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A New Class of Transform Plate Boundary

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Abstract. The theory of plate tectonics postulates that the relative motion between two neighboring plates occurs along three types of boundaries: divergent (spreading center, rift), convergent (subduction, collision), and horizontal (transform). Because the theory assumes rigid behavior of plates, transform plate boundaries must lie along small circles around the pole of rotation of relative motion between two neighboring plates. However, global models of current plate motion (e.g., NUVEL-1A) show that several boundaries with significant horizontal motion (i.e., the Dead Sea Fault and the Eastern Andean Frontal Fault Zone) do not lie along small circles but rather intersect the circles at 45°. The orientation of these faults can be explained by a new theory of intraplate tectonics, which predicts the first-order intraplate stress field in terms of small circles, great circles, and spiral lines that intersect both sets of circles at 45°. According to the theory, these transform faults are situated along the 45° spiral lines and follow the direction of maximum horizontal shear stress. The theory also predicts that the direction of interseismic relative plate motion between the two plates should be oriented at 45° to the transform plate boundary; this prediction can be tested within a few years using space geodesy. The alignment of these faults along spiral lines is explained by the theory's predicted stress field and a plasticity (von Mises) yield stress criterion for earthquake rupture. It is suggested that these faults represent a new class of transform plate boundary between large deformable plates and not between rigid sub-plates, as formerly postulated.

1 Introduction

Transform faults are tectonic plate boundaries along which horizontal motion occurs parallel to the strike of the fault. The term was first introduced by Wilson (1965) in order to explain the abrupt termination of mid-ocean ridges and mountain belts. The most common transform faults are sub-marine faults, which offset segments of mid-ocean ridges (oceanic transforms). Other transform faults, which connect two subduction zones or a ridge with a subduction or collision zone, are rarer and occur both in continental and in oceanic lithosphere.

Wilson's (1965) original definition of transform faults offered no constraint on the orientation of the faults. He defined the term transform fault as a horizontal shear fault that terminates abruptly at both ends, but which nevertheless may show great displacement. However, when plate kinematics was treated mathematically, Morgan (1968) postulated that all the (transform) faults common to two blocks (plates) must lie on small circles concentric about the pole of relative motion. The additional constraint on the faults' orientation is implied from the fundamental assumption of the theory of plate tectonics: that tectonic plates behave as rigid (underformable) blocks.

The geometric relations between the direction of relative plate motion and the orientation of transform faults was used by Morgan (1968) to demonstrate that tectonic plates can be treated as rigid plates moving on a spherical shell. This relation describes well the geometry of oceanic transforms and remains a key assumption in quantitative estimates of current plate motion (e.g. Minster and Jordan, 1978; De Mets et al., 1990, 1994). However, not all transform faults are aligned parallel to the direction of relative plate motion. A small divergence between the direction of relative plate motion and transform fault orientation results in compression or tension normal to the fault's strike and may explain the formation of compressional or tensional structures along faults (e.g., Garfunkel, 1981). A large divergence between the two orientations cannot be explained by a small departure from the assumed rigid behavior of

