Tectonics of strike-slip restraining and releasing bends

W. D. CUNNINGHAM[1] & P. MANN[2]

[1]*Department of Geology, University of Leicester, Leicester LEI 7RH, UK (e-mail: wdc2@le.ac.uk)*

[2]*Institute of Geophysics, Jackson School of Geosciences, 10100 Burnet Road, R2200, Austin, Texas 78758, USA (e-mail: paulm@ig.utexas.edu)*

One of the remarkable tectonic features of the Earth's crust is the widespread presence of long, approximately straight and geomorphically prominent strike-slip faults which are a kinematic consequence of large-scale motion of plates on a sphere (Wilson 1965). Strike-slip faults form in continental and oceanic transform plate boundaries; in intraplate settings as a continental interior response to a plate collision; and can occur as transfer zones connecting normal faults in rift systems and thrust faults in fold–thrust belts (Woodcock 1986; Sylvester 1988; Yeats *et al.* 1997; Marshak *et al.* 2003). Strike-slip faults also are common in obliquely convergent subduction settings where interplate strain is partitioned into arc-parallel strike-slip zones within the fore-arc, arc or back-arc region (Beck 1983; Jarrard 1986; Sieh & Natawidjaja 2000).

When strike-slip faults initiate in natural and experimental settings, they commonly consist of en échelon fault and fold segments (Cloos 1928; Riedel 1929; Tchalenko 1970; Wilcox *et al.* 1973). With increased strike-slip displacement, and independent of fault scale (Tchalenko 1970), fault segments link, and the linked areas along the 'principal displacement zone' may define alternating areas of localized convergence and divergence along the length of the strike-slip fault system (Fig. 1; Crowell 1974; Christie-Blick & Biddle 1985; Gamond 1987). Typically, divergent and convergent *bends* are defined as offset areas where bounding strike-slip faults are continuously linked and continuously curved across the offset, whereas more rhomboidally shaped *stepovers* are defined as zones of slip transfer between overstepping, but distinctly separate and subparallel strike-slip faults (Wilcox *et al.* 1973; Crowell 1974; Aydin & Nur 1982, 1985). However, fault stepovers may evolve into continuous fault bends as the bounding faults and connected splays propagate and link across the stepover (e.g. Zhang *et al.* 1989; McClay & Bonora 2001). Thus, the two terms 'stepover' and 'fault bend' are often used interchangeably.

Bends that accommodate local contraction are referred to as restraining bends, and those that accommodate extension are referred to as releasing bends (Fig. 1; Crowell 1974; Christie-Blick & Biddle 1985). Double bends have bounding strike-slip faults which enter and link across them, whereas single bends are essentially strike-slip fault-termination zones. Restraining and releasing bends are widespread on the Earth's surface, from the scale of major mountain ranges and rift basins to sub-outcrop-scale examples (Swanson 2005; **Mann** this volume). Releasing bends have also been documented along oceanic transforms connecting spreading ridges (Garfunkel 1986; Pockalny 1997), and extra-terrestrial restraining bends have been interpreted to occur on Europa and Venus (Koenig & Aydin 1998; Sarid *et al.* 2002).

Strike-slip restraining and releasing bends are sites of localized transpressional and transtensional deformation, respectively. Thus, bends are characterized by oblique deformation that is ultimately controlled by larger-scale relative plate motions either acting on relatively straight, long interplate boundaries (Garfunkel 1981; Mann *et al.* 1983; Bilham & Williams 1985; Bilham & King 1989) or acting across more complex zones of intraplate deformation where faults tend to be shorter, less continuous and more arcuate (**Cunningham** this volume). Within the bend, oblique deformation may be accommodated by oblique-slip faulting or partitioned into variable components of strike-slip and dip-slip fault displacements (Jones & Tanner 1995; Dewey *et al.* 1998; Cowgill *et al.* 2004*b*; **Gomez *et al.*** this volume). As seen in deeply eroded outcrop exposures or from subsurface geophysical surveys, double restraining bends and releasing bends commonly define positive and negative flower structures respectively, and strike-slip bends or 'duplexes' in plan view (Fig. 1; Lowell 1972; Sylvester & Smith 1976; Christie-Blick & Biddle 1985; Harding 1985; Woodcock & Fisher 1986; Dooley *et al.* 1999), although considerable structural variation and complexity occurs (Barka & Gulen 1989; May *et al.* 1993; Wood *et al.* 1994; Waldron 2004; Barnes *et al.* 2005; Decker *et al.* 2005; Parsons *et al.* 2005). Single bends commonly have horsetail splay fault

From: Cunningham, W. D. & Mann, P. (eds) *Tectonics of Strike-Slip Restraining and Releasing Bends.*
Geological Society, London, Special Publications, **290**, 1–12.
DOI: 10.1144/SP290.1 0305-8719/07/$15.00

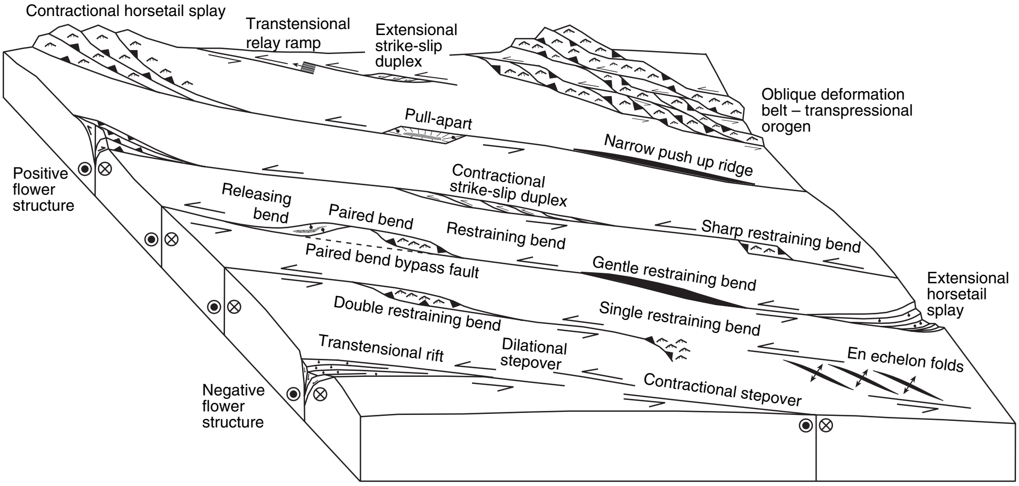

Fig. 1. Tectonic features associated with strike-slip restraining and releasing bends.

geometries in plan view, with strike-slip displacements terminally accommodated by oblique-slip and dip-slip faulting (McClay & Bonora 1997). Adjacent restraining and releasing bends called 'paired bends' by **Mann** (this volume) are commonly described from strike-slip systems in all tectonic settings and may reflect a volumetric balancing between crustal thickening and uplift at restraining bends, and crustal thinning and basin formation at releasing bends (Woodcock & Fischer 1986).

Restraining bends are sites of topographic uplift, crustal shortening and exhumation of crystalline basement (Segall & Pollard 1980; Mann & Gordon 1996; McClay & Bonora 2001), whereas releasing bends are sites of subsidence, crustal extension, significant basin sedimentation, high fluid flow, and possible volcanism (Aydin & Nur 1982; Mann *et al.* 1983; Hempton & Dunne 1984; Dooley & McClay 1997). Restraining bends and releasing bends are commonly elongate, lazy-S- or Z-shaped features in plan view, and they may form the dominant topographic and structural feature within a deforming region. With increased strike-slip offset, S- and Z-shaped pull-apart basins may evolve into more rhomboidally shaped features (Mann *et al.* 1983).

