Geological Society, London, Special Publications

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Geological Society, London, Special Publications 2007; v. 290; p. 189-201
doi:10.1144/SP290.5

Relatively simple through-going fault planes at large-earthquake depth may be concealed by the surface complexity of strike-slip faults

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Abstract: At the surface, strike-slip fault stepovers, including abrupt fault bends, are typically regions of complex, often disconnected faults. This complexity has traditionally led geologists studying the hazard of active faults to consider such stepovers as important fault segment boundaries, and to give lower weight to earthquake scenarios that involve rupture through the stepover zone. However, recent geological and geophysical studies of several stepover zones along the San Andreas fault system in California have revealed that the complex nature of the fault zone at the surface masks a much simpler and direct connection at depths associated with large earthquakes (greater than 5 km). In turn, the simplicity of the connection suggests that a stepover zone would provide less of an impediment to through-going rupture in a large earthquake, so that the role of stepovers as segment boundaries has probably been overemphasized. However, counter-examples of fault complexity at depth associated with surface stepovers are known, so the role of stepovers in fault rupture behaviour must be carefully established in each case.

Major active strike-slip faults are often characterized by major (kilometre-scale) discontinuities, or stepovers. The surface fault expression within these stepover zones can be exceptionally complex. Primary fault strands or primary displacement zones (PDZs) may not directly connect, or connect through abrupt bends, and through-going fault strain may be accommodated by multiple oblique faults and (or) folds.

In many analyses of seismic hazards, these stepover zones are considered to be important fault segment boundaries (for example, King & Nabelek 1985; Sibson 1985, 1986). Because of the complex and disrupted nature of the stepover zones, segment-based rupture probability studies usually assign lower weight to scenarios that require rupture through a stepover (for example, the Working Group on California Earthquake Probabilities 1999, 2003). Because of their potential importance for earthquake dynamics, many quantitative studies of stepovers have been made (see Harris & Day 1993 for a review of the literature). Recent numerical modelling studies (for example, Harris *et al.* 1991; Harris & Day 1993) suggest that stepover width plays an important role in the potential for through-going rupture.

However, recent studies of the dominantly right-lateral strike-slip San Andreas fault system (Fig. 1) in central and southern California, USA, have revealed that at depths associated with major earthquakes (greater than 5 km), the connection through some stepovers may be simpler and more direct than that expressed at the surface. Fault rupture through such stepovers may be more likely than previously suggested, perhaps resulting in less-frequent, but larger earthquakes.

Below we outline the geological and geophysical evidence for simplicity at depth associated with several restraining and releasing stepovers in the San Andreas fault system. We also discuss a counter-example revealed by geophysical studies in southern California. Lastly, we look at the palaeoseismic and historic earthquake evidence for faults associated with simple-at-depth stepovers in order to examine the possibility of an earthquake that has ruptured through a stepover.

Throughout this paper we make extensive use of hypocentre locations relocated using the double difference technique to define the active fault surface at depth. In a recent application of this technique, Schaff *et al.* (2002) state that location errors for the relocated hypocentres are typically one to two orders of magnitude smaller than the 1.2 km horizontal and 2.5 km vertical average 95% confidence estimates for the standard catalogue data in northern California. However, the relative location of closely spaced relocated hypocentres is likely to be better than absolute location of relocated hypocentres, so the analysis that follows is based on the shape of the fault at depth as defined by the relative location of the hypocentres, rather than details of the position of the fault surface at depth, relative to surficial features, as defined by the absolute location of the hypocentres.

From: CUNNINGHAM, W. D. & MANN, P. (eds) *Tectonics of Strike-Slip Restraining and Releasing Bends.*
Geological Society, London, Special Publications, **290**, 189–201.
DOI: 10.1144/SP290.5 0305-8719/07/$15.00

