The January 26, 2001 Bhuj Earthquake, India[1].

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The Mw7.6 Bhuj earthquake that shook the Indian Province of Gujarat on the morning of January 26, 2001 was the most deadly in India's recorded history (Figure 1). One month after the earthquake official Government of India figures placed the death toll at 19,727 and the number of injured at 166,000. Preliminary indications are that 600,000 people were left homeless, with 348,000 houses destroyed and an additional 844,000 damaged. The Indian State Department estimates that the earthquake affected, directly or indirectly, 15.9 million people, nearly 50% of the population of Gujarat. More than 20,000 cattle were reported killed. Government estimates place direct economic losses at $1.3 billion, although more recent estimates indicate losses may exceed $5 billion.

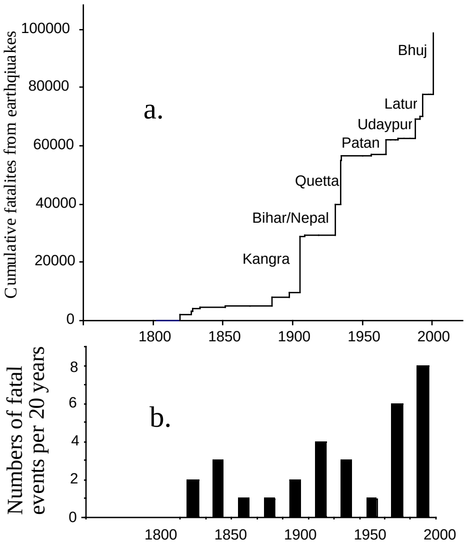

Figure 1 (a) More than 100,000 fatalities from earthquakes have occurred on the Indian Plate in the past two centuries. Prior to 1800 the historical record is incomplete although we know of no event in the past millennium that has claimed as many lives as the Bhuj event (*Bapat et al* 1983; *Iyengar and Sharma*, 1998). Government estimates following the Kangra, 1905 earthquake indicate 19,500 fatalities (*Ambraseys & Bilham*, 2000). The 1737 Calcutta cyclone is mistakenly included in many lists of Indian earthquakes (*Bilham*, 1994). (b) The rate of occurrence of fatal earthquakes in the past two decades is more than double its mean value in the past two centuries.

The Bhuj earthquake occurred on the Kachchh Peninsula (Figure 2), which has a long history of strong earthquakes (*Bapat et al.,*, 1983). The region is bordered to the north and to the south by ancient rift systems (*Biswas*, 1970; 1971; 1987; *Srivastava*, 1971). Structures within these rift systems (*Rajendran and Rajendran*, 1998, 2001) and on the

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Kachchh mainland (*Malik et al*., 2000) are now subjected to compressional stress and reverse faulting resulting from India's collision with Asia (*Gowd*, 1996; *Chandra*, 1977). Compresssional features appear to be of at least two different ages, with folding events occurring prior to 120 Ka and a distinct set of new features activated much more recently (*Rockwell,* personal communication, 2001).

The first historical Kachchh earthquake to attract international attention was the 1819 Allah Bund (Dam-of-God) earthquake, which created a 6-m-high, 6-km-wide natural dam across the Puran or Nara river (which enters the Rann of Kachchh from the north). A lake 30 km in diameter, Lake Sindri, was formed south of the Allah Bund and although this is now partly filled with sediments and evaporites, it remains as a monsoon-filled depression to this day. A lake also formed north of the Bund in 1819 which drained in 1826 when a torrent broke through several artificial dams on the Puran and cut a gorge through the Bund, flooding regions downstream. The geometry of this gorge was investigated briefly by Sir Alexander Burnes whose two accounts (in 1826, 1827) differ in numerical detail. Captain William Baker, a canal engineer of considerable integrity (*Phillimore,* 1968), undertook a precise spirit leveling line across the Bund in 1844, but his important cross-section was mislaid in Bombay in 1846, and not discovered for more than a half century (*Baker*, 1846; *Oldham* 1898). From the details of Baker's leveling line, and the assumption that the measured topography is entirely due to the 1819 earthquake, it is possible to infer 11.5±1 m of reverse slip on a NNE dipping fault that terminated 300-600 m below the surface (*Bilham, 1998*).

Damage to Bhuj and Anjar during the 1819 earthquake was substantial (*McMurdo, 1823; 1839*). Much like those from the 2001 event, damage reports from 1819 describe widespread collapse of structures on the Kachchh mainland, accompanied by substantial liquefaction features in the Rann of Kachchh. Damaging earthquakes also occurred in 1845, 1856, 1857, 1864, 1903, 1927, 1940, 1956 and 1970 in the Kachchh region but with less severity ($5<M<6$) (*Oldham*, 1883, *Bapat et al.*, 1983). The most recent of these are well located (*Tandon, 1956*, *Chung and Gao, 1995*); the others are known only by accounts of local damage. The events of 1845 (mistakenly atributed to 1844 –see *Bilham*, 1998) were felt in Karachi (*Phillimore,* 1968) and are reputed to have generated a tsunami and to have caused changes in channel depth near and north of Lakput on the western edge of the Kachchh Peninsula (*LeGrand-Jacob, 1860*). Accounts describe numerous aftershocks so that these events may have exceeded $M=7$. Events in 1856 and 1857 are known from reports in accounts of the Great Trigonometrical Survey of India (*Phillimore,* 1968; *Bilham & Gaur,* 2000). The 1956 Anjar earthquake killed 152 people.

