A media-based assessment of damage and ground motions from the January 26th, 2001 M 7.6 Bhuj, India earthquake

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We compiled available news and internet accounts of damage and other effects from the 26th January, 2001, Bhuj earthquake, and interpreted them to obtain modified Mercalli intensities at over 200 locations throughout the Indian subcontinent. These values are used to map the intensity distribution using a simple mathematical interpolation method. The maps reveal several interesting features. Within the Kachchh region, the most heavily damaged villages are concentrated towards the western edge of the inferred fault, consistent with western directivity. Significant sediment-induced amplification is also suggested at a number of locations around the Gulf of Kachchh to the south of the epicenter. Away from the Kachchh region intensities were clearly amplified significantly in areas that are along rivers, within deltas, or on coastal alluvium such as mud flats and salt pans. In addition we use fault rupture parameters inferred from teleseismic data to predict shaking intensity at distances of 0–1000 km. We then convert the predicted hard rock ground motion parameters to MMI using a relationship (derived from internet-based intensity surveys) that assigns MMI based on the average effects in a region. The predicted MMIs are typically lower by 1–2 units than those estimated from news accounts. This discrepancy is generally consistent with the expected effect of sediment response, but it could also reflect other factors such as a tendency for media accounts to focus on the most dramatic damage, rather than the average effects. Our modeling results also suggest, however, that the Bhuj earthquake generated more high-frequency shaking than is expected for earthquakes of similar magnitude in California, and may therefore have been especially damaging.

1. Introduction

The M7.6 Bhuj earthquake occurred in the state of Gujarat, India at 03:16 GMT (8:16 am, local time) on January 26th, 2001 (figure 1). The event struck within the Kachchh peninsula near India's western coast and was felt over much of the Indian subcontinent. Damage in some parts of Gujarat was severe. Eyewitnesses reported that approximately one building in ten remained standing in Bhuj and Anjar, the closest large cities to the epicenter. Considerable damage was also reported in Hyderabad in southern Pakistan, while cities on the ancient Indian craton at similar distances from the epicenter were not severely shaken. Although some multistorey concrete buildings completely collapsed in moderately shaken regions, many other structures remained intact, indicating that poor quality construction aggravated the damage. The Bhuj earthquake also generated substantial liquefaction and hydrological effects, including mud-volcanoes (e.g., Tuttle *et al* 2001a, 2001b), lateral spreading, and liquefaction in port cities.

Although instrumental recordings of the Bhuj earthquake are unfortunately scarce, isoseismal intensities provide an important data set. The

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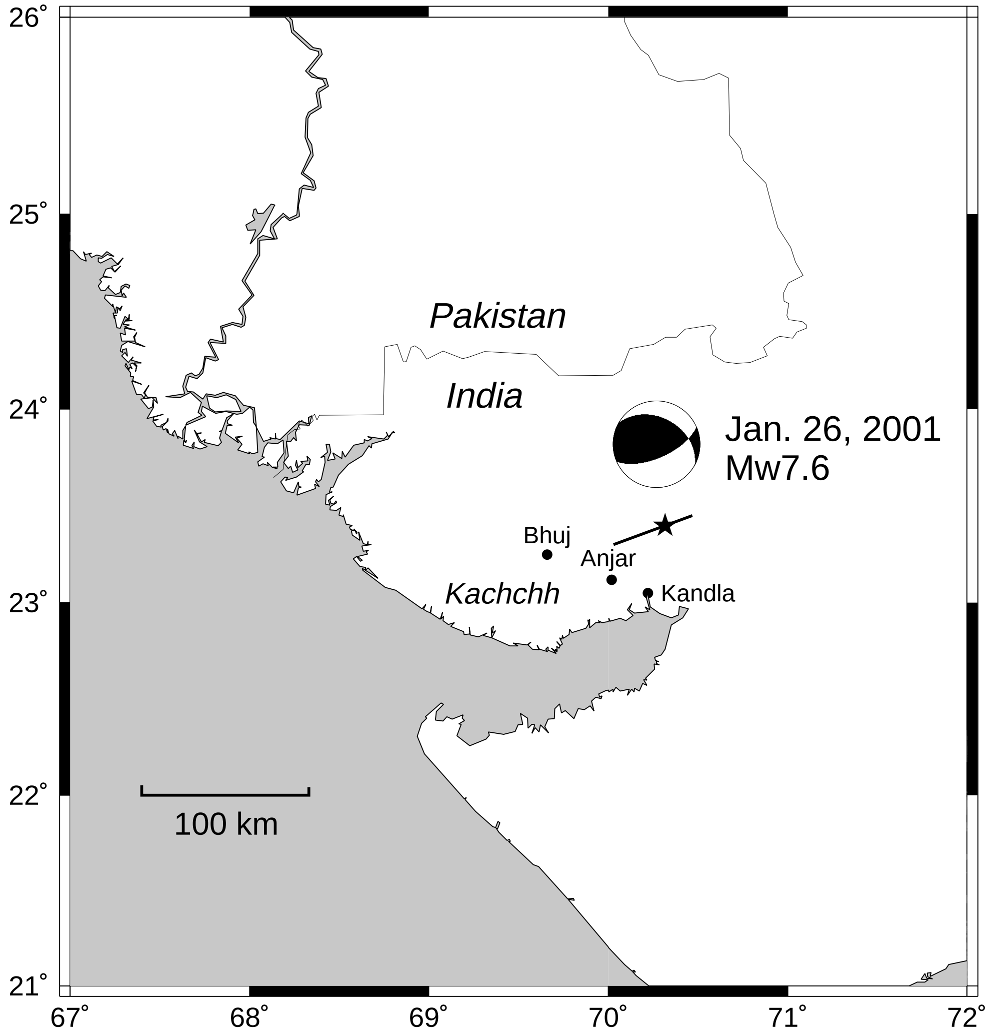

Figure 1. Map showing location of the 26th January, 2001 Bhuj, India earthquake within the Rann of Kachchh. The straight line shows a "pseudo-fault" with strike and length from Yagi and Kikuchi (2001). The focal mechanism corresponding to this solution is also shown. Preliminary aftershock relocations indicate a south-dipping rupture plane.

distribution of strong motion instruments in India is not adequate to calibrate directly the MMI values relative to physical ground motion parameters. However, the Bhuj earthquake was well-recorded at teleseismic distances. Intensity results from the Bhuj earthquake will thus be useful to better constrain the magnitude of historic Indian earthquakes (e.g., Ambraseys and Bilham 2000).

Extensive news articles were written in the early aftermath of the Bhuj earthquake and were published in both conventional newspapers and on the web. We compiled available accounts from reputable sources and interpreted them to obtain modified Mercalli intensity (MMI) values following conventional practice. Our final data set includes MMI values for nearly 200 sites throughout the Indian subcontinent, with the highest concentration of values within 300 km of Bhuj.

We anticipate that our results will eventually be supplanted by MMI maps determined from ground observations and conventional mail surveys. However, we proceeded with a determination of a "media-based intensity map" for two reasons. First, we believe the map does provide a good characterization of shaking effects throughout the subcontinent. But more importantly, we construct our MMI map based solely on media accounts so that the results can be compared to both media-based maps for earlier earthquakes and to the MMI distribution determined for the Bhuj earthquake using conventional ground- and mail-based surveys. These comparisons should provide useful insights into the nature of the biases that can result from determination of intensity distribution based only on news reports. Because such sources often provide the only source of information for older earthquakes (pre-1900, typically), the issue of "media biases" often looms large in the interpretation of intensity data for important historic earthquakes. Furthermore, it is likely that web and media-based assessments will become increasingly common in future large earthquakes world-wide.

