The January 26, 2001 Bhuj Earthquake and the Diffuse Western Boundary of the Indian Plate

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Although the 2001 Bhuj, India, earthquake has been interpreted as a continental intraplate earthquake with analogies to the New Madrid seismic zone in the central U.S., it occurred within the Indian plate's diffuse western boundary with Eurasia. In general, continental plate boundary zones are broad. India's northern boundary is a zone of faulting and earthquakes extending thousands of kilometers north from the Himalayas. Its southern boundary is also diffuse, recognized because models of a single plate containing both India and Australia did not account for large "intraplate" earthquakes. Diffuse seismicity and faulting similarly show that India has a broad western boundary in the India - Arabia - Eurasia triple junction region, including the Bhuj earthquake's location. Although present data are inadequate to determine the geometry and kinematics of the boundary zone, a possible tectonic model would be that a Sind block or microplate is breaking off the Indian plate near the triple junction, as occurs at other plate boundaries. This model has similarities to aspects of the Sierra Nevada block and eastern California shear zone. The scales are comparable: Bhuj is about 400 km from the nominal boundary, which in U.S. terms is about halfway across the boundary zone between the Pacific and North American plates, in the Nevada seismic belt where magnitude 7 earthquakes occur. In contrast, New Madrid is about 2400 km from the San Andreas, the nominal plate boundary. Thus the earthquake seems to give insight into the Indian plate's western boundary rather than into intraplate tectonics.

INTRODUCTION

Ideas about the geometry of plate boundaries, like airline fares, are subject to change with little notice. New geodetic, seismological, paleomagnetic, topographic, and geological data often lead to reevaluation of previous ideas about a plate boundary's geometry. Hence in presenting a map of plate boundary zones, *Gordon and Stein* [1992] noted that "the precise geometry of these zones, and in some cases their existence, is under investigation." Successive ideas about the boundary geometry of the Indian plate illustrate this process. In the early days of plate tectonics, India and Australia were viewed as forming a single rigid Indo-Australian plate divided from adjacent rigid plates by narrow boundaries [*Wilson*, 1965; *Morgan*, 1968]. However, the broad zones of seismicity (Figure 1) surrounding and within the presumed single rigid plate rapidly led to the identification of diffuse plate boundaries. Molnar and Tapponnier [1975] interpreted the broad zone of seismicity, elevated topography, and active faulting to the north of India as a broad region of continental convergence. Within this

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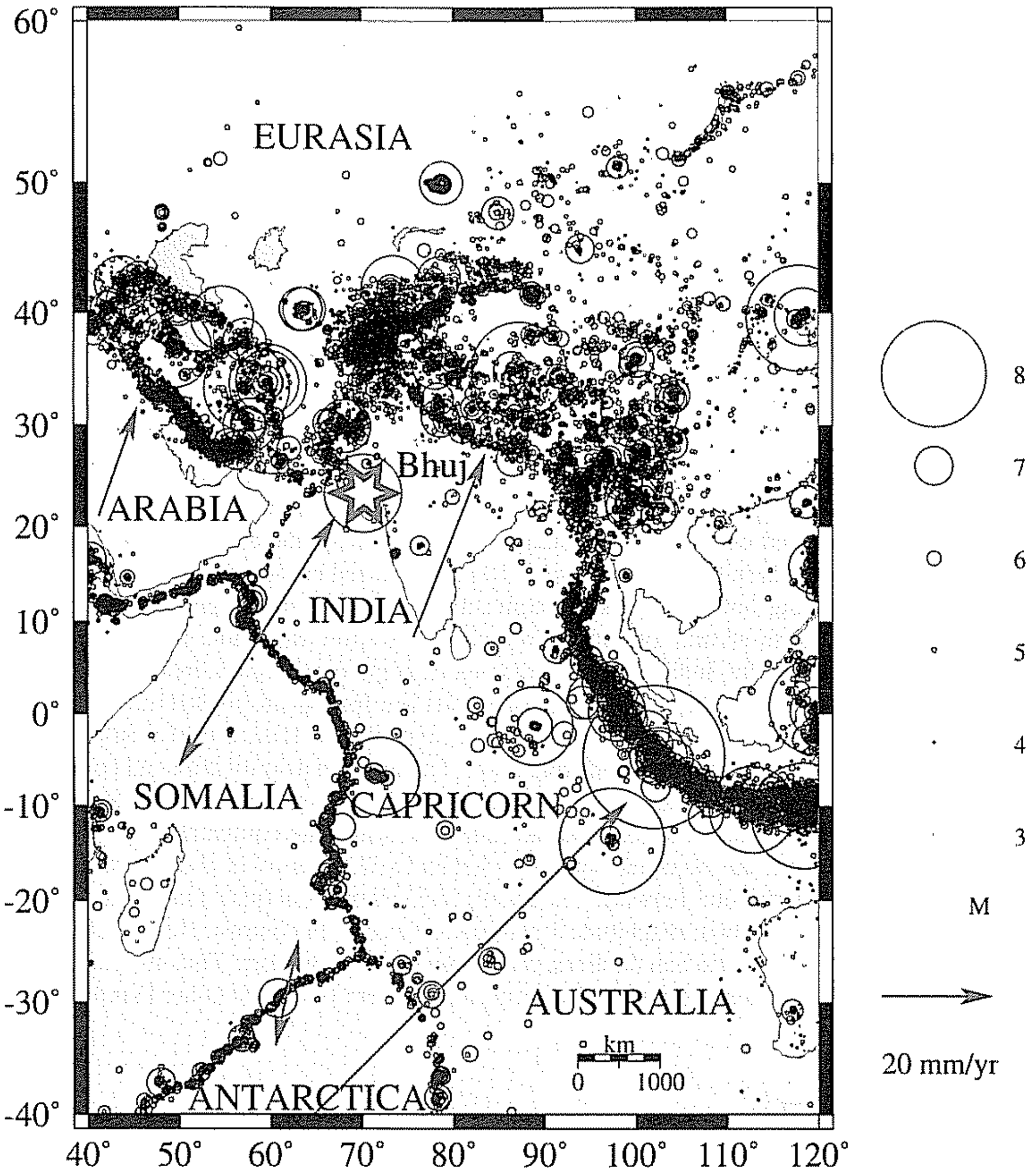