Restraining bends produce elongate, individual massifs with anomalously high topographic elevations such as the Denali Range in Alaska (Fitzgerald *et al.* 1993), the Lebanon and Anti-Lebanon ranges of the Middle East (**Gomez *et al.*** this volume), or the Cordillera Septentrional on the island of Hispaniola (Mann *et al.* 1984, 2002). Releasing bends produce pull-apart basins and fault-bounded troughs that comprise some of Earth's lowest topographic depressions, such as the Dead Sea (ten Brink *et al.* 1999), Death Valley (Christie-Blick & Biddle 1985) and submarine basins underlying the Gulf of Aqaba (Elat; Ben-Avraham 1985), the Cayman trough (Leroy *et al.* 1996, AAPG) and the Gulf of California (Persaud *et al.* 2003).

Restraining and releasing bends along both continental and oceanic strike-slip faults may act as barriers to earthquake propagation (King & Nabelek 1985; Sibson 1985; Barka & Kadinsky-Cade 1988) or conversely, they may provide nucleation sites for major earthquakes (e.g. Shaw 2006). There are also documented cases of large fault bend earthquakes ($M > 7$) having complex rupture mechanisms with multiple faults being activated within the bend, as well as major faults rupturing through the bend (Bayarsayhan *et al.* 1996; Harris *et al.* 2002). Because the length of fault segment rupture is proportional to earthquake magnitude (Scholz 1982), identification of fault bends between parallel strike-slip fault segments that may act as seismic propagation barriers is important in assessing the potential severity of future earthquakes in areas of active strike-slip faulting. Documenting three-dimensional fault connectivity and kinematics within an individual fault bend is important for assessing whether the bend may act as a future earthquake propagation barrier (**Graymer *et al.*** this volume).

In addition to earthquake hazards, tectonically active fault bends have other societal relevance. Restraining bends may:

1. exhume crystalline basement rocks that contain important mineral deposits (e.g. Pinheiro & Holdsworth 1997);

2. host hydrocarbons in their interiors and flanking basins (Christie-Blick & Biddle 1985; Escalona & Mann 2003; Decker *et al.* 2005); and
3. form major topographic uplifts that provide a locally significant rain catchment area and potential groundwater resources (Gobi Altai and Altai restraining bends, Cunningham *et al.* 1996; Cunningham 2005, this volume).

The societal significance of releasing bends includes the following:

1. pull-apart basins form depressions containing significant sedimentary accumulations that may host hydrocarbons, metalliferous deposits, evaporites and other industrial minerals (e.g. the Vienna Basin, Hamilton & Johnson 1999; Hinsch *et al.* 2005);
2. releasing bends may be zones of high heat flow and crustal dilation that can be exploited as sources of geothermal energy, such as the Coso geothermal area of California (Lees 2002) and the Cerro Prieto geothermal area of Mexico (Glowacka *et al.* 1999); and
3. releasing bends may create large valleys that provide fertile agricultural land and flat-lying urbanized areas, such as the Imperial Valley of southern California, the Silicon Valley of northern California, the Vienna Basin of Austria, and the Dead Sea–Sea of Galilee Valley in the Middle East.

Origin and evolution of strike-slip fault bends

Factors that influence and control the origin and progressive development of restraining and releasing bends are complex and numerous, but can be grouped into several major research themes.

Fault geometry and reactivation

The shape, topography and internal architecture of a fault bend is fundamentally controlled by several factors, including the orientation of the plate motion vector relative to the master strike-slip fault; the original width of the stepover; and whether the bend is a strike-slip fault termination; a double bend along a single continuously linked strike-slip fault; or a stepover where parallel strike-slip fault segments are offset and may or may not overlap. For example, wide stepovers may contain fewer faults that bridge the gap between master strike-slip faults, whereas narrow stepovers may have greater linkage between major faults within the bend (Dooley & McClay 1997; McClay & Bonora 2001). Because fault bends typically form in mechanically heterogeneous crust, pre-existing faults and basement fabrics may be reactivated instead of new faults generated. The orientations of reactivated older structures are unlikely to be ideal for either pure strike-slip or pure dip-slip motions, thus oblique-slip displacements on reactivated faults are typically important within fault bends, and workers should therefore be aware of field criteria that indicate fault reactivation (Holdsworth *et al.* 1997).

Strain magnitude and distribution

Strike-slip displacements along master faults that enter a fault bend will be partially or wholly accommodated by deformation within the bend (Segall & Pollard 1980). Thus, large displacement strike-slip faults are capable of producing the largest restraining and releasing bends. However, small restraining and releasing bends may also exist along major strike-slip faults, especially when early formed bends are bypassed as the system evolves (Bennett *et al.* 2004; **Mann** *et al.* this volume), or when fault bends nucleate late in the history of a strike-slip fault system (Sieh & Natawidjaja 2000), or when the releasing stepover and basin depocentre has progressively migrated along the master strike-slip system, instead of maintaining a fixed position relative to the adjacent sliding blocks (**Wakabayashi *et al.*** 2004; this volume; Lazar *et al.* 2006). Depending on the angle between the master strike-slip fault and the far-field displacement direction, the degree of strain partitioning of oblique deformation within the bend into separate thrust, normal and strike-slip displacements will control bend evolution. Kinematic partitioning of non-coaxial strike-slip and coaxial strains is common when the far-field displacement direction is strongly oblique ($<20^\circ$) to the deformation zone boundary (Dewey *et al.* 1998). In addition, three-dimensional strain in strike-slip settings typically involves vertical-axis rotations (e.g. Jackson & Molnar 1990). Thus, the progressive evolution of a fault bend may involve local vertical axis rotations within the bend, and vertical axis rotations in the larger region that the bend occurs within (Luyendyk *et al.* 1980; Westaway 1995; Cowgill *et al.* 2004*b*). This may be indicated by changes in strike trends, and can be proven palaeomagnetically (Luyendyk *et al.* 1985). Progressive vertical-axis rotations within a fault bend will result in changing fault kinematics as the faults rotate relative to the external stress field. Vertical-axis rotations may thus lead to fault abandonment and propagation of new faults. In addition, strain hardening processes may operate locally within the bend and may influence whether old faults remain active or lock up (Cowgill *et al.* 2004*a*).

Stress field considerations

The orientation of the maximum horizontal stress ($S_{\mathrm{H}_{\max}}$) relative to the deformation zone boundary will strongly influence the degree of transpression or transtension within the fault bend region (Tikoff & Teyssier 1994). Fault bends that form where $S_{\mathrm{H}_{\max}}$ is at a high angle to the deforming zone will tend to have large dip-slip displacements, thus forming large restraining bend mountains (e.g. Karlik Tagh Range, China, Cunningham *et al.* 2003) or wide and deep releasing-bend basins (e.g. Sea of Japan, Jolivet *et al.* 1994) When regional plate-motion changes lead to stress-field changes in transform boundary settings, ratios of strike-slip to dip-slip displacements within fault bends will change and the fundamental architecture and topographic development of the bend will reflect that change. In addition, fault bends may switch from transtensional to transpressional systems or vice versa, if the original fault bend was at a low angle relative to $S_{\mathrm{H}_{\max}}$ (Tikoff & Teyssier 1994). Thus, transtensional basins may become inverted and restraining bends may be cross-cut by overprinting transtensional faults (**Legg *et al.*** this volume). Stress fields within individual fault bends may also evolve with progressive faulting, structural compartmentalization and increased mechanical interaction between intersecting faults, resulting in fault motions that are internally guided (Muller & Aydin 2004; **Waldron *et al.*** this volume; **Fodor** this volume).

