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EARTH SCIENCES

LAWRENCE BERKELEY LABORATORY / UNIVERSITY OF CALIFORNIA

EARTH SCIENCES DIVISION

THE CENTER FOR COMPUTATIONAL SEISMOLOGY (CCS)

The Center for Computational Seismology (CCS) was established in October 1982 by Lawrence Berkeley Laboratory and DOE's Office of Basic Energy Sciences. The center was conceived by seismologists E. L. Majer at LBL and T. V. McEvilly, L. R. Johnson, and Shimon Coen at the University of California, Berkeley to provide a focused environment of seismic data management and modern computational methods, now distributed among many research groups at LBL and on the UCB campus. CCS utilizes the central computing facilities at LBL augmented with specialized hardware and software for processing and analyzing seismic reflection data. The facility operates on a flexible computer system, with user convenience enhanced for computational seismology through interactive graphics and a diverse program library. The goal is a hospitable computing environment for LBL/UCB researchers, students and visiting scientists developing and using state-of-the-art computational methods in seismology, and the evolution of a package of readily available and portable state-of-the-art programs. CCS can draw upon the continuing development of hardware and software at the LBL Computer Center to avoid the risk of being dependent on outdated methods and facilities. Furthermore, CCS is closely linked with the Computer Science and Mathematics group at LBL (CSAM), whose expertise in computer science represents a major resource.

To date, research at CCS has involved processing reflection data on geological areas of extreme structural complexity. Work is also progressing on source mechanism studies for earthquakes and explosions, as well as on the development of new methods for interpreting seismic wave propagation effects. The unification in a single research unit of theoretical and observational seismology with advanced computational capabilities has progressed nicely in the first months of CCS existence. By June 1983 CCS had reached a level of active use by 5 scientists, 12 students, 3 visiting scientists, and 1 post doctoral fellow in a wide range of investigations supported by DOE, DOD, USGS, NSF, GRI, and industry. It seems clear that CCS has filled a very real need.

The Movement of Geothermal Fluid Through the Subsurface of the Cerro Prieto Field, Baja California, Mexico

S. E. Halfman and M. J. Lippmann

After carrying out a successful exploration effort, the Comisión Federal de Electricidad (CFE) began the development of the Cerro Prieto geothermal field in Baja California, Mexico (Figures 1 and 2) in the mid 1960s. Commercial production of electrical power began in 1973. Today, the output is at 180 MWe and is expected to increase to 620 MWe by mid 1985.

The success of CFE's endeavor at Cerro Prieto made this liquid-dominated geothermal field ideal for an international program of cooperative investigations. In 1977, a five-year agreement was signed between CFE and the U. S. Energy Research and Development Administration, now the U. S. Department of Energy (DOE), to conduct a joint study of this system (Witherspoon et al., 1978; Lippmann, 1982). This project resulted in an intensive analysis of the reservoir and a wide variety of standard and new geological, geochemical, geophysical, and reservoir engineering techniques were carried out. The results obtained under the CFE/DOE agreement are helping Mexico to

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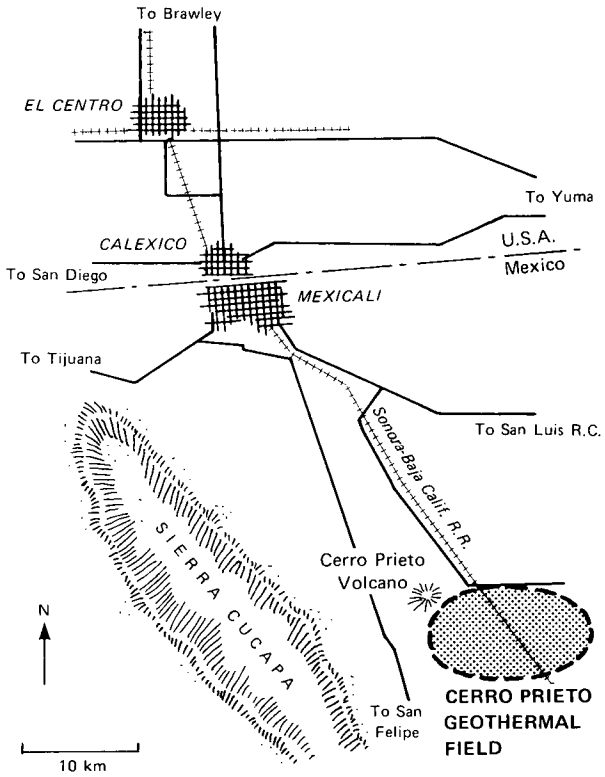

