Stepovers that migrate with respect to affected deposits: field characteristics and speculation on some details of their evolution

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Abstract: Traditionally, geologists have viewed strike-slip stepover regions as progressively increasing in structural relief with increasing slip along the principal displacement zones (PDZs). In contrast, some stepover regions may migrate along the strike of the PDZs with respect to deposits affected by them, leaving a 'wake' of formerly affected deposits trailing the active stepover region. Such stepovers generate comparatively little structural relief at any given location. For restraining bends of this type, little exhumation and erosion takes place at any given location. Another characteristic of migrating stepovers is local tectonic inversion that may migrate along the strike of the PDZs. This is most easily observed for migrating releasing bends where the wake is composed of former pull-apart basin deposits that have been subject to shortening and uplift. This type of basin inversion occurs along the San Andreas Fault, wherein the wake is affected by regional transpression. Some migrating stepovers may evolve by propagation of the PDZ on one side of the stepover, and shut-off of the PDZ on the other side. Possible examples of migrating stepovers are present along the northern San Andreas fault system at scales from metres (sag ponds and pressure ridges) to tens of kilometres (large basins and transpressional uplifts). Migrating stepovers and 'traditional' stepovers may be end members of stepover evolutionary types, and the ratio of wake length to the amount of slip along the PDZs during stepover development measures the 'migrating stepover component' of a given stepover. For a 'pure' migrating type, the wake length may be equal to or greater than the PDZ cumulative slip during the time of stepover evolution, whereas for a 'pure' traditional type, there would be no wake.

Bends and stepovers occur along all strike-slip systems (e.g. Crowell 1974*a*, *b*; Christie-Blick & Biddle 1985). To aid discussion one can define stepover terms as follows: (1) main strike-slip faults or bounding faults also known as principal displacement zones or PDZs, and (2) transverse or relay structures that accommodate the transfer of slip between the PDZs on either side of the stepover region (Fig. 1). Geological features related to stepovers and bends have received considerable attention from researchers (e.g. Crowell 1974*b*; Mann *et al.* 1983; Christie-Blick & Biddle 1985; Westaway 1995; Dooley & McClay 1997). Studies of the evolution of stepover features have traditionally considered stepovers as features that progressively increase in structural relief with increasing slip on the PDZs connected to them (e.g. Mann *et al.* 1983; Dooley & McClay 1997; Dooley *et al.* 1999; McClay & Bonora 2001); such stepovers will be referred to herein as 'traditional' stepovers. More recently, Wakabayashi *et al.* (2004) presented field evidence for a type of stepover that appears to have migrated with respect to the affected deposits rather than increased in structural relief with greater slip accommodation; such stepovers will be referred to herein as 'migrating' stepovers.

In this paper, I will review some field examples presented by Wakabayashi *et al.* (2004) and present an updated discussion speculating on the evolution of such structures. The new material presented in this paper, compared with Wakabayashi *et al.* (2004) includes the following:

1. A discussion of a full spectrum of hypothetical migrating stepover types with different migration alternatives and evaluation of different reference frames (whereas the earlier paper discussed only one type of migrating stepover).
2. The earlier paper considered migrating stepovers as a counter-example to 'traditional' stepovers, whereas herein a unifying model is proposed with migrating stepovers and 'traditional' stepovers as end members of stepover evolution types.
3. More detailed maps are provided for the field examples, and additional diagrams are provided to aid in visualization of the various stepover models proposed.

From: Cunningham, W. D. & Mann, P. (eds) *Tectonics of Strike-Slip Restraining and Releasing Bends.* Geological Society, London, Special Publications, **290**, 169–188.
DOI: 10.1144/SP290.4 0305-8719/07/$15.00

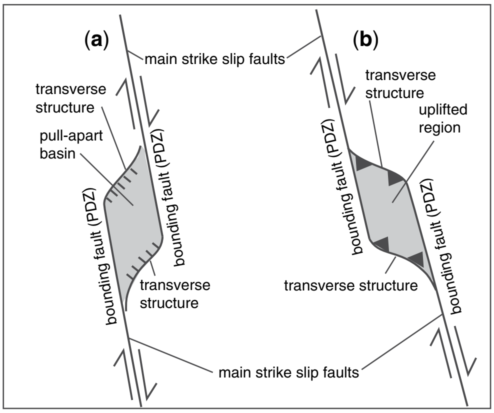


Fig. 1. Simple classification of some structures associated with stepovers or bends along strike-slip faults. An idealized releasing stepover (**a**), and restraining stepover (**b**), are shown.

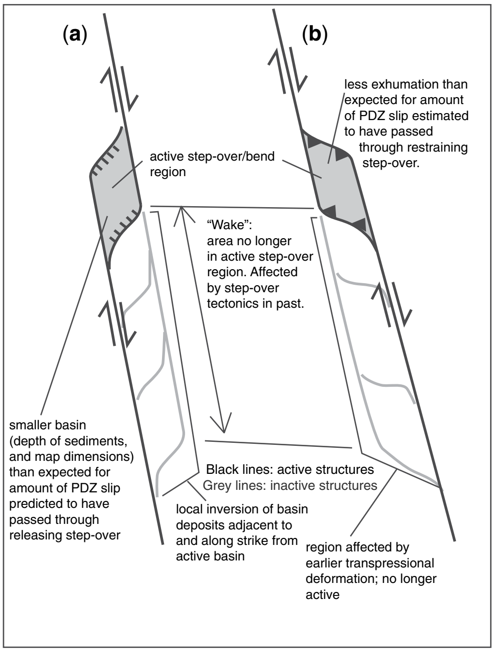


Fig. 2. Diagram illustrating some of the features associated with migrating stepovers described in the text.

Field examples of migrating stepovers from the San Andreas fault system

General field characteristics

Field observations along the San Andreas fault system of coastal California suggest that some types of stepovers or bends migrate with respect to formerly affected deposits (Wakabayashi *et al.* 2004). Some field observations suggesting migrating stepovers are as follows (shown schematically on Fig. 2):

1. Structural relief of a stepover region is much smaller than expected for the estimated amount of slip accommodated by the structure during its lifetime. For releasing stopovers, this means a smaller basin than expected, and for restraining bends this means much less uplift and exhumation than expected. Note that the amount of expected slip through the stepover region is not necessarily the total amount of slip on the PDZ, because a stepover may form much later than the fault (the Olema Creek Formation example presented below may be an example).
2. Tectonic inversion has occurred out-of-phase with known regional tectonic changes.
3. Former basinal deposits are found along the strike of a PDZ adjacent to an active pull-apart basin (or, more generally, an active transtensional basin), forming a 'wake' (by analogy to the wake of a ship) that appears to mark the earlier presence of a pull-apart environment.
4. For some stepovers, propagation of PDZs has occurred, and some also exhibit progressive along-strike dying out of activity on a PDZ.

The San Andreas fault system

The dextral San Andreas fault system (SAFS) of coastal California accommodates 75–80% (38–40 mm/a) of present Pacific–North American plate motion (e.g. Argus & Gordon 1991), and 70% (540–590 km) of the dextral displacement that has accumulated across the plate boundary over the last 18 Ma (Atwater & Stock 1998). Regional fault-normal convergence across the northern San Andreas system (NSAFS) occurs at less than 10% of the dextral slip rate (Argus & Gordon 1991, 2001). Although this regional convergence contributes to some of the shortening seen along the NSAFS, the most prominent transpressional features are largely driven by local restraining bends or stepovers along strike-slip faults (e.g. Aydin & Page 1984; Bürgmann *et al.* 1994; Unruh & Sawyer 1995).

Subduction, associated with the development of the Franciscan Complex, occurred along the western margin of North America prior to the initial interaction between an East Pacific Rise and the subduction zone at about 28 Ma, but the SAFS did not become established until about

18 Ma (Atwater & Stock 1998). Since 18 Ma, SAFS has progressively lengthened and accumulated dextral displacement, as the Mendocino triple junction (fault–fault–trench triple junction), migrated NE and the Rivera triple junction (ridge–fault–trench triple junction) migrated SE (e.g. Atwater & Stock 1998). In addition to the Franciscan and related rocks, the Coast Range basement also includes the Salinian block, a continental fragment composed of granitic and high-grade metamorphic rocks that has been translated into the Coast Ranges from the SE along SAFS faults and faults that predated the transform regime (Page 1981). The Franciscan structural grain is defined by a series of nappe sheets, composed of both coherent and mélange units (Wakabayashi 1992, 1999). The nappe sheets have been folded about subhorizontal fold axes that trend more westerly than the strike of the SAFS faults. Most of the major faults of the NSAFS cut Franciscan basement or form the contacts between Franciscan and Salinian basement, although some cut across Salinian basement (Page 1981).

The SAFS comprises multiple dextral strands, including the San Andreas Fault. The distribution of active structures and dextral slip rates has shifted irregularly throughout the history of the transform-fault system, as new faults have formed, old ones have shut off, and slip rate distribution within the system changed (e.g. Powell 1993; Wakabayashi 1999). Deposition of Late Cenozoic sedimentary and volcanic rocks has occurred during the development of the transform margin, and these deposits are critical for evaluating tectonic processes associated with the SAFS (e.g. Page 1981).