Feedback between climate, topography, faulting and thermal history

Long-term climate patterns and mountain erosion rates compete with mountain uplift and influence the extent of topography generation or destruction for all mountain ranges, including restraining bends (Anderson 1994; Willett *et al.* 2001). If a restraining bend achieves a steady state between uplift and erosion, then its dimensions will stabilize, and thus individual faults will tend to remain active and new faults may not form (Beaumont *et al.* 1991; Norris & Cooper 1997; Willett 1999). In addition, larger releasing bends that evolve into marine basins may also influence local climate, driving changes in precipitation, erosion and rates of sediment deposition – thus influencing the overall dimensions of the releasing bend basin (e.g. Sea of Marmara, Turkey).

Progressive exhumation of deeper crustal rocks in restraining bends by uplift and erosion, and in releasing bends through normal faulting and erosion, will lead to changes in the thermal evolution of the fault bend. This can be demonstrated by fission-track and other geothermometric data which reveal the timing and rates of exhumation (Fitzgerald *et al.* 1995; Blythe *et al.* 2000; Batt *et al.* 2004). If heat flow increases within a restraining bend region, then it may lead to increased buoyancy and topographic uplift. This may lead to positive feedback between uplift and erosion and progressive exhumation of mid-crustal rocks similar to the crustal aneurysm model proposed for structural culminations in the Himalayan syntaxes (Zeitler *et al.* 2001). In releasing bend settings, high extensional strains in pull-apart basins may lead to increased heat flow and possibly volcanism; extrusive rocks may then constitute volumetrically significant basin fill (Dhont *et al.* 1998).

Because all of these factors will be different for every fault bend, it follows that restraining and releasing bends should be diverse in nature – with each one having unique topographic, geomorphological, architectural and evolutionary characteristics. Analogue models of fault bends have recreated some of the fault patterns and topographic characteristics of natural examples, and have documented progressive stages of evolution (Hempton & Neher 1986; Dooley & McClay 1997; McClay & Bonora 2001); however, they have not included many of the factors considered here, and so they must be regarded as somewhat generic.

With this previous work in mind, and in order to bring together workers from around the world who are actively investigating strike-slip fault bends, an international meeting on the tectonics of strike-slip restraining and releasing bends in continental and oceanic settings was convened in London on 28–30 September 2005, under the auspices of the Geological Society of London. This volume includes contributions that were presented at the conference, and new results by others whose research connects with the conference theme.

This volume

The 17 papers included in this volume cover a variety of topics and regions related to tectonics, geology and geophysics of restraining and releasing bends. The papers are organized into three major themes: (1) bends, sedimentary basins and earthquake hazards; (2) restraining bends, transpressional deformation and basement controls on development; and (3) releasing bends, transtensional deformation and fluid flow. Many papers have multiple emphases, and these subdivisions are general guides to subject content only. The brief discussion below is meant to summarize key results and conclusions of each study, without being exhaustive. In addition to this volume, the reader is referred to several other important volumes which cover related topics of strike-slip fault tectonics (Sylvester 1988); continental transpressional and transtensional tectonics (Holdsworth *et al.* 1998); intraplate strike-slip deformation belts (Storti *et al.* 2003); strike-slip deformation, basin formation and sedimentation (Biddle & Christie-Blick 1985); and continental wrench tectonics and hydrocarbon habitat (Harding 1985; Zolnai 1991).

The volume begins with a review paper by **Mann**, which contains a global compilation of active and ancient releasing and restraining bends, with the aim of defining common modes of origin and tectonic development. He identifies five main tectonic settings for strike-slip faults and related bends:

1. oceanic transforms separating oceanic crust and offsetting mid-oceanic spreading ridges;
2. long and linear plate-boundary strike-slip fault systems separating two continental plates whose plate-boundary kinematics can be quantified for long distances along strike by a single pole of rotation (e.g. the San Andreas fault system of western North America);
3. relatively shorter, more arcuate, indent-linked, strike-slip fault systems bounding escaping continental fragments in zones of continent–continent or arc–continent collision (e.g. the Anatolian plate);
4. straight to arcuate trench-linked strike-slip fault systems bounding elongate fore-arc slivers generated in active and ancient fore-arc settings by oblique subduction (e.g. Sumatra); and
5. continental interior, intraplate strike-slip fault systems removed from active plate boundaries, formed on older crustal faults, but acting as ‘concentrators’ of intraplate stresses.

By far the most common, predictable and best-studied setting for restraining and releasing bends occurs in continental plate boundary strike-slip fault systems, where arrays of two to eight en echelon pull-apart basins mark transtensional fault segments, and single and sometimes multiple large restraining bends mark transpressional segments; fault areas of transtension versus transpression are determined by the intersection angles between small circles about the interplate pole of rotation and the trend of the strike-slip fault system. These longer and more continuous boundary strike-slip systems also exhibit a widespread pattern of ‘paired bends’ or ‘sidewall ripouts’, or adjacent zones of pull-aparts and restraining bends that range in along-strike-scale from kilometres to hundreds of kilometres. Four evolutionary models to explain the origin and evolution of bends are presented:

1. progressive linkage of en echelon shears within a young evolving shear zone;
2. formation of lenticular ‘sidewall ripout’ structures at scales ranging from outcrop to regional;
3. interaction of propagating strike-slip faults with pre-existing crustal structures such as ancient rift basins; and
4. concentration of regional maximum compressive stress on pre-existing, basement structures in intraplate continental regions.

With over 225 modern bends in this global compilation, it follows from uniformitarian principles that restraining bends and releasing bends must also have been widespread in the geological past. Whilst most modern restraining and releasing bends have obvious topographic expression, ancient examples may occur in regions that have been eroded flat, or are buried beneath sedimentary cover, or are overprinted by younger orogenic events and thus may be difficult to discern.

Bends, sedimentary basins, and earthquake hazards

Many of the original ideas regarding continental transforms and restraining and releasing bends were developed by workers in California investigating the San Andreas system (e.g. Crowell 1974). Early work focused on the on-land expression of the diffuse plate boundary, whereas it is now recognized that some of the interplate strain is also accommodated offshore in the southern California borderland region. This subject is addressed by **Legg *et al.***, who provide a review of restraining bends and releasing bends formed during the last 20 Ma along the diffuse Pacific–North American transform boundary in the southern California borderlands. By combining multi-beam swath bathymetry, high-resolution seismic imaging, earthquake and geological data, they describe two major strike-slip restraining bends in the largely submarine setting – structures that are beautifully imaged because of the diminished effects of submarine erosion as compared to on-land examples. Pre-existing rift trends have influenced the stepping geometry of the major strike-slip faults, and there is a common association of double restraining bends bounded by releasing bends, an association which is also seen in on-land examples in southern California. The largest restraining bends approach 100 km in length, and could be sites of major (*M*7 or greater) earthquakes. Because of their offshore setting and rugged topography, the active faults within large restraining bends pose a potential tsunami hazard which is only now being appreciated.

