Seismic velocity structure in the Hot Springs and Trifurcation areas of the San Jacinto fault zone, California, from double-difference tomography

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SUMMARY
We present tomographic images of crustal velocity structures in the complex Hot Springs and Trifurcation areas of the San Jacinto Fault Zone (SJFZ) based on double-difference inversions of earthquake arrival times. We invert for \(V_P, V_S\) and hypocentre location within 50 \(\times\) 50 \(\times\) 20 km\(^3\) volumes, using 266 969 \(P\) and 148 249 \(S\) arrival times. We obtain high-fidelity images of seismic velocities with resolution on the order of a few kilometres from 2 to 12 km depth and validate the results using checkerboard tests. Due to the relatively large proportion of \(S\)-wave arrival times, we also obtain stable maps of \(V_P/V_S\) ratios in both regions. The velocity of the Trifurcation Area as a whole is lower than adjacent unfaulted material. We interpret a 4-km-wide low velocity zone with high \(V_P/V_S\) ratio in the triifurcation itself as related to fault zone damage. We also observe clear velocity contrasts across the Buck Ridge, Clark and Coyote Creek segments of the SJFZ. The Anza segment of the SJFZ, to the NW of the trifurcation area, displays a strong (up to 27 per cent) contrast of \(V_S\) from 2 to 9 km depth. In the Hot Springs area, a low velocity zone between the Claremont and Casa Loma Strands narrows with depth, with clear velocity contrasts observed across both segments. A roughly 10-km-wide zone of low velocity and low \(V_P/V_S\) ratio at the NW tip of the Hot Springs fault is indicative of either unconsolidated sediments associated with the San Jacinto basin, or fluid-filled cracks within a broad deformation zone. High \(V_P/V_S\) ratios along the Anza segment could indicate a preferred nucleation location for future large earthquakes, while the across-fault velocity contrast suggests a preferred northwest rupture propagation direction for such events.

Key words: Earthquake dynamics; Seismicity and tectonics; Body waves; Seismic tomography; Transform faults; Crustal structure.

1 INTRODUCTION
Detailed imaging of fault zone velocity structure can reveal important information about the previous behaviour and likely future properties of earthquakes on the fault. As examples, fault zone regions with relatively high and low seismic velocities may be correlated, respectively, with areas of high slip and end points of ruptures (e.g. Michael & Eberhart-Phillips 1991). Anomalous ratios of \(P\) - and \(S\)-wave velocities, \(V_P/V_S\), can indicate fluid content (e.g. Hauksson & Unruh 2007; Lin & Shearer 2009), changes in lithology (Pickett 1963; Hamilton 1979; Castagna et al. 1983; Christensen 1996), metamorphism (Hall & Simmons 1979; Christensen & Mooney 1995; Zhao et al. 2011), brittle damage (e.g. O’Connell & Budiansky 1974; Shearer 1988; German 2007) and possible nucleation locations of large events (e.g. Thurber et al. 1995; Zhao et al. 1996; Chen et al. 2001; Kayal et al. 2002; Zhao et al. 2011). A persistent velocity contrast across the fault can induce a preferred rupture propagation direction, and affect the crack versus pulse mode of rupture and generated frictional heat (e.g. Ben-Zion & Andrews 1998; Shi & Ben-Zion 2006; Ampuero & Ben-Zion 2008). Lateral and along-strike variations in the velocity structure can lead to dynamic migration and arrest of earthquake ruptures (e.g. Brietzke & Ben-Zion 2006; Zhao et al. 2010; Bennington et al. 2013). Coherent low velocity fault zone layers can act as seismic trapping structures that may increase considerably the near-fault ground motion (e.g. Ben-Zion & Aki 1990; Peng & Ben-Zion 2006; Avallone et al. 2014), and may be used to test the hypothesis of preferred rupture direction on the fault (e.g. Ben-Zion & Shi 2005; Dor et al. 2006; Mitchell et al. 2011). An accurate knowledge of the velocity structure is also important for correct derivations of earthquake locations and focal mechanisms (e.g. Oppenheimer et al. 1988).

Allam & Ben-Zion (2012), hereinafter referred to as ABZ12, derived detailed images of seismic velocities in the plate boundary region around the San Jacinto fault zone (SJFZ) in southern California using the double-difference tomography method of Zhang & Thurber (2003). These regional-scale results were obtained...
Tomography of the San Jacinto fault area

1.1 Geological and regional setting

The 230-km-long San Jacinto Fault Zone (SJFZ; Fig. 1) is the most seismically active fault zone in southern California (Hauksson et al. 2012) and accommodates a large proportion of the plate motion in the region (Fialko 2006). Extensive palaeoseismic work indicates that the SJFZ has repeatedly produced large ($M_w > 7.0$) earthquakes in the past 4000 yr (Rockwell et al. 2006; Rockwell & Seitz 2008), and has the potential to rupture along nearly the entire length of the fault zone in a single event (Salisbury et al. 2012; Onderdonk et al. 2013); the last through-going event likely occurred on 22 November 1800. GPS-derived slip rates vary between 8 and 20 mm yr$^{-1}$ (Kendrick et al. 2002; Fay & Humphreys 2005; Fialko 2006), and surface creep measurements indicate that slip is accommodated co-seismically on at least the central portions of the fault zone (King & Savage 1983). Taken together, these pieces of evidence suggest that a significant slip deficit currently exists for the SJFZ, which represents a clear seismic hazard to the region.