There are many examples of transtensional (pull-apart) basins and local transpressional structures related to stepovers and bends along the various dextral faults of the SAFS (e.g. Aydin & Page 1984; Nilsen & McLaughlin 1985; Crowell 1974*a*, *b*, 1987; Yeats 1987). Local transpressional and transtensional geological features along strike-slip faults occur across a range of scales, from tens of kilometres for large basins and push-up regions, to metres for sag ponds and small pressure ridges (Crowell 1974*a*).

I will review examples of migrating stepovers and bends from the NSAFS (see Fig. 3 for locations). For releasing structures, such as pull-apart basins, the basins have migrated along bounding strike-slip faults (PDZs) with respect to their former basinal deposits. For restraining structures, such as fold and thrust belts or transpressional welts, the features have migrated along bounding strike-slip faults with respect to deposits that were deformed by these structures. The deposits interpreted to have been affected by stepover tectonics that now lie outside of an active stepover area are referred to as the ‘wake’.

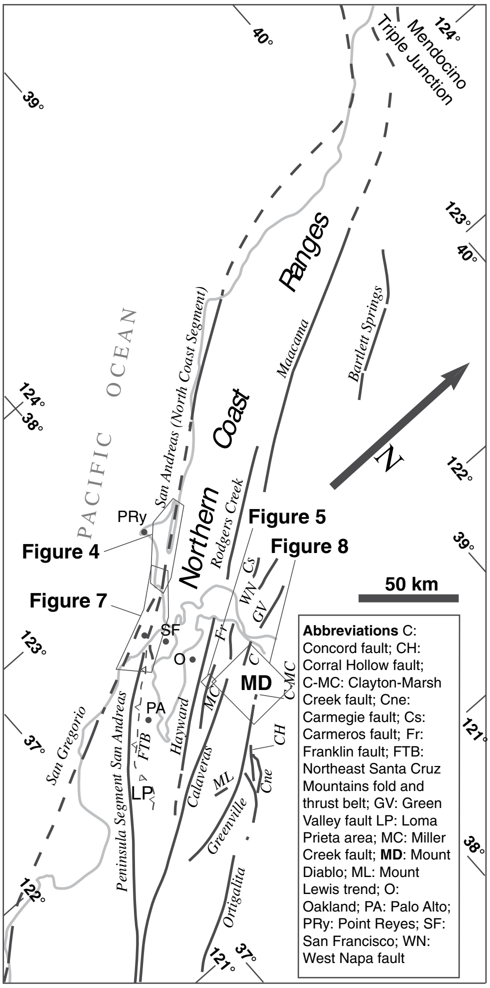


Fig. 3. The northern San Andreas Fault system, showing major dextral strike-slip faults and other features discussed in the text. Note that the Northeast Santa Cruz Mountains fold and thrust belt (FTB) is not the only fold and thrust belt in this area, but this specific belt is shown because it is specifically discussed in the text. Adapted from Wakabayashi (1999).

Migrating releasing bends

Because transtensional tectonics within the NSAFS are a local consequence of releasing stepovers and bends in an otherwise transpressional setting (for the last *c.* 8 Ma, Atwater & Stock 1998; Argus & Gordon 2001), the migration of such a stepover away from pull-apart basin deposits results in the subsequent uplift and shortening (locally driven inversion) of such deposits. Below I will describe pull-apart basins that may have migrated with respect to their deposits at three scales: tens of kilometres, kilometres, and meters (but not presented in that order).

Tomales Bay depocentre and Olema Creek Formation

The Olema Creek Formation (OCF), composed of loosely consolidated muds, sands, silts, and gravels, is about 110–185 ka old and crops out in a 3.5-km-long by 0.5-km-wide belt south of Tomales Bay, bounded to the west by the active San Andreas Fault and to the east by the 'eastern boundary fault', a strand of the San Andreas Fault system that has not been active in Holocene times (Grove *et al.* 1995; Grove & Niemi 2005; Fig. 4). The San Andreas Fault in this area is north of the junction of the San Gregorio and San Andreas Faults, and consequently has the combined displacement of the two strands, which is about 210 km (22–36 km for the San Andreas, 180 km for the San Gregorio; Wakabayashi 1999). Although the San Andreas Fault south of the San Gregorio–San Andreas Fault intersection has only been active for 1.5 to 2 Ma, the San Gregorio Fault may have been active since the inception of the San Andreas fault system at about 18 Ma. Thus the San Andreas Fault in the vicinity of the OCF may be about 18 Ma. old. This section of the San Andreas Fault separates Franciscan Complex basement on the east from Salinian basement on the west.

The OCF was deposited in estuarine, deltaic and fluvial environments similar to the head of the modern Tomales Bay and the coastal flat associated with its associated feeder streams, but is now exposed at elevations up to 70 m above sea-level, and deformed with beds tilted to dips of up to 65° (Grove *et al.* 1995; Grove & Niemi 2005). The steeper dips (up to 65°) are associated with the southernmost exposures of the OCF, whereas the northernmost exposures have dips of 5–10° (Grove & Niemi 2005). The OCF regionally dips northward ('shingles') at shallow angles, so that the deposits young northwestward (Grove *et al.* 1995; Grove & Niemi 2005; Fig. 4 inset). Because there is no evidence that a regional change in plate motions took place after 100 ka, the change in tectonic regime that affected the OCF must have been a local one. Moreover, the northward shingling of the OCF, and the progressively greater deformation toward the southern limit of exposure, also reflect a local rather than regional tectonic inversion, as well as a process that has migrated northward along the strike of the San Andreas Fault. The slip rate of the San Andreas Fault since the initial deposition of the Olema Creek Formation has been estimated as about 25 mm/a (Niemi & Hall 1992; Grove & Niemi 2005), so about 4.8 km of dextral slip has accumulated on the San Andreas Fault during that time. The subsiding environment along the San Andreas Fault, an environment in which the OCF was deposited, may have been related to a releasing bend or stepover, possibly between the San Andreas Fault and the eastern boundary fault. It may not have (or may not be) a true pull-apart, but may instead be a transtensional basin between the San Andreas and the eastern boundary fault or equivalent bounding structure. The subsiding area may have migrated northward to Tomales Bay, leaving a wake of deposits outside of the active depocentre and subject to shortening (Grove *et al.* 1995). The San Andreas Fault appears to step right within Tomales Bay, based on the geometry of the shoreline and the position of the San Andreas Fault north of Tomales Bay (Fig. 4). A right step may be present in northern Tomales Bay, corresponding with the deepest part of the bay (where the −36-foot contours are shown on Fig. 4). The topographic valley occupied by southern Tomales Bay may be related to the above-mentioned stepover, or it may also be a result of generally transtensional reach of the fault in the southern part of Tomales Bay. The presence, along the eastern shore of Tomales Bay, of the emergent 125–155-ka Millerton Formation (Fig. 4), which includes marine and estuarine deposits, suggests that there is no direct connection between subsidence in the southern Tomales Bay and the probable right step in the northern part of the bay.

No transverse faults have been identified within the OCF. Fold axes oblique or at high angles to the San Andreas Fault have been mapped within the OCF exposures (Grove *et al.* 1995), but these are probably associated with the uplift and shortening of the deposits rather than being related to transverse structures formed during deposition. Because the present-day sea-level is a high stand (e.g. Vail *et al.* 1977; Keller & Pinter 1996, 194–196), the emergence of the OCF is a product of vertical tectonics, rather than a lowering of sea-level since deposition. As noted above, the vertical tectonics appear to have been local, and the locus of uplift, as well as the deposition that preceded it, appears to have migrated northward along the San Andreas Fault. The southern edge of the modern depocentre analogue of the OCF deposits appears to be 10 km NW of the southern limit of the exposed OCF. Consequently, the length of the wake associated with depositional environment of the OCF is estimated to be about 10 km (Fig. 4).

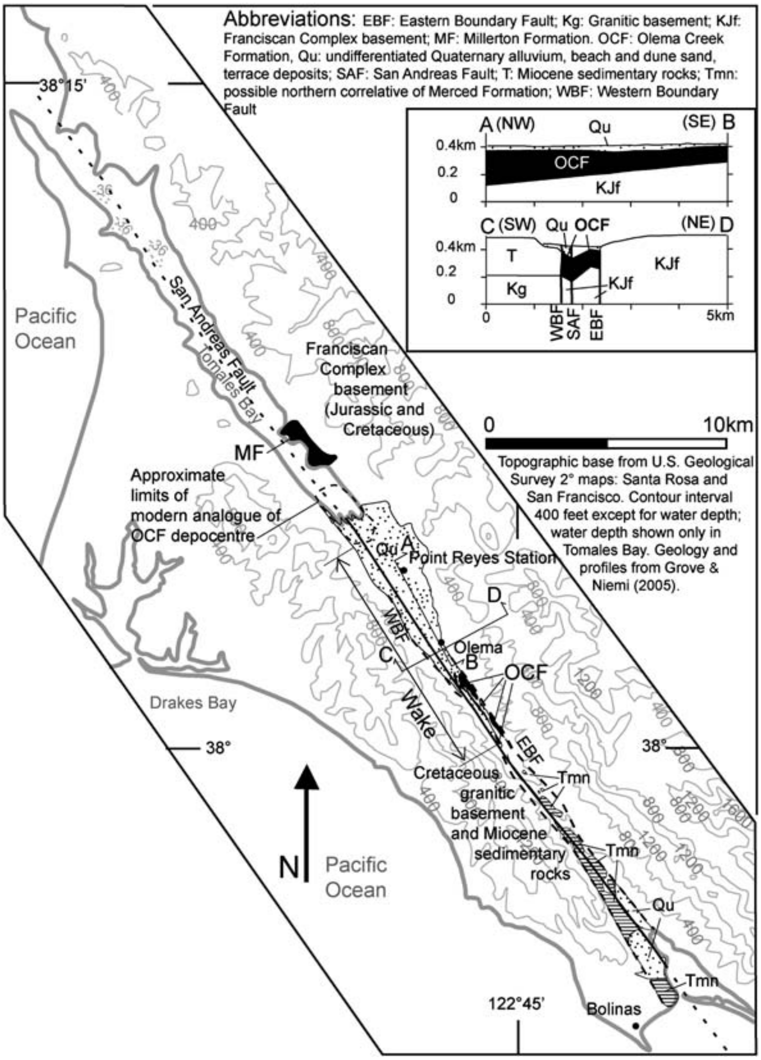


Fig. 4. Geology associated with the Olema Creek Formation and associated structures.