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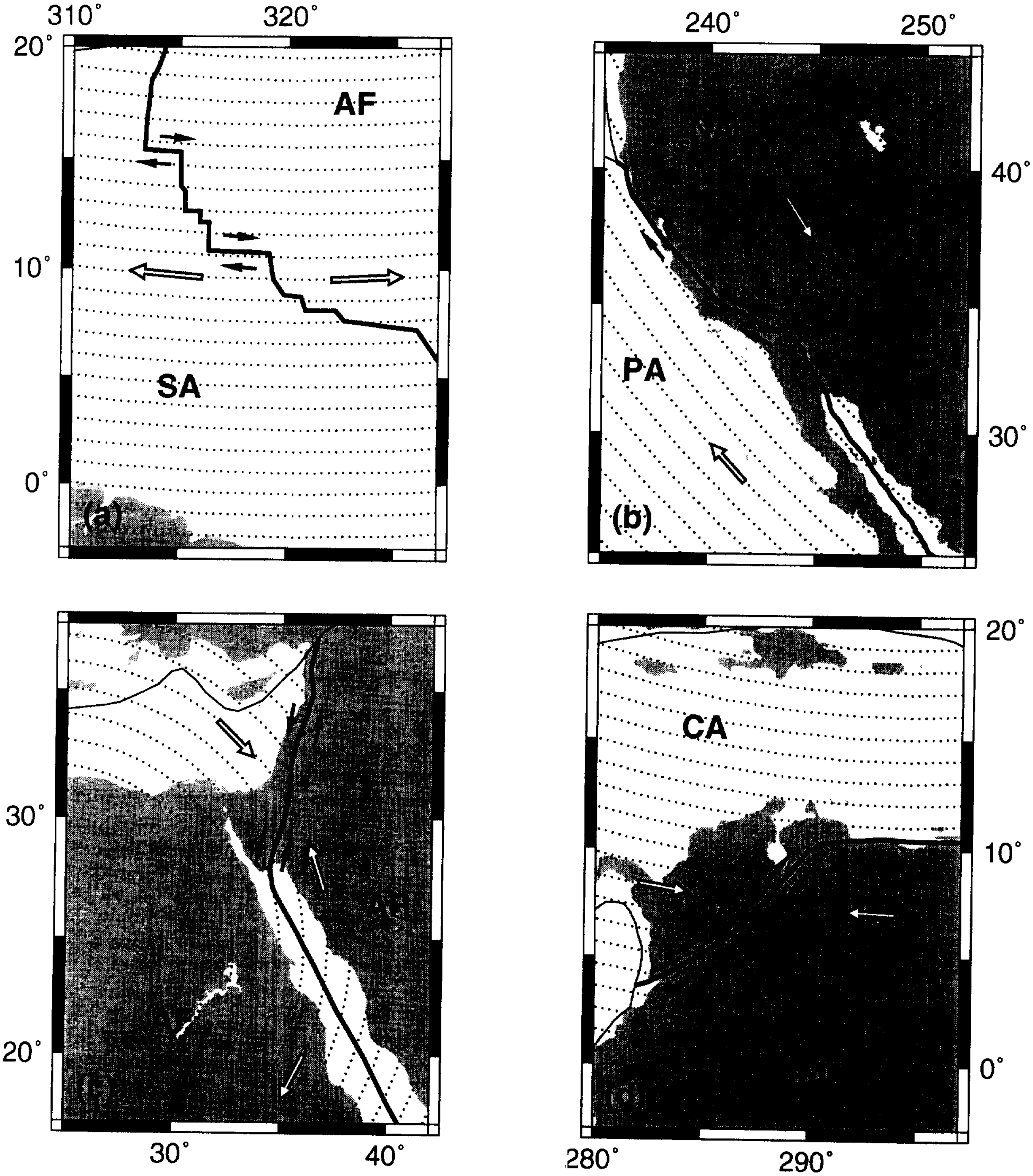

Fig. 1. Observed and NUVEL-1A predicted orientations of transform plate boundaries along the mid-Atlantic ridge (a), the San Andreas Fault (b), the Dead Sea Fault (c), and the Eastern Andean Frontal Fault Zone (d). Plate boundaries are marked by solid lines and small circles by dotted lines. Black arrows show the observed relative displacements along the transforms, and white arrows show the relative plate motion predicted by NUVEL-1A. Plate abbreviations: AF, Africa; AR, Arabia; CA, Caribbean; NA, North America; PA, Pacific; SA, South America.

plates. Where it is observed, it is explained as (1) deformation within a broad region along the plate boundary (i.e., southern California), or (2) rigid sub-plates with a relative motion parallel to the strike of the fault (i.e., Arabia and Israel-Sinai sub-plate).

This study re-examines the geometric relations between relative plate motion and the orientation of transform faults in the light of a recently proposed new theory of intraplate tectonics (Wdowinski, 1996). The theory expands upon the classical theory of plate tectonics by assuming an elastic-plastic behavior of plates. Using the theory's predicted stress field and a plasticity (von Mises) yield stress criterion for earthquake rupture, I propose the existence of two classes of transform plate boundaries: (1) those oriented parallel to the direction of relative plate motion (classical transforms); and (2) transforms that intersect the direction of relative plate motion at 45°. I suggest that the second class of transform faults represents a heretofore undefined type of plate boundary that separates large deformable plates and not rigid sub-plates.

