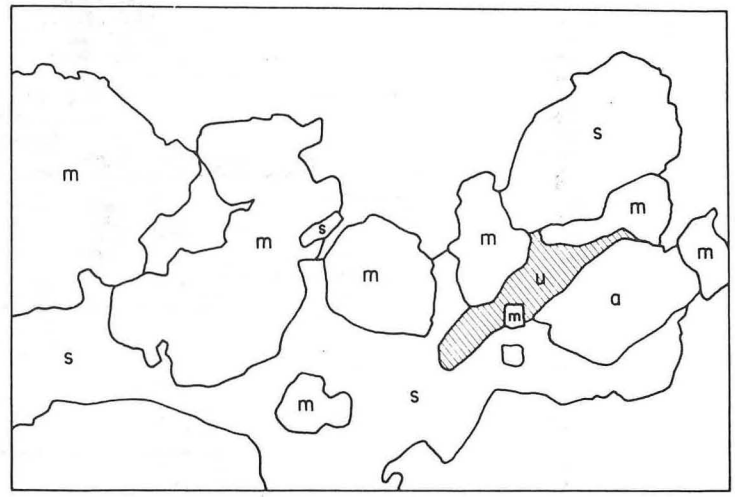


Figure 3. Frequency distributions of $\delta^{18}O$ from the contact zones investigated at Eldora and Platoro, Colorado.





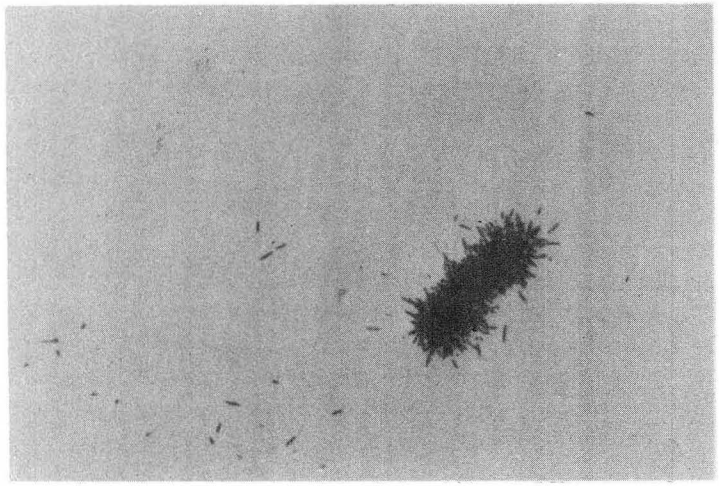


Figure 4. Uraniferous mineral, with dense association of fission tracks, from quartz monzonite of Eldora Stock adjacent to contact with country rock. Sparser fission tracks are associated with sphene. Plane-polarized light. (u-uraniferous mineral; s-sphene; m-magnetite; a-allanite; d-diopside; h-hematite. Lighter areas are feldspars and quartz).

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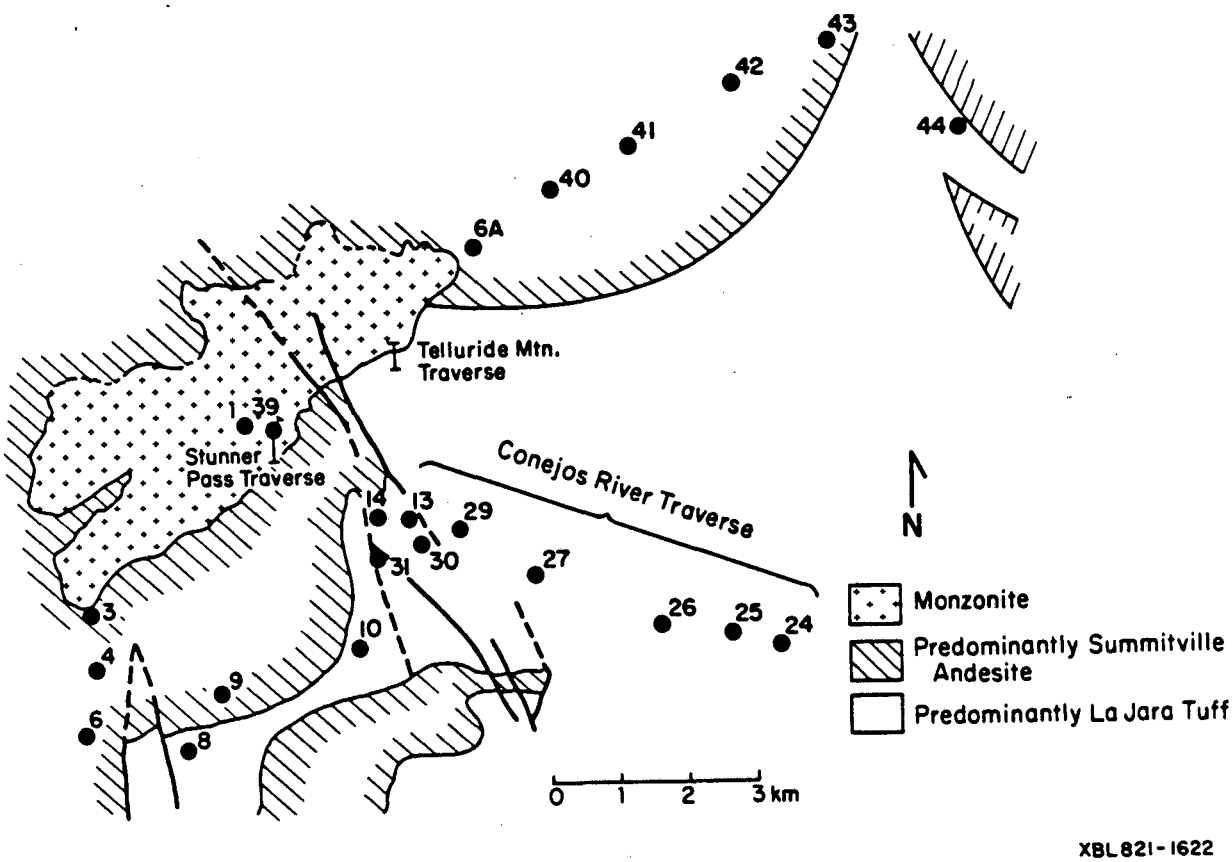

Figure 5. Simplified geologic map of the Platoro area, Colorado, showing sampling traverses in monzonite, tuff and andesite.