The structurally complex SJFZ consists of multiple segments (Fig. 2), which have distinct surface expressions, each of which exhibit different seismic and geometrical properties (e.g. Lewis et al. 2005; Wechsler et al. 2009, Salisbury et al. 2012). Despite this complexity, the SJFZ is a mature fault zone, in the sense (Ben-Zion & Sammis 2003) that it can have through-going ruptures, which formed gradually over the past 1.5 Ma and has accommodated roughly 24 km of total displacement (Sharp 1967; Rockwell et al. 1990; Kirby et al. 2007). The SJFZ is predominantly right-lateral, with some heterogeneity in focal mechanisms from the more structurally complex sections (Harte et al. 1994; Bailey et al. 2010). The central portion of the SJFZ, often called the Anza section, is the most geometrically simple region with only a single active surface trace, the Clark Fault. Within the Clark segment is the Anza Seismicity Gap (Sanders & Kanamori 1984), which is defined by a lack of microseismicity. Palaeoseismic trench sites at various locations along the Clark Fault indicate that it has a complicated rupture history featuring both large through-going events as well as segmented smaller ruptures (Salisbury et al. 2012; Marilyani et al. 2013).

Southeast of Anza is the Trifurcation Area, where the Coyote Creek and Buck Ridge segments branch off at low angles from the Clark fault. The Buck Ridge segment is a restraining bend, while the Coyote Creek segment is a releasing bend. Though they vary in age and cumulative slip, all three segments are currently seismically active in this region, producing a cloud of distributed seismicity throughout the Trifurcation Area. The complicated geometry also produces large variations in focal mechanism (Bailey et al. 2010; Hauksson et al. 2012). Previous studies examining the geomorphology (Wechsler et al. 2009) and geology (Dor et al. 2006) in the region demonstrate the existence of asymmetric rock damage at the surface, which is generally thought to be diagnostic of preferred propagation of earthquake ruptures on a bimaterial fault interface (e.g. Ben-Zion & Shi 2005; Shi & Ben-Zion 2006). Dorsey & Roering (2006) showed distinct variations in fault-normal basin profiles, with convex profiles to the NW of the trifurcation and concave profiles within the trifurcation area itself, a signal likely produced by the increased extensional component of the Coyote Creek releasing strand. Pronounced lithology contrasts are observed across all three fault strands (Sharp 1967; Morton et al. 2012), with contacts between sedimentary and crystalline rocks in a variety of along-strike locations. Since 2010 April, the Trifurcation area has exhibited increased seismic activity following the El Mayor-Cucapah earthquake (Hauksson et al. 2011).

Northwest of Anza is the Hemet Stepover, a releasing step associated with the San Jacinto basin, where slip is transferred from the Claremont segment to the Casa Loma-Clark segment. Though the surface traces are distinct, palaeoseismic work indicates that the two segments can rupture in a single through-going event with large (~5 m) displacement (e.g. Rockwell et al. 2006; Salisbury et al. 2012; Marilyani et al. 2013). Compressional features at the Northwestern tip of the Casa Loma fault (Ben-Zion et al. 2012), in an area of otherwise extensional deformation, demonstrate the complexity of the system as a whole. The Hot Springs Fault Zone, to the Southeast of the Hemet Stepover, consists of several oblique-slip anastomosing fault segments partly responsible for the uplift of the San Jacinto and Santa Rosa Mountains (Onderdonk 1998). Although most of the slip occurred during the Pleistocene, a cluster of microseismicity ($M_w < 3.0$) at the southeastern end of the Hot Springs fault zone persists from 5 to 15 km depth. This seismicity is spatially distributed and difficult to correlate with any known surface structure.

Recently, the density of seismic stations in the immediate vicinity of the SJFZ increased considerably. As one component of a multidisciplinary effort to study the fault zone environment, approximately 75 new broad-band and strong-motion seismometers have been deployed in the region. The sites have been strategically located to provide dense arrays of seismometers crossing the various fault strands, as well as to fill instrumental gaps in the regional network. Single instruments were also placed at a range of fault-normal distances to provide a basis for comparison to near-fault instruments. In particular, both the Trifurcation and the Hot Springs regions have been targeted with arrays of instruments at a variety of fault-normal distances. These new instruments, combined with the recent intensification of seismic activity, have greatly increased the amount of data available for use in seismological imaging studies.
Figure 1. Location map for the San Jacinto fault zone (SJFZ) environment with $M_w > 1.4$ earthquakes (red circles), seismic stations (blue triangles) and surface traces of large faults (black lines). The background colours indicate topography with brown being high and green being low. The two regions, the Trifurcation and Hot Springs areas, for which seismic velocities were inverted are shown. Only stations and events used in the inversions are shown. New stations deployed since 2009 are shown as green triangles. Map-view cross-sections at different depths for the two areas are shown in Figs 5 and 7. Cross-sections of velocities along profiles A–E are shown in Figs 6 and 8.
1.2 Previous imaging studies

Seismological data have been used to image the structure of the SJFZ at a variety of scales. Regional tomographic studies found evidence for both velocity contrasts across sections of the SJFZ and damage zones (Scott et al. 1994; Hauksson 2000; Hong & Menke 2006; Lin et al. 2007; Tape et al. 2009; Lin et al. 2010; Zigone et al. 2014), considered generally low resolution compared to the scales of these structures. More focused studies incorporating observations of fault zone seismic phases reported trapping structures in the Trifurcation Area (Li & Vernon 2001; Lewis et al. 2005; Yang & Zhu 2010) and in the Hot Springs Area (Li et al. 1997). Although diagnostic of particular fault zone structures, such works do not provide insight into 3-D variations in velocity structure. Hauksson (2000) inverted for \( V_p \) and directly for the \( V_p/V_s \) structure in Southern California, producing images with generally high \( V_p/V_s \) in sedimentary basins and low \( V_p/V_s \) in stable crustal blocks. However, some regions had \( V_p/V_s \) values as low as 1.2, which are likely unrealistic as such values have only been observed in exotic foams and polymers (Lakes 1987; Friis et al. 1988). Interestingly, Hauksson (2000) expected to observe areas of high \( V_p/V_s \) and low \( V_p \) adjacent to the SJFZ, while noting that such features are below the resolution of his study.

