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Fault zone fluids and seismicity in compressional and extensional environments inferred from electrical conductivity: the New Zealand Southern Alps and U. S. Great Basin

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Seismicity in both compressional and extensional settings is a function of local and regional stresses, rheological contrasts, and the distribution of fluids. The influence of these factors can be illustrated through their effects on electrical geophysical structure, since this structure reflects fluid composition, porosity, interconnection and pathways. In the compressional, amagmatic New Zealand South Island, magnetotelluric (MT) data imply a concave-upward ("U"-shaped), middle to lower crustal conductive zone beneath the west-central portion of the island due to fluids generated from prograde metamorphism within a thickening crust. Change of the conductor to near-vertical orientation at middle-upper crustal depths is interpreted to occur as fluids cross the brittle-ductile transition during uplift, and approach the surface through induced hydrofractures. The central South Island is relatively weak in seismicity compared to its more subduction-related northern and southern ends, and the production of deep crustal fluids through metamorphism may promote slip before high stresses are built up. The deep crustal conductivity is highly anisotropic, with the greater conductivity along strike, consistent with fault zone models of long-range interconnection versus degree of deformation. The central Great Basin province of the western U.S. by contrast is extensional at present although it has experienced diverse tectonic events throughout the Paleozoic. MT profiling throughout the province reveals a quasi one-dimensional conductor spanning the lower half of the crust which is interpreted to reflect high temperature fluids and perhaps melting caused ultimately by exsolution from crystallizing underplated basalts. The brittle, upper half of the crust is generally resistive, but also characterized by numerous steep, narrow conductors extending from near-surface to the middle crust where they contact the deep crustal conductive layer. These are suggested to represent fluidised/altered fault zones, with at least some fluids contributed from the deeper magmatic exsolution. The best-known faults imaged geophysically before this have been the listric normal faults bounding graben sediments as imaged by reflection seismology. However, the major damaging earthquakes of the Great Basin appear to nucleate near mid-crustal depths on near-vertical fault planes, which we suggest are being imaged with the MT transect data, and where triggering fluids from the ductile lower crust are available. In both compressional and extensional examples, the fluidised fault zones are hypothesized to act to concentrate slip, with major earthquakes resulting in asperities along the fault surface.

Key words: Fluids, seismicity, resistivity, magnetotellurics.

1. Introduction

Fluids are widely accepted to have fundamental effects on the rheology of crustal rocks both in an intergranular context (Tullis *et al.*, 1996) and at macroscopic fracture scales (Cox, 2002). They are generally viewed as weakening rocks by reducing effective normal stresses across existing faults or by promoting the growth of microcracks and pore interconnectivity leading to formation of new crustal scale shear zones. Consequently, models for the degree of seismicity and controls on nucleation need to consider the provenance of fluids entering the system.

It may be possible in some instances to verify or augment models of crustal seismicity, especially those invoking deep crustal fluids, based on geophysical structure. We argue that the roles of stresses, rheology and deformational framework can be illustrated through electrical geophysical structure since it depends on fluid composition, porosity, interconnection and pathways. To this end, we synthesize recent detailed transect studies involving magnetotellurics (MT) in two relatively young tectonic environments. The first is the active compressional regime of the New Zealand South Island and its major crustal break the Alpine Fault, while the second is the actively extensional Great Basin of the western United States, containing or bordering some of the most seismogenic regions of the country.

The MT method uses naturally occuring electromagnetic (EM) wave fields as sources for imaging the electrical resistivity structure of the Earth (Vozoff, 1991). In the con-

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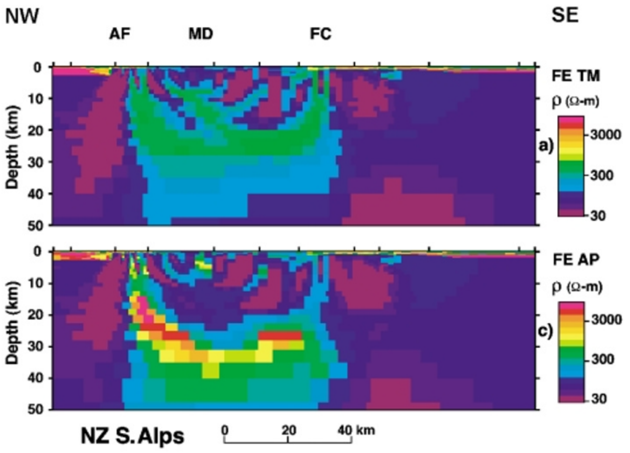