The mechanism of the 2001 Bhuj earthquake is currently unresolved, although, as in the 1819 and 1897 earthquakes, the event apparently occurred on a steeply-dipping thrust that did not break the surface. An unusual feature of the event is that aftershocks have occurred at considerable depth (20-30 km) suggesting rupture through much of the lithosphere. This appears to have similarities to the great 1897 Assam earthquake that occurred on a deep, steeply south-dipping reverse fault beneath the northern edge of the Shillong Plateau (*Bilham and England*, 2001). Aftershocks appear to favor a south-dipping rupture for the nodal plane of the 2001 mainshock (*Johnston*, personal communication 2001).

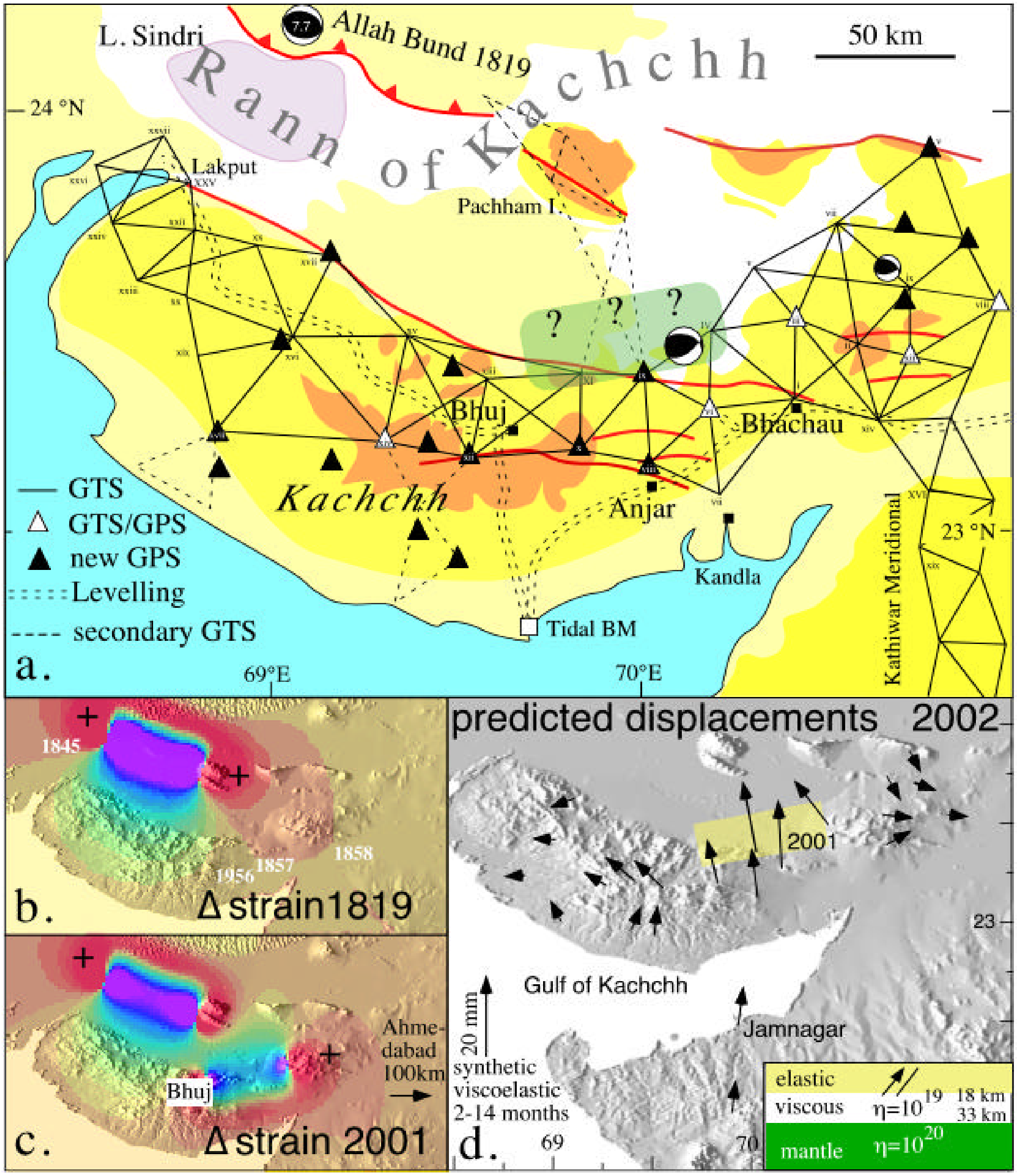

Figure 2a. GTS Geodesy and post-seismic GPS points in the Kachchh region. The inferred rupture is shaded and its area and location may change following processing of the 2001 data. Figure 2a & 2b illustrate estimated dilatational strain changes following the 1819 and 2001 earthquakes assuming simplified planar faults dipping 45°to the north and south respectively. Two red lobes of dilatational (Δ) contraction (+ compressive stress) extend eastward and westward from the Allah Bund region in 1819. The recent earthquake and earthquakes in 1856, 1857 and 1956 occurred in the eastern quadrant of maximum compressive stress (strain contraction) that has now shifted eastward toward Ahmedabad. Figure 2d indicates post-seismic changes predicted to occur in the year following the post-seismic survey. The model consists of a layered viscous rheology shown in the inset with a fault terminating 2.5 km below the surface using the focal mechanism solution similar tothat shown in 2a (Pollitz, personal communication, 2001.

Slip appears to have been less in 2001 than in 1819, although it is possible that a careful examination of the recent earthquake will reveal new insights into the mechanism and magnitude of the 1819 event. Despite the lack of a surface scarp, there are numerous surface cracks and localized compression and tension features near the epicenter. Geodetic measurements and epicentral aftershock studies currently underway, and anticipated InSAR imagery will ultimately resolve which of the nodal planes was active during the earthquake (Figure 2a). From the estimated seismic moment of the earthquake (Harvard/USGS/NEIC) we envisage a down-dip rupture width of 15-30 km, and an along-strike length of 50-100 km E/W with 1-4 m of slip. The surface manifestation of this rupture is likely to be a broad zone of distributed uplift with a corresponding region of subsidence south of the surface projection of the subsurface fault.

Seismic productivity in Kachchh