Figure 1. Location of the Cerro Prieto geothermal field. [XBL 788-10409]

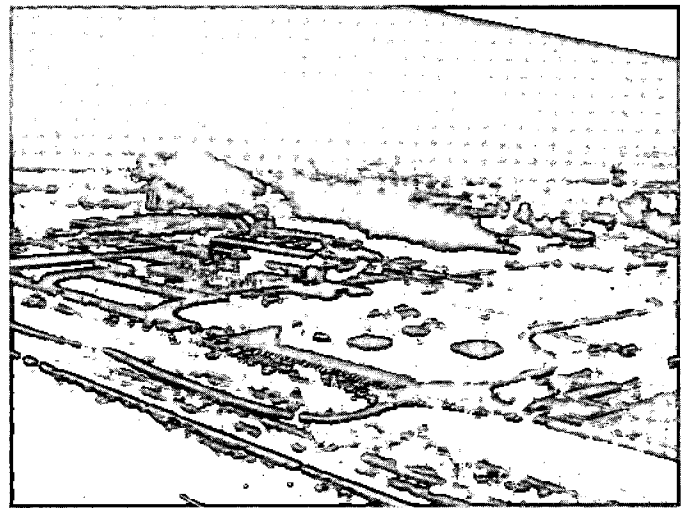

Figure 2. Panoramic view of the Cerro Prieto field. [XBL 803-3124]

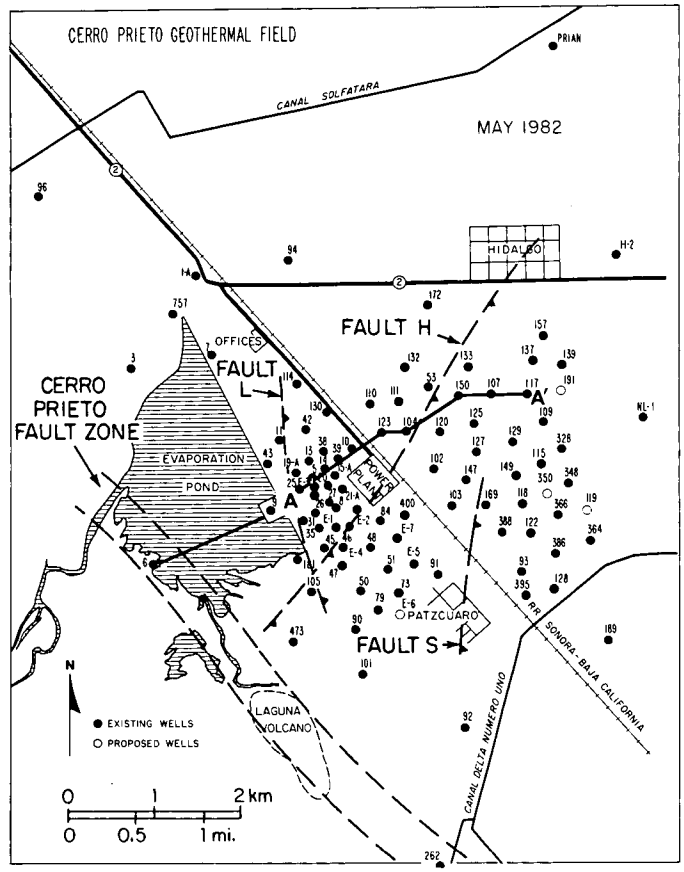

Figure 3. Location of wells, principal faults, and cross section A-A′ at Cerro Prieto. [XBL 827-2320B]

assess the potential of Cerro Prieto and to plan its most optimal development.