Fig. 1. Coast-to-coast, 2-D resistivity cross sections from inversion of TM mode (cross-strike) impedance data (top) and of $TM + H_z$ data (bottom) (modified from Wannamaker *et al.*, 2002). Physiographic features include Alpine Fault (AF), Main Divide (MD), and Forest Creek fault zone (FC). Section runs northwest (NW) to southeast (SE).

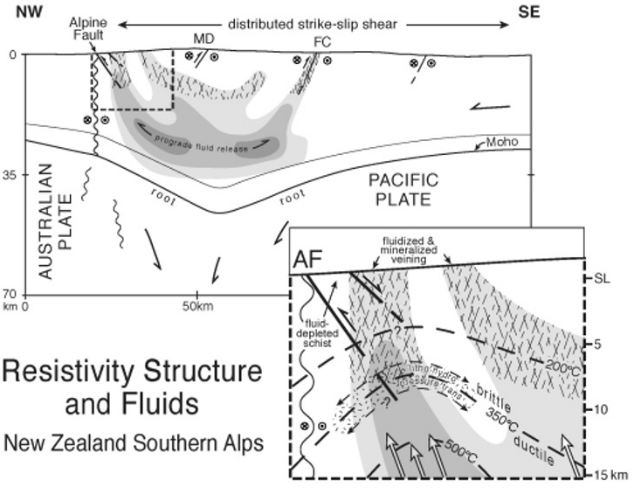

Fig. 2. Interpretive geological model from resistivity cross sections and external constraints on uplift, thermal regime and fluid compositions. Substantially influenced by Craw (1997) and Sibson and Scott (1998). P-wave velocity contours in km/s in upper panel after Stern *et al.* (2001).

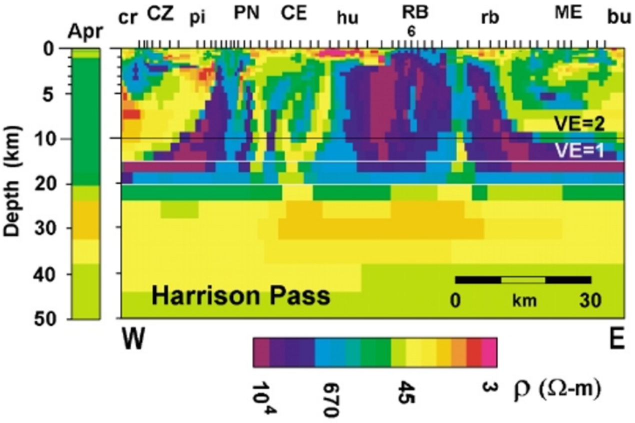

Fig. 3. 2-D inversion resistivity model for $TM + H_z$ data set of the southern Ruby Mtns core complex (Wannamaker and Doerner, 2002), central Nevada. Locations include Crescent Valley (cr), Cortez Range (CZ), Pine Valley (pi), Pinon Range (PN), Cedar Ridge (CE), Huntington Valley (hu), Ruby Mountains (RB), Ruby Valley (rb), Medicine Range (ME), and Butte Valley (bu). Color column at left (Apr) is 1-D a-priori model for inversion (op. cit.). Note VE break at 10 km depth.

ducting Earth, EM waves travel diffusively, such that high frequency (short period) waves penetrate a relatively short distance while low frequency (long period, >100 s) waves may reach the mantle. Present-day, routinely applied state of the art interpretation emphasizes local two-dimensional (2-D) assumptions with attempts to avoid or accommodate finite strike (3-D) effects under favourable conditions (Wannamaker, 1999). Transect MT data typically are transformed to electrical resistivity cross sections through nonlinear inversion, somewhat analogous to seismic tomography (Tarantola, 1987; Rodi and Mackie, 2001; Wannamaker *et al.*, 2002).

