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Basin formation and strain partitioning along strike-slip fault zones

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Abstract : Surface traces of large strike-slip fault systems are invariably composed of segments that appear as steps in map-view. In many such fault systems, the dominant sense of step-over of segments (on a regional scale) is releasing, resulting in the development of pull-apart basins and related structures. Previous attempts to explain this type of fault array have appealed to local heterogeneities, which may be more fortuitous than systematic. Here we propose a simple, geometrical model for the initial development of releasing step-overs based upon geometrical analyses of a number of strike-slip fault zones in various, diverse geological settings. These preliminary analyses indicate that constituent fault segments are considerably straighter than the fault zones, and that basin spacing (fault segment length) has a positive relationship with the radius of curvature of the fault zone. Since straight faults are more efficient at accommodating slip than curved or irregular traces, fault segmentation is necessary to accommodate a curved plate boundary. Net extension along transform/strike-slip systems must be compensated by intra-plate shortening and compression oriented perpendicular to the trend of the primary fault system, resulting in the partitioning of strain.

1. Introduction

Many basins along transform boundaries and intra-plate accommodation systems are the result of crustal 'pull-apart' (Burchfiel and Stewart, 1966) between *en-échelon* strike-slip faults. Modelling work (e.g. Cloos, 1955 ; Wilcox *et al.*, 1973 ; Hempton and Neher, 1986 ; Naylor *et al.*, 1986), and theoretical studies based on strain ellipsoid interpretation (see Sylvester, 1988, for a full reference list) indicate that *en-échelon* fault segments ("R" shears) should develop with predominantly restraining step-overs or bridges, i.e. *en-échelon* faults in dextral and sinistral systems should step to the left and right, respectively. Hence, in-line or lozenge horts and grabens, termination structures, restraining bend cut-off faults might be expected on individual segments of large-scale strike-slip fault zones (Harding *et al.*, 1985). Paradoxically, in many well-documented large-scale strike-slip fault zones the sense of step is predominantly releasing. Aydin and Nur (1985) and Mann *et al.* (1983) summarised the theories proposed for the origin of releasing step-overs as follows : bending of initially straight faults ; a weak zone oriented slightly off plane ; curvature on fault traces, and horizontal slip across preexisting fractures or dip-slip faults. However, these local conditions, which are probably more random than systematic, cannot account for the apparent predominance of releasing step-overs. Here, we propose a simple, empirical model for the development and spacing of pull-apart basins, based upon analysis of recurring geometrical relationships in well-documented strike-slip fault systems.

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2. Examples of Releasing Step-overs and Related Phenomena

We have studied the geometry of a number of transform/strike-slip systems from around the world, including the Dead Sea transform system, the Anatolian block in Turkey, faults systems in the Rocky Mountains and transform and related systems in Indonesia. A common feature of these systems is that the sense of step for individual fault segments is predominantly releasing, producing a *staircase fault array* in map view.

The right-lateral North Anatolian fault zone of Turkey (Fig. 1) has accommodated westward movement of the Anatolian Block since middle Miocene times (Sengör *et al.*, 1985). Predominantly right-stepping *en-échelon* fault segments characterise this fault zone, forming pull-aparts such as the Erzinçan, Niksar, and Susehri basins. These basins exhibit extreme extension and extension-related volcanism (Dewey and Pindell, 1985). The spacing between them is remarkably consistent, at around 120 km (Hempton and Dunne, 1984). Up to 8 other smaller releasing step-overs are observed along this fault zone with spacing of 70-100 km (Barka and Kadinsky-Cade, 1988). Other less important basins arise due to strain incompatibilities between blocks (Sengör *et al.*, 1985).

