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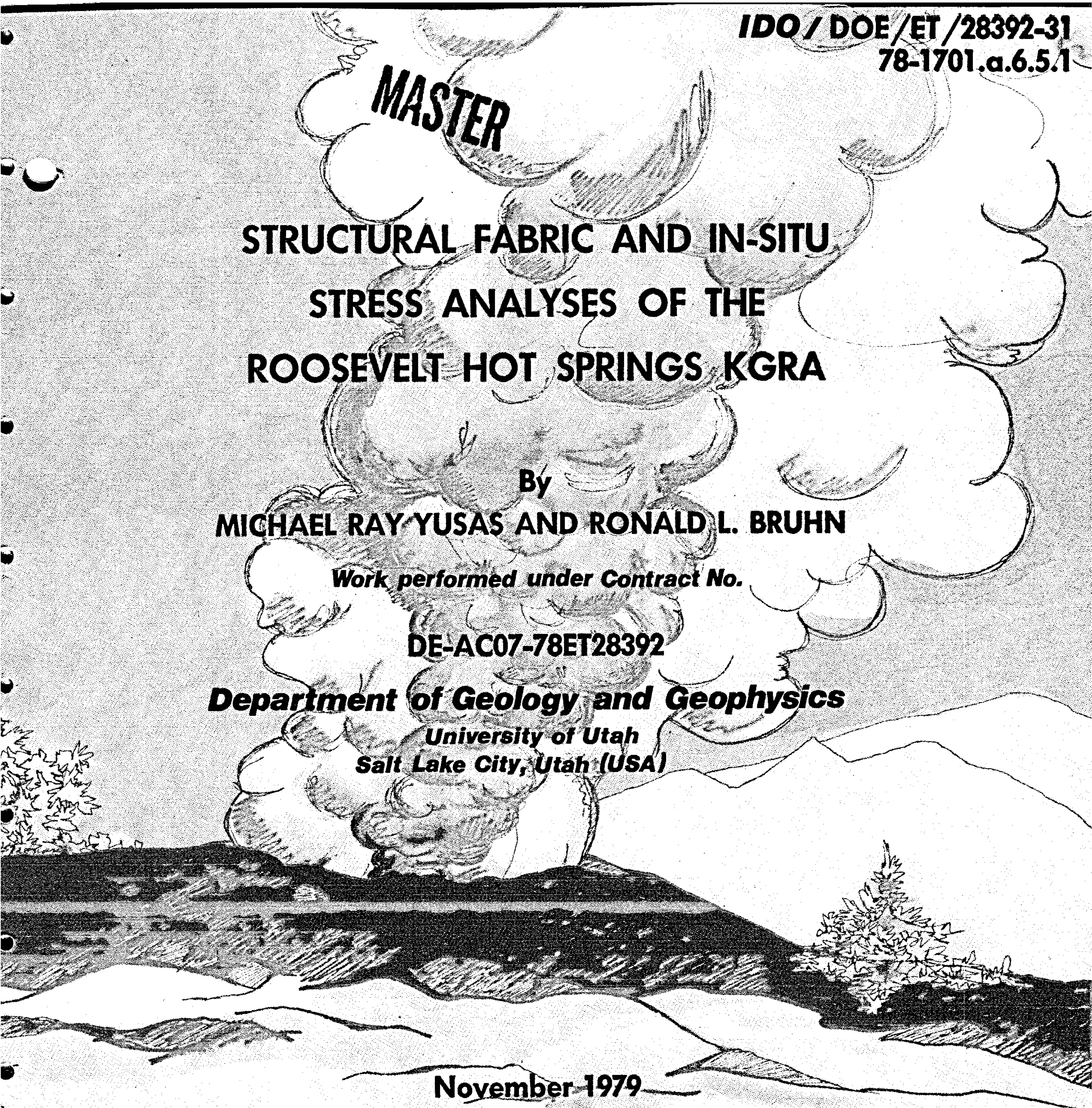

STRUCTURAL FABRIC AND IN-SITU STRESS ANALYSES OF THE ROOSEVELT HOT SPRINGS KGRA

By
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November 1979

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ABSTRACT

The Roosevelt Hot Springs Known Geothermal Resource Area (KGRA) is located along the west-central flank of the Mineral Mountains in southwestern Utah. The geothermal reservoir is a hot-water dominated system in fractured plutonic and metamorphic rock. A principal purpose of this study was to determine the geometry and origin of fractures as an aid to developing a structural model for the reservoir. The results may also be useful for the design of hydrofracture experiments at the Roosevelt KGRA.

Three major normal fault trends are present in the Mineral Mountains. North-northeast trending faults, including the Opal Mound Fault, form the center of low electrical resistivity and high heat flow anomalies. Major east-west trending structures such as the Hot Springs Fault form structural boundaries for the geothermal reservoir. A set of northwest trending faults also occurs in the KGRA.

Structural analysis was conducted by field mapping of joints, small shear zones, and dikes. Aplitic and rhyolitic dike patterns define three structural domains in the central Mineral Mountains. North of Hot Springs Fault a strong north-south trend of steeply dipping dikes is present. South of Hot Springs Fault within the KGRA the dominant trend is N20-30E. Diking in the interior of the pluton shows no strong, preferred orientation.

Three major styles of fracturing have been identified. A

fracture foliation occurs as a dense system of parallel, open fractures in coarse grained rocks of the pluton. Parallelism of the foliation with macroscopic cooling cracks and dikes has led to the interpretation that the foliation formed as a set of extension fractures due to cooling and contraction of the pluton.

Two orthogonal or nearly orthogonal sets of steeply dipping joints are present in all lithologies throughout most of the study area. Cataclasite and hydrothermal alteration along the joint surfaces increases near shear zones. The joint morphology and the orthogonal pattern leads us to conclude that most joints in this set formed as extensional fractures during cooling and uplift of the pluton. The amount of cataclasite and hydrothermal alteration along the joint surfaces increases near shear zones, suggesting that movement occurred along some of the joints during, or subsequent to, their formation.

The third major joint set is found throughout the central Mineral Mountains and consists of shallow to moderately dipping fractures. Joint density and evidence for shear is again directly related to proximity to shear zones. This joint set dips consistently 20 to 50 degrees to the west.

Strain relief tests for in-situ applied and residual stresses were made through repeated overcoring of resistence strain gauge rosettes. Strains measured were dominantly extensional. No preferred extension direction was found for the study area as a whole or for any individual site. Measured orientations were controlled by outcrop fracture patterns rather than by regional stress field. All principle strains measured fell within 10 degrees of an outcrop fracture. Strains recorded upon second overcoring were consistently smaller than the original measurements, while orientations of principal strains remained similar.

INTRODUCTION

Purpose

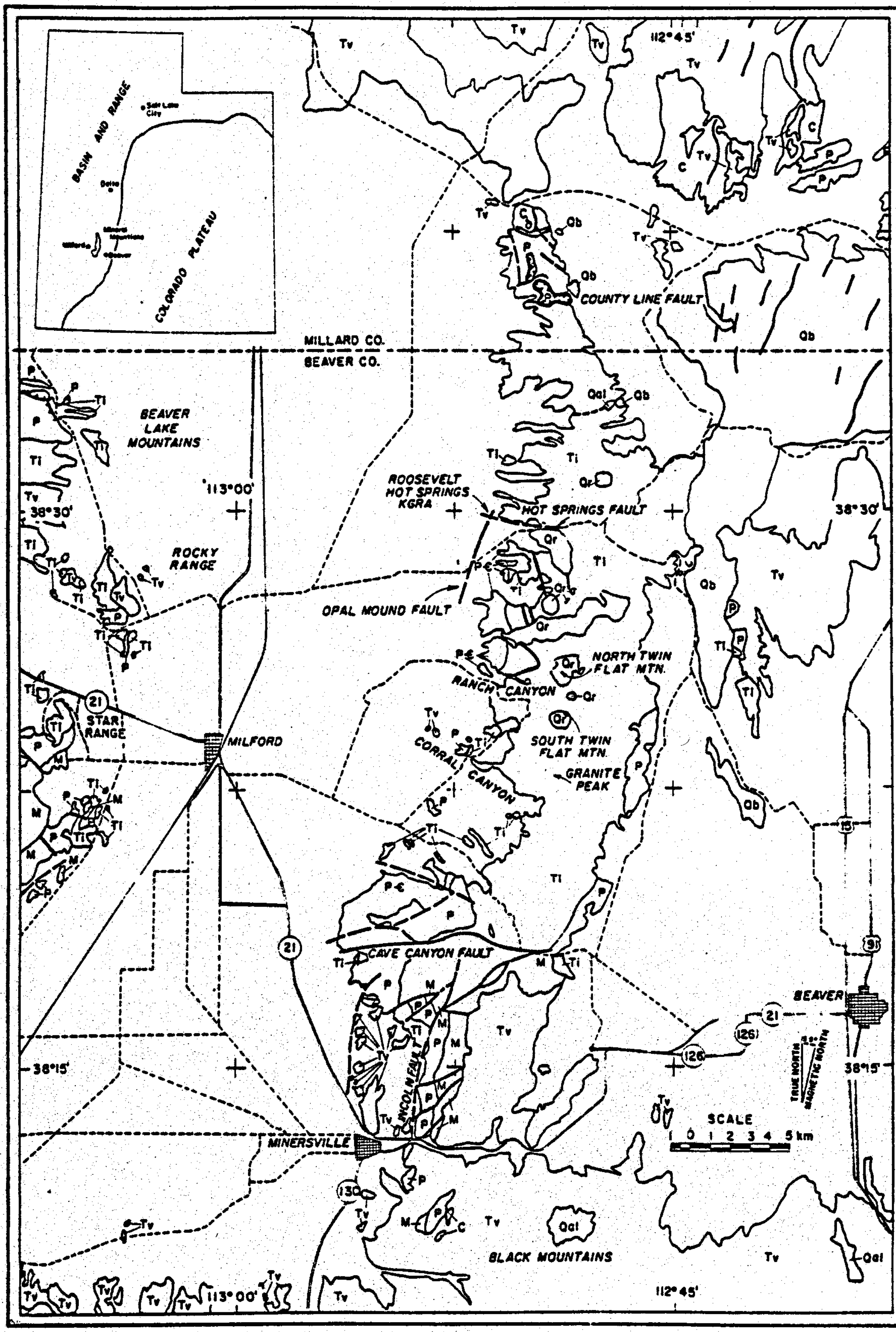
The Roosevelt Hot Springs Known Geothermal Resource Area (KGRA) is located along the west-central flank of the Mineral Mountains in southwestern Utah (Figure 1). The geothermal reservoir is a hot-water dominated system in plutonic and metamorphic rock (Lenzer and others, 1976). Much of the primary permeability has been developed through faulting and fracturing of these otherwise impermeable rocks. A principal purpose of this study is to determine the geometry and genetics of fractures and joints in the area as an aid to understanding the structure of the geothermal system.

A second purpose is to provide information necessary for the design of hydrofracture experiments at the Roosevelt KGRA. Batzle and Simmons (1976), as well as White and others (1971) have demonstrated that hot water geothermal systems are self-sealing through silicification of open fractures. It is important for commercial development of geothermal reservoirs to investigate artificial permeability enhancement. At a lecture before the Utah Geophysical Society, G. Crosby of Phillips Petroleum Company (principal developer of the Roosevelt Hot Springs KGRA) suggested that hydrofracture experiments be conducted at the Roosevelt KGRA to generate new fracture permeability and stimulate fluid flow.

