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ROCK DEFORMATION IN HYDROTHERMAL SYSTEMS:
THE NATURE OF FRACTURES IN PLUTONS
AND THEIR HOST ROCKS

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INTRODUCTION

The formation of magma chambers involves the interaction of several boundary layer forces that cause surfaces of structural weakness. During the crystallization of the magma, differential volume changes throughout the chamber generate large differential stresses in the crystalline margins of the chamber and eventually cause brittle failure of the hood zone.

The resultant stress variations associated with the hood failure are propagated throughout the chamber and contiguous host rocks and in turn cause local stress variations that affect the crys-

Vertical section of upper portion
of magma chamber

tallization path of the residual melt. Thermal energy dispersed into the host rocks also has a dramatic effect on their structural state, largely through the large differential expansion of pore fluids relative to the rock matrix.

The characteristics of the equations of state for the H_2O -rich pore fluids and volatile-bearing magmas have a dominating influence on the thermal and structural history of magma-hydrothermal systems. Proper analysis of the evolution of magma chambers requires that the state properties of these two fluids be fully incorporated into the analytical scheme. Consequently, the compilation of state properties and governing differential equations into mathematical analogs to natural systems and comparison of these models with information from the natural system shows great promise in extending our concepts of crystalline rocks.

This program has been designed to accumulate the types of field data that our earlier numerical studies of magma-hydrothermal systems (Knapp and Norton, 1981) indicated were important for the analysis of these systems, and analyze it in the aforementioned context.

The structural effects of thermal processes were identified in the field as prominent structural discontinuities in outcrops. Because structural elements are usually zones of weakness, the erosion and weathering processes greatly enhance their outcrop expressions. Simple field criteria were found to be sufficient to distinguish the thermally induced deformations from the deformations that occurred subsequent to complete cooling of the system.

The discovery that the thermal history of magmas was well preserved and enhanced by weathering was important progress during the current funding period of this contract. This discovery motivated us to design and develop mapping techniques to record the structural data on the ground from local domains characteristic of larger regions in the chamber, and in the air from low-angle oblique aerial photography of the entire region.

The ground system design is complete and preliminary testing is currently being carried out to verify the method. The essence of this system is on-site generation of Polaroid imagery. Annotation of the types and relative ages of structural elements are made on this image, then a similar image is generated on high-resolution color film for later use. This information is then compiled onto published geologic maps of the system, and map units of strain types are defined. The structural data is then digitized from photographic prints and analyzed more or less by standard methods.

STRUCTURAL VARIABILITY OF FOSSIL MAGMA CHAMBERS

Field mapping during the first year of this contract has demonstrated the ubiquity of fracture sets in plutons of crystalline rock and the length-to-aperture ratio of pores that coincide with grain boundaries of phenocrysts and with the ancient fluid flow channels. Fracture spacings on the order of one meter are common in every system studied to date. But these heavily fractured regions are surrounded by regions of 1- to 10-meter spacings.

Our observations suggest that these crystalline rock units have little resistance to internal increases in pore fluid pressure because of the abundance of pores that have aspect ratios on the order of 10^4 or 10^5 , and are undoubtedly saturated with and H_2O -rich aqueous phase.

As a first approximation, consider these pores to be elliptical cracks in cross section, where a/b is very large. The tangential stress at the crack tip will be enormous with only slight changes in internal pressure,

P_f . This effect will be realized even for rough-walled fractures, propped open by asperities.

The overwhelming conclusion of engineering significance is that granitic crystalline rocks have no structural resistance to thermal perturbations. A substantial design problem for nuclear waste disposal is posed by this observation because necessary precautionary buffers would have to be incorporated into disposal systems confined by crystalline rocks. The commonly proposed solution is twofold: (1) Construct structural

and thermal barriers around the waste. These must be sufficient to avoid thermal perturbations of even a few degrees centigrade in the crystalline rocks. (2) Establish a potential field for fluid flow that convects thermal energy away, but not the harmful radionuclides.

Both these options are tenuous. The moral safety obligation is clearly the ability to predict the exact consequences of thermal perturbation for each and every proposed disposal site. These predictions will require in-situ data on pre-existing fracture sets, and analysis of the consequences of man-caused thermal stresses on rocks. There is no effective technique for obtaining the data, therefore studies directed toward this problem should have high priority.