A vast amount of subsurface geologic and reservoir engineering data has been gathered from over 100 wells (some as deep as 11,600 ft) completed in the field (Figure 3). Previously, on the basis of geochemical, mineralogical, and downhole temperature logs, it has been shown that the geothermal fluid enters the field from the east, gradually flowing to the west as it ascends to shallower depths (Mercado, 1968 and 1976; Bermejo et al., 1979; Elders et al., 1983). However, in the models developed by these authors, the movement of hot fluids in the subsurface is shown only schematically. Recently, a hydrogeologic model for the Cerro Prieto reservoir in its natural (preproduction) state has been developed (Halfman et al., 1983). This model provides details on the westward and upward flow of geothermal fluid in the field and the geologic features controlling this movement.

Methodology

First a geologic model of the Cerro Prieto field was constructed based on geophysical and lithological well logs. Downhole temperature profiles and well production interval data were then incorporated into the geologic model to develop a geothermal fluid flow model that would show the actual fluid flow paths. This model was then used to identify which lithologic and structural features were controlling the movement of the geothermal fluid.

Seven distinct formations were defined by correlating groups of beds determined mainly from gamma-ray, spontaneous potential, deep induction, and formation density gamma-gamma logs. Faults were identified on the basis of significant vertical displacements of these formations and on the absence of sections of them in certain wells (Figure 4).

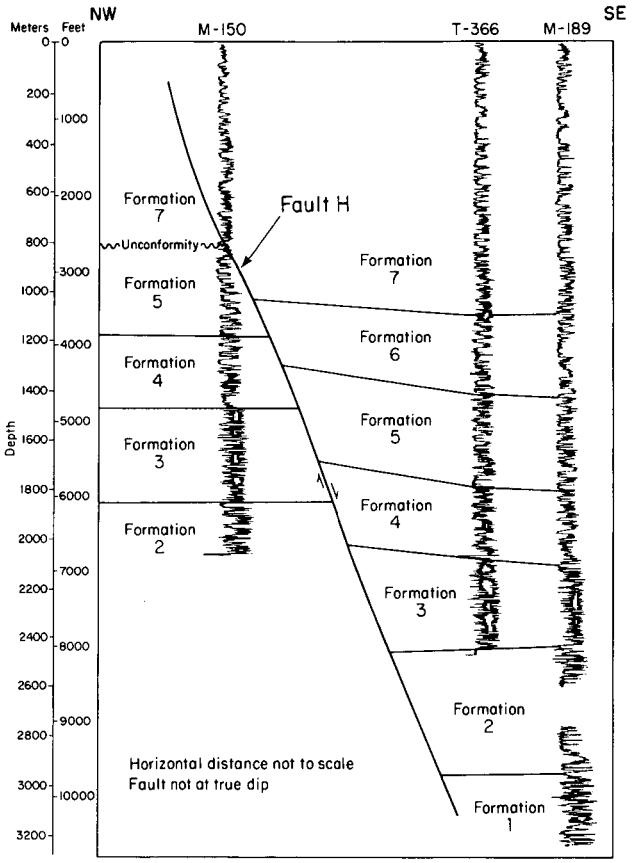

Figure 4. Simplified stratigraphy of the Cerro Prieto field. The traces correspond to gamma-ray (GR) logs.

[XBL 8210-2591]

Different large-scale geologic features that affect the flow of the geothermal fluid in the subsurface were identified by simplifying the geology of the field. The beds were categorized into three lithofacies groups (sandstone, sandy-shale, and shale) on the basis of the well log analysis criteria followed by Lyons and van de Kamp (1980). Basically, the sandstone group is comprised of thick, permeable and well defined sandstone beds (with some interbedded shales); the sandstone beds in the sandy-shale group are thinner and less permeable (with a higher percentage of intercalated shales), and are yet thinner (<10 ft) in the shale group. After assigning the beds to the different lithofacies groups, lithofacies cross sections were constructed incorporating the faults previously defined.

