Active Faulting in the Coso Geothermal Field, Eastern California

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ABSTRACT

New mapping documents a series of late Quaternary NNE-striking normal faults in the central Coso Range that dip northwest, toward and into the main production area of the Coso geothermal field. The faults exhibit geomorphic features characteristic of Holocene activity, and locally are associated with fumaroles and hydothermal alteration. The active faults sole into or terminate against the brittle-ductile transition zone (BDT) at a depth of about 4 to 5 km. The BDT is arched upward over a volume of crust in the 5 to 15 km depth range beneath the Coso geothermal field that is characterized by high heat flow and low P-wave velocities, and which may contain magma and/or hot, lithostatically pressured brines. The positive relief on the BDT may guide or control the down-dip geometry of active faults. Brittle faulting and seismogenic deformation above the shallow BDT may contribute to development of permeability in the geothermal reservoir, and provide pathways for upward circulation of hydrothermal fluids.

Introduction

In this paper we present new mapping and seismotectonic analysis of active strike-slip and normal faults in the central Coso Range, eastern California (Figure 1). The structures documented in this paper are part of a system of active faults along the southeastern margin of the Sierra Nevada microplate, and they transfer dextral transtensional shear through the Coso geothermal field. We discuss the down-dip geometry of these structures, their intersection with the brittle-ductile transition zone, and implications for permeability and hydrothermal circulation in the geothermal field.

Tectonic and Structural Setting

The Coso Range is a tectonically and volcanically active region along the eastern margin of the Sierra Nevada ("Sierran") microplate, which moves about 13 mm/yr northwest with respect to stable North America (Argus and Gordon, 1991; 2001; Dixon et al., 1995; 2000). Northwest motion of the Sierran microplate is accommodated by distributed strike-slip and normal faulting in the Walker Lane belt (Figure 1, overleaf), a 100-km-wide zone of active deformation bordering the eastern Sierra Nevada (Unruh et al, 2003).

Active crustal extension in the Coso Range primarily is driven by a releasing transfer of dextral motion from the Airport Lake fault to the Owens Valley fault, two major right-lateral strike-slip faults that form the eastern tectonic boundaries of the Sierran microplate south and north, respectively, of the Coso Range (Figure 1) (Unruh et al., 2002; Monastero et al., 2005). In detail, the Airport Lake fault zone splits into several branches at the southern end of the step-over region (Figure 2, overleaf). An eastern branch, consisting of north- to NNE-striking normal faults in northeastern Indian Wells Valley, extends northward across eastern Coso Basin and into the southern end of Wild Horse Mesa, where it continues northward and forms a dramatic series of scarps in Pliocene volcanic flows. The faults with the largest scarps in Wild Horse Mesa exhibit a distinct left-stepping pattern (Figure 2). A central branch, consisting of a zone of short NNE-striking, left-stepping surface traces, crosses the White Hills south of Airport Lake playa and becomes the Coso Wash fault, which is characterized by a single trace along the southeastern flank of the Coso Range. A western branch of the Airport Lake fault zone crosses the southern Coso Range and joins the Little Lake fault zone in southern Rose Valley (Figure 2).

The Coso Wash Fault

The north-northeast-striking Coso Wash fault is the most proximal active fault to the geothermal field (Figure 2). Geo-