2 Observations

Geological models of current plate motion (i.e. RM2 (Minster and Jordan, 1978), NUVEL-1A (De Mets et al., 1990, 1994)) provide the most consistent information on plate kinematics and allow us to test the above hypothesis regarding the orientation of transform faults. The most updated model, NUVEL-1A, consists of 12 rigid plates whose relative motion is obtained by inverting plate motion data on transform fault azimuths, spreading rates, and earthquake slip vectors. Figure 1a shows that the orientations of oceanic transform faults, which offset the various segments of the mid-Atlantic ridge, agree very well with the NUVEL-1A predicted trend of small circles around the Africa-South America PoR. This good fit reflects, to some extent, an input of transform fault azimuths along the Africa-South America boundary used by the NUVEL-1A model. Figure 1b shows that the northern segment of the San Andreas Fault lies, within 10°, along the trend of small circles around the Pacific-North America PoR. The divergence of the southern segment of the fault by up to 30° from the predicted orientation of small circles results in a wide region of diffuse deformation across the Pacific-North America plate boundary.

The orientations of transform faults do not always lie along the NUVEL-1A predicted direction of relative plate motion. Figure 1c shows that the orientation of the Dead Sea Fault, which represents the northern segment of the Africa-Arabia plate boundary, intersects the trend of small circles at close to 45°. A similar geometrical relation is observed along the Eastern Andean Frontal Fault Zone, which represents the western segment of the Caribbean-South America plate boundary (Figure 1d).

The Dead Sea Fault (DSF) is a more than 1000 km-long plate boundary that connects the divergent plate boundary along the Red Sea with the convergent Alpine-Himalayan belt to the north (Figure 1c). The well documented 105 km sinistral displacement across the Dead Sea Rift (Quenell, 1958) led Wilson (1965) to consider the DSF as a transform plate boundary separating the Arabian from the African plate. However, McKenzie et al. (1970) noticed that the orientation of the DSF does not follow the direction of relative motion between Arabia and Africa, as implied by the rules of plate tectonics, and suggested that the DSF represents a rigid plate boundary between Arabia and the Sinai sub-plate. Quantitative estimates of the relative motion between the Arabian and Sinai plates have shown that only the southern half of the DSF broadly follows the trend of small circles around the Arabia-Sinai PoR (Garfunkel, 1981; Joffe and Garfunkel, 1987). The northern half of the DSF cannot be explained by the rules of rigid plate tectonics (Garfunkel, 1981).

The Eastern Andean Frontal Fault Zone (EAFFZ) is a 1200 km-long dextral shear zone that separates the deforming North Andean block (Ecuador and Columbia) from the stable South American plate (Pennington, 1981) The North Andean block is often considered as a separate block that moves independently with respect to both the Caribbean and the South American plates (Freymueller et al., 1993). However, in the division of the Earth's surface into 12 major plates, the North Andean block is considered as part of the Caribbean plate (De Mets et al., 1990, 1994). Although seismic and geologic observations indicate 10±2 mm/yr of right-lateral displacement along the EAFFZ (Pennington, 1981; Freymueller et al., 1993), it has never been considered as a transform plate boundary, mainly because of the diffused nature of the deformation within the North Andean block. Like the DSF, the EAFFZ also strikes at close to 45° to the trend of small circles.

3 A new class of transform plate boundary

An explanation for the close to 45° intersection between the two last-mensioned transform faults (the DSF and the EAFFZ) and the trend of small circles (Figures 1c and 1d) is given by a recently advocated new theory of intraplate tectonics (Wdowinski, 1996). This section provides a brief description of the theory's assumptions and predictions. Thereafter, I apply the theory to the two tectonic environments adjacent to the DSF and EAFFZ, and provide a physical explanation for this newly proposed type of transform plate boundary.

3.1 A theory of intraplate tectonics

The theory of intraplate tectonics expands upon the classical theory of plate tectonics. As with the latter theory, the new theory is kinematic and uses spherical geometry. It is based on simple assumptions that link the well-established directions of relative plate motion to the displacement and deformation fields within a plate interior. The theory is based on the following assumptions:

1. *Tectonic plates are fragments of a thin spherical elastic-plastic shell.*
   At the time scale of the earthquake deformation cycle, the lithosphere behaves elastically at low stress levels and plastically at stress levels that exceed the yield stress. Elastic (recoverable) deformation dominates the interseismic stage, whereas plastic (permanent) deformation characterizes the coseismic stage.