Figure 1: General geology of the Mineral Mountains (Modified from Carter and Cook, 1978; Nielson and others, 1978).

LEGEND

CENOZOIC	Qal	QUATERNARY ALLUVIUM
	Qb	QUATERNARY BASALT
	Qr	QUATERNARY RHYOLITE
	Tv	TERTIARY UNDIFFERENTIATED VOLCANIC ROCKS
	Ti	TERTIARY INTRUSIVE ROCKS
	C	CENOZOIC UNDIFFERENTIATED SEDIMENTARY ROCKS
MESOZOIC	M	MESOZOIC SEDIMENTARY ROCKS
PALEOZOIC	P	PALEOZOIC SEDIMENTARY ROCKS
PRECAMBRIAN	P€	PRECAMBRIAN GNEISS & SCHIST
		FAULTS, DASHED WHERE APPROXIMATELY LOCATED
		THRUST FAULT, SAWTEETH ON UPPER PLATE


BASIN AND RANGE
COLORADO PLATEAU
MILLARD CO.
BEAVER CO.
BEAVER LAKE MOUNTAINS
113°00'
38°30'
ROCKY RANGE
ROOSEVELT HOT SPRINGS KGRA
HOT SPRINGS FAULT
OPAL MOUND FAULT
COUNTY LINE FAULT
112°45'
NORTH TWIN FLAT MTN.
RANCH CANYON
SOUTH TWIN FLAT MTN.
GRANITE PEAK
CORRAL CANYON
STAR RANGE
MILFORD
CAVE CANYON FAULT
LINCOLN FAULT
BEAVER
38°15'
MINERSVILLE
BLACK MOUNTAINS
SCALE
0 1 2 3 4 5 km
TRUE NORTH
MAGNETIC NORTH

<u>Tectonic Setting of the Mineral Mountains</u>

The Mineral Mountains are located in the southwestern portion of the Basin and Range Province near the transition to the Colorado Plateau (Figure 1). Two models are commonly used to explain regional Basin and Range structure (Stewart, 1971). One model considers valleys and ranges as normal fault-bounded systems of horsts and grabens. Tilting of fault blocks is attributed to differential slip on bounding faults or vertical displacement on assymmetric grabens (Stewart, 1978). In this model, bounding faults remain roughly planar with depth. An alternative model explains Basin and Range morphology in terms of tilted fault blocks bounded by listric faults. Normal displacement and rotation create ranges on the upslope and valleys on the downslope portion of fault blocks. Based on thickness of alluvial fill and a lack of shallow angle focal mechanisms predicted by the tilted block model, Stewart (1971) supported the horst and graben model. A regional cross section by Mackin (1960) indicates his preference for the tilted block model. Based on attitudes of Tertiary volcanics in southwestern Utah and eastern Nevada, Mackin shows the Wah Wah, San Francisco, and Mineral Ranges as eastward dipping fault blocks bounded by west dipping listric normal faults.

The Mineral Mountains lie in the eastern portion of the Sevier thrust belt, a region characterized by low angle faults. Cambrian Prospect Mountain Quartzite forms a basal decollement for a series of Sevier age thrust sheets in the Wah Wah and Mineral Ranges. Major low angle faults of Tertiary age are also found throughout Nevada and southwestern Utah. These faults are interpreted either as 1) gravity glide sheets off topographic highs (Armstrong, 1972); or as 2) the result of thin-skinned distension of units overlying uplifting and spreading plutons (Anderson, 1971); or 3) originally steeply dipping normal faults which have been rotated by later normal faulting (Proffett, 1977).

Geology of the Mineral Mountains

Geologic mapping in the Mineral Mountains has been conducted by Earll (1957), Liese (1957), Condie (1960), Evans (1977), and Bowers (1978). The Roosevelt KGRA has been mapped by Peterson (1975), and Nielson and others (1978). The description of the general geology is summarized from their work.

Gneisses and schists of probable Precambrian age form the oldest rocks in the range. They crop out along the western margin of the range and are present as large xenoliths in the Tertiary pluton which forms the core of the range. Contact metamorphosed Paleozoic limestones and quartzites are exposed in nearly vertical beds trending N30E on the eastern margin, and in an outcrop overlying a low angle normal fault on the western margin. Paleozoic sedimentary rocks are also exposed in the northern and southern portions of the range. The Tertiary Mineral Mountains Pluton crops out in the center of the range. The pluton is composed of fine to medium grained quartz monzonite and granite. Potassium-argon dating by Bowers (1978) indicates a minimum age of emplacement of between 11 and 14 million years before present. Rhyolite domes and flows have been extruded along north-south and east-west lines through the central Mineral

Mountains. The extrusive period has been dated by Evans and Nash (1978) as having occurred between .5 and .8 million years before present. Siliceous sinter deposits cropping out along the Opal Mound Fault form the youngest rocks in the range. Opal from the fault has been estimated by paleomagnetic methods as being less than .35 million years old (Brown, 1977).

Three major fault trends are present in the Mineral Mountains. The Opal Mound Fault forms the western boundary of a small graben trending north-northeast through the KGRA. Thermal gradient and resistivity anomalies are centered on this fault (Sill and Bodell, 1977). East-west trending high angle faults have been mapped in the northern Mineral Mountains, in Pass Canyon, and in Hot Springs Wash. Earll (1957) claimed major right-lateral strike-slip displacement for the fault in Pass Canyon. The sense of displacement on the Hot Springs Fault has not been determined. Nielson and others (1978) suggest that the north side is down, opposite the sense found by Crebs and Cook (1976). Nielson and others (1978) have also mapped a set of northwest trending high angle faults in the KGRA. The sense of displacement is not known for most faults due to a lack of marker horizons. Following this same northwest trend is a major west dipping cataclastic zone located at the eastern ends of Big and Little Cedar Cove. Based on offset of quartzite and sillimanite schist xenoliths Nielson and others (1978) claim 610 meters of normal displacement along a S80W vector.

Scope of this Study

A three part program has been conducted to understand the structural evolution of the reservoir and the development of fracturing in the Mineral Mountains. Field mapping of joint and dike patterns was done to determine structural orientations and paleostress patterns. Surficial in-situ strain relief tests were conducted to find the orientations and magnitudes of residual strains. Laboratory petrofabric analysis and rock mechanics tests were run to understand the mechanical behavior of the rocks.

STRUCTURAL MAPPING

Domain Selection

Time limitations made it impossible to examine the entire Mineral Range. Efforts were concentrated in the structural province bounded on the north by the east-west high angle fault south of the Millard-Beaver County line, and on the south by the high angle faults in Pass and Cave Canyons (Figure 1). These two structures separate the central Mineral Mountains from areas of distinctly different lithologies. Dominant rock types in the areas north and south of the central Mineral Mountains are Paleozoic and Mesozoic sedimentary rocks, as opposed to dominantly plutonic and volcanic rock in the study area.

Further subdivision of the area into study domains was based upon rock type, local structure, and amount of outcrop. Areas of limited outcrop were avoided to conserve time. To assess the influence of rock type on structural patterns domains were chosen to include most of the lithologies mapped by previous workers. Domains inside and outside the KGRA were selected to determine if the fracture systems in the geothermal area were distinctive. Structural boundaries of interest were igneous contacts, low angle faults, the major east-west faults, and the northwest trending faults of the KGRA. Domain locations are shown in Figure 2.

Figure 2: Study domain locations in the Mineral Mountains.

LEGEND

CENOZOIC	Qal	QUATERNARY ALLUVIUM
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	Qr	QUATERNARY RHYOLITE
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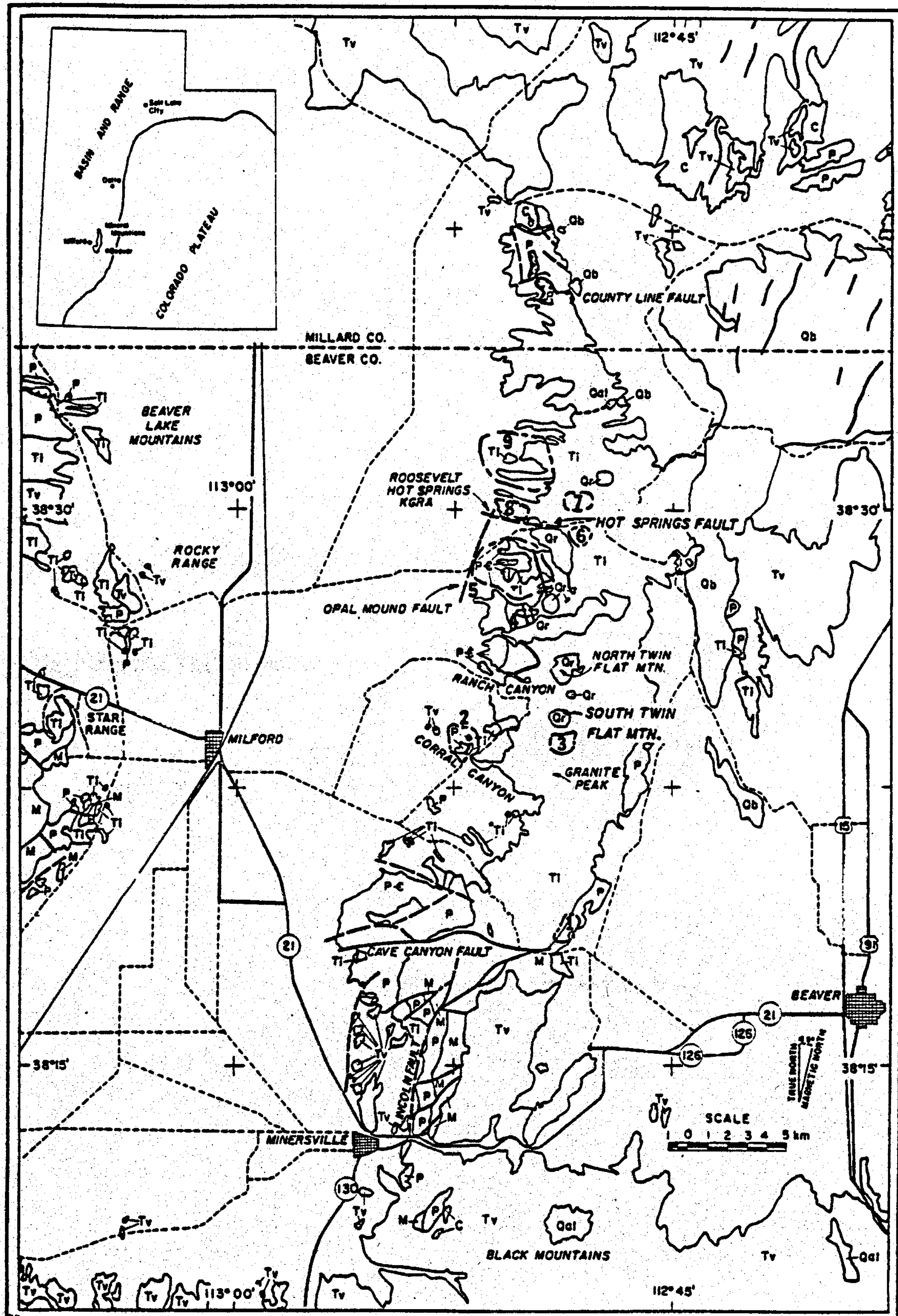
PRECAMBRIAN	P€	PRECAMBRIAN GNEISS & SCHIST
		FAULTS, DASHED WHERE APPROXIMATELY LOCATED
		THRUST FAULT, SAWTEETH ON UPPER PLATE
		STUDY DOMAINS


BASIN AND RANGE
COLORADO PLATEAU
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BEAVER CO.
BEAVER LAKE MOUNTAINS
ROCKY RANGE
STAR RANGE
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ROOSEVELT HOT SPRINGS KGRA
COUNTY LINE FAULT
HOT SPRINGS FAULT
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NORTH TWIN FLAT MTN.
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RANCH CANYON
CORRAL CANYON
GRANITE PEAK
CAVE CANYON FAULT
LINCOLN ZONE
MINERSVILLE
BEAVER
BLACK MOUNTAINS
112°45'
113°00'
38°30'
38°15'
SCALE
0 1 2 3 4 5 km
TRUE NORTH
MAGNETIC NORTH

Procedure

Structures studied in each domain were joints, dikes, and small shear zones. Emphasis was given to fracture patterns because of their importance in reservoir permeability. At each outcrop the orientations of these structures were recorded, joint spacings and dike sizes were measured or estimated, and the presence or absence of hydrothermal alteration and cataclastic material on joint surfaces was recorded. A summary of joint characteristics within each study domain is presented in Appendix A. Fracture orientation data were then plotted and contoured for each domain using the Schmidt method (Ramsay, 1967) on a lower hemisphere equal-area stereographic projection. Due to the small sample size, dike orientation data were not plotted for each domain, but rather were compiled for three broad regions over which trends are very similar. Over 3000 orientations were recorded and plotted in order to provide an adequate statistical base for the study.