Figure 1. Seismicity (1900-2001) of the Indian plate and surrounding regions, shown by circles with radius proportional to magnitude. Star denotes 2001 Bhuj earthquake. Single arrows show plate velocities with respect to Eurasia; double arrows show spreading rates from *Sella et al.* [2002]

zone, the northward motion of India with respect to Eurasia causes a collision zone thousands of kilometers wide, extending into China and Siberia, pushing Tibet out of the way and deforming Southeast Asia. This model is confirmed by GPS and focal mechanism data [*King et al.*, 1997; *Larson et al.*, 1999; *Holt et al.*, 2000]. The extent of the collision is illustrated by the data showing that the Tien Shan intracontinental mountain belt, 1000-2000 km north of the Himalayas, accommodates almost half the net plate convergence in the western part of the zone [*Abdrakhmatov et al.*, 1996].

Ideas about the southern boundary of the plate have also evolved. Deformation in the Central Indian Ocean is shown by large earthquakes (seven with M > 7, one M = 7.7, since 1912) [*Stein and Okal*, 1978; *Stein*, 1978] and widespread basement folding seen in seismic reflection and gravity data [*Geller et al.*, 1983; *Stein et al.*, 1989; *Van Orman et al.*, 1995]. This deformation was first attributed to intraplate deformation of a single rigid Indo-Australian plate. However, in this interpretation the "intraplate" deformation corresponded to a seismic moment release rate exceeding that at many plate boundaries. The difficulty in explaining the intense "intraplate" seismicity and deformation was resolved by a model [*Wiens et al.*, 1985; 1986] in which discrete Indian and Australian plates are separated by a diffuse plate boundary zone that may have formed in response to the Himalayan uplift. The two-plate model agrees with the focal mechanism and magnetic anomaly data. Its improved fit is statistically significant, showing that two plates can be resolved. Subsequent studies have refined the model by including a Capricorn plate between India and Australia [*Royer and Gordon*, 1997; *Gordon*, 1998; *Conder and Forsyth*, 2001] and show that India and Australia have been distinct for at least 3 Myr and likely longer.

With time, the Indian plate's western boundary with the Eurasian plate was also recognized to be diffuse. A broad zone of active strike-slip and thrust faults extends northward from the poorly defined India - Arabia - Eurasia triple junction region, making it of limited use to regard this boundary as a single fault (Figure 2). Seismicity east of the plate's nominal western boundary, generally assumed to be along the Ornach-Nal and Chaman faults [*Quittmeyer and Kafka*, 1984; *DeMets et al.*, 1990], led to this boundary being mapped as diffuse [*Gordon and Stein*, 1992; *Gordon*, 1998; *Bernard et al.*, 2000]. In this paper, we propose that the January 2001 Bhuj earthquake indicates that the India - Eurasia plate boundary zone is broader than previously mapped, and we suggest a possible model for the relation of the earthquake to the boundary zone. It is worth noting that the Arabia - Eurasia boundary is similarly diffuse, extending well north of the nominal boundary at the Makran subduction zone, so the triple junction is a broad region rather than a distinct point.

DIFFUSE BOUNDARY ZONE SETTING OF THE BHUJ EARTHQUAKE

The January 26, 2001 Bhuj earthquake (Figures 1, 2), a shallow (approximately 20 km) focus earthquake with M_w = 7.7, showed essentially pure thrust faulting on nearly E-W striking planes [NEIC, Harvard CMT project]. The earthquake occurred in a previously recognized E-W trending, seismically active, fold and thrust belt extending for several hundred kilometers [*Chung*, 1993; *Chung and Gao*, 1995; *Malik et al.*, 2000; *Talwani and Gangopadhyay*, 2001; *EERI*, 2001]. This belt includes the 1819 Rann of Kachchh or Allah Bund earthquake, estimated to have been of similar magnitude [*Bilham*, 1998; *Bendick et al.*, 2001]. The region is underlain by the Kachchh rift oriented approximately east-west and extending offshore to the west, and abutted at its eastern end by the Cambay rift, oriented roughly north-south. These rifts are thought to have formed in Precambrian time and reactivated beginning in early to late Jurassic time [*Biswas*, 1982; *Kolla and Coumes*, 1990].

