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TRACING CRUSTAL ISOTHERMS UNDER THE WESTERN MARGIN OF THE JEMEZ MOUNTAINS USING SAGE AND INDUSTRY MAGNETOTELLURIC DATA

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Abstract—The Jemez volcanic field in northern New Mexico is a natural laboratory to study the magnetotelluric (MT) response of sharply-varying, subsurface temperatures across a continental magmatic system. Over 60 geothermal wells provide unusually complete subsurface temperature data. Deep boreholes document that the 300°C isotherm occurs at only 2.0 to 4.5 km depth across the western margin of the Valles caldera. Precambrian basement is present at these depths and is highly resistive (>1000 ohm-m) outside the caldera. However, inversion of MT data maps a deeper (>10 km), upper crustal conductive zone with a geometry that closely matches the pattern of projected isotherms. This change must occur in the ductile portion of the crust since the temperature would be over 450°C. A mechanism that can explain this conductive occurrence is intergranular aqueous fluid connectivity at porosities of less than 1%. The interconnectivity is controlled by the dihedral angle, or the angle subtended by fluid-filled, grain-edge intersections. Experimental results predict water connectivity coincident with an isotherm in a ductile crust under an overlying impermeable cap. The positive correlation between the depth of the upper crustal conductive zone and projected isotherms may have profound rheological implications since aqueous connectivity would result in higher strain rates. Thus, tracing this zone could contribute greatly to understanding of contemporary deformation in the Rio Grande rift.

INTRODUCTION

SAGE (Summer of Applied Geophysical Experience) has accumulated geophysical data in the Rio Grande region of northern New Mexico since 1983. Included in these data are over 40 magnetotelluric (MT) soundings. MT is the recording and study of the natural, time-varying electric and magnetic fields at the surface of the earth. The objective of MT is to derive the geoelectric section (or structure) of the earth and relate it to the geologic structure, tectonics, and subsurface conditions. Recent SAGE MT modeling has emphasized the western margin of the Valles caldera in the Jemez Mountains. This region is a natural laboratory to study the response of MT to subsurface temperature changes because major variations are confirmed by extensive geothermal drilling. The SAGE MT modeling has been extended by the inclusion of MT data collected by Unocal in 1983 for geothermal exploration in the Valles caldera. This study includes only 4 of the 31 Unocal soundings; continued modeling of these data is currently in progress, therefore, this contribution is a preliminary result.

SUBSURFACE THERMAL AND GEOLOGIC DATA

The Jemez volcanic field is the most extensively studied young caldera complex in the U.S., with over 60 geothermal wells providing information to depths as great as 4.5 km (Goff et al., 1989, 1992). Measurements in the boreholes were used to prepare a temperature gradient map for the upper 1 km of the area (Figure 1; Sass and Morgan, 1988). The contours in Figure 1 clearly show that the subsurface temperatures are not symmetric in the Valles caldera but instead are strongly enhanced along its western margin. The changes in shallow temperature gradient from 150°C/