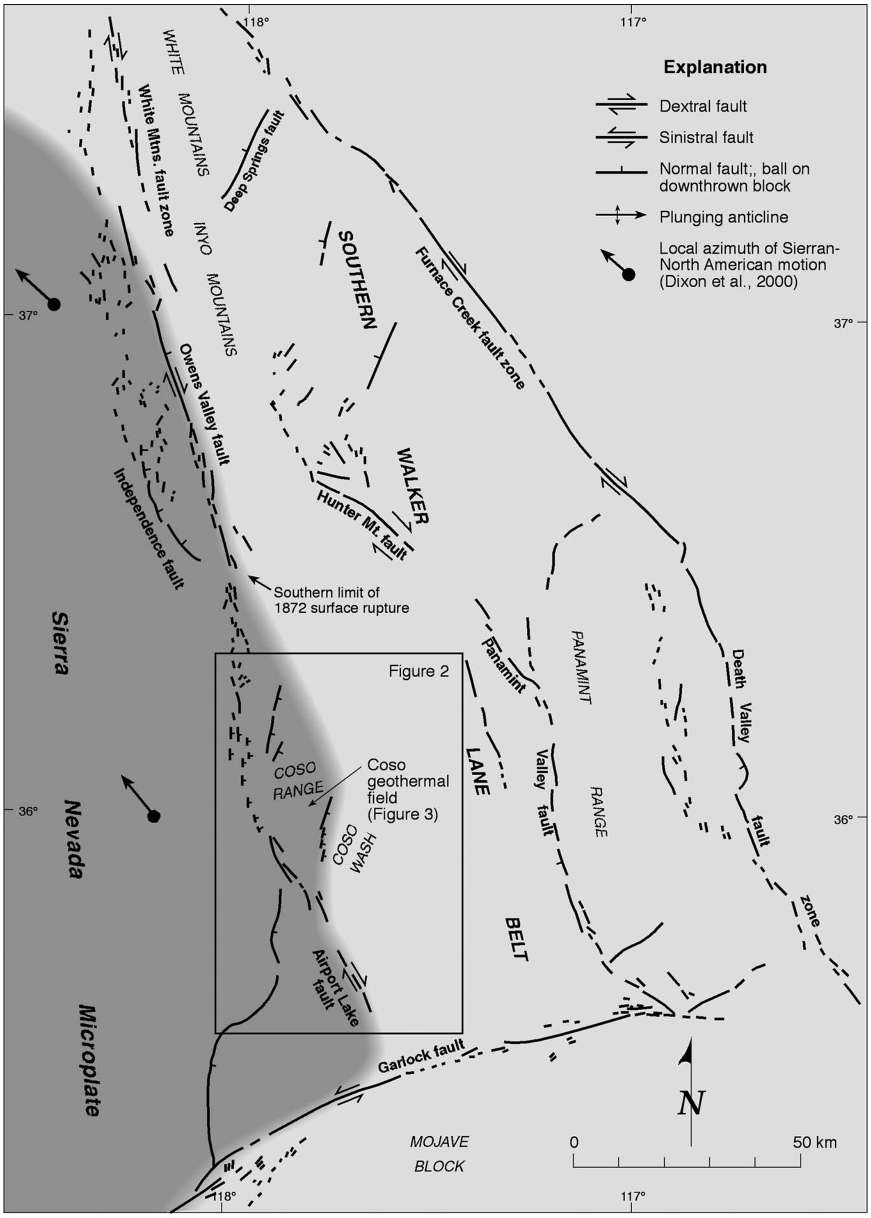

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Figure 1. Regional location map of the Coso Range and the southern Walker Lane belt. The extent of the rigid Sierra Nevada microplate is indicated by dark shading. Active faults in the southern Walker Lane belt from Jennings (1994).

detic data from the Coso Range indicate that this structure probably carries the largest proportion of total slip through the releasing stepover between the Airport Lake and Owens Valley fault zones (Monastero et al., 2005; Figure 1). The Coso Wash fault can be traced for about 9 km north of Airport Lake playa as a southeast-dipping fault that is well expressed by scarps in late Quaternary alluvial fan deposits. The fault along this reach consists of a series of alternating short NNE- and NW-striking segments that exhibit a left-stepping pattern (Figure 2).

At the southern end of the geothermal field, the vergence of the Coso Wash fault abruptly changes and it becomes a northwest-dipping fault zone (Figure 2). The active traces step northwest (left) from the western margin of Coso Wash into the bedrock of the Coso Range, and dip toward the main producing zones of the geothermal field at depth (Figure 3). The northwest-dipping fault segments are geomorphically well expressed by NW-facing scarps in bedrock and alluvium, and the faults locally pond alluvium in their down-dropped footwall blocks upstream of the scarps. Streams draining across the NW-dipping faults have pronounced nickpoints and are significantly more incised on their up-thrown sides. Some of the NNE-striking, NW-dipping normal faults are associated with active fumaroles (Figure 3).

