Intraplate neotectonics in India

The study of intraplate earthquakes is hampered by a great many problems, not all of which are of nature's doing. Granted that there is a very real difference between the seismic map of (say) the Himalayas and the Rann of Kutch, some of the difference is documentary rather than seismological, that is to say an artifact of the brevity of the instrumental and historical records. Put another way, a plate boundary characterized by recurrence intervals exceeding 2000 years could conceivably appear historically aseismic and thus remain ill-defined. We think that we now know enough about plate boundaries to identify them from morphological and structural clues, on other planets as well as on the earth, but without the benefit of seismology the vitality of such candidate boundaries is uncertain.

The interface between the Juan de Fuca and North America plates on the Cascadia coast is instructive. The plate boundary was of course long known, but it took the identification of a series of palaeotsunamis by Atwater[1] to reveal a ~ 600-year recurrence cycle of $M_w > 8$ earthquakes on the subduction fault. Geodetic techniques later showed that the boundary fault between the two plates and downdip of the seismogenic part of the fault had slipped aseismically by about 2 cm over a fault surface measuring 50 km × 300 km and equivalent to an earthquake of $M_w = 6.7$ (ref. 2). This was especially interesting to seismologists as an example of discontinuous movement in the plastic portion of the plate interface and as a possible example of the kind of slip event thought to have propagated updip to trigger the 1960 $M_w = 9.5$ Chilean and other great subduction earthquakes. In the present context the report nicely illustrates the elusive nature of some major geological structures. For, without the continuous monitoring of 14 permanent GPS stations, the movement was unlikely to emerge, especially as it amounted to a temporary and localized reversal of the long-term trend due to plate convergence and would thus have been swallowed up in the average rates yielded by pre-satellite geodesy.

The division of plates into subunits is likewise an arbitrary matter contingent on the assessment of both past and current events. The boundary between the Zagros and the Makran of southern Iran is a N–S lineament, sometimes termed the Zendan Fault, which is generally viewed as the contact between continental and marine sections of the northern, subducted extension of the Arabian plate[3]. Yet, despite the lack of seismicity, there is very good reason for viewing it as a (dextral) transform, the nothern extension of the Oman Line of earlier workers[4]. The structure was already in operation when the Zagros folds came into existence[5], and it has experienced at least 3.5 m of possibly transpressive and probably coseismic reverse slip over a distance of 15 km during the Holocene[6].

In contrast it is seismic data that provide the motivation for subdividing the Indo-Australia plate into three units[7]. The need arose from difficulties in fitting data along the three mid-oceanic ridge systems which meet at the Rodrigues triple junction. A division along the Ninetyeast Ridge, which displays a high level of seismic moment release, some of it in earthquakes of M 6 or 7, was not sufficient, and a further schism leading to the identification of the Capricorn plate was required.

The proposed boundaries between this and the redefined Indian and Australian plates are diffuse and very extensive. Two questions immediately come to mind, one whether a longer seismic sequence would call for further plate rearrangements and additional subdivisions, and two, how far the novel plate map invalidates the tenet that, whereas continental plate boundaries are sometimes hundreds of kilometres broad, those in oceanic crust are as crisp and narrow as in the original, idealized formulation of plate tectonic theory.

The answer to both questions, as often, depends on the aims of the enquiry. For understanding the gross tectonic map of the Indo-Pacific realm, a unitary Indo-Australian plate (or composite plate in the terminology of Royer and Gordon[7]) works well, with the central dogma of plate rigidity still intact within the plate heartlands. Anyone engaged in seismology, however, and especially in the evaluation of hazard, has to accept a messier map which is constantly subject to revision in the light of new instrumental data and improvements in neotectonic assessment.

In NE Brazil, seismology led and neotectonics followed. Radiocarbon dating of shoreline deposits suggested that there had been coastal uplift at rates that differed in adjoining segments; inland there was evidence for substantial normal faulting in the Holocene, and channel patterns hinted at active fault control. But it is a region safely distant from the Mid-Atlantic ridge, and the Holocene record might have been dismissed as spurious had not a swarm of earthquakes of $M \geq 5$ at Joao Camara clearly shown, by their linear arrangement, that structures in the basement were on the move. In due course, ^{14}C dating of trapped charcoal showed that faults in granite had been reactivated ~ 4700 years ago, and Holocene seismites were found indicative of events measuring $M = 6$ or above[8].