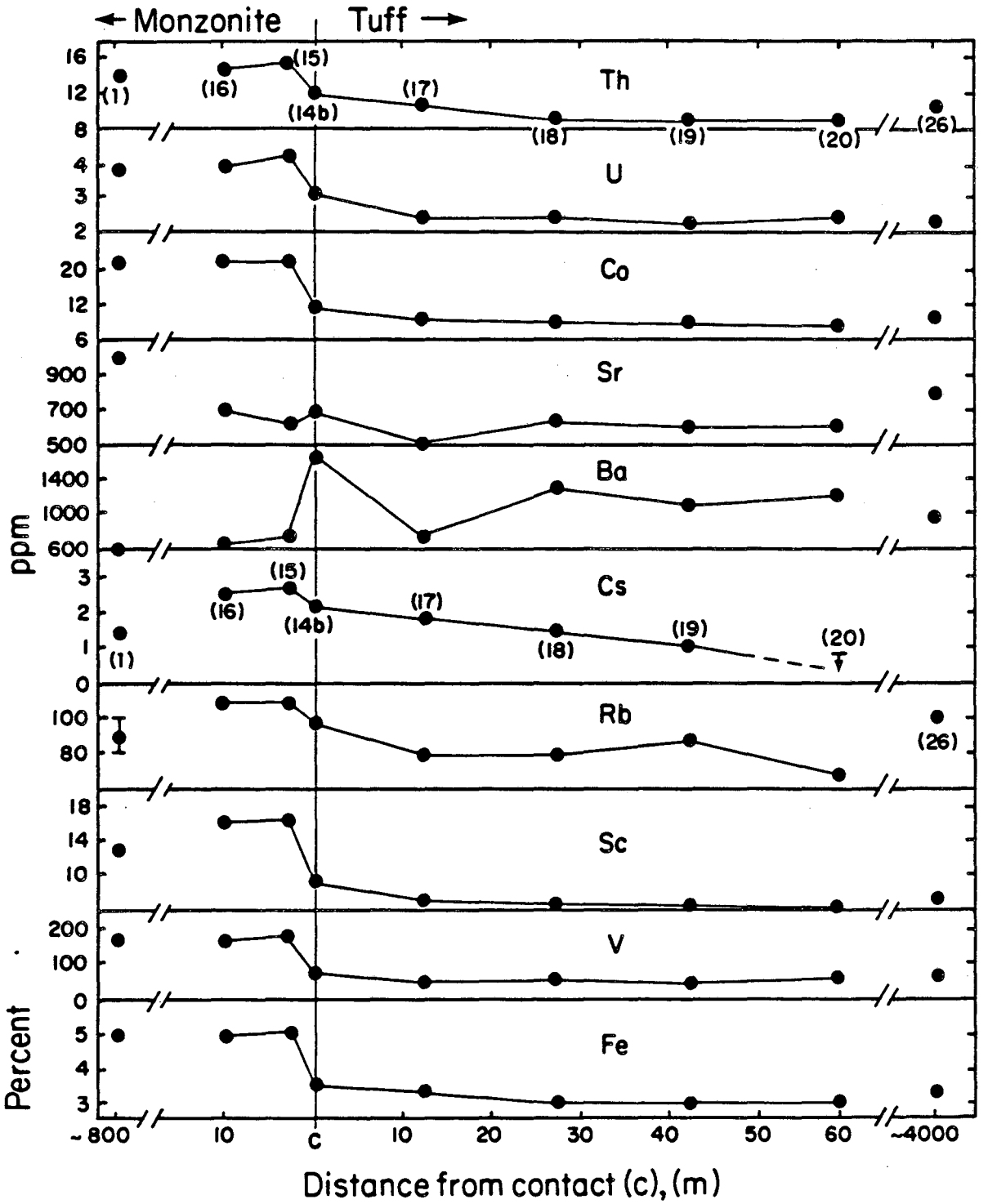

Figure 6. Element variations across the contact between monzonite and tuff, Telluride Mountain traverse, Platoro area, Colorado.