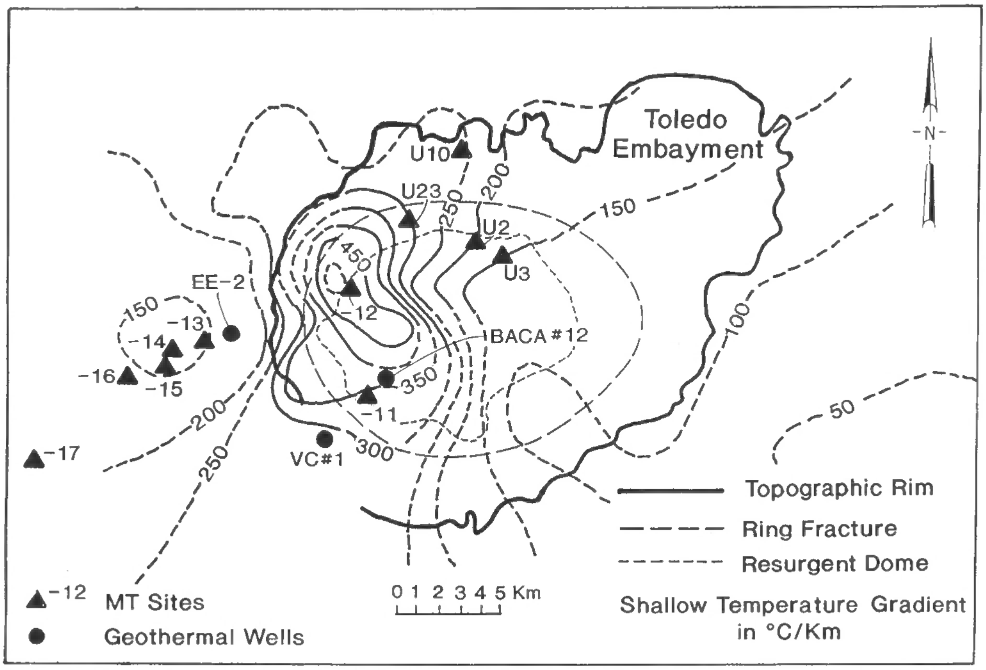


FIGURE 1. Map of temperature gradients in the upper 1 km in the Valles caldera region (after Sass and Morgan, 1988) and locations of SAGE MT sites -11 through -17 and Unocal sites 2, 3, 10 and 23.

km to 450°C/km over a distance of less than 10 km (Fig. 1) provide a unique environment to study the effects of in situ temperature. Temperatures below 1 km reflect the shallower patterns although fewer data points (deep drill holes) are available (Fig. 2). However, these wells document temperatures in excess of 300°C at depths of 2.0 to 4.5 km across the southwestern margin of the Valles caldera (Fig. 2). These deep wells, EE-2, VC #1, and BACA #12, were drilled as part of the Los Alamos National Laboratory's Hot Dry Rock (HDR) Project, the Department of Energy's Continental Scientific Drilling Program, and Unocal's geothermal exploration, respectively. The isotherms sketched in Figure 2 sharply dip down to the west, reflecting a cooler thermal regime west of the caldera. The depths of the measured 200°C and 300°C values in EE-2 yield a deep temperature gradient in the well of 90°C/km. This gradient is nearly equal to the background gradient of 100°C/km estimated beneath the Valles caldera by Swanberg and Li (1982).

Besides the unusually complete thermal data across the western margin of the Valles caldera, the wells also constrain subsurface geologic structures (Fig. 2). The major pattern is that of a dramatic shallowing of the Precambrian basement to the west from 3101 m depth at Baca #12 to 730 m depth at EE-2 (Goff et al., 1989). The Precambrian rocks range from unaltered to hydrothermally altered granitic rocks, gneisses, and schists. From a geophysical (MT) perspective it is reasonable to consider the upper crust below the basement to be nearly homogeneous in composition with sharply varying temperatures. Such temperatures are normally encountered in the deeper crust; since they occur in the shallow section, their signature can be better resolved by geophysical measurements.

MAGNETOTELLURIC SOUNDINGS

MT soundings were made in the Jemez Mountains in the late 1970s before the current generation of MT instruments employing remote reference, robust data processing, and improved electronics were available. Therefore, the results (Wilt et al., 1976; Hermance, 1979a) were of poor quality and of very limited value. Locations of 7 SAGE MT sites occupied in 1991-1993 and the 4 Unocal sites are shown in Figure 1. The data recorded at these sites are generally of excellent quality.

Remote reference MT recordings are made by measuring time-varying, vector electric and magnetic fields simultaneously at two sites usually 1-3 km apart. These results, after Fourier transform into frequency domain values, are used to compute tensor impedances (Vozoff, 1991; Jiracek et al., 1995). If the earth is two-dimensional (2-D), a simple rotation of the tensors provides impedance data in the 2-D strike direction and perpendicular to it. The rotated impedances can then used to derive apparent resistivity values in the two directions. The directions are designated TE (transverse electric) and TM (transverse magnetic) depending on whether the rotated electric field is in the strike direction or perpendicular to it, respectively. Such processing is often referred to as standard; another approach uses a distortion analysis (Groom and Bailey, 1989) to partially remove the effects of surficial three-dimensionality (3-D). This process extracts an estimate of the regional impedance (assumed to be 2-D) prior to standard processing. This approach was used on all SAGE MT data. The Unocal data were originally processed in the standard way and we have not completed the distortion analysis. However, four of the soundings do not show significant distortion and have been included in this study.