ABZ12 recently produced double-difference tomographic images of the Southern California plate boundary region using data from several regional networks, with spatial resolution generally on the order of \( \sim 1-5 \) km for \( P \)-wave velocity and \( 1-6 \) km for \( S \)-wave velocity. The obtained \( V_p/V_s \) ratios. The recent instrument deployments mentioned above, increased seismicity, and new methods for picking \( S \) waves (e.g. Gibbons & Ringdal 2006; Rosenberger 2010) allow this work to achieve both higher imaging resolution and lower disparity between the amount of data that are used for the \( P \)- and \( S \)-wave velocity images.

2 DATA AND METHODS

We use \( P \)- and \( S \)-wave arrival time data from 6070 events \( (M_w > 1.2) \) for the Trifurcation Area, and 10 986 \( (M_w > 1.4) \) events for the Hot Springs area recorded at 93 and 67 stations, respectively, between 200 January and 2013 April. In all, data of 16 096 events recorded at up to 133 stations are used, leading to combined total of 266 969 \( P \) and 148 249 \( S \) arrival time picks for the two regions. Many of the \( P \) and \( S \) picks were obtained using new \( P \) and \( S \) detectors (Kurzkon et al. 2014), based on separation of \( P \) and \( S \) phases by the use of the Singular Value Decomposition algorithm of Rosenberger (2010); all picks were reviewed before inversion. The main advantage of this method is that almost all the \( P \) picks have associated \( S \) picks for the same event-station combination. From these, we compute 197 859 differential arrival times for event pairs with hypocentral distances less than 1 km. Both the analyst-picked catalogue arrival times and those based on singular value decomposition are estimated to typically have picking errors below 20 ms.

We perform two separate inversions, one for the Trifurcation Area and one for the Hot Springs region, on two similarly discretized 50 km \( \times \) 50 km \( \times \) 20 km grids with uniform horizontal spacing of 250 m and vertical spacing of 500 m. Using ABZ12 as the starting model, we invert simultaneously for \( V_p, V_s \) and hypocentre location. Additionally, we employ a variety of checkerboard tests to verify that the discretization is supported by the resolution of the data set (Appendix A).
Following previously established methodology (Zhang & Thurber 2003; Thurber et al. 2006; Lin et al. 2010; Zhang et al. 2010), we apply a progressive hierarchical weighting scheme. In the first few iterations, the absolute arrival time data is weighted more importantly by a factor of 10. At the 18th iteration, the weighting is a factor of 10 towards the differential data. This weighting scheme ensures that the broad-scale velocity structure is established in the early iterations, while convergence to a stable result, which incorporates the higher-resolution differential arrival times, is achieved by the final iteration.

3 RESULTS

3.1 Inversion benchmarks

As in previous double difference tomography works (e.g. Thurber et al. 2006; Lin et al. 2010; Allam & Ben-Zion 2012), we evaluate the quality of the two final models based on four criteria: (1) improvement of fit to the arrival time data, (2) sufficient resolution calculated by the derivative weight sum, (3) plausibility of hypocentre relocations, in terms of alignment with known fault traces and consistency with the velocity structure and (4) resolution estimated from synthetic tests. The change in arrival time misfit rms for each model as a function of iteration number is shown in Fig. 3. After 24 iterations, the absolute arrival time misfit rms for P and S waves together is reduced from 114.1 to 29.6 ms for the Trifurcation Area, and from 121.1 to 45.9 ms for the Hot Springs area. The arrival time misfit rms is low enough for both regions that pick uncertainty is likely a major contributor. The initial model, ABZ12, already produced generally low arrival time misfits, though the final models represent significant improvement. Because of the progressive weighting scheme, successive iterations can temporarily increase the arrival time misfit rms. This is seen most clearly at iteration 13 for the Hot Springs area, where an increase in the weight of the differential arrival time data is accompanied by a large transient increase in arrival time misfit rms. Successive iterations improve the results beyond local minima and reduce the arrival time misfit rms to a stable value. A more complete discussion of the effects of the initial model, smoothing, damping and grid spacing, provided by Allam & Ben-Zion (2012) and previous double-difference tomography papers.

The derivative weight sum (DWS) is a measure of the sensitivity of each inversion node to changes in model parameters (Thurber & Eberhart-Phillips 1999). It is computed as the sum over all event-receiver pairs of the derivative of the arrival time with respect to a given model parameter (e.g. slowness), and it is generally proportional to the density of ray paths near each node. In this work, we plot contours for DWS values of 10 following Zhang et al. (2004). This value is somewhat ad hoc, but is based on the average DWS of all nodes compared to the DWS of particular nodes. In practice, the value chosen for the DWS contour threshold isn’t important, because the gradients in DWS are quite steep.

The relocated and catalogue epicentral locations are compared in Fig. 4 for the two regions. More detailed 3-D views of the two catalogues are available in Movie S4. The mean absolute value of the changes are 1.4 km laterally and 1.9 km vertically for the Hot Springs area, and 1.6 km laterally and 2.2 km vertically for the Trifurcation Area. Along geometrically simple fault segments, such as the Clark fault, the patterns seen in the relocated seismicity are consistent with previous relocation results for strike-slip environments (e.g. Waldhauser & Ellsworth 2000; Hauksson et al. 2012), with tight near-planar clustering around the fault trace. In the Trifurcation Area (Fig. 4a), the relocated seismicity is much better aligned with the various fault traces than the initial locations. Seismicity in the Anza section of the Clark fault is aligned in a fault-parallel orientation offset to the NE from the surface trace. Where the Buck Ridge and Coyote Creek strands branch from the Clark fault, there are no clear patterns in the broadly distributed relocated seismicity. Further to the SE, seismicity along both the Clark and Coyote Creek segments is aligned roughly along the surface traces, though there appear to be several linear features at low angle to the general strike of the faults in the region. To the SW of Anza, an area of seismicity not associated with any surface traces appears to be aligned orthogonally to the main fault strike.