The Kachchh region is more than 200 km from the closest plate boundary; hence the Bhuj earthquake occurred within the Indian Plate, albeit near a transform boundary. Geodetic measurements of plate deformation between southernmost India and the northern edge of the Gangetic Plain indicate a contraction rate of the Indian plate of 3±2 mm/yr (*Paul et al., 2001*). Were this entirely concentrated in the Kachchh region it would result in a minimum recurrence interval of approximately 1000 years for earthquakes such as the ones in 1819 and 2001 (assuming a dip of 45°on the causative faults). Historic data record at least one severe earthquake in the region west of Kachchh in about 1000 AD and perhaps another to the NE of the Allahbund in 1250-1300, (*Iyengar and Sharma,* 1998). Paleoseismic investigations of the 1819 Allah Bund revealed several pre-historic earthquakes in the past three millennia consistent with this view (*Rajendran and Rajendran,* 1998; 2001). However, since contractile strain almost certainly occurs elsewhere in India (*Subrahmanya,* 1996*; Bendick and Bilham,* 1999) it is possible that the deformation rate in western India is higher than in eastern and central India. Survey-mode GPS measurements that might confirm or refute this possibility were initiated in this region only in the past few years.

The 188 year interval between the 1819 and 2001 events cannot be explained purely by a simple failure-strain replenishment processes. In Figure 2a and 2b we estimate approximately the dilatational strain fields that may have accompanied these events events, calculated using boundary element methods (*Toda et al*., 1998). We approximate the Allah Bund rupture as an 90-km-long, 20-km-wide, planar dislocation with an average slip of 6 m with N 18° W strike. The geometry of the Allah Bund event is much simplified in this model since its relict surface expression is quite sinuous and possibly segmented (*Oldham,* 1926). We apply a regional compressive strain to the Gujarat region to emulate the regional compressive stress azimuth characterized by recent seismicity and measured principal stress directions. The result of this model suggests that the earthquakes of 1845-1865 were partly in response to the westerly-directed lobe of compression from 1819, although this is clearly speculative given our poor understanding of the epicentral regions of these events. The Anjar 1956 and Bhuj 2001 earthquakes occurred in the easterly-directed lobe of increased compressive stress from the 1819 event.

The region now inferred to be subject to enhanced strain contraction (compressive stress) has extended eastward, although its detailed geometry depends critically on the availability of the coseismic deformation field which is currently ambiguous. We know of no specific earthquake in the Ahmedabad region in the historical record, however, a large tsunami is reported to have occurred in 1524 that caused considerable alarm to the Portugese fleet assembled offshore at 17°34' *(Bendick and Bilham, 1999)*. A violent earthquake occurred in southern Gujarat in 1705, and minor shaking is reported at Surat in 1663 (*Iyengar and Sharma,* 1998) and 1684 (*Oldham, 1869, Bapat et al., 1983)* .