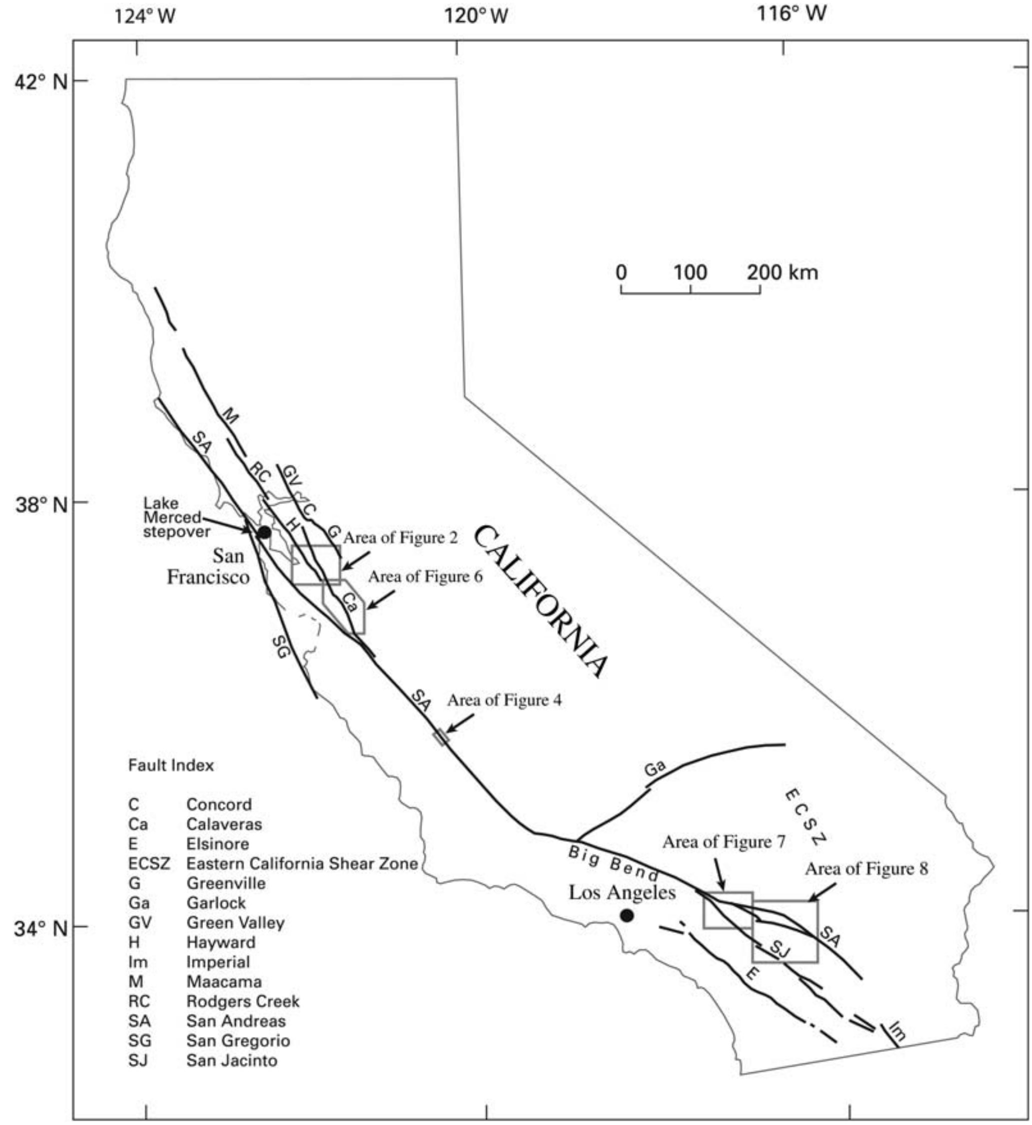

Fig. 1. Index map of the San Andreas Fault system in California, showing the location of the areas discussed in the text.

Restraining stepovers – Hayward–Calaveras Fault stepover

In the San Francisco Bay region, the San Andreas fault system includes several dominantly right-lateral strands, including the San Andreas, Calaveras and Hayward faults (Fig. 1). At the Earth's surface, the Hayward Fault splays from the southern Calaveras Fault, and about two-thirds of the total Calaveras slip is transferred on to the Hayward Fault, through a 25-km-long, 5-km-wide left step in the dominantly right-lateral faults (Fig. 2). This stepover is characterized by multiple oblique reverse faults (Fig. 2), with no single, simple direct surface connection between the main fault strands or PDZs.

However, at fault depths associated with large earthquakes (greater than 5 km), double-difference relocated microseismicity (Figs 2 & 3; Waldhauser & Ellsworth 2002; Hardebeck *et al.* 2004) reveals that the fault connections are much simpler, with a single continuous east-dipping fault at depth (Simpson *et al.* 2003, 2004; Manaker *et al.* 2005). Cross-sectional views of seismicity and geology suggest that the surface complexity is probably limited to the upper 3 to 5 km in the stepover