In the Hot Springs area (Fig. 4b), relocated seismicity around the Hot Springs fault and Casa Loma fault is clustered along fault-parallel lineations offset from the surface traces; to the SW of the trace for the Hot Springs and to the NE for Casa Loma. In the northern part of the imaged region, seismicity is widely distributed in without any clear lineation, though the relocated events cluster more tightly in general than the initial catalogue locations.

In order to assess the spatial resolution of the inversion results, we perform a suite of classical and modified checkerboard tests in Appendix A. In addition to the recovery of regional variations on scales from 3 to 8 km, we design tests to assess the capability of the inversion method to recover small-scale, high-amplitude, sharp-bounded structures commonly observed in close proximity to fault zones (e.g. Ben-Zion & Sammis 2003). These synthetic tests suggest a spatial resolution of approximately 3 km both horizontally and vertically, though smaller-scale features may still be present in the results, albeit somewhat smoothed. Although such tests can provide some confidence in model results, checkerboard tests cannot be directly interpreted for model resolution (e.g. Lévêque et al. 1993); resolution depends on the ray paths, which in turn depend on the velocity structure. Thus, an unrealistic velocity structure distributes resolution in unrealistic ways. Nevertheless, the checkerboard tests demonstrate that the ray coverage produced by the actual source-receiver geometry is sufficient to provide some confidence in the inversion results.
clear in the $V_p$ images, while the shapes and distributions of the low velocity zones are most clear in the $V_s$ images. The $V_p/V_s$ images correlate well with both fault zone structure (high $V_p/V_s$) and the locations of plutonic rock bodies (generally low $V_p/V_s$).

In the $V_p$ images (Figs 5 and 6), there are clear contrasts across the Buck Ridge segment at 2 km depth, across the Clark segment at 5 km depth, and across the Coyote Creek at 8 km depth. Along the Buck Ridge and Clark faults, the NE side has higher velocity; this pattern is reversed along the Coyote Creek fault. In the $V_s$ images, a prominent low velocity zone at the junction of the three faults becomes narrower with depth. Although the NE side of the fault is generally faster than the SW side, the lowest S-wave velocity is in an approximately 4-km-wide zone near the junction itself. Reduced S-wave velocity is also observed in the region between the Clark and Coyote Creek segments.

The highest velocity regions on the NE side of the fault, most prominent in the images at 2 km depth, correspond to the Thomas Mountain and Santa Rosa Mountain plutons, which are composed of relatively dense tonalitic and gabbroic rocks (Sharp 1967; Hill 1988). The depth extent of the two plutons is unclear, though high velocities persist to depths of 10 km or more in these areas. The Collins Valley pluton, more granitic in composition, also appears as a high velocity region south of the Coyote Creek fault, though it is along the edge of the resolvable region. Other igneous bodies, including the Horse Canyon and Cahuilla Valley plutons, do not have such obvious expressions in the seismic velocity, possibly because of competition with damage related signals (e.g. Wechsler et al. 2009); intense pulverization and other earthquake-related damage have been observed especially in the Horse Canyon pluton (Morton et al. 2012).

Due to the higher proportion of $S$-wave phase picks than used by ABZ12, the images of $V_p/V_s$ ratio are much more stable in the present work and can be more confidently interpreted (Fig. A3). At the junction of the three faults, an intense low velocity zone is observed in both $V_p$ and $V_s$, though the reduction in velocity is much greater for $V_s$. This creates a broad region of high $V_p/V_s$ ratio observable in both the 2 and 5 km depth images. Zones of high $V_p/V_s$ are also observed along all three fault strands at shallow depth, though they are largely absent by 8 km depth. High $V_p/V_s$ ratios are consistent with expectations for brittle damage associated with dilatancy (e.g. Lockner et al. 1992; Hamiel et al. 2004; Lewis & Ben-Zion 2010). The $V_p/V_s$ ratios near the faults also decrease with depth, suggesting a mechanical and/or fluid origin rather than lithological control on this signal. In contrast, relatively lower $V_p/V_s$ ratios in the plutonic rocks are within reasonable ranges for silicic rocks (Christensen 1996) and remain fairly constant with depth.

### 3.3 Tomographic images of the hot springs area

Fig. 7 shows map views of $V_p$ (left-hand panel), $V_s$ (middle panel) and the $V_p/V_s$ ratios (right-hand panel) at three different depths for the Hot Springs area, with white contours enclosing well-resolved areas with DWS higher than 10. Fig. 8 shows cross-section views along the profiles defined in Fig. 1(c). More detailed 3-D animations of the $V_p$ and $V_s$ structure of the Hot Springs area are shown in Movie S1. Contrasts in velocity across the fault segments are most

![Figure 4](https://academic.oup.com/gji/article-abstract/198/2/978/600782)

**Figure 4.** Map views of relocated seismicity (red) compared to the initial catalogue locations (blue) and surface traces (black lines) for the (a) Trifurcation Area, and (b) Hot Springs area. In both regions, the relocated hypocentres show linear features which correlate with various fault strands. In (a), linear seismicity along the Clark segment near Anza is offset to the NE of the surface trace, possibly indicating a slight fault dip. Seismicity throughout the Trifurcation area is broadly distributed, though there is some alignment of events in the southern and eastern Clark and Coyote Creek Strands. A band of linear seismicity branching perpendicularly from the trifurcation does not correlate with any surface trace. In (b), seismicity is aligned along both the Hot Springs and Casa Loma faults, though slightly offset from the surface traces.

