Recent and on-going MT studies of the San Andreas Fault zone in Central California

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Introduction

Numerous models have been proposed for the lithospheric structure of the San Andreas Fault (SAF) but it remains controversial if and how large transform faults penetrate the mantle lithosphere. Fluids, however, seem to be ultimately linked with many fault related processes. Fluids can be released in mineral reactions, by crushing and overprinting of existing fabric in high strain zones. Veins and fractures of a fault system can also provide the means for transport of fluids. Directly accessing the role of fluids within the core of the SAF is one of the major goals of the San Andreas Fault Observatory at Depth (SAFOD), a major earth science initiative to study the in-situ physical and chemical conditions of a large transform fault (Hickman et al., 2004).

Among the most intriguing and mysterious phenomena of fault zone related activity along the San Andreas Fault are observations of deep, non-volcanic seismic tremors (NVT) (Nadeau & Dolenc, 2005). These deep (> 30 km) tremors have only been observed in an area approximately 40 km SE of the SAFOD. The source mechanism of NVTs is to date not well understand. Recently, Shelly et al. (2007) suggested that tremors beneath Shikoku, Japan, are a different manifestation of so-called low-frequency-earthquakes (LFEs). They interpret tremors as a swarm of LFEs shaking the earth for hours, days or even weeks at a time. LFEs were previously inferred to represent fluid-enabled shear-slip on the fault plane (Shelly et al., 2006; Ide et al., 2007) instead of direct flow-induced oscillation as suggested by Katsumata and Kamaya (2003).

The presence or absence of NVT along the SAF appears to coincide with the transition from being locked (SW of Cholame) to intermediate creep (NW of SAFOD) and could reflect significant structural changes affecting the deep hydraulic system along this portion of the SAF which in turn could be detectable with MT. The *DeepRoot* magnetotelluric (MT) experiment near the SAFOD revealed a steeply dipping upper crustal high electrical conductivity zone which could represent a deep-rooted channel for crustal and/or mantle fluid ascent (Becken et al., 2008). In the scope of the projects *ELSAF* and *TremorMT*, we continue our efforts to image an entire segment of an active plate boundary with a network of MT stations, from the Pacific into the Great Valley, crossing the NVT region beneath the SAF near Cholame. Our present research activities onshore will be extended offshore with the *Deep San Andreas Fault Boundary Structure from Marine MT* experiment conducted by Scripps Institution of Oceanography, UCSD, in 2008.

This paper summarizes the most important results of the DeepRoot project give details about the objectives of the TremorMT measurements (completed in fall 2007) and the upcoming ELSAF experiments (planned for spring 2008).

Results from DeepRoot

MT data along a 45 km long profile across the SAF near the SAFOD (Fig. 1) was used to derive a crustal electrical resistivity model. Data analysis revealed that the majority of the data are consistent with 2D modelling assumptions. The dominant geoelectrical strike direction is N42.5°E in agreement with the strike of the SAF and other major geological units in the region.

A 2D resistivity cross-section was obtained from minimum structure inversion. The final resistivity model (Fig. 2) reveals an image of a heterogeneous upper crust with a number of conductive and resistive anomalies that are related to the sedimentary sequences, the Franciscan subduction complex and blocks of Salinian crust forming the basement to the NE and SW of the SAF, respectively. The most intriguing feature of the regional electrical resistivity model is an approximately 5-8 km wide, sub-vertical corridor of high electrical conductivity (EC) in the upper crust that widens in the lower crust (LCZ). The zone of high conductivity reaches the near-surface 5-10 km NE of the SAF and is sub-horizontally connected with the FZC at the SAF. Low resistivities of less than 5 Ohm-m are imaged within the EC to a depth of 8-10 km adjacent to the SAF. From there, the anomaly appears to link with a lower crustal high conductivity zone (LCZ) at non-seismogenic depths >12-15 km. Constrained inversions show that neither the upper branch of the high-conductivity zone (EC) nor its lower crustal root (LCZ) can be removed without significantly increasing data misfit.