Because the earthquake occurred about 400 km east of the nominal boundary between the Indian and Eurasian plates, and within a fossil rift system, it has been interpreted as a continental intraplate earthquake with analogies to the largest earthquakes in the New Madrid (central U.S.) seismic zone [*Abrams*, 2001; *Beavers*, 2001; *Bendick et al.*, 2001; *Ellis et al.*, 2001]. However, as summarized below, we consider it more useful to view the earthquake as part of the Indian plate's diffuse western boundary zone. This view is based on three lines of evidence: the nature of diffuse boundaries on other plates, the extent of diffuse boundaries elsewhere on the Indian plate, and the distribution of seismicity and faulting on India's western boundary.

In general, continental plate boundary zones are broad. They cover about 15% of the earth's surface [*Gordon and Stein*, 1992], and are especially noticeable at each of the Indian plate's boundaries (Figure 1). Although the precise role of the Bhuj area fold belt in the boundary zone has yet to be established, and boundary zones differ in their kinematics, both the distances involved and the earthquake magnitudes are consistent with other diffuse plate boundaries. Zone widths of 300-1000 km, and earthquakes with M > 7 are common. Examples include the other boundaries of the Indian plate, the Zagros (Arabia-Eurasia) collision zone [*Ni and Barazangi*, 1986], and others discussed in this volume.

Figure 3 shows a comparison at the same scale of part of the Indian and North American plates. The seismicity indicates the broad boundary zone between the Pacific and North American plates. This zone of earthquakes, faulting, and high topography extends as far east as Utah, approximately 1000 km from the nominal plate boundary along the San Andreas fault. Space geodetic data [*Bennett et al.*, 1999, and this volume] show that although most (about 75%) of the approximately 50 mm/yr motion between Pacific and North American plates occurs on the San Andreas system, the rest is spread over the broad boundary zone.

The remaining 25% of the motion between the Pacific and North American plates gives rise to large earthquakes at considerable distances from the San Andreas fault. Thus

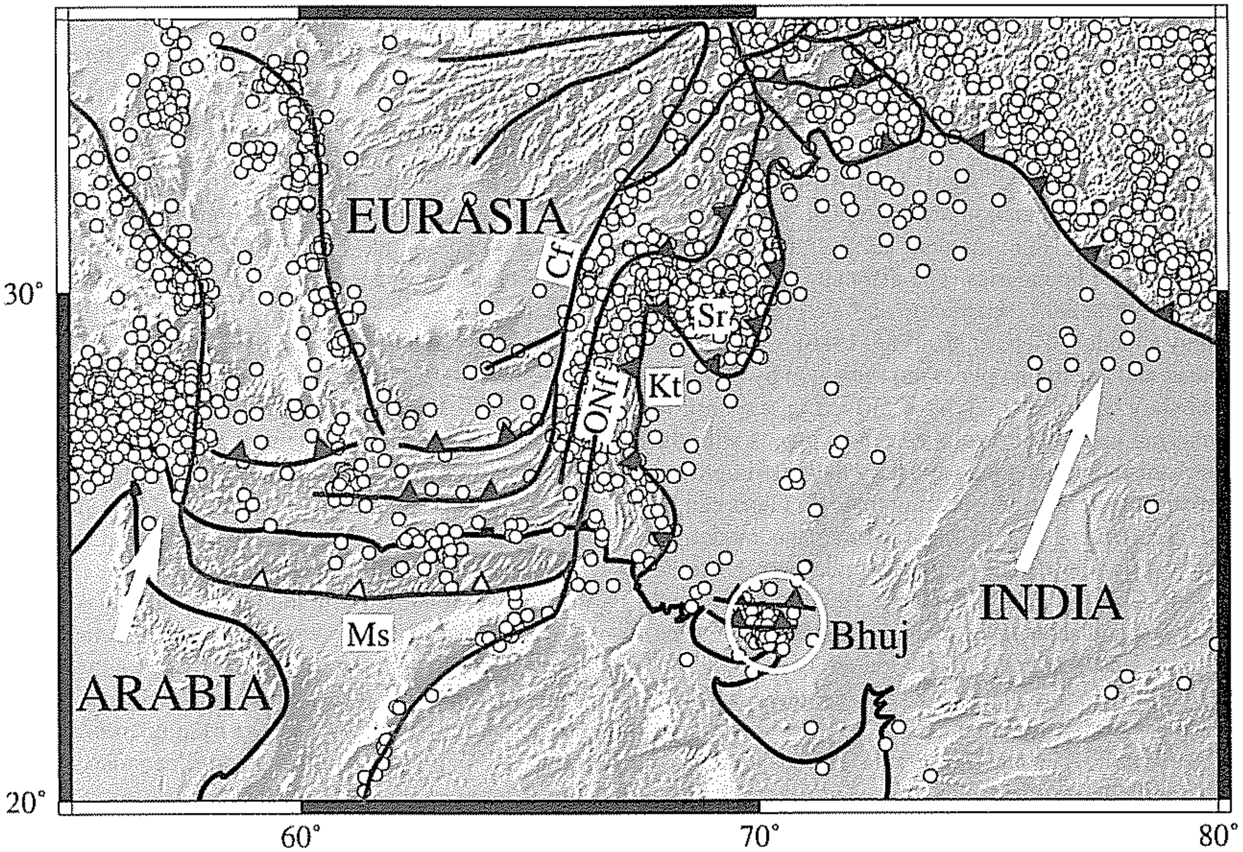

Figure 2. Seismicity (dots) and schematic tectonics of the India - Arabia - Eurasia triple junction region, showing the diffuse plate boundary zone. Circle denotes 2001 Bhuj earthquake. ONf and Cf denote the Ornach-Nal and Chaman faults. Kt is the Kirthar thrust belt, Ms is Makran subduction zone, and Sr indicates Sulaiman range. White arrows correspond to space geodetic estimates of Arabian and Indian plate motion with respect to Eurasia [Sella et al., 2002].