### 3.2 Tomographic images of the trifurcation area

Fig. 5 shows map views of $V_p$ (left-hand panel), $V_s$ (middle panel) and the $V_p/V_s$ ratios (right-hand panel) at three different depths for the Trifurcation Area, with white contours enclosing well-resolved areas with DWS higher than 10. Fig. 6 shows cross-section views along the profiles defined in Fig. 1(b). More detailed 3-D animations of the $V_p$ and $V_s$ structure of the Trifurcation Area are shown in Movie S1. Contrasts in velocity across the fault segments are most
Figure 5. Map-view cross-sections at depths 2, 5 and 8 km for the Trifurcation area of $V_p$ (left-hand panel), $V_s$ (middle panel) and the $V_p/V_s$ ratio (right-hand panel). The white contours enclose areas that are well sampled by the employed sources and receivers ($DWS > 10$); the DWS contours for the lower resolution $V_s$ model are shown on the $V_p/V_s$ images for reference. A prominent low velocity zone along the Anza segment and at the trifurcation has elevated $V_p/V_s$ ratio and is possibly a damage-related signal. Contrasts in velocity across each of the faults are clear in both $V_p$ and $V_s$. In general, the entire region near the three fault strands has lower velocities and higher $V_s$ ratios than the surrounding unfaulted regions, which consist mostly of plutonic igneous rocks with $V_p/V_s$ ratios consistent with silicic composition.
Figure 6. Vertical cross-sections (SW to the left-hand panel, NE to the right-hand panel) in the Trifurcation area along the profiles defined in Fig. 1. For each profile, $V_p$ (top panel), $V_s$ (middle panel) and $V_p/V_s$ (bottom) are shown. The white contours enclose areas that are well sampled by the employed sources and receivers ($DWS > 10$); the $DWS$ contours for the lower resolution $V_s$ model are shown on the $V_p/V_s$ images for reference. Sharp velocity contrasts and flower-shaped (narrowing with depth) low velocity zones are visible in most of the cross-sections. In particular, profile A in the Anza segment contains a low velocity zone with high $V_p/V_s$, and a sharp contrast where the fault abuts the Thomas Mountain pluton.
Figure 7. Similar to Fig. 5 for the Hot Springs area. A low velocity zone at the NW tip of the Hot Springs fault corresponds to the San Jacinto basin. Because it has a low $V_p/V_s$ ratio, it is likely of different provenance than the low velocity zone along the Anza segment.

San Jacinto basin, this zone extends with decreased amplitude to the SE along the Casa Loma-Clark fault all the way to the Anza segment, where the velocity is the lowest observed in this study. Sharp velocity contrasts exist along both the Hot Springs and Casa Loma-Clark segments in the upper 6 km, though there is no clear sign of the Hot Springs fault below this. High velocity regions to the NE and SW of the San Jacinto Basin correspond to the San Jacinto Mountains and Santa Rosa Hills respectively. A mild low velocity
zone in the centre of the San Jacinto Mountains is unaccounted for by any geologic or structural feature.

In the $V_p/V_s$ images, the most significant feature in this region is a low-ratio zone in the San Jacinto Basin. Low $V_p/V_s$ ratios in this range may be attributed to siliciclastic (e.g. Pickett 1963) or clay-rich rocks (Castagna et al. 1985) with fluid-saturated porosity (Kuster & Toksöz 1974; Shearer 1988), though the low ratio zone extends deeper than the estimated $\sim 4$ km depth of the basin (Langenheim et al. 2004; Graves 2008; Plesch et al. 2011). Farther to the SE, in the small area overlapping the other imaged region,
there is a clearly elevated ratio along the Anza segment and in the Trifurcation area as described in the previous section. The plutonic rocks around the Hot Springs area feature $V_p/V_S$ ratios largely consistent with the local lithologies. The more mafic rocks in the northwestern San Jacinto Mountains have relatively high $V_p/V_S$ ratios, which grade into the lower ratios of the more granitic central San Jacinto Mountains.

4 DISCUSSION

The seismic velocity models presented in this study are currently the highest resolution available in the two regions. There is general agreement where the two models overlap; in the vicinity of Anza, very low velocities and elevated $V_p/V_S$ ratios exist in both models. The spatial patterns in $V_p$, $V_S$ and the $V_p/V_S$ ratios contain important information on rock properties in complex regions of the SJFZ. However, some care must be taken in the interpretation of these patterns as the observed seismic velocities are subject to trade-offs among density, temperature, lithology, fluid content, pressure, crack density and anisotropy (e.g. Christensen 1996; Karato & Hung 1998). Though these trade-offs cause non-uniqueness, we nevertheless point to informative correlations between various aspects of the obtained images, results of previous works and expected features of crustal fault zones.

Variations in $V_p/V_S$ value indicate changes in crack density, lithology, anisotropy and/or fluid content (Christensen 1996; Karato & Jung 1998). Mafic, calcareous, foliated and most metamorphic rocks have high $V_p/V_S$ values around 1.75–1.8 (Christensen 1996; Gercek 2007). On the other hand, siliciclastic rocks (e.g. sandstone), clay-rich rocks (e.g. shale) and quartzite have low $V_p/V_S$ values (Castagna et al. 1985). For all of these lithologies, temperature and pressure have very little effect at crustal ranges (Christensen 1996). Thus, the effect of lithology on the $V_p/V_S$ ratio, though strong, does not vary at the depth ranges examined in this study. In contrast, crack density is predicted to decrease with depth due to healing mechanisms (e.g. Finzi et al. 2009; Lyakhovsky & Ben-Zion 2009), while porosity also in general decreases (e.g. Bjørkum et al. 1998), both of which result in a decreased $V_p/V_S$ ratio with depth (Gercek 2007). The effects of porosity and crack density on $V_p/V_S$ have been studied through modelling of cracked media (O’Connell & Budiansky 1974; Shearer 1988; Thomsen 1995), observational and laboratory measurements (Hamilton 1979; Castagna et al. 1985; Bachrach et al. 2000) and local-scale $V_p/V_S$ tomography (e.g. Gentile et al. 2000).