FIELD AREAS

During the past two years, I have studied thirty fossil magma chambers on a reconnaissance basis. An extensive set of fracture imagery has been collected, together with information related to the geological history of the plutons. The areas selected for this portion of the study include the following fossil magma chambers:

Arizona:	Cochise Stronghold Diamond Joe Dells Granite Four Metals Breccia Pipe (Patagonia Batholith)	
Utah:	Alta Clayton Peak Little Cottonwood	} Wasatch System
California:	Papoose Flat Tuolumne Intrusive Series	
Washington:	Golden Horn	
Montana:	Boulder Batholith	
British Columbia:	Ponder Pluton	

The areas of prime importance to this study represent a diversity of geographic and geologic environments. These pluton systems contain chambers that have been eroded to very shallow depths (Golden Horn, eastern Wasatch) as well as intermediate depths (Inyo, Diamond Joe). Their sizes range from several kilometers across (Ponder, Boulder Bathylith and Cochise) to small stocks (Mayflower, Flagstaff and Little Cottonwood in the Wasatch system). The magma compositions represented in this group comprise a wide range of volatile contents and ages. Their ages range from Precambrian (Dells) to mid-Tertiary (Cochise).

Papoose Flat

The granitic bodies in the Inyo Mountains are satellites of the Sierra Nevada batholith. Among these plutons the Papoose Flat pluton is the most interesting from a structural viewpoint (Sylvester et al., 1978). The enlightened field studies by these authors provide a comprehensive data base on the history of deformation during the inflation of the magma chamber. Superimposed on the primary foliation that they recorded is an intricate set of structural features that appears to represent the thermal history of the crystalline portions of the pluton.

The folia in the pluton define a concentric pattern of semicontinuous bands centered about the southern portion of the pluton. These folia are defined by 1-10 cm thick surfaces within which are streaky lenses of quartz, plagioclase, K-feldspar and biotite, and partially granulated megacrysts. The megacrysts often display flow boundary effects,

Palinspastic Geologic Map Papoose Flat Pluton

that define the viscose flow directions and magnitude. The folia are remnants of the magma flow potential field; their distribution around the chamber suggests concentric streamlines of magma flow preserved by the inwardly moving crystallization front. Their spacing varies from a meter to several meters. The regularity of this spacing suggests that the loss of energy and crystallization and circulation of magma, although closely coupled processes, proceeded in a stepwise manner. Relatively free circulation of magma, accompanied by crystallization in a separate region of the chamber, could cause these features. The shear surfaces caused by magma flow are preserved as the pressure increase caused by crystallization exceeds the strength of the chamber walls. Brittle failure of the chamber and the associated pressure drop cause crystallization of a layer of magma equivalent to the spacing between folia. The folia spacing should therefore be a measure of the strain rate caused by magma pressure variation.

Superimposed on the foliation surfaces (~~~~) are both quartz (---) and quartz-K-feldspar-muscovite veins (—).

The quartz veins are along flexuous fractures that have steep dips on the average, but tend to follow the older folia for short distances. These younger fracture sets result from the subsolidus cooling of the chamber margins while the interior portions were crystallizing and exerting an outward pressure on the chamber walls.

The structural history of the Papoose Flat pluton is a direct consequence of its thermal history. Therefore, its history has been approximated by a mathematical analog of Sylvester's vertical section of this system. In this simple model, a magma solidus of $T=800^{\circ}\text{C}$ would retreat from the chamber walls in $<10^5$ years. This rate would require a strain approximately every 1000 years to produce sequential zones of pressure-quenched magma separated by shear boundary surfaces.

Analysis of this system is continuing with data collected last spring. More data is needed on the system, but the outcrops are currently resting under a blanket of snow.

Diamond Joe

The structural history of this magma chamber is exceedingly well exposed and accessible. Radial and concentric structural elements are obvious in both aerial photographs and topographic maps. The combination of nearly 2500 ft of vertical exposure and a high-angle normal fault that offsets one-third of the pluton provides a unique opportunity to study this fossil chamber.

Radial fractures contain quartz and muscovite and decrease in frequency towards the core region of the chamber. The radial sets include prominent NW and NE trending elements that have localized sulfide depositions, and appear to have had post thermal history offset. The core is composed of a rock with slightly lower mafic content, light-colored outcrops and a low frequency of radial and concentric structural elements.

The extent of structural information in these outcrops goes well beyond the 1:24,000 scale imagery and the traditional plan representation of outcrops. Primary flow structures formed during inflation and early cooling history of the magma chamber are apparent in nearly vertical faces in the form of curvilinear foliation surfaces spaced several hundred feet apart. These surfaces dip inwards toward the central core; their

dip increases from $\sim 30^\circ$ near the core to $\sim 60^\circ$ near the margins of the pluton. Although their microscopic character is poorly known, they correlate well with the magma streamlines one would expect.