Structural Analysis

Understanding the genesis of structures in the Mineral Mountains is a first step in understanding the development of the geothermal reservoir. Combining analysis of orientation data with field observations of structural characteristics has helped determine the styles and causes of fracturing and dike intrusion in the range.

Dike Patterns

Nielson and others (1978) have mapped three major dike phases in the central Mineral Mountains and determined relative ages through cross-cutting relationships. The oldest and most common dikes are granitic in composition and aplitic or pegmatitic in texture. Thickness ranges from several centimeters to two hundred meters, and exposed lengths range from a few meters to a kilometer. The largest dikes occur in Domains 8 and 9 north of the Hot Springs Fault. Aplites and pegmatites are common throughout the study area with the exception of the southeastern margin of the pluton (Domain 1). In Domain 1 the only pegmatite found was a 1-2 meter thick dike which defines the contact between the pluton and the Paleozoic sedimentary rocks. Density of diking is irregular, high in some areas while absent in others with no apparent pattern.

Microdiorite dikes are found intruded along fault zones in the KGRA. Presence of microdiorite clasts in cataclastic fault material indicates that some dikes were intruded during or prior to faulting. Microdiorites range in thickness from less than a meter to four meters and in length from meters to a kilometer. These dikes have been found only in areas of intense faulting, such as below the low angle fault near Corral Canyon (Domain 2) and in the KGRA (Domain 5).

Rhyolitic dikes form the youngest intrusive rocks in the study area, cropping out between Wild Horse and Ranch Canyons. They range in thickness from a meter to twenty meters and in length from ten meters to a kilometer. Many rhyolite dikes show a flow foliation. A few dikes have been found in Domain 1, oriented parallel to bedding in the marbles and parallel to jointing in the pluton.

Dike orientations have been compiled for three regions in the central Mineral Mountains (Figure 3): Domains 8 and 9 north of the Hot Springs Fault; Domain 5 in the KGRA south of Hot Springs Fault; and the pluton interior in Domain 3. In each region dike trends are fairly constant. Microdiorite dikes have not been included in the rose diagrams because their orientations are directly controlled by fault patterns. Rhyolitic and granitic dikes are plotted together because their orientations in any one area are similar and the rhyolite sample size was too small for meaningful comparison.

Figure 3 shows the three regions for which the dike orientation data was compiled. A strong north-south trend of diking is present north of the Hot Springs Fault, while to the south in the KGRA a more north-northeasterly trend is dominant. We do not see any strong preferred orientation in the pluton's interior.

Genesis of the dikes is important for making a paleostress interpretation. The theoretical basis for determining paleostress orientations from dike patterns has only been developed for intruded dilational dikes, not dikes that formed from replacement and differentiation of cooling igneous rock. Presence of flow structures in the microdiorites and rhyolites shows that they are a result of forceful intrusion. Condie (1960) has concluded that the aplitic dikes represent late phase replacement dikes rather than magmatic dilation dikes. From field observations in my study area, I interpret the aplitic dikes to be intruded dilational dikes. Contacts between dikes and country rock are sharp, not gradational as would be expected

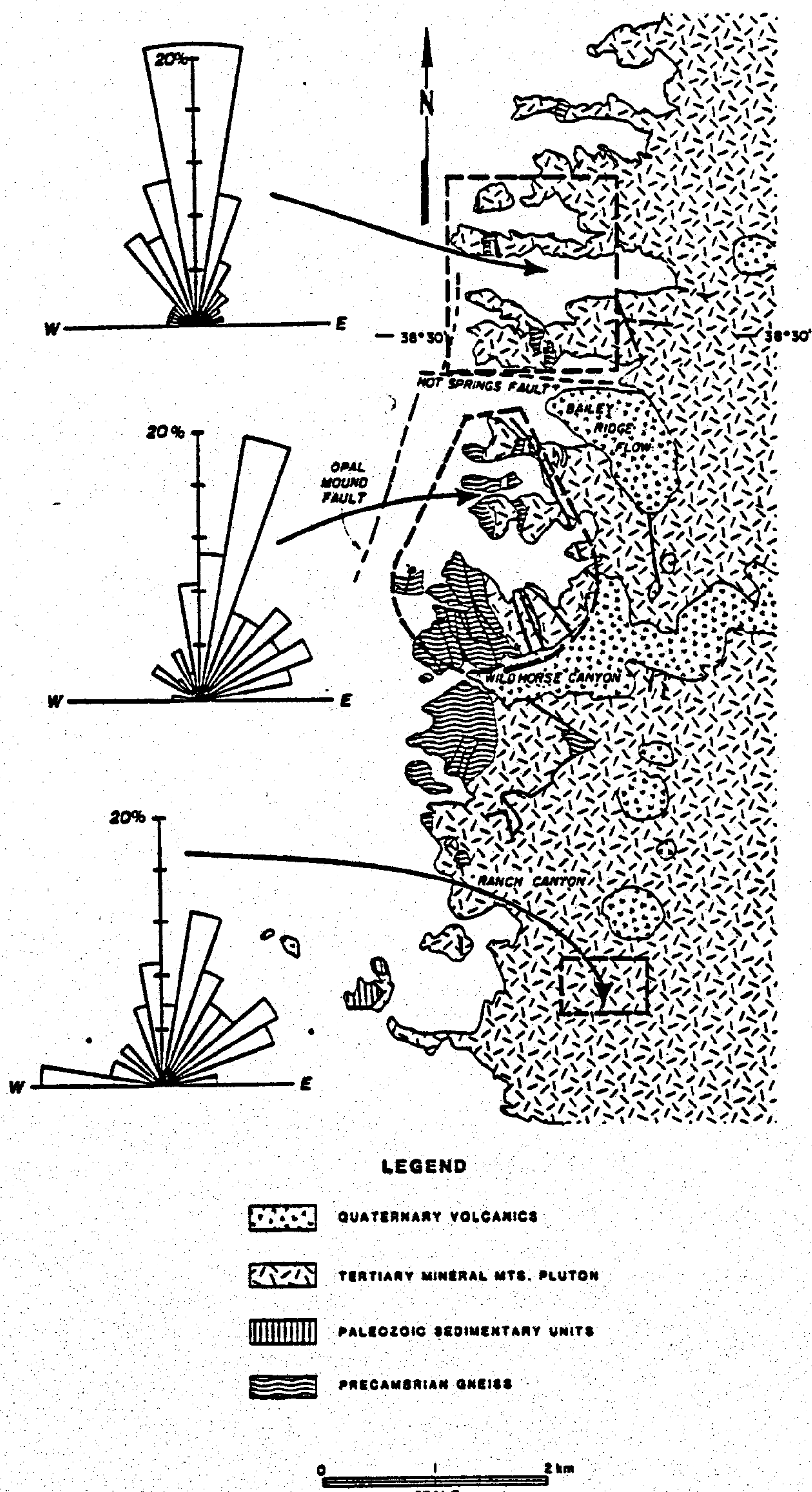


Figure 3: Rose diagrams of strikes of 50 steeply dipping dikes compiled for three regions in the central Mineral Mountains.

from replacement. Aplites in the study area are planar bodies with regular widths and constant orientation characteristics that Goodspeed (1941) attributed to intruded dikes. The lack of evidence for fluid flow cited by Condie (1960) is not evidence against forceful intrusion. Mesoscopic flow textures are absent because elongate crystals or inclusions are not found in the dikes.

Ode (1957) and Nakamura (1977) outlined the theoretical basis for defining stress orientations based on diking patterns and linear alignment of volcanic centers. They claim that dike emplacement is mechanically similar to propagation of a hydraulic fracture. The hydrofracture or dike plane should be oriented normal to the minimum compressive stress and should contain the maximum and intermediate stresses (Hubbert and Willis, 1957). Ode (1957) has shown that dike patterns may be controlled by a combination of regional tectonic stress and a local stress field produced by the injection of magma through a central core. He successfully modeled the volcanic center and dike field of Spanish Peaks, Colorado as an externally loaded elastic plate containing a circular hole with an internal hydrostatic pressure. Under this loading system, dikes will propagate radially from the hole (volcanic center). The direction of dike propagation is perpendicular to the minimum compressive tectonic stress at distances away from the influence of the volcanic centers. Nakamura (1977) demonstrated that volcanoes show similar alignment in the tectonic stress field. He emphasized that the morphology of the extrusive centers was important in determining whether the volcano represented the central core or a dike-fed subsidiary cone. Cones which had undergone several phases of eruption (polygenetic in his terminology) were fed by a central pipe, while those with only one phase of eruption (monogenetic) were usually fed by dikes formed along rifts. Since monogenetic cones are a reflection of deep seated dikes, they too should align normal to the minimum compressive stress. Rhyolite domes and flows in the Mineral Mountains represent single extrusive events (Evans, personal communication, 1979) and so can be used for stress interpretation.

Local gravitational effects must be considered when interpreting dike patterns in areas of large topographic relief. Fiske and Jackson (1972) found that a dike system in Hawaii was more strongly affected by gravity than by active tectonic forces. Gravitational spreading of the shield volcano produced an extensional stress field with the minimum compressive stress horizontal. Unfortunately, no estimate of relief can be made for the Mineral Mountains at the time of dike emplacement.

Extension directions interpreted from dike patterns are east-west north of Hot Springs Fault and west-northwest in the KGRA. No interpretation is possible for the pluton interior. An east-west extension axis is also interpreted from the linear alignment of rhyolite domes.

Fracture Systems

One style of fracturing common to many outcrops throughout the Mineral Mountains is a pervasive fracture foliation. This foliation appears as a very dense fracturing of the pluton. Spacing between fractures varies but is approximately one centimeter. Morphology of the fabric is dependent on whether there has been shear along the fractures. Where shear has not occurred, the fractures are roughly parallel and have little alteration on their surfaces. Commonly, more than one preferred orientation is present at an outcrop. Where shear displacement has occurred, the fracture foliation appears as zones of anastomosing fractures with hydrothermally altered and slickensided surfaces. Fracture density is much greater in the shear zone than in the undisturbed rock. Evidence for shear occurs most frequently in areas of intense faulting, such as Domains 4, 5, and 7. Where little faulting has occurred, as in Domain 3 of the pluton interior, evidence for shear has not been observed.