At least one of the NW-dipping segments of the Coso Wash fault terminates to the northeast against a NW-trending bedrock feature mapped as a "tectonic breccia zone" by Whitmarsh (1997) ("TBZ" on Figure 3). This zone is marked by a prominent white tonal lineament on air photos, and is characterized by a several-meter-wide zone of sheared, comminuted and hydrothermally altered granite. The SE-dipping Coso Hot Springs segment of the Coso Wash fault lies northeast of the "tectonic breccia zone". The scarp and associated alteration zone along the Coso Hot Springs fault abruptly die out to the SW, but can be traced to within 10 m or less of the "tectonic breccia zone". We interpret the "tectonic breccia zone" to be a displacement transfer structure that accommodates the change in vergence between the NW-dipping segments of the Coso Wash fault within and adjacent to the geothermal field, and the SE-dipping Coso Hot Springs segment of the fault to the northeast. Fluvial deposits that cross the southern part of "tectonic breccia zone" are locally faulted and exhibit NE-facing scarps, indicating late Holocene north-down motion on this structure to accommodate slip on the Coso Hot Springs segment of the Coso Wash fault.

North of Coso Hot Springs, the Coso Wash fault dips consistently southeast and can be traced as a series of east-facing scarps in Holocene alluvium northward to the area around Haiwee Springs, where it dies out as a distinctive geomorphic feature (Figure 2). North of Haiwee Springs, Coso Wash terminates as a Quaternary basin and narrows to a steep canyon cut in the Cretaceous bedrock and Pliocene basalts of Wild Horse Mesa. Analysis of stereo aerial photography indicates that east-facing bedrock scarps and possibly fault-related east-facing bedrock slopes continue north of Haiwee Spring. These features probably represent a continuation of Quaternary faulting north of Coso Wash, as recognized by Walker and Whitmarsh (1998). The Coso Wash fault and the step-faulted terrain appear to merge north of Haiwee Springs, essentially combining the eastern and central branches of the Airport Lake fault zone, and the entire system terminates in a rhombic array of faults south of Upper Centennial Flat (Figure 2).