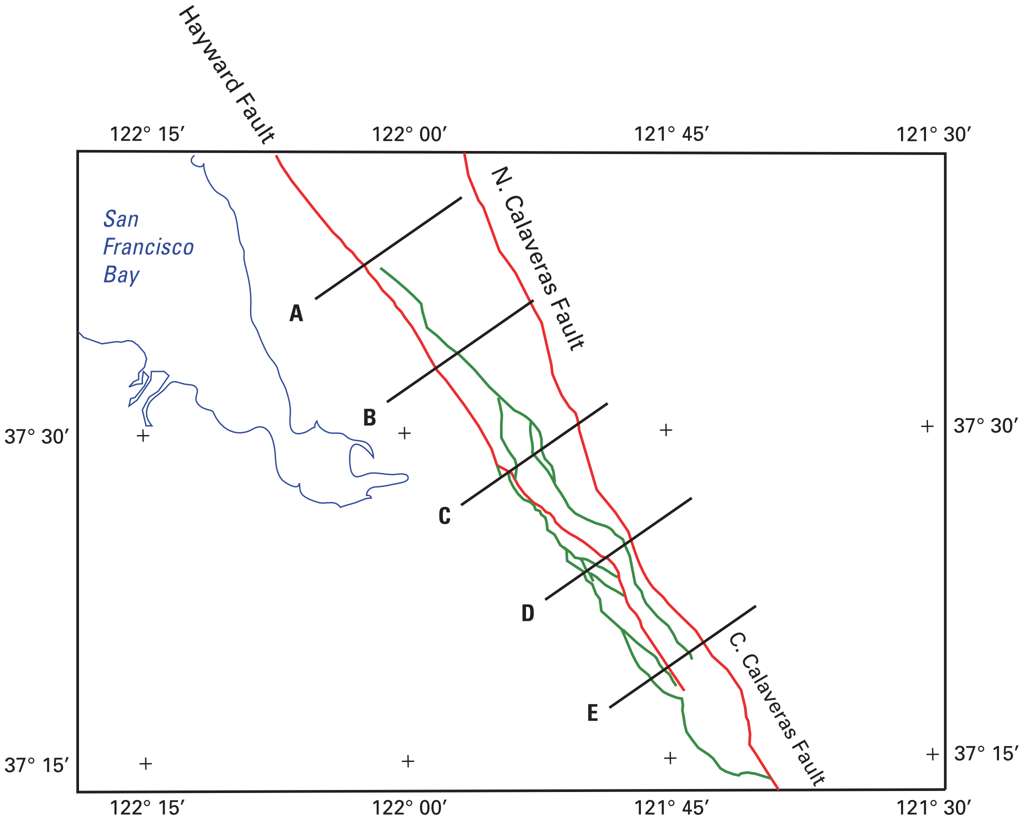

Fig. 2. Map of the southern Hayward and northern and central Calaveras faults (in red) in the southern San Francisco Bay region, California, including the left (restraining) stepover of 3–5 km width. Oblique faults forming the complex surface zone of deformation within the stepover are shown in green, the 1984 through 2000 double-difference relocated seismicity below 5 km is shown as black dots. Note that the deep seismicity defines a simple fault connection with a 12° westward bend. The locations of the cross-sections (A through E) in Figure 3 are also shown. (Modified from Bryant 1982; Graymer *et al.* 1996; Wentworth *et al.* 1998; Simpson *et al.* 2004.)

zone (Fig. 3). Seismicity occurs in diffuse and discontinuous clumps and probably reflects sporadic activity on the multiple oblique faults in this near-surface volume. Below 5 km, cross-sections of seismicity strongly suggest a single through-going structure connecting the central Calaveras Fault to the Hayward Fault. This picture is supported by geophysical studies of the region (Ponce *et al.* 2004; Manaker *et al.* 2005), which show a steeply east-dipping Hayward Fault joining with a steeply east-dipping central Calaveras Fault.

Releasing stepovers

San Andreas Fault, Cholame Valley

In Cholame Valley south of Parkfield in central California, the main creeping trace of the right-lateral San Andreas Fault makes a releasing right stepover bend across an elongate (rhombochasm?) valley (Fig. 4). This 3.5-km-wide stepover lies at the north end of a locked segment of the fault last ruptured in the great M 7.9 Fort Tejon earthquake of 1857. Viewed in a larger context, a straight edge laid along the San Andreas Fault in Central California reveals that a 35 km section of the Parkfield reach of the San Andreas trace north of the Cholame Valley stepover appears to be warped to the NE, perhaps by non-elastic behaviour of the crust at the transition from creeping to locked behaviour (Simpson *et al.* 2006).

Aftershocks of the 1966 and 2004 M *c.* 6 Parkfield earthquakes and background earthquakes in the intervening period (Figs 4 & 5) lie several kilometres to the SW of the main creeping trace (Bakun *et al.* 2005), approximately under the straight-edge line connecting San Andreas segments to north and south of the Parkfield reach with an approximately three-degree bend in trend, and under the creeping SW Fracture Zone, which experienced post-seismic offset in the 2004 event. The complexity shown by the surface traces and the discordance of the location and geometry of the main trace relative to the seismicity is probably limited to the upper few kilometres. The cross-sections of seismicity strongly suggest a bifurcation of active slip in the upper 6 kilometres on to both the SW Fracture Zone and the main San Andreas Fault (Fig. 5d), perhaps in a flower structure, whereas below 6 km the seismicity is more readily fitted with a single through-going fault surface.

San Jacinto Fault, San Bernardino Valley

Analysis of geophysical data in San Bernardino Valley in southern California (Anderson *et al.* 2004) suggests that the simplicity at depth within releasing stepovers may eventually lead to the evolution of a simpler fault trace at the surface. Inversion of gravity data indicates a rhombohedral-shaped basin beneath San Bernardino Valley that is bisected by the neotectonic trace of the right-lateral strike-slip San Jacinto Fault (Anderson *et al.* 2004; Fig. 6). The absence of surface faults associated with the bounding faults of the pull-apart basin indicates that the basin, reflecting a 5-km-wide extensional step, presumably resulted from an earlier history of faulting. The evolution of a simpler surface trace is consistent with sandbox models of releasing stepovers (Dooley & McClay 1997).

San Bernardino Valley is also the location where slip on the San Jacinto Fault may be transferred on to the San Andreas Fault in an apparent extensional stepover, as proposed by Morton & Matti (1993). Focal mechanisms in the valley show predominantly normal motion (Jones 1988; Hauksson 2000), consistent with slip stepping to the right across the valley. Anderson *et al.* (2004), however, argued that most, if not all, of the 25 km of cumulative strike-slip displacement on the San Jacinto Fault (documented to the SE of San Bernardino Valley) exits the valley at its north end on several distinct strands of the modern San