The Dead Sea sinistral transform fault system (Fig. 2) forms the boundary between the Sinai-African Plate and the Arabian Plate to the east, accommodating displacement between the Red Sea spreading centres and the Zagros Mountains/Taurus thrust front in the north. The pole of rotation of the Arabian Plate relative to the Sinai Plate is located at N 33°, E 24° (Girdler, 1990), giving a small circle radius of 800-900 km. Fault segment lengths average approximately 200 km, and consistently step to the left, forming a series of pull-apart basins. Each fault segment is discrete as evidenced by fault tips terminating in 'horsetail' fault arrays and related structures (Ron and Eyal, 1985), and recent extension has occurred close to the termination of the Jordan fault on the western margin of the Dead Sea

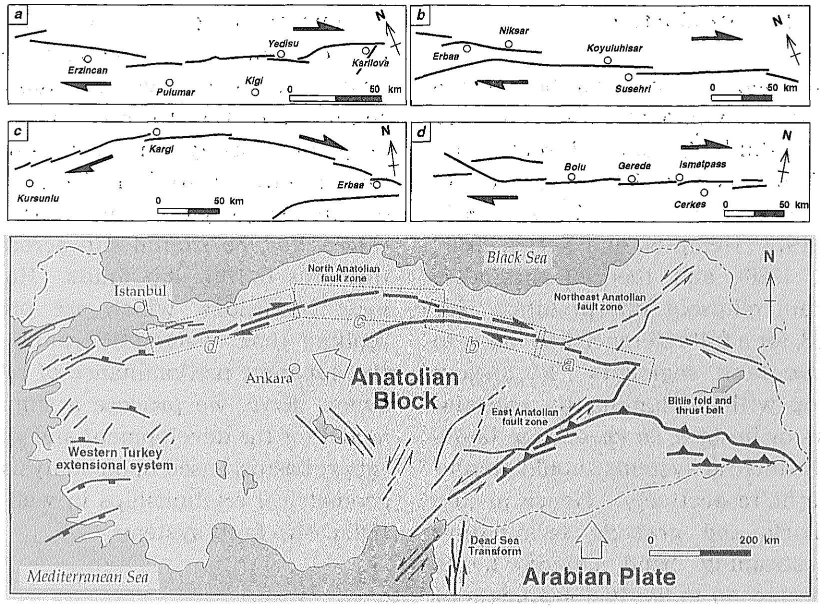

Fig. 1 Simplified tectonic map of Turkey (modified after Barka and Kadinsky-Cade, 1988) with detailed insets of sections of the North Anatolian fault zone. En échelon fault segments consistently step to the right along the dextral fault zone.

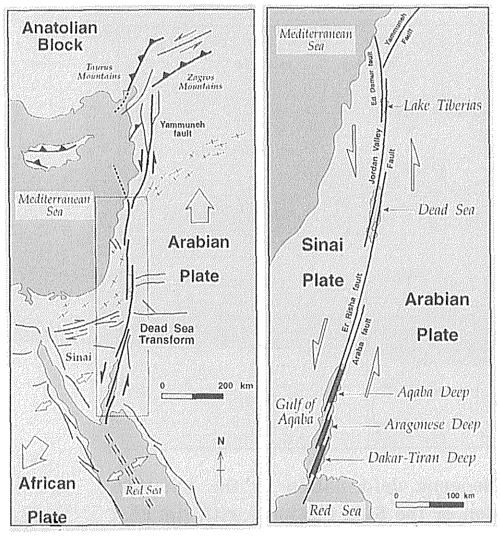

Fig. 2 Highly simplified tectonic maps of the Dead Sea transform (after Aydin and Schultz, 1989), which accommodates displacement between the Red Sea spreading centres and the Zagros Mountains/Taurus thrust front in the north. Fault segment lengths average approximately 200 km, and consistently step to the left, forming a series of pull-apart basins, including the Dead Sea and Lake Tiberias.