2. Example Resistivity Structures from Compressional and Extensional Orogens

2.1 New Zealand Southern Alps

The South Island of New Zealand contains a modern plate boundary of oblique, continent-continent collision between the Pacific and Australian plates, marked at the surface by the regional Alpine Fault (Korsch and Wellman, 1988; Walcott, 1998). Dominant crustal lithology southeast of the fault is Torlesse terrane greywacke of 20–25 km thickness near the SE coast, increasing to near 40 km in the west-central section due to crustal thickening by the collision over the past 7 Myr. Exhumed metagreywackes from depths as great as 25 km appear in the hanging wall of the Alpine Fault just SE of its trace and are accompanied by strongly uplifted crustal isotherms (Allis and Shi, 1995; Craw, 1997).

Forty-one wideband magnetotelluric soundings were collected in a 150 km-long transect across the central South Island (Wannamaker *et al.*, 2002). Two-dimensional inversion applied to the MT data revealed a concave-upward ("U"-shaped), middle to lower crustal conductive zone beneath the west-central portion of the island (Fig. 1). The average conductivity of this zone in the strike direction appears much higher than that required across strike, and may represent anisotropy or along-strike conductive strands narrower than the transverse magnetic (cross-strike) mode MT data can resolve.

The deep crustal conductor under the Southern Alps is interpreted to represent mainly a volume of fluids arising from prograde metamorphism within a thickening crust (Wannamaker *et al.*, 2002) (Fig. 2). Fluid interconnection, rock weakening and electrical conduction are promoted by shear deformation (Cox, 1999). A transition to vertical orientation of the conductor ∼10 km depth toward the trace of the Alpine Fault is interpreted to occur as fluids ascend across the brittle-ductile transition in uplifting schist, and approach the surface through induced hydrofractures (Sibson and Scott, 1998). The high-grade schist becomes resistive after depletion of fluids and continues to extrude toward the Alpine Fault. The high degree of lower crustal anisotropy is believed to reflect the dominantly strike-slip component of motion, such that fracture interconnection is preferentially increased in this orientation (Cox, 1999). We

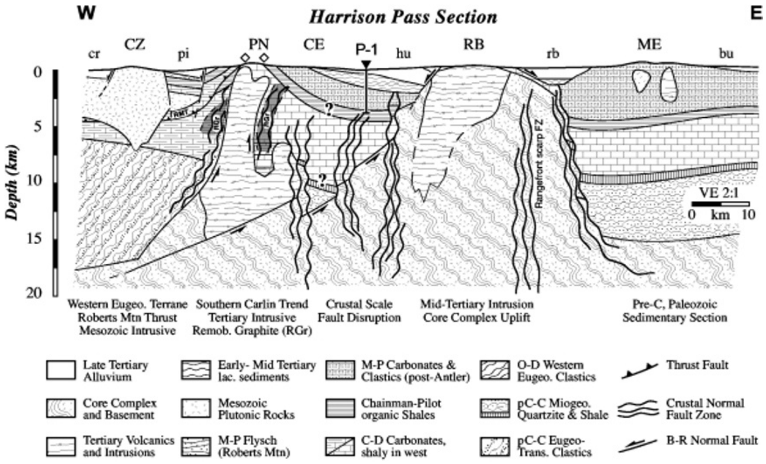

Fig. 4. Geological interpretation for upper 20 km of Harrison Pass resistivity model, modified from Wannamaker and Doerner (2002). RGr is remobilized graphite and P-1 is PanAm Jiggs #1 exploration well. Landmarks as in Fig. 3.

stress that it is the compressional component of orogeny in the central South Island that is responsible for the production of fluid, although the dominant sense of motion in the region is strike slip.

2.2 Central Great Basin, Nevada, U.S.A.

The original setting of the north-central Great Basin is that of a west-facing Proterozoic rift margin, with thick Phanerozoic passive margin sedimentation up to 15 km thick (Burchfiel *et al.*, 1992; Karlstrom *et al.*, 2001). This setting is closely analogous to current passive continental margins such as the east coast of the United States. Our study area lies at the transition between the eugeoclinal (shelf) platform, and deep-water, pelitic miogeoclinal sediments, interpreted to lie above a major, rift-margin normal fault. The region has experienced repeated compressional and extensional deformation, and magmatism, which have contributed to the total expression of electrical resistivity.