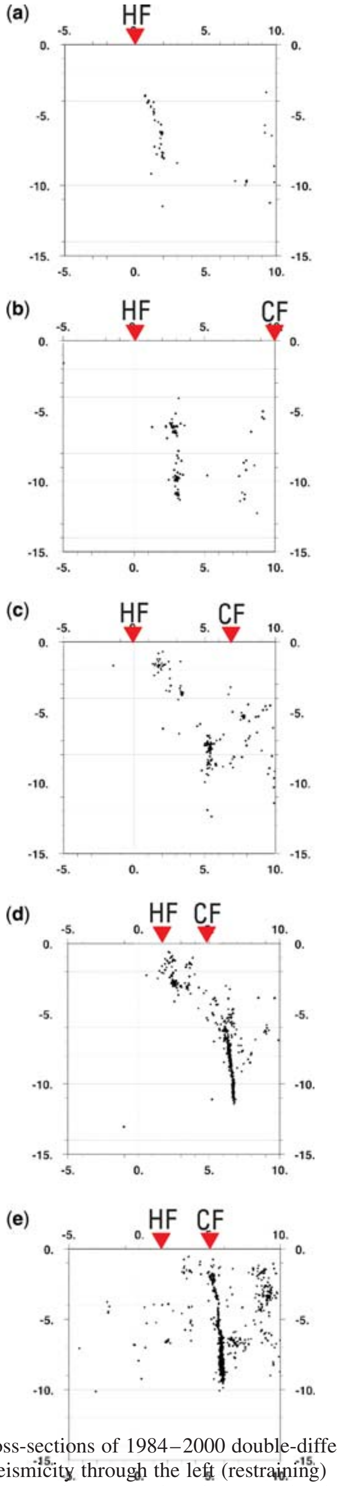

Fig. 3. Cross-sections of 1984–2000 double-difference relocated seismicity through the left (restraining) stepover between the Hayward Fault (HF) and Calaveras Fault (CF). No vertical exaggeration is shown; the horizontal and vertical scale is in kilometres; the horizontal scale zero-point is along the projection of the Hayward Fault north of the stepover; and hypocentres projected into the section are within 2.5 km of the section plane. Note that the broad, complex zone of deformation above 5 km is well illuminated by seismicity in section D, whereas in all sections the seismicity below 5 km defines a through-going single structure (modified from Simpson *et al.* 2004).

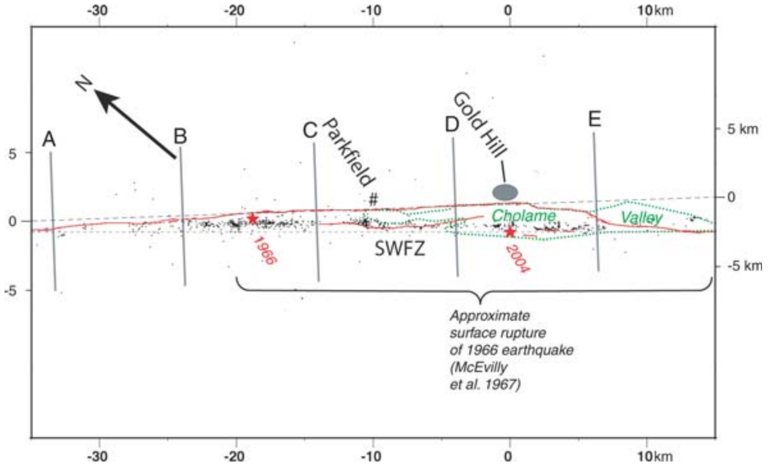

Fig. 4. Map of the San Andreas fault zone near Parkfield, California, including the 3.5-km right (releasing) step in the active fault traces and the SW Fracture Zone (SWFZ) shown with red lines. Also shown are the double-difference relocated seismicity below 6 km from 2004 aftershocks (small black dots), the epicentres of the 1966 and 2004 earthquakes (red stars), the extent of surface rupture from the 1966 earthquake (McEvilly *et al.* 1967), and the outline of Cholame Valley (green dotted line), possibly a pull-apart basin associated with the right step, and the locations of the cross-sections shown in Figure 5. The dashed line follows the average azimuth of the San Andreas Fault surface traced in the Parkfield area (N42°W), and marks the centre of the cross-sections shown in Figure 5. Note that the seismicity defines a relatively narrow, very gently bent (3°), fault connection. The scale is in kilometres, the azimuth of the upper and lower figure boundary is N40°W (modified from Simpson *et al.* 2006).

Jacinto Fault. This would seem to preclude a large amount of slip on the San Jacinto Fault stepping to the NE across the valley to directly link on to the San Andreas Fault, at least during most of the history of movement on the fault during the past 1.5 Ma (Matti & Morton 1993). Double-difference relocated seismicity in the stepover region (Hauksson & Shearer 2005), although less focused on narrow, discrete fault strands than the examples from central and northern California, shows one and possibly two SW-dipping zones of seismicity beneath the strike-slip basin below 10 to 12 km (Fig. 6); selected focal mechanisms indicate normal right-lateral oblique faulting. The deeper, more concentrated zone of seismicity projects up to the trace of the San Andreas Fault and may reflect a very young, simpler connection at depth between the San Jacinto and San Andreas faults.

Complexly bent faults – Central Calaveras Fault

Along the southern reach of the central Calaveras Fault (Fig. 7), the surface expression of the PDZ displays (from south to north) a left bend of 7° (L7 on Fig. 7), a right bend of 30° (R30), a left bend of 30° (L30), a left bend of 18° (L18), a right bend of 12° (R12), a right bend of 26° (R26) and a left bend of 30° (L30), over a distance of about 40 km. The northern two bends form a releasing bend or right step about 3 km wide, with a small associated pull-apart basin at San Felipe Valley (Chuang *et al.* 2002). Faulting along the 40 km reach is complex, including numerous short, disconnected fault strands, but no identifiable primary through-going surface trace. Shallow seismicity along this reach is generally diffuse and locally complex (Schaff *et al.* 2002).

Deeper seismicity, however, defines a relatively simple narrow planar fault surface through most of this area. The fault surface dips very steeply east to NE and forms a notably straight line in map view over most of its length (Fig. 7), in contrast to the multiple bends in the mapped surface traces. Previous workers (Reasenberg & Ellsworth 1982; Schaff *et al.* 2002) have pointed out two potential stepovers on the fault at depth (Fig. 6), but those authors correctly point out that neither of the proposed deep stepovers is related to any of the surface bends. The northernmost of the proposed deep stepovers is located approximately at the point where the Silver Creek Fault impinges on to the Calaveras Fault, so this discordance may reflect minor young movement on the Silver Creek Fault.