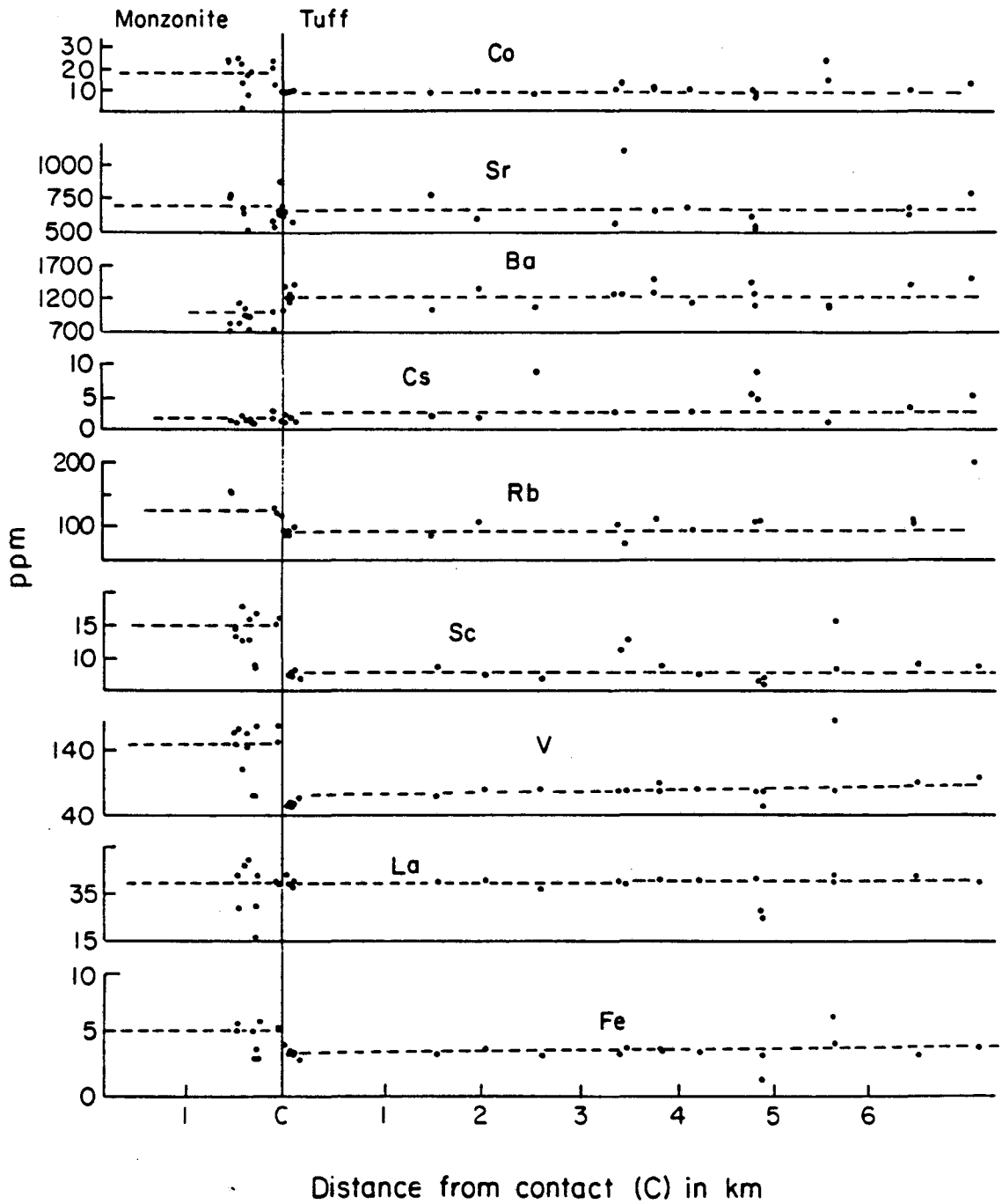

Figure 7. Element variations with distance from the contact between monzonite and tuff, Platoro area Colorado.