2. Isoseismal intensities

Beginning in the immediate aftermath of the Bhuj earthquake, we compiled news accounts from traditional print media sources in the United States and India as well as internet-based sources. A summary of these reports, including their sources, is listed in table 1. From the available accounts, we assigned modified Mercalli intensities (e.g., Stover and Coffman 1993) based on the severity of shaking. In a few cases, news sources document that the event was not felt at a given location. In the Kachchh region, the most heavily damaged regions are generally assigned MMI values of IX–X, corresponding to heavy damage to masonry structures. Few values in excess of X are assigned, reflecting the paucity of accounts describing significant damage to modern, engineered structures. In the town of Sukhpur, however, one account describes a 10-year old child being flung into the air. We assign MMI of XI–XII for this location.

Intensity values can be interpreted as point data; our results for the Bhuj earthquake are shown in figure 2. Typically, however, such data are used to define isoseismal contours. This approach is fraught with potential biases, as discussed at length by Hough *et al* (2000). In particular, any general approach to interpolation or contouring will not reflect the systematic dependence of ground motions on site geology. Ideally, knowledge of local geologic structure can provide important constraints, but such information was not available to us.

To map out the shaking distribution over the entire subcontinent, we employ a simple mathematical approach whereby the data are contoured using a continuous curvature gridding algorithm. A uniform grid of estimated intensity values, $I(x, y)$, is determined by solving the equation

$$(1 - T) \cdot L(L(I)) + T \cdot L(I) = 0, \qquad (1)$$

where T is a tension factor between 0 and 1, and L indicates the Laplacian operator (see Wessel and Smith 1991). A tension factor of 0 yields the minimum curvature solution, which can produce minima and maxima away from constrained values. With a value of 1, no minima or maxima occur away from control points. A tension factor of 1.0 is used to avoid introduction of extreme values not constrained by data (figure 3); the results are not very sensitive to the precise value chosen. Figure 4 presents a close-up view of the Kachchh region.

The intensity maps reveal 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 as high as 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 up to VI–VII were reached at areas built on landfill in southern and central Mumbai as well as along Bombay Harbour.

Interesting features can be seen in the intensity distribution within the Kachchh region as well. The most heavily damaged villages are concentrated towards the western edge of the inferred fault, suggesting substantial western directivity from the epicenter. Some of the largest mud volcanoes were also documented in this region (Tuttle *et al* 2001b.) Significant sediment-induced amplification is also suggested at a number of locations around the Gulf of Kachchh, including Kandla (immediately south of the epicenter) and many of the villages on mud flats around the gulf.

The distribution of intensities in Kachchh are quite consistent with the spatial extent of liquefaction features as described by Tuttle *et al* (2001a, 2001b). In northern Kachchh the correspondence is not coincidental, as observations of liquefaction were used to assign some of the MMI values in some unpopulated areas. No liquefaction was observed in southwestern Kachchh, however, and the low MMI values in this region were assigned based on relatively light damage in this area.

3. Predicted ground motions

Although the Bhuj earthquake was not recorded by strong motion instruments, it was well-recorded at teleseismic distances (e.g., Yagi and Kikuchi 2001). We use a simplified source model determined from instrumental data to predict ground motions at local and regional distances using the finite fault method of Beresnev and Atkinson (1997). This analysis is complicated by the fact that neither the ground motions nor the fault parameters are well-constrained. We therefore seek to investigate only the general consistency between the inferred and predicted ground motions.

Our fault model is based on the moment, rupture length, width, and strike from the results of Yagi and Kikuchi (2001), assuming a south-dipping fault plane. Preliminary results (e.g., Yagi and Kikuchi 2001) suggest that the fault occurred on a thrust fault that did not break the

Table 1. *Bhuj earthquake intensities.*

Location	Lat.	Long.	MMI	Report	Source
Adhoi, Gujarat	23.400	70.513	9–10	Total devastation	Kutchinfo.com
Adipur, Gujarat	23.082	70.066	9–10	Total devastation	Zee News
Ahmedabad, Gujarat	23.043	72.578	7	Some damage	The Indian Express
Ahmedabad, Gujarat	23.030	72.577	7	Damage to Mosque, bridge	(several)
Ahmedabad, Gujarat	23.009	72.590	7–8	Several high-rise buildings collapsed	(several)
Ahmedabad, Gujarat	23.009	72.568	7–8	Damage to soft-storey high-rise buildings	Outlook, Times of India
Ahmedabad, Gujarat	23.050	72.577	6	Walls slightly cracked	Zee News, Asian Age
Ahmedabad, Gujarat	23.058	72.564	7–8	Water table rose 2.5 cm	Times of India
Ahmedabad, Gujarat	23.030	72.551	7–8	Several high-rise buildings collapsed	(several)
Ajmer, Rajasthan	26.270	74.420	6	Buildings cracked	The Hindu
Akola, Maharashtra	20.420	77.020	3	Felt lightly, duration estimated	Sandhyanand
Allahabad, Uttar Pradesh	25.280	81.540	3	Felt, many dizzy	The Hindu
Amravati, Maharashtra	20.560	77.480	3	Felt lightly, duration estimated	Sandhyanand
Amreli District, Gujarat	21.360	71.150	7–8	190 “pucca” buildings destroyed	Kutchinfo.com
Anand District, Gujarat	22.320	73.000	6–7	Some buildings collapsed, many damaged	Kutchinfo.com
Anjar, Gujarat	23.117	70.019	10–11	Most old buildings leveled	Asian Age Zee News
Ayyampettai, Tamil Nadu	10.902	79.182	3	Felt	The Hindu
Badin, Sindh (Pakistan)	24.663	68.838	8–9	Water emitted from cracks Building damage	The Dawn
Bagathala, Gujarat	22.847	70.717	8–9	Most buildings damaged or destroyed	Asian Age

Table 1. *(Continued)*

Bahawalpur, Punjab (Pakistan)	29.391	71.699	6–7	Buildings cracked	The Dawn
Bajana, Gujarat	23.118	71.768	8	New springs	Times of India
Bakhasar, Rajasthan	24.430	71.090	7–8	Several buildings collapsed	The Indian Express
Balamba, Gujarat	22.716	70.436	8–9	Most buildings damaged or destroyed	Zee News
Bangalore, Karnataka	12.958	77.583	3–4	Felt widely, people ran outside	The Hindu
Bangladesh, Bangladesh	22.350	91.830	3	Felt, western and central regions	123india.com
Bapatla, Andhra Pradesh	15.905	80.466	3	Felt	The Hindu
Beraja, Gujarat	22.986	69.600	5–6	Cracks in buildings	Panjokutch.com
Bhachau, Gujarat	23.287	70.352	9–10	Most buildings destroyed	Zee News Kutchinfo.com
Bhadreshwar, Gujarat	22.916	69.891	8–9	Many buildings severely damaged	Kutchinfo.com
Bharuch, Gujarat	21.719	72.971	7–8	Several buildings damaged	Kutchinfo.com
Bhavnagar District, Gujarat	21.460	72.110	7	Many “pucca” buildings destroyed	Kutchinfo.com
Bhilwara, Rajasthan	25.210	74.400	6	Buildings cracked	The Hindu
Bhubaneshwar, Orissa	20.150	85.520	3	Felt	Pragativadi
Bhuj, Gujarat	23.245	69.662	11–12	Widespread devastation, pipes destroyed	(several)
Bhujpur, Gujarat	22.867	69.635	7–8	Ground level sunk (liquefaction)	Panjokutch.com
Bidada, Gujarat	22.900	69.463	6–7	Light damage	Panjokutch.com
Bidar, Karnataka	17.570	77.390	3	Felt	Indiaexpress.com
Buldhana, Maharashtra	20.320	76.140	3	Felt lightly, duration estimated	Sandhyanand
Butchireddipalem, Andhra Pradesh	14.531	79.884	3	Felt	The Hindu
Chandigarh, Chandigarh	30.420	76.540	3	Many people felt giddy/nauseous	ASC Report
Chennai, Tamil Nadu	13.040	80.170	4	Kitchen utensils fell	The Hindu
Chhasra, Gujarat	22.969	69.816	8–9	80% houses totally damaged	Panjokutch.com