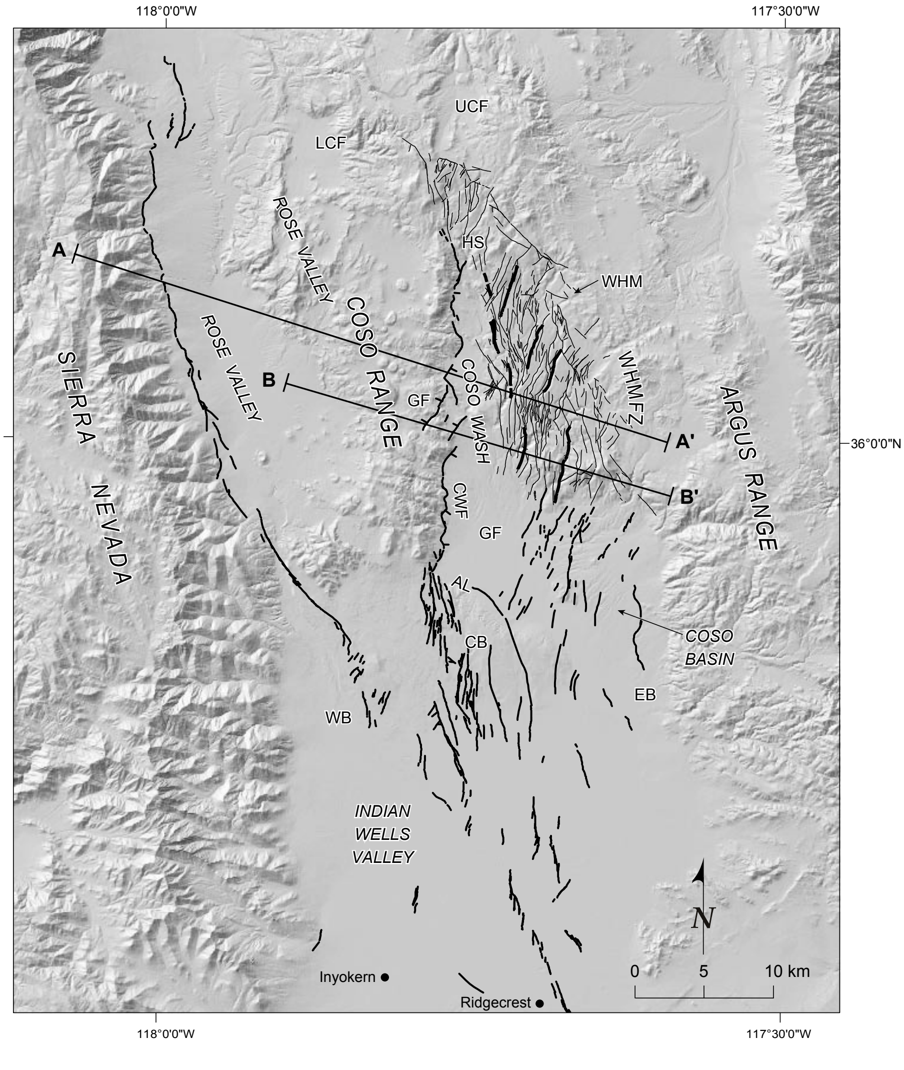

Figure 2. Northward branching of the Holocene-active Airport Lake fault zone (ALFZ) in northern Indian Wells Valley, Rose Valley, the Coso Range and Wild Horse Mesa. WB=Western branch; CB=Central branch; EB=Eastern branch; WHM = Wild Horse Mesa; WHMFZ = Wild Horse Mesa fault zone; CWF = Coso Wash fault; AL = Airport Lake playa; HS = Haiwee Spring; GF = geothermal field; UCF = Upper Cactus Flat; LCF = Lower Cactus Flat. Faults with prominent scarps in Wild Horse Mesa are highlighted in bold. Late Quaternary faults modified from Duffield and Bacon (1981) and Whitmarsh (1997), with additional original mapping. Locations of cross sections A-A′ (Figure 4) and B-B′ (Figure 5) shown.

The Brittle-Ductile Transition and Active Faults in the Geothermal Field

The segments of the Coso Wash fault south of Coso Hot Springs dip northwest toward the geothermal production area (Figure 3), which overlies a zone in the 5 to 15 km depth range that is characterized by elevated heat flow, low P-wave velocities, and anomalous attenuation of seismic energy (Reasenberg et al. 1980; Wilson et al., 2003). Several workers have interpreted the crust beneath the geothermal field to host a late Quaternary magma chamber (Reasenberg et al. 1980; Manley and Bacon, 2000; Wilson et al., 2003). Temperature gradients in the geothermal field determined from down-hole measurements range between about 85-120 C/km (Monastero and Unruh, 2002), implying that the temperature near the top of the inferred magma chamber ranges from 425 C to 600 C. This range exceeds the temperature at which quartz-rich rocks begin to deform by ductile flow in laboratory experiments (i.e, about 350 °C; Fournier, 1999) at strain rates of about 10^{-14} per second or lower, which characterizes the average secular deformation rates in the Coso range (Monastero et al., 2005). Based on these data, we infer that the transition from brittle deformation to ductile flow occurs at a depth of about 4 to 5 km beneath the geothermal field. If this is correct, then the brittle-ductile transition zone (BDT) must be arched upwards over the interpreted magma chamber beneath the central Coso Range. This interpretation is consistent with the marked shallowing of the base of seismicity from regional depths of about 10 km to as shallow as about 4.5 km beneath the central Coso Range (see Figure 7 in Monastero et al., 2005).

Given these relations, we infer that segments of the Coso Wash fault likely sole into or terminate at the BDT at shallow depths beneath the geothermal field. This relationship is illustrated in two cross-sections (Figures 4 and 5) that include hypocenters of small earthquakes recorded by the southern California seismic network, and which were relocated for this study.

Cross section A-A’ (Figure 4) extends from the Sierra Nevada on the west to Wild Horse Mesa on the east, and crosses the Coso Hot Springs area north of the geothermal field (Figure 2). The southeast-dipping Coso Hot Springs segment of the Coso Wash fault is interpreted to terminate against or sole into the east-sloping BDT east of the geothermal field. The faults of the eastern branch of the Airport Lake fault zone in Wild Horse Mesa also are interpreted to terminate against the BDT, and together with the Coso Hot Springs fault form a negative flower structure. The relocated hypocenters suggest the presence of blind east- or northeast-dipping seismogenic faults that terminate against the west-sloping BDT beneath the western Coso Range (Figure 4).