Orientation of this fracture fabric was difficult to measure, so no extensive data set was collected. It was noted that the orientation consistently conformed to that of the macroscopic joint sets.

Grain size, rather than rock composition, seems to have controlled whether this foliation or discrete mesoscopic joint planes developed. The aplitic dikes have a similar composition to the coarse grained granites but exhibit a distinctly different fracturing style. Jointing within dikes is commonly dense but the rock does not have the pervasive fracturing of the coarse grained granite.

Differing fracture styles of the coarse and fine grained rocks is a reflection of differences in rock strength. Coarse grained granites in the Mineral Mountains are much weaker than the fine grained dikes and so fracture more intensely at lower stress levels. Grain size-dependent rock strengths can be explained by the Griffith's theory of fracturing (Brace, 1964). Tensile strength of a crystal is inversely proportional to length of the Griffith crack it contains. The maximum length of a crack is the longest dimension of the crystal. As a result, small crystals have higher strengths, and fine grained rocks should be stronger than coarse grained. This result of elasticity theory has been sustained by laboratory testing. Coarse grained rocks fracture at lower stress levels than fine grained rocks in uniaxial and triaxial compression tests (Paterson, 1978).

Brazil tests for tensile strength have been conducted on cores from the Mineral Mountains. Cores with a diameter to thickness ratio of 10 to 1 were compressed along a diameter until the rock fractured. Theoretical analysis of stress distributions in uniaxially loaded cores has shown that the fracture forms as a result of a tensile stress oriented normal to the compression axis (Wijk, 1978). The tensile strength of the core can then be calculated from the compressive load at failure.

Table 1 summarizes tensile strengths measured in rocks from the study area. Gneiss samples were taken from strain relief test site SF south of Wildhorse Canyon. Granite samples 1 through 8 were taken from Domain 1, while samples 9 through 20 came from stress relief test site GR located on the eastern flank of the Mineral Mountains (see Appendix 2 for strain relief test site locations). The grain size in granite samples 1 through 8 ranged from 0.5 to 2 mm and averaged approximately 1 mm. The grain size in the remaining granite samples ranged from 1 to 5 mm and averaged approximately 2 mm. Though other

Table 1: Tensile Strengths of Rocks in the Mineral Mountains

Lithology	Sample	Tensile Strength (bars)
Gneiss	1	74.5
	2	59.1
	3	66.0
	4	69.2
Granite	1	59.3
	2	32.8
	3	82.5
	4	69.0
	5	67.3
	6	74.4
	7	87.2
	8	79.0
	9	29.0
	10	28.8
	11	33.3
	12	33.2
	13	30.0
	14	20.6
	15	19.8
	16	23.0
	17	18.2
	18	19.6
	19	20.8
	20	21.4

factors like differences in mineralogy may be affecting the strengths measured, a trend towards increasing strength with decreasing grain size is noted.

The pervasive fracture foliation probably represents intense extensional fracturing. Griggs and Handin (1960) classify brittle fractures as either shear fractures or extension fractures. Shear fractures are characterized by slip along the failure surface and by an orientation approximately 30 degrees to the maximum compressive stress. Displacement on extension fractures is normal to the fracture surface. Extension fractures commonly form normal to the least compressive stress or normal to the greatest tensile stress.

The genetic classificiation of fractures based on field observations must rely on evidence for displacement along or across the fracture plane. In the Mineral Mountains, shear textures on the fracture foliation are common in the vicinity of faults. Where faulting is absent, as in Domain 3 of the pluton interior, there is no evidence for displacement along the fracture fabric. It is inferred that observed evidence for shear along fractures of this foliation is due to fault-induced displacements on original extension fractures.

Two orthogonal or nearly orthogonal sets of steeply dipping joints are present at most outcrops in the Mineral Mountains. Commonly, at a single outcrop joints of one set are more dominant; but over a domain both are represented. Joint spacing is variable, ranging from centimeters to tens of meters. The largest spacings are found in the coarse grained plutonic phases of Domain 3 where most fracturing occurs as the fabric discussed before. Steeply dipping joints in the fine grained plutonic phases and gneisses have much greater densities, with spacings seldom greater than two meters. Joint density is directly related to proximity to faults. In Domain 2, joint spacing decreases from around 0.5 meters to less than a centimeter with decreasing distance to a major low angle fault. Similar relationships are found in Domain 5 of the KGRA. It was noted in Domain 8 however that proximity to the Hot Springs Fault had no apparent effect upon joint density.

Surfaces of these steeply dipping sets are generally planar and open. As with joint density, morphology is directly related to proximity to faults. The composition of the pluton is such that small amounts of shear displacement form coatings of cataclasite with greenschist grade hydrothermal alteration on joint surfaces. Presence of cataclasite on joint surfaces is therefore good evidence that shear displacement has taken place. Cataclastic and hydrothermal alteration of joint surfaces has been observed most frequently in areas of intense faulting, such as in Domains 2 and 5. Throughout the rest of the study area shear textures on joints of this set are present at only a few scattered outcrops.

As illustrated in Figure 4, these steeply dipping joint sets maintain a roughly uniform trend throughout the central Mineral Mountains. Strong east-west and subsidiary north-south concentrations of poles to joint planes are found in the plots for Domains 2, 3, 7, 8, and 9. The preferred east-west orientation in Domains 8 and 9 north of Hot Springs Fault reflects the tendency of the numerous large north-south aplitic dikes to fracture normal to their contacts. The

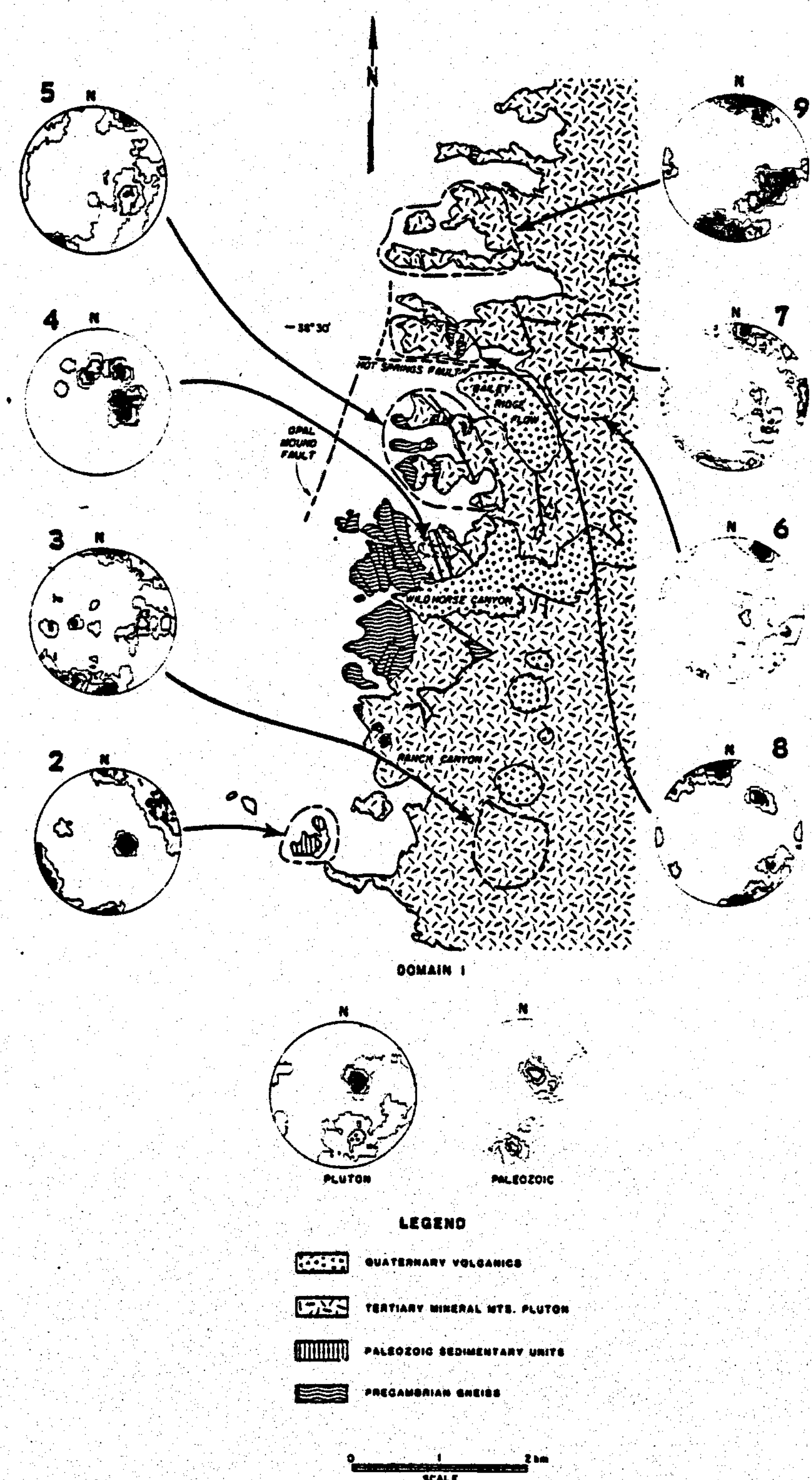


Figure 4: Lower hemisphere equal-area stereographic projections of poles to fracture planes. Refer to figure 2 for location of Domain 1.

apparent dominance of the east-west striking set in Domain 3 is not real since north-south trending joints are equally important but form much larger and less dense features. The only variation from this north-south and east-west trend is found in Domains 1, 5, and 6. The few steeply dipping joints present in Domain 1 are oriented N30E86E; parallel to the contact between plutonic and sedimentary rock. Joints in Domain 5 of the KGRA, and Domain 6 south of Hot Springs Fault trend N59-70W, with a secondary north-south set.

Unlike joint densities, orientations of these steeply dipping joint sets are not affected by proximity to faults. As illustrated in Figure 4, joints beneath a major low angle cataclastic zone in Domain 2 show the same pattern as those unaffected by faulting in Domain 3. High-angle joints exposed in Wild Horse Canyon below the major shear zone mapped by Nielson and others (1978) trend N60W, parallel to the dominant trend throughout the KGRA. Joints near high-angle faults in the KGRA also maintain this strong N60W trend.

These orthogonal or nearly orthogonal joint sets probably formed as extensional joints during cooling and contraction of the pluton. Open, planar, smooth surfaces are characteristic of tensional cooling cracks (W. P. Pariseau, personal communication, 1978). The steeply dipping sets show little evidence for shear except where faulting has initiated late, minor displacement.

Orientation of the steeply dipping joint sets is consistent with the pattern expected from cooling and extensional fracturing of a pluton. Balk (1937) showed that orthogonal joint sets are characteristic of large intrusive bodies. Near the margins of plutons they form parallel and perpendicular to the igneous contacts, mapping isothermal surfaces during cooling. In the Mineral Mountains the joints are not always orthogonal, but variations can be explained by irregularities in the contacts.

Relationships between joint and dike trends further support the extensional origin of these joint sets. Comparison of Figures 3 and 4 shows that joint orientations are consistently normal or parallel to local dike trends. Dikes represent structures oriented normal to the direction of maximum extension. Structures oriented parallel to extensional features are probably also extensional, if no large rotations in the strain field can be documented. As noted earlier, extension directions inferred from dike patterns and linear alignment of rhyolite domes show only east-west to west-northwest directed extension. No large rotations in extension directions have been noted.