The average regional strike direction determined by distortion analysis was 5° east of north which is the approximate overall strike of the Rio Grande rift. Some SAGE soundings still displayed "static shifts" (Jiracek, 1990) after distortion analysis. The shifts were corrected by using auxiliary transient electromagnetic (TEM) data collected by SAGE. The Unocal soundings were selected to be free of such shifts.

Inversion of the resulting MT data was performed using the 2-D rapid relaxation method of Smith and Booker (1991), which produces a smooth, minimum structure version of the true geoelectric section. Data used in the inversion were the TM apparent resistivity and impedance phase results from the 11 sites located in Figure 1. Using the TM data is consistent with the conclusion by Wannamaker et al. (1984) that 3-D MT results identified as TM by standard analysis can be correctly modeled by 2-D algorithms in many (most) cases. Therefore, although the Valles caldera is clearly 3-D (e.g., features in Fig. 1) we expect valid 2-D inversion results. The distortion analysis and static shift corrections that we made also support this contention.

Figure 3 presents TM observed apparent resistivity data versus period (the reciprocal of frequency) compared to the inversion calculated results at three sites. These comparisons are representative of the inversion fits which are considered to be good. The three soundings are chosen to illustrate the marked variation of MT data across the western margin of the Valles caldera. Site U10 is in the caldera, MT-13 is just outside the caldera near the HDR drill site, and MT-17 is on the western edge of the volcanic rocks, nearly on the outcropping Precambrian core of the

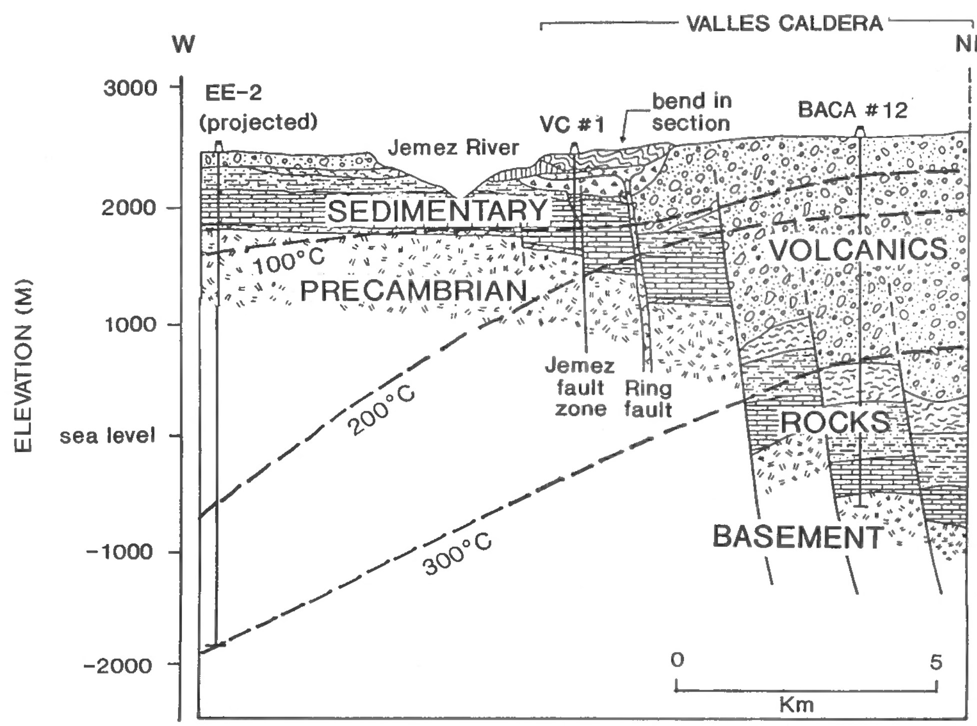


FIGURE 2. Cross section of simplified geology and smoothed isotherms across southwestern margin of Valles caldera (after Sass and Morgan, 1988).

