24. Crawford, A. J., Falloon, T. J. and Green, D. H., in *Boninites and Related Rocks* (ed. Crawford, A. J.), Unwin Hyman, London, 1989, p. 1.
25. Hatton, C. J. and Sharpe, M. R., see ref. 24, p. 174.
26. Piercey, S. J., Murphy, D. C., Mortensen, J. K. and Paradis, S., *Geology*, 2001, **29**, 731.
27. Smithies, R. H., *Earth Planet. Sci. Lett.*, 2002, **197**, 19.
28. McDonough, W. F., Sun, S-S., Ringwood, A. E., Jagoutz, E. and Hofmann, A. W., *Geochim. Cosmochim. Acta*, 1992, **56**, 1001.
29. Evensen, N. M., Hamilton, P. J. and O'Nion, R. K., *Geochim. Cosmochim. Acta*, 1978, **42**, 1199.

ACKNOWLEDGEMENTS. We thank the Department of Science and Technology, New Delhi for providing research grant for the present work (ESS/CA/A9-40/95). We are grateful to the two anonymous reviewers for their constructive comments which improved the earlier version of this manuscript considerably. R.K.S. also acknowledges CSIR for financial assistance as Senior Research Fellow.

Received 4 January 2003; revised accepted 20 May 2003

Evidence of a Mid–Late Holocene seismic event from Dhadhar river basin, Gujarat alluvial plain, western India

Rachna Raj*, N. Mulchandani, S. Bhandari, D. M. Maurya and L. S. Chamyal

Department of Geology, M. S. University of Baroda, Vadodara 390 002, India

Soft-sediment deformation structures have developed in a major slump at Itola in the Dhadhar river basin of Gujarat alluvial plain. The slump plane parallels the active Dhadhar lineament. Pseudonodules, pinching and folding, convolute folds, concave-up paths, clay diapirs, flamed convolutions and minor faults are the major deformational structures identified. Radiocarbon dating of an associated charcoal layer has given a maximum age of 5570 ± 30 yr BP. The soft-sediment deformation structures conform to the criteria for attributing them to a seismic event during Mid–Late Holocene.

RECOGNITION of past seismic events is important for understanding the seismic phenomena in areas experiencing earthquakes, such as western India. Soft-sediment deformation structures formed during or shortly after deposition of horizontal sedimentary layers in Quaternary geological records are important indicators of past seismic activity[1–5]. We report here soft-sediment deformation structures developed in the sediments of a large slump structure at Itola in the Dhadhar river basin of Gujarat alluvial plain (Figure 1 *a*, *b*).

The geomorphic evolution of Gujarat alluvial plain has primarily been attributed to Holocene tectonic activity based on detailed studies on fluvial geomorphology and the exposed Late Quaternary sequences of the Sabarmati, Mahi and Narmada basins[6]. A recent study of the Dhadhar basin has also indicated that it has evolved as a result of regional phases of tectonic movements during Quaternary[7]. The course of the Dhadhar river which originates in the Aravalli uplands is controlled by ENE–WSW trending Dhadhar lineament in the alluvial plain. The river, before meeting the Gulf of Cambay, exhibits a deeply incised channel and several entrenched meanders all along its course in the Gujarat alluvial plain. Three distinct geomorphic surfaces have been observed in the Dhadhar valley[7] (Figure 1 *b*). The oldest surface is the vast alluvial plain comprising sediments which are comparable to the Late Pleistocene sediments of the neighbouring Mahi and Narmada river basins. The second surface comprises an extensively dissected zone in the vicinity of the river channel which along with the incised cliffs has been attributed to tectonic uplift of the area during Early Holocene[8]. The youngest surface is an uplifted Holocene valley fill terrace. A similar geomorphic set up is reported from the Sabarmati, Narmada and Mahi river basins[6,8], which points towards the geomorphic evolution of Dhadhar valley in response to regional-scale tectonic activity along the subsurface Cambay basin faults.