We have collected about 150 magnetotelluric (MT) soundings in northeastern Nevada in the region of the Ruby Mountains metamorphic core complex uplift, to illuminate controls on core complex evolution and deposition of world-class disseminated gold deposits (Wannamaker and Doerner, 2002). To first order, the resistivity structure is one of a moderately conductive, Phanerozoic sedimentary section fundamentally disrupted by intrusion and uplift of resistive crystalline rocks (Fig. 3). Late Devonian and early Mississippian organic shales of the Pilot and Chainman Formations together form an important conductive marker sequence in the stratigraphy. They show pronounced increases in conductance due to graphitization caused by Elko-Sevier era compressional shear deformation and possibly by intrusive heating. A very large package of low resistivity rocks toward the west end of the profile may signify the deep water clay- and organic-rich sediments of the ancestral miogeocline.

The resistive crystalline central massifs adjoin the host stratigraphy across crustal-scale, steeply-dipping fault zones (Fig. 4). The zones provide pathways to the lower crust for heterogeneous, upper crustal induced, electric current flow (Wannamaker and Doerner, 2002). Due to their cross-cutting nature, we infer that these zones are of Basin and Range age. The cross section of Fig. 4 differs from the original of Wannamaker and Doerner in entertaining the possibility that crystalline crust dips at a lower angle to the west and was exhumed from beneath the Pinon Range to the west (Howard, 2003). Lower crustal resistivity everywhere under the profiles is low and is consistent with a low rock porosity (<1 vol.%) containing hypersaline brines and possible water-undersaturated crustal melts (Wannamaker, 2000), residual to the mostly Miocene regional extension. Since extension per se actually cools the crust (Mackenzie, 1978) and would resorb original fluids, the current condition requires basaltic underplating, crystallization, and fluid exsolution to create a conductor.

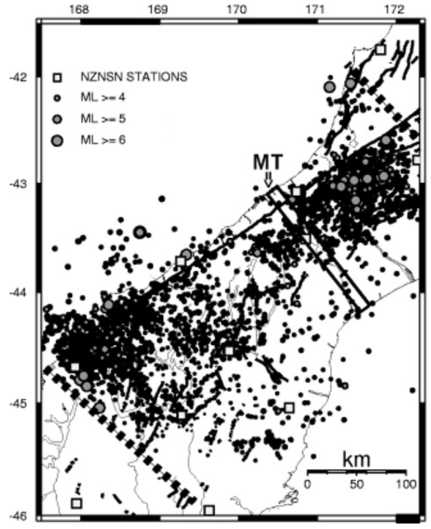

Fig. 5. New Zealand South Island seismicity map from stations of the New Zealand National Seismic Network (NZNSN) for the period 1990–1997 (modified from Leitner *et al.*, 2001), by permission of D. Eberhart-Phillips. Network stations are indicated by squares. Thick dashed lines denote approximate limits of central transpressional regime of the South Island (Leitner *et al.*). Long open rectangle marked MT denotes location of our magnetotelluric transect.

3. Fluids and Seismicity in Compressional and Extensional Regimes

3.1 New Zealand Southern Alps

Seismicity in the central South Island is markedly lower than that towards its northern or southern ends (Leitner *et al.*, 2001) (Fig. 5). Depth to the bottom of the seismogenic zone is about 12 km and is fairly uniform over most of the island. An exception is for areas of the central South Island just southeast of the Alpine Fault where the zone bottom is only 7–10 km deep. Leitner *et al.* interpret this to reflect existence of a block-like region with a higher compressional stress component and fault orientations less favourably aligned for slip, in contrast to the purely strike-slip Marlborough region 200–300 km to the northwest. However, it also is tempting to correlate this low seismicity region with reduced stress buildup due to generation of deep crustal metamorphic fluids as deduced through electrical conductivity and low seismic velocity.