major seismicity occurs at distances from the San Andreas comparable to that of the Bhuj earthquake from the nominal plate boundary. For example, the 2-3 mm/yr of deformation observed geodetically across the Dixie Valley fault [*Thatcher et al.*, 1999; *Wernicke et al.*, 2000], about 400 km inland from the San Andreas, yields earthquakes such as the 1915 Pleasant Valley (M_{PAS} = 7 3/4), 1954 Fairview Peak (M_{PAS} = 7.2), and Dixie Valley (M_s = 6.8) earthquakes [*Yeats et al.*, 1997]. The comparable Wasatch fault motion, about 1000 km from the San Andreas, appears to have caused earthquakes of similar size [*Swan et al.*, 1980].

Hence the location and magnitude of the Bhuj earthquake within the diffuse seismicity of the Indian plate's western boundary are consistent with what is seen at other plate boundary zones. In western U.S. terms, this location corresponds to Nevada, clearly within the deforming plate boundary zone, where the earthquakes reflect the kinematics and dynamics of the boundary zone [*Flesch et al.*, 2000]. In contrast, the New Madrid seismicity is about 2400 km from the San Andreas fault, the nominal boundary, with no obvious relation to the Pacific-North America boundary zone. These earthquakes instead appear to be intraplate earthquakes due to small motions within the plate interior [*Newman et al.*, 1999], presumably because plate-wide stresses [*Zoback and Zoback*, 1981; *Grana and Richardson*, 1996] cause motion on fossil faults. In our view, the two situations have no obvious tectonic similarity. Although the Bhuj earthquake can be used to study strong ground motions within the Indian continent, which may have some analogies to those expected in a large New Madrid earthquake, this would also be the case for any large earthquakes bordering a continental region, including large thrust earthquakes due to India - Eurasia convergence on the Himalayan front.

IS THERE A SIND MICROPLATE?

We interpret the Bhuj earthquake's thrust mechanism and its location within a previously recognized band of seismic-