The exposed sediment succession at Itola forms part of a large slump structure that laterally extends for about 25 m. The slump plane trends in ENE–WSW direction which is parallel to the Dhadhar lineament (Figure 1 *b*). The exposed sediment succession is about 6 m thick and consists of several horizons of sands, silts and clays with thin layers of charcoal (Figure 1 *c*). Soft-sediment deformational features are observed mainly within the silt and clay horizons intercalated with thin layers of terrigenous charcoal. Radiocarbon dating of a charcoal sample from this horizon (Figure 1 *c*) gave an age of 5570 ± 30 yr BP.

The various soft-sediment deformation structures identified include pseudonodules, pinching and folding, minor faulting, contorted structures which include convolute folds, concave-up paths, and intruded structures like clay diapirs, flamed convolutions, isolated flamed structures and sand dykes. The pseudonodules observed are of different morphologies consisting of isolated masses of sands present in the clayey deposits (Figure 2 *a*). The pseudonodules are generally irregular and resemble drop and sag-type structures described by Steward[9]. The formation of sand nodules by shaking effect has been experimentally proved by Kuenen[10], who simulated the deformational behaviour of sand overlying the clay. The formation of sand nodules in the area can be explained in

*For correspondence. (e-mail: naveenrachna@indiatimes.com)

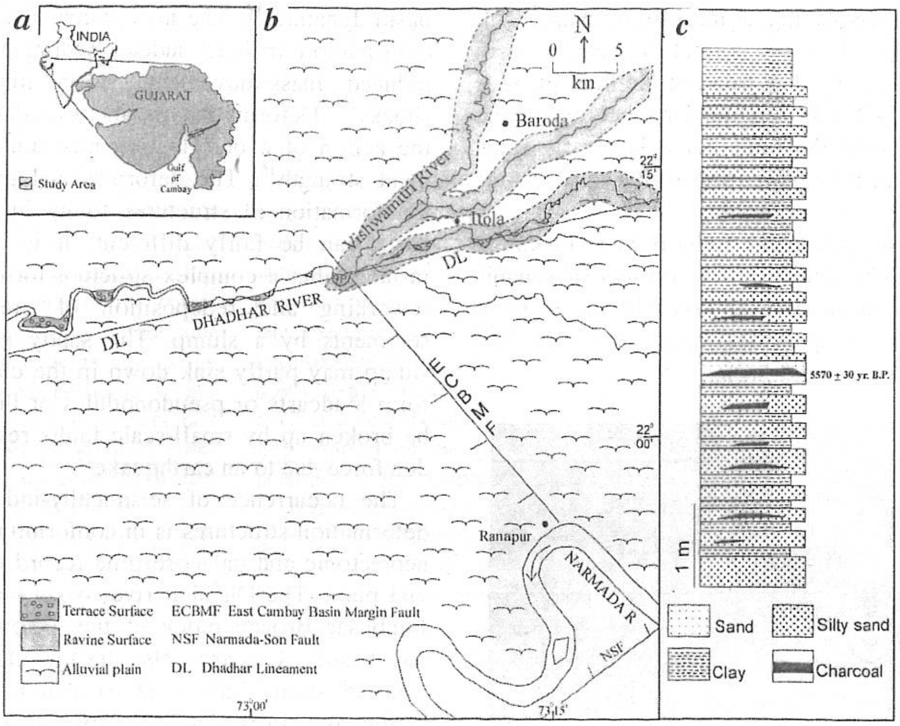

Figure 1. *a*, Location map; *b*, Generalized geomorphic map showing major surfaces and structural features and *c*, Litholog of the Itola terrace section showing position of the dated charcoal.