Royer and Gordon[7] draw attention to many earthquakes of $M > 5.5$ outside their plate boundary zones, including the reverse event of 1993 in the interior of the Indian subcontinent. Any newcomer to the geodynamics of India is conditioned by repeated mention of the indenter model of orogenesis to consider the peninsula (like NE Brazil) a classic cold, thick, rigid continental slab, and thus to share in the surprise with which many greeted the Killari (Latur) earthquake of 30 September 1993 ($M_w = 6.1$), the Jabalpur earthquake of 21 May 1997 ($M_w = 5.8$; ref. 9) and the Kutch (Bhuj) event of 26 January 2001 ($M_w = 6.1$).

The last was especially perplexing in the light of recent geodetic data showing < 0.003 microstrain/year deformation between Bangalore and Kathmandu during 1991–1994 (ref. 10). The Killari earthquake falls within the measurement period (as does the 1988 Udaypur earthquake in Nepal), which is taken[10] to show that the two events had a negligible effect on continent-wide deformation. But one could invert the argument and conclude that measurements of regional deformation will not readily identify areas of anomalous strain: the absence of significant deformation in the southern peninsula since 1869 places a lower limit of 10,000 years for the renewal time of earthquakes, where shear failure requires strain of ~ 100 μrad (ref. 10). In any case, strain accumulation may be occurring along a series of buckles which have been missed by geodetic survey lines.

Does the earthquake record fare better than the available geodetic evidence as a guide to seismic potential? The Anjar earthquake of 21 July 1956 ($M_w = 6.0$) occurred close to the great Kutch earthquake of 1819 (estimated $M_w = 7.8$) and has been interpreted as a reverse fault event with an estimated stress drop of 162 bar (ref. 11). The Allahbund that formed in 1819 is thought to be a fault-related fold rather than a surface rutpure[12]. The 1997 Jabalpur earthquake had a predominantly thrust mechanism on a fault striking N80°E (ref. 13). The Mt Abu earthquake of 24 October 1969 ($m_b = 5.3$), 300 km NE of Anjar, and the Broach earthquake of 23 March 1970 ($M_w = 5.4$), 300 km SE of Anjar, were also reverse fault events on thrusts running N68°E and ~ E–W, respectively and plausibly interpreted as reactivated extensional structures[11].

The 1993 Latur earthquake reflects pure reverse faulting on a fault striking NW–SE (ref. 14). Many authors would place it within an ancient rift, and its location exposes it to strain rates which are distorted by proximity to a plate boundary, but these factors do not invalidate the proposition that the current tectonic regime promotes stress concentration within narrow zones.

The above amounts to saying that, within the Indian plate (and perhaps other such regions) an alternative approach to conventional seismic zoning is to focus on the boundaries *between* the zones. The data compiled by Bhatia *et al.*[15] are broadly consistent with the buckling axes proposed, here as they identify a north-western region which contains the Kutch earthquake of 1819 at 24°N, the Narmada–Son lineament which runs between 21°N in the west and 24°N in the east, a central zone which includes the Latur event (~ 18°N; ref. 14) and its predecessors, and the Western and Eastern Ghats regions, including the Koyna cluster (17°15'N). The boundary that has been proposed[16,17] between the mid-continent and the southern shield stress provinces runs close to the epicentre of the 11 December 1967 ($M = 6.5$) Koyna event.

To this pattern (Figure 1) could be added the E–W zones of uplift recognized by Subrahmanya[18] and by Ramaswamy[19], both at 13°N (II) and at the latitude of Cochin (~ 10°N) (I), the latter perhaps including the area of moderate seismicity reported[20] near the Palghat Gap (~ 11°N). The coastal emergence that has been noted[21] north of 18°15'N may fall in the next zone to the north.