Geothermal Fluid Flow Paths

Following a method outlined by Howard (1981), actual fluid flow paths became readily apparent when downhole temperature profiles (Bermejo et al., 1979; Bermejo, personal communication, 1982) and well production intervals were superimposed on lithofacies cross section A-A′ (Figure 5). In this section, the parts of the temperature profiles shown by heavy lines indicate temperatures of 300° C and higher. The points corresponding to 300° C are placed under the location of the respective wells. The maximum temperature of wells cooler than 300°C are indicated next to the corresponding curve.

According to Elders et al. (1983) and Goldstein et al. (1983), the heat source for the Cerro Prieto system is associated with a swarm of dikes intruded in the eastern regions of the field. These rocks heat the circulating fluid, which is thought to enter the field from the east through permeable sandstone beds (in Sand Unit Z) underlying a relatively impermeable shale layer (Shale Unit O). Then the fluid moves westward through permeable sandstones and gradually flows upward to shallower depths through faults and sandy gaps in the shaly layers acting as local cap rocks (arrows in Figure 5 indicate the direction of the fluid flow). Eventually, in the western part of the field, some of the geothermal fluid leaks to the surface and the rest mixes with local colder groundwaters.

By incorporating other lithofacies cross sections (Halfman et al., 1983) into this model, the direction of the geothermal fluid flow through Sand Unit Z is indicated by arrows in Figure 6. As shown by this figure, the fluid is generally believed to enter the field (at great depth) from the east, gradually moving westward (and rising to shallower depth), and finally reaching the surface in the western regions of the field. Several wells to the southeast are cooler (e.g., M-189), suggesting that these wells are bypassed by the hot fluids entering the field from the east.

Summary and Conclusions

By integrating the geologic model of Cerro Prieto with downhole temperature profiles and well production intervals, we have identified the geothermal fluid flow paths in the field. The model has shown that the movement of hot fluids in the subsurface is strongly controlled by stratigraphic and structural features. It also indicates that a continuous cap rock does not exist at Cerro Prieto that would prevent the upward migration of geothermal fluids to the surface. This supports the conclusion of Grant et al. (1981) and Grant and O'Sullivan (1982) that the reservoir, especially its western part, is a leaky aquifer.

The results of our model are consistent with mineralogical observations and interpretations (Elders et al., 1983), with reservoir engineering and geochemical studies of this geothermal system (Mercado, 1976; Grant et al., 1983), and were used to simulate the behavior of the Cerro Prieto field in its natural state and under exploitation (Lippmann and Bodvarsson, 1983; Tsang et al., 1983).