Two observations seem to contradict the interpretation that the steeply dipping sets are extension joints formed during cooling and contraction of the pluton. First, these sets occur in the gneisses as well as the pluton. It is doubtful that the gneisses underwent a cooling and contractional history similar to the pluton. In a structural analysis of a pluton at Hanover, New Mexico, Aldrich (1974) also found a set of fractures in the sedimentary country rock which appeared to be very similar in orientation and appearance to cooling extension fractures in the adjacent pluton. He proposed that this set in the country rock also formed in extension by doming during intrusion. This is a possible explanation for occurrence of the same joint sets in both gneiss and granite in the Mineral Mountains. An alternate suggestion is that the gneisses have been extended by contraction of the pluton. Osipov (1974) claimed that an intrusive rock should undergo 8 to 14 percent volumetric contraction. When confined, 40 percent of the strain is accommodated by fracturing of the pluton and surrounding country rock. Transferring contractional strain from the pluton to country rock requires some degree of welding along the contact. If the pluton can separate from the country rock, then the strain may be relieved. It is significant that steeply dipping joints are only poorly developed at the contact between plutonic and sedimentary rock in Domain 1. Presence of a large pegmatite dike along the contact indicates partial decoupling of the pluton from the country rock during cooling, which may have inhibited the development of extension joints.

A more serious objection to the interpretation of the orthogonal joint sets as extensional structures is the observation that their frequency increases dramatically with decreasing distance to faults. In Domain 2, for example, spacing of what would otherwise be labeled cooling joints is directly related to distance from a low angle shear zone. If these joints were extension joints formed only due to the contraction of the pluton, faulting would have no effect on fracture density.

It is proposed that rock fracturing in the Mineral Mountains was strongly influenced by the contractional history of the pluton. Smith and others (1976) have shown that in some cases strength anisotropies and residual stresses (Friedman, 1972), rather than in-situ stresses, controlled the orientation of fractures in rocks. Similarly, strength anisotropies imposed on the rock during cooling have controlled the orientation of fault induced fractures. Increase in joint density towards faults is then explained by displacement related stresses fracturing the rock along previous planes of weakness.

A second joint set common to many outcrops throughout the central Mineral Mountains is a group of shallow to moderately dipping fractures. All lithologies contain joints of this set. As with the other styles of fracturing, appearance is dependent on whether shear displacement has taken place on the surfaces. Cataclastic material with hydrothermal alteration, considered to be evidence for shear, has been noted on low to moderate angle joints in the pluton interior of Domain 3, in Domain 5 of the KGRA, and beneath low angle faults in Domain 7. Below the low angle fault in Domain 2 shallow west-dipping joints appear as large, smooth, unaltered surfaces. To the north of Hot Springs Fault in Domains 8 and 9 few joints of this set show evidence for shear. Joint densities are variable in different domains. Joint spacing within the marbles of Domain 1 is dense and regular, at intervals generally less than one meter. Greater ranges are found in the adjacent pluton. In Domains 2 and 8 joints of this set have a regular spacing, with no apparent relationship between faulting and density. Shallow to moderately west dipping fractures in the KGRA are best developed and densest near the northwest trending high angle faults.

Joint orientations are shown in Figure 4. With the exception of joints in Domain 1, dips are consistently to the west. Strikes vary between domains, as is expected from a shallow dipping set, but the west dip remains fairly constant. In the anomalous Domain 1 these joints dip to the south.

The classification of these low to moderate-angle joints into a single group is based on their consistent orientation throughout the study area. A genetic classification would distinguish three separate groups, those formed as extension joints due to cooling and contraction, those formed as extension joints related to unloading, and those formed as shear joints due to fault displacement.

Shallow dipping joints in Domain 1 are probably extension joints formed during cooling and contraction of the pluton. Their planar and parallel surfaces appear similar to the steeply dipping extension joints. Strong evidence supporting the claim for formation during pluton cooling is their orientation parallel to the few rhyolitic dikes found in the domain.

Shallow dipping joints in Domain 2 appear to be sheeting joints related to unloading. No evidence for shear displacement has been observed despite their location below a major fault. The joints form large surfaces which intersect higher angle joints. This joint geometry separates the outcrop into roughly lenticular blocks. Jahns (1943) labeled joints with this appearance sheeting joints and suggested they form due to uplift and removal of overburden.

Many shallow to moderately dipping joints in the KGRA appear to be shear joints. West dipping fractures in outcrops near faults have the characteristic cataclastic and hydrothermal alteration on their surfaces showing that some displacement has taken place. Joint strikes, however, are seldom parallel to those of associated faults. Whether these joints are true shear fractures or extension fractures which underwent later shear displacement could not be determined.

Development of Fracture Permeability

Fracture permeability in the Roosevelt geothermal reservoir has been created by two major mechanisms: 1) deep and intensive extensional fracturing related to cooling and contraction of the pluton; and 2) fracturing initiated by fault displacements. Extensional fracturing takes the form of a pervasive fracture foliation as well as steeply dipping macroscopic joint sets. Geophysical studies in the Roosevelt area, particularly those of P. Wanamaker (personal communication, 1979), have been interpreted to indicate a major boundary, with highly fractured rock overlying less fractured rock at a depth of between 1.5 km and 2.0 km. Triaxial compression tests (Paterson, 1978) have shown that extension fractures cannot develop under confining pressures greater than 1 kilobar, the overburden pressure expected at depths of 2 kilometers. It is suggested that this 1.5 to 2 km deep boundary represents the maximum depth of extensional fracturing in the Roosevelt KGRA.

Displacement induced fractures have been shown to follow previously developed extensional trends. Fault displacements fracture the rock along preferred planes of weakness formed in the rock during cooling and contraction of the pluton. It is predicted that hydrofractures created to enhance reservoir permeability will also be controlled by these strength anisotropies represented by surficial joint trends.

STRAIN RELIEF MEASUREMENTS

In order to gain additional information on the stress history, strain relief measurements were conducted at several sites in the Mineral Mountains. It was hoped that the present active and residual stresses could be determined.

Site Selection

Sites for the strain relief tests were selected based upon ease of access, topography and outcrop characteristics. The need for large amounts of drilling water confined the possible sites to those that could be reached by truck. Preference was given to areas of low relief in order to eliminate any effects of topographic loading. The most important factors in site selection were the outcrop and rock characteristics. Outcrops in which a joint provided a large, flat, and roughly horizontal surface were important for good measurements. Evidence that the block was in-situ (i.e. not rotated any significant amount) was considered essential.

This list of necessary outcrop characteristics limited the number of adequate sites in the Mineral Mountains. Most coarse grained outcrops were useless for strain relief tests due to the pervasive fracture foliation. In the KGRA the only rocks sufficiently coherent for overcoring were the Precambrian gneisses. Unfortunately the density of jointing within these units is generally much greater than in the pluton, to the extent that most of the potentially useful outcrops were composed of blocks too small for good measurements. The same is true for most of the aplitic dikes. As a result, only two outcrops near the KGRA (labeled SF and MM) and two distant from it (CD and GR) were chosen for study. Site locations and descriptions are given in Appendix B and illustrated in Figure 5.

Method

Foil resistance strain gauge rosettes were bonded to smoothed, horizontal joint surfaces. Individual elements of the rosettes were sufficiently long to record strain over several grain diameters. After sealing to prevent water damage, two rosettes were connected in opposite arms of a Wheatstone bridge circuit and balanced. One of the gauges was then overcored and the resulting strain release recorded. The other rosette compensated strains due to changes in ambient air temperature. In order to separate applied from residual stresses each rosette was overcored with a 15 cm and a 7.6 cm barrel (Greiner and Illies, 1977). For a detailed description of this technique see Swolfs and others (1974).

Orientations and Magnitudes of Principal Strains

Unreduced results of strain relief measurements are presented in Appendix C. Test results are designated by their site label and measurement number (GR2 refers to the second measurement at site GR). Throughout this paper, extensional strains are considered positive and contractional strains negative.

Figure 5 illustrates the orientations of the principal strains measured upon initial overcoring. The orthogonal axes shown are

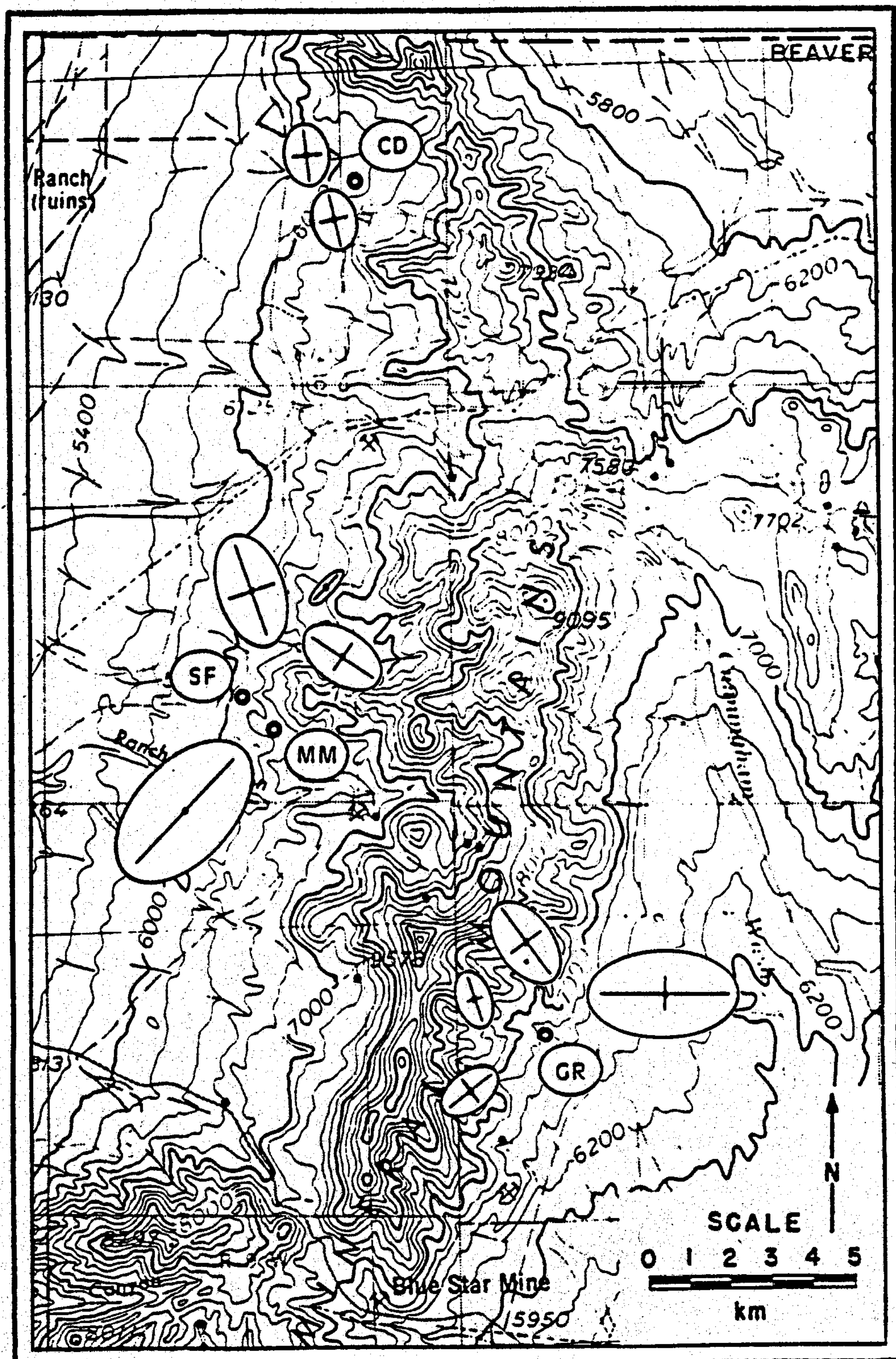


Figure 5: Orientations and magnitudes of principal strains measured in surficial strain-relief tests. For strain-relief axes 1 cm is equal to 250 microstrains.

scaled to represent the magnitudes of the maximum (e_1) and minimum (e_2) extensional strains. Axes are drawn parallel to the orientations of measured maximum and minimum extension directions. Note from Figure 5 that no preferred extension direction has been found for the Mineral Range as a whole or for any individual site. Variations in extension direction of as much as 90 degrees were recorded at one site. Measured orientations are controlled by outcrop fracture patterns rather than any regional stress. The e_1 directions for cores GR4 and SF2 fall within one degree of the strike of the closest fracture. With the exception of cores GR2 and GR3, one of the principal strains for every test lies within 10 degrees of a fracture in the outcrop. The controlling fracture is not necessarily the closest or even a member of the best developed set. In the Precambrian gneisses fracturing more closely controls principal strain directions than the metamorphic foliation. In general, the large amount of scatter in maximum extension directions is directly due to the scatter in orientations of steeply dipping joints.