An important consideration for understanding the evolution of restraining and releasing bends is whether their location remains fixed with respect to adjacent laterally moving blocks or whether they migrate along strike with increased fault displacements. **Wakabayashi** addresses this question by looking at numerous examples from the San Andreas system, where he documents the sedimentary and structural record of stepover migration, including 'wakes' of deposits trailing behind migrating stepovers as well as the sedimentary and structural expression of migrating inversion of former releasing bends. Importantly, he compares the sedimentary wake length to the overall displacement of the master fault system, in order to quantify the magnitude of stepover migration. Two end members are possible: stepovers that migrate for the entire duration of strike-slip displacement, and those that remain fixed. Fixed restraining bends will tend to have the largest structural relief and greatest erosional exhumation, and will form regionally significant topographic and structural culminations. However, other smaller restraining bends with less relief may have existed for just as long, but their migration limits their topographic and structural development, because uplifted/downdropped areas are soon abandoned as deformation moves along strike. The implication is that size of bend may not reflect longevity.

Although fault bends are widely regarded as earthquake propagation barriers for most major active strike-slip fault systems (Sibson 1985; Barka & Kadinsky-Cade 1988), surface fault complexity may mask relatively simple patterns at depth (>5 km deep). This is expected if the faults within the stepover define a flower structure and surface faults root into a singular master fault. In a paper by **Graymer *et al.*** the authors demonstrate that carefully located hypocentres beneath both restraining and releasing bends in California, where large earthquakes have occurred, define singular or simple fault patterns. They conclude that stepover zones provide less of an impediment to through-going rupture than previously assumed. Exceptions may be those large bends which have complex multilayered fault patterns reflecting both strike-slip and thrusting displacements and which have master strike-slip displacements migrating through the bend and eventually bypassing the bend. Their conclusions complement results from Lettis *et al.*'s (2002) compilation of 30 historical strike-slip earthquake ruptures involving 59 stepover basins, which indicated that strike-slip events with small to large displacements usually propagate through stepovers less than 1–2 km wide. With increasing displacements, 2–4-km-wide stepovers may be through-ruptured. However, stepovers of 4–5 km width always arrest fault rupture, regardless of the amount of displacement.

Although all major continental transform boundaries tend to have restraining and releasing bends along them, the Scotia–Antarctic transform boundary is particularly interesting, because it has both oceanic and continental crustal elements along its length, and stepover nucleation and development are directly related to the distribution of the two different types of crust. **Bohoyo *et al.*** present new geophysical data that are used to image and map the distribution of restraining and releasing bends along this remote submarine plate boundary. Their most important conclusion is that the distribution of releasing bend basins, and other bathymetric troughs formed by transtension, is directly controlled by the distribution and shape of rheologically weak continental fragments which rift more easily than surrounding, stronger oceanic crust. In contrast, restraining bends and areas of transpression occur at the interface between crust types, where oceanic crust underthrusts continental blocks.

Restraining bends, transpressional deformation and basement controls on development

One of the most interesting distant effects of the Indo–Eurasia collision is the active intraplate transpressional mountain building in western China and, in particular, Mongolia. In a paper by **Cunningham**, the geological and structural characteristics of 12 separate restraining-bend mountain ranges from the Altai, Gobi Altai and easternmost Tien Shan are reviewed and compared. All bends have individual structural, topographic and dimensional characteristics, due to multiple factors which influence their characteristics, including: stepover width; pre-existing basement structures, angular relation between main fault trace and $S_{H_{max}}$; and local tectonic setting. The significant structural and topographic diversity challenges simplistic models of restraining-bend evolution. In addition, there is an orogenic continuum: from isolated restraining bends along major strike-slip faults, to thrust-dominated transpressional ridges with only minor strike-slip transfer zones between thrust ridges. The key point is that as restraining bends grow along-strike and across-strike they may coalesce with neighbouring ranges and lose their individual identities. Mature oblique deformation belts may obscure the original restraining bends uplifts which were the initial nucleation sites for mountain building.

The island of Jamaica is essentially the morphological expression of a large Late Miocene to Recent restraining bend along the North

America–Caribbean plate boundary, and its origin and progressive development are described by **Mann *et al.*** By analysing geodetic, geological and seismic data they document the continued uplift and evolution of the bend in eastern Jamaica (Blue Mountains), along with less well-expressed bends in central and western Jamaica. However, seismicity along the south coast of the island suggests that a more linear short-cut fault is developing, which will bypass the range, and that the interplate strain may progressively transfer to that fault system. Another important conclusion of their study is that the restraining bends of Jamaica were initially localized by older basement faults related to Palaeogene rifts which trend northwesterwards and oblique to the evolving plate boundary.

Seyrek *et al.* provide a careful correlation of Pleistocene basalts across the northern Dead Sea transform boundary, coupled with new age data to calculate slip rates along the plate boundary since the Pliocene (*c.* 3.73 Ma). An important implication of their work is that the calculated displacement vectors and slip rates require that the northern continuation of the transform in southern Turkey must be convergent, and that the entire Amanos Mountain and Karasu Valley region constitutes a gentle restraining bend with active uplift in the Amanos Mountains. The overall geometry and kinematics are very similar to the Lebanon stepover, where ***Gomez et al.***, using geological and geomorphological fieldwork, cosmogenic dating, seismicity data, GPS results, and the analysis of relative plate motions, propose a two-stage history to the bend: an early wrench-dominated stage, followed by the modern strain-partitioned transpression-dominated stage. The switch was probably driven externally by changes in relative plate motions. The recognition of strain-partitioned deformation within the modern bend has implications for the regional seismic hazard; multiple strike-slip faults are active within the bend region and growing anticlines may hide seismically active blind thrusts.

A pair of papers by **Smith *et al.*** and **Morley *et al.*** addresses the structural evolution of transpressional zones along the active, left-lateral Mae Ping Fault Zone in central Thailand. By using satellite images, geological maps and magnetic data, they document a regional-scale strike-slip duplex within and adjacent to the Khlong Lan restraining bend. Importantly, Morley *et al.* review published cooling-age data and provide new apatite and zircon fission-track data to document the spatial and temporal evolution of uplift and exhumation within the restraining bend. Deformation and exhumation appear to have been focused at the corners of the restraining bend, as blocks migrate out of the bend during progressive strike-slip displacements in a manner similar to that described by Cowgill *et al.* (2004*a*, *b*) for the Akato Tagh bend on the Altyn Tagh Fault of Tibet. Smith *et al.* and Morley *et al.* also link their results from Thailand to an evolving deformation regime initially driven by terrane collision, but later driven by escape tectonics due to the Indo–Eurasia collision.

An unusual example of a restraining bend formed within a fold and thrust belt is presented by **Zampieri *et al.*** who document a north–south polydeformed relay zone cutting across the Italian Alps, a zone that has localized transpressional deformation at a prominent restraining stepover. Liassic and Palaeogene north–south extensional structures were reactivated during Alpine compression as a strike-slip relay zone within the thrust belt. Reactivation of normal faults and inversion of the older graben fill produced a complex restraining bend with different degrees of shortening on either side of the stepover, due to juxtaposed sequences with strongly contrasting rheological properties. There are very few studies of restraining bends formed locally along transfer faults within major fold-and-thrust belts, especially where older extensional structures have been reactivated; however, their study suggests that other examples await discovery.