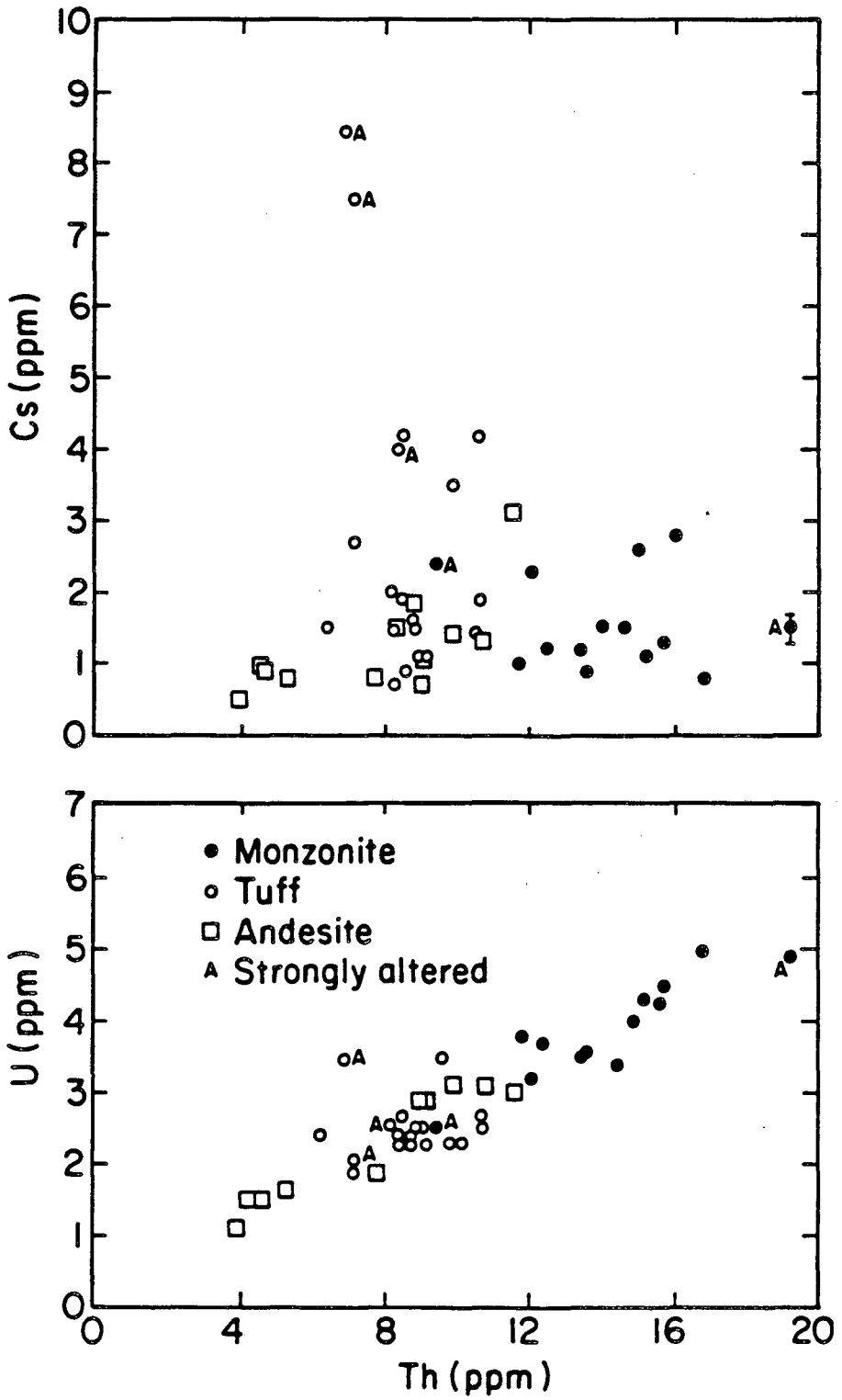

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Figure 8. Cesium and uranium versus thorium in strongly altered and less altered tuff, monzonite and andesite of the Platoro caldera.

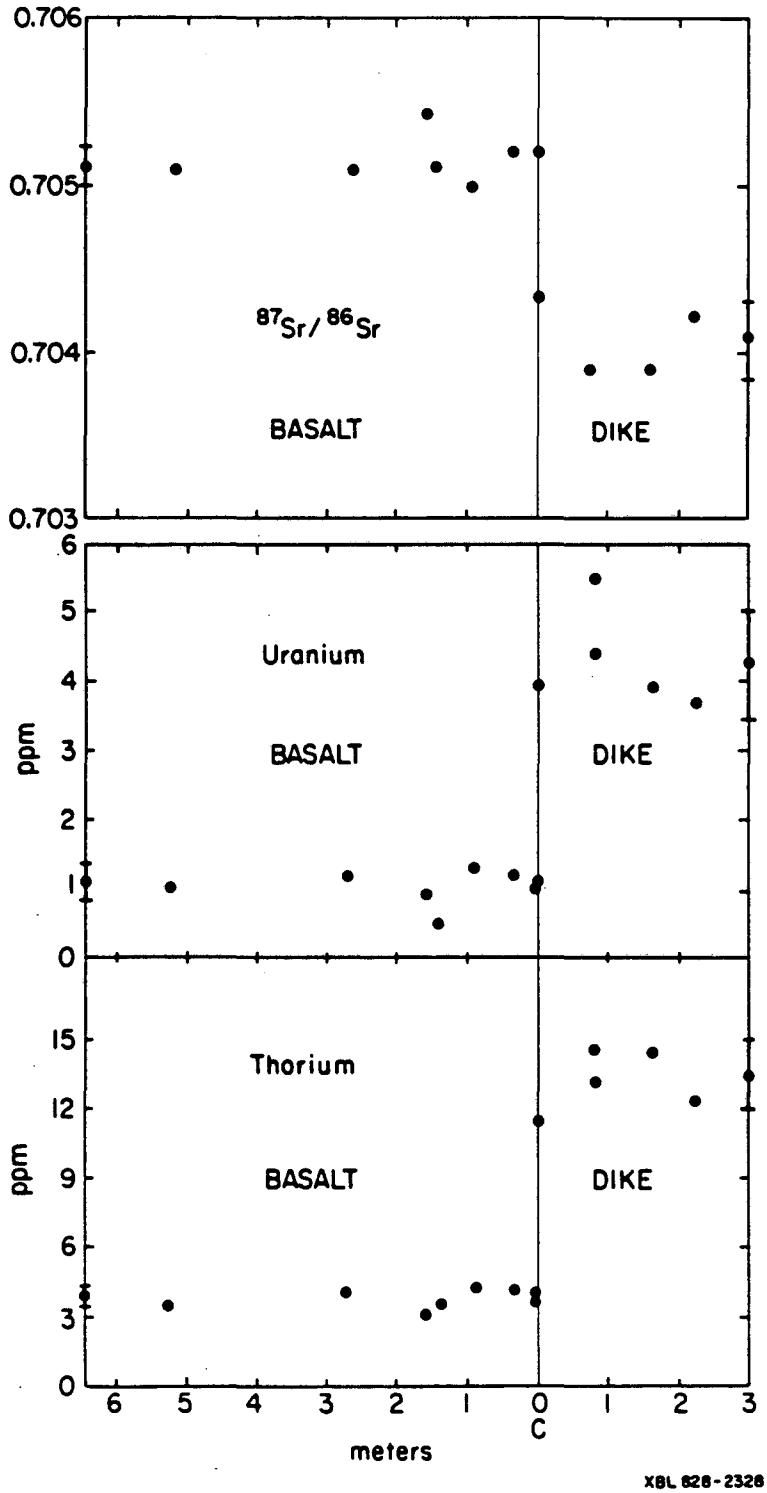

Figure 9. Strontium isotope ratios, uranium and thorium in rhyodacite dike and basalt, quarry on Hood River, Oregon.