Cross section B-B’ (Figure 5) passes through the main production area southwest of Coso Hot Springs (Figure 2). At this latitude the active segments of the Coso Wash fault dip northwest (Figure 3), and we interpret that they terminate against or sole into the BDT as it slopes to the west beneath Rose Valley (Figure 5). The cluster of hypocenters beneath Rose Valley west of the geothermal field is associated with a blind, north-trending seismogenic fault zone. Focal mecha-

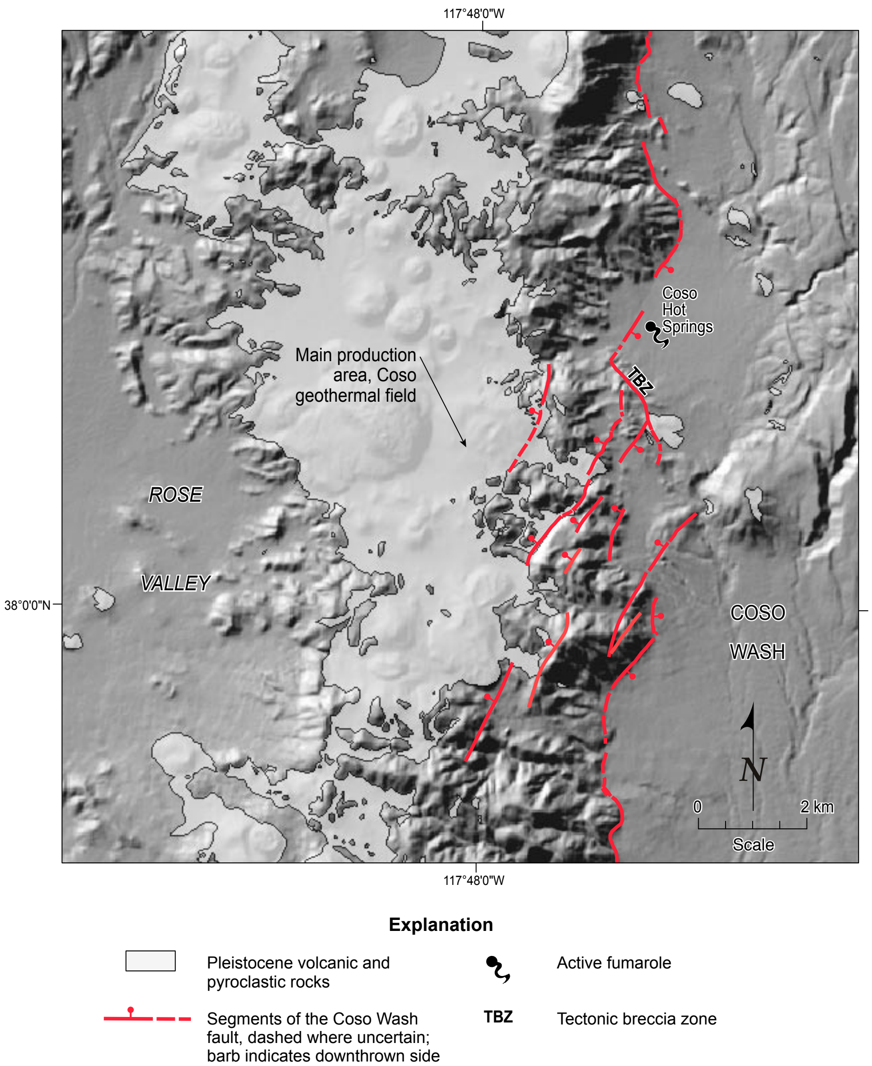

Figure 3. Map of the central Coso Range and the geothermal production area showing active surface traces of the Coso Wash fault. Note that the traces adjacent to the geothermal field dip northwest, toward and into the production area, whereas the traces to the north and south dip southeast beneath Coso Wash.

nisms from small earthquakes in this fault zone indicate primarily right-lateral slip.

Discussion

The majority of the seismicity in the upper 3 km beneath the geothermal field probably is related to production and injection of geothermal fluids, and thus is an indicator of where permeable zones are. Clusters of hypocenters in the upper 3 km beneath the main production area of the geothermal field on cross section B-B' are associated with down-dip continuations of the NW-dipping segments of the Coso Wash fault (Figure 5). We suggest that these structures contribute to permeability in the reservoir and provide pathways for upward circulation of geothermal fluids. Numerical modeling of the Coso Hot Springs area northeast of the geothermal field (Figure 3) by Person et al. (this volume) supports this hypothesis, and suggests that circular convection cells develop in the faulted, brittle crust above the BDT and interact with the Coso Wash fault zone to produce an upwelling plume.