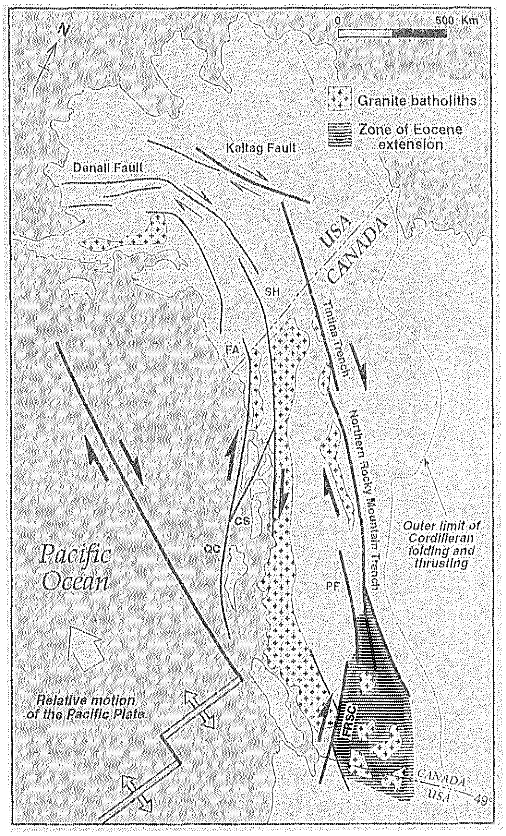

Fig. 3 Highly simplified tectonic map of the Canadian Cordilleran fault system and associated phenomena (adapted from (Price and Carmichael, 1986) The Tintina Trench, northern Rocky Mountain Trench, Pinchi and Fraser River-Straight Creek fault zones are segments of a 2500 km dextral, intra-continental transform fault zone. Fault segments are right stepping, and the large horizontal displacements between segments are manifested by extreme extension and alkaline volcanism. Abbreviations : FA, Fairweather fault ; CS, Chatham Strait fault ; QC, Queen Charlotte fault ; PF, Pinchi fault ; FRSC, Fraser River and Straight Creek faults.

(Gardosh *et al.*, 1990), thus precluding a 'bending' origin. Transverse faults cutting the basins at a high angle to the main fault zone (Ben-Avraham *et al.*, 1990 ; ten Brink and Ben-Avraham, 1989) accommodate limited block rotation through translation of marginal basin areas along these 'curved' fault systems.

The Tintina Trench, northern Rocky Mountain Trench, Pinchi and Fraser River-Straight Creek fault zones (Fig. 3) are segments of a dextral, intracontinental transform fault zone. This fault zone is more than 2500 km long, cutting diagonally across the Canadian Cordillera (Price and Carmichael, 1986). Separate, *en-échelon* fault segments have major releasing step-over separation of 600-700 km. The 450 km total dextral displacement on these faults was transformed southwards into oblique convergence and shortening in the southern Canadian Rockies, in Late Cretaceous and Palaeogene times. Fault segments are right stepping, and the large horizontal displacements between segments are manifested by extreme extension and alkaline volcanism. The radius of the best fit small circle to the fault zone is 3430 km (Price and Carmichael, 1986).

In the central Indonesian region, the Late Miocene collision of the microcontinental Sula Platform with the East Sulawesi Ophiolite