Table 1. *(Continued)*

Location	Lat.	Long.	MMI	Report	Source
Chidambaram, Andhra Pradesh	11.399	79.762	3	Felt	The Hindu
Chitrod, Gujarat	23.40	70.70	8	Damage to temple	INTACH field rep.
Cuddalore, Andhra Pradesh	11.753	79.769	3	Felt	The Hindu
Dalauda, Madhya Pradesh	23.934	75.099	NF	Not felt by observer ground	ASC report
Deesa, Gujarat	24.25	72.167	7–8	Church collapsed	Indiaexpress.com
Deshalpur, Gujarat	23.735	70.681	6–7	Light damage to village	Panjokutch.com
Dholavira, Gujarat	23.438	66.766	9	Archeological Society building destroyed	Express
Dhori, Gujarat	23.438	66.766	9–10	Fissures, sand blows, sand craters	Reuters, Zee News
Dhrandadhra, Gujarat	22.991	71.467	8	New springs	Times of India
Dhrol, Gujarat	22.574	70.407	8	Among worse-affected towns	Several
Dhule, Maharashtra	20.580	74.470	5	Felt strongly	Kesri
Dudhai, Gujarat	23.318	70.134	9–10	Most buildings destroyed	Times of India
Dwarka, Gujarat	22.247	68.965	8	Temples damaged	Times of India
Gandhidham, Gujarat	23.074	70.131	9–10	Many high-rise building collapsed	Star News, AP
Gandhinagar, Gujarat	23.296	72.635	8	Water table rose 2.5 cm	Times of India
Ganeshpuri-Vajreshwari Maharashtra	19.492	72.998	8	Change in hot springs temp., level	Star News
Ghotki, Sindh (Pakistan)	28.000	69.325	3	"Brief spell of earthquake"	The Dawn
Goa (entire), Goa	14.200	74.000	3–4	People fled outside, articles rattled	Sandhyanand
Gundala, Gujarat	22.901	69.752	9–10	Heavy damage, all houses destroyed	Kutchinfo.com
Guntur, Andhra Pradesh	16.294	80.444	3	Felt	The Hindu
Gwalior, Madhya Pradesh	26.140	78.100	4–5	Felt strongly, utensils fell	Sandhyanand
Halvad, Gujarat	23.017	71.174	8	New springs	Times of India
Haryana (entire)	30.300	74.600	3	Felt for "around 20 sec."	Sandhyanand
Himachal Pradesh	32.290	76.100	3	Felt for "around 20 sec."	Sandhyanand

Table 1. *(Continued)*

Hoshangabad, Madhya Pradesh	22.460	77.450	4–5	Felt strongly, utensils fell	Sandhyanand
Hyderabad, Sindh (Pakistan)	25.250	68.380	7–8	Damage to buildings, dozens injured	The Dawn
Hyderabad, Andhra Pradesh	17.387	78.480	2–3	Felt only in tall buildings	The Hindu
Jacobabad, Sindh (Pakistan)	28.279	68.428	3	“Brief spell of earthquake”	The Dawn
Jaipur, Rajasthan	26.893	75.790	6	Some buildings cracked	The Hindu
Jaiselmer, Rajasthan	26.914	70.790	7	Buildings cracked, damaged	The Indian Express
Jalgaon, Maharashtra	21.050	75.400	3	Felt	Kesri
Jalore, Rajasthan	25.220	72.580	6	Buildings cracked	The Hindu
Jamnagar, Gujarat	22.467	70.067	9	Many buildings destroyed	Zee News Kutchinfo.com
Jawaharnagar, Gujarat	23.367	69.986	10	Many buildings completely destroyed	Indian Express, AP
Jhinjhuwada, Gujarat	23.356	71.747	8	New springs	Times of India
Jodhpur, Rajasthan	21.883	70.033	7–8	Collapse of building dome	The Indian Express
Junagadh, Gujarat	21.516	70.457	7–8	Many buildings destroyed	Kutchinfo.com
Kabul (Afghanistan)	34.561	69.083	3	Felt	The Indian Express
Kandla, Gujarat	23.051	70.215	9	Many buildings severely damaged	(several)
Kandla Port Trust, Gujarat	22.982	70.218	9	Several buildings collapsed Piers damaged, widespread liquefaction	Times of India
Kanpur, Uttar Pradesh	26.280	80.240	3–4	Felt, furniture rattled	Indiaexpress.com
Karachi, Sindh (Pakistan)	24.510	67.040	5–6	Doors opened and closed, building cracks	ASC Report
Kathmandu (Nepal)	27.734	85.282	3–4	Some reports of objects swinging	AFP
Kera Badadia, Gujarat	23.083	69.598	7	All buildings damaged	Panjokutch.com
Kerala	10.0	76.25	NF	Not felt	Indiaexpress.com
Khadan, Sindh (Pakistan)	24.492	68.987	9	6” Cracks, sand/water emitted	The Dawn
Khaipur, Sindh (Pakistan)	27.280	68.440	5–6	Some damage	The Dawn
Khangharpur, Gujarat	NL	NL	8–9	6” Cracks, sand/water emitted	Reuters