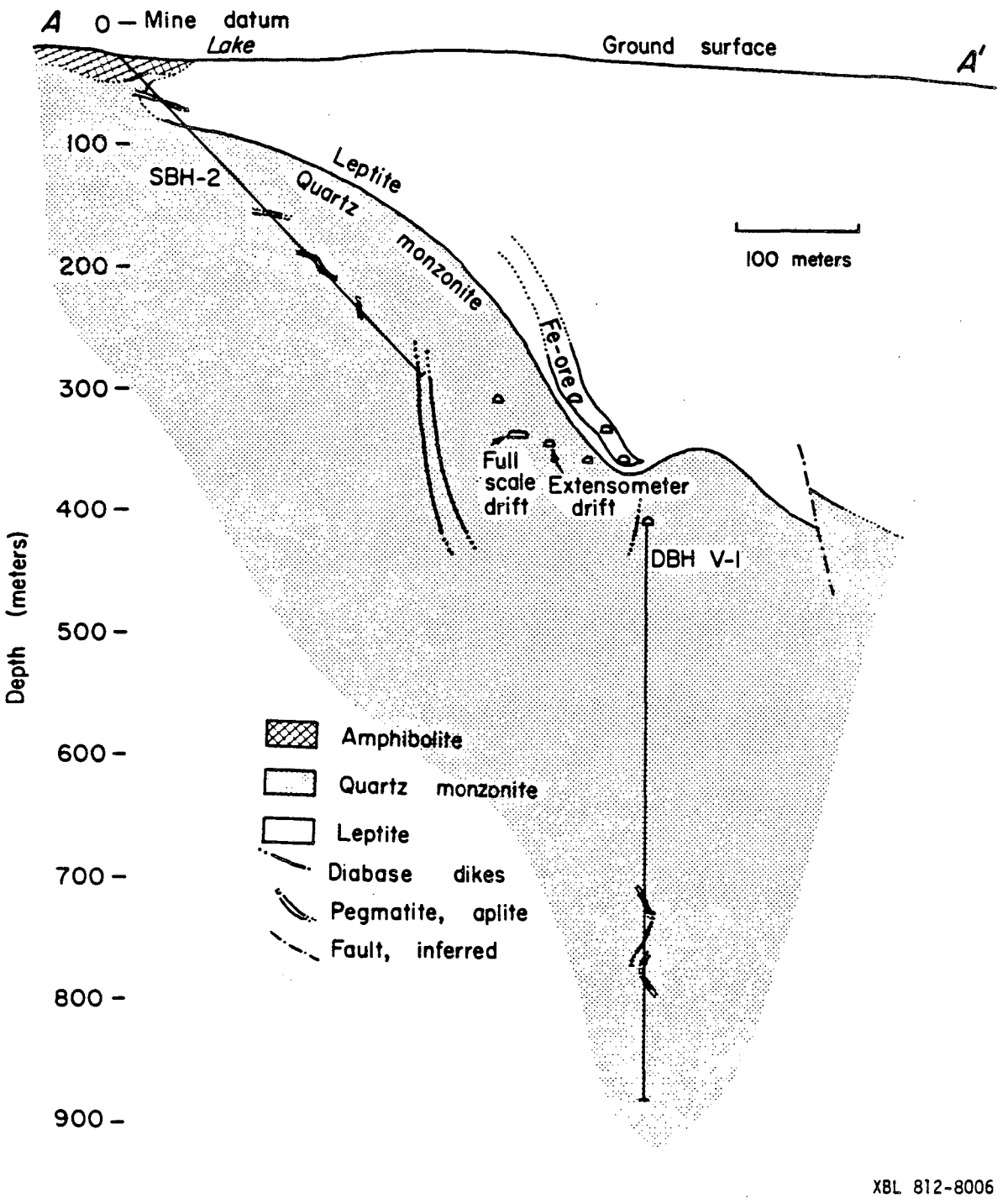

Figure 10. Vertical cross-section through the Stripa experimental area.