In the majority of tests conducted, maximum extension directions measured remained the same for both the 15 and 7.6 cm overcoring. The rotation of extension axis for core GR4 was probably caused by the use of a different size gauge for the second overcoring. A rosette with shorter elements which measured strain relief over fewer grain dimensions was used for the inner core. Rotations of the extension direction for cores GR2, MM, and CD1 have not been explained. Unlike the extension, directions for the outer core, those measured upon second coring do not lie parallel to outcrop fractures.

Table 2 summarizes the strain magnitudes measured. A quick examination shows the large variations in magnitudes recorded, not only between sites but at one site as well. At site GR, ranges in strain magnitude of 200 to 486 microstrains were measured upon initial overcoring. This observation is consistent with the results of other workers (Friedman, 1972). Greiner and Illies (1977) reported ranges of ± 20 percent in magnitude for one of their test sites. At present, no estimate of the accuracy for the magnitudes can be made.

Engelder and Sbar (1977) demonstrated that the scatter in magnitudes they measured was due to differing fracture densities. They found a good correlation between increasing surface area of outcrops bounded by steeply dipping fractures and increasing strain magnitude. No similar relationship was noticed for strain relief tests in the Mineral Mountains. Surface area between steeply dipping fractures at site GR is roughly three times that of SF (6 square meters as opposed to 2), but strains measured were similar. Intuitively, one would expect that variations in strain magnitude could be due to differing distances to free surfaces. This was not found to be the case. Rosette GR1 was located approximately one meter from an open joint, while rosette GR2 was 0.5 meters from the same joint. Note from Table 2 that GR1 recorded slightly larger strains.

Patterns of Rock Response

Two basic types of rock response to overcoring were noted. The first, typified by test core GR2, resembles the ideal case of elastic strain relief. The rock expanded rapidly to a stable state and

Table 2: Results of Strain Relief Measurements

	overcore diameter (cm)	maximum strain (microstrains)	minimum strain (microstrains)	azimuth (e_1)
GR1	15	200	104	N55E
	7.6	-23	-39	N55E
GR2	15	179	54	N18W
	7.6	48	-38	N81E
GR3	15	486	133	N87W
	7.6	696	96	N88W
GR4	15	183	147	N42W
	7.6	150	113	N60W
MM	15	515	-166	N43E
	7.6	72	-53	N7W
SF1	7.6	405	231	N18W
SF2	15	278	132	N56W
	7.6	10	-145	N57W
SF3	15	135	-36	N45E
	7.6	54	19	N45E
CD1	15	181	123	N13W
	7.6	25	5	N75W
CD2	15	209	98	N06W
	7.6	42	-19	N03W

suffered no further deformation (see time-strain curve Figure 6). The time required for stabilization was less than the 10 to 15 minutes used in reconnecting the gauge to the Wheatstone Bridge. This is the type of response observed by Greiner and Illies (1977) which they interpreted to be elastic release of applied tectonic stresses.

Uniaxial compression tests were conducted to test whether the rock was elastic. Typical results (see Appendix D for results of tests) illustrated in Figure 7 show that none of the rocks acted elastically under loads of up to 350 bars. Even the Precambrian gneisses which appear in the field to be very competent showed significant hysteresis and permanent deformation after unloading. The upward concavity of the curve is typical for loading of rocks at low confining pressures (Friedman, 1975), representing the strain due to close of previously existing microfractures in the rock. Results of uniaxial compression tests show that rocks in the Mineral Mountains are not elastic at the surface, and this first mode of rock response to overcoring is not an elastic release of stress.

Rocks exhibiting the second style of response showed strong time dependent effects. The time-strain curve for sample GR4 (Figure 8) shows the characteristic long-period strain release. This pattern was observed only in 7.6 cm corings conducted in the lab under constant temperature. Readings were taken at longer intervals than was customary for field tests, and readings were continued even if strain differences of as little as 1 microstrain per hour were recorded. Field experiments were terminated when strain changes between 10 minute reading intervals reduced to ±3 microstrains.

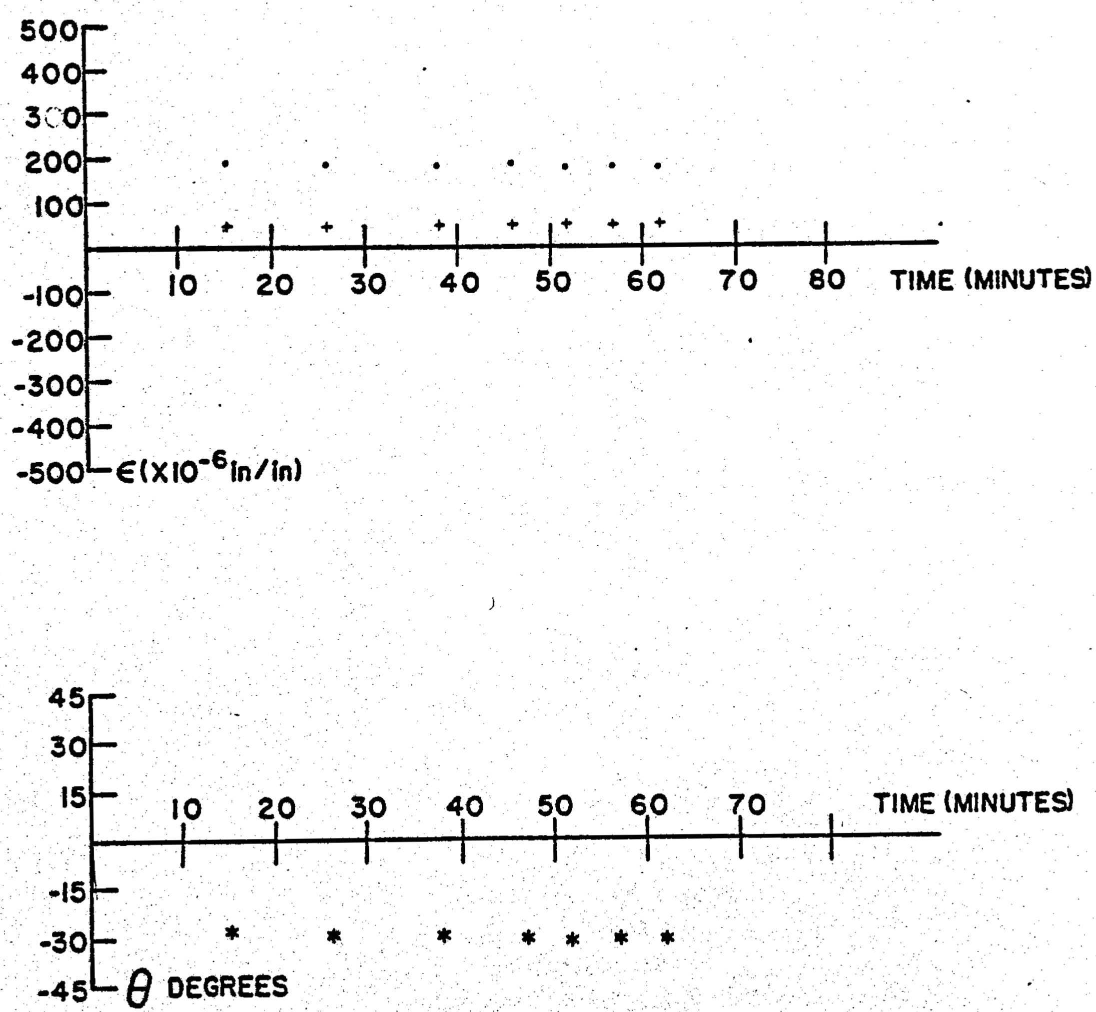


Figure 6: Variations in maximum strain (·), minimum strain (+), and angle between a principle strain and element 3 of the rosette (*) for test core GR2.

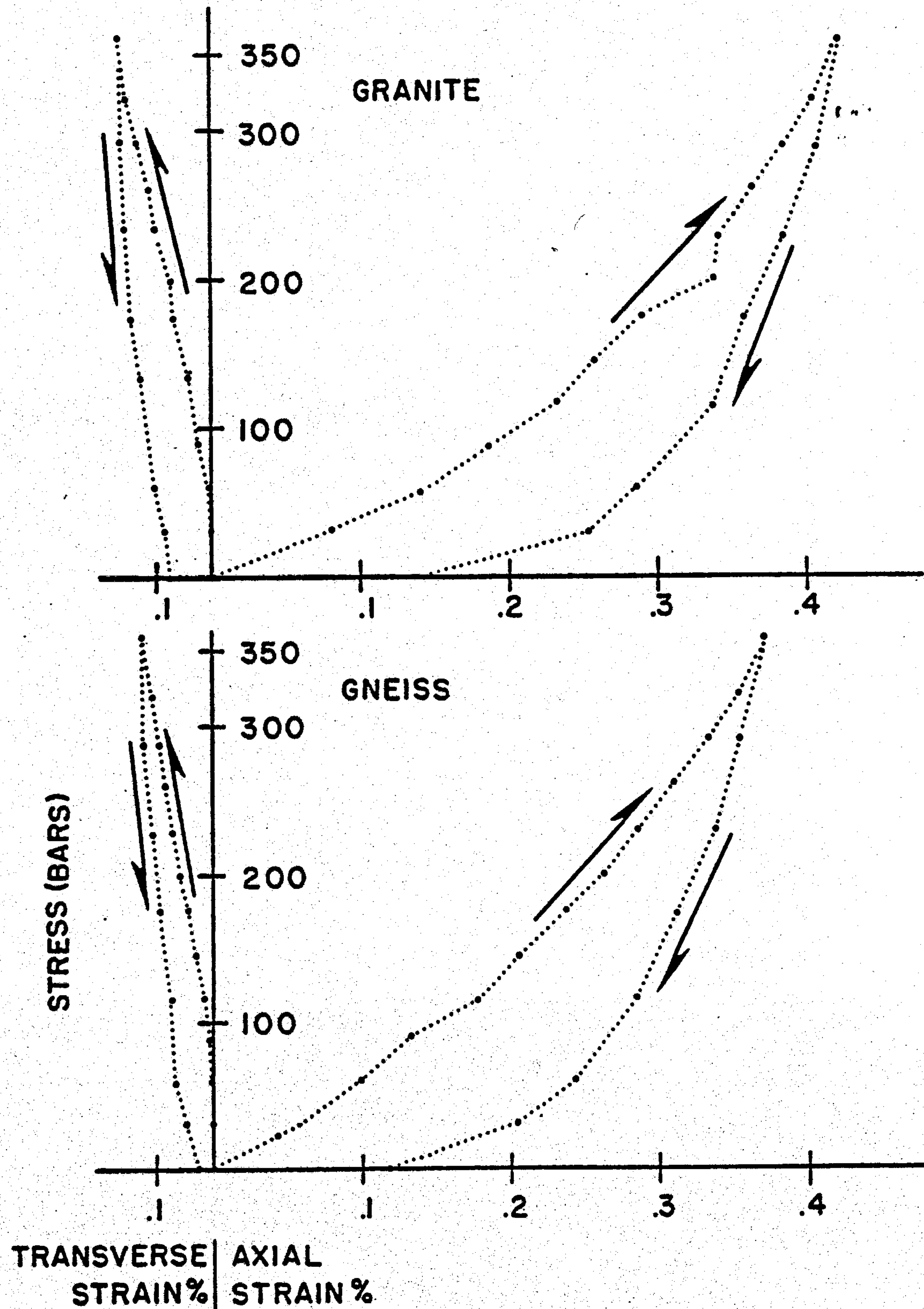


Figure 7: Typical stress-strain curves for uniaxial compression of gneiss and granite cores from the Mineral Mountains.