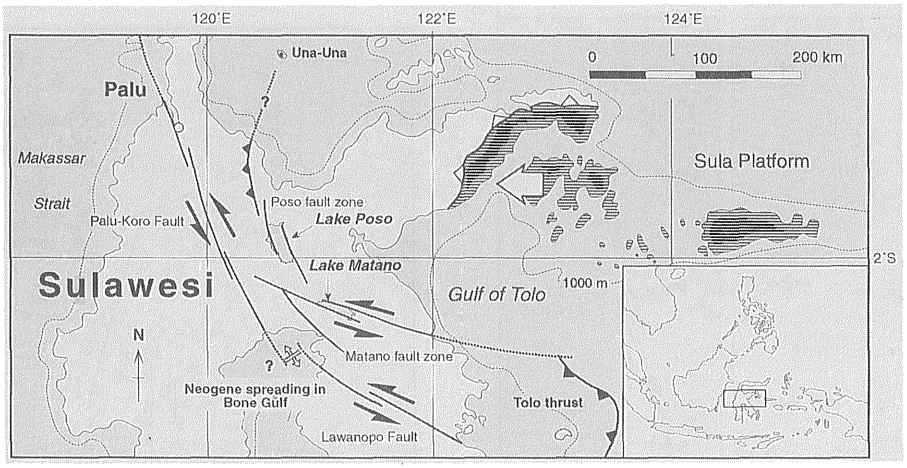

Fig. 4 Highly simplified tectonic cartoon of Neogene deformation in the Sulawesi region of Indonesia. Late Miocene collision of the Sula Platform with the East Sulawesi Ophiolite resulted in the formation of a strongly arcuate collisional complex of folds, thrusts and conjugate shears in eastern central Sulawesi, and a series of curvilinear sinistral strike-slip fault zones (Palu-Koro, Poso, Matano and Lawanopo fault zones). Fault segments on these zones consistently step to the left, and are associated with a number of pull-apart basins such as Lake Poso and Lake Matano, along with other in-line grabens and sags.

(Davies, 1990) has resulted in the formation of a strongly arcuate collisional complex of folds, thrusts and conjugate shears in eastern central Sulawesi that fits a small circle with its focus at the point of collision, 160 km to the east (Parkinson, 1991). The development of a series of major curvilinear sinistral strike-slip fault zones (Palu-Koro, Poso, Matano and Lawanopo fault zones) can also be correlated with the collisional event. Fault segments on these zones consistently step to the left, and are associated with a number of pull-apart basins such as Lake Poso and Lake Matano, along with other in-line grabens and sags (e.g. Ahmad, 1977 ; Tjia, 1981 ; Silver *et al.*, 1983 ; Parkinson, 1991 ; Fig. 4). Both Lake Matano and Lake Poso have an aspect ratio of *c.* 3 : 1 identical to that predicted by Aydin and Nur (1982). The currently active Palu-Koro and Matano fault zones represent a 700 km long composite transform fault system which links the North Sulawesi Trench with the Tolo Thrust. Total displacement on this system, which is currently being taken up by subduction in the North Sulawesi Trench, may be of the order of 250 km (Silver *et al.*, 1983). Individual fault zones lie on a series of small circles, the foci of which correspond to poles of rotation. Migration of the pole of rotation with time may have resulted in the sequential clockwise rotation and *extrusion* of a series of blocks at successively greater distances from the Sula Platform collision zone (Parkinson, 1991).

3. Why a Releasing Step-Over ?

Extension of the crust raises isotherms, thus raising the brittle-ductile transition zone to a higher level, increasing heat flow, and thereby reducing crustal peak shear strength (Sibson, 1983). Segall and Pollard (1980) suggested that within releasing step-overs, the mean compressive stress decreases, promoting the formation of secondary features such as joints and oblique-slip extensional faults and joints indicating that these features dissipate strain, whereas restraining step-overs restrict the development of secondary features thereby presenting a barrier to displacement accommodation or rupture propagation (cf. Brown and Sibson, 1989).

Furthermore, shallow seismicity along major

Table 1 Geometric, seismic and relevant volcano-plutonic characteristics of selected strike-slip systems. (Abbreviations : CCIT, Canadian Cordillera intra-continental transform ; SA-I-CP, San Andreas-Imperial-Cerro Prieto fault zone ; PMFZ, Poso-Matano fault zone ; P-K/LFZ, Palu-Koro/Lawanopo fault zone).

