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Interaction of Shallow and Deep Geothermal Reservoirs at Coso, Eastern California, as Inferred from 3-D Seismic Velocity Models and Seismicity

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ABSTRACT

We inverted P and S-P arrival times from 11,500 earthquakes that occurred in central eastern California, to determine the 3-D Vp and Vp/Vs velocity structures to depths of 25 km. The abundant seismicity is scattered across the region with spatial clusters along the crest of the Sierra Nevada and in the Indian Wells Valley and Coso region. The seismicity appears to be related to broad regional crustal extension superimposed on right lateral shear as well as localized movement of crustal fluids in the Coso area. Layered zones of both high and low Vp, Vs, and Vp/Vs are present beneath the Coso area. These zones consists of the geothermal area at 0 to 3 km depth, a zone of 4-6% geothermal fluids of H_2O extending from 6 to 11 km depth, and a possible magma chamber in the depth range of 11 to 16 km. The abundant seismicity in the 2 to 8 km depth range may be induced by fluid flow between the deeper geothermal reservoir and the surface geothermal area. The presence of a capped geothermal H_2O zone and a deeper magma chamber possibly feeding small successively shallower chambers, suggests two different sources providing heat to the surface geothermal area.

Introduction

As the Sierran microplate moves to the northwest, a 100-km-wide zone of crustal deformation is formed along its eastern margin (Argus and Gordon, 1991; Monastero et al., 2002, and Unruh et al., 2002). Our study area that includes the southern part of the Sierra Nevada and southwestern most part of the Basin and Range Province crosses this zone of crustal deformation, where the southeastern boundary of the Basin and Range and the Sierran microplate meet (Figure 1).

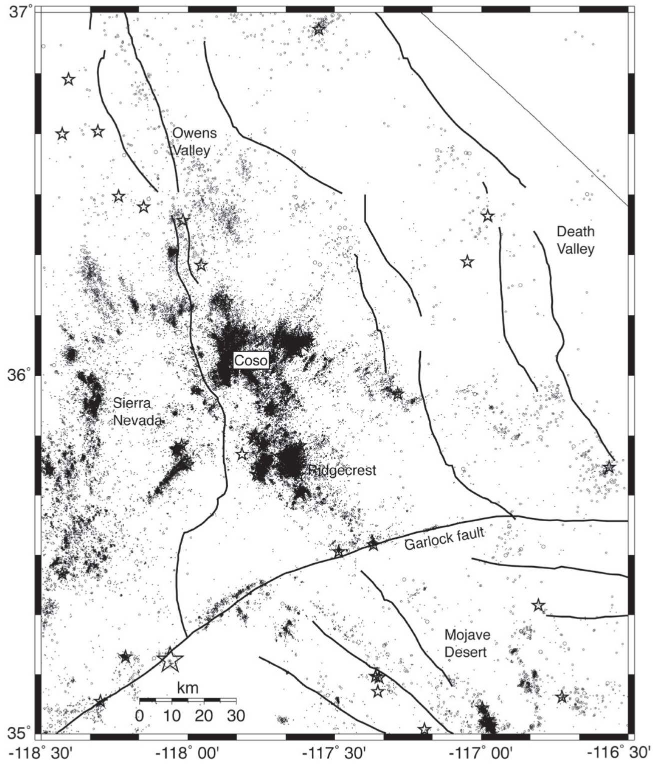

Figure 1. Map of eastern California showing seismicity from 1981 to 2002 and major late Quaternary faults. The Coso study area is indicated by the box labeled "Coso".

The tectonic strain rates in the region are moderate and are insufficient to explain the ongoing abundant microseismcity, in particular at Coso. Although 23 years of seismicity exhibits a broad distribution extending from the southern Sierra in the west to the Panamint Mountains in the east, the seismicity is both spatially and temporally clustered. The apparent broad distribution of seismicity suggest that strain is not being concentrated along major faults, but rather is being absorbed regionally along many poorly developed faults. This seismic behavior may be related to fluid flow, formation of new faults, the loss of potential energy resulting from the high topography, or the change in crustal thickness from both changes in topography and depth to Moho. In particular, the concentration of seismicity near Coso suggests a different causal stress field than the stress field driving the regional extension. Previous studies of the Coso area have also suggested a relationship between the geothermal activity and seismicity (Walter and Weaver, 1980).

In this study we analyze the regional earthquake data to determine the 3-D Vp and Vp/Vs velocity structure, and to improve earthquake hypocenters and focal mechanisms in the study region. We use the method of Thurber (1993) and the detailed approach described in Hauksson (2000) to invert for the regional velocity structure. The P and S arrival times and cross-correlation differential travel times were also input into the double-difference program of Waldhauser and Ellsworth (2000) to further refine the hypocenters in the study area.

Previously Walck and Clayton (1987) detected a low Vp zone in the depth range of 5 to 10 km at the southern end of the Coso range. Walck (1988) found a systematic decrease in Vp/Vs with depth beneath the Coso area. Both of these studies were limited to the depth range from the surface to 10 km depth.