2. *Plates deform in response to uniform horizontal tractions induced by their neighboring plates in the direction of relative motion between two adjacent plates.*
   This assumption implies that along each plate boundary, both tractions and boundary displacements follow the direction of relative plate motion (small circles - Figure 2). The magnitude of the boundary displacement is highest at the Euler equator of relative plate motion and decreases with distance from the equator, reflecting the uniform traction condition in spherical coordinates. Because the magnitude of the boundary displacement is independent of the rate of plate motion, but follows the direction of the relative plate motion (small circles), this assumption yields three types of deformable plate boundaries: inward-, outward- and tangential-displaced boundaries (Figure 2). Inward- and outward-displaced boundaries lie along convergent (subduction and collision) or divergent (spreading center and rift) rigid plate boundaries, whereas tangential-displaced boundaries lie along transform plate boundaries. The difference between inward- and outward-displaced boundaries lies in the relative motion of the plate boundary toward or away from the plate interior. The boundary displacement is directed either toward or away from the plate interior (Figure 2). Similarly, the boundary displacement of a tangential-displaced boundary is directed either clockwise or anticlockwise to the plate interior (Figure 3).

3. *Interseismic elastic deformation concentrates in finite width regions parallel to one of the plate's boundaries.*
   Tectonic plates can be divided into three major regions of similar strength: strong oceanic regions, intermediate strength stable continental regions, and weak plate boundary regions. The interseismic elastic deformation concentrates in the weakest regions within each plate. The deformation in entirely oceanic plates (e.g., Pacific or Nazca plates) and entirely continental plates (Arabian plate) is distributed throı out the entire width of the plate. Weak plate boundary regions, such as sections of plates overriding subduction zones mostly along the Pacific rim, absorb most of the deformation in a narrow region adjacent to the plate boundary. The deformation in combined oceanic-continental plates (e.g., North American, South American) concentrates in the weak continental region of the plate.

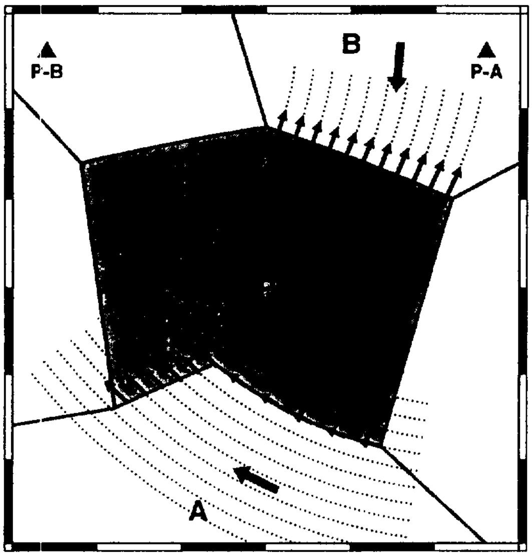

Fig. 2. Schematic illustration of a deformable plate (P) with boundaries that are displaced inward, outward, and tangentially in the direction of relative plate motion (small circles - dotted lines) with respect to the adjacent plates. Poles of rotation are marked by solid triangles.

4. *The interseismic elastic deformation is homogeneous distributed within the deforming regions.*
   During the interseismic stage of the earthquake deformation cycle, the deforming regions are subjected to (linear) elastic deformation, which is assumed to be homogeneously distributed throughout the width of the region.

5. *Radial components of the stress tensor are negligible.* This assumption allows us to use plane stress in spherical coordinates (thin shell approximation).