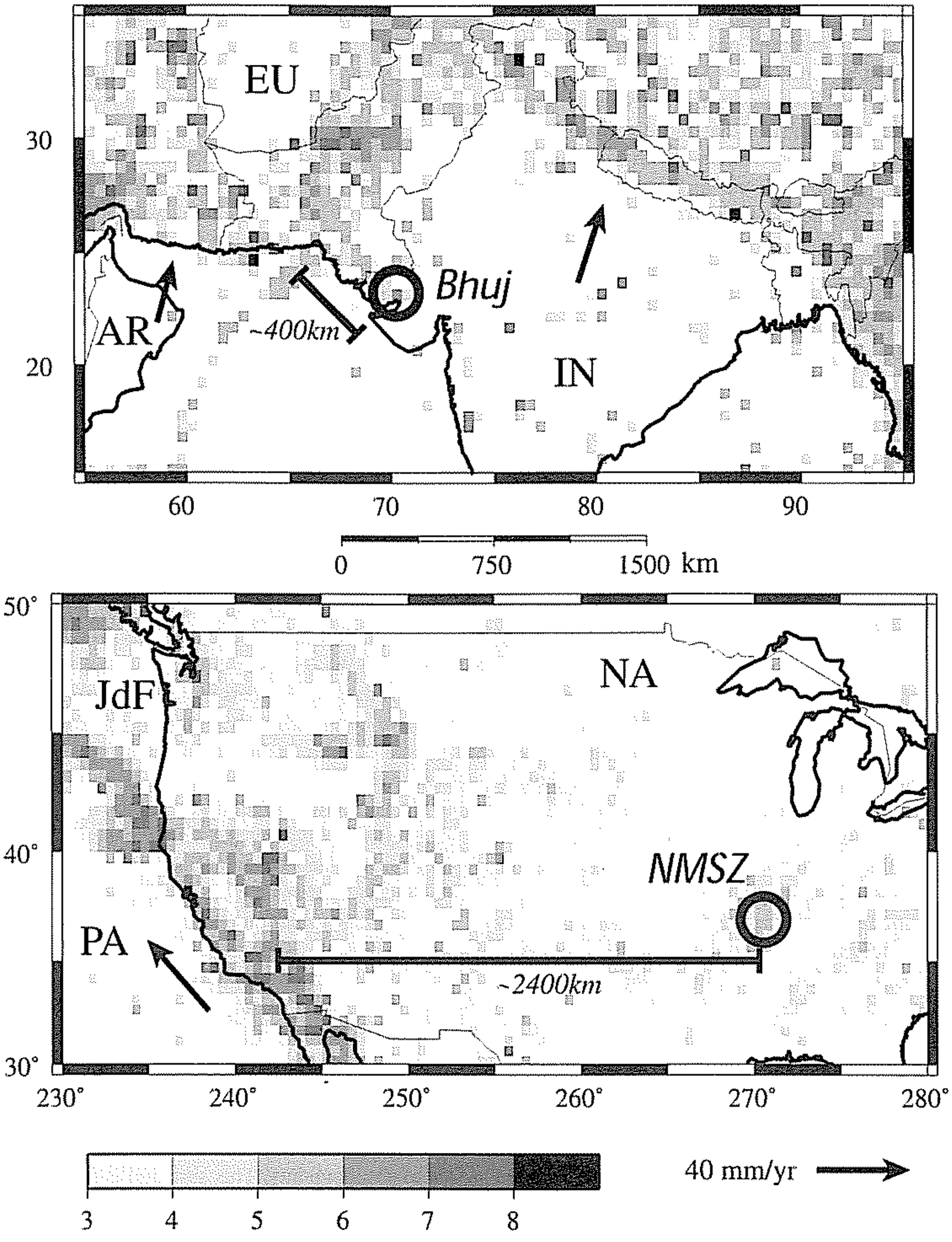

Figure 3. Earthquake magnitude release (1900-1999) for part of Indian plate and surroundings (*top*) and the western U.S. (*bottom*), plotted at same spatial scale. In each pixel, cumulative seismicity is estimated by summing the moment release inferred from published magnitudes, re-interpreting its sum as the magnitude of a single event, and shaded as shown by the horizontal bar. The Bhuj earthquake is about 400 km from the nominal boundary, a distance which in U.S. terms is about halfway across the boundary zone between the Pacific and North American plates, in the central Nevada seismic belt where magnitude 7 earthquakes occur. In contrast, the New Madrid seismic zone (NMSZ) is about 2400 km from the nominal boundary.

ity and active faulting as implying that the Indian plate's western boundary zone extends somewhat farther east than previously proposed by Gordon and Stein [1992]. This does not represent a major change in the previously drawn boundary zone geometry, given that those diffuse boundaries were recognized as approximate. With hindsight, the 1819 earthquake and the fold and thrust belt might have indicated the wider boundary, which the 2001 earthquake highlights.

Although we consider the case for treating the Bhuj earthquake as part of the plate boundary zone to be strong, based on the evidence outlined, proving (or disproving) this hypothesis is not yet possible. We believe this issue could be resolved by high-precision space geodetic data. It is worth bearing in mind that although the concept of western North America as a wide boundary between rigid Pacific and North American plates was advocated by *Atwater* [1970] following pre-plate tectonic concepts of *Carey* [1958], *Wise* [1963], and *Hamilton and Myers* [1966], space geodetic data [*Clark et al.*, 1987] were required to establish that the difference between the ~36 mm/yr motion on the San Andreas inferred for the past several thousands of years [*Prescott et al.*, 1981; *Sieh and Jahns*, 1984] and the 3-Ma average Pacific-North America plate motion of ~48 mm/yr [*DeMets et al.*, 1987] reflected a broad boundary zone rather than a difference between short- and long-term rates of motion. Subsequently, space geodetic data became available with sufficient site density and precision to illustrate the distribution of motion within the diffuse boundary.

Absent such data, we can only speculate on the precise relation of the Bhuj earthquake to the kinematics of the Indian plate's western boundary zone. Plate boundary zones are sometimes modeled as broad diffuse zones of continuously distributed deformation, and in other cases as containing distinct microplates. With the data available, a continuous model would be the simplest, but we think there are also reasons for going into more detail and considering a model in which much of the boundary zone acts as a microplate. Figure 4 shows a possible microplate model consistent with the faulting, seismicity, and motions of the three major plates (India, Eurasia, and Arabia) in the area. In the model, we hypothesize that in the triple junction region, a Sind microplate or block has broken, or is breaking, off from the Indian plate. (We use the name "Sind" because although the Bhuj earthquake occurred within the Indian state of Gujarat, most of the block is within the Pakistani province of Sind. The region is famed for General Sir Charles Napier's reported telegram "peccavi" - "I have sinned" - to the British Foreign Office in 1843 announcing its conquest, though other accounts attribute this pun to a cartoon criticizing the invasion.) We suggest this geometry based on the distribution of seismicity, which suggests the presence of a comparatively rigid and thus less seismically active block bordered by the Bhuj fold and thrust belt to the south and the Sulaiman range [*Bernard et al.*, 2000] to the north. The location of the southern boundary may be influenced by the presence of the fossil rifts, as is often the case [*Burke and Dewey*, 1973]. The nominal western boundary is drawn as the Ornach-Nal fault but the actual boundary presumably is a zone extending eastward of the Kirthar fold and thrust belt. The eastern boundary is more problematic; in the absence of a structural feature we presume it to extend northward from the eastern end of the Bhuj fold and thrust belt, through the scattered seismicity, to the Sulaiman range. If this block exists, its origin may reflect resistance from the collision at the Sulaiman range.