Using more recent seismicity (1981-2002) and methods, we determine the regional velocity structure and refine the hypocenters to understand how the structure may play a role in shaping the spatial and temporal character of the abundant regional seismicity. In particular, we are interested in examining to depths of 20 to 25 km and to compare our results to other studies such as Wilson et al. (2003) who use mostly vertical rays from teleseisms.

Results: Separating H_2O and Magma Beneath Coso

Numerous previous studies have shown that magma exists beneath the Coso geothermal area. For instance, Wilson et al. (2003) used teleseismic receiver functions from the Coso area to show that a magma chamber exists in the 5-to-15 km depth range, below sea level. However, they found two observations, a positive crustal discontinuity at 15 km depth and a flat Moho beneath the Coso region, which were hard to explain without an additional upper mantle magma source zone.

We find anomalous structure in Vp, Vs, Vp/Vs, and Poisson's ratio beneath Coso (Figure 2). The Vp model shows a spherical low Vp of 5.8 km/s in the depth range of 6 to 16 km, almost centered on the Coso geothermal field. This Vp low of 5.8 km/s is embedded in mid crustal rocks of Vp of 6.0 km/s. The Vs shows a similarly shaped low of Vs of 3.4 km/s, with an additional low of Vs of 3.5 km/s that is elongated for 11 to 16 km to the northwest. When these two lows are superimposed as Vp/Vs two anomalies can be identified. First, a flattened anomaly in the depth range of 6 to 11 km of low Vp/Vs elongated to the southwest is imaged. Second, a deeper anomaly, 11 to 16 km, of high Vp/Vs elongated to the northwest is imaged.

These observations are also shown in Figure 3 as the depth distribution of the Poisson's ratio. The geothermal field is imaged as low Poisson's ratio extending from the surface to 3 km. The low Poisson's ratio suggests the absence of mafic rocks or magma (Christensen, 1996). Most of the relocated seismicity occurs below the 3 km depth of the geothermal field. The depth range of 2-to-8 km exhibits a high level of seismicity. The region from 6 - 11 km depth is characterized by low Vp, Vp/Vs and Poisson's ratio, suggesting the existence of H_2O rather than magma, when using relations from Nakajima et al. (2001). Nakajima et al. (2001) argued that low Vp/Vs suggested the presence of H_2O, because Vp is reduced proportionally more than Vs when the stiffness of the rock matrix is reduced by the presence of water saturate cracks. The presence of seismicity within this region is also consistent with the region being brittle. The region from 11 - 16 km depth of low Vp, high Vp/Vs, and high Poisson's ratio suggest 2% to 5% fraction of volume of magma (Nakajima et al, 2001). In this depth range the Vs is reduced proportionally more than Vp as melt filled cracks slow down the S waves. Further, the virtual absence of seismicity in this deeper depth range is consistent with the presence of magma.

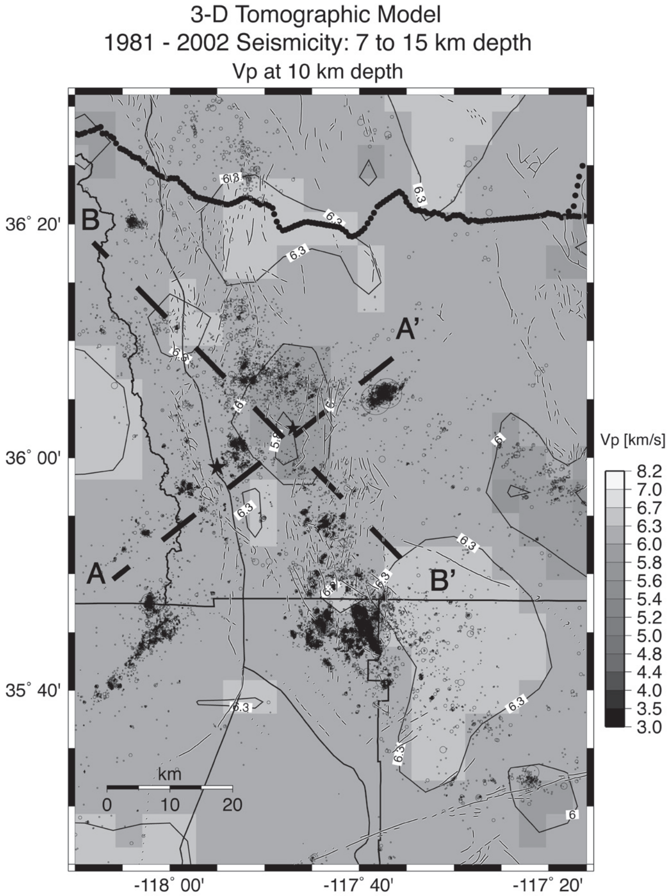

Figure 2. Map of Vp model in the Coso area at 10 km depth. The two thick dashed lines indicate the locations of the two cross sections shown in Figure 3. The irregular curve of filled circles to the north is the location of the refraction line shot by Ruppert et al (1998). The 1981-2002 seismicity in the depth range of 7 to 15 km is shown as black circles, whose size is proportional to magnitude. The location of the Coso geothermal area is indicated by the black star while the location of Red Hill volcano is indicated by a large black star to the southwest.