Fault System	**Sense of slip**	**No. of releasing stepovers**	**No. of restraining stepovers**	**Spacing of pull-aparts (where applicable)**	**Radius of small circle, where calculated**	**Volcano-plutonic activity**	**Depth to earthquake foci (average)**	**Sources of data**
Garlock	Sinistral	27	3	20-30 km (eastern zone)	?	-	-	Aydin & Schultz (1989)
Dead Sea	Sinistral	35	5	200-250 km (average)	800-900 km	Volcanism associated with normal faults	6-12 km	van Eck & Hofstetter (1990) Aydin & Schultz (1989)
Poso-Matano ***Palu-Koro/Lawanopo***	Sinistral Sinistral	4 8	- 1	60-65 km (PMFZ) 80-100 km (P-K/LFZ)	165-170 km ~ 700 km	Alkaline volcanicity, Una-Una? Granodiorites intrusions	< 20 km < 20 km	Ahmad (1977), Parkinson (1991) Tjia (1981), Parkinson (1991)
North Anatolian	Dextral	11	3	70-120 km	600-700 km	Rhyolitic and dacitic cones with associated volcanics	< 10 km	Barka & Kadinsky-Cade (1988) Hempton & Dunne (1984) Aydin & Schultz (1989)
Calaveras	Dextral	6	-	< 20 km	-	-	< 12 km (concentrated < 6 km)	Oppenheimer (1989)
CCIT	Dextral	3	-	600-700 km* (* to point of stepover)	~ 3500 km	Mid Cretaceous plutonic activity; Eocene dykes and other volcanics	-	Gabrielse (1985) Price & Carmichael (1986) Tipper et al. (1981)
Southern San Andreas (SA-I-CP faults)	Dextral	3	-	5-100 km	-	Rhyolite, obsidian, pumice associated with domes; ?spreading centres	4-6 km (not > 8 km)	Sanders & Kamamori (1984) Johnson & Hill (1982)

strike-slip/transform systems is concentrated within releasing step-overs (Sanders and Kanamori, 1984 ; Table 1), commonly exhibiting swarm-like behaviour. For example, earthquake activity along the Dead Sea transform system is clustered within the various pull-apart basins. The focal depth for these shocks is typically less than 12 km (van Eck and Hofstetter, 1990). Likewise, in California where the focal depth for clusters of shocks in basins such as the Salton Sea, are commonly between 3 and 10 km (Sanders and Kanamori, 1984), whereas focal depths for earthquake activity in regions of transpression are far deeper ($>$ 20 km ; Sibson, 1983 ; Sylvester, 1988). Epicentres of recent, shallow ($<$20 km) earthquakes in central Sulawesi are clustered around Lake Matano, Lake Poso and grabens in the northern part of the Palu-Koro valley (e.g. Fitch, 1970 ; Silver *et al.*, 1983), whereas a number of much deeper ($>$100 km) shocks have epicentres clustered around a restraining double bend on the Poso Fault Zone, to the north of Lake Poso (Silver *et al.*, 1983 ; Parkinson, 1991). Other studies such as that by Barka and Kadinsky-Cade (1988) indicate that large earthquakes with deep foci tend to cluster in or around restraining bends or double bends, and thus these features appear to be barriers to rupture propagation, and thereby sites of strain accumulation (cf. Brown and Sibson, 1989 ; Sibson, 1983). Conversely the relatively larger number of small, shallow earthquakes associated with releasing step-overs indicates that these are sites of strain dissipation. In general, restraining step-overs are probably transient, local features, developed at the initial stages of fault propagation due to plate margin asperities, which are subsequently removed by earthquake ruptures (e.g. Wesnousky, 1988).

The presence of volcanics (especially alkaline volcanics) in releasing step-overs (Price and Carmichael, 1986) indicates a very high degree of crustal extension, which may result in rapid thinning of the lithosphere and the subsequent rise of fertile mantle (Dewey and Pindell, 1985). Rapid emplacement of mantle-derived garnet peridotites (Helmers *et al.*, 1990) into upper crustal levels in the Palu-Koro fault valley of central Sulawesi may have been facilitated in this way (Parkinson, 1991). Anomalous heat introduced by crustal thinning in pull-aparts is dissipated rapidly through the steep side-walls of the basin both by conduction (Pitman and Andrews, 1985) and by convection through fluid migration along dilatant fault planes (Sibson, 1977 ; 1983). Large thermal anomalies in pull-aparts are thereby avoided, and basin subsidence is purely a function of the magnitude of master fault displacement (cf. ten Brink and Ben-Avraham, 1989).