The formulation of the theory, which uses spherical geometry, is described in detailed by Wdowinski (1996). The theory yields simple predictions about the direction of the elastic intraplate displacement, strain, and stress fields in terms of small circles, great circles, and spiral lines around the PoR of two adjacent plates. The newly defined spiral lines (Wdowinski, 1996) are two orthogonal sets of trajectories, clockwise and anticlockwise, that intersect both small and great circles at 45° (Figure 4). The theory predicts that the principal axis of the

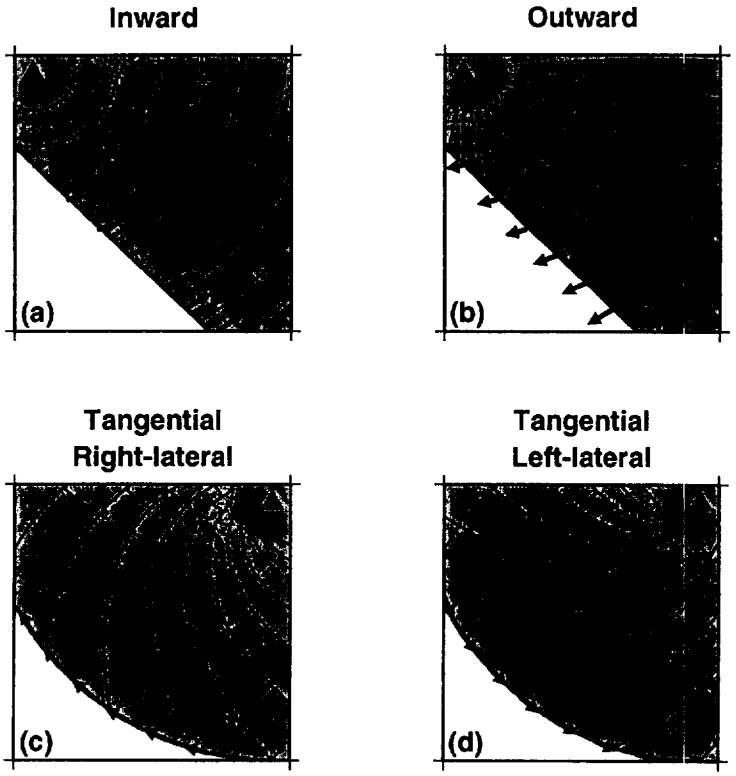

Fig. 3. Predicted directions of maximum (solid lines) minimum (dashed lines) and shear (dotted lines) horizontal stresses adjacent to the various plate boundary types. These directions follow the trajectories of small circles, great circles, and spiral lines. Arrows represent boundary displacements and triangles represent the location of the pole of rotation.

maximum horizontal stress (SHmax) follows the trajectories of small circles for inward-displaced boundaries, great circles for outward-displaced boundaries, and spiral lines for tangential-displaced boundaries (Figure 3). The theory was successfully tested by a systematic comparison of the predicted stress field along the various plate boundaries with more than 4000 reliable observed directions of SHmax provided by the world stress map project (Zoback, 1992).

3.2 Application of the theory

The theory predictions are now applied to the regions adjacent to the Arabian-African and the Caribbean-South American plate boundaries and are compared with the observed direction of SHmax provided by the world stress map project. Figure 5a shows the observed direction of SHmax (short solid lines) within the Arabian plate and in the vicinity of the DSF, and the NUVEL-1A predicted trajectories of small and great circles around the Arabian-African PoR (dotted lines). The alignment of the few available data points (emphasised by circles) within the interior of the Arabian plate with the trend of small circles suggests that the stress field within the Arabian plate is consistent with an inward-displaced boundary. The observed direction of SHmax along the DSF and to its west consists of two populations, one oriented WNW-ESE and the other NNW-SSE (Eyal and Reches, 1983; Eyal, 1996). The predicted direction of SHmax for this region, according to the trend of small circles, is 310-330°, which fall between the two observed directions of SHmax. Figure 5c shows a similar alignment of the observed direction of SHmax with the trend of small circles around the Caribbean-South American PoR. This alignment suggests that the stress field across the Caribbean-South American plate boundary is also consistent with an inward-displaced boundary.

The two comparisons reveal another important observation: both the DSF and the EAFFZ are aligned, throughout their length, along the NUVEL-1A predicted trend of spiral lines (Figures 5b and 5d). According to the theory, the 45° spiral lines adjacent to inward-displaced boundary follow the direction of maximum horizontal shear stress. Thus, both the DSF and the EAFFZ are aligned along the theoretically predicted direction of maximum horizontal shear stress.