Given the finite sampling of geophysical models along the length of the orogen, it is unclear how exact is the correspondence in plan view between the low resistivity (fluidised) domain and the region of reduced seismicity in the central South Island. However, a nearly coincident low velocity zone is seen in the same area and appears to persist at least 50 km to the southwest (Stern *et al.*, 2001, 2002). Moreover, followup MT soundings taken by the New Zealand IGNS (T. G. Caldwell, pers. comm.) show that the lower crustal conductor persists to the southwest nearly 100 km.

Despite alternate interpretations (Leitner *et al.*, 2001), this geophysical correspondence is rather striking and tempts an interpretation in terms of reduced strength and an inability to allow stress buildup (cf. Unsworth *et al.*, 2000). In Fig. 1 are visible numerous smaller scale conductive lineaments in the upper 10–15 km of moderate to steep dip that we suggest may be low-strength, fluidised fault zones accommodating much of the strike slip motion. Nearly half of the relative motion between the Australian and Pacific plates is distributed over a distance of up to 200 km to the southeast of the Alpine Fault (Beavan *et al.*, 1999; Beavan and Haines, 2001; Leitner *et al.*, 2001). These breaks may contribute to the very low effective elastic thickness ($T_e \approx 5$ km) estimated for the interior of the central South Island (Stern *et al.*, 2002).

Occasional large seismic events of the central South Island are oblique thrust in nature and appear to originate exclusively near the trace of the Alpine Fault (Rhoades and van Dissen, 2003). This is the area interpreted to be depleted of fluids of deep generation in the model of Fig. 2. Thus, the potential for buildup of relatively great stresses in this locale is not surprising. Overall, however, the total seismic moment of the central South Island appears to be insufficient to explain the entire degree of strike slip deformation (R. Norris, pers. comm., 2004), again suggesting some aseismic or subdetectable deformation is at work.

3.2 Central Great Basin, Nevada, U.S.A.

The numerous crustal breaks imaged with MT in this area are interpreted to represent fluidised/altered fault zones which may also contribute to the low effective elastic thickness ($T_e < 10$ km) estimated regionally for the Great Basin (Lowry *et al.*, 2000). The best-known faults imaged geophysically before this in the province have been the listric normal faults bounding graben sediments, according to reflection seismology. However, the major and potentially most damaging earthquakes of the region (in addition to seismicity peaks generally) appear to occur at mid-crustal depths near the brittle-ductile transition on steeply dipping slip zones, where shear stresses have reached a maximum (Smith *et al.*, 1989) (Fig. 6). Although our profiling does not cross the location of one of these major historical quakes specifically, we believe our image may exemplify such steeply dipping slip zones, and that magnetotellurics has been the first technique to show that such zones have a geophysical expression. Surface traces of normal faults along the western margin of the Ruby Mountains show that there is ongoing Holocene deformation in the area (Wesnousky and Willoughby, 2003).

It is tempting to conclude that lower crustal fluids may have a triggering role in these deep quakes given their proximity to interpreted nucleation sites. Steep fault zones of the brittle domain could extend into the ductile regime and enhance permeability through transtensional fissuring (suction pump effects) (Sibson, 2000; Cox, 2002). This mechanism could present an opportunity for fluids at lithostatic pressures from the ductile regime to enter the lower reaches of the crustal scale faults and reduce effective normal stresses. Sudden reductions in fluid pressure are interpreted to accompany such fluid breakthroughs, and enhanced fluid flow to the surface has been observed in some cases for months afterward (Sibson, 1994, 2000). That ductile lower crust can flow laterally independent of degree of extension of the upper crust has been inferred from the nearly flat reflection seismic Moho over large areas of the Great Basin (Allmendinger *et al.*, 1987).