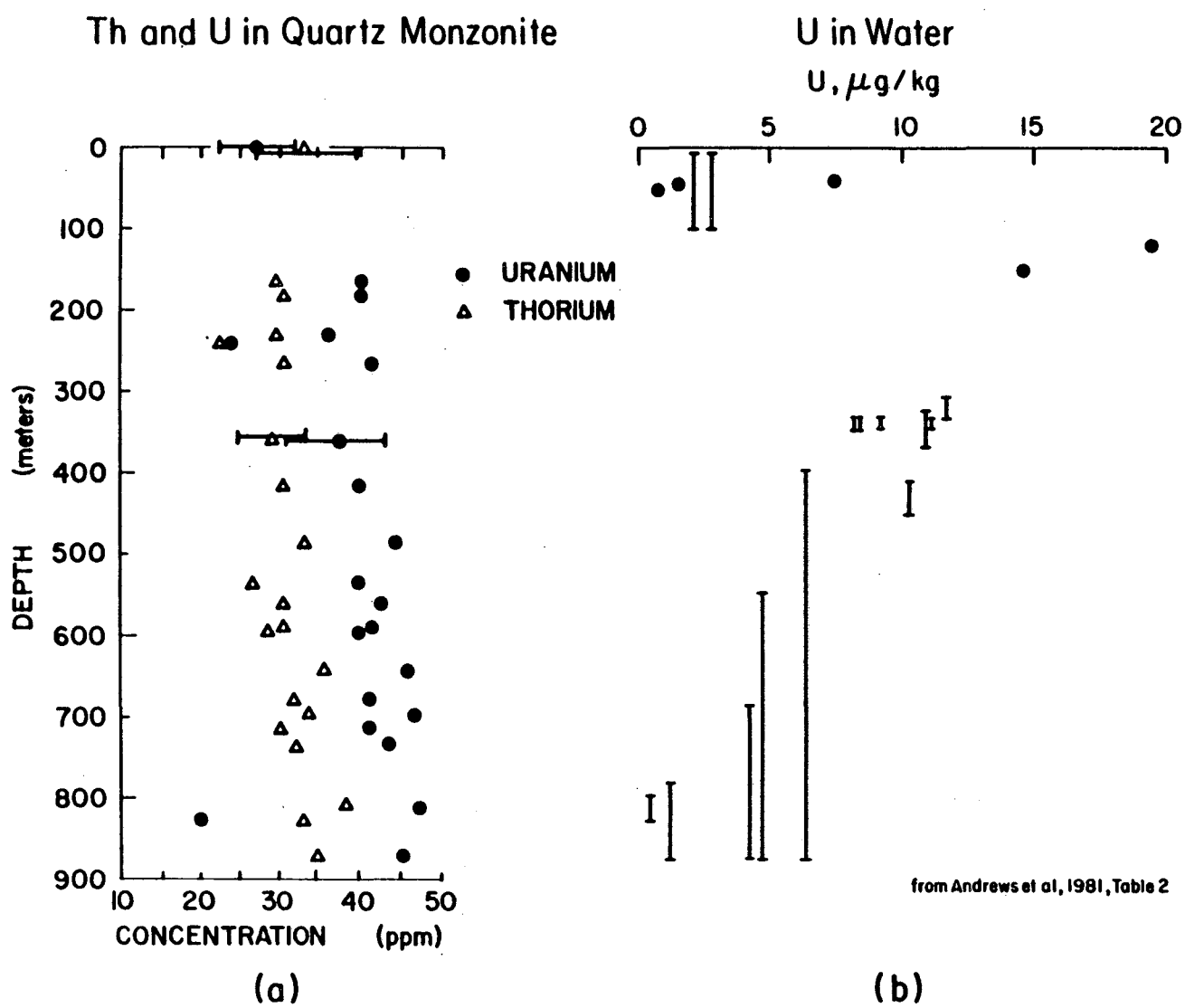

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Figure 11. Distribution of Th and U in rock and U in groundwater at Stripa, Sweden. Vertical bars represent water samples from varying depth intervals (from Andrews et al., 1982).

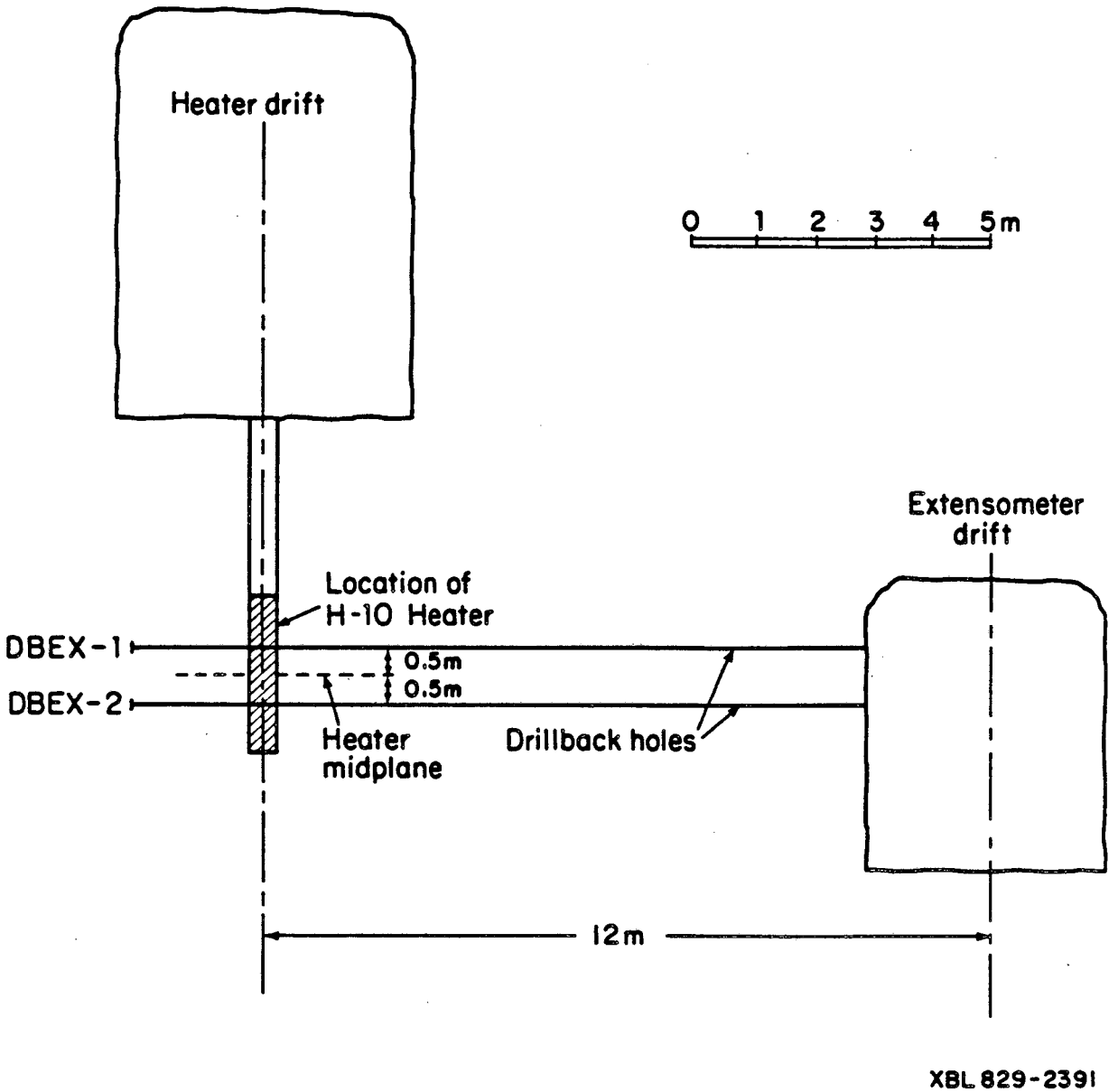

Figure 12. Vertical cross-section through the H-10 heater hole and the heater and extensometer drifts, Stripa experimental facility, showing the location of drill-back holes.