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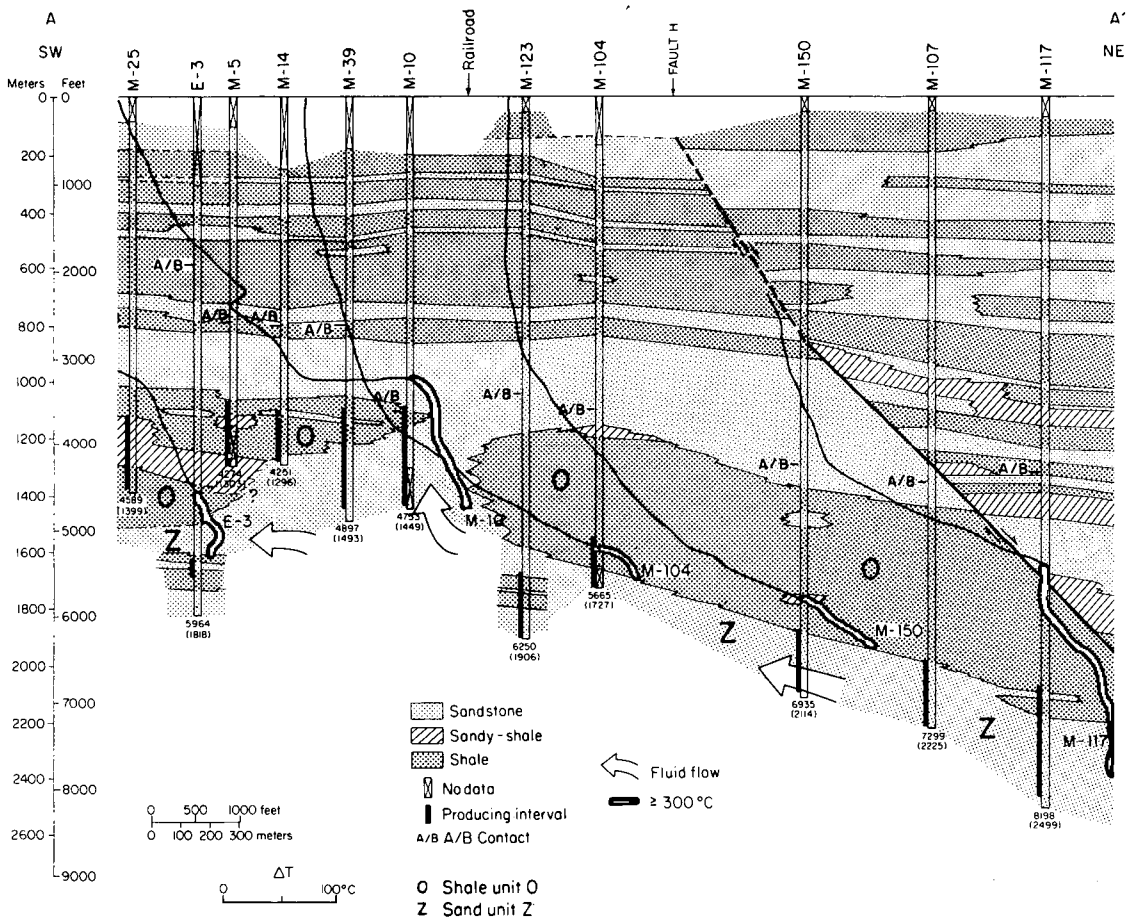

Figure 5. Lithofacies cross section A-A′, showing well locations, lithofacies groups, faults, temperature profiles, producing intervals, Shale Unit O, Sand Unit Z, and arrows indicating direction of fluid flow. On the temperature profiles, the points corresponding to 300° C are placed under the location of the respective wells. The parts of the temperature profiles shown by heavy lines indicate temperatures of 300° C or greater.

[XBL 828-10945A]

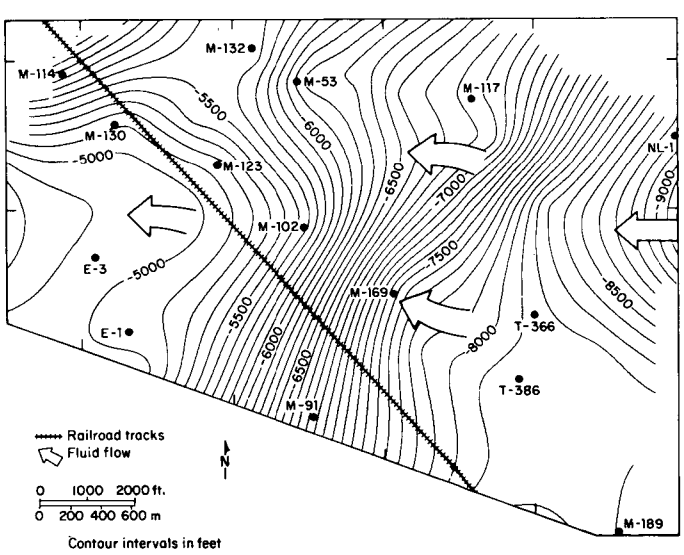

Figure 6. Contour lines indicate the top of Sand Unit Z. Arrows indicate the direction of geothermal fluid flow through this unit.