Geodesy

The 2001 Bhuj earthquake occurred near the northern edge of a dense network of primary and secondary triangulation points of two first-order triangulation networks (Figure 2) – the Cutch Coast Series (*Strahan,* 1893) and the Kathiawar Meridional Series (*Thullier,* 1894). These triangulation networks form part of the Great Trigonometrical Survey of India (GTS) that was completed towards the end of the 19th century (*Phillimore,* 1968). The principal triangulation of the Kachchh region was completed in May 1858 with a mean angle measurement accuracy of 7 μradians, with the exception of a small number of angles in western Kachchh that included lines-of-sight that grazed hillsides (±15 μrad). Anticipated co-seismic epicentral angular changes are expected to exceed 100 μradians. The original survey monuments consist of subsurface marks on bedrock, or on a buried stone tablets, surmounted by masonry columns with cemented upper marks. Each mark consists of a 1-cm-diameter chiselled depression surrounded by a 15 cm chiselled circle. Our field teams discovered some of the points intact, but in many cases new points were established consisting of pins cemented into exposed rock outcrops (Figure 2).

Two moderate earthquakes occurred during the initial surveys. According to survey officer D. J. Nasmyth, the November 1856 earthquake distorted angles by up to 24 μrad in a triangle of the Kathiawar series approximately 25 km east of Bhachau (*Strahan,* 1893). Two months later (in January 1857) an earthquake was sufficiently severe to damage the 4-m-high column at Khari Rohar 15 km ESE of Anjar (23°5' 70°13'), threatening to overturn the 18-inch theodolite upon it (*Strahan, 1893,* p. viii). A leveling network from Ahmedabad through Bhachau to Anjar included some of these triangulation points in 1874-5 and in 1889-90. When these heights were remeasured after the 1956 Anjar earthquake it was discovered that elevation changes of up to a meter had occurred (*Singh*, 1992).

Despite these indications of significant and repeated deformation, and despite important recent progress in implementing GPS geodesy in India (*Kulkarni,* 1998; *Bilham and Gaur,* 1999) no GPS control specifically for earthquake-related studies had been established in the Kachchh region prior to the earthquake. To our knowledge no published record exists of re-measurement of the Kachchh angles or positions, although unpublished re-measurements for mapping and control purposes are available in government archives that may now be available. Subsequent to the earthquake several Indian groups of geodesists from the Indian Institute of Geomagnetism (IIG), the Indian Institute of Technology Bombay (IITB), the Centre for Mathematical Modelling & Computer Simulation (CMMACS), Bangalore; and the Wadia Institute of Himalayan Geology, Dehra Dun, undertook a series of measurements in the Kachchh region. A subset of measurement points measured by these several groups is shown in Figure 2. The measured points extend approximately 100 km east, west and south of the epicenter.

The GPS data are currently being processed to determine coseismic changes during the earthquake. However, the number of GTS control points currently recovered is insufficient to constrain more than simple subsurface dislocation geometries (Figure 2a). We also recognize that the several previous earthquakes since 1860 in the region will have contributed to the cumulative deformation field. We anticipate that planned InSAR imagery using recent images may distinguish between the coseismic strain change, and previous earthquakes and inteseismic deformation.

In addition to the recovery of coseismic strain changes, new GPS points have been destributed far from the epicenter in order to capture future post-seismic deformation resulting from viscous flow in the lower crust (Figure 2d). Preliminary aftershock depths and inferred rupture dimensions suggest that the Bhuj earthquake will have significantly purturbed the lower crust. Whereas the viscosity of the lower crust has been investigated near plate boundaries, it has not been possible to do this in a mid-continent setting due to the absence of well-recorded events in these areas. The surface response to anticipated viscous flow will lead to a broadening of the coseismic deformation-field that will be detectable over periods of decades. Preliminary estimates of viscoelastic vertical and horizontal deformation rates are projected to exceed 1 cm/yr (Figure 2d) for a simple starting model of an elastic crust overlying viscous lower crust and mantle (Pollitz, written communication 2001). A network of new geodetic points have been selected for their long term stability to record these changes over the next century, to distances of more than 100 km from the epicenter. The surface strain rates in the next several years will give an estimate of the viscosity of the weak lower crust in a continental setting.

Isoseismal Intensities

A full compilation of shaking effects for the 2001 earthquake will not be available for some time (e.g. *Narula and Chaubey*, 2001), but we have compiled news accounts from the immediate aftermath of the earthquake and interpreted them to obtain Modified Mercalli intensities (MMI) at over 180 locations throughout India and Pakistan. Maps of the resulting intensity distribution are shown in Figure 3. To generate these maps we use a simple mathematical approach to interpolate between locations with known intensity values. Away from the constrained data points, the maps therefore do not reflect geologic site conditions, which influence shaking levels substantially.