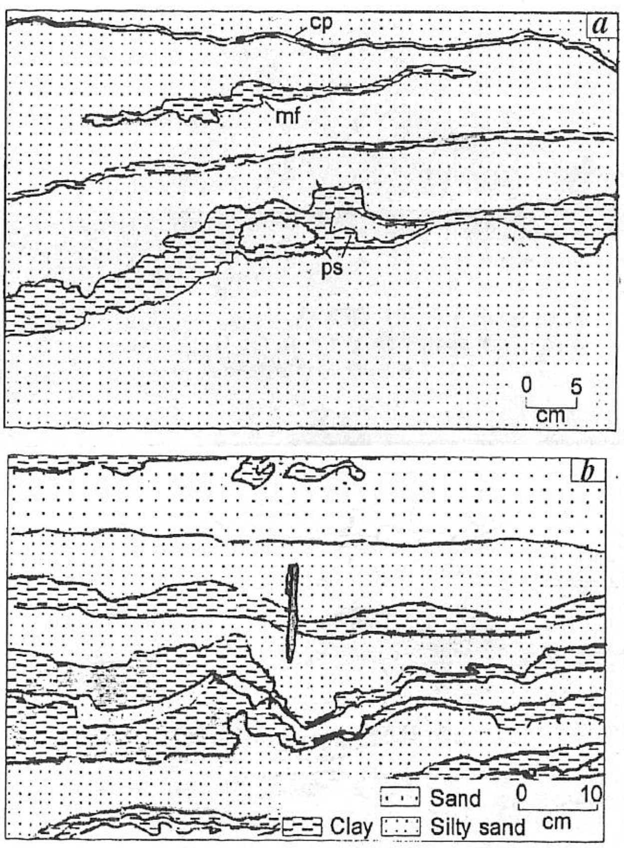

Figure 2. Line drawing over photograph showing *a*, pseudonodule (ps), microflame (mf) and concave-up path (cp) structures and *b*, Pinching and folding developed due to subsidence of the overlying silty sand in clay.

a similar way. The overlying sand has subsided into the clay unit and got enclosed by the clay resulting in detachment of the sand and formation of pseudonodules under the effect of shaking[11]. Pinching and folding have been observed at several places in the alternating clay and silt horizons (Figure 2 *b*), and are formed due to liquefaction causing subsidence in the overlying silt horizons. The horizons showing maximum pinching and folding may have experienced maximum subsidence (Figure 2 *b*).

Convolute folds were found at several places, which are laterally diffused into completely undeformed horizon of similar composition and texture. Such folds have been defined as distorted stratifications that form laterally alternating convex and concave-upward morphology[12]. Concave-upward structures (cp), the laminae of which show the concentration of clays are identified as concave-up paths[12] (Figure 3 *a–c*). These structures (cp) form a series of folded layers that closely follow the concave-up shape of the synclines. The concave-up paths at places are bifurcated (bcp; Figure 3 *b*, *c*) or contorted into small folds (fp; Figure 3 *b*). At places, the boundaries of the paths locally curve up to form microflame structures (mf; Figure 3 *b*, *c*). Chaotically disturbed irregular convolute structures[12] (ic) were also noticed (Figure 3 *b*) with irregular morphology and size. Clay diapirs (dp) have been recognized at places in the deformed horizons, intruding and deforming the overlying silts and sands (Figure 3 *c*). They range in height from 2 to 3 cm and are up to 2 cm in width. Alfaro *et al.*[13] describe such deformational structures as displaying a mushroom shape. Numerous minor faults showing normal movement have been found (Figure 4 *a*, *b*). The trend of the fault plane is parallel to the ENE–WSW trending Dhadhar lineament. Injection of sand along the fault plane is clearly seen. These structures appear to have formed due to a seismic event.

The recognition of earthquake tremors in sedimentary record is tenuous. The detection of imprints of seismic activity in ancient succession, if possible, is of paramount importance as it provides valuable insight into basin dynamics[14]. The main mechanisms of soft-sediment deformation include sudden sediment loading, gravity-induced mass-movement, storm impact and seismic shocks[15]. Deformation in unconsolidated sands requires the action of a deformation mechanism to reduce sediment strength[16]. The deformational process involved in the formation of structures found in the Dhadhar river basin can be fairly different. It is quite possible, for instance that a complex structure formed because of the reworking and redeposition of previously deposited sediments by a slump. The sandy material within the slump may partly sink down in the clayey substratum to form loadcasts or pseudonodules or these structures may be broken up by small-scale faults resulting from a sudden force due to an earthquake[17].