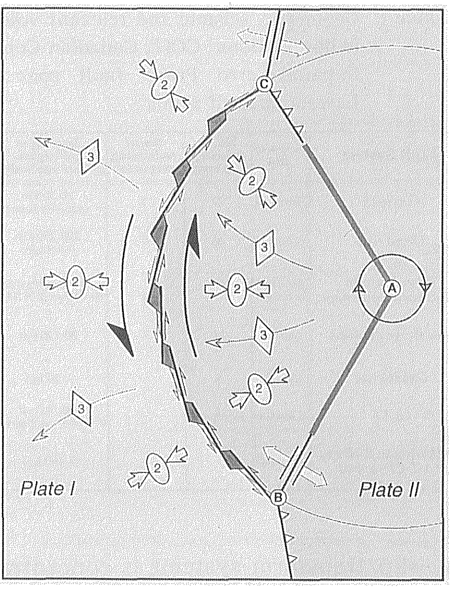

Fig. 5 Schematic diagram illustrating a simple geometric model to explain the development and spacing of pull-apart basins along a strike-slip fault zone. Sinistral movement along a boundary B-C, separating two plates (I and II), results in a series of *en-échelon* fault segments which are considerably straighter than the fault zone itself. Segments must step to the left to accommodate the curved plate boundary, necessitating rhombochasm development at regular intervals along the zone. Net extension along the fault zone must be compensated by shortening normal to its trend, resulting in secondary structures (2). Furthermore, rotation of the stress field along the length of the fault zone results in complicated Tertiary structures (3) with curvilinear, radial axes. Further details are discussed in the text.

4. An Empirical Model for the Formation of Releasing Step-Overs

The above considerations support the conjecture that releasing step-overs are efficient at accommodating large displacements along strike - slip / transform fault systems. The model we propose (Fig. 5) consists of an idealised three plate system with two triple junctions, B and C and a small circle linking the two junctions. Assuming perfect clockwise rotation of plate 2 relative to plate 1, about a pole, A, displacement between the two junctions must be accommodated by sinistral strike-slip faults. Straight fault segments are more efficient at accommodating slip than curved or irregular traces (Aydin and Nur, 1985), avoiding any large strain incompatibilities that bends create (Andrews, 1989) ; thus fault segments will propagate until the strike of the segment is no longer compatible with the changing plate trajectory/boundary, necessitating a step-over in the system. To maximise efficiency these step-overs must be releasing, and the resultant non-parallelism of the segments may give rise to compressional structures between fault tips, such as those observed along the Dead Sea transform (van Eck and Hofstetter, 1990).

4.1 Secondary and tertiary structures

Strike-slip and transform fault systems have classically been interpreted, in terms of the plate tectonic paradigm, as *conservative* boundaries (so that, ideally, horizontal displacement on releasing step-overs is balanced by that on restraining step-overs). From the above it is clear that many such systems are transtensional. Clearly if, in our ideal system spreading at junction C is balanced by subduction/thrusting at B, then crustal extension along the fault zone must be compensated by concomitant compression and shortening elsewhere, or rotation of plate 2 could not be effectively accommodated. The geometry of the system necessitates that the horizontal compression axis in plates 1 and 2 will be oriented at a high angle to the trend of the strike-slip fault zone (Freund, 1974), and secondary structures associated with shortening will be oriented subparallel to the fault zone. This entails the coexistence of two mutually perpendicular tectonic stress fields - one is regional and controls relative plate motion, the other results in local intra-plate deformation. Furthermore, since the orientation of the horizontal compression axis rotates along the length of the fault zone, tertiary compressional structures such as folds with subradial, curvilinear axes, would also be expected. Nearer the focus of the small circle in plate 2 convergence and interference of compressional structures will result in a highly complex deformation pattern, and it is likely that this region would experience significant uplift. This may offer an explanation for the pronounced uplift seen in the East Arm of Sulawesi, where Plio-Pleistocene reef limestones are encountered at elevations of c. 2500 m.