3.3 Physical explanation

A physical explanation for the alignment of transforms along spiral lines can be obtained from the assumed elastic-plastic behavior of plates. Elastic (recoverable) deformation occurs at low stress levels and dominates the interseismic stage of the earthquake deformation cycle; plastic (permanent) deformation occurs at stress levels that exceed the yield stress and dominates the coseismic stage. Recent studies indicate that frictional strength of transform faults is very low and that the

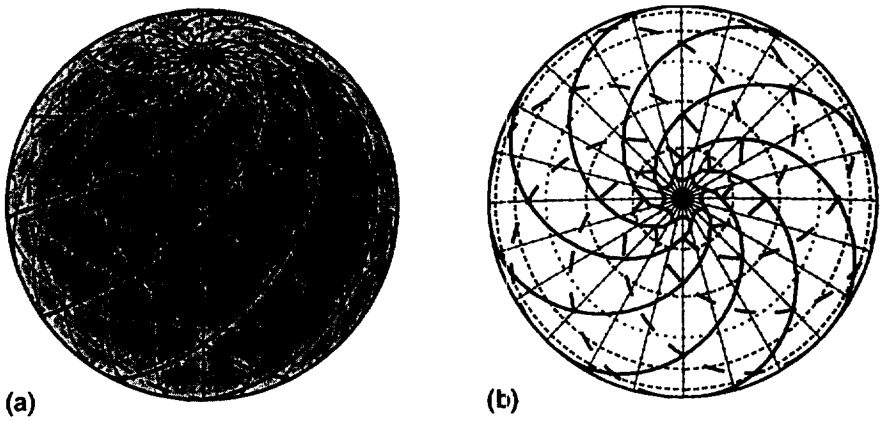

Fig. 4. Spherical coordinate presentation of 45° spiral lines as viewed from an oblique angle to the pole of rotation (PoR) (a) and from directly above the PoR (b). Small circles are represented by thin dotted lines, great circles by thin solid lines, clockwise spirals by thick solid lines, and anticlockwise spirals by thick dashed lines.

commonly used friction-law yielding criteria cannot be applied to these faults (Lachenbruch and Sass, 1980, Zoback, 1991). A more appropriate criterion to determine the transform fault's yield stress is the von Mises criterion (plasticity), which assumes a frictionless slip surface. This criterion indicates that slip along a given plane occurs when the component of the shear stress acting on the plane in the slip direction attains a critical value (yield stress). For a system of several possible slip-planes, the active slip-plane is that on which the critical value of shear stress is first attained. Thus, the preferred slip direction is the one aligned closest to the direction of maximum shear stress.

Continental transform faults, such as the San Andreas Fault (SAF), the DSF, and the EAFFZ, consist of series of sub-parallel faults, where some of them show a significant horizontal displacement. The preferred direction of plastic yielding explains well the accumulation of displacement along certain faults - those that are oriented closest to the direction of maximum horizontal shear stress. According to the theory of intraplate tectonics, the direction of maximum horizontal shear stress follows the trajectories of small and great circles for tangential-displaced boundaries and 45° spiral lines for inward- and outward-displaced boundaries. For each plate boundary there are two orthogonal sets of directions of maximum horizontal shear stress, one consistent with a right-lateral slip and the other with a left-lateral slip. For an inward-displaced boundary, a right-lateral slip can occur along the clockwise set of spiral lines, whereas left-lateral slip can occur along the anticlockwise set.

Applying the theory to the various plate boundaries reveals that: (1) the orientation of transform faults along the Pacific-North America plate boundary, which is a right-lateral tangential-displaced boundary, should follow the trend of small circles (Figure 1b), and (2) the orientation of transform faults along the Arabia-Africa and the Caribbean-South America plate boundaries, which are inward-displaced boundaries, should follow spiral line trajectories (Figures 5b and 5d). Indeed, the SAF, is aligned along small circles, the DSF is aligned along anticlockwise spiral lines, and the EAFFZ is aligned along clockwise spiral lines. The alignment of the DSF along the anticlockwise spiral line trajectories and that of the EAFFZ along clockwise spiral line trajectories is consistent with the observed left-lateral motion along the DSF and right-lateral motion along the EAFFZ.