Fossilized remnants of immiscible fluids are well preserved along the margin of the core zone in the uppermost exposures of the pluton. They occur as ellipsoidal bodies of varying size, with aspect ratios ranging from 1:1 to 1:6, and make up less than one percent of the outcrops.

Often these bodies occur in a paternoster pattern, as if strung on the fracture planes they evidently caused. Isolated bodies are common, but each has at least one fracture coinciding with the major axes of the ellipsoid and extending two to four times the length of the major axes into the host.

These bodies are generally zoned outwards from a central void, presumably once filled with a volatile phase, to a rim of K-feldspar sometimes lined with quartz crystals and muscovite, and are bounded by a sharp contact with their host rock. The K-spar rim is radially fractured and often occurs in micrographic intergrowth with quartz. Muscovite is normally present, but appears to have been formed during the circulation of hydrothermal fluids through the flexuous fracture system that interconnects the ellipsoids.

The ellipsoids are evidently the result of crystallization and fractionation of an immiscible three-phase material from the enclosing magma + crystals. As these immiscible bodies segregated, their somewhat lower density caused them to rise toward the cupola of the pluton. Their path is apparent from the vertical alignment of their major ellipsoidal axes. Following crystallization of the surrounding host, these bodies cooled, crystallized and exerted large differential stresses as a consequence of the large negative value of the isovolumetric coefficient of crystallization stress, $(\partial P / \partial T)_V$, bars $^{\circ}\text{C}^{-1}$:

The decrease in temperature not only causes an increase in differential stress because of the pressure exerted by the crystals + magma + fluid material, but also a simple thermal contraction of the host. Both of these effects tend to increase σ_1 and drive the material toward the failure surface.

Aplites, quartz-muscovite veins and quartz veins are distributed along the radial fracture sets, many of which were caused by localized processes around the immiscible fluid bodies. The core region of the pluton appears to be a larger example of this process that seems to have caused the extensive radial fracture pattern in the outer portions of the pluton.

Wasatch Plutons

The plutons in the Wasatch Mountains of Utah represent sequential magmatic events that span 17 million years. The plutonic rocks range in age from 24 million years in the westernmost portion of the mountain range, to 41 million years on the eastern side where there are also volcanic rocks of comparable age. The combination of erosion, thrust faulting and basin and range tilting has exposed the deep portions of a large magma chamber near the western range front, yet preserved the volcanic and sub-volcanic portions of the system on the east. This provides a unique opportunity to see the magma-volcano structure all the way from the lower central chamber (Little Cottonwood), upward through the volatile rich subcupola regions (Alta and Clayton Peak) and into the volcanic edifice and cupola region (Pine Creek, Park City).

Each of these plutons is thoroughly fractured, as we suspected from the earlier work on the Mayflower pluton (Villas and Norton, 1977). In

that pluton, we found that the range in fracture abundance was from 0.06/cm to 0.21/cm. The larger abundances were restricted to within 100 meters of the Mayflower vein system. However, the fracture system at the Mayflower, as in nearly all fractured media, comprises only a small portion of the total porosity of the rock. Fracture

frequencies in the other plutons are 0.1/cm over 10^4 m^2 regions, but frequencies are rarely less than 0.005/cm. The style of fractures, however, varies considerably among the plutons, a feature that will be mapped this field season. Some preliminary mapping has been completed and preliminary analysis of the structural-thermal characteristics.

The fracture orientations in the eastern portion of the Wasatch in the vicinity of the Mayflower pluton are not related to the stress field

during the anticlinal folding, but

relate to the much younger intrusive

event. These features are apparent on a lower hemisphere stereographic plot

of the poles of the major fissure

zones present in the Park City district,

where the outlined areas delimit the

variation of fissure attitude and X represents the axis of the Park

City anticline. The shear fracture planes in the pluton partially

correlate with the major vein direction, but clearly formed during the

pluton's cooling history. The mineralized fractures in the pluton are

SHEAR

MINERALIZED

also nearly vertical and appear to form a conjugate set of related fractures. They are predominantly tension fractures, or at least have had only minor shear displacement.

The data base is being expanded to the other pluton systems in the western and central portions of the range.