Table 1. *(Continued)*

Location	Lat.	Long.	MMI	Report	Source
Kharaghodha Tank, Gujarat	23.231	71.747	8	New springs	Times of India
Khavda, Gujarat	23.840	69.720	9	Most buildings destroyed Possible mud volcano	Times of India
Kheda District, Gujarat	22.450	72.450	6–7	Many buildings damaged	Kutchinfo.com
Kolhapur, Maharashtra	16.707	79.224	3	Felt	Indiaexpress.com
Kolkata, West Bengal	22.340	88.240	3–4	Overhead fixtures swung	Star News, Sandhyanand
Kota, Rajasthan	25.178	75.835	6	Railway station cracked	The Indian Express
Kotdi-Roha, Gujarat	23.136	69.255	9	Two dead, heavy damage to KVO houses	Panjokutch.com
Kotri, Sindh (Pakistan)	25.220	68.220	4–5	25 women fainted, strong shaking	The Dawn
Koyna, Maharashtra	17.398	73.767	3–4	Felt for “around 40 sec.”	Sandhyanand
Kuda, Gujarat	23.113	71.385	8	New springs	Times of India
Kumbakakonam, Tamil Nadu	10.961	79.182	4–5	People ran, strongly felt	The Hindu
Lahore, Punjab (Pakistan)	31.542	74.399	4–5	Reported as “severe”	The Dawn
Larkana, Sindh (Pakistan)	27.330	68.150	3	“Brief spell of earthquake”	The Dawn
Lodhai, Gujarat	23.402	69.880	10–11	Most buildings destroyed	Midday
Lucknow, Uttar Pradesh	26.550	80.590	3–4	Furniture rattled	Indiaexpress.com
Luna, Gujarat	23.714	69.252	8–9	Water jet observed	Kutchinfo.com
Machilipatnam Andhra Pradesh	16.187	81.135	3	Felt	The Hindu
Maheshwari, Madhya Pradesh	22.110	75.370	6	Maheshwari fort cracked	Sandhyanand
Maliya, Gujarat	23.093	70.748	8	New springs, water levels increased	Times of India
Mandsaur, Madhya	23.030	75.080	5–6	Household articles knocked down	ASC Report
Mandvi, Gujarat	22.834	69.343	9	Many buildings collapsed, bridges damaged	Times of India
Matiari, Sindh (Pakistan)	25.596	68.443	6–7	Wall collapse	The Dawn
Mehsana District, Gujarat	23.420	72.370	7–8	12 “Pucca” buildings destroyed	Kutchinfo.com

Table 1. *(Continued)*

Mirpurkhas, Sindh Pakistan	25.522	69.010	7–8	Walls and roofs collapsed	The Dawn
Mithi, Sindh (Pakistan)	24.732	69.792	7–8	Walls and roofs collapsed	The Dawn
Modhera, Gujarat	23.587	72.132	6–7	Sun Temple damaged	Indya.com
Morbi, Gujarat	22.811	70.827	8	Many buildings severely damaged	ASC Report
Mota Asambia, Gujarat	22.968	69.447	10	Most buildings destroyed	Kutchinfo.com
Multan, Punjab (Pakistan)	31.452	71.455	6–7	Buildings cracked	The Dawn
Mumbai (Andheri) Maharashtra	19.123	72.912	5	People fled outside	ASC Report
Mumbai (Antop Hill) Maharashtra	19.028	72.843	6	Buildings cracked	Sandhyanand
Mumbai (Bandra) Maharashtra	19.058	72.836	3–4	Felt distinctly	ASC Report
Mumbai (Colaba) Maharashtra	18.907	72.809	6	People fled into streets	Sandhyanand
Mumbai (Crawford Market) Maharashtra	18.950	72.829	6	Buildings cracked	ASC Report
Mumbai (Dahisar) Maharashtra	19.258	72.837	5	Windows rattled	ASC Report
Mumbai (Kurla) Maharashtra	19.076	72.912	6	Buildings cracked	Kesri
Mumbai (Malad) Maharashtra	19.183	72.832	4–5	Felt strongly	ASC Report
Mumbai (Mankhurd) Maharashtra	19.050	72.931	6	Buildings cracked	Sandhyanand
Mumbai (Mazegaon) Maharashtra	18.968	72.841	6	Building cracked	ASC Report
Mumbai (Mumbai Central) Maharashtra	18.993	72.827	6	Glassware broke, fixtures swung	ASC Report
Mumbai (Navynagar) Maharashtra	18.912	72.813	5–6	People fled into streets	Sandhyanand

Table 1. *(Continued)*

Location	Lat.	Long.	MMI	Report	Source
Mumbai (Vikhroli) Maharashtra	19.096	72.929	5–6	Buildings cracked	Sandhyanand
Mumbai (Wadala) Maharashtra	19.028	72.843	6–7	Section of fire station collapsed	Sandhyanand
Mumbai (Worli) Maharashtra	19.015	72.819	6	Felt strongly, building damage	Times of India Sandhyanand
Muzzafarnagar Uttar Pradesh	29.280	77.440	3	Felt by many	Sandhyanand
Nakhatrana, Gujarat	23.352	69.258	9	Sand blows, fountains	Times of India
Nalasopara, Maharashtra	19.417	72.782	5	Household objects shaken	ASC Report
Nanded, Maharashtra	19.090	77.270	3	Felt lightly, duration estimated	Sandhyanand
Nandiad, Gujarat	22.687	72.854	7	Buildings visibly shaken	BBC Talking Point
Nandurbar, Maharashtra	21.230	74.190	3	Felt	Kesri
Nashik, Maharashtra	20.001	73.781	6–7	Several buildings damaged	Sandhyanand, ASC Report
Naushahro Firoz, Sindh Pakistan	26.848	68.122	6–7	Buildings damaged	The Dawn
Navlakhi, Gujarat	22.969	70.464	8	Railway tracks submerged Liquefaction	Asian Age Times of India
Navsari, Gujarat	20.954	72.919	7–8	98 “Pucca” buildings collapsed	Kutchinfo.com
Nawabshah, Sindh Pakistan	26.236	68.394	7–8	Buildings damaged	The Dawn
New Dehli, NCT	28.380	77.120	3–4	Felt, overhead fixtures swung	NDTV
Neyvel, Andhra Pradesh	11.607	79.491	3	Felt	The Hindu
Nindo Shahr, Sindh	24.638	69.037	I	Several injured	The Dawn
Noida, Uttar Pradesh	28.605	77.260	3–4	Overhead fixtures swung	ASC Report
Okha, Gujarat	22.462	69.061	8	Port facilities slightly damaged	Sandhyanand
Osmanabad, Maharashtra	18.080	76.060	3	Felt lightly, duration estimated	Sandhyanand
Palanpur, Gujarat	24.171	72.430	7–8	Many buildings collapsed Old bridge damaged	(several)

Table 1. *(Continued)*

Pali, Rajasthan	25.460	73.250	6	Buildings cracked	The Hindu
Papanad, Tamil Nadu	10.536	79.282	3	Felt	The Hindu
Papanasam, Tamil Nadu	10.922	79.270	3	Felt	The Hindu
Patan, Gujarat	23.874	72.109	7–8	Many buildings collapsed	Kutchinfo.com
Patdi, Gujarat	23.197	71.792	8	New springs	The Times of India
Patna, Bihar	25.370	85.130	3	Felt	The Tribune
Peshawar, NWFP Pakistan	33.276	71.860	3	Felt	The Dawn
Pokhran, Rajasthan	26.550	71.580	6	Buildings cracked	Indian Express
Pondicherry, (UT)	11.933	79.835	4–5	Celebrations disrupted, utensils fell	The Hindu
Ponnuru, Andhra Pradesh	16.067	80.560	3	Felt	The Hindu
Porbander, Gujarat	21.644	69.603	7–8	Any buildings destroyed	Zee News, Kutchinfo.com
Pune, Camp, Maharashtra	18.310	73.550	5	furniture, windows rattled	ASC Report
Pune, Hadapsar Maharashtra	18.503	73.887	NF	Observers were on ground floor	ASC Report
Pune Lohegaon-Vimannagar Maharashtra	18.589	73.898	4–5	Windows and furniture rattled	ASC Report
Pune, Lullanagar Maharashtra	18.496	73.859	3	Felt	ASC Report
Pune, Sassoon Road Maharashtra	18.533	73.853	4–5	Household articles, furniture shook	ASC Report
Punjab (entire)	30.400	75.500	3	Felt for “around 20 sec.”	Sandhyanand
Quetta, Baluchistan (Pakistan)	30.309	67.019	3	Felt	The Dawn
Radhanpur, Gujarat	23.841	71.603	8	Among worse-affected towns	Several
Rajkot, Gujarat	22.301	70.801	7–8	Many buildings collapsed	Zee News Times of India
Rapar, Gujarat	23.576	70.641	10	Most buildings destroyed	(several)
Ratnal, Gujarat	23.194	69.870	10	Most buildings destroyed	Kutchinfo.com