Other possibly simple-at-depth stepovers

Recent work has suggested that surface complexity may mask deep simplicity for several additional

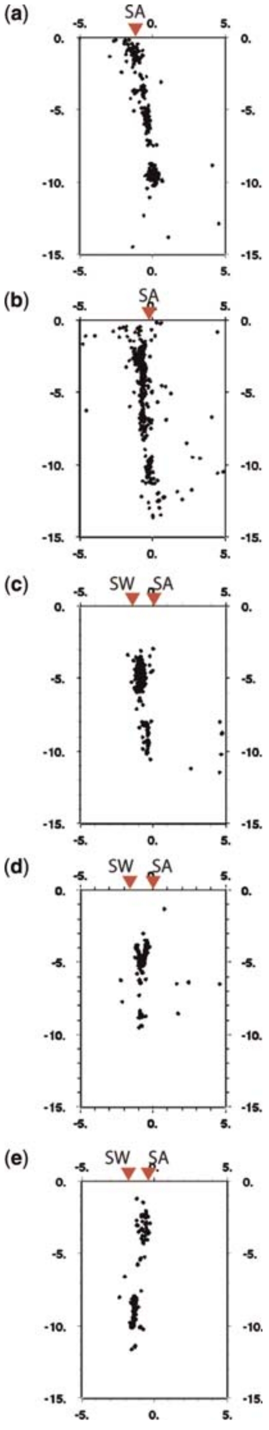

Fig. 5. Cross-sections of 1985 through 2004 double-difference relocated seismicity through the right (releasing) stepover in the right-lateral San Andreas fault zone near Parkfield, California. The surface position of the San Andreas Fault (SA) and SW Fracture Zone (SW) are marked with red triangles. The multi-strand nature of the stepover zone in the upper 5 km is well defined in section D, whereas in all sections the seismicity below 5 km suggests a single, through-going structure. Relocated seismicity from Bakun *et al.* (2005).

faults worldwide. Preliminary analysis of shallow fault dip based on a gravity inversion suggests that another simple-at-depth extensional stepover on the San Andreas Fault system may characterize the Lake Merced right step in the San Andreas Fault in San Francisco (Fig. 1; Zoback 2003). Simple-at-depth extensional stepovers have also been proposed for the North Anatolian Fault associated with the 1999 Izmit, Turkey, earthquake (Aochi & Madariaga 2003 although Harris *et al.* (2002) suggest that the narrowness of the stepovers (less than 2 km) is responsible for the through-going rupture) the Nojima–Rokko Fault system associated with the 1995 Kobe, Japan, earthquake (Wald 1996), and the suite of five faults associated with the 1992 Landers, California, earthquake (Felzer & Beroza 1999). Examination of each of these cases is beyond the scope of this paper, but it seems likely that the simple at-depth phenomenon described herein is not restricted to the San Andreas fault system.

A counter-example

A counter-example to the idea that faults within stepover regions become less complex at depth is the restraining bend in San Gorgonio Pass (Fig. 8), east of the San Bernardino releasing stepover. The San Gorgonio Pass restraining bend is located near the eastern end of the Big Bend (Fig. 1), where the San Andreas Fault steps 15 km to the left over a distance of approximately 20 km. The active strand of the San Andreas Fault has migrated in time and space during the past 5 Ma (Matti & Morton 1993) and geological mapping (Lawson *et al.* 1908; Noble 1932; Allen 1957; Matti & Morton 1993; Yule & Sieh 2003) does not indicate a continuous fault strand between the currently active strands of the San Andreas Fault, the San Bernardino segment of the San Andreas Fault (SBSSAF on Fig. 8) NW of the stepover, and the Coachella Valley segment of the Banning Fault (CVSBF on Fig. 8) to the SE.

Seismicity within the San Gorgonio restraining bend is diffuse, and is distributed on both strike-slip and thrust faults (Jones *et al.* 1986; Seeber & Armbruster 1995; Magistrale & Sanders 1996; Carena *et al.* 2004). The complexity of faulting at the surface apparently continues to the base of