A joint interpretation of the resistivity structure and the geochemical data from the SAFOD and nearby water wells suggests that the crust near the SAF provides pathways for crustal and upper mantle fluids, while the eastern fault block represents a trap of fluids. This interpretation is supported by (i) increasing He3/He4 ratios within the SAFOD (up to 11% mantle derived) to the NE of the SAF (Wiersberg, 2007) (ii) high He3/He4 ratios farther to the NE (up to 25% mantle), observed within the Varian-Philipps (VP) and Middle Mountain oil wells (Kennedy et al., 2007) (iii) an electrically conductive channel linking the upper crustal eastern conductor (EC) with a lower crustal conductive zone and a conductive anomaly within the upper mantle. Furthermore, super-hydrostatic fluid pressures within the SAFOD to the NE of the SAF (Zoback et al., 2006) and within the VP well (Johnson et al., 95) suggest that the EC represents a region of overpressured fluids trapped between an impermeable SAF, the WCF and below a surface seal. Elevated fluid pressures in this region could be related to continuous or episodical fluid supply of deep rooted fluids.

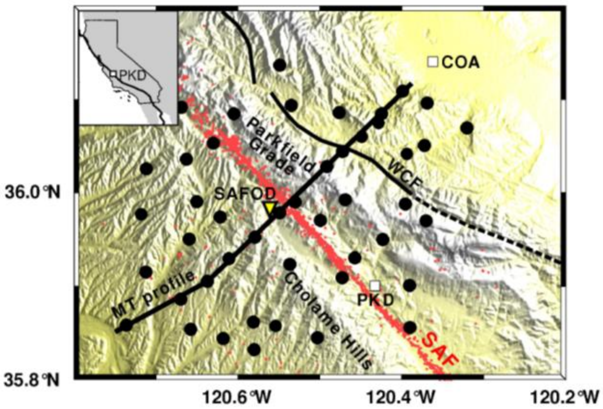

Fig. 1. Site map of DeepRoot experiment. Emphasis for this paper is on the MT data recorded at 66 sites along a 45 km long profile (solid black line), centred on the SAFOD site (yellow triangle). This profile includes 11 sites from a previous MT survey (Unsworth et al., 2000) in its central part. Solid black circles indicate site locations of additional long-period/broad-band recordings in array configuration. Red dots indicate the seismicity along the SAF (Thurber et al., 2006). PKD Parkfield; COA Coalinga; WCF Waltham Canyon Fault; inset shows a map of California, the SAF and the location of Parkfield.