The occurrence of seismically-induced soft-sediment deformation structures is in conformity with the available neotectonic and palaeoseismic record of the Gujarat alluvial plain. The Dhadhar river basin lies very close to the Jambusar–Broach block of the tectonically-active Cambay basin[6]. The area also lies in close vicinity of the Narmada–Son Fault (NSF) which has witnessed major earthquakes in recent times (Broach earthquake of 1970 of magnitude 5.4 and Jabalpur earthquake of 1997 of magnitude 6)[18,19]. Occurrence of earthquakes during his-

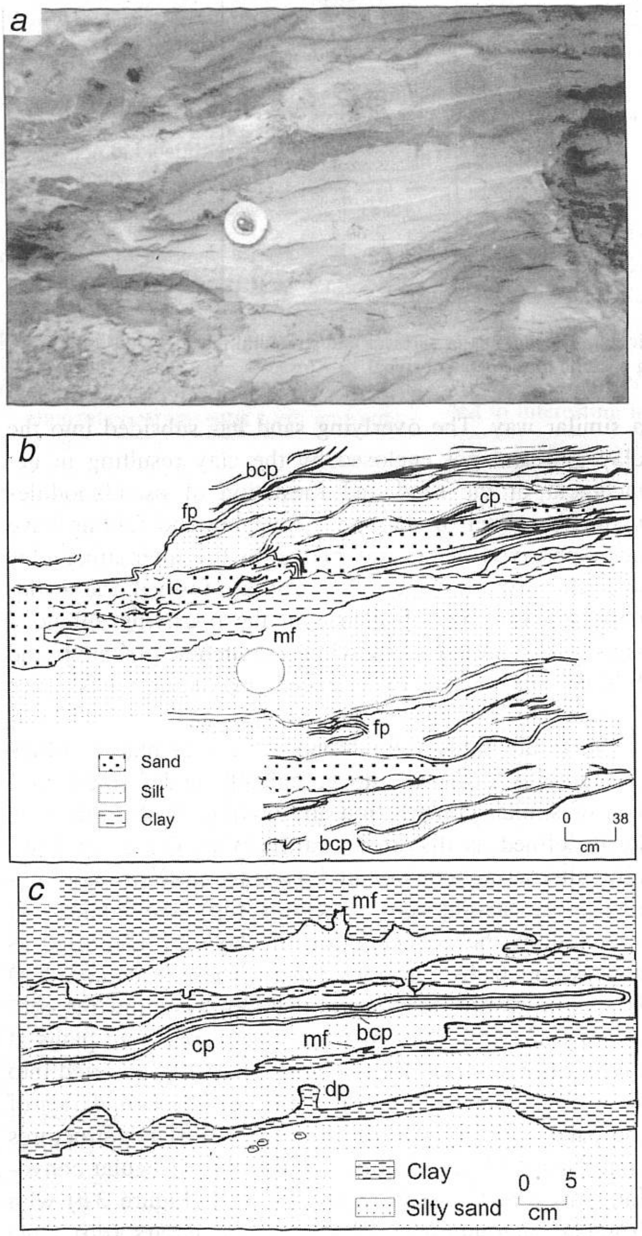

Figure 3. *a*, *b*, Photograph and line drawing showing microflame (mf), folded path (fp), concave-up path (cp), bifurcated concave-up path (bcp) and irregular convolution (ic); *c*, Line drawing over photograph showing diapirs (dp), concave-up path (cp), bifurcated concave-up path (bcp) and microflame (mf).