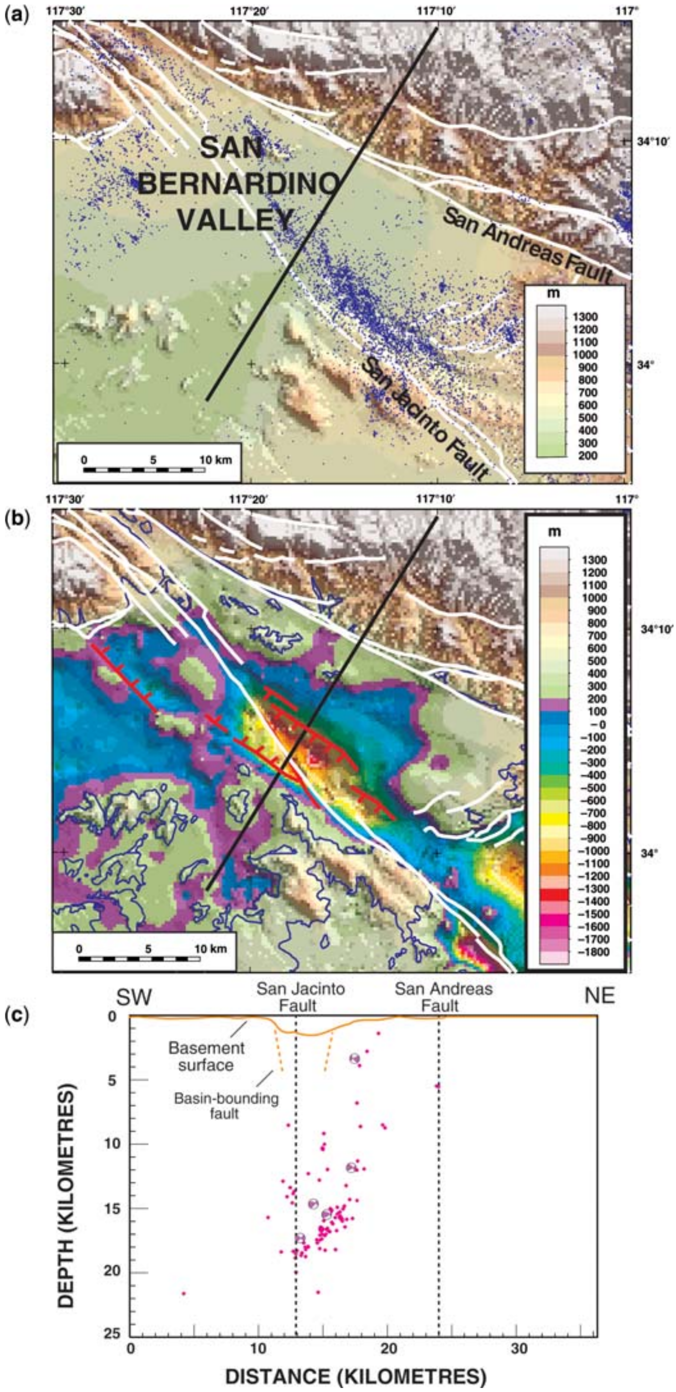

Fig. 6. Shaded-relief topography (**a**), basement topography defined by inversion of gravity data (**b**), and seismicity along a NE–SW profile (**c**) in the San Bernardino Valley region. Faults from Matti & Morton (1993) are shown in white on (a) and (b). The black line on (a) and (b) is the location of profile shown in (c). Dark-blue dots on (a) show double-difference relocated seismicity from Hauksson & Shearer (2005). Red faults on (b) are interpreted from analysis of gravity and magnetic data (Anderson *et al.* 2004). Double-difference relocated seismicity from Hauksson & Shearer (2005) within 1 km of the profile is shown on (c) as magenta dots. Beachballs are focal mechanisms consistent with normal faulting within 1 km of the profile from Hauksson (2000).