Table 1. *(Continued)*

Location	Lat.	Long.	MMI	Report	Source
Rohri, Sindh (Pakistan)	27.410	68.570	3	"Brief spell of earthquake"	The Dawn
Salem, Tamil Nadu	11.390	78.120	NF	Not felt	ASC Report
Samakhiali, Gujarat	23.329	70.587	9	Water flooded salt pans Ground cracking	Times of India
Sanghar, Sindh (Pakistan)	26.050	68.937	6–7	Buildings damaged	The Dawn
Shikarpur, Sindh (Pakistan)	27.965	68.635	3	"Brief spell of earthquake"	The Dawn
Shillong, Meghalaya	25.340	91.560	3	Felt	Sandhyanand
Sirohi, Rajasthan	24.530	72.540	6	Buildings cracked	The Hindu
Sukhpur, Gujarat	23.232	69.600	11–12	10-yr old "flung into air"	The Asian Age
Sukkur, Sindh (Pakistan)	27.693	68.845	3	"Brief spell of earthquake"	The Dawn
Suraj Bari, Gujarat	23.207	70.703	8–9	Serious cracks in land bridge	Times of India
Surat, Gujarat	21.193	72.822	7–8	A few high-rise buildings collapsed Nuclear reactor fba not triggered, Indicating shaking less than 0.1g	(several)
Surendranagar, Gujarat	22.706	71.678	8	Many old buildings destroyed	Star News
Suvi, Gujarat	23.618	70.483	9–10	Damage to dam	IIT Kanpur
Tada, Andhra Pradesh	13.586	80.030	3	Felt	The Hindu
Tadepalli, Andhra Pradesh	16.477	80.601	3	Felt	The Hindu
Talhar, Sindh (Pakistan)	24.894	68.806	I	Two injured	The Dawn
Tando Allah Yar, Sindh (Pakistan)	25.459	68.716	6–7	Wall collapse, 1 dead	The Dawn

Table 1. *(Continued)*

Tarapur, Maharashtra	19.880	73.688	5–6	Reactors did not shut down	ASC Report
Thane, Maharashtra	19.120	73.020	4	Felt strongly, esp. on upper floors	ASC Report
Thatta, Sindh (Pakistan)	24.751	67.923	6–7	3 motorbike riders lost control	The Dawn
Thiruvaiyaru, Tamil Nadu	10.884	79.098	4–5	Some objects fell in market	The Hindu
Tivim, Goa	15.598	73.831	NF	Not felt	ASC Report
Tonk District Rajasthan	26.110	75.500	6	Buildings cracked	The Hindu
Udaipur, Rajasthan	27.420	75.330	7	Serious damage to factory	Sandhyanand
Ujjain, Madhya Pradesh	23.090	77.430	4–5	Felt strongly, utensils fell	Sandhyanand
Unchahar, Uttar Pradesh	25.857	81.630	3	Many people felt giddy/nauseous	ASC Report
Unnao, Uttar Pradesh	26.480	80.430	3–4	Furniture shook	Indiaexpress.com
Vadala, Gujarat	22.918	69.850	7–8	Most houses damaged, few collapsed	Panjokutch.com
Vadodara, Gujarat	22.303	73.187	6	Minor damage to buildings	ASC Report
Valsad, Gujarat	20.611	72.924	7	Many buildings damaged	Kutchinfo.com
Vidisha, Madhya Pradesh	23.320	77.510	4–5	Felt strongly, utensils fell	Sandhyanand
Vijayawada, Andhra Pradesh	16.517	80.635	3	Felt	ASC Report
Vishakhapatnam, Andhra Pradesh	17.728	83.304	3	Felt	The Hindu
Vondh, Gujarat	23.301	70.397	10	Most old buildings collapsed Some newer structures badly damaged	Zee News, AP
Wankaner, Gujarat	22.612	70.934	7	Fallen masonry	Times of India

City, province, and country (if not India); latitude; longitude; MMI value; summary of account on which MMI values are based; source of information.

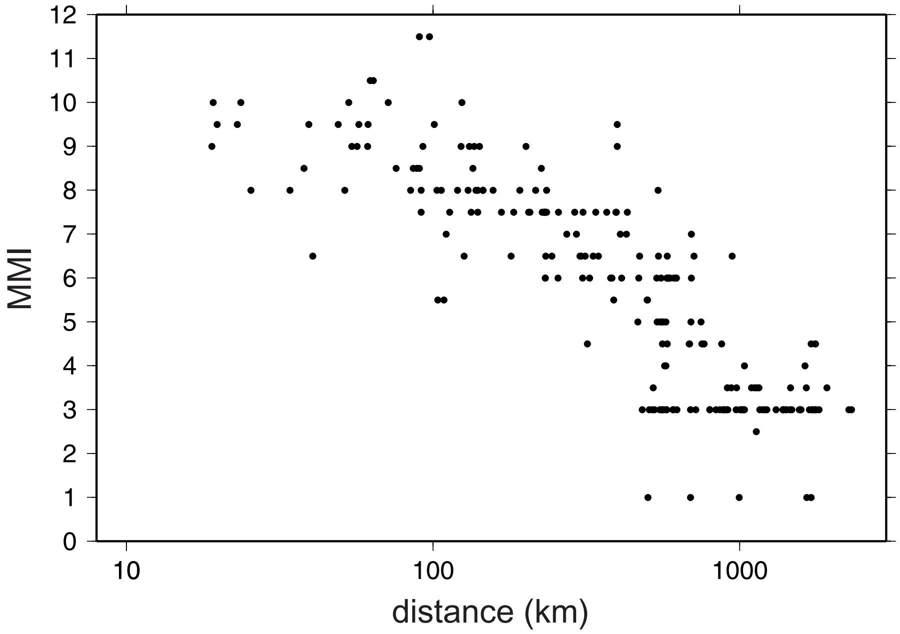

Figure 2. Inferred MMI values for the Bhuj earthquake are shown as a function of distance from the source. To estimate source distance, we calculate the nearest distance from each point to the "pseudo-fault" shown in figure 1.

surface (Bendick *et al* 2001). The estimated moment-magnitude, M, ranges from 7.5–7.7, nominally suggesting a rupture of 15–30 km width, 50–100 km length, and average slip of 1–4 m. Preliminary results from aftershock studies indicate that the rupture was no shallower than about 8–9 km. Some of these parameters are modified, however.

We increase the dip from 33 to 36 degrees in the light of aftershock results suggesting that the rupture extended to a depth of 35 km (Horton *et al* 2001). We also shorten the rupture length to 50 km and use a fault depth of 9 km based on the preliminary analysis of geodetic data. Finally, we use a smooth rupture model in which the average slip is determined from the moment and fault area. We calculate ground motions for hard rock site conditions ($\kappa = 0.005$; shear-wave velocity = 3.7 km/sec) and will consider the issue of site response separately. No crustal amplification is applied to the predictions. For our attenuation model we use the results of Singh *et al* (1999) for Lg attenuation in India: $Q = 508f^{0.48}$. We use a geometrical spreading function that includes a r^{-1} decay from 0 to 50 km and a $r^{-0.5}$ decay beyond 50 km.

