II. Technical Report

A. Project Objectives

Fault motion in the brittle, seismogenic upper crust of Southern California discretizes locally onto narrow (< 1 km wide) shear zones. The onset of crystal plasticity and continuous creep occurs at the brittle-ductile transition (BDT) at the base of the seismogenic crust, yet it is unclear how shear transitions across and below this boundary. Models of strike-slip shear zones across the BDT range from: 1) a continuation of a steeply dipping or vertical brittle fault zone into a narrow ductile shear zone at depth, 2) widening into a much broader shear zone at depth or 3) transfer of shear into a narrow subhorizontal mid-crustal zone (Fig. 1). As first illustrated by Sibson (1983), these kinematic scenarios have significant implications for the rheological behavior of the ductile portion of the lithosphere in Southern California and require resolution for the planned SCEC Community Rheological Model.

Rocks in the middle to lower crust are largely inaccessible to field observation in Southern California, except in scattered xenolith localities and exposures of the Rand, Pelona and Oroopia Schist. They can however be sampled in situ at depth using seismic waves. We applied a method that uses passive source teleseismic recordings to map the orientation and strength of rock fabric at depth (Schulte-Pelkum and Mahan, 2014a,b). Imaging ductile shear zones helps “constrain the geometry and rheology of ductile roots of faults zones” (Research Priority P3.b) as well as “constrain the extent of permanent off-fault deformation” (P3.e) and provide indirect geological information for hypothesis testing of deep inelastic fault-system behavior (SCEC5 topic ‘Beyond elasticity’ under ‘Understanding earthquake processes’) as well as help assess representations of fault-system rheology (SCEC5 topic ‘Stress and deformation over time’ under ‘Modeling the fault system’). Observational evidence from the deep lithosphere enables comparisons to current modeling efforts (e.g. Takeuchi and Fialko, 2012), which predict deformation fields depending on the rheology of the lower crust and uppermost mantle, and thus provide constraints on rock strength below the BDT and on the relationship of deformation on geological time scales to postseismic deformation on decadal to annual time scales (e.g. Freed and Bürgmann, 2004; Pollitz et al., 2001).

Plate motion across Southern California is mostly accommodated by right-lateral strike-slip faults, in addition to thrusts and left-lateral faults. Strike slip faults with large displacements (100+ km) can separate rocks with different composition and fabric, resulting in cross-fault contrasts in physical properties. Determining whether such contrasts continue into the middle-lower crust can help distinguish between models for deep crustal shear, such as a narrow ductile shear zone vs. distributed ductile deformation scenarios. Some studies in the study area suggest that contrasts across these faults can continue through the lower crust to the Moho, with offsets in Moho depths (Zhu, 2000; Allam et al., 2014; Miller et al., 2014; Ozakin and Ben-Zion, 2015; Inbal et al., 2016; Barak and Klemperer, 2016). Particularly in receiver function studies, bias and reverberation overprint from near-surface low-velocity layers cause uncertainty and must be mitigated with good experimental design and processing (Schulte-Pelkum and Ben-Zion, 2012; Yeck et al., 2013). Thrust faults with cumulative displacements on the scale of kilometers can also juxtapose different lithologies with velocity contrasts that can be imaged (Schulte-Pelkum and Mahan, 2014a).

Aside from isotropic velocity contrasts formed by displacement of rocks of different composition across faults, deformation in the ductile regime can also result in shear fabric. The effect is well studied in the mantle owing to the anisotropy of olivine and its alignment under dislocation creep, which is typically compared to measurements of seismic anisotropy from shear-wave splitting in core phases (SKS; Long...
and Becker, 2010). However, exhumed lower crustal shear zones also show deformation fabric (e.g. Dumond et al., 2013) with seismic anisotropy on scales of several kilometers with strength comparable to those imaged in the mantle (Tatham et al., 2008; Ward et al., 2012; Schulte-Pelkum and Mahan, 2014b).

The project goal was to use a receiver function method developed by PI Schulte-Pelkum to image such dipping contrasts and shear fabric throughout Southern California, in order to test whether faults can be imaged into ductile depths. The method is sensitive to dipping isotropic contrasts (e.g. a fault contact with contrasts in mineralogy) as well as contrasts in the strength or orientation of dipping foliation. Depth of the contrast is determined via the arrival time in the receiver functions. Both types of contrasts are relevant to fault imaging. Further analysis and modeling allows separation of dipping isotropic velocity contrasts from contrasts in rock fabric if necessary. Shear zones down to a thickness of 2-3 km can be resolved with this method.

B. Results

We processed all available data for stations in southern California with data at the SCSN and IRIS data centers. Figure 1a shows resulting strikes and approximate depths of the largest dipping isotropic contrasts/dipping foliation contrasts at each station across the study area. Figure 2 shows strikes by depth range for the LARSE-2 dense line. The map (Fig. 1a) and regional zooms (e.g. Fig. 2) show that the dip/foliation signal in the receiver functions is pervasive and not necessarily localized near fault surface traces. However, seismicity also does not always lie beneath fault traces. Fig. 1b shows a cross section through a seismicity catalog of the region (Hauksson et al., 2012), plotted by Ross and Ben-Zion (pers. comm., 2018). The root of the Clark strand of the San Jacinto Fault shows dip shallowing from near vertical at 10 km depth to ~45 deg at 14-19 km depth as well as a lack of near-surface seismicity. Similar listric geometries are seen elsewhere in the seismicity catalog, with some cross sections on the Elsinore Fault showing near vertical seismicity planes and dipping structures in the e.g. San Jacinto trifurcation area (Ross et al., 2017) and on the southern San Andreas Fault as well as its Banning and Mission Creek strands (Ross and Ben-Zion, pers. comm.). We interpret these findings as the expression of fabric inheritance (more discussion below).