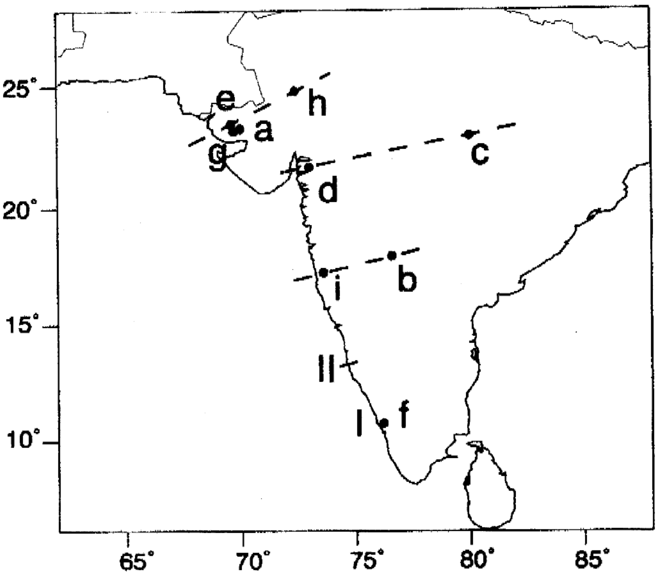

Figure 1. Location of the proposed buckles (dashed lines). Western limit of lineaments proposed by Subrahmanya[18] and Ramaswamy[19] at II and by Ramaswamy[19] at I. Filled circles mark earthquakes: a, Anjar; b, Killari/Latur; c, Jabalpur; d, Broach; e, Kutch; f, Palghat; g, Bhuj; h, Mt Abu; i, Koyna.

The spacing between the proposed compressional belts is close to the wavelength of ~ 200 km proposed by Bendick and Bilham[22]. Any such association does not necessarily imply that only synforms are at issue, as reverse faulting may develop below the neutral surface in thick, flexured units[23], and in any case many major anticlinal structures grade down into reverse faults[24]. There is a hint of a northward reduction in wavelength, which would accord with serial development of the buckles where the deformation front is migrating south in response to Himalayan collision. But it is premature to pursue such subtleties until the validity of the buckling model gains support from some independent source.

One potential avenue is detailed aftershock analysis. Another, is to seek out deformation by satellite altimetry, using radar or laser ranging, along transects crossing the proposed belts. In favoured locations (such as urbanized areas or where bare bedrock predomiantes), radar interferometry could prove productive. At the very least, space geodesy would help to reveal areas where elastic strain is accumulating to dangerous levels and, after any earthquakes during the period of measurement, whether any such strain is released.

The monitoring of present-day deformation needs to be complemented with neotectonic (including palaeoseismic) studies designed to extend the evidence for relatively localized shortening beyond the very brief period spanned by history and instrumental observation. Earthquakes in stable continental regions on pre-existing zones of weakness can still take us by surprise[25], because any associated faults have very small displacements in the current tectonic regime. Again, evidence for an earthquake of similar size to the Killari event, viz. $M_w = 6.1$, about 1500 years ago and 40 km away at Ter, shows that the Killari earthquake 'appears as an event that is isolated in time and space only when viewed through a small time frame'[13]. Neotectonic analysis is essential to kinematic analysis as well as to the identification of earthquake clustering in time and space[26].

The buckle scheme would then provide an interesting alternative to seismic gap and asperity models by showing how elastic strain in a plate, however small in absolute terms, can be focused on narrow sub-parallel strips, only some of which are necessarily occupied by longstanding basement structures. Strain release at any one location does not preclude further such release soon after; indeed, the evidence from Kutch suggests that the contrary can apply. Unless there are existing basement structures, as in the Narmada–Son lineament (Broach and Jabalpur earthquakes[27]) ready to be reactivated by the regional stress field[28], seismicity is likely to be characterized by shallow focal depths.

The potential value of the model for hazard management is obvious: rather than illusory prediction it provides a map showing which of belts of a country are prone to rupture and thus permits preventive engineering and relief preparation to be selective. Whether other plates reflect a similar pattern of strain accumulation and release remains to be seen.