Previously the largest recorded intraplate earthquake in India occurred in 1897 and its magnitude (M=8.1±0.1) was determined only recently from the sparse global seismic network of the time (*Ambraseys, 2000*) and from geodetic estimates of seismic moment

(*Bilham and England, 2001*). The 1967 M≥6.5 Koyna intraplate earthquake was not felt sufficiently far from the epicenter to calibrate the far-field perceived intensity scale. The magnitudes of numerous other Indian earthquakes are known only from their intensity distributions, and an accurate attenuation versus distance relationship for Modified Mercalli Intensities on the Indian craton is currently unavailable.

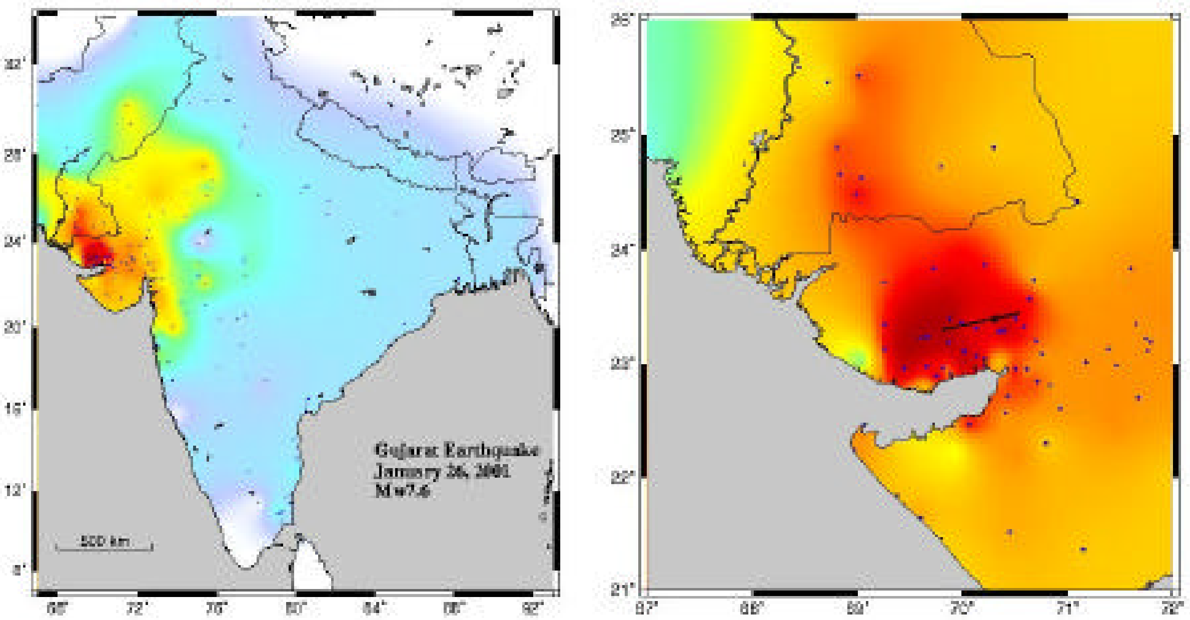

Figure 3. The distribution of intensities (MMI values) throughout Indian subcontinent is shown at left (3A); the intensity distribution in the Kachchh region is shown at right (3B). Approximate location of fault is indicate on Figure 3B (black line). Small circles indicate locations at which MMI values are assigned. Scales below include ground motion parameters. Peak velocities and accelerations reflect general ranges inferred from earthquakes in California for given MMI levels (e.g., Wald et al., 1999) and may not be representative of those experienced in other tectonic regimes. Instrumental data from the Bhuj earthquake will ultimately allow us to calibrate directly the intensity data with ground motion parameters.

For the first time, the seismological community will be able to estimate the attenuation of acceleration across the Indian craton using intensity observations from an intraplate M≥7.6 earthquake with a well-resolved instrumental magnitude. Although strong-motion accelerograph recordings of the Bhuj earthquake are sparse, we anticipate that the distribution of strong motion instruments in India will be adequate to calibrate Modified Mercalli Intensity (MMI) values relative to acceleration and frequency data. Isoseismal intensities obtained in the last few weeks already provide an important data set with which to initiate this study. Armed with a newly calibrated attenuation curve we anticipate that we will be able re-evaluate intensity data from historic Indian earthquakes in order to refine their estimated magnitudes (e.g., *Johnston, 1996a,b*; *Bilham,* 2000). Results from the Bhuj earthquake may also provide a critical calibration for events that occurred in similar tectonic settings worldwide, including the 1811-1812 New Madrid earthquake (see below).

Although preliminary, the intensity maps already show several interesting features. The event was felt only lightly at the higher-elevation cities on Deccan lavas throughout central and southern India. Away from the Kachchh region, intensities were clearly amplified significantly in areas that are along rivers, within deltas, or on coastal alluvium. One example is the Narmada River Valley in the province of Madhya Pradesh, where MMI values up to VI were reached at distances of over 600 km. Significant site effects were also observed within Mumbai (Bombay). Most of the city experienced shaking at the MMI V level, but intensities of VI-VII were reached at areas built on landfill in southern and central Mumbai as well as along Bombay Harbour.