Reconnaissance examination of both the Alta and Little Cottonwood have revealed that a wealth of information is present on the structural evolution of this large system. In the Albion basin, the Alta pluton and its host rock contacts are well exposed. This border zone of the pluton is thoroughly fractured and foliated. The foliation surfaces (dashed) vary in attitude and trend, but are always crosscut by the K-feldspar quartz veins (solid) and their halos.

The porphyritic core of the Alta pluton deflected the stress trajectories so that the fractures in its vicinity were dispersed from the N45E trend found in the margins, to a NS trend. This suggests that the porphyritic phase crystallized from a volatile rich magma that had a negative, isovolumetric thermal coefficient of pressure $(\partial P/\partial T)_V$.

Data from other regions in this pluton and in the Little Cottonwood pluton are being processed and the local stress fields are being reconstructed.

Dells Granite

The style of chemical and structural alteration in the Dells Granite is a striking example of advective transport of aqueous components along systematic fractures and concomitant diffusional interchange between these aqueous fluids and minerals within the parallelepipedal matrix blocks. The geological history of the reactions between the Dells Granite and aqueous solutions distributed among the pore structure can be represented as a mathematical model (Norton and Taylor, 1979, pages 426-440). Furthermore, the Dells has some very interesting and unique characteristics that could facilitate quantitative interpretation of its history in a manner not previously enjoyed on a natural system. The unusual color bands in the matrix blocks contain critical information on the paleohydrologic system that could be mapped in the field, calibrated with laboratory analyses and interpreted with the transport equations. Aside from the geologic importance of this system, the structural and chemical alteration effects are interesting analogs to the feedback systems that will be generated in the vicinity of radioactive waste disposal sites.

Porosity. The reddish-brown-black cylindroid bands systematically distributed with respect to fracture controlled flow channels provide a picturesque map of the pore structure of the granite. In accord with the definition of total porosity in fractured media (Norton and Knapp, 1977),

$$\phi_{\text{Total}} = \phi_{\text{Flow}} + \phi_{\text{Diffusion}} + \phi_{\text{Residual}},$$

the following observations can be made.

1. Continuous vertical intersecting fractures are apparent from the 1:24,000 and 1:48,000 topographic maps. Fractures spaced at about 50 to 100 meters can be resolved from the topographic maps with 20 ft contour intervals:

The channels of both Willow and Granite creeks faithfully follow the local fracture pattern. The overall pattern detected by this sketch varies from nearly orthogonal sets along the main highway and Willow Creek to less continuous featureless orientations adjacent to and east of the railroad. Although the fracture spacing estimated by this method is misleading for purposes of calculating the rock permeability and associated flow porosity, I suspect that air photographs with field checking at this scale could be used to define the time-averaged stress field.

2. The central region (along highway) is characterized by cylindrical form diffusion bands localized between nearly orthogonal fracture sets. The spacing on these fractures varies from 0.5 to 2 meters and appears to comprise the flow porosity of the system:

$$\phi_{\text{Flow}} = n_x d_x + n_y d_y$$

where n_x and n_y represent the fractures/cm in the horizontal plane, and d_x and d_y the corresponding apertures.

Theory

The mathematical representation of the natural system follows directly from the abstraction of the outcrop features into a representative elemental volume (REV) that depicts the transport properties of the system.

I. The REV for consideration of transport processes for the overall pluton and host rocks is shown at the right. At this scale we note the controlling parameters one can map are the frequency, n , of the flow channels, and the chemical composition, ζ_r^e , of the e th component in the matrix blocks. The aperture, d , and the chemical composition, ζ_f^e , of the e th component in the aqueous phase are necessary parameters but are not directly mappable.

II. The REV for consideration of transport processes involving local diffusion of components through an interconnected pore geometry filled with aqueous phase and local reaction among minerals and aqueous solutions is closely represented by the schematic (Fig. 1 in Norton and Taylor, 1979).

In this case the mappable parameters are the chemical composition, ζ^E , of the components across the matrix blocks and the diffusion porosity, ϕ_D . Auxiliary measurements would be the tortuosity of diffusion pores and surface area of minerals exposed to the aqueous phase along the diffusion pores.

The principle of conservation applied to either REV for any scalar, vector or tensor quantity, λ , is of the form:

$$\int_V (\partial \lambda / \partial t)_{xyz} dV + \int_S \vec{J}_\lambda \cdot d\vec{S} = 0 \quad (A)$$

where $\vec{J}_\lambda$ denotes the flux across the surface, S , that encloses the volume, V , of the REV. The details and complexities of more detailed formulation and solution of equation (A) are in part standard techniques and in part require some more work. Nonetheless, integration of equation (A), particularly for the long complex history of the Dells, could provide a lot of insight into chemical migration and structural alteration of plutons.