In another example of polyphase deformation in an intraplate restraining bend, but in an older Palaeozoic setting, **Waldron *et al.*** document the detailed and complex internal structures within a portion of a flower structure that formed during right-lateral Carboniferous strike-slip movement along the Minas fault zone in Nova Scotia. Their study underscores the importance of detailed structural analysis to unravel different phases of folding, thrusting and oblique deformation within a zone of localized transpression. The structures that they observe are consistent with a progressive change in the local angle of convergence, increased strain partitioning, and pure-shear dominated transpression. An important implication of their work is that as the restraining bend developed, significant topography was generated, and the deformation migrated laterally from inner, dominantly steep transpressional zones, to outer, low-angle zones enhanced by the presence of Late Palaeozoic evaporite layers that promoted low-angle thrust faulting and gravitational spreading.

Releasing bends, transtensional deformation and fluid flow

Single restraining and releasing bends that form at strike-slip fault terminations are usually sites of oblique deformation where strike-slip displacements are progressively transformed into dip-slip displacements. The architecture and fault kinematics within such transitional zones can be very complex. **Mouslopoulou *et al*.** address this problem in a detailed study of the termination zone of the North Island strike-slip fault system against the Taupo back-arc rift of northern New Zealand. They find that the strike-slip fault system splays into five main strands as it approaches the rift. These strike-slip faults link with the rift margin normal faults, but do not displace the normal faults. This geometry requires that the faults bend and that slip vectors on the strike-slip faults must progressively steepen to accommodate increasing dip-slip components near the active Taupo Rift. Data from displaced landforms, fault trenching, gravity and seismic profiles are used to quantify displacements, and to evaluate rotational and non-rotational mechanisms of displacement transfer.

In a similar study investigating the kinematic linkage between strike-slip faults and extensional faults, but on a local outcrop scale, **Fodor** documents the role of transtensional relay ramps in accommodating displacement transfer within releasing bends along Upper Tertiary strike-slip faults in the Vertes Hills of the Pannonian basin in Hungary. His study comes from a mined area with exceptional exposures. Normal and oblique-normal faults change their strike, dip and slip vectors systematically to accommodate extension across the relay ramp. Fault slip inversion for different groups of faults demonstrates that inclusion of transfer-zone faults modifies the results of palaeostress calculations, because displacements on the transfer-zone faults are not governed by the regional stress field, but by their bounding strike-slip faults (i.e. guided slip). This influence of bounding-strike-slip faults on local stress fields should be considered by anyone attempting palaeostress calculations using fault stepover data.

Releasing bends and dilational stepovers are typically complex sites of fracturing, veining and fluid flow. In a theoretical and field-based study using outcrop data from the Carboniferous Northumberland basin in England, **DePaola *et al.*** document how deformation within dilational stepovers with low angles of oblique divergence ($<30^\circ$) may evolve from wrench- to extension-dominated transtension as strain increases. Veins, dykes, fracture meshes and faults record progressive transtensional deformation, including reactivation of earlier-formed structures. The complex pattern of structures within the stepover may inhibit development of a through-going single fault. Therefore, the stepover may be long-lived and persist as a site of subsidence, and provide long-term enhanced structural permeability favourable to fluid migration and mineral precipitation.

It is well known that many world-class mineral deposits have formed where fluid flow is focused in dilational sites along fault bends (Sibson 2001; Cox 2005). **Berger** presents structural, lithological and geochronological evidence which reveals the importance of fault bends in controlling the locations of volcanism and associated epithermal volcanic centre-related hydrothermal gold and silver systems in Nevada. Specifically, by analysing the temporal and spatial evolution of volcanism and the relationship between high-grade gold deposits and faults that formed at the stepover, he concludes that migrating corner zones where strike-slip faults link to oblique-slip and dip-slip faults are important sites of hydrothermal veining, and that high-grade bonanza ores were deposited along abandoned normal-fault systems *following* stepover migration. Another complicating factor is that abandoned stepovers have locally experienced contractional deformation and inversion, further affecting the permeability structure within the stepover. The author also documents a rarer case of hydrothermal mineralization in extensional veins within a restraining bend in the Excelsior Mountains of Nevada.

Summary

Because restraining and releasing bends often occur as singular self-contained domains of complex deformation, they provide appealing natural laboratories for Earth scientists to study fault processes; earthquake seismology; active faulting and sedimentation; fault and fluid-flow relationships; links between tectonics and topography; tectonic and erosional controls on exhumation; and tectonic geomorphology. A major challenge for future workers will be to untangle the deformational history of those regions where multiple fault bends have grown large enough to interact, coalesce and structurally interfere. Finally, the deep expression of fault bends and the manner in which they are coupled to ductilely deforming lower crust and lithospheric mantle remain poorly understood (Tikoff *et al.* 2004).

This special publication stems from an international conference hosted by the Geological Society of London during September 2005, on the tectonics of strike-slip restraining and releasing bends in continental and oceanic settings. We are grateful to all authors for contributing to the volume, and are indebted to the many conscientious referees who provided professional reviews ensuring the high quality of the volume.

The following colleagues and friends kindly helped with the reviewing of the papers submitted for this volume: P. Barnes, Wellington, New Zealand; G. Batt, London, UK; C. Burchfiel, California, USA; R. Burgmann, California, USA; C. Childs, Dublin, Republic of Ireland; E. Cowgill, California, USA; S. Cox, Canberra, Australia; N. de Paola, Perugia, Italy; T. Dooley, Texas, USA; M. Gordon, Texas, USA; C. Henry, Nevada, USA; J.-C. Hippolyte, Savoie, France; P. Klipfel, Nevada, USA; L. Lavier, Texas, USA; M. Legg, California, USA; K. McIntosh, Texas, USA; S. Mazzoli, Naples, Italy; M. Menichetti, Urbino, Italy; C. Morley, Bangkok, Thailand; M. Murphy, Texas, USA; D. Peacock, Llandudno, Wales, UK; A. Robertson, Edinburgh, Scotland, UK; J. Rowland, Auckland, New Zealand; G. Scheurs, Berne, Switzerland; L. Seeber, New York, USA; R. Sibson, Dunedin, New Zealand; M. Swanson, Maine, USA; A. Sylvester, California, USA; F. Taylor, Texas, USA; D. van Hinsbergen, Utrecht, Netherlands; J. Waldron, Alberta, Canada; R. Walker, Oxford, UK; L. Webb, New York, USA; N. Woodcock, Cambridge, UK.

References

ANDERSON, R. 1994. Evolution of the Santa Cruz Mountains, California, through tectonic growth and geomorphic decay. *Journal of Geophysical Research*, **99**, 20 161–20 179.

AYDIN, A. & NUR, A. 1982. Evolution of stepover basins and their scale independence. *Tectonics*, **1**, 91–105.

AYDIN, A. & NUR, A. 1985. The types and role of stepovers in strike-slip tectonics. *In*: BIDDLE, K. T. & CHRISTIE-BLICK, N. (eds) *Strike-Slip Deformation, Basin Formation, and Sedimentation*. SEPM Special Publications, **37**, 35–44.