Figure 4 also shows possible kinematics of the proposed Sind block. A few mm/yr of motion relative to India along its southern boundary, causing N-S compression, would yield the observed zone of seismicity and active faulting. The northern boundary with Eurasia would have the observed thrust motion along the Sulaiman range. On the west we expect strike-slip motion along the Ornach-Nal fault, consistent with the observed strike-slip focal mechanisms, and we regard the thrust events along the Kirthar fold belt as a secondary complexity. Its eastern boundary would have thrust and strike-slip motion relative to India. Thus the southern and eastern boundaries would take up 5-10% of the net convergence between India and Eurasia. If this were so, an obvious question is why the southern boundary is more active seismically and better defined structurally than the eastern boundary. Perhaps the block has started forming recently via eastward propagation of the fold and thrust belt, so the eastern boundary is not fully formed. As discussed shortly, microplates elsewhere have rapidly evolving boundaries.

Although this microplate model is derived from kinematic considerations of plate motion, it is dynamically plausible. *Li et al.'s* [this volume] modeling shows that the plate boundary forces would concentrate stress and seismicity if the fossil rifts were weaker than their surroundings, a situation which in our view would provide the microplate's southern boundary. This situation is reminiscent of the way *Cloetingh and Wortel's* [1985] model of a single Indo-Australian plate predicted high stresses within the region later recognized to be the diffuse southern boundary of the Indian plate, and stress orientations consistent with the soon-recognized directions of plate motion there [*Wiens et al.*, 1986].

Our interest in exploring such a microplate model derives in large part from the fact that microplates are common fea-

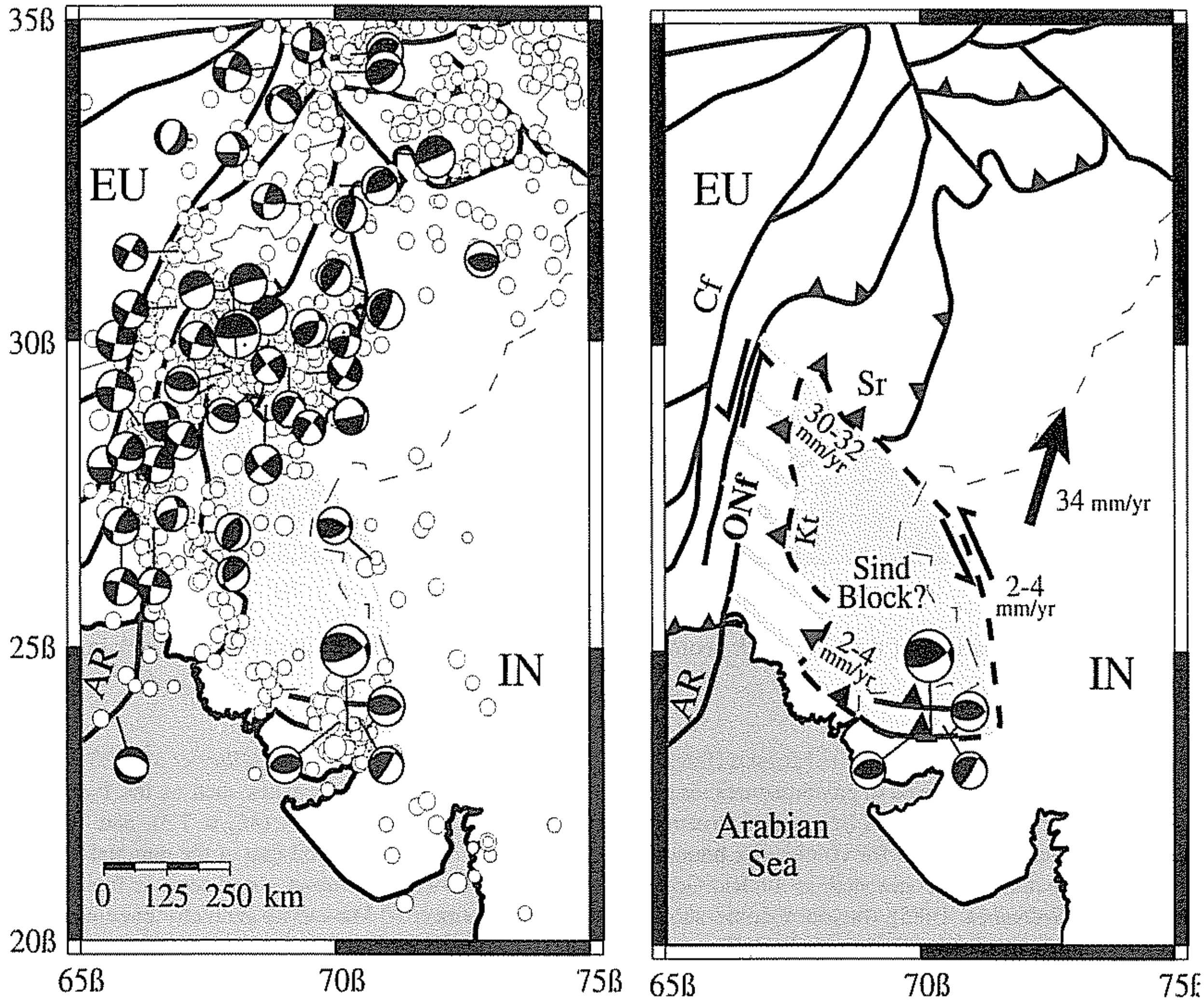

Figure 4. Left: Seismicity and focal mechanisms (1976-2001) from Harvard CMT project for the region of the Bhuj earthquake Light grey region shows the proposed Sind block Right: Schematic relative motions and boundaries of the proposed Sind block Thick black arrows correspond to space geodetic estimates of Arabian and Indian plate motion with respect to Eurasia [Sella et al , 2002]