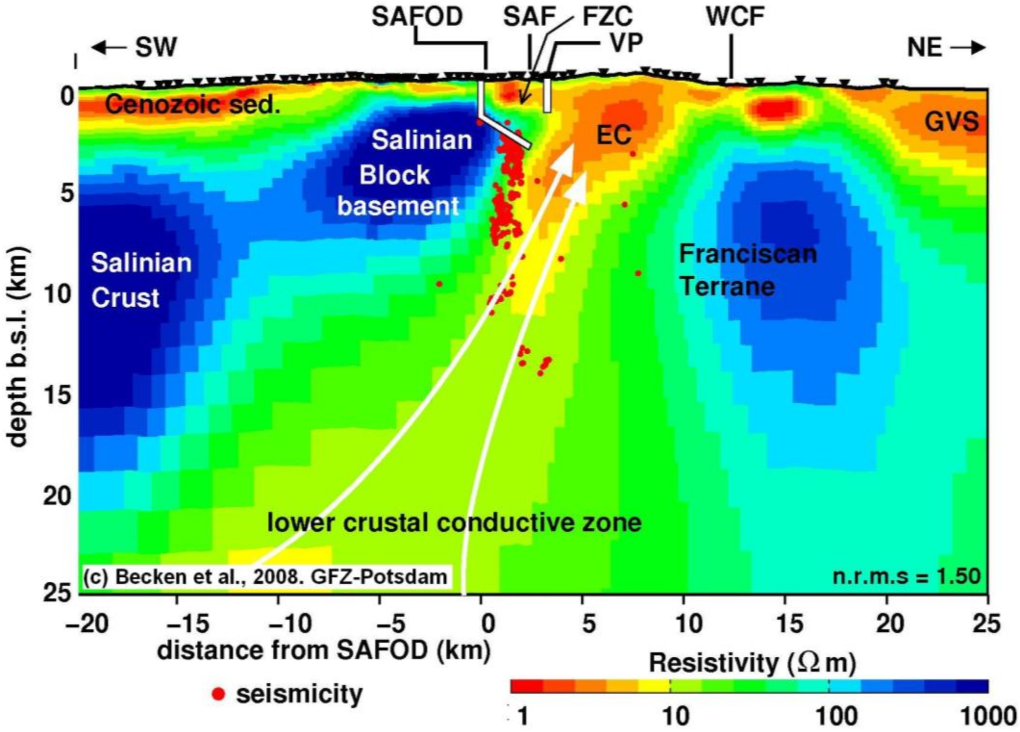

Fig. 2. MT resistivity model along the 45 km profile across the SAF near the SAFOD site. Superimposed on the models are the SAFOD main hole and the Varian-Philipps well (VP); red dots indicate the seismicity (Thurber et al., 2006) within 3 km distance from the profile. We speculate that a deep-reaching sub-vertical corridor of high conductivity, linking the upper crustal eastern conductor (EC) with a lower crustal conductivity zone (LCZ) and further with a mantle conductor, images a channel for deep crustal or mantle fluids (sketched with white arrows). This channel is enclosed by the resistive Salinian Block basement and Salinian Crust to the SW and a resistive block in the NE at mid-crustal levels (labelled Franciscan Terrane). At the SW end of the profile, above the resistive Salinian Crust, the model indicates a 2 km thick conductive layer near-surface, that coincides with low seismic p-wave velocities (1.5-3.5 km/s) (Hole et al., 2006) and can be attributed to presumably Pliocene and Miocene marine sediments (Diblee, 1972). The model recovers also the shallow fault-zone conductor (FZC) below Middle Mountain (e.g. Unsworth et al., 2000). The sediments of the Great Valley Sequence (GVS) could be responsible for the high conductivity imaged in the upper crust of the NE part of the profile.

Within the upper crust, these fluids do not migrate through the seismically-defined SAF. Instead, upper crustal migration pathways are provided within the high-conductivity EC sandwiched between the SAF and a SW-dipping segment of the WCF, interpreted to represent a thrust-fault penetrating at least to the bottom of the seismogenic zone (Carena, 2006). Seismically active as well as blind thrust-faults in this region could also provide the means for fracture-related fluid-flow, in agreement with the modelling assumptions of Miller (1996).

High lower crustal conductivities within a 25 km wide zone around the SAF indicate anomalously high fluid content. Constrained inversion shows that a lower crustal barrier for fluid flow is incompatible with the MT data. The resistivity model strongly supports deep fluid circulation and migration through the lower crust. The exact geometry of these deep pathways cannot be resolved. However, inversion models containing a narrow, steeply dipping conductive zone as an a priori conductive structure achieve the best data fit, and seem to support the existence of a narrow pathway.

We speculate that the source region for the fluids is related to a mantle conductivity anomaly below the Pacific plate (beyond the axes limits of Fig. 2). This mantle anomaly could be related to fluids released from a subducted slab of oceanic crust, which may exist in this region (Zoback et al., 2002). However, a longer MT profile extending to the coast and continued off-shore is required to constrain this feature. Further geochemical sampling of water wells along the MT profile would be necessary to test if elevated mantle gas content exists between the SAF and the WCF as predicted by the MT model. Farther to the NE, mantle derived fluids should be minor constituents to the fluid composition, similar to the observations to the SW of the SAF.

TremorMT and ELSAF

Analysis of triggered event data from the borehole High Resolution Seismic Network (HRSN) at Parkfield, California, revealed tremor-like signals originating to the south within the Cholame Valley, approximately 40 km SE of Parkfield. Their locations indicate that, within the search radius, the tremors are confined to a ~25-km segment of the SAF and occur at depths of between approximately 20 and 40 km. Nadeau & Dolenc (2005) suggested that either fluids are not important for the SAF tremors or an alternative fluid source (when compared with subduction zones) exists below the seismogenic zone in this area. Ellsworth et al. (2005) confirmed the observation of non-volcanic tremors in May 2005 during the deployment of a multi-level borehole seismic array in the SAFOD main hole. An apparent correlation between tremor and local micro-earthquake rates at Cholame (Nadeau and Dolenc, 2005) suggests that deep deformation associated with the Cholame tremors may be stressing the shallower seismogenic zone in this area. Further evidence for stress-coupling between the deep tremor zone and the seismogenic SAF is observed in the correlation between tremor and the 2004, M6 Parkfield earthquake, approximately 10 km NW of Cholame.