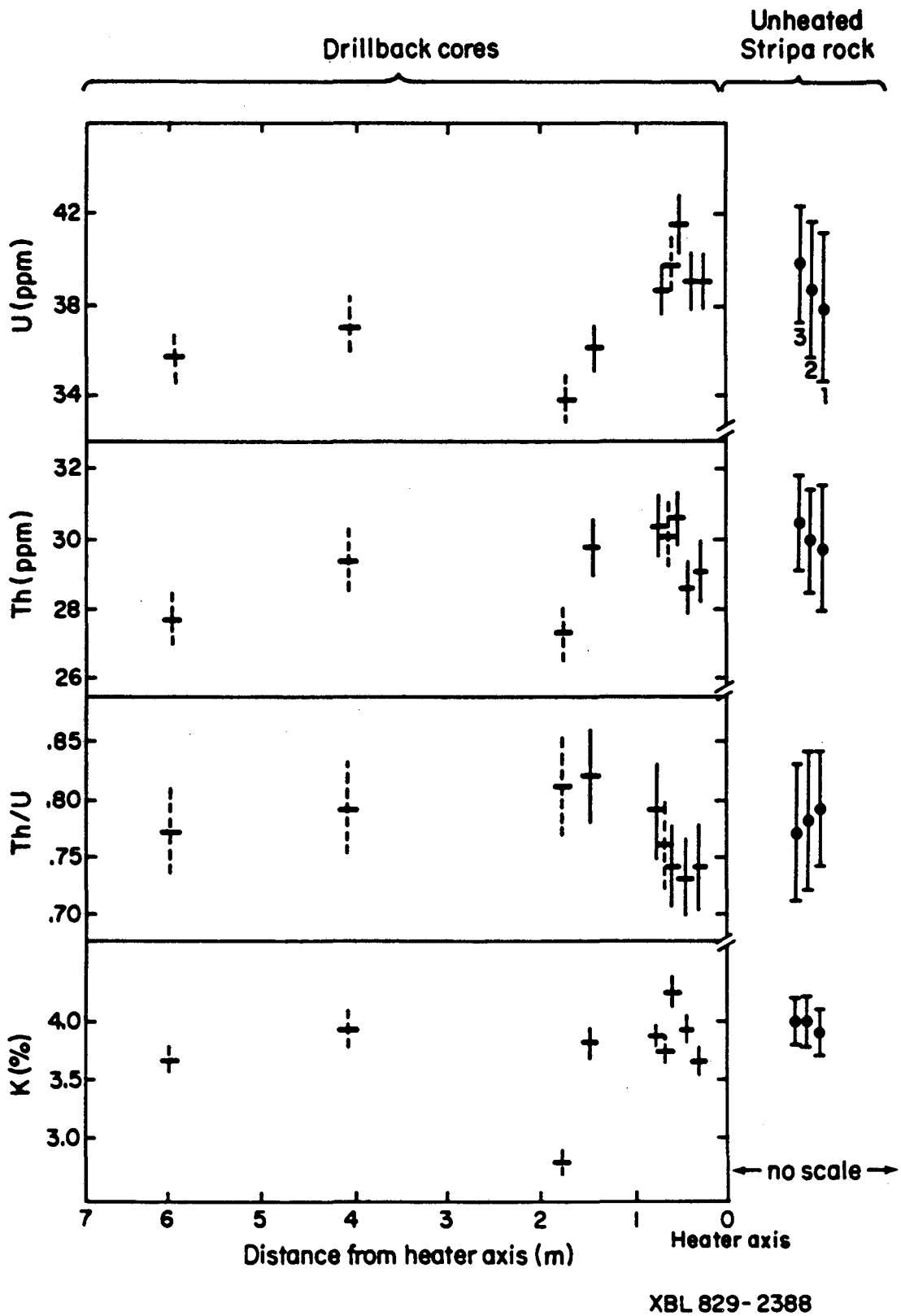

Figure 13. Variation of U, Th, and K with distance from the H-10 heater and comparison with analyses of unheated Stripa rock.