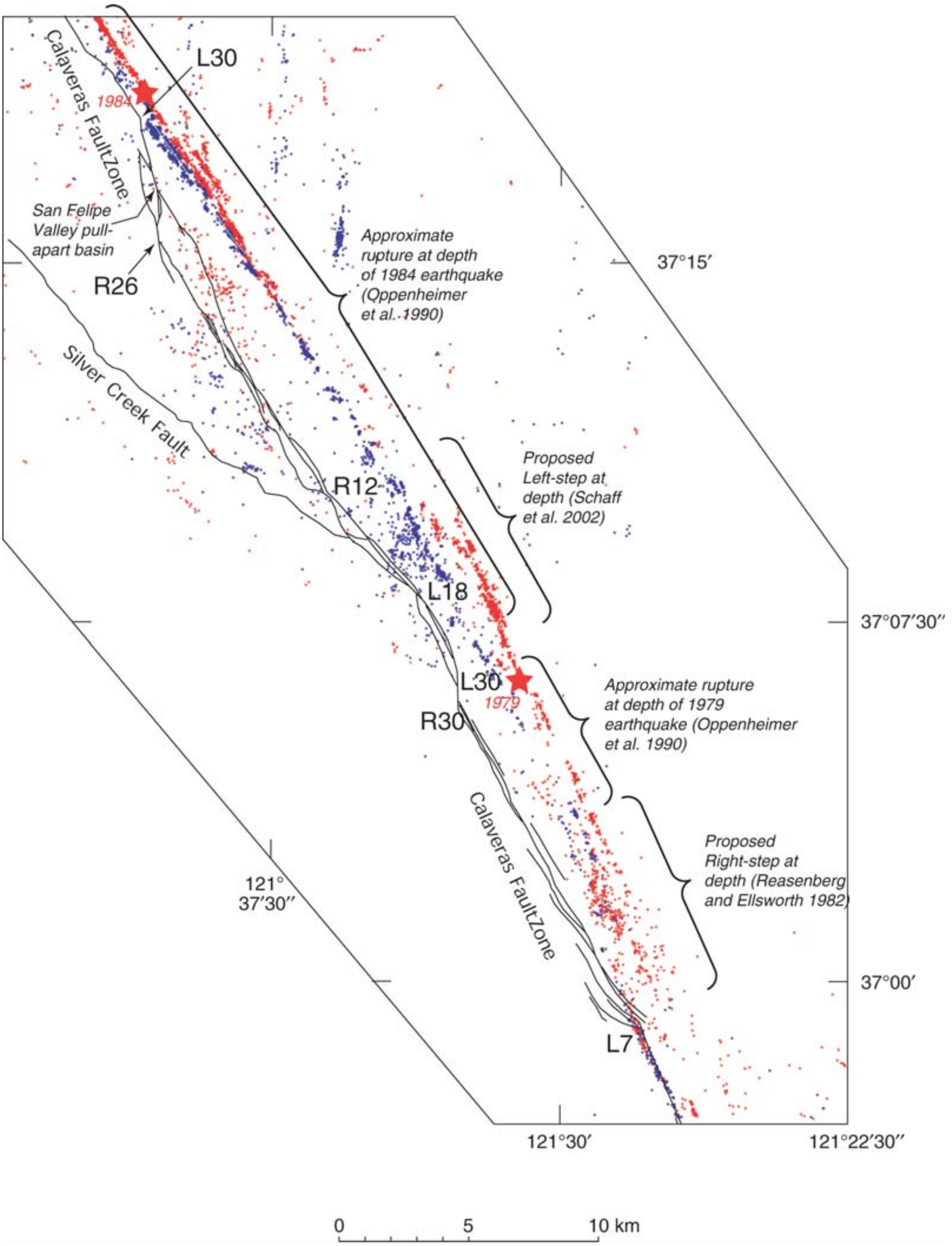

Fig. 7. Simplified map of the right-lateral southern Calaveras Fault showing right (releasing) and left (restraining) bends. The microseismicity below 5 km is shown in red, above 5 km in blue. The epicentres of the 1979 and 1984 earthquakes are shown as red stars. The rupture length of those earthquakes (Oppenheimer *et al.* 1990) is also shown, along with the deep discontinuities in the fault surface proposed by Reasenberg & Ellsworth (1982) and Schaff *et al.* (2002). Note that although the surface fault zone is complex, and the shallow microseismicity is in places diffuse, the deep microseismicity defines a single, east-dipping, gently bent, through-going fault over most of its length, proposed discontinuities at depth are unrelated to surface discontinuities, and the 1984 earthquake rupture extends through multiple bends in the surface fault (modified from Wentworth *et al.* 1998; Simpson *et al.* 2004).

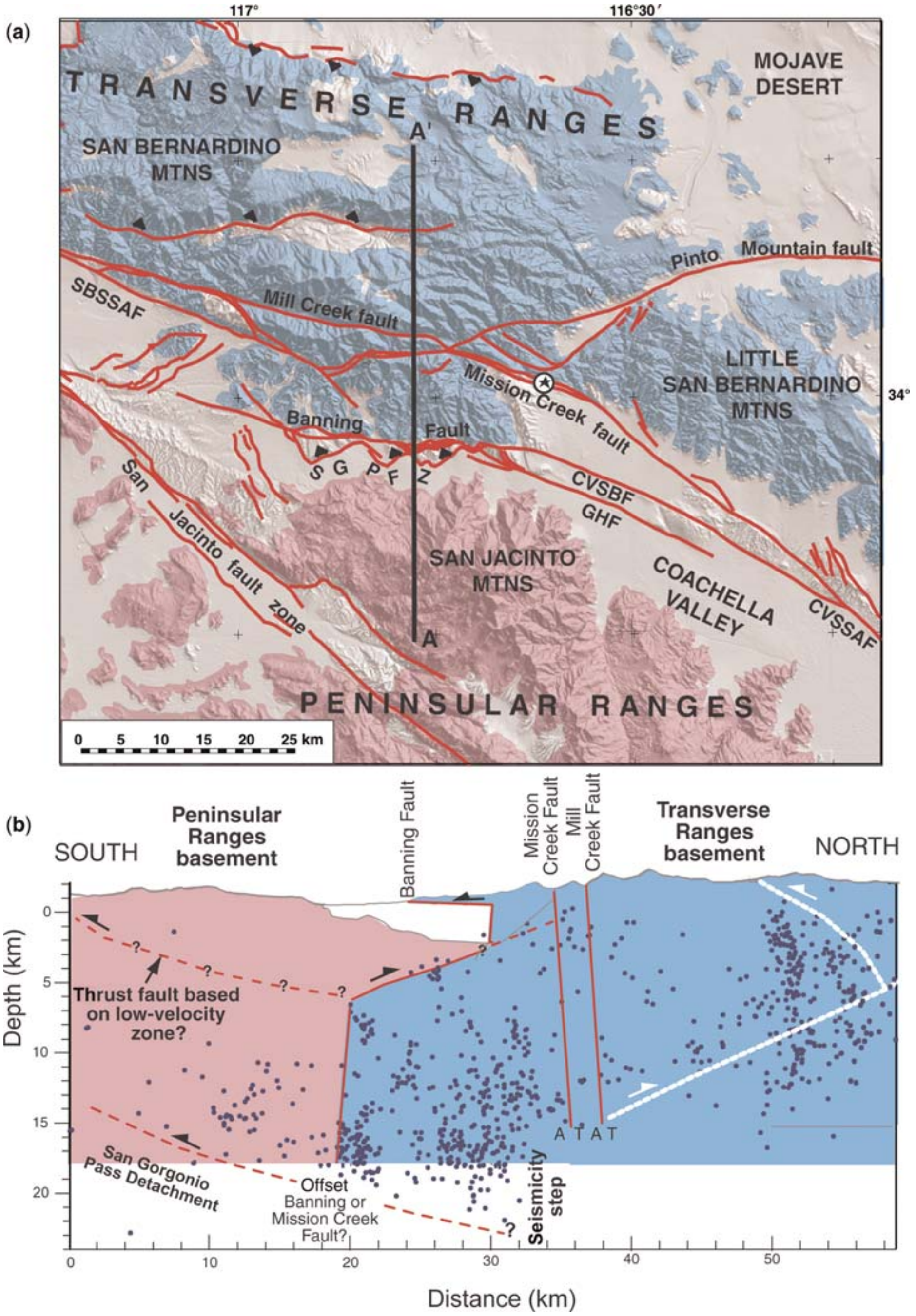

Fig. 8. Simplified geological map (**a**) of the San Gorgonio Pass region, modified from Matti & Morton (1993). Pink shows the extent of Peninsular Ranges basement terrane outcrops; blue shows the extent of Transverse Ranges basement terrane outcrops. Strands of the San Andreas Fault Zone include the Banning, Mission Creek, Mill Creek, San Bernardino segment (SBSSAF); the Coachella Valley segment of the Banning Fault (CVSBF), the Garnet Hill Fault (GHF), and the Coachella Valley segment of the San Andreas Fault (CVSSAF). SGPFZ, San Gorgonio Pass Fault zone. The star marks the location of the 1986 M_{L} 5.9 North Palm Springs earthquake. The location of cross-section (**b**) is shown by a thick black line. The geometry of the cross-section is constrained by geological and geophysical analysis in Langenheim *et al.* (2005). Dark-blue dots are locations of double-difference relocated seismicity within 1 km of the profile.