BARKA, A. A. & GULEN, L. 1989. Complex evolution of the Erzincan basin (western Turkey). *Journal of Structural Geology*, **11**, 275–283.

BARKA, A. A. & KADINSKY-CADE, K. 1988. Strike-slip fault geometry in Turkey and its influence on earthquake activity. *Tectonics*, **7**, 663–684.

BARNES, P., SUTHERLAND, R. & DELTEIL, J. 2005. Strike-slip structure and sedimentary basins of the southern Alpine fault, Fiordland, New Zealand. *Geological Society of America Bulletin*, **117**, 411–435.

BATT, G., BALDWIN, S. L., COTTAM, M. A., FITZGERALD, P. G., BRANDON, M. T. & SPELL, T. L. 2004. Cenozoic plate boundary evolution in the South Island of New Zealand: new thermochronological constraints. *Tectonics*, **23**, doi: 10.1029/2003TC001527 TC4001.

BAYARSAYHAN, C., BAYASGALAN, A., ENHTUVSHIN, B., HUDNUT, K., KURUSHIN, R. A., MOLNAR, P. & OLZIYBAT, M. 1996. 1957 Gobi-Altay, Mongolia, earthquake as a prototype for southern California's most devastating earthquake. *Geology*, **24**, 579–582.

BEAUMONT, C., FULSACK, P. & HAMILTON, J. 1991. Erosional control of active compressional orogens. *In*: MCCLAY, K. R. (ed.) *Thrust Tectonics*. Chapman and Hall, New York, 1–18.

BECK, M. E., JR, 1983. On the mechanism of tectonic transport in zones of oblique subduction. *Tectonophysics*, **93**, 1–11.

BEN-AVRAHAM, Z. 1985. Structural framework of the Gulf of Elat (Aqaba), northern Red Sea. *Journal of Geophysical Research*, **90**, B1, 703–725.

BENNETT, R., FRIEDRICH, A. & FURLONG, K. 2004. Codependent histories of the San Andreas and San Jacinto fault zones from inversion of fault displacement rates. *Geology*, **32**, 961–964.

BIDDLE, K. T. & CHRISTIE-BLICK, N. 1985. Glossary – strike-slip deformation, basin formation and sedimentation. *In*: BIDDLE, K. T. & CHRISTIE-BLICK, N. (eds) *Strike-Slip Deformation, Basin Formation and Sedimentation*. SEPM Special Publications, **37**, 375–384.

BILHAM, R. & KING, G. 1989. The morphology of strike-slip faults: examples from the San Andreas fault, California. *Journal of Geophysical Research*, **94**, 10 204–10 216.

BILHAM, R. & WILLIAMS, P. 1985. Sawtooth segmentation and deformation processes on the southern San Andreas fault, California. *Geophysical Research Letters*, **12**, 557–560.

BLYTHE, A., BURBANK, D., FARLEY, K. & FIELDING, E. 2000. Structural and topographic evolution of the central Transverse Ranges, California, from apatite fission track, U–Th/He, and digital elevation model analysis. *Basin Research*, **12**, 97–114.

CHRISTIE-BLICK, N. & BIDDLE, K. T. 1985. Deformation and basin formation along strike-slip faults. *In*: BIDDLE, K. T. & CHRISTIE-BLICK, N. (eds) *Strike-Slip Deformation, Basin Formation, and Sedimentation*. SEPM Special Publications, **37**, 1–34.

CLOOS, H. 1928. Experimente zur inneren Tektonic. *Centralblatt fur Mineralogie*, **1928B**, 609–621.

COWGILL, E., ARROWSMITH, R., YIN, A., XIAOFENG, W. & ZHENGLE, C. 2004*a*. The Akato Tagh bend along the Altyn Tagh fault, northwest Tibet, 2: active deformation and the importance of transpression and strain hardening within the Altyn Tagh system. *Geological Society of America Bulletin*, **116**, 1443–1464.

COWGILL, E., YIN, A., ARROWSMITH, R., FENG, W. & SHUANHONG, Z. 2004*b*. The Akato Tagh bend along the Altyn Tagh fault, northwest Tibet, 1: smoothing by vertical-axis rotation and the effect of topographic stresses on bend-flanking faults. *Geological Society of America Bulletin*, **116**, 1423–1442.

COX, S. F. 2005. Coupling between deformation, fluid pressures, and fluid flow in ore-producing hydrothermal systems at depth in the crust. *Economic Geology*, **100th Anniversary Volume**, 39–76.

CROWELL, J. C. 1974. Origin of late Cenozoic basins of southern California. *In*: DICKINSON, W. R. (ed.) *Tectonics and Sedimentation*. SPEM Special Publications, **22**, 190–204.

CUNNINGHAM, W. D. 2005. Active intracontinental transpressional mountain building in the Mongolian Altai: defining a new class of orogen. *Earth and Planetary Science Letters*, **240**, 436–444.

CUNNINGHAM, W. D., OWEN, L. A., SNEE, L. & LI, JILIANG. 2003. Structural framework of a major intracontinental orogenic termination zone: the easternmost Tien Shan, China. *Journal of the Geological Society, London*, **160**, 575–590.

CUNNINGHAM, W. D., WINDLEY, B. F., DORJNAMJAA, D., BADAMGAROV, G. & SAANDAR, M. 1996. Late Cenozoic transpression in southwestern Mongolia and the Gobi Altai–Tien Shan connection. *Earth and Planetary Sciences*, **140**, 67–82.

DECKER, K., PERESSON, H. & HINSCH, R. 2005. Active tectonics and Quaternary basin formation along the Vienna basin transform fault. *Quaternary Science Reviews*, **24**, 307–322.

DEWEY, J. F., HOLDSWORTH, R. E. & STRACHAN, R. A. 1998. Transpression and transtension zones. *In*: HOLDSWORTH, R. E., STRACHAN, R. A. & DEWEY, J. F. (eds) *Continental Transpressional and Transtensional Tectonics*. Geological Society, London, Special Publications, **135**, 1–14.

DHONT, D., CHOROWICZ, J., YURUR, T., FROGER, J.-L., KOSE, O. & GUNDOGDU, N. 1998. Emplacement of volcanic vents and geodynamics of Central Anatolia, Turkey, *Journal of Volcanology and Geothermal Research*, **85**, 33–54.

DOOLEY, T. & MCCLAY, K. 1997. Analog modeling of strike-slip pull-apart basins. *AAPG Bulletin*, **81**, 804–826.

DOOLEY, T., MCCLAY, K. & BONORA, M. 1999. 4D evolution of segmented strike-slip fault systems: applications to NW Europe. *In*: FLEET, A. & BOLDY, S. (eds) *Petroleum Geology of Northwest Europe: Proceedings of the 5th Conference, Petroleum Geology '86*, Geological Society, London, 215–225.

ESCALONA, A. & MANN, P. 2003. Three-dimensional structural architecture and evolution of the Eocene pull-apart basin, central Maracaibo basin, Venezuela. *Marine and Petroleum Geology*, **20**, 141–161.

FITZGERALD, P., SORKHABI, R., REDFIELD, T. & STUMP, E. 1993. Uplift and denudation of the central Alaska range: a case study in the use of apatite fission-track thermochronology to determine absolute uplift parameters. *Journal of Geophysical Research*, **100**, 20 175–20 192.