In the Beresnev and Atkinson (1997) approach, a rupture is simulated using fault plane subelements, each of which is treated as a point-source with a spectral shape constrained to have an ω^2 shape. The method is attractive for this application because of its computational ease and because there are few model parameters to be assigned. It is limited in its ability to model the time-domain characteristics of low-frequency ground motions, but we consider it likely that the damage from the Bhuj earthquake is primarily controlled by relatively high-frequency shaking.

The most important free parameters in this method is the "strength parameter," S_f, which is related to the maximum slip velocity, v_m, according to

$$v_m = 0.618y(\Delta\sigma)S_f/(\rho\beta), \tag{2}$$

where β is the shear wave velocity, y is the rupture propagation velocity as a fraction of β, $\Delta\sigma$ is the sub-event stress-drop, and ρ is density (Beresnev and Atkinson 2001). As discussed by Beresnev and Atkinson (2001), the amplitude of high-frequency radiation depends strongly on S_f. S_f was found to vary between 1.0 and 2.4 for a wide range of earthquakes in eastern and western north America. In our application, the depth of faulting is another unknown. We therefore calculate peak ground acceleration (PGA) for a suite of possible rupture models with varying depths and strength parameters. We vary the depth to the upper edge of the rupture between 1 and 8 km and vary the strength factor between 1.2 and 2.4. The predicted ground motions are more sensitive to the strength factor than to depth. Unfortunately, it is difficult to constrain the strength parameter (or, equivalently, the slip velocity.) For north America, its average value is 1.6. We find that a strength factor close to this value (1.8) predicts a PGA of 10% g at the distance of Ahmedabad, consistent with the single strong motion recording that was released

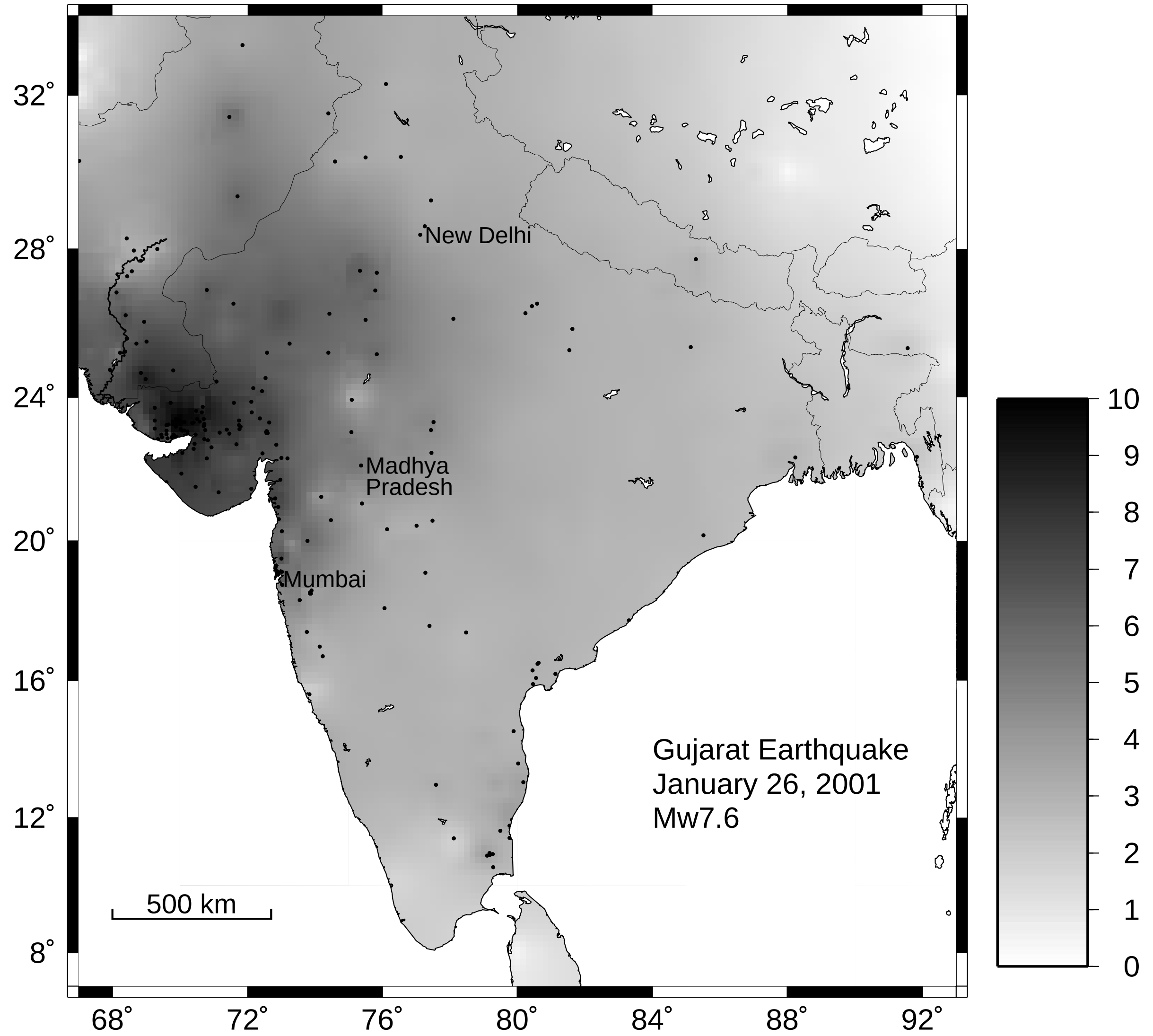

Figure 3. Map of intensity distribution for the 2001 Bhuj earthquake determined using a smoothing parameter of 1.0. MMI values are constrained at approximately 200 locations indicated with small circles. Gray scale reflects MMI values according to scale shown at right. Colour versions of these maps, which illustrate the intensity distribution more clearly, are available on-line, at *http://pasadena.wr.usgs.gov/office/hough)*.

in the aftermath of the earthquake (figure 5). We therefore provisionally adopt this as our preferred strength factor value.

To compare predicted and estimated intensities, we convert predicted PGA to MMI using the calibration established by Wald *et al* (1999). It should be borne in mind that PGA (and thus MMI) is predicted for rock sites, and that MMI on soil will be as much as 1–2 units larger than on rock (Hough *et al* 2000; Atkinson 2001). Although it is clearly difficult to compare data and models in cases where both are uncertain, we find that the predicted ground motions are able to match several salient features of the shaking distribution determined from MMI data. In both data and models we find the highest shaking to the north and northwest of the epicenter and relatively low shaking to the southwest of the epicenter, as shown in figure 6. For a wide range of strength factors, the model corroborates the macroseismic observation that potentially damaging ground motions can occur at distances of at least several hundred km from the source. That is, peak ground accelerations on the order of 5% g generally correspond with the threshhold of damage (e.g., Wald *et al* 1999). Because site response at soil sites can typically elevate MMI values by one to two units (e.g., Hough *et al* 2000; Atkinson 2001), the predicted ground motions shown in figure 6 are high enough to cause damage, at soft-sediment sites especially, over the extent of the MMI IV region in these figures.