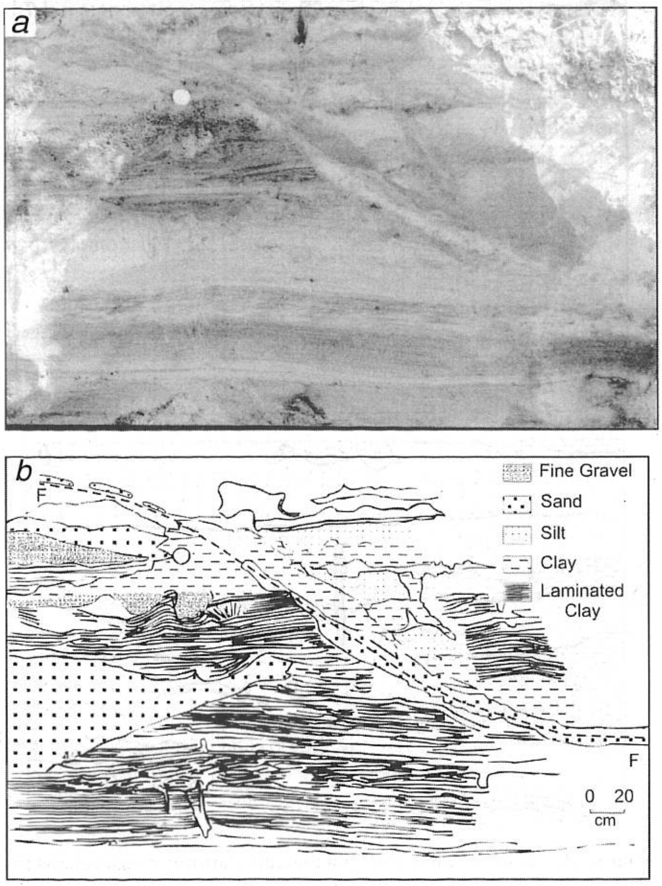

Figure 4. *a* and *b*, Photograph and line drawing showing minor faulting and injection of sand along the fault plane.

torical times is also known from the Gujarat alluvial plains. Two earthquakes in the Jambusar–Broach block of the Cambay basin shook the area in 1821 and 1935 (ref. 18), which suggests continuing instability of the Cambay basin during the recent past as well. Radiocarbon dating of a charcoal sample from the deformed strata has yielded an age of 5570 ± 30 yr BP. The age obtained indicates the time of formation of the sample. Since the sample dated is of terrigenous charcoal deposited along with the surrounding sediments, the seismic event is certainly younger than the obtained date. Younger Mid–Late Holocene seismic events have been reported from the Gujarat alluvial plain[6]. Maurya *et al.*[20] reported soft-sediment deformation structures attributed to a seismic event bracketed between 3300 and 2800 yr BP from the neighbouring Mahi river basin. Further northwest, Rajendran *et al.*[21] have identified an event of ~ 3000 yr BP at Dholka near Ahmedabad. On a preliminary basis, the liquefaction feature reported from Dholka[21] appears to be comparable with the palaeoseismic event reported from the lower Mahi basin[20]. At present there is no direct evidence to link the seismic event seen at Itola with the event reported from the Mahi basin. However, the event delineated in the present study is definitely younger than 5570 ± 30 yr BP. Since no other dated palaeoseismic events are known from the surrounding region, no definite correlation of the event can be attempted.