[XBL 8210-2579]

Geologic Systems as Analogues for Long-Term Radioactive Waste Isolation

H. Wollenberg and S. Flexser

The ability of host rocks in the near-field repository environment to retain radionuclides and to inhibit their transport into and through the groundwater system are important considerations of nuclear waste isolation. Natural occurrences in rock types considered likely candidates for repository hosts in the United States — granitic rock, tuff, basalt, and bedded salt — are being investigated as to their abilities to retain and inhibit such transport of radionuclides.

In addition to the authors, coinvestigators on this project, which is sponsored by the Nuclear Regulatory Commission, are Douglas Brookins, Mark Abashian, and Mark Murphy of the University of New Mexico, and Lewis Cohen and Alan Williams of the University of California, Riverside.

Initial investigations concentrated on granitic rock. Fission-track analyses of the occurrence of ~ 17 million-year-old uranium veins in quartz monzonite at Marysvale, Utah, by M. Shea (1981) indicated that uranium moved from veins at most only a few centimeters, either by diffusion through the rock matrix or by migration along microcracks.

Investigation of a contact zone between 65 million-year-old quartz monzonite intrusive into a Precambrian gneissic terrane near Eldora, Colorado, showed that uranium and trace elements have not moved more than a few meters from the granitic rock-gneiss contact (Brookins et al., 1981; Flexser and Wollenberg, 1982). At Eldora, it was suggested by Hart et al. (1968) and substantiated recently by our oxygen isotope analyses that cooling of the intrusive was essentially by conduction; a circulating hydrothermal system in the Precambrian rocks did not accompany or follow the intrusion.

More recently we have investigated contact zones between intrusive rocks and rock types presently considered candidates for waste repositories — a monzonite intrusive into tuffaceous terrane and contact zones between a dike in bedded salt, and felsic dikes in basalt of the Columbia River Plateau.

Tuff

The presence of strong hydrothermal circulation in tuffaceous rock in response to the intrusion of the ~ 29 million-year-old 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, we have investigated the contact zone and areas away from the contact between the stock and the La Jara member of the Treasure Mountain tuff, primarily to determine if there was movement of radioelements and fission-product-analog trace elements from the monzonite into the tuff, or within the tuff, in response to the circulating hydrothermal system. A roughly concentric aureole of $\delta\ ^{18}O$ depletion was noted by Williams around the south and east margins of the stock,

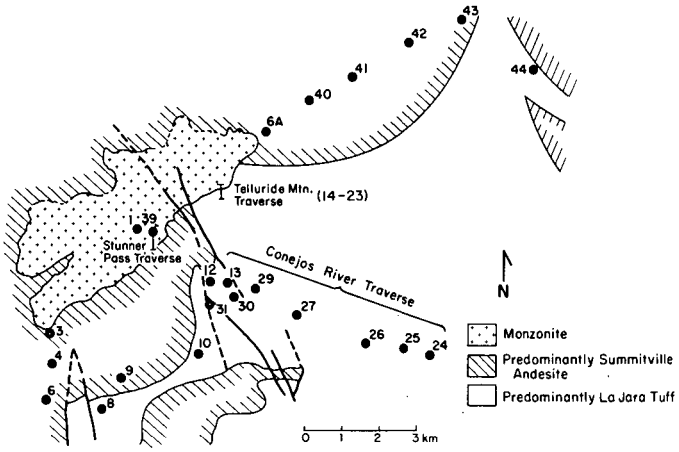

Figure 1. Location and simplified geologic map, showing samples and traverses near Platoro, Colorado.

[XBL 821-1622]

with depletion enhanced along two major faults, attesting to the importance of fracture permeability in the circulation of this system. Temperatures of hydrothermal systems were estimated to be in the range 250–370 °C.

Samples from the Alamosa River stock area were collected at several locations as shown in Figure 1. 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, to subsequently examine the distribution of radio- and trace elements.

Results of neutron activation analyses of trace elements in samples of monzonite and tuff from the traverse across the contact at Telluride Mountain comprise Figure 2. 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.