The variability in the diffusion bands preserved in the outcrop seems to reflect both the supply of components by the fluid flowing through the fracture network, diffusion into the matrix blocks and diffusion from within the matrix blocks. Calibration of the band color, etc., to the distribution of the ϵ th components for a few blocks would permit the construction of a comprehensive field map of band widths, the distance of bands, δ , from the flow channels. These parameters then permit approximation of time through solutions of:

$$\begin{aligned} \phi_D (\partial \zeta_{\text{Fluid}}^{\epsilon} / \partial t) + \phi_m (\partial \zeta_{\text{Mineral}}^{\epsilon} / \partial t) \\ + \phi_D D_{\epsilon} (\partial^2 \zeta_{\text{Fluid}}^{\epsilon} / \partial X^2) = 0 \end{aligned} \quad (\text{B})$$

that tend to be of the form:

$$\zeta^{\epsilon} = \zeta_{\text{Time}=0}^{\epsilon} \operatorname{erfc} (X / 2 \{D_{\epsilon} t\}^{1/2}) \quad (\text{C})$$

Equation (C) in conjunction with data on $\zeta_{\text{Rock}}^{\epsilon}$ across the diffusion bands allows direct estimations of time.

The compositional bands are of unusual form for simple diffusion from a flow channel. Diffusion through the aqueous solution-filled pores, followed by local reaction with mineral phases, seems to have been the predominate process. We may be seeing the results of several perturbations imposed on this

single fracture system. For example, equation (C) represents distribution of $\zeta^\varepsilon = f(x)$ that is nonlinear but tends not to have extrema, whereas in the Dells there seem to be extrema in the concentration versus distance from the flow channel function:

The apparent oscillatory character of these bands can be explained by a process of rapid local reaction among components diffusing inward

from the flow channel with outward diffusion of components from the matrix block at differing rates (e.g., classic Liesegang structure). I am not aware of this as an important process in hydrothermal vein deposits, but it is common in the weathering of metal sulfides. In the weathering system, inward diffusion of O_2 and outward diffusion of ferrous ions develop oscillatory bands.

The present-day hydrologic system offers a unique opportunity to determine the effective permeability of the near surface joint system. Natural or man-induced (flushed) tracers can be mapped in wells and streams across the central region. Relaxation times with fracture spacing then leads to a direct estimate of permeability.

The natural heat generated by radiogenic activity is substantial in these plutons, and must be analyzed in order to separate the hydrothermal effects imposed by a relatively young basalt igneous event and those derived from the much older granite itself.

The structural features in the Dells are conspicuous, particularly the systematic joint sets that delimit parallelepipedal matrix blocks in the central portion of the outcrop area. Pegmatites, miarolites and

dikes containing layers of pegmatitic and aplitic material are also common. Although some deformation of the granite has occurred after its thermal history, the systematic parallelepipedal fractures contain hydrothermal alteration effects, probably related to the cooling history.

Medora Krieger (1965) has briefly described the latter fracture set and presented some orientation data from an unknown portion of the pluton:

Krieger (1965) Fig. 26.
Contour diagram of 274
joints in the Dells Granite;
the poles are plotted on
the lower hemisphere.

Correlation of the fractures with mineral alteration types and determination of their relative ages has not been done, however. I have noted numerous locations where relative ages can be established and the work will be part of the work plan for next year.

Stronghold Granite

The Stronghold Granite, 26 m.y. old, outcrops over an area of 65 km², forming the spectacular geomorphic character of the Dragoon Mountains. Erosion has exposed the coarse-grained core, porphyritic border and aplitic facies of the pluton, and contact relationships with host rocks. The host rocks range in composition from schist (Precambrian Pinal) to carbonate (Paleozoic) to volcanics (Cretaceous). They occur in an elongate root pendant, which divides the outcrop area of the pluton into eastern and western segments of equal area, and along the side margin of the pluton.

The 700-meter vertical exposure and diversity of contact relationships contain a wealth of information on the thermal history of what appear to be the upper portions of a large magma chamber.

ular bodies of pegmatite, aplite and rhyolite porphyry in the border facies of the pluton. The latter two are particularly abundant in the southwestern margin of the pluton, where most of the detailed mapping has been concentrated. This flow layering is not common, but it does represent magma streamsurfaces that were later cut by the irregular bodies of volatile-rich late-stage differentiates of the main mass of magma. Superimposed on these high-temperature features are numerous fracture sets, at least some of which were flow channels for hydrothermal fluids.