1. Sim, J. D., Earthquake-induced structures in sediments of Van Norman Lake Fernando, California. *Science*, 1973, **182**, 161–163.
2. Sim, J. D., Determining earthquake recurrence intervals from deformational structures in young lacustrine sediments. *Tectonophysics*, 1975, **29**, 144–152.
3. Allen, C. R., Geological criteria for evaluating seismicity. *J. Geol. Soc. Am. Bull.*, 1975, **86**, 1041–1057.
4. Weaver, J. D., Seismically-induced load structures in the basal coal measures. *Geol. Mag.*, 1976, **113**, 535–543.
5. Sieh, K. E., Prehistoric large earthquakes produced by slip on the San Andreas Fault at Pallet Creek, California. *J. Geophys. Res.*, 1978, **83**, 3907–3939.
6. Maurya, D. M., Rachna Raj and Chamyal, L. S., History of tectonic evolution of Gujarat alluvial plains, western India during Quaternary: A review. *J. Geol. Soc. India*, 2000, **55**, 343–366.
7. Rachna Raj, Fluvial response to Late Quaternary tectonic changes in the Dhadhar River basin, Mainland Gujarat. *J. Geol. Soc. India*, in press.
8. Maurya, D. M., Malik, J. N., Rachna Raj and Chamyal, L. S., The Holocene valley fill terraces in the lower Mahi valley, Gujarat. *Curr. Sci.*, 1997, **73**, 539–542.
9. Steward, A. D., On certain slump structures in the Tortonian sandstones of Apple-Cross. *Geol. Mag.*, 1963, **100**, 205–218.
10. Kuenen, P. H., Experiments in geology. *J. Trans. Geol. Soc. Glasgow*, 1958, **23**, 1–28.
11. Obermeier, S. F., Using liquefaction-induced features for palaeoseismic analysis. in *Palaeoseismology* (ed. McCalpin, J. P.), Academic Press, New York, 1996, pp. 331–396.
12. Rossetti, D. F., Soft-sediment deformation structures in late Albian to Cenomanian deposits, Sao Luis Basin, northern Brazil: evidence for palaeoseismicity. *Sedimentology*, 1999, **46**, 1065–1081.
13. Alfaro, P., Domenech, C., Estenez, A. and Soria, J. M., Estructuras, de defomacion en sedimentos del cuaternario reciente de la cuenca del Bajo Segura (Alicante) Discusion sobre su possible origin sismicro. *J. Geogaceta*, 1995, **17**, 91–94.
14. Rodriguez-Pascua, M. A., Calvo, J. P., Vicente, G. De and Gomez-Gras, D., Soft-sediment deformation structures interpreted as seismites in lacustrine sediments of the Prebetic Zone, SE Spain, and their potential use as indicators of earthquake magnitudes during the Late Miocene. *Sediment. Geol.*, 2000, **135**, 117–135.
15. Rossetti, D. F. and Goes, A. M., Deciphering the sedimentological imprint of paleoseismic events: an example from the Aptian Formation, northern Brazil. *Sediment. Geol.*, 2000, **135**, 137–156.
16. Owen, G., Deformation processes in unconsolidated sands. in *Deformation of Sediments and Sedimentary Rocks* (eds Jones, M. E. and Preston, R. M. F.), Geol. Soc. Spl. Publ., 1987, vol. 29, pp. 11–29.
17. VanLoon, A. J., Soft-sediment deformations in the Kleszczow Graben (Central Poland). *Sediment. Geol.*, 2002, **147**, 57–70.
18. Gupta, H. K., Mohan, I. and Narain, H., The Broach earthquake of 23 March 1970. *Bull. Seismol. Soc. Am.*, 1972, **62**, 47–61.
19. Gupta, H. K., Chadha, R. K., Rao, M. N., Narayna, B. L., Mandal, P., Ravikumar, M. and Kumar, N., The Jabalpur earthquake of 22 May 1997. *J. Geol. Soc. India*, 1997, **50**, 85–91.
20. Maurya, D. M., Rachna Raj and Chamyal, L. S., Seismically-induced deformational structures from mid-late Holocene terraces in lower Mahi valley, Gujarat. *J. Geol. Soc. India*, 1998, **51**, 755–758.
21. Rajendran, K., Rajendran, C. P., Thakkar, M. and Gartia, R. K., Sand blows from the 2001 Bhuj earthquake reveal clues on past seismicity. *Curr. Sci.*, 2002, **83**, 603–610.

ACKNOWLEDGEMENTS. Research grant received from the Department of Science and Technology (Project No. SR/FTP/ES/11-2000) is acknowledged. We thank Birbal Sahni Institute of Palaeobotany, Lucknow for dating the charcoal sample (sample no. BS 2036).

Received 19 December 2002; revised accepted 21 May 2003