The NW-dipping segments of the Coso Wash fault at the latitude of the main production area probably transfer active deformation to the blind seismogenic faults on the west side of the Coso Range shown in Figures 4 and 5, as well as other seismogenic structures in the northwestern Coso Range (Unruh et al., 2002). Geodetic data in Monastero et al. (2005) document that about 5 to 8 mm/yr of NW-directed dextral shear passes across the central Coso Range between Coso Basin and southern Coso Wash to the area between northern Rose Valley and Upper Centennial Flat (Figure 2). We interpret that the abrupt change in dip of the Coso Wash fault from southeast to northwest signals the transfer of deformation directly from Coso Wash across the geothermal production zone to the northwestern Coso Range, thus comprising part of the kinematic linkage between the dextral Airport Lake and Owens Valley fault zones (Figure 1).

Conclusions

New mapping of active faults in the central Coso Range has documented segments of the Coso Wash fault that dip northwest, towards and into the main production area of the geothermal field. The NW-dipping faults terminate downward against the BDT at about 4.5 km depth, which is arched upward over a crustal volume that may contain magma or lithostatically pressured brines. These relations recall a generalized model by Fournier (1999) for hydrothermal processes in magmatic-epithermal environments. In Fournier's model, emplacement of a magma body may locally elevate the BDT to shallow depths. The elevated BDT separates a hydrostatically pressured domain above, in which meteoric water is heated and flows convectively along permeable pathways, from a domain below that is effectively sealed by continuous ductile flow, and which transmits heat to the hydrostatic domain by conductive processes. In the case of the Coso geothermal field, permeability is likely enhanced if not created by active normal faults that accommodate distributed transtensional dextral shear .

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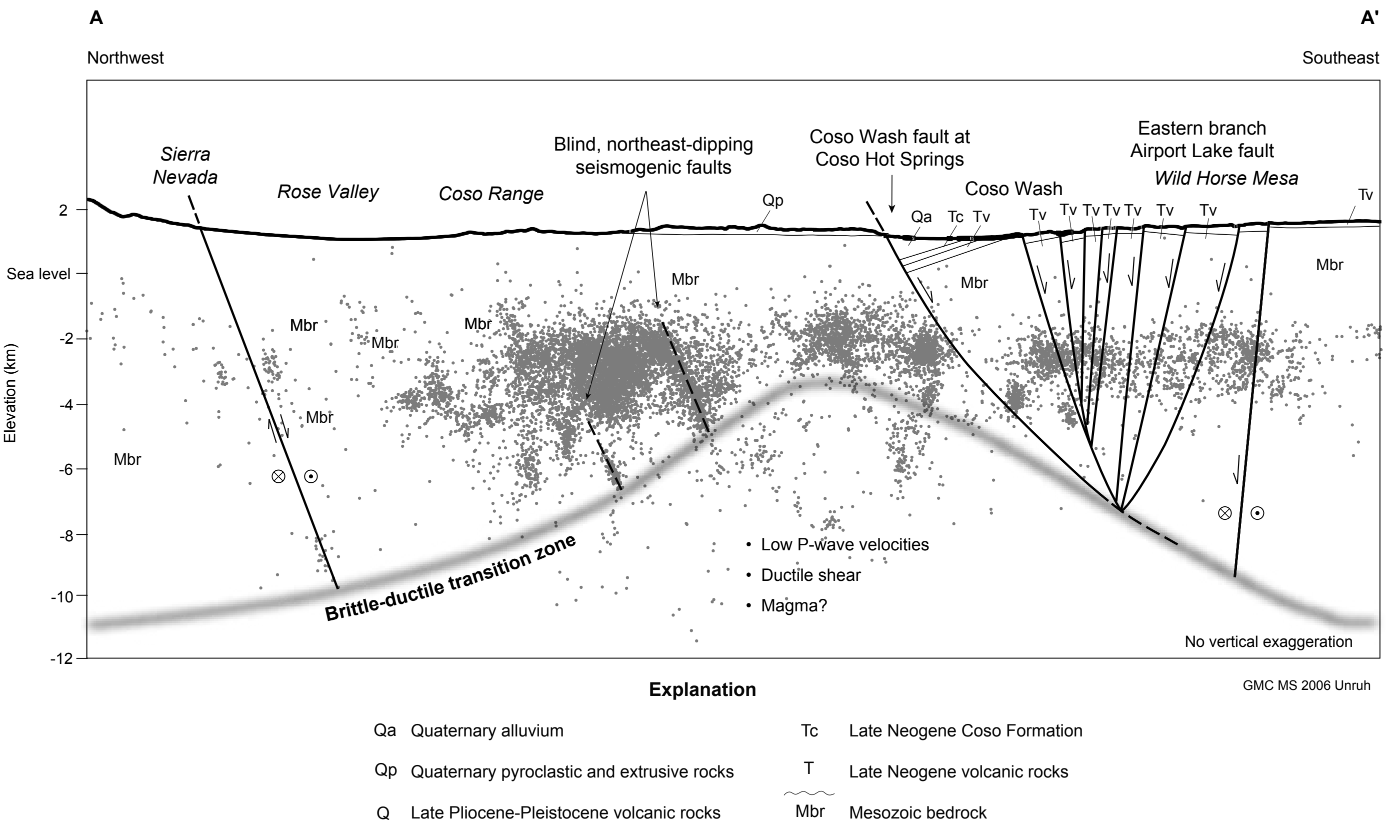