Because fault-related damage consists of shear and tensile fractures with very high aspect ratio (e.g. Mitchell & Faulkner 2009), fluids in damaged rocks lead to high $V_p/V_S$ ratios (Shearer 1988). Taken altogether, these observations lead us to interpret near-fault regions of low velocity and high $V_p/V_S$ that narrow with depth as signatures of fault zone damage.

Previous earthquake tomography models for the region by Magistrale & Sanders (1995), Hauksson (2000), Tape et al. (2009, 2010) Lin et al. (2010) and ABZ12 show the same overall patterns of contrasting high and low velocity along the various fault strands. Similar patterns are also observed in noise-based imaging results of Hillers et al. (2013) and Zigone et al. (2014) for the SJFZ area. The more local images by Scott et al. (1994) and Hong & Menke (2006) in the Trifurcation Area also show low velocity at the trifurcation and higher velocities on the NE side of the fault. None of these works obtained sufficient resolution to image low velocity fault zones that may act as seismic trapping structures (e.g. Lewis et al. 2005; Yang & Zhu 2010).

Near-fault low velocity zones that narrow and diminish with depth are observed on virtually all of the fault-normal cross-sections (Figs 6 and 8), but are especially clear on 8B, 8E and 6B, which correspond to the San Jacinto Basin, the Anza segment of the Clark Fault and the trifurcation area, respectively. See also fig. 16 of Zigone et al. (2014). Previous work on the San Jacinto Basin suggests it is likely a shallow feature restricted to the upper 2–4 km (Langenheim et al. 2004; Graves 2008; Plesch et al. 2011). If so, the deeper low velocity zone seen in this region could possibly be attributed to fault-related damage, though the generally low $V_p/V_S$ ratio in the area is consistent with high-porosity fluid-filled silicic rocks.

The Anza section of the Clark Fault, which lies in the overlap between the two imaged regions, contains both a ~15 km long segment of aligned seismicity as well as the ~10 km ‘Anza Seismicity Gap’ (Sanders & Kanamori 1984) that lacks seismicity in the recorded catalogue. Both the seismicity and the velocity contrast (Fig. 6A) are offset to the NE from the surface trace of the fault, suggesting a slight dip to the NE. To the SE, where the Clark fault joins the Buck Ridge and Coyote Creek, the lowest observed velocities in the entire region, which coincide with the highest $V_p/V_S$ ratios, extend in a ~5-km-wide zone around the fault (Figs 6B and C) and narrow with depth. The velocity contrast to the NE of the fault zone is very sharp, as it is in direct contact with the high velocity Thomas Mountain pluton. This is the opposite polarity of the contrast of the Clark fault in the Hot Springs area, but the same polarity of the contrast across the Hot Springs fault (Fig. 8B). In general, there are variations in both the strength and the sense of the velocity contrast across different branches of the SJFZ. Further to the SE of the trifurcation, contrasts can be observed across all three depths, though the Clark segment has the deepest and strongest contrast.

High $V_p$ and $V_S$ as well as moderate $V_p/V_S$ ratios are observed in nearly all of the plutonic rocks in the imaged areas. These features are shown in Figs 8(a) and (b) for the Santa Rosa Hills, Figs 8(b) and (c) for the San Jacinto Mountains, Figs 8(D), (E) and (F) for the Thomas Mountain pluton, and Figs 6(B) and (C) for the Cahuilla Valley and Santa Rosa plutons. These are generally medium-grained Mesozoic tonalitic rocks that have been offset by the various fault strands of the SJFZ. The high observed velocities are consistent with previous work on pluton-derived precariously balanced rocks (Brune 1996; Brune et al. 2006), suggesting that these high velocities cause a deamplification of coseismic ground motion. Such deamplification in regions of high velocity has also been observed in numerical simulations of large earthquakes (e.g. Graves et al. 2011).

The off-fault plutonic rocks in the region generally have $V_p/V_S$ ratios that do not vary with depth, as seen in Figs 6 and 8. In most of these igneous rocks, the $V_p/V_S$ ratios are slightly lower than those of the initial model, with values consistent with the silicic composition (Christensen 1996). However, the northwestern portion of the San Jacinto Mountains (Figs 7, 8A and B) has slightly elevated $V_p/V_S$ ratio; this is to be expected from the more mafic composition (Hill 1988). To the southeast, the San Jacinto Mountains become more silicic, and correspondingly feature decreased $V_p/V_S$ value. The highly silicic Thomas Mountain, Cahuilla Valley and Santa Rosa plutons in the Trifurcation area (Fig. 5) have low $V_p/V_S$ ratios that also do not show depth dependence.