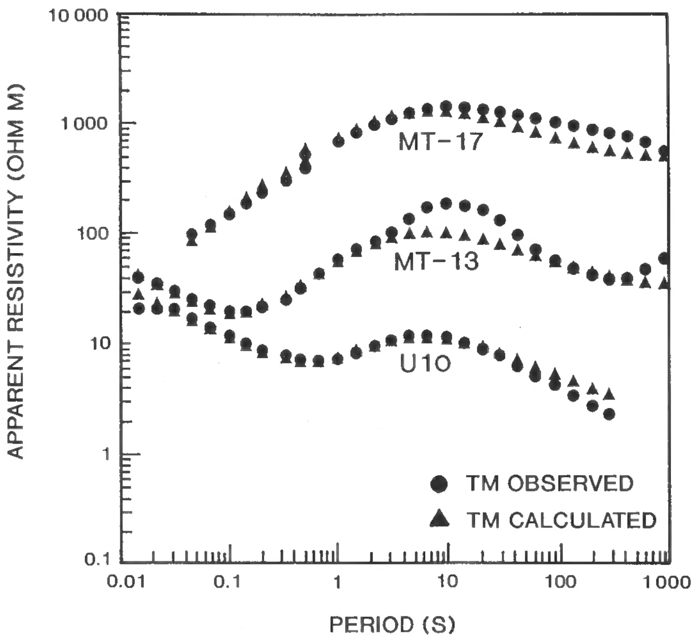


FIGURE 3. Observed and calculated TM apparent resistivity sounding data at MT sites U10, -13 and -17.

Nacimiento uplift west of the Jemez Mountains. The soundings clearly show that low resistivity (i.e., high conductivity) dominates the electrical nature of the crust under the caldera (U10 sounding) compared to the highly resistive section farther to the west at MT site MT-17. The uppermost resistivity at each site, as manifested by the apparent resistivities at the shortest periods, is about equal at 30 ohm-m. All three soundings also detect a significant decrease in resistivity at depth, which is evident by the descending branches of the sounding curves at periods higher than about 10 s. This important observation is quantified and its consequences are discussed in the following sections.

GEOELECTRIC SECTION

Figure 4 contains the inverted 2-D 25 km-long geoelectric section in the upper 5 km along a profile oriented (95° true) perpendicular to the average regional geoelectric strike. A clearly defined zone of low resistivity (<100 ohm-m) in the upper 1 km west of the caldera compares very well with the east dipping geometry of the depth to the Precambrian basement measured in the HDR boreholes (Fig. 2). The deeper resistive Precambrian rocks are mapped by resistivity values over 1000 ohm-m. Such values are expected for a dry crystalline rock. Under the caldera, the effects of hydrothermal fluids and conductive alteration products result in much lower resistivity (<100 ohm-m) in the same Precambrian rock. In an expansion of the geoelectric section to 40 km depth (Fig. 5), the section west of the caldera is dominated by a deep conductor (<1000 ohm-m) dipping down to the west. The precise depth to this conductive occurrence is not sharply resolved by the MT results; it is probably between the lower 1000 and 300 ohm-m contours. Most importantly, by comparison with the temperature contours in Figure 2, its shape is conformal with the shallower isotherms. Figure 2 also confirms that isotherms greater than 300°C must be present at these depths (>10 km). The observation that the depth to an upper crustal conductive zone has a striking correlation with isotherms projected from deep geothermal wells in the Jemez Mountains is a significant new result.

INTERPRETATION AND CONCLUSIONS

The only three possible sources for crustal conductive zones are water, magma, and conductive minerals such as graphite. Because graphite is much more conductive (~10^{-5} ohm-m; Duba and Shankland, 1982) than highly saline water (10^{-2} ohm-m minimum; Nesbitt, 1993), which is in turn more conductive than magma (about 0.5 ohm-m; Hermance, 1979b), much less graphite is required to produce a conductive zone.

Teleseismic studies suggest that magmatic partial melt is present in the depth range of 8 to 13 km (below sea level) beneath the Valles caldera (Lutter et al., 1995), but its horizontal range is only about 6 km. Forward computer modeling of such a body, assuming approximately 10% melt, show that MT measurements are insensitive to this target. Therefore, the deep conductive zone detected under the entire western portion of the Jemez Mountains must be much more extensive.