tures of evolving plate boundaries, especially near triple junctions. In these cases, the boundary zones between the major plates contain smaller regions that move relative to the surrounding plates while sustaining little internal deformation. These regions can thus be modeled as rigid blocks or microplates, whose motions are described by rotations about Euler poles in keeping with rigid plate tectonics. Such models have been applied to the East Pacific Rise near Easter Island [*Engeln and Stein*, 1984; *Engeln et al.*, 1988; *Naar and Hey*, 1989]. In this region the ridge axis is evolving by transferring motion from one ridge segment to a propagating parallel one, so the propagating ridge tip is connected to the dying ridge by a propagating transform, leaving a discrete microplate between the two ridges. A similar transfer of spreading has generated the Juan Fernandez microplate at the Pacific - Nazca - Antarctic triple junction, so a succession of microplates cause the triple junction to evolve northward [*Anderson-Fontana et al.*, 1986; *Bird et al.*, 1998]. The Mesozoic magnetic anomaly record also indicates fossil microplate systems including ones along the East Pacific Rise [*Mammerickx et al.*, 1988] and at the Pacific - Farallon - Phoenix triple junction [*Tamaki and Larson*, 1988].

Microplate models have also been applied for continental plate boundaries, such as for the evolution of the Afar block at the Nubia - Somalia - Arabia triple junction [*Acton et al.*, 1991]. Without the benefit of marine magnetic anomalies, the boundaries between continental blocks are more difficult

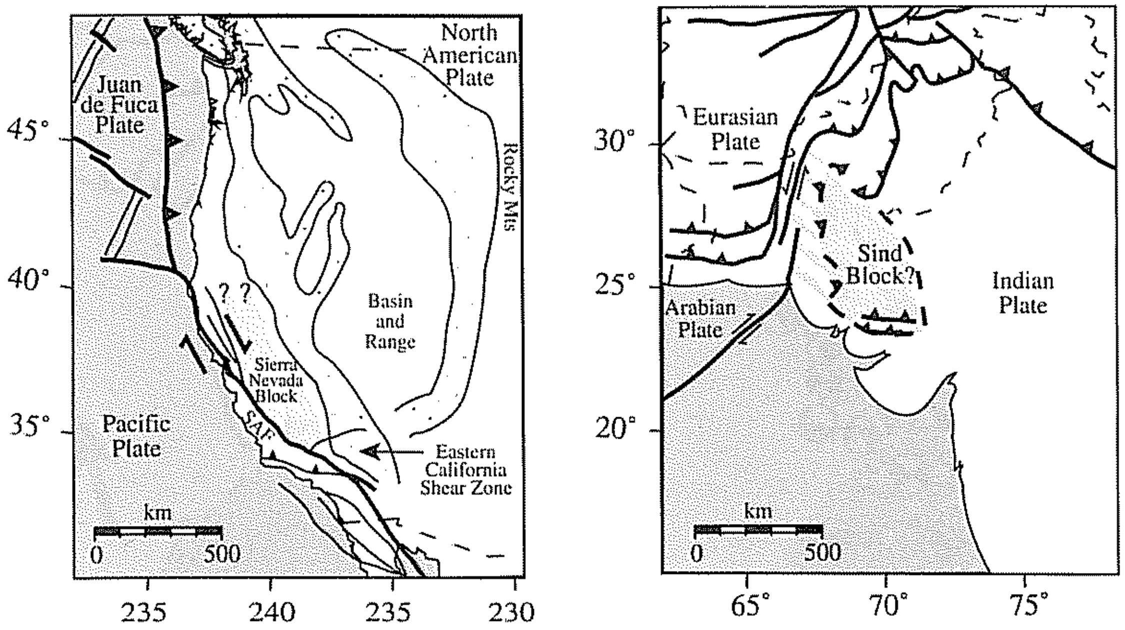

Figure 5. Comparison of the Sind block geometry proposed here to that of the Sierra Nevada block in the western U.S.

to identify, but blocks have been identified from differential rotations and translations observed in paleomagnetic or geodetic data, and block boundaries can be mapped structurally. Block models have been used for continental boundary regions including extensional zones such as the Rio Grande Rift [*Brown and Golombek*, 1985], transform zones such as the Dead Sea transform zone or the San Andreas [*Garfunkel and Ron*, 1985], and collision zones like Tibet [*Achache et al.*, 1984].

As we have noted, the boundary zone between the Pacific and North American plates may have some analogies with the western boundary of the Indian plate. An intriguing feature of the Pacific - North America boundary zone is that within the broad zone there appears to be a Sierra Nevada block, a relatively rigid microplate east of the San Andreas fault system, which forms the nominal plate boundary (Figure 5) [*Wright*, 1976]. The boundary zone between the Sierra Nevada block and the extensional Basin and Range province to the east is formed by a set of faults known as the "Eastern California shear zone." (This name, originally used for the faults in the Mojave desert, is now often used to include the related faults extending northward, including those giving rise to the central Nevada seismic zone.) Geologic and geodetic data show that much of the strike-slip plate motion not observed along the San Andreas, approximately 25% of the total, is taken up within this fault zone [*Wallace*, 1984; *Sauber et al.*, 1986, 1994; *Dokka and Travis*, 1990; *Argus and Gordon*, 1991; *Hearn and Humphreys*, 1998; *Miller et al.*, 2001]. Hence, as noted earlier, large earthquakes such as the Fairview Peak, Dixie Valley, 1992 Landers (M_w = 7.3), and 1999 Hector Mine (M_w = 7.1) occur well east of the nominal plate boundary. The eastern California shear zone is thought to have formed about 6-10 Ma and its geometry continues to evolve [*Dokka and Travis*, 1990].