seismicity at depths of 15 to 20 km (Fig. 8). Double-difference relocated seismicity does not indicate a simpler fault configuration at depth (Hauksson & Shearer 2005). The diffuse nature of seismicity in San Gorgonio Pass appears to reflect very complex three-dimensional brittle deformation along interlaced strike-slip and thrust faults. Analysis of aeromagnetic and gravity data defines intertonguing thrust wedges within San Gorgonio Pass, with wedging of Peninsular Ranges batholithic crust northward above Transverse Ranges basement at seismogenic depths (Fig. 8(b); Langenheim *et al.* 2005). Given the multilayered crustal deformation occurring in this region, it is not surprising that the San Andreas Fault exhibits a complex rupture pattern throughout the crust of the restraining stepover. The inability to identify a single, through-going strand of the San Andreas Fault using seismicity does not preclude a through-going rupture, but the seismicity does not support a simpler fault at depth within this stepover. Aftershocks of the 1986 M_L 5.9 North Palm Springs earthquake (Fig. 8) indicated not only the main rupture plane (right-lateral strike-slip on an approximately 45° dipping plane) but also a gently north-dipping décollement plane at the base of the rupture (Nicholson *et al.* 1986), informally named the San Gorgonio detachment. Deformation may eventually bypass the San Andreas Fault in the San Gorgonio Pass area by distributing slip on to the Eastern California Shear Zone and the San Jacinto Fault. The Eastern California Shear Zone accommodates 20 to 25% of Pacific–North America plate motion (Savage *et al.* 1990; Sauber *et al.* 1994), whereas the San Jacinto Fault may be slipping as much as twice the rate of the southern San Andreas Fault (Johnson *et al.* 1994).

Palaeoseismic and historic earthquake evidence

The possibility of an earthquake rupturing through a stepover can be investigated by studying the historic and palaeoseismic record for faults on either side of a stepover. Although palaeoseismic data are insufficient to prove through-going rupture, or even to strongly suggest it in most cases, it can show whether such a rupture is possible.

On the Hayward–Calaveras system, the most recent earthquake (1868) is thought to be limited to the Hayward Fault (Lawson 1908; Yu & Segall 1996), but there is no palaeoseismic evidence for the timing of the most recent surface-breaking earthquake on the central Calaveras (Working Group on California Earthquake Probabilities 2003), and direct observations of surface rupture and triangulation data from 1868 are not detailed or complete enough to preclude any central Calaveras rupture, so it is not possible to interpret a rupture through the stepover related to this or earlier quakes.

On the San Andreas Fault near Parkfield, historic earthquakes (1966 and 2004) appear to have occurred entirely within the stepover region, although they both appear to have ruptured through the sharp releasing step in Cholame Valley (Fig. 4; McEvilly *et al.* 1967; Thurber *et al.* 2006). Likewise, the 1857 earthquake ruptured through the releasing step in Cholame Valley at least as far north as Parkfield, and palaeoseismic data north and south of the right stepover, although poorly constrained, are compatible with the model of a through-going prehistoric rupture. South of the stepover, the most recent prehistoric earthquake post-dates a radiocarbon date of 1058 to 1291 AD (Stone *et al.* 2002), whereas north of the stepover the most recent prehistoric earthquake post-dates a radiocarbon date of 1440 to 1640 AD (Toké *et al.* 2004).

On the central Calaveras Fault, King & Nabelek (1985) suggested that the rupture length for both the 1979 (Coyote Lake) and 1984 (Morgan Hill) earthquakes were limited by bends in the surface fault. However, as shown on Fig. 6, the rupture at depth for both earthquakes clearly passed significant bends in the surface trace, including the pull-apart basin at San Felipe Valley in 1984, and the southern tip of the 1979 rupture formed where the surface trace was relatively straight. The southward rupture propagation at depth in both earthquakes was much more likely to be limited by deep discontinuities as suggested by Reasenberg & Ellsworth (1982) and Schaff *et al.* (2002), but, as pointed out above, the deep discontinuities are unrelated to bends in the surface trace.

Conclusions

Although fault stepovers at the Earth's surface have been used to define fault-segment boundaries, the observation of relative fault simplicity at depth (greater than 5 km) under some stepovers suggests that large quakes may be nominally affected by the complexity seen at the surface. However, not all stepovers are accompanied by simplicity at depth; some appear to be associated with complex faulting at depth. Other former stepovers seem to have been superseded by simple faults at the surface. One appealing structural model, supported by sandbox models of pull-apart basins, is one in which faults are initially prone to near-surface complexity (stepovers), while being simple at depth. If the deep fault remains stable through geological time, then the surface complexity is abandoned in favour of surface simplicity. If, on the other hand, the deep fault locus changes with time, the result can be fault complexity both at depth and surface. The geological setting of the fault may also influence its simplicity or complexity.

Whatever the underlying mechanism, the role of the stepover as a fault-segment boundary that will affect fault rupture does not have an obvious correlation with surface complexity. Deep discontinuities unrelated to surface complexity may be far more important in determining rupture length. Before stepovers are used in earthquake assessment, they must be evaluated using relocated microseismicity, potential field geophysics, and(or) palaeoseismic data. Present usage probably assigns undue importance to stepovers as impediments to through-going fault rupture, and therefore systematically underestimates the probablility of less-frequent, larger-magnitude earthquakes.

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