Temperatures below 10 km are above the critical temperature of 374°C for pure H_2O so the term *aqueous fluid* is preferred instead of water since liquid and gaseous H_2O are indistinguishable above the critical point. For aqueous fluid to accumulate in the crust there must be sources and a capping mechanism. Sources include deep circulating meteoric water, crustal devolatization by metamorphic reactions, and fluids released from mantle-derived magmas crystallizing higher up in the lithosphere. The magmatic volatiles are mainly H_2O and CO_2 (Wilson, 1989), the solubility of which decrease as the magma migrates upward. The fate of ascending volatiles depends on pressure, temperature, time, and whether crustal melting or retrograde metamorphism occurs (Thompson and

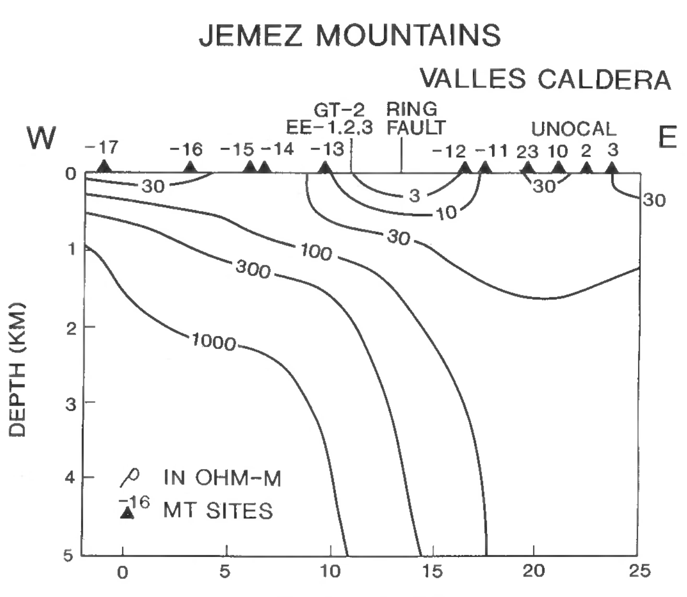


FIGURE 4. Smooth 2-D inverse 25 km-long geoelectric section across the western margin of the Valles caldera to a depth of 5 km.

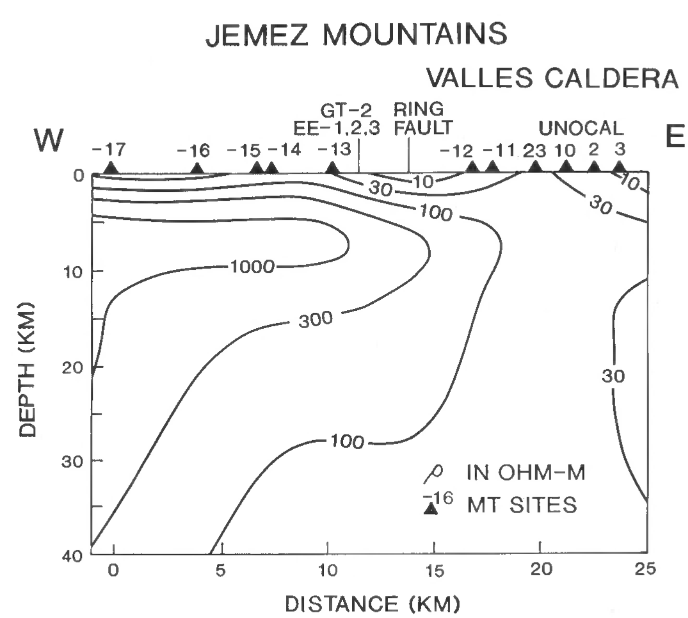


FIGURE 5. Smooth 2-D inverse 25 km-long geoelectric section across the western margin of the Valles caldera to a depth of 40 km.

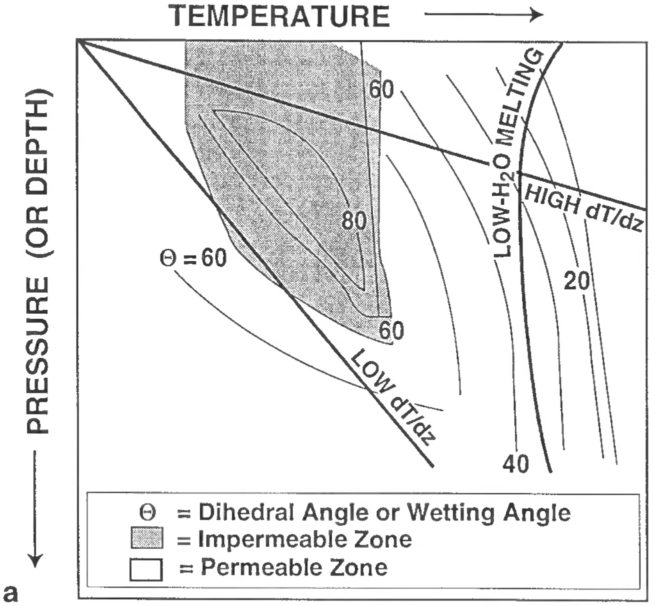
Connolly, 1990). H_2O is very soluble in granitic melts and retrograde metamorphism moves water into hydrated minerals, which are resistive (Olhoeft, 1981). A theoretical reason to expect trapping of free aqueous fluids in cracks at the brittle-ductile transition in the crust was presented by Bailey (1990). However, the temperatures measured in boreholes strongly dictate that the midcrustal conductive zone in the Jemez Mountains is deeper than the brittle-ductile transition, which would be at ~450°C (Sibson, 1984).