Inverted graben along the Miller Creek Fault

The Miller Creek Fault is a dextral-reverse fault between the Calaveras and Hayward faults that is presently moving at a low slip rate (probably a few tenths of a mm/a), but during earlier times it apparently represented a major strand of the SAFS (Wakabayashi & Sawyer 1998*a*; Wakabayashi 1999; Figs 3 & 5). The Miller Creek Fault may have initiated movement 10–12 Ma ago and has a cumulative dextral displacement of 30–50 km (Wakabayashi 1999). Basement rocks are not exposed along the Miller Creek Fault because they are overlain by Miocene deposits, but the basement probably consists of Franciscan Complex, Great Valley Group, and related rocks (e.g. Page 1981). Although the Miller Creek Fault has been considered a reverse or thrust fault in the past (e.g. Wakabayashi *et al.* 1992), palaeoseismic and field evidence suggests that the fault has been a strike-slip fault during the Quaternary (Wakabayashi & Sawyer 1998*b*). The evidence supporting Quaternary strike-slip movement includes subhorizontal slickenlines on fault surfaces in a palaeoseismic trench, and the steep fault dip ascertained from the trace of the fault over topography (Fig. 5). A palaeoseismic trench across this fault at a ridgetop saddle revealed a graben, filled with

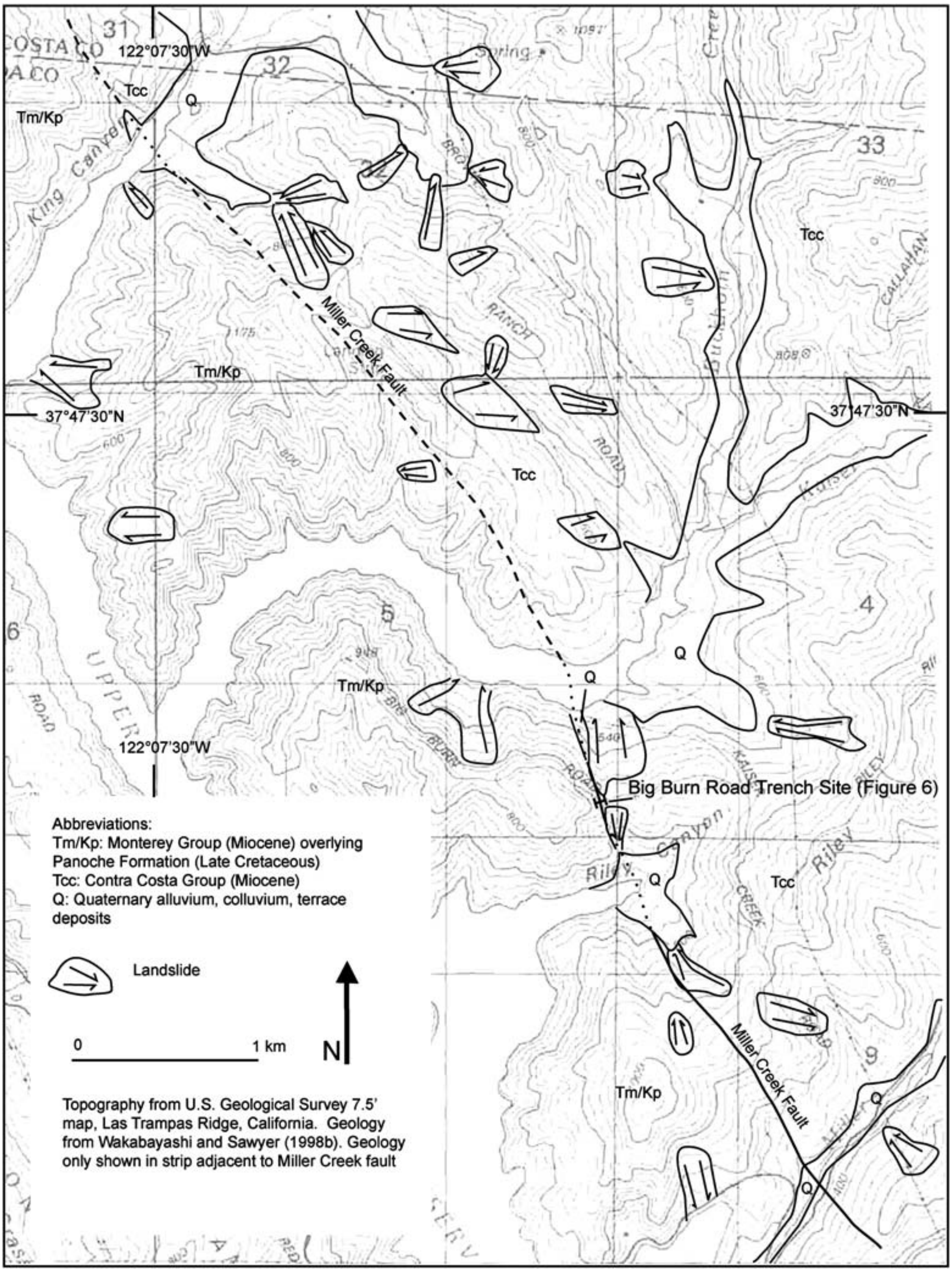
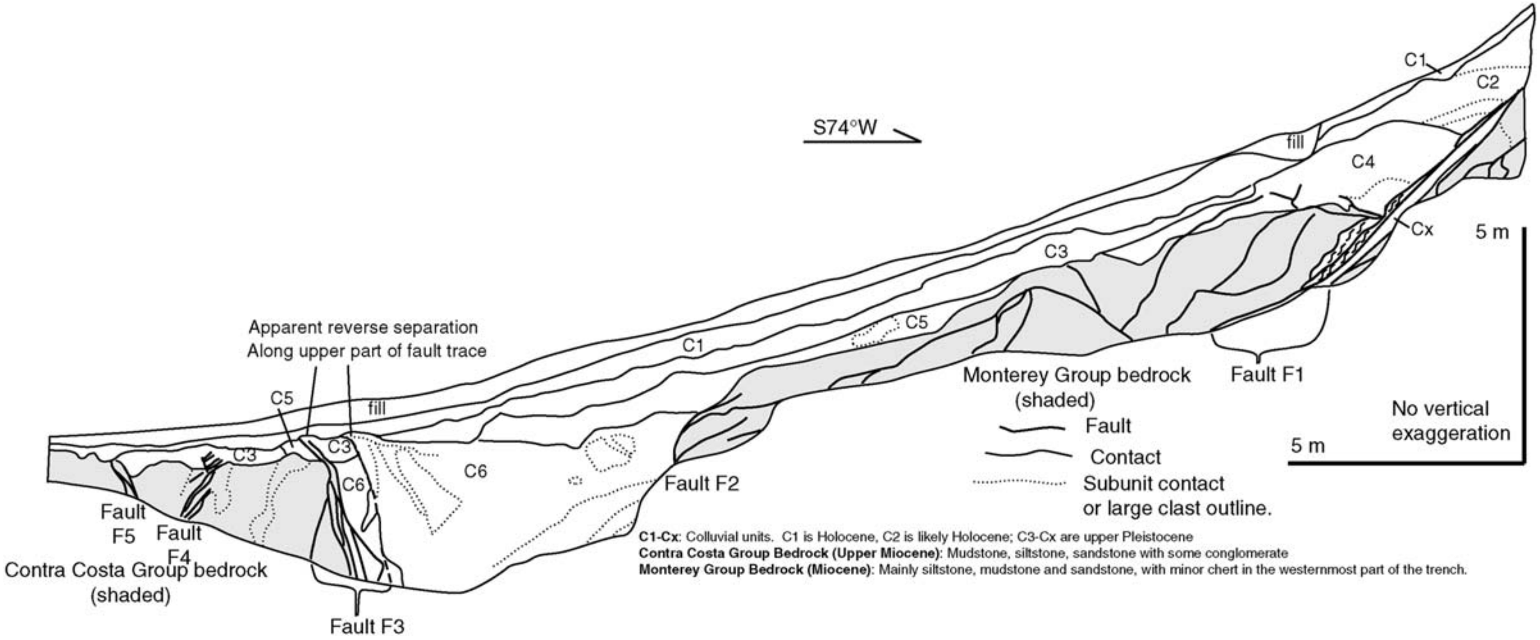


Fig. 5. The Miller Creek Fault in the vicinity of the Big Burn Road trench site shown in Figure 6.