Variations in the distribution of felt intensity are also apparent in the Kachchh region . The most heavily damaged villages are concentrated towards the western edge of the inferred fault, implying substantial western directivity from the epicenter. Significant sediment-induced amplification is also suggested at a number of locations around the Gulf of Kachchh, including Kandla and many of the villages on mudflats around the Gulf of Kachchh. Liquefaction features produced in the Rann of Kachchh included sand volcanoes and fissure that expelled enormous volumes of sediment, infilling broad river channels and spreading outwards as much as 3-5 km.

Implications for Future Hazard: India and Beyond

The 2001 Bhuj earthquake has important implications for earthquake hazard, not only India, but also in other parts of the world where the source zones and/or the wave travel paths are similar.

The occurrence of the Bhuj earthquake less than 200 years after the severe 1819 event provides further evidence that large intraplate earthquakes can occur in clusters in regions of the crust where the strain rate is relatively low. The event highlights the potential hazard faced by areas that lie outside more rapidly deforming plate boundary regions.

The parallels between Kachchh earthquakes and the 1811-1812 New Madrid earthquakes are remarkable. All of these earthquakes occurred within failed rift systems. The largest New Madrid earthquake may also have been similar in size to the Bhuj event. A recent reinterpretation of the February 7, 1812 New Madrid event obtained an Mw7.5 (*Hough et al.*, 2000); previous studies had inferred Mw values as high as 8.0 (*Johnston*, 1996). Finally, both the Bhuj and the largest New Madrid event both occurred on thrust faults favorably oriented for slip in the current stress regime that failed to produce either extensive or pronounced surface ruptures.

The distribution of shaking intensity in the Bhuj and New Madrid earthquakes was remarkably similar (Figure 4). Both events were felt at coastal regions as much as 2000 km from the epicenter, both caused light damage at sediment sites as far as 600 km away, and both generated substantial liquefaction over an extremely broad region. A thorough analysis of shaking effects from the Bhuj earthquake may help us better constrain the magnitude of the New Madrid earthquakes.

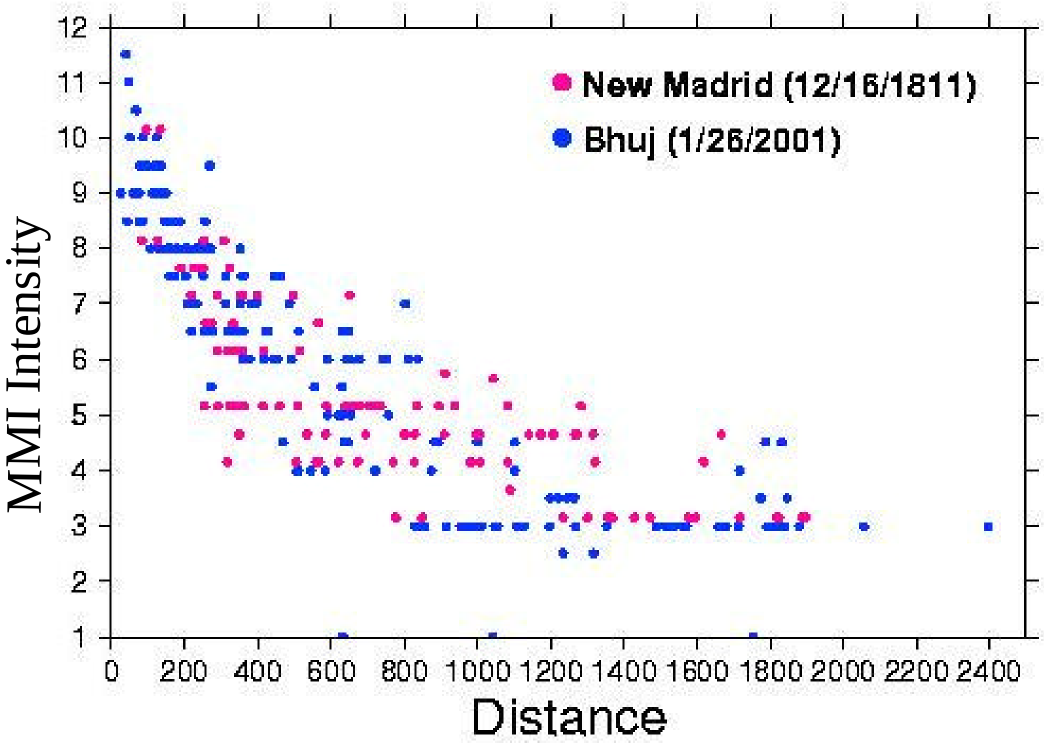

Figure 4. Our MMI values for the Bhuj earthquake are shown as a function of distance (blue circles) along with those determined by *Hough et al*. (2000) for the December 16, 1811 New Madrid earthquake (red circles). Distances for the Bhuj values are determined from the NEIC epicenter; values at short (<100 km) distances therefore do not reflect the distance to the fault.