The question of whether graphite or other conductive minerals exist in the deep crust must also address the sources and accumulation processes (Hyndman et al., 1993). The source of graphite is usually thought to be from the reduction of CO_2-rich fluids. CO_2 itself is a nonconducting fluid. Even though the amount of graphite needed to produce a conductive zone is small, there must be a connected film (Katsube and Mareschal, 1993) on regional scales. Intergranular graphite films may explain low resistivities in a 10 km deep borehole in Germany (Jodicke, 1992; Haak et al., 1991) and in the deep Precambrian shield of Canada (Katsube and Mareschal, 1993). Duba et al. (1994) emphasized that a suite of conductive accessory minerals (ilmenite, magnetite, pyrite, pyrrhotite) including graphite was measured in the German drill cores. A graphite explanation is not usually invoked in conductive rift settings because a continuous supply of deep aqueous fluid is expected in an extensional environment. However, in rocks of identical bulk composition, including volatile components, the occurrence of graphite could be temperature controlled.

New experimental data (Holness, 1993, 1995; Fig. 6a) bear on the electrical properties of deep, low-porosity, crustal metamorphic rocks. They concern the interconnectivity of intergranular (not fracture controlled) aqueous fluid as a function of pressure and temperature *within* the ductile crustal environment. The dihedral angle or wetting angle (Brenan, 1991) is the angle subtended by intersecting grain walls at pore corners in a recrystallized rock (Fig. 6b). The values of dihedral angle define the 3-D continuity; therefore, interconnectivity of the grain-edge porosity. Interconnectivity can only exist if the angle is less than a critical value of about 60° for 1% porosity (Hyndman, 1988). Complete grain-edge wetting is achieved at 0° dihedral angle. Holness' (1993) results are for a pure quartz-H_2O equilibrium system where the wet melting temperature is about 1100°C. The melting temperature is less when feldspar is added (Holness, 1995); it would be near 650°C for a wet crust of granitic composition (Wyllie, 1971). Therefore, actual pressure and temperature values have been omitted in Figure 6a since we want to emphasize only the major features of the plot.

Two hypothesized geothermal gradients (Fig. 6a) illustrate that two regions of fluid connectivity may exist in the crust under an impermeable cap where $\theta>60°$. For a high geothermal gradient as found in the Jemez Mountains, fluid interconnectivity would occur at a near constant temperature approaching the rock melting curve. The known borehole temperatures (Fig. 2) and the estimated depth to the conductive zone from Figure 5 (>10 km) leads us to believe that the conductive zone occurs below the brittle-ductile transition (~450°C in a quartzo-feldspathic crust; Sibson, 1984). The dihedral angle considerations in Figure 6a dictate that the depth to the conductive zone would be an isotherm.

Watson and Brenan (1987) suggested that it is tempting to conclude that the dihedral angle-controlled fluid distributions apply to any conditions in the Earth where recrystallization has occurred, i.e., any pressure-temperature condition above the lowest metamorphic grade. For the fluid distribution to be dominated by equilibrium wetting, the rock must respond to stress in a ductile way rather than in a brittle manner. It is clear from many experimental results (e.g., Cooper and Kohlstedt, 1986) that a connected fluid phase decreases the strength of the rock and enhances the strain rate. The strength of the crust has the general profile depicted in Figure 7 but several interdependent factors (Sibson, 1984) can perturbate it. In the ductile portion of the crust an increase in the geothermal gradient, water content, or quartz content will decrease the strength and the brittle-ductile transition will migrate upward. More locally, a zone of interconnected water within the ductile region would facilitate increased pressure-solution creep, which enhances the rate of diffusional creep. This effect is large where grain wetting occurs in olivine-basalt partial melts (Cooper and Kohlstedt, 1986) and it also is expected to be true for aqueous fluid wetting. The process involves the diffusion of dissolved minerals along grain boundaries from regions of higher stress (at asperities) where the solubility is high to regions of low stress where the solubility is low. Therefore, fluid interconnectivity is of utmost importance.