Late Quaternary colluvium, that is bounded by Late Miocene bedrock (graben is bounded by faults F3 and F2 in Fig. 6; Wakabayashi & Sawyer, 1998*a*, *b*). The apparent separation of the eastern graben-bounding faults (fault F3) near the ground surface (i.e. reflecting the most recent movement) is reverse, rather than normal (Fig. 6), indicating a reversal of separation sense (inversion) in the



C1-Cx: Colluvial units. C1 is Holocene, C2 is likely Holocene; C3-Cx are upper Pleistocene
Contra Costa Group Bedrock (Upper Miocene): Mudstone, siltstone, sandstone with some conglomerate
Monterey Group Bedrock (Miocene): Mainly siltstone, mudstone and sandstone, with minor chert in the westernmost part of the trench.

Fig. 6. Trench log of the Miller Creek Fault at the Big Burn Road trench site.

latest Pleistocene. In addition, the colluvium in the graben contains abundant Claremont chert – a lithology not present directly upslope from the saddle. This can reflect either: (1) considerable erosion of the ridge, removing upslope Claremont chert since deposition of the colluvium in the graben, or (more likely) (2) strike-slip movement of the graben material relative to the western side of the graben since deposition, moving the graben away from a position wherein Claremont chert was upslope. A possible modern analogue of the graben has not been found north or south of the trench site, probably because the trace of the fault away from the ridgetop saddle is covered by young landslides or deep colluvium (Fig. 5). Such landslides and colluvium would accumulate at a rate far in excess of the likely tectonic subsidence associated with a several-metre-scale pull-apart along the fault; slip rates on the fault have been estimated at a few tenths of a millitre per year at most (Wakabayashi & Sawyer 1998*b*). The local inversion noted in the trench suggests that the graben deposits may be a small-scale analogue of the Olema Creek Formation, but the lack of an identified 'wake' or modern depocentre, precludes a direct comparison.

Merced/San Gregorio depocentre and the Merced Formation

The Plio-Pleistocene Merced Formation, consisting of lightly cemented marine sandstones and siltstones, crops out in a belt $\leq$2.5 km wide, extending 19 km along the east side of the San Andreas Fault (Brabb & Pampeyan 1983; Fig. 7). Right separation of basement and Late Cenozoic features along the San Andreas Fault on the San Francisco Peninsula (Peninsula San Andreas Fault) is 22 to 36 km, and if the long-term slip rate is similar to the Holocene rate, then the fault did not begin moving until 2 Ma or later (Wakabayashi 1999). The basement cut by the San Andreas Fault along this reach is composed of Franciscan Complex rocks.

The Merced Formation records basinal deposition, and subsequent uplift and shortening along the San Andreas Fault. The relationship between the Merced Formation and its proposed analogue depocentre west of the Golden Gate is somewhat more complicated than the Olema Creek Formation example, because the intersection of the San Gregorio Fault occurs offshore and may influence tectonic subsidence and associated deposition (Bruns *et al.* 2002).

There is some controversy concerning the age of the basal Merced Formation, but it is probably 2 Ma or younger, and the youngest Merced may be 500 ka or younger (Wakabayashi *et al.* 2004). The Merced Formation and the overlying basal part of the Colma Formation are interpreted as sediments that were deposited in trangressive–regressive cycles related to eustatic sea-level fluctuations within a subsiding basin, with deposition keeping pace with tectonic subsidence (Clifton *et al.* 1988).

The Merced Formation is now exposed at elevations up to 200 m on the San Francisco Peninsula, with dips as steep as vertical (Bonilla 1971; Brabb & Pampeyan 1983). No transverse faults have been identified within the Merced Formation. No regional evidence exists for a $<$500 ka regional change in plate motions, and neither is there evidence for shortening initiating throughout this region at $<$500 ka, so the inversion of the Merced Formation appears to be a local phenomenon.

Deposition of the Merced Formation appears to be related to a stepover along the San Andreas Fault. Slip on the San Andreas Fault steps 3 km right to the Golden Gate Fault, forming an active pull-apart basin off the Golden Gate (Bruns *et al.* 2002; Fig. 7). Although there is clearly a net right stepover of the San Andreas Fault from its reach on the San Francisco Peninsula to where it comes on land north of the Golden Gate, the overall pattern of fault-slip transfer is more complex. If the active pull-apart is a product of slip transfer from the San Andreas Fault to the Golden Gate Fault, then slip must then step left again to the north on to the on-land San Andreas Fault north of the Golden Gate (Fig. 7). Indeed, Geist & Zoback (2002) suggest that the tsunami associated with 1906 earthquake along this reach of the San Andreas Fault was a product of vertical seafloor movement along the releasing stepover restraining stepover pair noted above. The Golden Gate Fault appears to be the offshore continuation of the San Bruno fault. Zoback *et al.* (1999) showed a basin in the right-step region, based on seismic reflection and gravity studies, and identified extensional focal mechanisms in the area. Seismic and potential field data suggest that the San Andreas Fault directly south of the active pull-apart has little separation, little evidence for recent activity, and did not move until the Late Quaternary, whereas the Golden Gate Fault has much greater cumulative separation (Jachens & Zoback 1999; Zoback *et al.* 1999; Bruns *et al.* 2002). The onshore, southern continuation of the Golden Gate Fault, the San Bruno Fault, is no longer active (Hengesh & Wakabayashi 1995*a*; McGarr *et al.* 1997). One interpretation of the activity history of the two faults is that the offshore San Andreas Fault south of the pull-apart is very young, having recently propagated northward to that position, whereas the southern part of the Golden Gate Fault is becoming dormant as the San Andreas propagates (Wakabayashi *et al.* 2004); however, an alternative

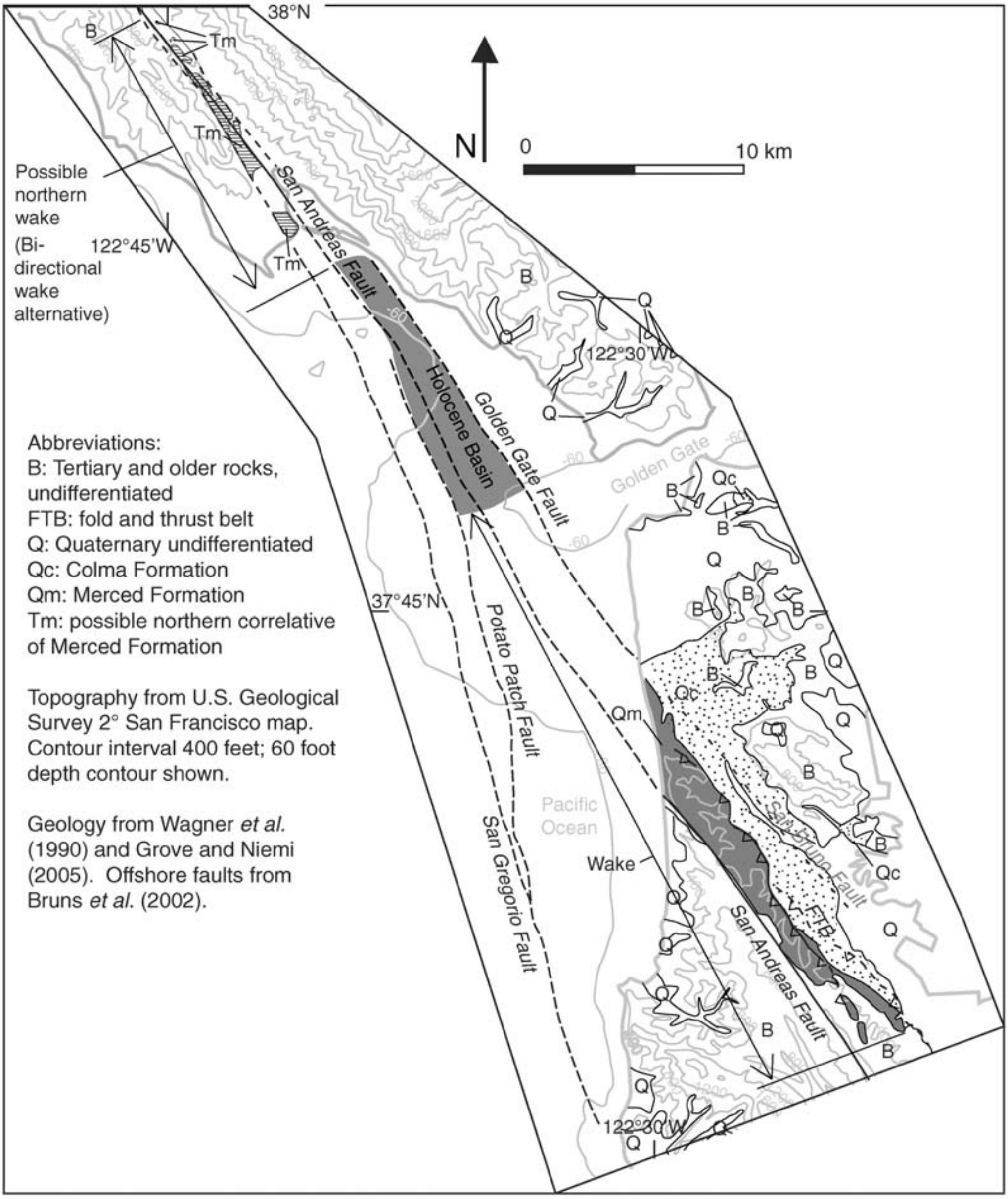


Fig. 7. Geology of the Merced Formation and related structures.

explanation is evaluated in the discussion section of this paper.