Near Cholame, earlier MT work found evidence for a resistive crust beneath the SAF (Park & Biasi, 1991) which could be indicative of a dry zone capable of trapping fluids in the lower crust and/or the upper mantle. This hypothesis would be consistent with low mantle derived He content in the Jack-Ranch Highway-46 Well (Kennedy et al., 1997) near Cholame and in support of a locally well-confined source region for the non-volcanic tremors (Nadeau & Dolenc, 2005). It would mean, however, that the geological and / or rheological situation near Cholame is markedly different from Parkfield, where the resistivity model and the fluid chemistry (Kennedy et al., 1997; Wiersberg & Erzinger, 2007) suggest a pathway for fluids into the brittle regime of the SAF system.

All of the above observations suggest that fluids play the key role in the generation of non-volcanic tremors, and that tremors (and associated fluids) appear to be closely linked to fundamental processes governing both the deep roots and the seismogenic zone of large fault zones. The presence or absence of NVT appears to coincide with the transition of the SAF from being locked (Cholame) to intermediate creep (SAFOD) and could reflect significant structural changes affecting the deep hydraulic system along this portion of the SAF which in turn could be detectable with MT. Tests based on constrained inversions of the DeepRoot MT data across the SAFOD clearly show that a resistive lower crust is inconsistent with the data (Becken et al., 2008). This also means however, that we could resolve a resistive lower crust if it should exist beneath the Cholame segment of the SAF. Furthermore, if migration of fluids from the lower into the upper crust is blocked by an impermeable seal, the upper crust should be more resistive. In fact, the eastern conductor (EC) which we interpret as the upper crustal branch of the fluid channel near the SAFOD appears to be absent in preliminary inversion models of the southernmost short profile of Unsworth et al. (unpublished), located just 5 km NW of Cholame.

To address these questions we have been continuing our research activities with the TremorMT (GFZ-funded) and ELSAF (DFG+GFZ funding) projects to image an entire segment of the SAF with a network of MT stations, deployed from the Pacific Ocean into the Great Valley, crossing the SAFOD near Parkfield and the NVT source region beneath the SAF near Cholame. In autumn 2007, we measured MT data along a 130 km long profile across the