4 Discussion and Conclusions

Other examples of continental transforms that are oriented along spiral lines are the Great Sumatran Fault (GSF) and the North Anatolian Fault (NAF). The GSF is a dextral strike-slip fault located 200-300 km inland from the Sumatran trench, where the Australian plate subducts beneath the Eurasian plate. The orientation of the GSF, which is parallel to the trench, intersects small circles around the NUVEL-1A Australia-Eurasia PoR at 30-35°. However, seismic and geodetic observations (McCaffrey, 1991; Tregoning et al., 1994) indicate that the convergence between Australia and Southeast Asia along the Sumatra and Java trenches differ from the NUVEL-1A direction by 5-12°, suggesting a 40-45° intersect between the orientation of the GSF and the direction of relative plate motion between Australia and Southeast Asia. The NAF is also a dextral strike-slip fault system that separates the Anatolian Block (AB) from the Eurasian plate. Although the classical plate tectonic configuration considers the AB as part of the Eurasian plate, recent geodetic measurements (Oral et al., 1994; Le Pichon et al., 1995) indicate that, at short time scales, the AB behaves as part of the Arabian plate transferring most of the motion of Arabia westward. Thus, the NAF can be considered as the boundary be-

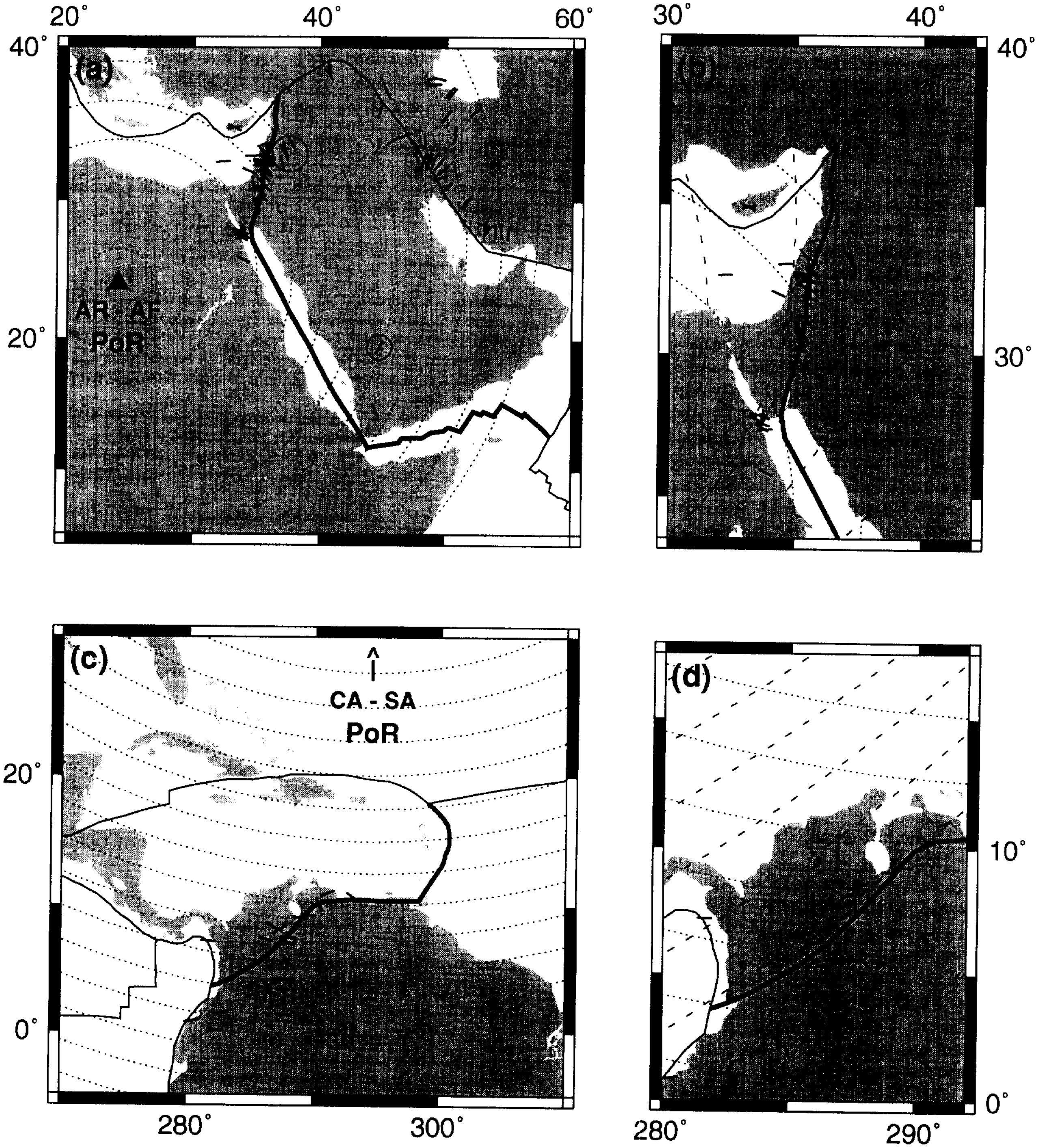

Fig. 5. Observed (short solid lines) and predicted (small circles - dotted lines) directions of SHmax across the Arabian-African (a) and the Caribbean-South American (c) plate boundaries. Circled data in (a) emphasize the few observed directions of SHmax within the Arabian plate. Both the Dead Sea Fault (b) and the Eastern Andean Frontal Fault Zone (d) are oriented parallel to the 45° spiral lines (dashed lines) around the NUVEL-1A pole of rotation (PoR).

tween the Arabian and the Eurasian plates. Interestingly enough, the E-W arc shape of the NAF follows the trend of right-lateral spiral line trajectories around the NUVEL-1A Arabia-Eurasia predicted PoR.

The elastic-plastic behavior of plates explains well the alignment of transform faults along the direction of maximum horizontal shear stress. A similar explanation can be obtained for rigid-plastic behavior of plates, which is also known as the slip-line theory. By assuming rigid-plastic behavior, the mathematical solution of the plastic deformation is significantly simplified. However, this assumption does not allow any prediction about the interseismic elastic deformation, which is observed nowadays by repeated space geodetic measurements. Tapponnier and Molnar (1976) applied the slip-line theory's solution of a rigidly indented