No fault scarp breccias, analogous to those found in some strike-slip bains (Crowell 1982), have been identified within the Merced Formation, possibly owing to high rates of sedimentation that kept pace with vertical tectonics in the depocentre (Wakabayashi *et al.* 2004). This is consistent with the bathymetry that appears to show a lobe of deposition west of the Golden Gate, but no expression of the Holocene pull-apart (Fig. 7).

The southern limit of the exposed Merced Formation on the San Francisco Peninsula is presently about 27 km south of the southern margin of the Holocene basin, similar to the total offset on the Peninsula San Andreas Fault. This would be defined as the wake length associated with this stepover (Fig. 7). The along-strike length of the modern depocentre is up to 15 km. These relationships suggest that the active pull-apart migrated with respect to its wake (the Merced Formation) at about the same rate as the slip rate on the Peninsula San Andreas Fault. In other words, the pull-apart migrated with the Pacific plate side of the fault. Wakabayashi *et al.* (2004) suggested that the migration of the stepover was accommodated by the San Andreas Fault propagating northward, whilst the Golden Gate–San Bruno Fault progressively shut off activity. This migration process will be evaluated further in the discussion section of this paper.

Deposits similar to the Merced Formation are present on the Marin Peninsula, north of the Golden Gate (Tm on Fig. 7). However these deposits appear to be older (Clark *et al.* 1984) and they may be related to a basin other than that in which the Merced Formation was formed. Alternatively, they may be related to the same depocentre, having moved north of the depocentre as a consequence of processes such as a change in the position of the San Gregorio Fault to a more easterly location, displacing basinal deposits northward relative to the depocentre at the slip rate of the San Gregorio Fault (Hengesh & Wakabayashi 1995*b*), or they may be part of a northern wake that is a consequence of northward migration of the stepover at less than the slip rate of the San Andreas Fault (the mechanism will be evaluated in the discussion section).

Migrating restraining bends

Lack of evidence for large structural relief associated with most restraining bends and steps

The northern SAFS has several left (restraining) stepovers, slip transfers, or bends which have accommodated tens of kilometres of slip (Wakabayashi 1999). Examples include the Hayward–Calaveras slip transfer zone; the northern termination of the Green Valley Fault; and the northernmost part of the SAFS in the region of the Mendocino triple junction (Fig. 3). If the same family of transverse structures accommodated all of the slip during the evolution of the restraining bend region, then considerable structural relief should result, associated with significant shortening, exhumation, and rock uplift. Using an assumption based on material movement through a stepover region that remains parallel to the PDZ, Wakabayashi *et al.* (2004), suggested that the predicted amount of rock uplift would be 6 km and more if the same transverse structures had remained active during the history of the Mt Diablo restraining stepover, the Calaveras–Hayward restraining slip transfer zone, and the connection between the eastern SAFS faults to the Mendocino triple junction. Late Cenozoic exhumation exceeding 2–3 km should be associated with Late Cenozoic apatite fission-track ages, based on the estimated geothermal gradients along the NSAFS, but restraining stepovers are not associated with such young apatite fission-track ages, with the exception of the Loma Prieta region (Wakabayashi *et al.* 2004).

The lack of structural or thermochronological evidence for large amounts of structural relief associated with most restraining stepovers in the NSAFS suggests that the restraining bends and stepovers may have migrated with respect to rocks originally deformed in these areas – analogous to the migrating releasing stepovers discussed above. Some examples are described below. In contrast to migrating releasing stepovers that leave basinal deposits behind them, the wakes (material formerly affected by the stepover) of migrating restraining stepovers/bends record deformation, uplift, exhumation and erosion.

Mount Diablo restraining stepover

The Mount Diablo restraining left stepover lies between the Greenville Fault to the south and the Concord Fault to the north (Unruh & Sawyer 1995, 1997), i.e. along the easternmost active dextral faults of the SAFS in the San Francisco Bay area (Figs 3 & 8). Mount Diablo is the most prominent topographic landmark in the San Francisco Bay region, with an elevation more than 500 m greater than the highest ridges outside of the stepover area, and it is underlain by an active fold-and-thrust belt called the Mount Diablo fold-and-thrust belt (MFTB), whose strike is oblique to that of the Concord and Greenville faults (Fig. 8). Comparable slip rates on the PDZs and the MFTB are consistent with the evolution of the fold and thrust belt within a restraining stepover as originally proposed by Unruh & Sawyer (1995; data summarized in Wakabayashi *et al.* 2004). The total Late Cenozoic dextral slip that has transferred through the Mount Diablo stepover is at least 18 km, the displacement on this reach of the Greenville fault (Wakabayashi 1999; Fig. 3). The age of initiation of the Concord and Greenville faults is not well constrained. If the average slip rates for the faults are assumed to equal the Holocene slip rate, then the faults would be about 6 Ma old, but there is evidence that the eastern faults of the San Andreas fault system had much higher slip rates prior to about 2 Ma (Wakabayashi 1999). The Greenville and Concord faults cut Franciscan basement.

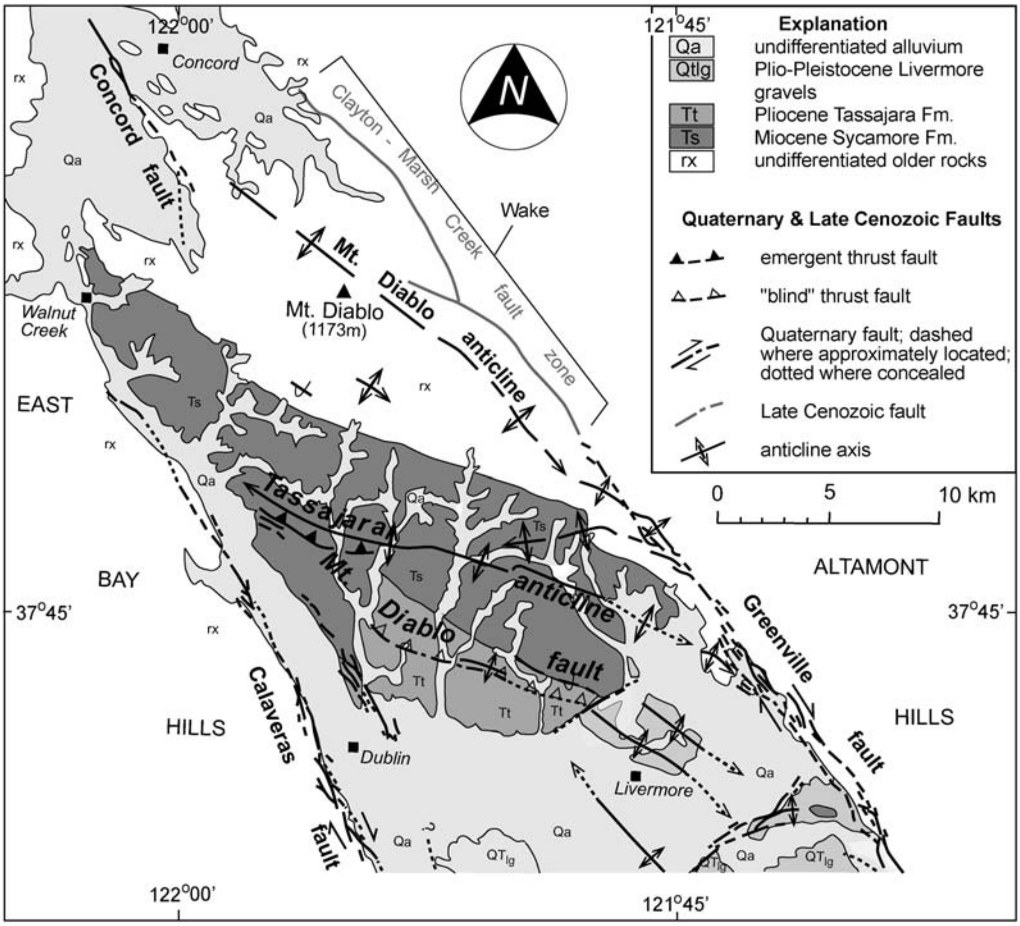


Fig. 8. Geology of the Mt Diablo restraining stepover area. Modified from Wakabayashi *et al.* (2004).

Wakabayashi *et al.* (2004) estimated that the stepover geometry and the amount of slip accommodated on the PDZs should have resulted in at least 6 km of rock uplift at Mt Diablo if the stepover did not migrate with respect to the affected deposits. In contrast, apatite fission-track ages, that predate the transform regime (T. A. Dumitru data in Unruh 2000), indicate exhumation of less than 2–3 km. The northern end of the eastern PDZ, the Greenville–Clayton–Marsh Creek Fault, has not been active in latest Quaternary times, whereas the southernmost part of the Concord Fault exhibits characteristics of an immature (young) fault (Wakabayashi *et al.* 2004). These observations and field data indicating southward (foreland) propagation of the MFTB suggest that the stepover has migrated southward with respect to affected deposits. The 'wake' of this stepover may be 15 km long or longer, based on the inactive length of the Clayton–Marsh Creek fault system.