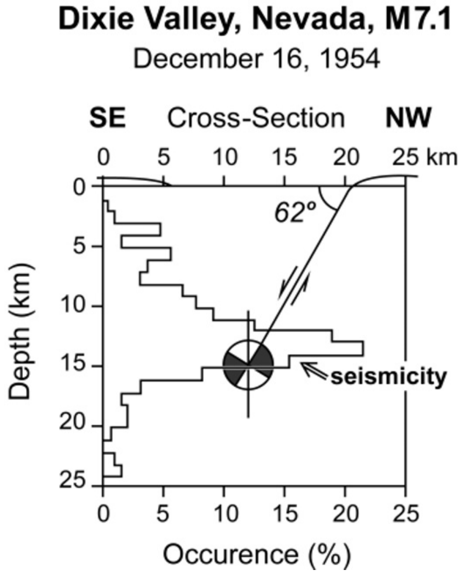

Fig. 6. Cross section of normal fault and focal depth frequencies associated with the large Dixie Valley normal faulting earthquake, western Nevada. This is one of three quakes of $M > 7$ occuring in historic times in the Great Basin, all of which have similar geometries and nucleation depths. Redrawn and condensed from Smith *et al.* (1989).

3.3 Stress Regime Intercomparisons

In this section, we compare inferences on fluids and seismicity with those arising from detailed MT and seismic studies of the San Andreas strike slip fault system in California, U.S.A. Contiguous array MT surveying across the San Andreas system at creeping, transitional and locked segments showed that the lowest, most deeply extending low resistivities and reduced seismicity were associated with active creep (Unsworth *et al.*, 1999, 2000; Unsworth and Bedrosian, 2004; Bedrosian *et al.*, 2002, 2004). Seismicity was restricted to regions outside the low resistivity, which were interpreted to reflect fluidised and altered zones incapable of supporting significant stress internally. In some contrast to the compressional and extensional examples we have considered, the source of fault zone fluids in strike slip domains may be less obvious and depend on specifics of the surrounding lithologies and tectonics.

On the New Zealand South Island, detailed profiling of seismicity by Leitner *et al.* (2001) about 25 km to the southwest of our MT transect (Franz Joseph area) shows seismicity sometimes concentrating in steep linear textures. Although this geometry is reminiscent of some of the finer resistivity structure we imaged farther north, if the San Andreas models are correct then such linears may be forming adjacent to the fluidised fault zones rather than in them. The conductive fault zones facilitate a concentration of movement, with seismic events potentially spawned at asperities in the broader fault zone. Fault zone fluids are replenished from the prograde metamorphism at deeper levels, where slight fluid overpressures may be generated, and released possibly through fault valve mechanisms (Sibson, 1994). As mentioned, the major earthquakes are confined to the fluid-depleted zone within ~10 km of the Alpine Fault where large stresses may accumulate (Rhoades and van Dissen, 2003).

In the extensional Great Basin, we again accept that relatively brittle asperities in the neighbourhood of steep, low-strength fluidized fault zones will host the major earthquakes, with potential stresses therein increasing toward a maximum in the lowermost brittle domain (middle crust) due to crustal column pressures (Smith *et al.*, 1989). Like the New Zealand Alps, the fluid source is from below in the ductile lower crust. Extension of the deepest brittle faults of the Great Basin into the aseismic ductile zone promotes permeability and fluid flow (Sibson, 2000; Cox, 2002), possibly by producing a tensional stress zone in the ductile rocks to attract fluid. Minor stress fluctuations are expected to disperse some of this fluid upward to either induce the major events or maintain a general state of low strength in the large steep fault zones. The relationship of these steep crustal scale faults with the listric (shallowing), graben-bounding faults imaged in reflection seismology is unclear.

4. Conclusions

In both compressional and extensional examples reviewed here, steep crustal-scale conductors appear associated with major fault zones and lower crustal fluidization in seismogenic areas. The relatively simple compositions and history in New Zealand allow a fairly direct identification of the conductors as fluid pathways. Fluids are generated by prograde metamorphism below the domain of seismicity and may have a role in curtailing stress buildup either by reducing the depth extent of the brittle regime or by reducing effective normal stresses. The association of steep conductors with fault zones in the Great Basin is more inferential due to a protracted tectonic history, but they appear to represent structures associated with brittle strain accommodation and cross cut prior features. Given that the major earthquakes of the Great Basin appear to nucleate at mid-crustal depths near the brittle-ductile transition, our geophysical images may have identified examples of the controlling fault zones and imply availability of triggering or weakening fluids from the nearby lower crustal ductile domain. In both regional examples, we consider earthquakes to nucleate in asperities near along the path of the fault zone, which itself is maintained at low strength by continued fluid injection.

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