On a broader scale, analyses of samples from the Conejos River traverse, 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.

With regard to the Platoro occurrence, the following conclusions are evident:

- The oxygen isotopic studies show the effect of extensive hydrothermal activity on the intruded rocks, as well as the host tuffaceous and flow rocks.
- Convective cooling has been demonstrated by Williams (1980) for the Alamosa River Stock.
- The distribution of U, Th, rare-earth elements, V, K, Ti, in each rock is apparently unaffected by the intrusion. This is true also for Rb, Sr, and others, although for some of these elements there is no strong contrast in chemical contents between the rocks.
- Some elements show evidence for contact zone mobility within 10 meters of the contact.
- Both the monzonite and tuff have retained their bulk chemistry during and after intrusion.
- The absence of substantial migration of U and Th between the tuff and monzonite, even in a convective sys-

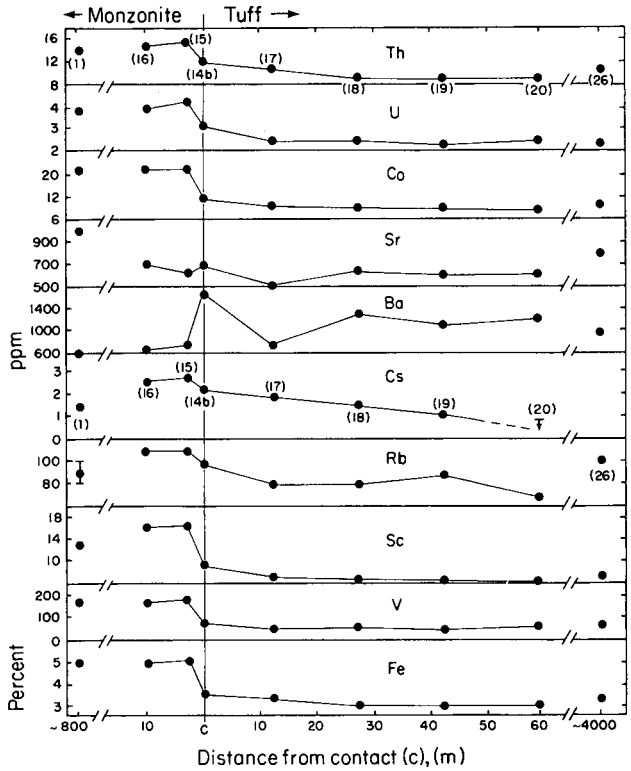

Figure 2. Variation in element contents between monzonite and tuff, Telluride Mountain traverse.

[XBL 828-2325]

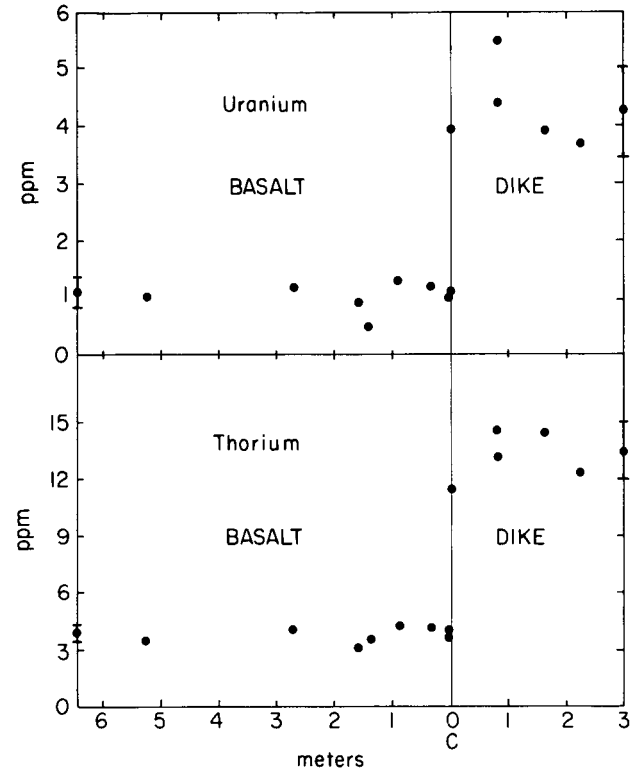

Figure 3. Variation of uranium and thorium in a rhyodacite dike and basalt at a quarry on the east fork of the Hood River, Oregon. Error bars on ordinates indicate standard deviations for samples of the two rock types.