The wall rocks of the Stronghold pluton are thoroughly altered and fractured Escabrosa, Martin and Abrigo limestones, and Bolsa quartzite in this portion of the system.

Fractures in the host rocks can be traced into the border facies of the Stronghold Granite, demonstrating the intimate relationship of structural and mineralogical effects associated with heat transfer from the magma chamber. The granite in the Gordon Camp area contains local porphyritic pods within the border zone that were sources of mechanical energy for the formation of the structural features. Miarolitic cavities lined with feldspar and quartz, as well as numerous quartz veins--the fossil remains of an H_2O -rich fluid--are also common features.

With the presence of winter in the other study areas and favorable climate in the Dragoon Mountains, the field mapping will concentrate on the Stronghold. The new mapping system MAPFSII will be used extensively in this effort.

ENGINEERING ASPECTS OF CRYSTALLINE ROCKS

Nuclear waste dumps are just like magma chambers, only not as intense. The dispersion of energy from a nuclear waste site alters the surrounding rock much like the thermal energy from a magma chamber alters its host rocks.

The mechanical, chemical and thermal consequences of thermal perturbations in crustal rocks are intimately related through the state properties of naturally occurring fluids and minerals. This observation suggests that with rare exception can the environmental effects of thermal energy dispersion away from subsurface radiogenic waste be predicted on the basis of experiments or theory exclusive of one or more of those transport phenomena inevitably associated with thermal perturbations.

Geological models of magma-hydrothermal systems derived from field observation, laboratory experiment and mathematical modeling are reasonable analogs of the redistribution of energy, mass and momentum expected in the vicinity of subsurface radiogenic waste dumps. Even though the time integrated effects of thermal energy dispersion away from magma chambers may be substantially more extensive than expected around artificial thermal perturbation of lower energy content, the effectiveness of all thermal anomalies in the earth's crust for altering rocks and fluids is striking.

Each and every geological study of active and fossil magma-hydrothermal systems (FMHS) has observed the systematic relationship between the extent of mineral and chemical alteration of rocks and the occurrence of continuous fluid flow paths (Meyer 1950; Villas and Norton 1977, Haynes and Titley 1980). More recently, systematics have even been discovered in the orientation, continuity and relative age of the fracture controlled channels

(Norton, unpublished). The overall conclusion of these studies is that an intimate relationship exists between the heat flow, state-of-stress and extent of mass transfer among minerals and fluids. The properties of phases in rocks that have been thermally perturbed are such that the emplacement of the thermal anomaly is sufficient to cause large circulation patterns even in originally impermeable host rocks.

An inevitable consequence of emplacing thermal sources in rocks is the generation of a potential field for fluid flow; the magnitude and direction of the flow is dependent on the intrinsic rock permeability (Norton and Knight 1977). Because of the extremely low rock permeabilities of crystalline rocks obtained from laboratory measurements on core samples and the more representative but apparently small values inferred from other methods (Brace 1979), these rocks are assumed to be very effective containers for exothermic waste dumps. The total porosity of crystalline rocks tends to be relatively small and under ambient conditions most of these pores are apparently not interconnected (Norton and Knapp 1977). However, even if a small percentage of these isolated pores, ϕ_R , are redistributed into continuous open flow channels, ϕ_{flow} , large effective permeabilities will be generated. Field observations by Haynes and Titley (1980) provide clear-cut evidence that the grain boundary pores in igneous rocks are readily redistributed into systematic cross-cutting flow channels that constitute permeabilities as large as tens of millidarcy in some instances. The extensive chemical alteration in these systems is caused by fluid flow through fractured media as a result of both the change in temperature and pressure conditions locally and also variation in the composition of pore fluids as a consequence of fluid source regions that occur in rocks or environments of contrasting

composition. This observation contravenes the idea that mineral alteration reactions are effective sealants of fracture controlled flow channels. Indeed, in natural systems the most extensive chemical depletions are noted in rocks that are characterized by mineral alteration reactions with large volumes of reactions (Villas and Norton 1977, Brimhall 1977, Norton unpub.).

The paradigm of relationships in natural systems suggests a very intimate coupling between the processes that transport thermal, mechanical and chemical energy. Although the effectiveness of any particular system is strongly dependent on the characteristics of the causative energy source, the coupling can be assumed to exist in all such thermal systems. The extent of these effects must be evaluated to insure safe waste dumps.

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