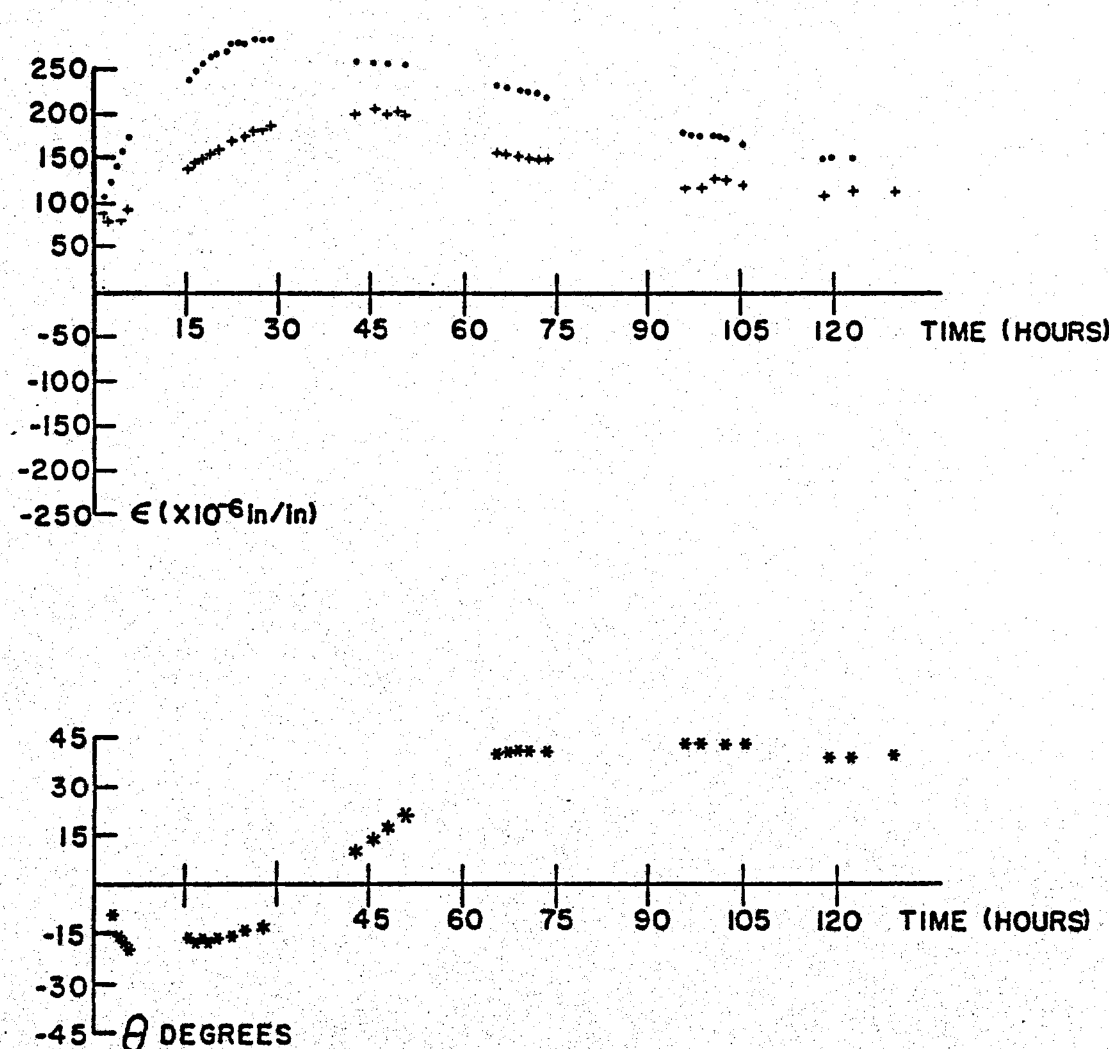


Figure 8: Variations in maximum strain (·), minimum strain (+), and angle between a principle strain and element 3 of the rosette (*) for test core GR4.

The difference between this long-period pattern of strain relief and the first style of response noted may represent 1) a dependence of strain release measured upon volume of rock released; or 2) a long period drift in internal resistance of the Wheatstone Bridge.

Swolfs and others (1974) noted that both the orientations and magnitudes of strains relieved were dependent on the volume of rock released by overcoring. Tullis (1977) also demonstrated that residual strains should vary significantly for various size domains released. We do not believe that the long-period response noted in lab tests reflects a difference in residual strain distribution between 7.6 and 15 cm cores. The second corings of rosettes GR1 and GR2 were conducted in the field and no long-period responses were noted. In addition, the similarity of strain orientations measured upon 15 and 7.6 cm overcorings for the majority of the tests suggests that there is no large difference in residual strain distributions between the core sizes.

We believe, but cannot prove, that there is some long-period drift in the resistance of the instrumentation and that it must be corrected before conducting tests of long time duration.

Mechanism of Strain Relief

In order to interpret the significance of the strain relief measurements some consideration must be given to what exactly was measured. First, it must be emphasized that strains, as opposed to stresses, are directly measured by all overcoring techniques. When rock responds elastically, conversion to stresses is valid and requires only a knowledge of elastic moduli. Rocks in the Mineral Mountains do not behave elastically under surficial conditions so conversion of measured strains to stresses would be pointless and misleading.

None of the strains measured were due to the release of any applied loads. Applied stresses are, as defined by Tullis (1977), "stresses that arise within a body as a result of surface tractions on its volume, or thermal gradients." Voight (1966) has defined residual stresses as "systems of stresses on the inside of a body which are in equilibrium, or approach equilibrium, when neither normal nor shear stresses are transmitted through its exterior surfaces." Residual strains are "potentially recoverable elastic distortions of constituent crystals or grains that satisfy internal equilibrium conditions and that exist in a given volume of rock with no external loads across its boundaries" (Friedman, 1972). The test sites were all bounded by open, steeply dipping joints incapable of transmitting horizontal stresses (see Appendix B). While not always visible at the outcrop tested, it can be inferred from surrounding outcrops that shallow dipping fractures form released surfaces at the base of all outcrops measured. All the strains measured must have been entirely residual.

Two mechanisms have been suggested to explain residual stresses and strains in rocks. Friedman (1972) has shown how true elastic stresses can be stored in sandstones which are loaded before cementation. In the uncemented state contacts between grains act as pin connections transferring only normal stresses. With cementation these stresses become "locked in" the grains. Subsequent uplift does not remove the load but rather redistributes the stresses between the cement and original crystals, effectively storing an elastic stress. A similar mechanism could occur in plutonic rocks. When the magma crystallized to the point that grains come into contact, the stress distribution would be similar to that in the uncemented sandstone. Stresses in the crystals would be different from the hydrostatic state in the remaining magma, and complete crystallization would lock in the grain stresses.

Tullis (1977) argues against residual elastic stress as a mechanism for strain relief. He modeled residual stresses as sinusoidally varying surface forces on a homogenous elastic block. By invoking the principle of St. Venant, he shows that residual elastic stress can be measured by overcoring techniques only for peculiar geometries of stress distribution. He shows that even when these geometries occur, the measured stresses should be random.

I do not believe that residual elastic stress is the major strain mechanism operating in tests conducted in the Mineral Mountains. While no preferred extension directions were found for either the range as a whole or for a single site, the principle strains measured were not random. Orientations recorded were clearly controlled by fracture patterns. In addition, the strong hysteresis and permanent deformation observed in uniaxial compression tests has shown that the rocks tested do not behave elastically at the earth's surface.

The other major mechanism used to explain residual strains is an anelastic process involving the permanent opening of microfractures following overcoring. Nichols (1975), as well as Engelder and others (1977), found that their maximum extension direction was normal to the dominant orientation of microfractures in the test core. Engelder and others (1977) also found that magnitude of strain measured was directly related to the density of open microfractures. This mechanism has not been used to explain contractions of the rock after overcoring. Permanent closing of microfractures is not intuitively reasonable.

Petrofabrics of selected cores were analyzed to test the microfracture hypothesis. Orientations of open cracks in quartz grains from three orthogonal slides were measured on the universal stage. Figure 9 shows the relationship between outcrop joints, microfractures, and strain relief. For all sites except MM there is a good correlation between the orientations of microfractures and joints. Test core GR2 contains a great circle distribution of microcracks that resembles the distribution of joints. Similarly, correlatives for most joint sets can be found in the associated microfracture plots. The main difference between the two diagrams for site MM is an absence of low angle joints.

Correlation of microfracture maxima to strain relief is less certain. Strain relief by microfracture opening requires a concentration of poles parallel to the measured extension direction. No such microfracture set is found in the plot for SF1 (Figure 9c). A concentration of poles parallel to the maximum extension direction can be found in plots for sites GR and MM (Figure 9 a,e). Unfortunately, this maximum is not the only one present or even the strongest one.

Figure 9: Relationship between outcrop joint patterns, test core microfracture orientations and maximum extension directions.

a. Stereographic projection of poles to 101 microfractures in test core GR2. Contour intervals 1, 2, 3, 4, 5, max 5 percent per area.