Figure 4. Cross section A-A′ through Coso Hot Springs.

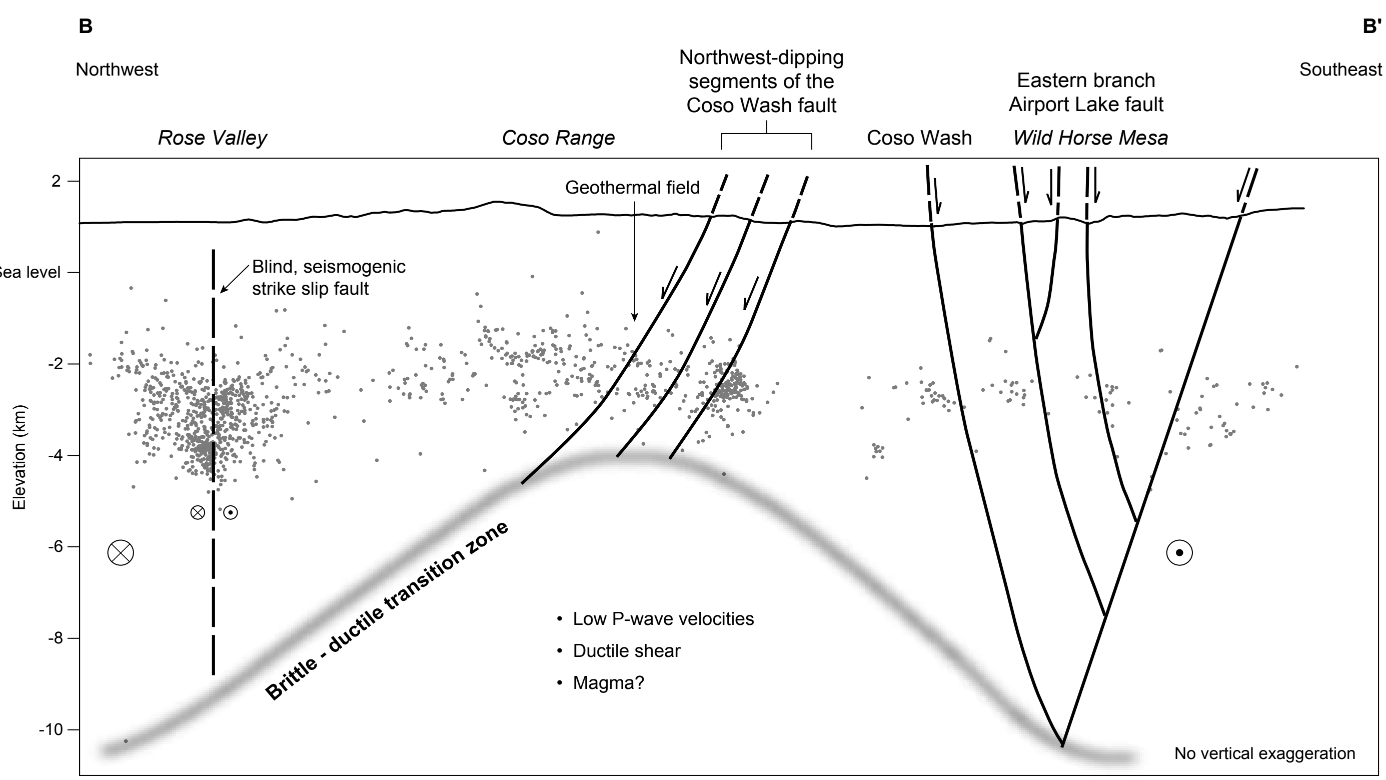

Figure 5. Cross section B-B′ through the main production area of the geothermal field.

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