[XBL 828-2328]

tem, supports continued assessment of such rocks for nuclear waste repository consideration.

Basalt

Sites were identified in the Pacific northwest where intrusive rocks cut basalt of the Columbia River Plateau. A quarry on the east fork of the Hood River, Oregon provides excellent exposures of a rhyodacite dike cutting basalt of the Frenchman Springs member of the Wanapum Formation. Uranium and thorium contents of the sample set from the quarry are plotted on Figure 3. The contrast in U and Th between the dike and the basalt is evident, and on a whole-rock hand-sample scale the gamma spectral data indicate that there has been no appreciable migration of U or Th from the dike into the basalt. Results of recent strontium isotope analyses (D. G. Brookins, private communication) confirm this lack of element migration. More detailed examination of fracture orientation, and analyses of fracture-surface and fracture-filling material by neutron activation and radiographic methods are required to see whether radioelements moved preferentially through the basalt's fracture system at the time of, or subsequent to intrusion of the dike.

Salt

A condition analogous to a repository in bedded salt might be provided by the occurrence of a dike intruding salt beds. Such occurrences are located in the Delaware Basin salt beds of southeastern New Mexico, in salt beds of the Salina Basin in northwestern New York, and in salt beds of the Zechstein in West Germany.

From the latter deposit, at the Kalibergwerke mine, we were fortunate to receive a set of samples of basaltic dike rock and adjacent bedded salt. Gamma spectrometric measurements of the salt samples, spaced from the dike contact to a distance of 1.2 m, indicate that the dike has appreciable radioelement content, while, with the exception of a salt sample at 45 cm from the dike, which contains some organic material, the radioelement content of the salt is below the sensitivity of the gamma measurements.

Samples were also obtained of a kimberlitic dike and adjacent salt of the upper Silurian Salina Group, from the Cayuga Mine of the Cargill Company, near Ithaca, New York. The salt bed at Cayuga, ranges from 5 ft or less to more than 60 ft in thickness. As exposed in workings at a depth of ~ 700 m, the dike rock is a greenish gray kimberlite with prominent olivine phenocrysts, altered almost completely to serpentine. The dike is extremely brecciated in places and varies in width from a few inches to several feet over short distances. The dike breccia is intimately intruded by the salt, and where this has occurred the salt is reddish in color rather than its normal whitish-gray. Apart from this distinctive color, there are no macroscopic effects apparent in the salt at its contact with the dike.

Whole-rock gamma spectrometric analyses of radioelements in Cayuga Mine samples obtained from dike and salt exposed in workings on the 2300-ft level indicate that, as with the Kalibergwerke samples, uranium and thorium

in the salt are below detection limits of this method. Potassium content of the salt is significantly lower than at Kalibergwerke, attesting to the relative purity of the Cayuga salt, which has no adjacent potash beds.

Selected samples of the Cayuga salt will be analyzed for trace elements by neutron activation and will be prepared for identification of fluid inclusions and analyses of their contents.

Summary

Detailed examinations of intrusive contacts in tuffaceous and granitic rock indicate that radioelements and fission product analogue elements have apparently not migrated from the intrusives into or through the country rock, nor is there appreciable evidence for redistribution of these elements in the country rock in response to convective or conductive thermal events associated with the intrusives. Gamma spectral analyses of samples from contact zones between dikes and Columbia River Plateau basalt and bedded salt also suggest the absence of radioelement migration or redistribution. These observations suggest that, even in the absence of engineered barriers, and over time spans of millions to tens of millions of years, radio- and trace elements have not moved appreciably into or through rock types presently considered as candidates for radioactive waste isolation.

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