Transfer of slip from eastern faults of the San Andreas Fault system to the Mendocino triple junction

The largest-scale restraining bend or stepover in the NSAF may occur near the northern terminus of the system at the Mendocino triple junction (Figs 3 & 9). San Andreas-age dextral faults are not present north of the Mendocino triple junction (Kelsey & Carver 1988). In the northernmost SAFS, 230–250 km of dextral slip, the aggregate amount of displacement of faults east of the San Andreas Fault (eastern faults), must transfer westward to the Mendocino triple junction, otherwise there would be enormous slip incompatibilities along the eastern faults, with zero displacement at their northern tips and a large displacements to the south (Wakabayashi 1999). Transfer of slip from the eastern faults to the Mendocino triple junction is a restraining slip transfer or stepover. For any range of transverse structure dips and strikes, this stepover geometry predicts an unrealistic amount of rock uplift for which there is no evidence (tens of kilometres, Wakabayashi *et al.* 2004). The actual geometry of transverse structures in the triple-junction region may be complex. Some strike-slip faults south of the triple junction change into thrust faults north of the triple junction (Kelsey & Carver 1988). The uplift rates are higher in the triple-junction region than to the north along the subducting margin or to the south along the transform boundary (Merritts & Bull 1989), and this uplift does not appear to be limited to that directly associated with reverse movement along the structures noted above. Tens of kilometres south of the triple junction, there are discrete high-angle faults that strike more westerly than the dextral strands of the San Andreas Fault system, and cut Franciscan nappe structures and later out-of-sequence thrust faults that imbricate the Franciscan nappes. Late Cenozoic deposits are not present along or across these structures, so it is difficult to verify whether these are palaeo-transverse structures as suggested by Wakabayashi (1999) and Wakabayashi *et al.* (2004).

The eastern faults, such as the Hayward–Rodgers Creek–Maacama trend, and the Green Valley Fault, die out northward as well-defined faults (Figs 3 & 9). This may be because the eastern faults are young and propagating northward, whilst slip transfers to the triple junction that is migrating at about 25 mm/a NW relative to the westernmost of the eastern faults (Wakabayashi 1999; Wakabayashi *et al.* 2004). In order to transfer slip to the migrating triple junction, new transverse faults must continue to form (Fig. 9). Thus, the stepover region progressively migrates so that large-scale displacement or structural relief has not developed on any given transverse structure. The northernmost SAFS may be another example of a restraining stepover that has migrated with respect to the rocks deformed within the stepover. It is difficult to estimate the length of the wake, because the boundaries of the active stepover area are not well defined, and because the nature of Late Cenozoic deformation in the region SE of the triple junction has not been determined, owing to the lack of Late Cenozoic deposits. The 'wake' of the stepover region may be 200–250 km long, based on the presence of possible old transverse structures cutting basement as far as south as the inboard 10 Ma contour in Figure 9; the lack of such structures in the San Francisco Bay area; and the temporal–spatial distribution of slip on the eastern fault strands (Wakabayashi 1999). This wake corresponds only with the activity history of the eastern faults, not the older Mendocino triple junction itself.

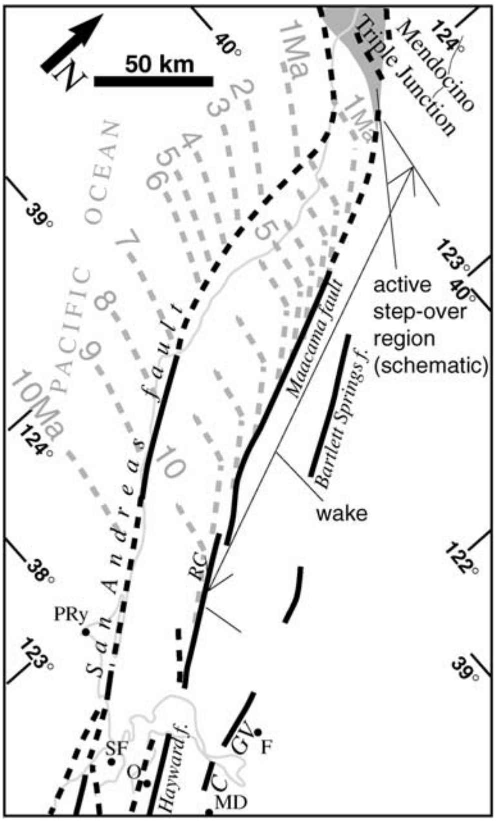


Fig. 9. Migration of the restraining transfer zone to the Mendocino triple junction. Approximate past positions of the triple junction (west of the the San Andreas Fault), and transverse structures (east of the San Andreas Fault; this is the wake) shown in greyed dashed lines with corresponding age designations. Longitude/latitude and other reference points are valid only for present, given that they would differ upon restoration to the different time frames. Abbreviations, in addition to those given in Figure 3: F, Fairfield; RC, Rodgers Creek fault; TV, Tolay volcanics. Adapted from Wakabayashi (1999).

Discussion: models for migrating stepovers

Migrating stepovers: speculation on modes of migration

I have interpreted the above stepover and bend regions as having migrated with respect to deposits that were originally within the stepover or bend regions. Although alternatives such as regional plate-motion changes do not appear to explain the field relations (for examples involving basin deposits), other types of processes require further explanation. Block rotation may account for local inversion, but it should not leave a wake of deformation or inverted deposits parallel to a PDZ. Because the Miller Creek Fault example does not have an identified wake or modern analogue depocentre, block rotation is an alternative mechanism to explain the inversion of Late Pleistocene graben deposits there. Another alternative that may explain some of the types of field relations described may be reorganization of an evolving transform fault. By creating new faults, removing bends and irregularities, and other changes in distribution of slip, it may be possible to locally invert deposits, as material may shift from a locally transtensional mode to a transpressional one, or vice versa. Similarly to the block rotation mechanism, however, the rearrangement of an evolving transform fault should not create wakes on one or both sides of a stepover region along the strike of a fault.

Below, I present a simple model for migrating stepover evolution. It is probably obvious that this model is vastly simpler than real stepovers. For simplicity, I have used PDZs that do not change through time other than propagating in some cases; two transverse structures bounding releasing stepovers (for simple rhombochasm-type pull-apart geometry); and one transverse structure for restraining bends (it is simply the bent PDZ; other off-PDZ structures are not explicitly defined). It is hoped that this cartoon simplification does not overly simplify the problem to the point that the model fails to address geological reality.

For stepovers to have migrated with respect to affected deposits as I have proposed above, new transverse structures associated with the bend or stepover regions must have progressively formed in the direction of the migration (Fig. 10b frame sequence B-1 to B-2b or B-2c; Fig. 10c frame sequence C-1 to C-2b). If the same transverse structures migrated instead of new structures forming, the material bounded by them would have migrated with them and, if the structures were still active, the stepover or bend would have grown in structural relief (Fig. 10b frame sequence B-1 to B-2a; Fig. 10c frame sequence C-1 to C-2a). A migrating stepover probably has an early stage of development in which a stepover region grows to a certain size (Fig. 10a) before migration begins with respect to formerly affected deposits, in contrast to progressively growing stepover regions that maintain the same set of transverse structures and continue to grow (Fig. 10b & 10c). The nature of fault propagation and migration of restraining bends and releasing bends have important geometric differences, and so they are discussed separately below.

In addition to the creation of new transverse structures and the shut-off of old ones, migration of releasing bends suggests that the strike-slip fault on one side of the pull-apart may propagate in the direction of basin migration (PDZ1 in Fig. 10b, frame B-2b), whereas the fault on the other side of the basin will progressively shut off (PDZ2 in Fig. 10b, frame B-2b). The propagation and shut-off of bounding strike-slip faults is consistent with the seismic reflection interpretation of Bruns *et al.* (2002) for the relationship of the Merced Formation to offshore pull-apart structures. In some (or many) cases, transverse structures may not be discrete faults, but may be zones of distributed deformation (perhaps above blind normal or oblique faults) accommodating the differential displacement between reaches of PDZs with differing senses of movement (for example, pure strike-slip v. normal-oblique). On the other hand, it is clear from examples presented here and from global examples of releasing bends that actual basin geometry is usually vastly more complex than the schematic model pull-apart shown in Figure 9b, so other types of kinematic links may be associated with the observed fault separations.

The mechanism illustrated in Figure 10b, frame B-2b, predicts that the tip of the trailing PDZ moves faster than the slip rate of the fault relative to Block b, meaning that the overall migration rate of the pull-apart is also faster than the slip rate, and the tip of the fault propagates into the Block a. The seismic reflection data of Bruns *et al.* (2002) show evidence for recent offset, but little cumulative vertical separation, along the northernmost Peninsula San Andreas Fault that forms the western boundary of the Merced Formation and either the western boundary or one of the western faults bounding the analogue Holocene pull-apart basin (Fig. 7). Wakabayashi *et al.* (2004) interpreted these data to indicate that the northernmost Peninsula San Andreas Fault was young as a result of propagation of the tip of the fault. Alternatively the seismic evidence may suggest that the northernmost Peninsula San Andreas is long-lived but exhibits little cumulative displacement because most of the slip has transferred to the eastern PDZ by that point. For the Olema Creek Formation, the depocentre (associated with a transtensional reach along the San Andreas Fault or pull-apart) may have migrated 10 km relative to its former deposits, whereas if it migrated at the slip rate of the San Andreas Fault, then the migration distance would have been about 4.8 km.