McMurdo in his many accounts of the 1819 earthquake drew attention to the relative immunity of structures on bedrock compared to those on sediments. A similar observation has been made in the 2001 Bhuj earthquake. It is clear that had this been included as a post-1819 earthquake reconstruction guideline, damage in many areas in 2001 would have been reduced, however, much of the severe damage in villages was the result of construction methods based on unreinforced, undressed masonry. Since 1819 the population has increased by a factor of ten in Gujarat and seismic resistant building codes have been implemented. Yet in 1819 2000 people were killed, and in 2001 close to 20,000. It is difficult to escape the grim observation that the same fraction of the Kachchh population lost their lives in the two earthquakes. Yet the long-term legacy of the Bhuj earthquake need not only be one of tragedy if the seismological and earthquake engineering communities can exploit the available data to the fullest extent possible and make use of the lessons learned. The Bhuj earthquake provides an important opportunity to better understand the hazard posed by earthquakes that occur in or affect intracratonic regions.

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References

Ambraseys, N., and R. Bilham, (2000)A note on the Kangra Ms=7.8 earthquake of 4 April 1905. *Current Scienc*e, **79**, 101-106.

Baker, W.E., (1846) Remarks on the Allah Bund and on the drainage of the eastern part of the Sind basin. *Trans. Bombay Geogr. Soc.*, 7, 186-188.

Bapat, A, R. C. Kulkarni, and S. K. Guha (1983). Catalog of Earthquakes in India and Neighborhood from historical period up to 1979, *Ind. Soc. Earthq. Tech. Roorkee*, pp. 211.

Bendick, R. and R. Bilham (1999). Search for buckling of the southwest Indian coast related to Himalayan collision. In Himalaya and Tibet: mountain roots to mountain tops. Ed. A. Macfarlane, R. Sorkhabi, and J. Quade. *Geological Society of America Special Paper* **328**. pp.313-323.

Bilham, R. (1994). The 1737 Calcutta Earthquake and Cyclone Evaluated, *Bull. Seism. Soc. Amer.* **84** (5), 1650-1657.

Bilham, R. (1995). Location and magnitude of the 1833 Nepal earthquake and its relation to the rupture zones of contiguous great Himalayan earthquakes, *Current Science,* **69** (2), 155-187.

Bilham, R., (1999). Slip parameters for the Rann of Kachchh, India, 16 June 1819, earthquake, quantified from contemporary accounts. In Stewart, I. S. & Vita-Finzi, C. (Eds) Coastal Tectonics. *Geological Society London*, **146**, 295-318.

Bilham, R., and P. England (2001). Plateau pop-up in the Great 1897 Assam earthquake, *Nature(Lond.)* , in press.

Bilham, R., and V. K. Gaur (2000). The geodetic contribution to Indian seismotectonics, *Current Science* **79**(9), 1259-1269.

Biswas, S. K. and Deshpande, S. V. (1970): Geological and tectonic maps of Kutch. - In: *Bull. Oil Nat. Gas Comm.* 7: 115-116.

Biswas, S. K. (1987). Hydrocarbon exploration in western offshore basins of India, in Recent Geoscientific studies in the Arabian Sea off India, *Geol. Survey of India, Spec. Pub.* 24, 185-194.

Biswas, S.K.(1971): Note on the geology of Kutch. - *Quart Jour. Geol. Min. Metal Soc. India.* **43**: 223-235.

Biswas, S.K. (1987). Regional tectonic framework, structure and evolution of the western marginal basins of India; *Tectonophysics*, **135**; 307-327

Burnes, A. (1835). A memoir on the Eastern Branch of the River Indus giving an account of the alterations produced by it by an earthquake in 1819, also a theory of the Runn, and some conjectures on the Route of Alexander the Great, drawn up in the years 1827-28, *Trans. Royal Asiatic Soc.*, 3, 550-588, 1835.

Chandra, U. (1977). earthquakes of peninsular India- a seismotectonic study; *Bull. Seism. Soc. Amer*, **67**, 1387-1413

Chung, W.-Y. and H. Gao (1995). Source mechanism of the Anjar, India, earthquake of 21 July, 1956 and its seismotectonic implications for the Kutch rift basin, *Tectonophysics*, 242, 281-292.

Gowd, T. N., Srirama Rao, S. V. and Chary, K. B. (1996). Stress field and seismicity in the Indian Shield: Effects of the collision between Indian and Eurasia. *Pageoph*. 146: 1-27.

Hough, S.E., J.G. Armbruster, L. Seeber, and J.F. Hough (2000). On the Modified Mercalli Intensities and Magnitudes of the 1811-1812 New Madrid, Central United States earthquakes, *J. Geophys. Res.*, *105*, 23839-23864.

Iyengar, R. N., and S. D. Sharma, (1998) Earthquake History of India in Medieval times, *Central Building Research Institute*, Roorkee, India pp. 124, July 1998.