die into a rigid-plastic media to explain the observed large-scale fault pattern of Asia. They suggested that the orientation and sense of displacement along major strike-slip faults in Asia are consistent with the predicted trajectories and the sense of motion along either α or β slip-lines, which represent the two orthogonal directions of maximum horizontal shear stress. Both the elastic-plastic and the rigid-plastic behavior of plates explain well the accumulation of displacement along existing faults, but not the formation of these fault along particular trends. The formation of a new fault is usually determined according to the Navier-Coulomb criterion that considers the internal friction of rocks.

The theory of intraplate tectonics predicts the existence of a new class of transform plate boundary that follows the trajectories of 45° spiral lines around the PoR of two adjacent plates. The alignment of the DSF and the EAFFZ along the NUVEL-1A predicted spiral line trajectories supports the theory's prediction, but does not provide strong enough evidence to contradict previous tectonic models suggesting that these transform faults represent boundaries between rigid sub-plates (McKenzie et al., 1970; Garfunkel, 1981; Joffe and Garfunkel, 1987). However, the theory provides an additional testable prediction - the elastic intraplate displacement field across transform plate boundaries - that could be tested over a period of a few years using space geodetic measurements. Intraplate displacements across a classical (small circle) transform plate boundary, as observed in California, are parallel or sub-parallel to the fault orientation (Lisowski et al., 1991). Whereas intraplate displacements across the new class (spiral lines) of transform plate boundary, as predicted by the theory, should follow the direction of relative plate motion between the two plates (small circles), and hence should be oriented at 45° to the transform plate boundary.

The estimated geological average displacement rate across the DSF and the EAFFZ are 6 and 10 mm/yr, respectively (Joffe and Garfunkel, 1987; Pennington, 1981). Very accurate Global Positioning System (GPS) measurements can provide within 3-5 years sufficient accuracy to determine within 1 mm/yr (Zhang et al., 1996) the direction of the interseismic displacement across both the DSF and the EAFFZ. Thus, within a few years we will be able to better estimate whether these boundaries are better described by the predicted new class of transform plate boundary, or by the classical transform plate boundary separating between rigid sub-plates.

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