1. Atwater, B. F., *Science*, 1987, **236**, 942–944.
2. Dragert, H., Wang, K. and James, T. S., *Science*, 2001, **292**, 1525–1528.
3. White, R. S. and Klitgord, K. D., *Earth Planet. Sci. Lett.*, 1976, **32**, 199–209.
4. Flacon, N. L., *Adv. Sci.*, 1967, **24**, 31–42.
5. Shearman, D. J., *Geogr. J.*, 1976, **142**, 393–410.
6. Vita-Finzi, C., in *Tectonic and Climatic Evolution of the Arabian Sea Region* (ed. Clift, P. D. *et al.*), Geol. Soc. London (in press).
7. Royer, J.-Y. and Gordon, R. G., *Science*, 1997, **277**, 1268–1274.
8. Bezerra, F. H. and Vita-Finzi, C., *Geology*, 2000, **28**, 591–594.
9. Bhattacharya, S. N., Ghose, A. K., Suresh, G., Baidya, P. R. and Saxena, R. C., *Curr. Sci.*, 1998, **73**, 855–863.
10. Paul, J. *et al.*, *Proc. Indian Acad. Sci. (Earth Planet. Sci.)*, 1995, **104**, 131–146.
11. Chung, W.-Y. and Gao, H., *Tectonophysics* 1995, **242**, 281–292.
12. Rajendran, C. P. and Rajendran, K., *Bull. Seismol. Soc. Am.* (in press).
13. Rajendran, C. P. and Rajendran, K., *Tectonophysics*, 1999, **308**, 67–81.
14. Gupta, H. K., Rastogi, B. K., Mohan, I., Rao, C. V. R. K., Sarma, S. V. S. and Rao, R. U. M., *Tectonophysics*, 1998, **287**, 299–318.
15. Bhatia, S. C., Kumar, M. R. and Gupta, H. K., *Ann. Geofis.*, 1999, **42**, 1153–1161.
16. Gowd, T. N., Rao, S. V. S. and Gaur, V. K., *J. Geophys. Res.*, 1992, **97**, 11879–11888.
17. Singh, R. P., Sato, T. and Nyland, E., *Phys. Earth Planet. Inter.*, 1995, **91**, 245–251.
18. Subrahmanya, K. R., *Tectonophysics*, 1996, **262**, 231–241.
19. Ramaswamy, S., *Geol. Surv. India, Spec. Publ.*, 1989, **24**, 333–339.
20. Rajendran, C. P. and Rajendran, K., *Curr. Sci.*, 1996, **70**, 304–307.
21. Sukhtankar, R. K., *Geol. Surv. India, Spec. Publ.*, 1989, **24**, 319–325.
22. Bendick, R. and Bilham, R., *Geol. Soc. Am., Spec. Pap.*, 1999, **128**, 313–320.
23. Price, N. J. and Cosgrove, J. W., *Analysis of Geological Structures*, Cambridge Univ. Press, Cambridge, 1990.
24. King, G. C. P. and Vita-Finzi, C., *Nature*, 1981, **292**, 22–26.
25. Ramesh, D. S. and Estabrook, C. H., *Proc. Indian Acad. Sci.* (*Earth Planet. Sci.*), 1998, **107**, L225–L233.
26. Rajendran, K. and Rajendran, C. P., *Tectonophysics*, 1999, **305**, 355–370.
27. Jain, M., Woodcock, N. H. and Tandon, S. K., *J. Geol. Soc. London*, 1998, **155**, 897–901.
28. Talwani, P. and Rajendran, K., *Tectonophysics*, 1991, **186**, 19–41.

ACKNOWLEDGEMENTS. I thank Kusala Rajendran for comments on a draft of this paper and K. R. Subrahmanya for valuable discussions.

Received 23 October 2001; revised accepted 6 November 2001

CLAUDIO VITA-FINZI

Department of Mineralogy,
Natural History Museum,
Cromwell Road,
London SW7 5BD
e-mail: cvitafinzi@hotmail.com