Johnston, A.C. (1996a). Seismic moment assessment of earthquakes in stable continental regions--III. New Madrid 1811-1812, Charleston 1886, and Lisbon 1755, *Geophys. J. Int.*, **126,** 314-344.

Johnston, A.C. (1996b). Seismic moment assessment of earthquakes in stable continetal regions--II. Historical seismicity, *Geophys. J. Int.* **125**, 639-678.

Kulkarni, M.N. (1998) Application of Geodesy to Monitor Earthquake Hazard: An Overview, Proceedings of 11th Synposium on Earthquake Engineering, Roorkee University, Dec. 1998, *GIS at Development,* Centre for Spatial Data Management & Services, Delhi, May-June 1999, **3**(3), 31-33.

LeGrand Jacob (1860). G., Extract of a journal kept during a tour made in 1851 through Kutch, giving an account of the Alum mines and changes effected by a series of earthquakes in 1844 by a series of earthquakes, *Trans. Bombay Geog. Soc*. **15**, 56-66.

MacMurdo, J. (1839). Observations of the Sindhoo, or River Indus. *Proc. Bombay Geog. Soc.* 124.

MacMurdo, J. (1823). Papers relating to the earthquake which occurred in India in 1819, *Trans. Literary Soc. Bombay*, **3**, 90-116.

Malik, J. N., P. S. Sohoni, S. S., Merh and R. V., Karanth (2000). Palaeoseislology and neotectonism of kachchh, W. India, Active Fault Research for the New Millennium, *Proceedings of the Hokudan International Symposium and School on Active Faulting*, Okumura, K., Goto, H., and Takada, K., eds.

Narula, P. L. and S. K. Chaubey (2001). Macroseismic surveys for the Bhuj (India) earthquake of 26 January 2001. http://www.nicee.org/NICEE/Gujarat/narula.htm

Nuttli, O. W. (1973). The Mississippi Valley earthquakes of 1811 and 1812: Intensities, ground motion, and magnitudes, *Bull. Seism. Soc. Am.*, *63*, 227-248.

Oldham, R. D. (1898). A note on the Allah Bund in the north west of the Runn of Cuch. *Mem. Geol. Surv. Of India*, 28, 27-30.

Oldham, T. (1883). A catalogue of Indian earthquakes from the earliest time to the end of A. D. 1869, *Mem. Geol. Surv. India*, **19**, 163-215.

Paul, J., Burgmann, R. ; Gaur, V. K. ; Bilham, R. ; Larson, K. M. ;Ananda, M. B. ; Jade, S. ; Mukal, M. ; Anupama, T. S. ; Satyal, G., Kumar, D. (2001). The motion and active deformation of India, *Geophys. Res. Lett.* **28** (4), 647-651.

Phillimore, R. H., (1968) Historical Records of the Survey of India: 1841 to 1861 Andrew Waugh, 5, pp.566, Dehra Dun.

Rajendran, C.P., K. Rajendran, and B. John (1998). Surface Deformation related to the 1819 Katchchh earthquake: Evidence for current activity, Current Sc.,75 (6), 623-626.

Rajendran, K. and C.P.Rajendran (1999). Seismogenesis in the stable continental Interiors: An appraisal based on two examples from India; Tectonophysics, 305, 355-370.

Rajendran, C.P., and Kusala Rajendran (2001). Character of Deformation and past seismicity Associated with the 1819 kutch earthquake, Northwestern India; Bull. Seism. Soc. Amer., in press.

Singh, A. N. (1992). An estimate of the vertical velocity field in India from historic leveling data, Internal report, Survey of India.

Srivastava, P.K. (1971). Recent sediments in Ranns of kutch, Journ. Geol. Soc. of India; 12; 392-395.

Strahan,G. (1893). *Synopsis of the results of the Great Trigonometrical Survey of India, Descriptions and coordinates of the principal and secondary stations and other fixed points of the Cutch Coast Series, or Series L, of the South West Quadrilateral*, **XXXIII**, Dehra Dun.

Subrahmanya, K. R. (1996). Active intraplate deformation in South India, *Tectonophysics*, **249**, 267-282.

Tandon, A.N. (1956). The Rann of Kutch earthquake of 21 July 1956, Ind. J. Met. and Geophys., 10, 137-146.

Thullier, H. R. (1894). *Synoptical Volume of the Great Trigonometrical Survey of India, Kathiawar Meridional Series*, **XXXIV**, Dehra Dun.

Toda, S., R. S. Stein, P.A. Reasonberg, J. H. Dieterich and A.Yoshida (1998). Stress transferred by the 1995 Mw=6.9 Kobe, Japan, earthquake:Effect on aftershocks and future earthquake possibilities, J. Geophys. Res., 103, 24543-24565.

Wald, D.J. , V. Quitoriano, T.H. Heaton, and H. Kanamori (1999). Relationships between peak ground acceleration, peak ground velocity, and modified Mercalli intensity in California, *Earthq. Spectra, 15*, 557-564.