FITZGERALD, P., STUMP, E. & REDFIELD, T. 1993. Late Cenozoic uplift of Denali, and its relation to relative plate motion and fault morphology. *Science*, **259**, 497–500.

GAMOND, J. 1987. Bridge structures as sense of displacement criteria in brittle fault zones. *Journal of Structural Geology*, **9**, 609–620.

GARFUNKEL, Z. 1981. Internal structure of the Dead Sea leaky transform (rift) in relation to plate kinematics. *Tectonophysics*, **80**, 81–108.

GARFUNKEL, Z. 1986. Review of oceanic transform activity and development. *Journal of the Geological Society*, London, **143**, 775–784.

GLOWACKA, E., GONZALEZ, J. & FABRIOL, H. 1999. Recent vertical deformation in Mexicali Valley and its relationship with tectonics, seismicity, and the exploitation of the Cerro Prieto geothermal field, Mexico. *Pure and Applied Geophysics*, **156**, 591–614.

HAMILTON, W. & JOHNSON, N. 1999. The Matzen project – rejuvenation of a mature field. *Petroleum Geoscience* **5**, 119–125.

HARDING, T. P. 1985. Seismic characteristics and identification of negative flower structures, positive flower structures, and positive structural inversion. *AAPG Bulletin*, **69**, 582–600.

HARRIS, R., DOLAN, J. F., HARTLEB, R. & DAY, S. M. 2002. The 1999 Izmit, Turkey, earthquake: a 3D dynamic stress transfer model of intra-earthquake triggering. *Bulletin of the Seismological Society of America*, **92**, 245–255.

HEMPTON, M. & DUNNE, L. 1984. Sedimentation in pull-apart basins: active examples in eastern Turkey. *Journal of Geology*, **92**, 513–530.

HEMPTON, M. & NEHER, K. 1986. Experimental fracture, strain, and subsidence patterns over en echelon strike-slip faults: implications for the structural evolution of pull-apart basins. *Journal of Structural Geology*, **8**, 597–605.

HINSCH, R., DECKER, K. & WAGREICH, M. 2005. 3-D mapping of segmented active faults in the southern Vienna basin. *Quaternary Science Reviews*, **24**, 321–336.

HOLDSWORTH, R. E., BUTLER, C. A. & ROBERTS, A. M. 1997. The recognition of reactivation during continental deformation. *Journal of the Geological Society*, London, **154**, 73–78.

HOLDSWORTH, R. E., STRACHAN, R. A. & DEWEY, J. F. (eds) 1998. *Continental Transpressional and Transtensional Tectonics*. Geological Society, London, Special Publications, **135**.

JACKSON, J. A. & MOLNAR, P. 1990. Active faulting and block rotations in the western Transverse ranges, California. *Journal of Geophysical Research*, **95**, 22 073–22 087.

JARRARD, R. D. 1986. Terrane motion by strike-slip faulting of fore-arc slivers. *Geology*, **14**, 780–783.

JOLIVET, L., TAMAKI, K. & FOURNIER, M. 1994. Japan Sea, opening history and mechanism: a synthesis. *Journal of Geophysical Research*, **99**, 22 237–22 260.

JONES, R. R. & TANNER, P. W. G. 1995. Strain partitioning in transpression zones. *Journal of Structural Geology*, **17**, 793–802.

KADINSKY-CADE, K. & BARKA, A. A. 1989. Effects of restraining bends on the rupture of strike-slip earthquakes. *In*: SCHWARTZ, D. P. & SIBSON, R. (eds) *Proceedings of Conference XLV on Fault Segmentation and Controls of Rupture Initiation and Termination*. USGS Open-File Report, **89-315**, 181–192.

KING, G. & NABELEK, J. 1985. Role of fault bends in the initiation and termination of earthquake rupture. *Science*, **228**, 984–987.

KOENIG, E. & AYDIN, A. 1998. Evidence for large-scale strike-slip faulting on Venus. *Geology*, **26**, 551–544.

LAZAR, M., BEN-AVRAHAM, Z. & SCHATTNER, U. 2006. Formation of sequential basins along a strike-slip fault: geophysical observations from the Dead Sea basin. *Tectonophysics*, **421**, 53–69.

LEES, J. 2002. Three-dimensional anatomy of a geothermal field, Coso, southeast-central California. *In*: GLAZNER, A., WALKER, J. & BARTLEY, J. (eds) *Geologic Evolution of the Mojave Desert and Southwestern Basin and Range, Boulder, Colorado*, Geological Society of America Memoirs, **195**, 259–276.

LEROY, S., LEPINAY, B., MAUFFRET, A. & PUBELLIER, M. 1996. Structure and tectonic evolution of the Eastern Cayman Trough (Caribbean Sea) from multichannel seismic data. *AAPG Bulletin*, **141**, 222–247.

LETTIS, W., BACHHUBER, J., WITTER, R., BRANKMAN, C., RANDOLPH, C., BARKA, A., PAGE, W. & KAYA, A. 2002. Influence of releasing step-overs on surface fault rupture and fault segmentation: examples from the 17 August, 1999, Izmit earthquake on the North Anatolian fault, Turkey. *Bulletin of the Seismological Society of America*, **92**, 19–42.

LOWELL, J. D. 1972. Spitsbergen Tertiary orogenic belt and the Spitsbergen Fracture Zone. *Geological Society of America Bulletin*, **83**, 3091–3102.

LUYENDYK, B. P., KAMMERLING, M. J. & TERRES, R. 1980. Geometrical model for Neogene crustal rotations in southern California. *Bulletin of the Geological Society of America*, **91**, 211–217.

LUYENDYK, B. P., KAMMERLING, M. J., TERRES, R. & HORNAFIUS, J. S. 1985. Simple shear of southern California during Neogene time suggested by paleomagnetic declinations. *Journal of Geophysical Research*, **90**, 12 454–12 466.

MCCLAY, K. & BONORA, M. 2001. Analog models of restraining stepovers in strike-slip fault systems. *AAPG Bulletin*, **85**, 233–260.

MANN, P. & GORDON, M. 1996. Tectonic uplift and exhumation of blueschist belts along transpressional strike-slip fault zones. *In*: BEBOUT, G., SCHOLL, D., KIRBY, S. & PLATT, J. (eds) *Dynamics of Subduction Zones*, Geophysical Monographs, **96**, American Geophysical Union, Washington, DC, 143–154.

MANN, P., MATUMOTO, T. & BURKE, K. 1984. Neotectonics of Hispaniola: plate motion, sedimentation, and seismicity at a restraining bend. *Earth and Planetary Science Letters*, **70**, 311–324.

MANN, P., CALAIS, E., RUEGG, J. C., DEMETS, C., DIXON, T., JANSMA, P. & MATTIOLI, G. 2002. Oblique collision in the northeastern Caribbean from GPS measurements and geological observations. *Tectonics*, **21**, 1057, doi:10.1029?2001TC001304.

MARSHAK, S., NELSON, W. & MCBRIDE, J. 2003. Phanerozoic strike-slip faulting in the continental interior platform of the United States: examples from the Laramide orogen, mid-continent, and Ancestral Rocky Mountains. *In*: STORTI, F., HOLDSWORTH, R. & SALVINI, F. (eds) *Intraplate Strike-slip Deformation Belts*, Geological Society, London, Special Publications, **210**, 159–184.