In contrast, the zone of relatively high $V_p/V_S$ ratios around the Anza segment (Figs 5 and 6) which narrows with depth is consistent with expectations for brittle damage associated with dilatancy (e.g. Lockner et al. 1992; Hamiel et al. 2004; Lewis & Ben-Zion 2010);
both $V_p$ and $V_S$ are reduced in these areas, but $V_S$ is more strongly affected. Low near-fault $V_p/V_S$ values that narrow with depth in the Hot Springs area (Figs 7 and 8) are likely the combined result of several effects. Poorly-consolidated or highly porous sedimentary rocks tend to have low $V_p/V_S$ ratios (Castagna et al. 1985; Bachrach et al. 2000) as do clay-rich rocks, which have been observed near fault zones and are thought to be related to faulting processes (e.g. Faulkner et al. 2008; Frost et al. 2009; Heesakkers et al. 2011). Since sedimentary basins also tend to narrow with depth, these two mechanisms are difficult to distinguish.

Various seismological studies have observed high $V_p/V_S$ ratios in the nucleation zones of several large earthquakes; examples include the 1989 $M_7.5$ Loma Prieta (Lin & Thurber 2012), 1995 $M_7.3$ Kobe (Zhao et al. 1996), 1999 $M_7.7$ Chi-Chi (Chen et al. 2001), 2001 $M_7.7$ Bhuj (Kayal et al. 2002) and a suite of $M_7\sim6.0$ Friuli area events (Gentile et al. 2000). These studies often indicate both a high $V_p/V_S$ ratio before and a further increased ratio after the large events, suggesting that an along-fault region of high $V_p/V_S$ is both a preferred nucleation site for, and a consequence of, large events. Considering these observations, the high $V_p/V_S$ area near Anza is a particularly conspicuous feature of the present results. Indeed, palaeoseismic work suggests this area as a possible nucleation site for, and a consequence of, large earthquakes (Rockwell et al. 1990) that may rupture the entire SJFZ (Salisbury et al. 2012). Model simulations of seismicity that assimilate the available instrumental and palaeoseismic data identify the near Anza region as a likely nucleation site of approaching future large earthquake (Zoller & Ben-Zion 2014).

The across-fault velocity contrast in this section of the fault suggests a preferred NW rupture propagation direction (e.g. Ben-Zion & Andrews 1998; Ampuero & Ben-Zion 2008), with implications for strong directivity towards the populous San Bernardino and Los Angeles basins.

5 CONCLUSIONS

The high resolution velocity models of the Hot Springs and Trifurcation areas of the San Jacinto Fault Zone contain detailed information about the structure of both the fault zones and the surrounding rocks. The inclusion of a large proportion of S-wave arrival time picks results in $V_p$ and $V_S$ models at similar resolution, allowing the creation of $V_p/V_S$ maps which can be interpreted to provide insight into properties of damaged fault zone rocks and possible high fluid content. Pronounced bimaterial interfaces are observed across virtually every fault strand, with some variation in both strength and polarity of the velocity contrast. Kilometers-wide zones of low velocity and high $V_p/V_S$ ratio likely reflecting rock damage which narrow with depth, most pronounced along the Clark fault near and south of Anza, are likely the result of past and ongoing brittle deformation processes. Around the Hot Springs fault low $V_p/V_S$ ratios likely reflecting fluids and high porosity are observed. These patterns are distinctive from that of the nearby plutonic rocks, which have relatively high velocity and low $V_p/V_S$ with no obvious depth dependence. Examined together, the $V_p$, $V_S$ and $V_p/V_S$ images suggest the Anza region as the logical hypocentre location for a future large earthquake with a preferred NW rupture propagation direction. Combined with palaeoseismic studies that show previous such events, geodetic studies that show slip deficit, increased rate of $M>4.5$ events south of Anza since 1980, and related model simulations, these results have important implications for the earthquake hazard in Southern California.

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REFERENCES


Zhao, D., Kanamori, H., Negishi, H. & Wiens, D., 1996. Tomography of the San Jacinto fault area


**APPENDIX: RESOLUTION ANALYSIS WITH SYNTHETIC TESTS**

Checkerboard tests are used commonly to assess the spatial resolution of tomographic inversions. Though it is well known that these tests have limitations (e.g. Lévêque et al. 1993), they offer useful first-order estimates of spatial resolution and thus provide confidence in the interpretation of structural features. Such tests are typically applied to large-scale regional tomography where the wavelength of the perturbations is large with respect to the total size of the inversion region, with amplitudes that are relatively small compared to an average 1-D velocity model, and with smooth transitions from positive to negative amplitude. Fault zone structure, on the other hand, often features small-scale variations with high amplitude and sharp transitions. With these considerations in mind, we conduct various synthetic tests, including classical checkerboard tests and cases tailored to fault zone environments, to assess the ability of the employed method to resolve particular features of interest.

The performed tests demonstrate the horizontal and vertical resolution regionally, detection of fault-zone specific low velocity zones, and the stability of Vp/Vs ratios. Inversion results for four different models are shown: (i) a 3-D checkerboard with equal dimensions of 3 km and sharp boundaries, (ii) a 0.5-km-wide vertical low velocity zone embedded in a 1-D gradient model, (iii) a vertical low velocity zone embedded in 5 km vertical checkers embedded in a 1-D gradient model and (iv) 8 km checkers with smooth boundaries in a 1-D gradient model. We begin by describing the methodology common to all the cases.

First, we construct the synthetic ‘true’ model (e.g. a checkerboard) assuming a constant Poisson ratio of 1.73. Second, we compute the P- and S-wave arrival time catalogue for the model using the built-in ray-tracing of the TomoDD software (Um & Thurber 1987) for the actual source–receiver pairs used in the inversion (Fig. 1). Finally, we treat this catalogue as the observed data and perform a double-difference inversion starting from a homogeneous model. Entirely separate inversions are performed for the Hot Springs and Trifurcation areas. The results of these inversions demonstrate how well the assumed ‘true’ structure is recovered from the source–receiver geometry and inversion parameters used in this work. In the following, we limit discussion of images to regions considered well resolved (inside white contours; DWS $\geq$ 10).