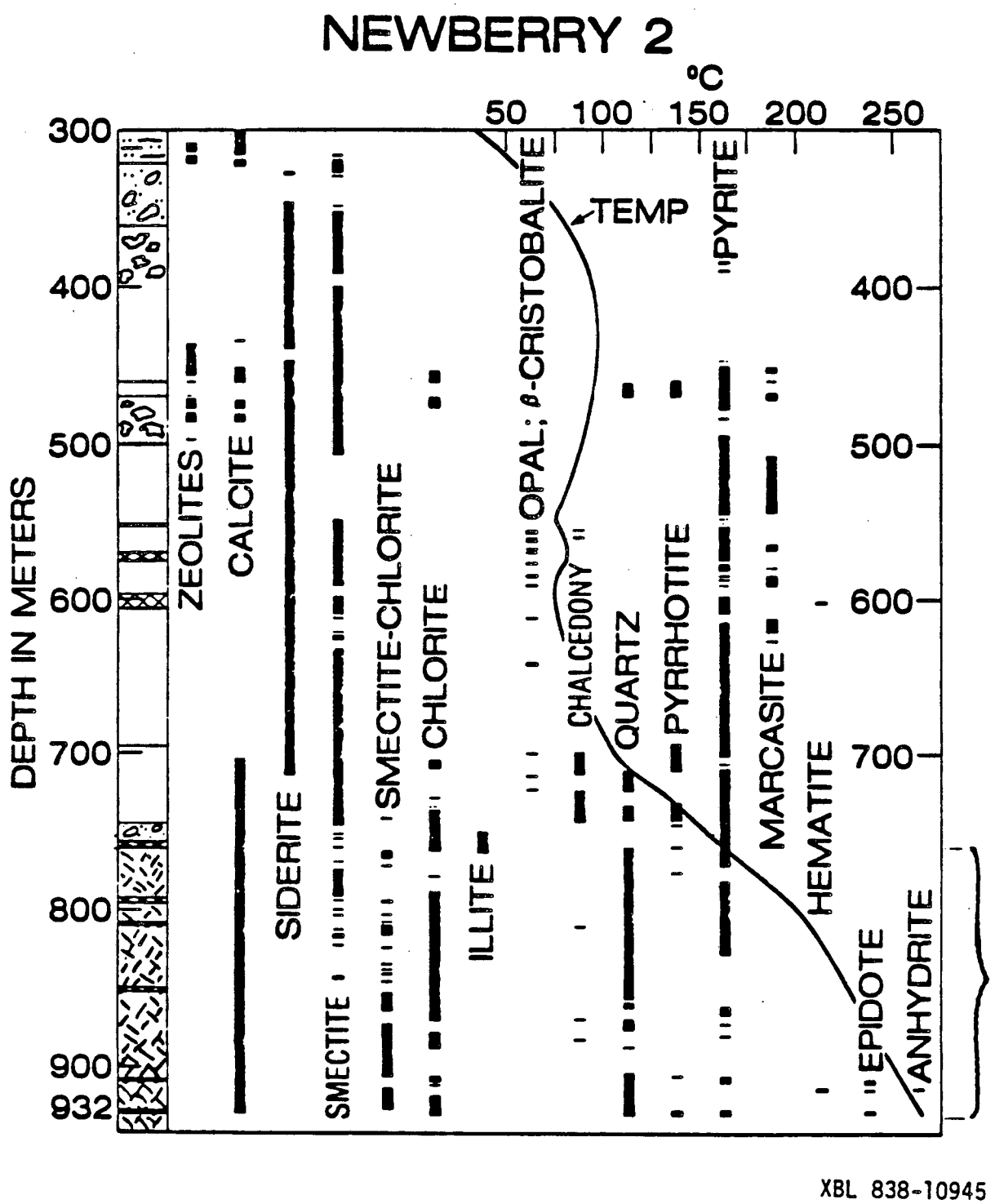

Figure 14. Preliminary observations of the mineralogy in the Newberry 2 hole, Oregon (Keith and Barger, 1982). The bracketed basaltic zone in the bottom portion of the hole indicates the extent of our samples.

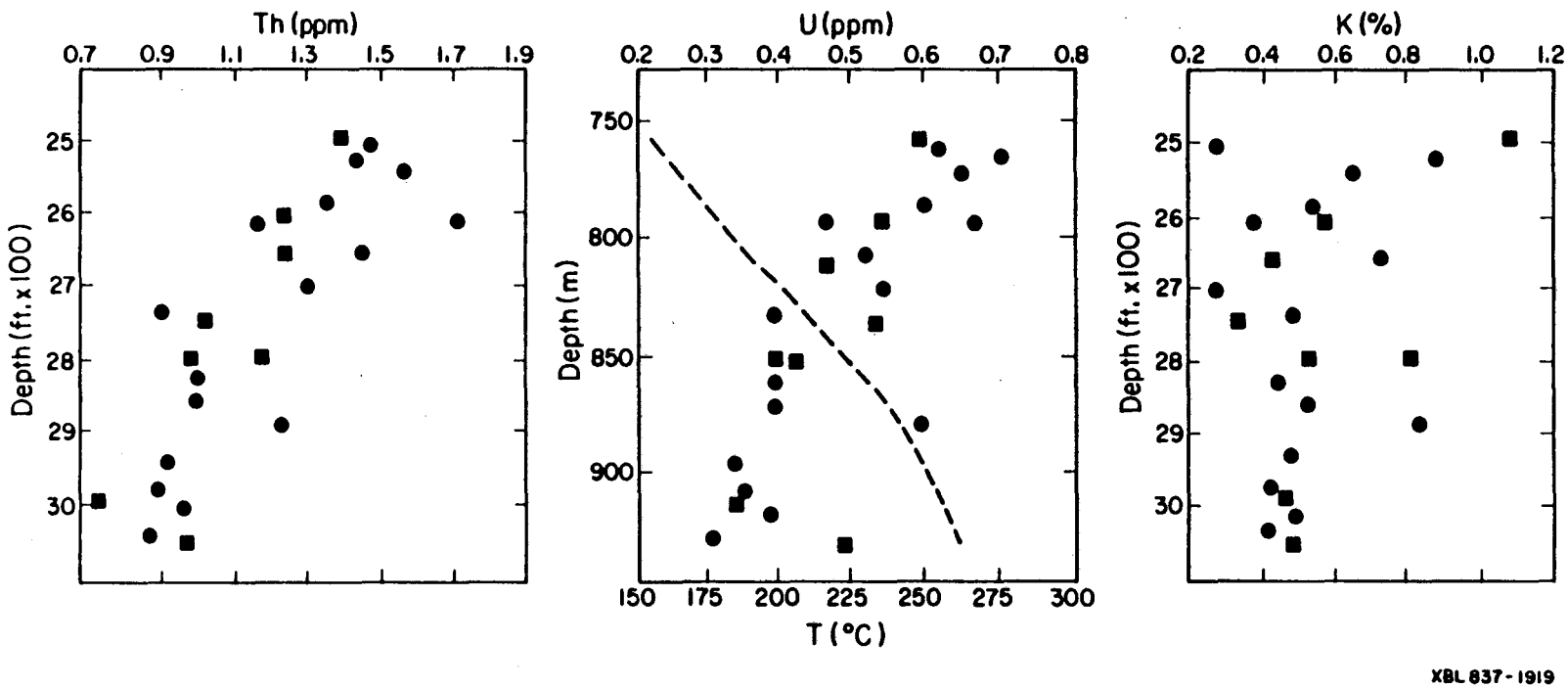

Figure 15. Variation with depth of radioelements in basalt of the Newberry 2 core. The most strongly altered samples are designated by squares. The dashed line is the temperature gradient determined by bottom-hole measurements during drilling (Macleod and Sammel, 1982).

This report was done with support from the Department of Energy. Any conclusions or opinions expressed in this report represent solely those of the author(s) and not necessarily those of The Regents of the University of California, the Lawrence Berkeley Laboratory or the Department of Energy.

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