MAY, S., EHMAN, K., GRAY, G. & CROWELL, J. 1993. A new angle on the tectonic evolution of the Ridge basin, a 'strike-slip' basin in southern California. *Geological Society of America Bulletin*, **105**, 1357–1372.

MULLER, J. R. & AYDIN, A. 2004. Rupture progression along discontinuous oblique fault sets: implications for the Karadere rupture segment of the 1999 Izmit earthquake, and future rupture in the Sea of Marmara. *Tectonophysics*, **391**, 283–302.

NORRIS, R. & COOPER, A. 1997. Erosional control on the structural evolution of a transpressional thrust complex on the Alpine fault, New Zealand. *Journal of Structural Geology*, **19**, 1323–1342.

PARSONS, T., BRUNS, T. & SLITER, R. 2005. Structure and mechanics of the San Andreas–San Gregorio fault junction, San Francisco, California. *G^3, Geochemistry Geophysics Geosystems*, **6**, Q01009, doi: 10.1029/2004GC000838.

PERSAUD, P. *ET AL*. 2003. Active deformation and shallow structure of the Wagner, Consag and Delfin basins, northern Gulf of California, Mexico. *Journal of Geophysical Research*, **108**, doi:10.1029/2002JB001937, 2003.

PINHEIRO, R. V. L. & HOLDSWORTH, R. E. 1997. The structure of the Carajas N-4 ironstone deposit and associated rocks: relationship to Archaean strike-slip tectonics and basement reactivation in the Amazon region, Brazil. *Journal of South American Earth Sciences*, **10**, 305–319.

POCKALNY, R. 1997. Evidence of transpression along the Clipperton Transform: implications for processes of plate boundary organization. *Earth and Planetary Science Letters*, **146**, 449–464.

RIEDEL, W. 1929. Zur Mechanik geologischer Brucherscheinungen. *Zentralblatt für Mineralogie, Geologie und Paleontologie*, **1929B**, 354–368.

SARID, A. R., GREENBERG, R., HOPPA, G. V., HURFORD, T. A., TUFTS, B. R. & GEISSLER, P. 2002. Polar wander and surface convergence of Europa's ice shell: evidence from a survey of strike-slip displacement. *Icarus*, **158**, 24–41.

SCHOLZ, C. H. 1982. Scaling laws for large earthquakes: consequences for physical models. *Bulletin of the Seismological Society of America*, **72**, 1–14.

SEGALL, P. & POLLARD, D. 1980. Mechanics of discontinuous faults. *Journal of Geophysical Research*, **85**, 4337–4350.

SIBSON, R. H. 1985. Stopping of earthquake ruptures at dilational fault jogs. *Nature*, **316**, 248–251.

SIBSON, R. H. 2001. Seismogenic framework for hydrothermal transport and ore deposition. *Reviews in Economic Geology*, **14**, 25–50.

SIEH, K. & NATAWIDJAJA, D. 2000. Neotectonics of the Sumatran fault, Indonesia. *Journal of Geophysical Research*, **105**, 28 295–28 326.

SHAW, B. 2006. Initiation propagation and termination of elastodynamic ruptures associated with segmentation of faults and shaking hazard. *Journal of Geophysical Research*, **111**, B08302, doi:1029/2005JB004093.

STORTI, F., HOLDSWORTH, R. E. & SALVINI, F. (eds) 2003. *Intraplate Strike-Slip Deformation Belts*. Geological Society, London, Special Publications, **210**.

SWANSON, M. 2005. Geometry and kinematics of adhesive wear in brittle strike-slip fault zones. *Journal of Structural Geology*, **27**, 871–887.

SYLVESTER, A. G. 1988. Strike-slip faults. *Geological Society of America Bulletin*, **100**, 1666–1703.

SYLVESTER, A. & SMITH, R. 1976. Tectonic transpression and basement controlled deformation in the San Andreas fault zone, Salton trough, California. *AAPG Bulletin*, **60**, 2081–2102.

TCHALENKO, J. S. 1970. Similarities between shear zones of different magnitudes. *Geological Society America Bulletin*, **81**, 1625–1640.

TEN BRINK, U. *ET AL*. 1999. Anatomy of the Dead Sea transform: does it reflect continuous changes in plate motion? *Geology*, **27**, 887–890.

TIKOFF, B. & TEYSSIER, C. 1994. Strain modelling of displacement-field partitioning in transpressional orogens. *Journal of Structural Geology*, **16**, 1575–1588.

TIKOFF, B., RUSSO, R., TEYSSIER, C. & TOMASSI, A. 2004. Mantle-driven deformation of orogenic zones and clutch tectonics. *In*: GROCOTT, J., MCCAFFREY, K. J. W., YAYLOR, G. & TIKOFF, B. (eds) *Vertical Coupling and Decoupling in the Lithosphere*. Geological Society, London, Special Publications, **227**, 41–64.

WAKABAYASHI, J., HENGESH, J. V. & SAWYER, T. L. 2004. Four-dimensional transform fault processes: progressive evolution of step-overs and bends. *Tectonophysics*, **392**, 279–301.

WALDRON, J. 2004. Anatomy and evolution of a pull-apart basin, Stellarton, Nova Scotia. *Geological Society of America Bulletin*, **116**, 109–127.

WESTAWAY, R. 1995. Deformation around stepovers in strike-slip fault zones. *Journal of Structural Geology*, **17**, 831–846.

WILCOX, R. E., HARDING, T. P. & SEELY, D. R. 1973. Basic wrench tectonics. *AAPG*, **57**, 74–96.

WILLETT, S. D. 1999. Orogeny and orography: the effects of erosion on the structure of mountain belts. *Journal of Geophysical Research*, **104**, 28 957–28 981.

WILLETT, S. D., SLINGERLAND, R. & HOVIUS, N. 2001. Uplift, shortening, and steady state topography in active mountain belts. *American Journal of Science*, **301**, 455–485.

WILSON, J. T. 1965. A new class of faults and their bearing on continental drift. *Nature*, **207**, 343–347.

WOOD, R., PETTINGA, J., BANNISTER, S., LAMARCHE, G. & MCMORRAN, T. 1994. Structure of the Hanmer strike-slip basin, Hope fault, New Zealand. *Geological Society of America Bulletin*, **106**, 1459–1473.

WOODCOCK, N. 1986. The role of strike-slip fault systems at plate boundaries. *Philosophical Transactions of the Royal Society of London A*, **317**, 13–29.

WOODCOCK, N. & FISCHER, M. 1986. Strike-slip duplexes. *Journal of Structural Geology*, **8**, 725–735.

YEATS, R., SIEH, K. & ALLEN, C. 1997. *The Geology of Earthquakes*, Oxford University Press, New York and Oxford, 568 pp.

ZEITLER, P. K., MELTZER, A. S. *ET AL*. 2001. Erosion, Himalayan geodynamics, and the geomorphology of metamorphism. *GSA Today*, **11**, 4–8.

ZHANG, P., BURCHFIEL, C., CHEN, S. & DENG, Q. 1989. Extinction of pull-apart basins. *Geology*, **17**, 814–817.

ZOLNAI, G. 1991. Continental wrench-tectonics and hydrocarbon habitat. *AAPG Continuing Education Course Note Series,* **30**, American Association of Petroleum Geologists Education Department, Tulsa, Oklahoma.