Fig. A1 shows map-view images of $V_p$ for the two regions based on a checkerboard (bottom panel) with uniform dimensions of 3 km in the x, y and z directions. The velocity anomalies vary in the range $5.5 \pm 0.5$ km s$^{-1}$. Within the well-resolved area the velocity anomalies are recovered with approximately 1-km-wide smoothing of the ‘true’ sharp boundaries. In the Trifurcation region, there are minor streaking artefacts, indicating a balanced spatial distribution of sources and receivers. In the Hot Springs region, there are clear streaking artefacts at both 3 km depth and 9 km depth, though nearly all the individual anomalies are discrete and separate enough to be identifiable. Fig. A2 shows cross-section views of the same model. The well-resolved region is small with respect to the total volume, but anomalies in the Trifurcation area of interest with dense seismicity are recovered with little smearing. The Hot springs region shows good recovery in nearly all of the cross-sections from 2 to 15 km depth. In general, the results of this test provide confidence in the interpretation of any velocity feature of dimensions 3 km or larger both horizontally and vertically.

Fig. A3 shows map-view images of the $V_p/V_s$ ratios for the same model shown in Figs A1 and A2; the ‘true’ model has a homogeneous $V_p/V_s$ ratio of 1.73. The Trifurcation area results within the white contour show small deviations from this value, and with no obvious spatial pattern. The Hot Springs region results are noisier and have an artificial diamond-shaped pattern of high and low $V_p/V_s$ due to the streaking artefacts seen in Figs 1 and 2. This feature is expected because the Hot Springs region has a slightly smaller proportion of $S$ arrival time picks compared to the Trifurcation area. Nevertheless, these inversion artefacts are very low amplitude compared to the results of the actual inversion (Figs 5–7). These images provide significant improvements over previous work (Allam & Ben-Zion 2012) where the $V_p/V_s$ images were dominated by large-scale numerical fluctuations.

Fig. A4 shows map-view images of $V_p$ results for a 500-m-wide vertical low velocity zone in a 1-D gradient. The low velocity zone extends to the bottom of the model at 20 km depth and has a linear gradient with depth from 4 to 5 km s$^{-1}$, while the surrounding medium has a gradient from 5 to 6 km s$^{-1}$. In the inversion results for both regions, the narrow fault zone structure is recovered although with larger width and lower velocity reduction. The velocity structure outside the low velocity zone is very well recovered; the inversion recovers the 1-D model starting from a homogeneous model. Fig. A5 shows results for a similar model with the addition of 6-km-wide checkers. In spite of the more complicated structure, the 500-m-wide low velocity zone can still be identified clearly in the images. These results indicate that although the 500-m-wide zone is below the nominal resolution of the data set for checkers, it is nevertheless recovered, albeit somewhat smeared spatially. We note that some of the low velocity zones observed in the actual tomographic results (Figs 5–7) may be sharper features with even greater reduction in velocity. Nevertheless, we refrain from discussing any such potential small-scale features in the main body of the paper.

Fig. A6 shows results for a checkerboard model with smoothed boundaries between 8 km checkers and a linear 1-D gradient. The smoothing applied to the ‘true’ model is approximately 1 km wide. In the Trifurcation area, these relatively large-scale anomalies are recovered well with smooth boundaries of approximately the same width as the ‘true’ model. In the Hot Springs area, there are again some clear streaking artefacts, especially to the east. The boundaries between the anomalies are slightly smoother than in the ‘true model’. We note that this smoothing is approximately the same as in Figs A1 and A5, suggesting that gradients in the crust sharper than ~1 km in width will be smoothed in the real inversion results.

In summary, the examined synthetic tests suggest a spatial resolution of approximately 3 km both horizontally and vertically, though genuine smaller-scale features may still be present in the results in somewhat smoothed forms. The synthetic $V_p/V_s$ images are stable and free from large-amplitude artefacts, providing confidence in the interpretation of the $V_p/V_s$ features seen in the real inversion results.
Figure A1. Map-view images of $V_p$ based on a checkerboard (bottom panel) with uniform dimensions of 3 km in the $x$, $y$ and $z$ directions. The velocity values are in the range $5.5 \pm 0.5$ km s$^{-1}$. Recovery in both regions is generally good, though streaking artefacts are present in the Hot Springs region.
Figure A2. Cross-section views of $V_p$ for the model shown in Fig. A1 (right-hand panels).
Figure A3. Map views of $V_p/V_s$ for the model shown in Figs A1 and A2. The 'true' $V_p/V_s$ ratio is a constant 1.73. Both regions are relatively free of artefacts; the Trifurcation area has a higher proportion of $S$ arrival time picks compared to the Hot Springs area, resulting in fewer artefacts.
Figure A4. Similar to Fig. A1 for a 500-m-wide vertical low velocity zone in a 1-D gradient. The low velocity zone is present, although smoother, in the inversion results.
Figure A5. Similar to Fig. A4, with the addition of 6-km-wide checkerboard anomalies. Despite the more complicated structure, the 500-m-wide velocity zone can still be identified in the results.
Figure A6. Similar to A1 for a model with smooth 8-km-wide checkerboard anomalies in a 1-D gradient. The anomalies are recovered reasonably well, especially in the Trifurcation area.
**SUPPORTING INFORMATION**

Additional Supporting Information may be found in the online version of this article:

**Movies S1.** Animations of the velocity structure of the Trifurcation region. Views of $V_p$ (a–c) and $V_s$ (d–f) are shown with moving cross-sections in the (a) fault-normal, (b) fault-parallel, and (c) surface-parallel directions.

**Movies S2.** Similar to Fig. S1 for the Hot Springs region.

**Figure S3.** Colour scales used for the animations shown in S1 and S2.


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