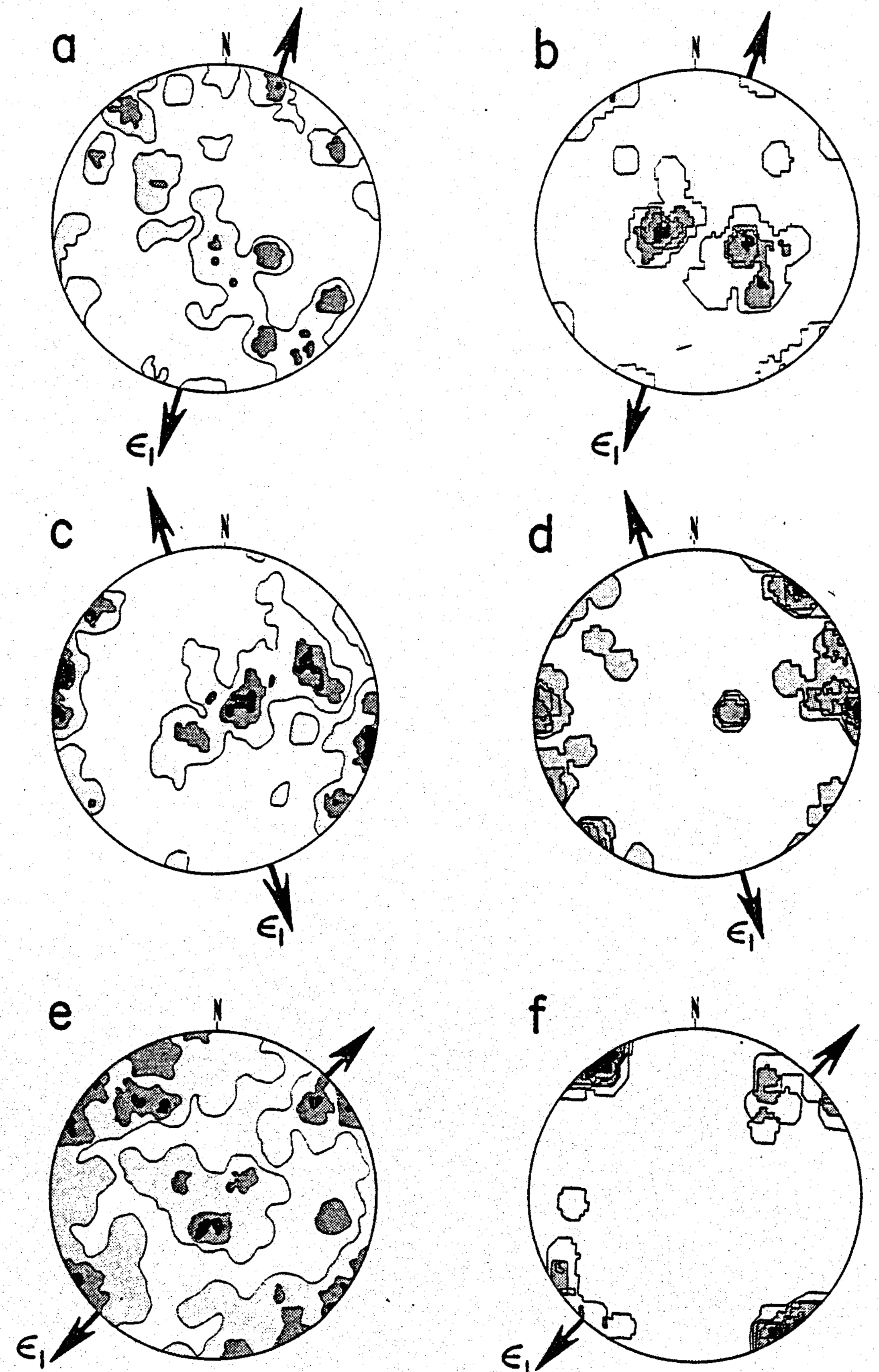
b. Stereographic projection of poles to 50 joint planes at site GR. Contour intervals 1, 4, 8, 12, 16, max 18 percent per area.

c. Stereographic projection of poles to 111 microfractures in test core SF1. Contour intervals 1, 2, 3, 4, 5, max 7 percent per area.

d. Stereographic projection of poles to 36 joint planes at site SF. Contour intervals 1, 4, 8, 12, 16, max 19 percent per area.

e. Stereographic projection of poles to 99 microfractures in test core MM. Contour intervals 1, 2, 3, 4, 5, max 6 percent per area.

f. Stereographic projection of poles to 25 joint planes at site MM. Contour intervals 1, 5, 19, 15, 20, max 28 percent per area.


a
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e
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<u>Comments on Surficial Strain-Relief Techniques</u>

Results of in-situ strain relief measurements in the Mineral Mountains have led to several conclusions about the general usefulness of the technique and the success of its application to the Roosevelt KGRA.

First, empirical use of results from surficial strain relief tests has limitations. There has been success in predicting the orientations of hydrofractures where only one strong structural trend was present (Overbey and Rough, 1971). It has been demonstrated that most rocks in the central Mineral Mountains have two, nearly orthogonal, preferred weakness planes represented at the surface by joints. In-situ strain relief tests have mapped out both trends. From surficial tests alone there is no way to predict which plane of weakness an induced fracture would follow. Strain relief tests conducted on oriented core from wells should prove more definitive than surface techniques.

No prediction of hydrofracture orientation will be attempted from the strain relief tests because of the location of test sites. Outcrop characteristics forced the choice of sites outside of the KGRA. Structural strends at these sites were atypical of the KGRA as a whole. Smith and others (1976) showed that strain relief measurements cannot be extrapolated from one structural domain to another and that hydrofracture orientation will not remain constant between domains.

It is difficult to imagine how overcoring of strain gauge rosettes at the earth's surface can measure an applied tectonic or gravitational stress. Most outcrops contain some sort of detachment planes (joints, bedding, etc.) which decouple the rock from the applied stress field. All strains measured in this and probably in other surficial tests must be residual. The good correlation between the results of surface tests and deeper hydrofracture experiments (Overbey and Rough, 1971) (Smith and others, 1976) does not indicate that the surface outcrops are influenced by the same stress field as at depth as claimed by Greiner and Illies (1977). It demonstrates rather that rocks at hydrofracture depths maintain the same anisotropies in strength that are present at the surface and that anisotropies more strongly control measured stresses than the ambient stress field.

Last, neither the release of residual elastic stress (Friedman, 1972), nor the permanent opening of microfractures (Nichols, 1975) is a universally suitable mechanism for explaining the mechanics of strain relief. Residual elastic strain has been discredited on theoretical grounds (Tullis, 1977), and by experimental results (Greiner and Illies, 1977; Engelder and others, 1977). We propose that the exact mechanism of strain relief will not be understood until a detailed study at microscopic and submicroscopic scales is conducted.

APPENDIX A

CHARACTERISTICS OF JOINTS IN STUDY DOMAINS ONE THROUGH NINE.

Joints of Domain 1

Fracture set	1	2	3
Orientation	marble N70-80W 59-72N pluton N70-79E 48-56N	marble N43-85W 17-31S pluton N31-61W 18-26S	not common
Density	1 per .1-3m	1 per .1-1m	
Cemented/Open	cemented by calcite	open	
Hydrothermal alteration on surface	none	none	
Genesis	extension	extension	

Joints of Domain 2

Fracture set	1	2	3
Orientation	N80-90W 81-90S	N15-27W 73-90W	N8-25E 17-21W
Density	1 per .02-.5m	1 per .02-.5m	1 per .5-1m
Cemented/Open	open	open	open
Hydrothermal alteration on surface	few with alteration	few with alteration	none
Genesis	extension	extension	extension

Joints of Domain 3

Fracture set	1	2	3
Orientation	N74W-N87E 82S-74N	N61-63W 75-90N	N12W-N37E 32-55W
Density	1 per 1-30m	1 per 1-30m	1 per .01-1m
Cemented/Open	open	open	most tightly sealed
Hydrothermal alteration on surfaces	none	none	some altered
Genesis	extension	extension	shear

Joints of Domain 4

Fracture Set	1	2	3
Orientation	N4W-N9E 21-25W	N68E-N32W 36-51S	
Density	1 per .1-.2m	1 per .1.5m	
Cemented/Open	most open	most tightly sealed	
Hydrothermal alteration on surfaces	present on all	present on all	
Genesis	shear	shear	

Joints of Domain 5

Fracture set	1	2	3
Orientation	N59-61W 85-89S	N10-26E 32-45W	N2-10W 77-90W
Density	1 per 1-5m	1 per .1-1m	1 per .1-.5m
Cemented/Open	open	most open	open
Hydrothermal alteration on surfaces	present on scme	present on some	present on some
Genesis	extension	shear	extension

Joints of Domain 6

Fracture set	1	2	3
Orientation	N60-70W 78-88S	N0-53E 10-27W	N17-27E 65-78W
Density	1 per 1-1.5m	irregular	irregular
Cemented Open	open	most open	open
Hydrothermal alteration on surfaces	none	present on some	none
Genesis	extension	no field evidence	extension

Joints of Domain 7

Fracture set	1	2	3
Orientation	N81-83W 84-86S	N4-6W 86-90W	N17-21E 49-53W
Density	1 per .02-2m	1 per .01-2m	1 per .01-.5m
Cemented/Open	most open	open	cemented with hematite or mylonite
Hydrothermal alteration on surfaces	present on some	present on some	present on most
Genesis	extension	extension	shear

Joints of Domain 8

Fracture set	1	2	3
Orientation	N77-86W 84S-84N	N1E-N8W 78E-82W	N18-20W 47-51W
Density	1 per .1-.5m	1 per .1-.5m	1 per .1-.5m
Cemented/Open	open	open	open
Hydrothermal alteration on surfaces	none	none	none
Genesis	extension	extension	no field evidence

Joints of Domain 9

Fracture set	1	2	3
Orientation	N78-87E 84-88S	N9W-N7E 82E-80E	N43-55W 49-59W
Density	1 per .1-1m	1 per .1-1m	1 per .5-1m
Cemented/Open	open	open	open
Hydrothermal alteration on surfaces	present on some	present on some	none
Genesis	extension	extension	no field evidence

APPENDIX B

STRAIN RELIEF TEST SITE LOCATIONS AND DESCRIPTIONS.

Site GR

Site GR is located along the eastern margin of the Mineral Mountains near a quarry in the SE 1/4 of the NW 1/4 of Section 20, T28S R8W. Measurements were taken on a hilltop outcrop of fine grained, leucocratic granite. Jointing at the outcrop consists of two shallow dipping sets, N20E-N13W 13-21E and N3-19E 21-31W, which have undergone some shear displacement. A few widely spaced steeply dipping extension joints form open, released surfaces around the outcrops cored. Outcrop and joint patterns are shown in Figure 13. Measurements 1 and 2 were taken from the large flat outcrop to the left of the tree; while measurements 3 and 4 were taken from the outcrop to the right.

Site MM

Site MM is located just west of Kirk Canyon in the SE 1/4 of the SW 1/4 of Section 72, T27S R9W. The measurement was taken on a hillside block of fine grained hornblende gneiss. Metamorphic foliation in the rock is vertical, striking N61E. Jointing at the outcrop consists of two orthogonal extension joint sets, oriented N45-59E 82S-80N and N50-60E 88S-80N. Joint spacing ranges from 0.5 to 1 meter. The outcrop tested and joint patterns are shown in Figure 14.

Site SF

Site SF is located south of Wild Horse Canyon in the SE 1/4 of the NE 1/4 of Section 28, T27SR9W. Measurements were taken from a hillside block of fine grained banded gneiss. The main foliation in the gneiss is folded. Jointing at the outcrop consists of two steeply dipping sets, N46-52W 84-90S and N3W-N83 81E-81W, and a shallowly west dipping set N22W-N28E 9-14W. The outcrop is cut by an approximately 15 cm thick quartz-feldspar vein trending N24W 57E through the measured outcrop. The outcrop tested and joint patterns are illustrated in Figure 15. Measurement 1 was taken from the far left borehole, measurement 2 from the far right borehole, and measurement 3 from the middle.

Site CD

Site CD is located along the northwestern flank of the Mineral Mountains in the SW 1/4 of the NW 1/4 of Section 23, T26S R9W. Measurements were taken from a ridgetop block in a vertical aplitic dike trending N15E. Two sets of extension points are present at the outcrop, N16W-N4E 70-90S and N18-74E 12-30W. The block is totally detached on a shallowly west dipping joint oriented N45E 25 W. The block measured and joint patterns are shown in Figure 16. Measurement number 1 was taken in the borehole to the right, and measurement number 2 in the left.

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