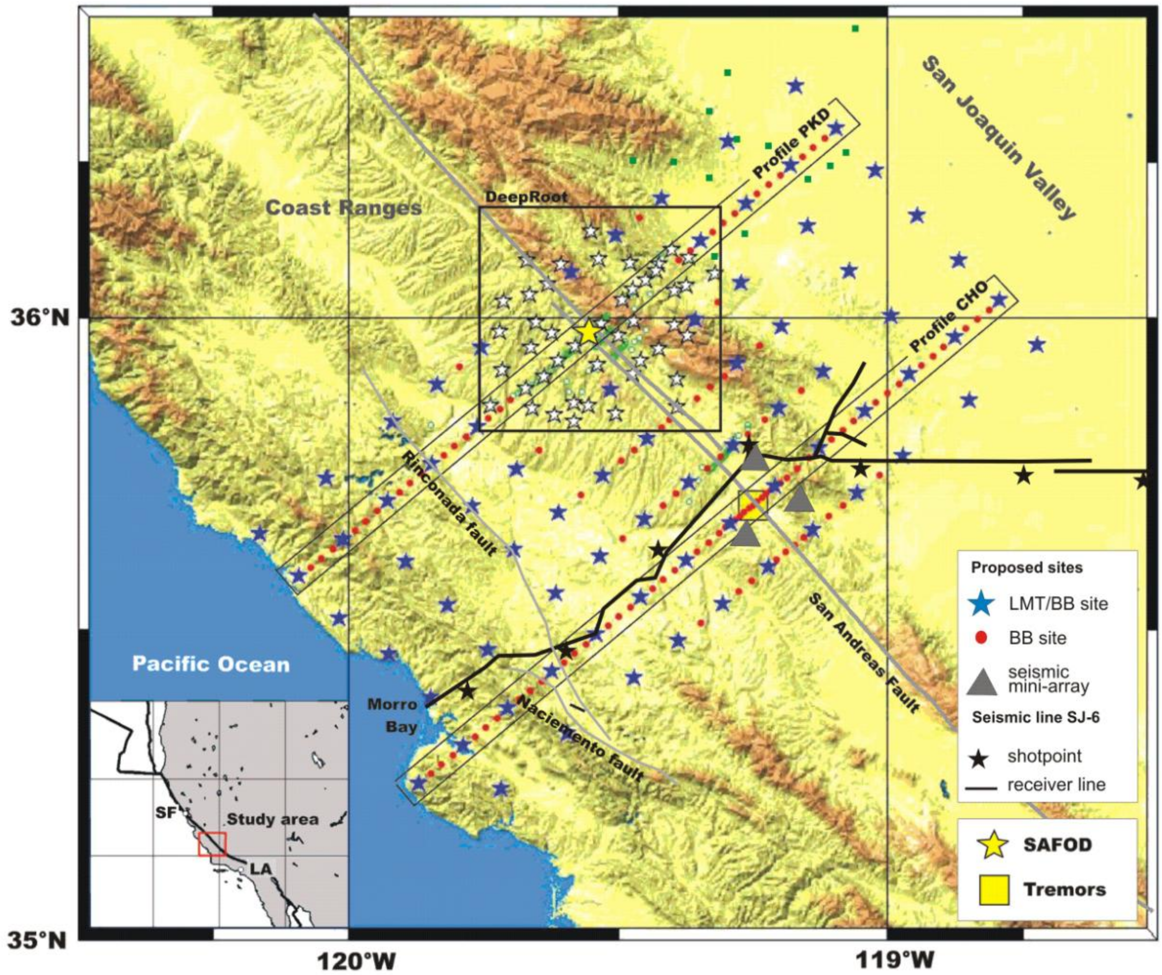

Fig. 3: Proposed and existing MT sites in the Cholame-Parkfield area in Central California. Blue asterisks and red dots indicate the proposed new combined long-period(LMT)/broad-band(BB) and BB-only sites, respectively, white asterisks and green dots indicate existing MT sites, acquired by the GFZ Potsdam and the UC Riverside in 2005/6 and by Unsworth et al. (1997). Additional MT data recently gathered in the NE part by S. Park (collaborator in DeepRoot) are shown as green squares. The SAFOD site near Parkfield is marked with a yellow star and the region of the non-volcanic tremors near Cholame is indicated by a yellow rectangle. Phase I of the project (TremorMT, GFZ funded) was successfully completed in fall 2007 with data acquisition along the 130 km long profile (CHO) and extending the existing 50 km long MT/seismic profile of the DeepRoot project from the Pacific coast into the San Joaquin Valley (profile PKD). In phase II of the project (ICDP, ElSAF) profiles CHO and PKD will be connected spatially with an array of LMT/BB and BB magnetotelluric sites, as indicated with blue asterisks and red dots. Gray triangles indicate the locations of the seismic mini-arrays (phase I); the solid black line and black asterisks indicate the location of the existing seismic refraction/reflection line SJ-6 (Murphy & Walter, 1984).

Coast Ranges and centred above the source region of non-volcanic tremors near Cholame (project TremorMT). We extended the existing DeepRoot profile to a length of 130 km to better constrain lower crustal and upper mantle conductivity structure. Furthermore, four small-aperture seismic arrays (SSAA) were deployed by Ryberg & Haberland (GFZ) in cooperation with the USGS in the vicinity of Cholame to test if the location accuracy of the NVT-events (in particular the depth estimate) could be improved. Preliminary results of the SSAA work, which was carried out in cooperation with W. Ellsworth from the USGS, are very promising as we observed numerous tremor-type signals in a 6 week period which are currently being analyzed. With ELSAF we will continue to collect MT data in spring 2008 with an array of MT sites connecting the high-resolution profiles across the SAFOD and the Cholame Valley. With the 3D array of MT sites we can resolve along-strike variations between the Colame and Parkfield segments of the SAF (see Fig. 3 for existing and planned MT sites).

Furthermore, our research activities onshore will be extended offshore in a collaborative research effort with our colleagues from Scripps Institution of Oceanography, UCSD. Brent Wheelock, Kerry Key, and Steven Constable will be extending our land profiles with their Scripps funded 'Deep San Andreas Fault Boundary Structure from Marine MT' experiment. The offshore data will be collected in autumn/winter 2008. The combination of onshore and offshore data will help us to see the whole picture as modelling shows that important parts of the San Andreas Fault structure, e.g. a deep rooted source of fluids in the upper mantle, can only be fully imaged by extending the MT array offshore.

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