In the case of the Merced Formation, the original releasing stepover structure may have been created at about the time of the creation of the Peninsula San Andreas Fault at about 2 Ma, based on the estimate for the age of the basal Merced Formation and the estimate for the age of inception of slip on the Peninsula San Andreas Fault from division of the slip amount by the Holocene slip rate. In contrast, the structure related to the deposition of the Olema Creek Formation may have formed at about 200 ka, based on the age of the oldest Olema Creek Formation deposits, on a fault that may have formed at 18 Ma. Thus, the two examples appear to represent migrating stepovers that formed at different times relative to the evolution of the strike-slip that they were/are associated with.

Figure 10b, frame B-2b, may illustrate only an end-member case of how releasing stepovers migrate. In the case illustrated, the stepover migrates at a rate slightly faster than the slip rate

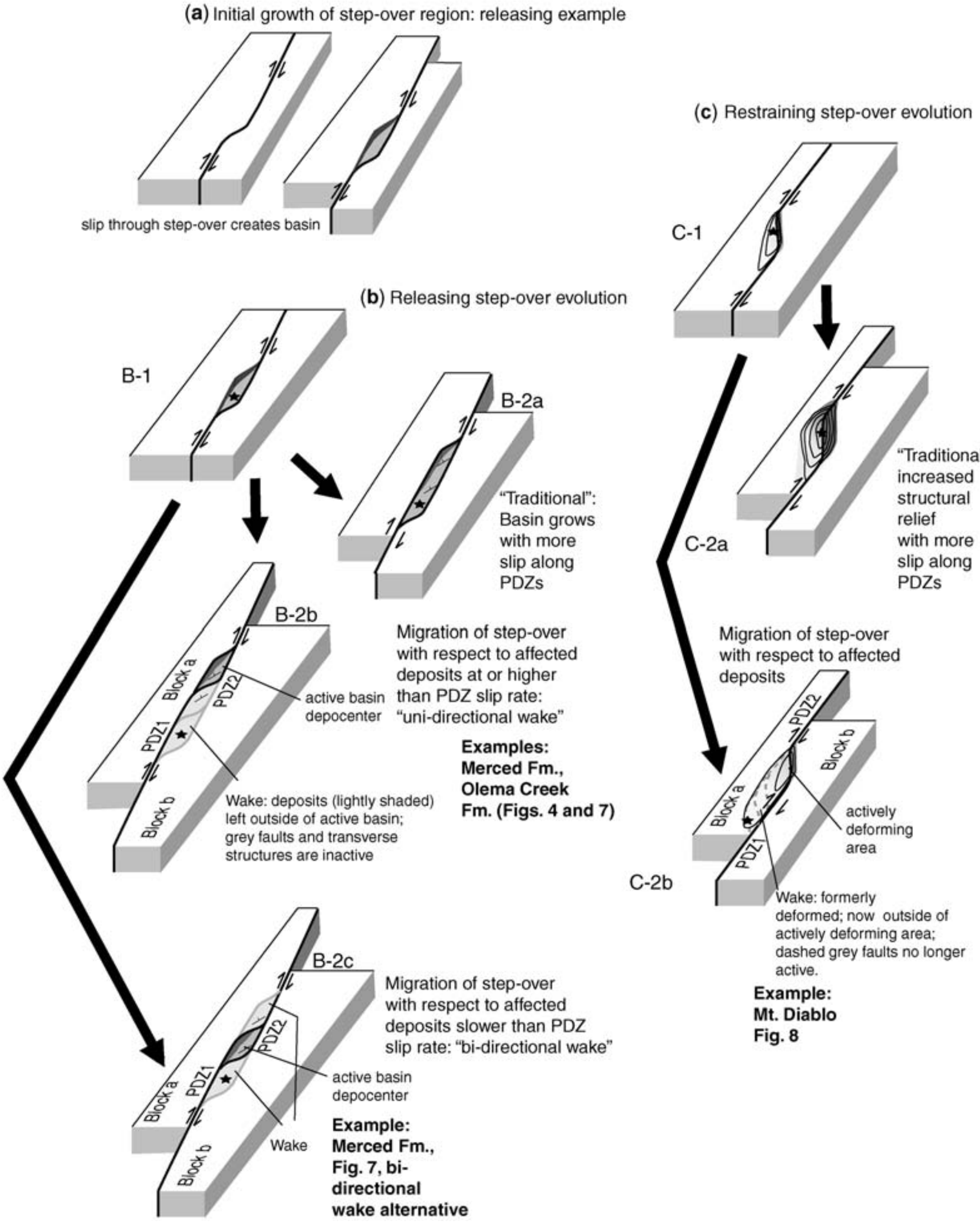


Fig. 10. Progressive evolution of releasing and restraining stepover and bend regions along strike-slip faults. The star in each diagram is a reference point that represents a point within deposits affected by the stepover.

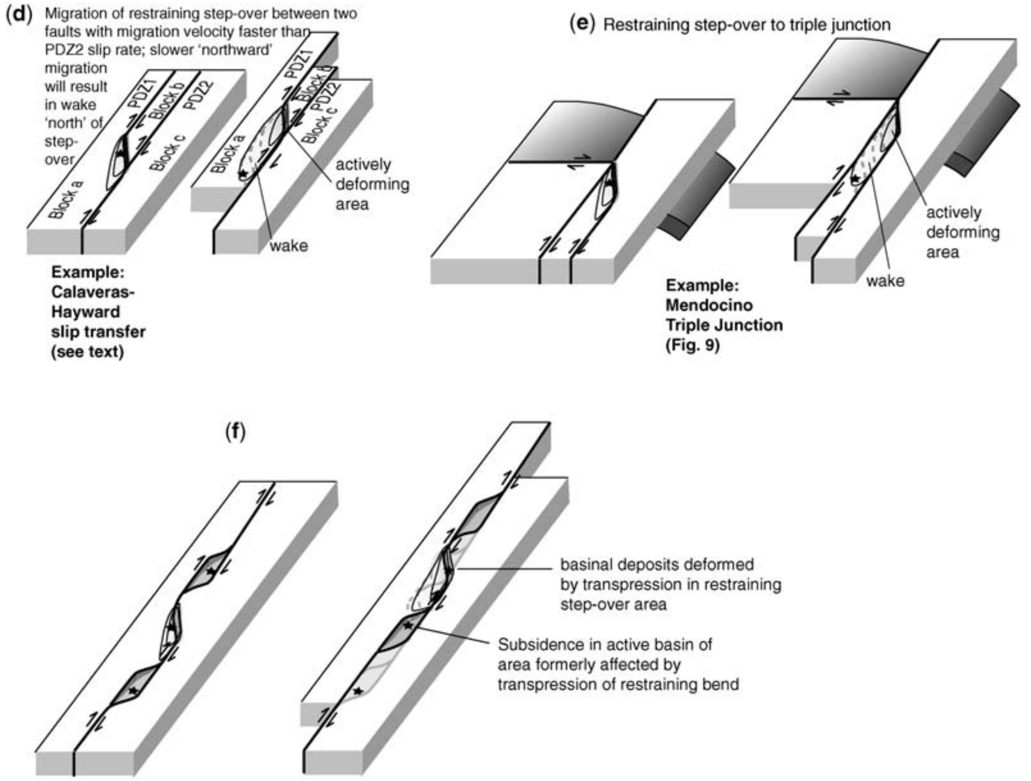


Fig. 10. *Continued.*

of Block a relative to Block b (i.e. faster than the slip rate of the fault). This example was based on interpretations of the Merced and Olema Creek formations, but there is no reason to believe that the opposite case cannot occur in which a pull-apart migrates southeastward along a NW-striking dextral fault at or slightly faster than the rate of the eastern side of the fault relative to the western side. Such an example would leave a wake NW of the pull-apart basin. Intermediate examples would be those in which the pull-apart migration rate lags behind the fault slip rate. Such examples should have 'bi-directional' wakes, or wakes both NW and SE of the pull-apart basins (Fig. 10b, frame B-2c). The Merced-like strata in Marin County (Tm in Fig. 7) have been interpreted to be a part of the Merced Formation faulted northward by eastward stepping of the San Gregorio Fault (Hengesh & Wakabayashi 1995*b*) or older deposits unrelated to the Merced Formation (Wakabayashi *et al.* 2004). An alternative explanation is that the strata represent the northern wake of the migrating Merced Formation pull-apart, and that the pull-apart has a bi-directional wake. The uncertainty in the amount of PDZ slip (22 to 36 km) is large enough to be consistent with either the bi-directional or uni-directional wake alternatives.

In the case of the regionally transpressive San Andreas fault system, the wake of releasing step-overs is subject to shortening and uplift (positive inversion) as a consequence of the regionally transpressive regime. As noted by Wakabayashi *et al.* (2004), such inversion may occur along a neutral transform, or even transtensional regime, if a migrating restraining stepover follows the migrating releasing stepover and interacts with the wake of the former (Fig. 10f). In addition, inversion of releasing stepover wakes may occur in a neutral transform system depending on the geometry of crustal/lithospheric flow into the stepover region. This is because some crustal or lithospheric flow toward the pull-apart area probably occurs, otherwise a pull-apart will create a void that extends as deep as the depth of strike-slip movement.