Shortening and compression perpendicular to the transform system 'is not compatible with conventional wrench tectonics' (Wentworth and Zoback, 1989), however, the predicted pattern of secondary structures is consistent with deformation patterns adjacent to the San Andreas transform in the California Coast Ranges. The maximum horizontal compression axis is sub-perpendicular to both the mean orientation of fold axes in the easternmost Coast Ranges and the curvilinear trend of the San Andreas transform (Mount and Suppe, 1987 ; Wentworth and Zoback, 1989). Similarly, along the Dead Sea transform system the regional stress field is oriented NNW-SSE, yet meso- and macro-structures indicate contemporaneous development of a local, secondary stress field with maximum horizontal compression oriented E-W (i.e. sub-perpendicular to the trend of the transform) in northern Israel and the Lebanon (Ron & Eyal, 1985). Folds striking at angles approaching 90° to fault segments are observed along the left-lateral Garlock Fault in eastern California (Searles Valley Syncline and Slate Range Anticline, Smith, 1991).

4.2 Spacing of pull-apart basins

The data for some of the fault systems presented in Table 1 illustrate that with an increase in the radius of the best fit small circle there is a proportionate increase in the maximum basin spacing/fault-segment length, implying a genetic control. For smaller radii the rate of change of arc is greater, and thus incompatibility between fault segment strike and plate vector is achieved with a shorter segment, necessitating a step-over. Large transform fault systems may, in time, smooth their surficial traces leading to fewer step-overs per unit length (see Wesnousky, 1988), than that predicted by the model. In this instance smaller releasing fault step-overs are likely to be destroyed through basin cut-off faults, with only major step-overs preserved intact over long periods of geological time.

5. Conclusions

Fault arrays producing pull-apart basins along strike-slip systems can be explained by a simple model which invokes fault segmentation to accommodate a curved or non-linear relative plate boundary, and whose spacing is a function of the radius of the best fit small circle. The development of restraining step-overs and double bends is relatively limited and confined to local fault segment interactions. Assuming a homogeneous brittle upper crust, negligible post-rifting thermal subsidence, and translation of total displacement through the step-over, total basin length (active and inactive) should give an approximate indication of the displacement accommodated by the fault zone. Extension in the resultant pull-apart basins must be compensated by shortening and compression directed perpendicular to the trend of the primary fault system.

The model proposed is, out of necessity, simple and cannot take into account plate margin asperities, the effect of spreading centres within pull-aparts (i.e. within transform alteration), a change in plate motion vectors, or triple-junction instability (e.g. Andrews, 1989). The thickness of the brittle or seismogenic crust will also exert an influence on segment length (Wallace, 1989). Analysis of geometrical relationships in other strike-slip systems not considered here, along with appropriate computer simulation and analogue (sandbox) modelling is necessary to corroborate (or refute) our preliminary conclusions.

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横ずれ断層帯における堆積盆形成と歪分割

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要　旨

巨大な横ずれ断層系は，地表では一定の間隔のステップ状に並ぶ断片として現れている．多くの横ずれ断層系において，断層断片の階段状のずれのセンスは，プルアパート堆積盆やそれに関連した構造を形成させる．これまでの研究では，このような断層は地域的な異方性に起因するものと考えられていたが，これは系統的な形成過程というよりも偶然に支配されているという考えである．しかしながら私たちは，いろいろな地質状況において横ずれ断層帯の形態を解析し，階段状の形態の形成過程の単純なモデルを提起する．この予備的な研究の結果，断層断片は断層帯そのものより直線的で，堆積盆の間隔（断層断片の長さ）は断層の曲率の半径と正の相関関係を持っている．直線的な断層は不規則な形態やカーブを描いた断層よりも効果的なので，断層が断片状になるためにはカーブを描いたプレート境界が必要となってくる．トランスフォームもしくは横ずれ断層帯での展張の合計は，もともとの断層系と直交した方向のプレート内短縮と圧縮によって埋め合わせ，結果として歪み分散をもたらしている．

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