The residuals between observed intensities and those predicted on rock, are also interesting to con-

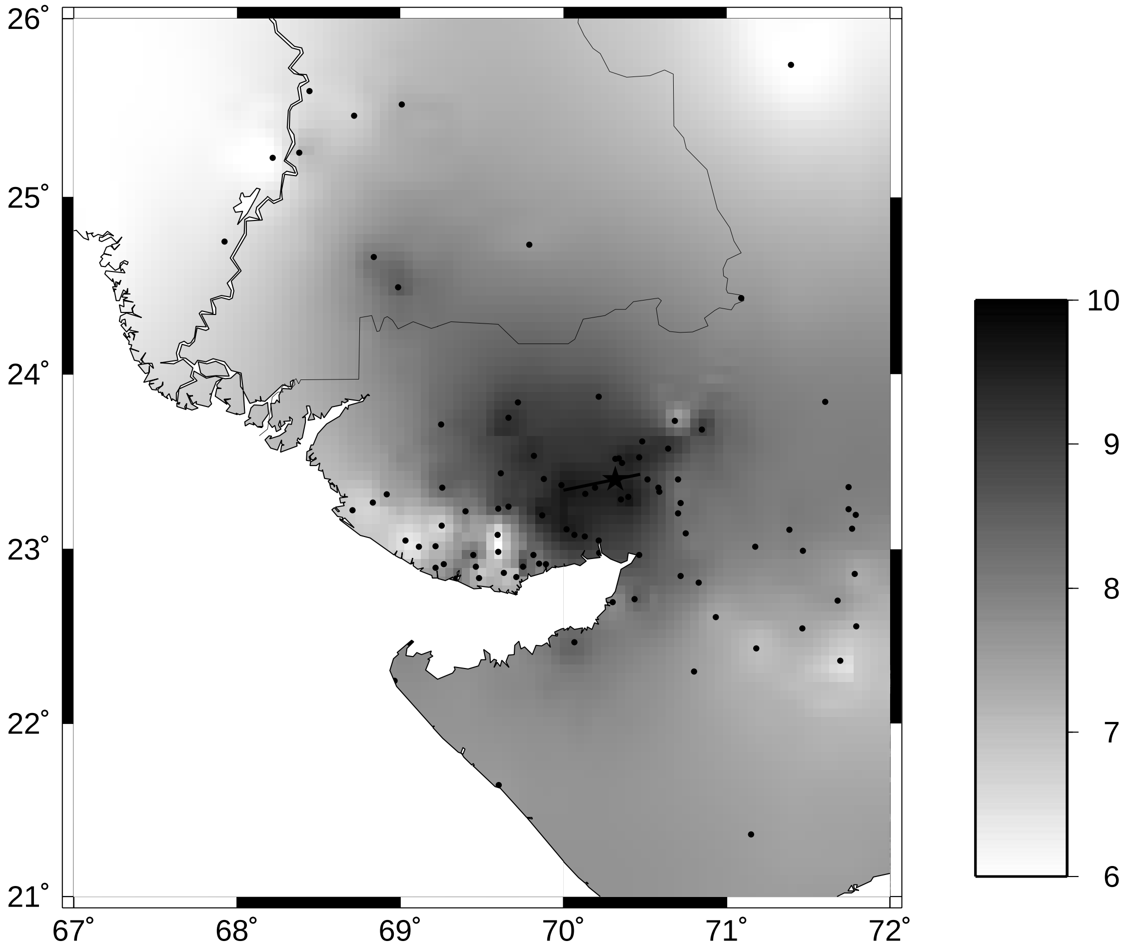

Figure 4. Close-up view of intensity distribution in the Kachchh region. Note that a different scale is used for intensities than that used in figure 3.

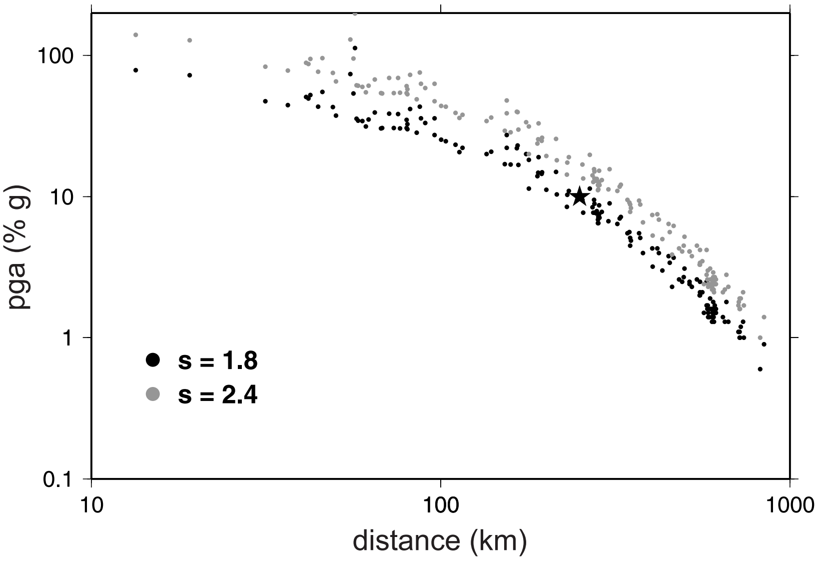

Figure 5. Peak ground acceleration values predicted on rock by the finite-fault model of Beresnev and Atkinson (1997) for strength factors of 1.8 (dark circles) and 2.4 (gray circles). Star indicates observed hard-rock peak acceleration observed at Ahmedabad.