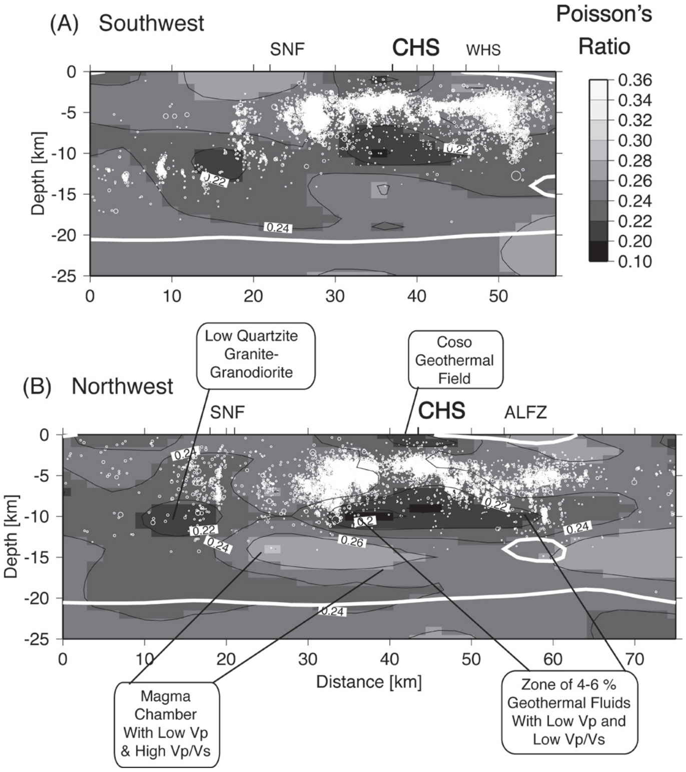

Figure 3. The Poisson's Ratio cross sections through Coso. Their location is shown in Figure 2. The magma chamber is interpreted to be at 10 to 15 km depth, a zone of 4-6% geothermal fluids at from 6 to 10 km depth and more elongated in shape, and the Coso geothermal area extending from depths of 2-3 km below sea level up to the surface.

The interpretation of this study are that the magma chamber is deeper, 11 - 16 km depth, than found in many other studies. The upper zones in 6 - 11 km and 0 - 3 km are both zones that contain geothermal fluids but are separated by an impermeable cap observed as strong seismic reflector (Wilson et al., 2003). The two geothermal fluid zones may only communicate through conduits provided by frequent earthquake swarms, possibly as a result of natural hydrofracturing in the depth range of 2 - 8 km. The most recent study of Wilson et al (2003) found an interface at 15 km where seismic velocities changed from high to low, which is consistent with our conclusions. They also found an upper crustal negative discontinuity at 4-5 km that suggested a decrease in Vs below the surface. Such a decrease is indeed imaged in this study as a decrease in Vp, Vs, and Vp/Vs.

The results of our study agree with Lees and Wu (2000) who found that the Poisson's ratio was below the crustal average of 0.25 or an average of 0.22 in the depth of surface to 3 km. They also found mostly low Vp/Vs in the near surface and concluded that the rocks are predominantly quartz-rich silicates. Lees and Wu (2000) however, were able to resolve small zones, with diameter on the order of 2 km, of higher Vp/Vs and Poisson's ratio, thus indicating larger crack density and more fluid flow.

Manley and Bacon (2000) analyzed the mineral composition and determined the thermobarometry for minerals in rhyolites in the Coso area. They studied rhyolites that erupted from both 10 km and 5 km depth. The younger rhyolites came from a shallower depth. Their results were consistent with one magma reservoir moving toward the surface or several shallower reservoirs. Such small shallow magma chambers may not exist today although they contributed to volcanisms in the past. We favor their interpretation of a large magma chamber extending from depth of 15 km up to 10 km. The magma chambers at 5 km depth that host younger rhyolites may be somewhat transient in nature or of smaller diameter (< 3 km) than would be resolved in this study. The presence of H_2O rich over pressurized geothermal fluids is also confirmed independently by Manley and Bacon (2000) using evidence from melt inclusions. They provide examples of 6.2 wt % total H_2O that were saturated at lithostatic pressures almost equivalent to 10 km of overburden. They also had other examples from the depth range of 5 to 10 km. Their findings thus are consistent with our interpretation of the velocity models and the possible magma chamber below 10 km and an over pressurized zone of high H_2O in the depth range of 5 to 10 km and the geothermal field at 0 to 3 km.

Acknowledgements

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