The Sierra Nevada block has obvious differences from the proposed Sind block, in that on a large scale it results from overall strike-slip between two major plates rather than a combination of convergence and strike-slip between three. However, it illustrates that a rigid block can evolve within a broad continental boundary zone and give rise to seismicity and faulting far from the nominal boundary. The possible analogy with the western U.S. also indicates that the kinematics of complicated boundary zones can be understood given extensive studies with adequate geological, seismological, and geodetic data. Hence although the present data are inadequate to resolve the tectonics of the Indian plate's western boundary and the relationship of the Bhuj earthquake to it, this situation should improve within a few years, given the attention drawn by the earthquake.

INTERPLATE VERSUS INTRAPLATE

This discussion bears out the point that whether to regard an earthquake as "interplate" or "intraplate" depends in part on the definitions we choose for "plates" and "plate boundaries". Various choices are possible because although faults, earthquakes, volcanoes, and topography are real, we associate them with the boundaries of plates that are human approximations. Hence the questions of when to regard a region as a plate and how to characterize its boundaries are not simple. Since the advent of plate tectonic theory our thinking has evolved from viewing plates as rigid and divided by narrow boundaries to accepting that plates can deform internally and are often separated by broad boundary zones.

Because the concepts of plates and plate boundaries are kinematic, kinematic data provide rigorous means of examining them. As noted earlier, we regard India and Australia as distinct plates and the earthquakes between them as plate boundary earthquakes, rather than as intraplate earthquakes within a single Indo-Australian plate. This view is based on the fact that models with two or three distinct rigid plates fit the observed rates and directions of plate motion recorded by magnetic anomalies and transform fault azimuths better [*Wiens et al.*, 1985; 1986, *Royer and Gordon*, 1997; *Conder and Forsyth*, 2001] than would be expected purely by chance due to the additional free parameters [*Stein and Gordon*, 1984].

Conversely, we can examine the rigidity of a plate by using space-based geodesy to find the motions of sites within it, and comparing these motions to those predicted assuming that the plate is rigid and so can be described by a single Euler vector [*Dixon et al.*, 1996; *Sella et al.*, 2002]. Such an analysis using GPS data shows that eastern North America is rigid to 1 mm/yr or better [*Newman et al.*, 1999], and similar values are obtained using data from very long baseline radio interferometry [*Argus and Gordon*, 1996]. Hence the New Madrid earthquakes can be regarded as intraplate in the sense that modeling the site velocities using separate blocks east and west of the New Madrid zone does not significantly improve the fit to the data.

Similar approaches help in deciding whether to regard earthquakes or site motions as being within a plate boundary zone. Beyond seeing whether a site or earthquake is within the boundary zone shown by seismicity or other deformation, we can ask whether the motion shown by geodesy, an earthquake, or other evidence is related in a coherent way to the motion of the major plates. One approach is to identify systematic misfits to plate motion data along a boundary and use the misfits to infer the motion of a microplate between the major plates [e.g., *DeMets et al.*, 1990; *DeMets and Stein*, 1990; *McCaffrey*, 1992; *Seno et al.*, 1996]. Another approach is to develop a smoothed velocity field from the different data, as was done for the western U.S. [*Shen-Tu et al.*, 1998; *Flesch et al.*, 2000] and the Indian plate's boundaries [*Holt et al.*, 2000], and assume that sites whose motions are well fit can be viewed as due to distributed deformation within the boundary zone. Thus although the Bhuj earthquake is outside the region used in *Bernard et al.'s* [2000] velocity field, the fact that the direction of slip is similar to that predicted by the velocity field favors the earthquake being within the boundary zone.

This last point bears out what we see as the major distinction between regarding earthquakes or other deformation as "interplate" or "intraplate". If an earthquake is on a plate boundary or within a boundary zone, we can use plate kinematics to describe the motion in it and relate it to the motions of the major plates involved. For example, site motions can be used to test whether a region can be usefully regarded as a microplate and the motions on a boundary of a microplate can be predicted from the major plate motions and the motion on the microplate's other boundaries [e.g., *Engeln et al.*, 1988; *Dixon et al.*, 2000]. Conversely, if an earthquake is far from what we believe to be the nearest plate boundaries, and the motion in it seems unrelated to the major plates' motions, then we regard the earthquake as intraplate. In the latter case we can say little about the motion, because rigid plate tectonics tells nothing about intraplate earthquakes beyond that they should not occur. We are thus left with the challenge of relating the motion to the poorly understood rheology and stresses within the plate. Hence our view is that earthquakes like the Bhuj earthquake that appear to be within the boundary deformation zone between major plates and have motion that seems directly related to the major plates' motion are more usefully regarded as interplate than intraplate.

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