For releasing stepovers, a model nearly identical to that illustrated in Fig. 10b B-2b (uni-directional wake with a propagating PDZ) was proposed for the Dead Sea pull-apart, arguably the world's most studied pull-apart basin, by ten Brink & Ben-Avraham (1989). More recently, Lazar *et al.* (2006) offered an alternative model for the Dead Sea basin, based on new subsurface geological and geophysical data, in which multiple sub-basins form and grow as strike slip progresses on en échelon segments of strike-slip faults. Lazar *et al.* (2006) propose that new transverse structures can progressively form as a result of slip on the PDZ displacing a bounding and converging strike-slip segment relative to the basins, rather than as a result of PDZ propagation. Although such a model may better explain the evolution of the Dead Sea basin than a migrating stepover model, it may be a bit more difficult to reconcile with the interpreted development of wakes proposed for the examples reviewed here.

Migrating restraining bends (Fig 10c, Frame sequence C-1 to C-2b) differ from the migrating releasing stepovers of Figure 10b (Frame sequence B-1 to B-2b) in that fault tips propagate opposite to the direction of the slip of the block that the fault is propagating into when considered relative to the block on the other side of the old PDZ (this will be simply described as 'propagating opposite to slip') rather than in the same direction (herein referred to as 'propagating ahead of slip'). Because of this, migrating restraining stepovers should always form uni-directional wakes, regardless of the migration velocity and direction. For cases involving a restraining stepover along a single strike-slip fault, fault propagation – coupled with progressive fault dormancy of the paired PDZ – must occur in order for the structure to migrate with respect to the affected deposits. Cases involving multiple faults, such as the Calaveras–Hayward Fault slip transfer zone and the Mendocino triple junction present different situations. For cases similar to that of the Calaveras–Hayward Fault slip transfer (not discussed in detail here, but discussed in Wakabayashi *et al.* 2004), illustrated in Figure 10d, propagation of the Hayward Fault (PDZ1 in Fig. 10d) will only occur if the slip-transfer region is migrating northwestward slower than the rate of the western side of the eastern fault north of the slip transfer (i.e. migrating slower than Block b in Fig. 10d). In the Calaveras–Hayward case, this would mean migrating northwesterly relative to the east side of the Calaveras Fault (Block c of Fig. 10d) slower than the 6 mm/a slip rate of the Calaveras Fault north of the slip transfer. In such a case, the Hayward Fault would propagate southeastward and the wake would form NW of the slip-transfer region. If the northwestward migration rate of the slip transfer zone is faster than Block b (Fig. 10d), then a wake should be formed SE of the migrating slip-transfer zone, and the southern part of the Hayward fault will progressively cease activity, as illustrated in the example of Figure 10d.

For the Mendocino triple-junction example (Fig. 9 & Fig. 10e), similar to the general restraining stepover example, the eastern faults of the San Andreas Fault propagate 'opposite' slip and the more inboard the fault, the faster the fault propagation rate, because the relative migration rate of the triple junction is the sum of the slip rates of all faults to the west.

Migrating stepovers and progressively growing stepovers as end members of general stepover types

As noted by Wakabayashi *et al.* (2004), both migrating and 'traditional' (progressively increasing structural relief) types of stepovers appear to be common worldwide. It is reasonable to believe that many stepovers may exhibit combinations of these characteristics. In other words, many stepovers may exhibit evidence of progressive increases in structural relief, but also have wakes of material formerly – but no longer – affected by the stepover. Migrating stepovers as described herein may represent one end member of stepover evolution, and stepovers that progressively grow in structural relief represent another end member. I suggest that we might attempt to classify the type of stepover evolution on the basis of how much of the slip along the PDZs has been accommodated by structural relief development v. wake development. If the wake length is greater than or equal to the estimated PDZ slip through the stepover region, then the PDZ slip has been accommodated by wake development and stepover migration. Comparatively short wakes for large amounts of PDZ slip would suggest that most of the slip has been accommodated by structural relief development in the stepover region. A problem with such a classification is that there are probably many examples where stepovers are much younger than the PDZs that they form along (the Olema Creek Formation is one likely example). In those cases, it may be difficult to determine the amount of slip along the PDZs that has been associated with stepover evolution. Three examples reviewed above for which I can estimate wake lengths (the Merced Formation, Mount Diablo, and the Mendocino triple junction) appear to have wake lengths that are close to the estimated amount of slip that has passed through the stepover region (Table 1). Thus, those three examples would be close to the 'migrating' end member among the larger family of stepovers. A fourth example, the Olema Creek Formation, with a PDZ displacement of 4.8 km and a wake length of 10 km, may represent a case where a releasing

Table 1. *PDZ displacement through stepover v. wake length*

Stepover	PDZ displacement (km)	Wake length (km)
Merced Formation	22–36	27 (uni-directional) 39 (bi-directional)
Olema Creek Formation	4.8	10
Mount Diablo	18	15
Eastern faults of San Andreas fault system: connection to Mendocino triple junction	230–250	200–250

bend migrated at a velocity greatly in excess of the PDZ slip rate. It too would be classed as a purely migrating type of stepover.

The Loma Prieta restraining bend may exhibit characteristics between the 'traditional' and migrating end-members of stepover/bend type. The exhumation associated with the Loma Prieta bend is large enough that Late Cenozoic apatite fission-track ages have been obtained from the area (Bürgmann *et al.* 1994), indicating much more significant structural relief than that associated with other restraining stepovers or bends along the NSAFS. The restraining bend may be associated with the fold and thrust belt that marks the eastern range-front of the San Francisco Peninsula, east of the San Andreas Fault (FTB in Figs 3 & 7). The northern limit of the fold and thrust belt is the northern limit of the Merced Formation exposures described above. The belt thins northward and the deformation at the northernmost limit of the belt appears to have begun within the last few hundred thousand years or so, whereas the belt shows evidence of activity for at least 2 Ma to the south (Kennedy 2002). Thus, it appears that the fold and thrust deformation is propagating northwestward along the San Andreas Fault. This propagation may be a consequence of progressive increase in structural relief of the Loma Prieta restraining bend area, or it may result from the northward migration of the Loma Prieta bend relative to affected deposits. The detailed evaluation of the spatial distribution and kinematics of aftershocks of the 1989 Loma Prieta earthquake by Twiss & Unruh (2007) may provide evidence for migration of the Loma Prieta stepover. Their analysis shows that the aftershocks of the 1989 earthquake define a blind dextral fault with a reverse component that forms several en échelon segments. This is suggestive of a young structure. Although the creation of a new master fault in the stepover region may be interpreted as the creation of a new transverse structure in a migrating restraining bend, it may simply be a consequence of rearrangement of faults in the stepover region rather than a product of systematic and progressive migration of restraining-bend deformation.

Migrating stepovers: complications and proposed field tests of mechanisms

I have reviewed field evidence for migrating stepovers and proposed models for their evolution. The field examples presented are certainly not perfect. Only the Mount Diablo example appears to have a well-defined active stepover region with active transverse structures, as well as evidence for propagating and inactive PDZs and possible older transverse structures. The Mendocino triple-junction example appears to have evidence for an active stepover region and propagating faults, but older transverse structures have yet to be confirmed. No transverse structures have been identified for any of the releasing bend examples, and neither is there sufficient geochronological data to indicate a younging of the age of the basal strata of the exposed deposits in the direction of migration, as would be predicted by the model.

To further test these models, additional geochronological data will be useful to see whether there is along-strike younging of the base of basinal deposits making up wakes of proposed migrating releasing bends. Field investigation should be able to determine whether progressively younger transverse structures (blind or otherwise) occur in the direction of migration. For restraining stepovers, analysis of uplift rates (by analysis of stream terrace deposits, for example) should show high recent uplift rates in the active stepover region, with slower rates in the past, whereas the wake region should show lower recent uplift rates but a period of fast uplift rates in the past. It may be possible to track a progressively migrating pulse of rapid uplift by examining a series of transverse drainages. This paper has examined only the most surficial aspect of stepover evolution and has neglected the mechanisms for accommodating the stepover evolution at the mid-crustal and lower levels. The deeper evolution of such structures will require evaluation of detailed seismic and potential field data in conjunction with surface geology and geodetic data.

Conclusions

Migrating stepovers, as defined herein, migrate with respect to affected deposits. Wakes of formerly affected deposits allow recognition of migrating stepovers. Many stepovers exhibit characteristics associated with migration with respect to affected deposits, whereas many others show evidence of significant increase in structural relief with time. A migrating stepover that experienced minimal structural-relief increase over its evolution may represent one end member of stepovers, whereas a stepover that has progressively increased in structural relief and time and not developed a wake may represent another end member. It is likely that many stepovers exhibit characteristics of both end members, and comparative importance of migration v. structural relief growth may be gauged by the ratio between the wake length and PDZ slip accumulated during stepover development. High wake length to PDZ slip ratios are indicative of stepovers that have formed largely by migration with respect to their deposits. Speculation as to what processes or physical variables control the type of stepover evolution is beyond the scope of this paper. The models for stepover development presented here are rather simplistic compared with the complex geology seen at many stepover regions. Nonetheless, relatively simple field tests can be used to evaluate the validity of these models.

I have benefited from discussions on this subject with many colleagues, especially the participants at the Geological Society of London conference on tectonics of strike-slip releasing and restraining bends, and T. Bruns, U. S. ten Brink, M. L. Zoback, C. Busby, K. Grove and T. Atwater. I am grateful for detailed, constructive and thought-provoking reviews by P. Mann and M. Legg.

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