Current exposures of schists are taken to originate from underplating during Farallon subduction (e.g. Chapman, 2017), with a pervasive lower crustal schist layer postulated and used to interpret crustal anisotropy (Porter et al., 2011). However, foliation dips from waveform inversion are not subhorizontal (Porter et al., 2011), with a mean dip of 54 deg from horizontal. Our results (which do not depend on waveform modeling) also show dominant intermediate to steep dips, instead of shallowly dipping to subhorizontal fabric (the latter is stronger in the Basin and Range province). Strikes of deep dipping fabric from the LARSE-2 passive source line show high-amplitude dipping signal from the Santa Monica Mountain and near the San Andreas Fault, but also south of the San Andreas Fault near a known exposure of Pelona schist, where an anomaly in SKS splitting was also interpreted as showing overprint from the schist on the regional mantle signal (Paul Davis, pers. comm.). The receiver function signal thus shows inherited fabric as well as fabric related to present day deformation. The modern strike slip fault system in the study area may thus root into much broader zones of shear at depth.

C. Interpretation

Southern California has undergone a complex and lengthy strain history. Most recently this has included a protracted history associated with active subduction, including shortening and volcanism, followed by intra and back arc extension in the Middle to Late Miocene. Current strain along the plate
boundary is largely accommodated by dextral shear, begun when an active spreading ridge came in contact with the plate boundary. An eastward jump into thermally weakened crust initiated opening of the Gulf of California, while ongoing organization of a complex system of strike slip faults produced extensional stepovers. Our point is that the strain history as defined by rock fabrics and anisotropy results from this complex history. Constraining bulk fabrics to any particular period and pattern of strain is thus challenging, especially given that the general strike of the fault systems from the Mesozoic onward are parallel to the plate boundary, although strike slip faults do clearly offset Miocene extensional structures at a low angle. Another issue is the likelihood that faults, plastic shear zones and rock fabrics evolve with time even for a single episode of strain such as the current phase of dextral shear. This is highlighted by evidence for deep crustal shear beneath otherwise rigid fault blocks in Southern California (as defined by GPS), such as the block west of the Elsinore fault in San Diego County.

In an initial interpretation, we argue that some, or perhaps most of the steeply east-dipping surfaces illuminated by receiver functions and seismicity are most likely related to reactivation. Reactivated faults commonly occur where they are aligned appropriately with respect to a modern stress field. Hence they are weaker and more likely to slip than faults that are created (i.e. new faults) in a particular stress field. It is the orientation of the older, pre-existing faults that matter most.

An important observation is that there appear to be instances of seismicity on what one would interpret as active faults that do not have a surface expression. This has implications for seismic hazard work that relies on paleoseismic investigations of mappable surface faults to define Late Quaternary moment release in Southern California; i.e., it is a mechanism of moment release that has not been identified or considered previously). In addition, these possible blind strike slip faults may contribute to strain that is seen geodetically (in GPS measurements) but not geologically (by geologists working on surface faults). One example of reactivation of fabric is that of normal faults formed previously in the late Miocene as part of the West Salton Detachment Fault (sensu lato). The current trace of the West Salton detachment is cut obliquely by the Elsinore and San Jacinto faults. Hence, the newly imaged faults may be part of synthetic high-angle fault arrays common in the hanging walls of listric detachments. Our imaging results thus support similar interpretations hinging on inheritance such as the models of fault development from a shallow detachment to intermediate/steep NE-dipping by Dorsey et al. (2012) and Mason et al. (2017) for the San Jacinto and Elsinore fault zones.

D. Figures
Fig. 1a: Strikes (bars) of dipping structures/dipping foliation from receiver functions at stations (white triangles), color coded by converter depth (color bar), plotted with CFM5 preferred surface fault traces and topography. Subsurface strikes are parallel to general NW-SE transform fault orientation (A) with rotation in areas such as Transverse Ranges/Santa Monica Mts (B). The dense LARSEI line shows strike perturbations near a Pelona schist outcrop that are also seen in SKS fast orientations (C). A shallow radial pattern is seen above a proposed magma body in the Coso geothermal field (D). Transform-orthogonal structures near the Salton Sea are also visible in receiver function strikes (E). Seismicity shows matching NE-dipping trends such as on the profile shown by the white line (F), cross section in panel below.

Fig. 1b: Seismicity from the catalog by Hauksson et al. (2012) on a cross section of the San Jacinto Fault (white line near F in Fig. 1a). Surface trace of the Clark strand of the San Jacinto Fault shown as red dashed line. Seismicity has a listric appearance when nearing the brittle-ductile transition near 20 km depth, with a dip of about 45 deg. Shallower seismicity at 12 km depth and above appears near vertical, but is sparse to nonexistent above 10 km depth below the main strand. Similar NE-dipping structures are seen in seismicity throughout the southern part of the study area along the Elsinore, San Jacinto, and San Andreas faults, with shallower dips away from the coast and steeper to near vertical dips closer to the coast (Elsinore fault). Figure by Ross and Ben-Zion (pers. comm.).
Fig. 2: Receiver function-derived strikes of dipping contrasts/foliation for the LARSE-2 passive source broadband line (zoom on area near C in Fig. 1a). Each panel shows arrivals from a different depth range. The line starts in the Santa Monica Mountains near the coast in the south and crosses the San Andreas Fault into the Mojave. Large-amplitude conversions are seen at 5-10 km depth in the Santa Monica Mountains, consistent with N-dipping thrust fabric. Strikes are parallel to the San Andreas and Northridge fault traces in the 10-20 km depth range. A strong signal is seen at 20-30 km depth just west of a known Pelona schist exposure. At similar depths and below, strikes near the SAF rotate away from the fault trace.
E. References