a

b

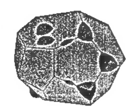
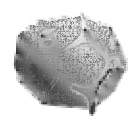
SCHEMATIC SINGLE GRAIN WATER DISTRIBUTION	DEEP CRUSTAL PROPERTIES		
	WATER	ELECTRICAL	RHEOLOGICAL
 Θ ≳ 60°	ISOLATED	RESISTIVE	LOW STRAIN RATE
 Θ ≲ 60°	CONNECTED	CONDUCTIVE	HIGH STRAIN RATE

FIGURE 6. **a**, Schematic pressure, temperature, dihedral angle plot for crustal conditions. Pattern of dihedral angle contours follows those of quartzite-H_2O system presented by Holness (1993). Shaded region is where aqueous fluids reside in isolated pores and the rock is impermeable to fluid flow ($\theta \geq 60°$). At dihedral angles $\theta<60°$ the rock has an interconnected fluid phase and is permeable to grain-edge fluid flow. High and low dT/dz geothermal gradients illustrate situations where interconnected aqueous fluid would be trapped beneath an impermeable cap (shaded region). Notice that for various values of high dT/dz the depth to the trapped fluid would vary but the temperature would be nearly constant, following an isotherm. **b**, Schematic single grain aqueous fluid distribution as a function of value of dihedral angle (60° ≤′θ60°), and implications in deep crustal metamorphic rocks.

We believe the correlation of the depth to the crustal conductive zone and the projected levels of isotherms across the western margin of the Valles caldera argues in favor of a dihedral angle wetting mechanism. The connection of the latter with rheology as outlined above, therefore, suggests that the mapping of deep conductive zones may be an indirect measurement of strain levels in the crust (Fig. 6b).

These considerations dictate that the conductive zone under the Jemez Mountains marks the depth at which saline aqueous fluid, perhaps of only 1% concentration, occurs as an interconnected film. This would be a zone where higher tectonic strain occurs as a function of time. The tracing of such a zone could greatly contribute to our understanding of contemporary deformation in the Rio Grande rift, including relations to faulting and the occurrence of earthquakes.

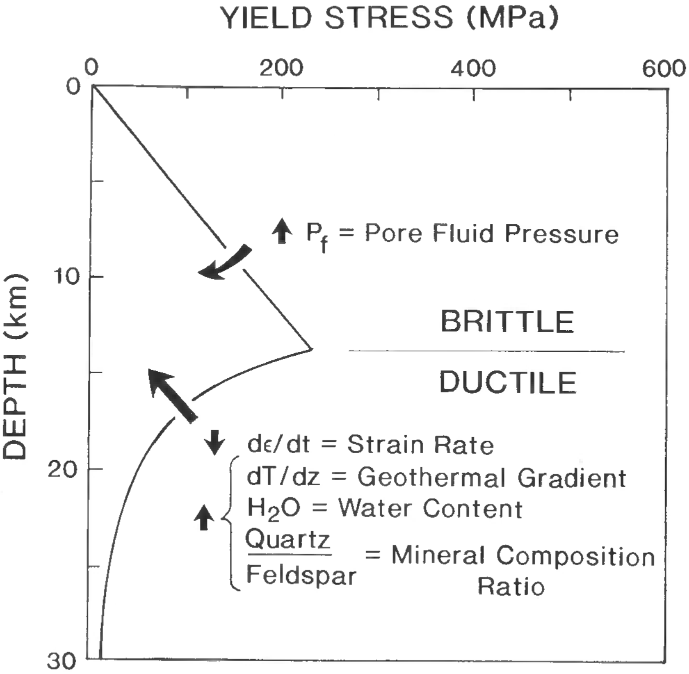


FIGURE 7. Synoptic diagram of crustal rheological behavior showing the effects of increasing pore fluid in the brittle regime and increasing strain rate, geothermal gradient, water content, quartz/feldspar ratio and decreasing strain rate in the ductile portion of the crust (redrawn from Sibson, 1984).

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