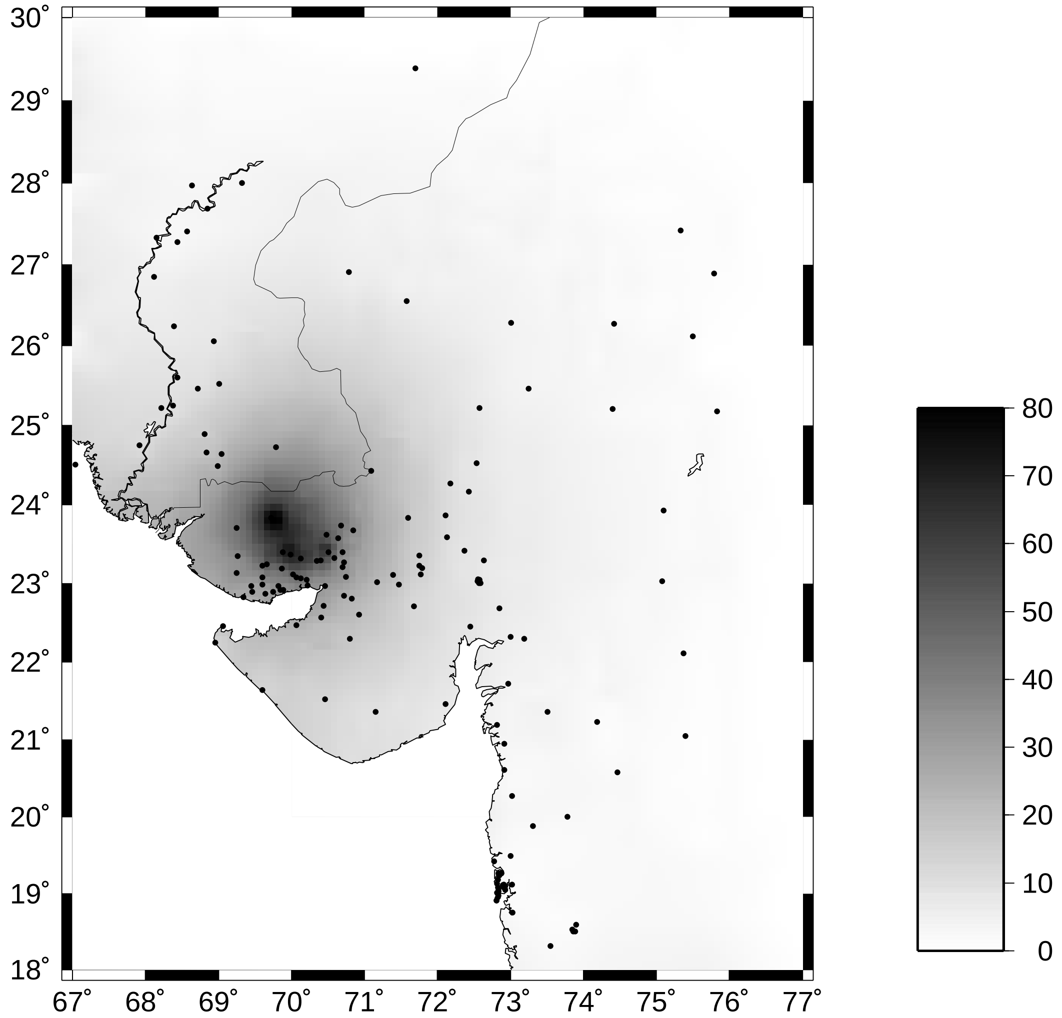

Figure 6. Predicted ground motions on rock for models with strength factor of 1.8. Note that intensities on soil would be 1 to 2 units higher. Note also that the scale is not the same as that used in figure 3, and indicates peak accelerations rather than intensity.

sider. We calculate residuals using ground motion predictions determined for $S_f = 1.8$, and find that most values are between 1 and 2 MMI units. The distribution of residuals is generally consistent with expectations for site response, as especially high residuals are found at presumed sediment sites to the northeast and southeast of the rupture. Relatively low residuals are also found at locations to the southwest, which lie on the Deccan lavas.

A coherent band of low residuals is also observed along the Indus River in Pakistan. Regional geologic maps indicate that these sites should be alluvial. However, we speculate that the relatively low ground motions in this region may reflect path rather than site effects. That is, the active plate boundary west and northwest of Gujarat will likely disrupt coherent *Lg* wave propagation, which will give rise to a higher apparent attenuation and lower intensities (Kennett 1989; Hanks and Johnston 1992). Considering the spatial distribution of residuals, we speculate that the true regional attenuation curve might be steeper than that predicted by that of Singh *et al.* (1999). appropriate for *Lg* waves for this particular earthquake.

Within 100 km of the fault, however, ground motions estimated from our MMI values are systematically higher than those predicted by the model, typically by 1–2 units. It is possible that most of this discrepancy is due to site response, which will tend to increase MMI on soil sites by at least one unit relative to that on rock sites. Other factors that may also be important are:

- the vulnerability of local buildings to shaking, and
- a tendency for media accounts to focus on the most extreme damage in hard-hit regions, especially in large cities, and
- the nature of the ground motions in an intraplate region.

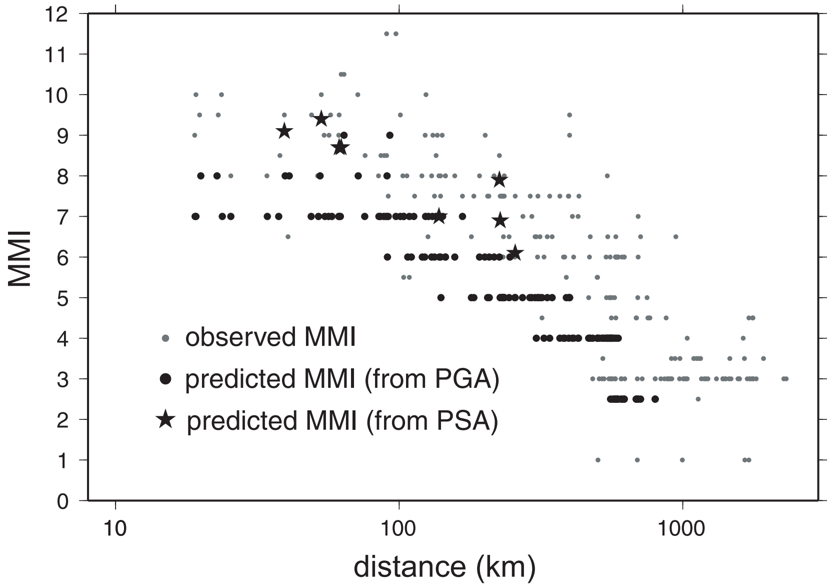

Figure 7. Our MMI values for the Bhuj earthquake are shown as a function of distance (small gray circles) along with predicted values calculated using a MMI-PGA relationship (large black circles) and one between MMI and response spectra (black stars).

It is difficult to estimate the bias contributed by each effect. However, we consider it unlikely that moderate estimated MMI values (IV–VI) are significantly amplified because of building vulnerability because these values reflect light damage (cracking of walls) and other effects (objects being knocked off shelves) that should not depend strongly on building type. It therefore appears likely that the other two factors account for more of the unit discrepancy, at least at close distances. Because news accounts generally focus on the most extreme rather than the typical damage in a region, it is not surprising that MMI values derived from media accounts will be systematically higher than those determined from average effects, in the manner employed by the Wald *et al* (1999) study.

One must also consider the possibility that a PGA-MMI relationship determined for earthquakes in California is not appropriate for an intraplate region. In particular, it has been suggested that because intraplate ground motions are generally characterized by a higher level of high-frequency energy, they might be more damaging (to some types of structures especially) than comparable earthquakes in interplate regions (e.g., Greig and Atkinson 1993; Atkinson 2001). To test this possibility, we recalculate predicted MMI values for a small number of locations using relationships between MMI and response spectra determined by Atkinson and Sonley (2000). These relationships are also determined for earthquakes in California. However, Atkinson (2001) validates their applicability in intraplate regions using the 1988 Saguenay earthquake, and argues that the relationships are generally appropriate because frequency content is handled explicitly. Figure 7 presents the MMI results determined from both PGA and response spectra, both on rock, and shows that the latter are indeed higher than the former. On an average, the MMI values are increased by approximately 1 unit when the response spectra relations are used. If one considers the expected influence of site response, the MMI predicted from response spectra are in reasonably good agreement with the observations.

4. Implications for the 1819 Allah Bund earthquake

The 1819 Allah Bund earthquake in the northern Rann of Kachchh was discussed at length by Oldham (1926) in one of his last important contributions. His interest in this event was initially stimulated by his efforts to complete his father's account of Indian earthquakes (Oldham 1883) and by the discovery of Baker's profile (Baker 1846) during a clean-out of the Bombay office of the Geographical Journal of Bombay in 1896. Baker's profile across the Allah Bund had been accidentally omitted by the editor from his narrative describing surface deformation but forms the basis of subsequent surface rupture parameter estimation by Bilham (1998).

Oldham collated newpaper reports of the 1819 event to produce an isoseismal contour map. This map was used by Richter (1958) to produce one of the first magnitude estimates for the event. His magnitude, 8.0, was derived from a comparison

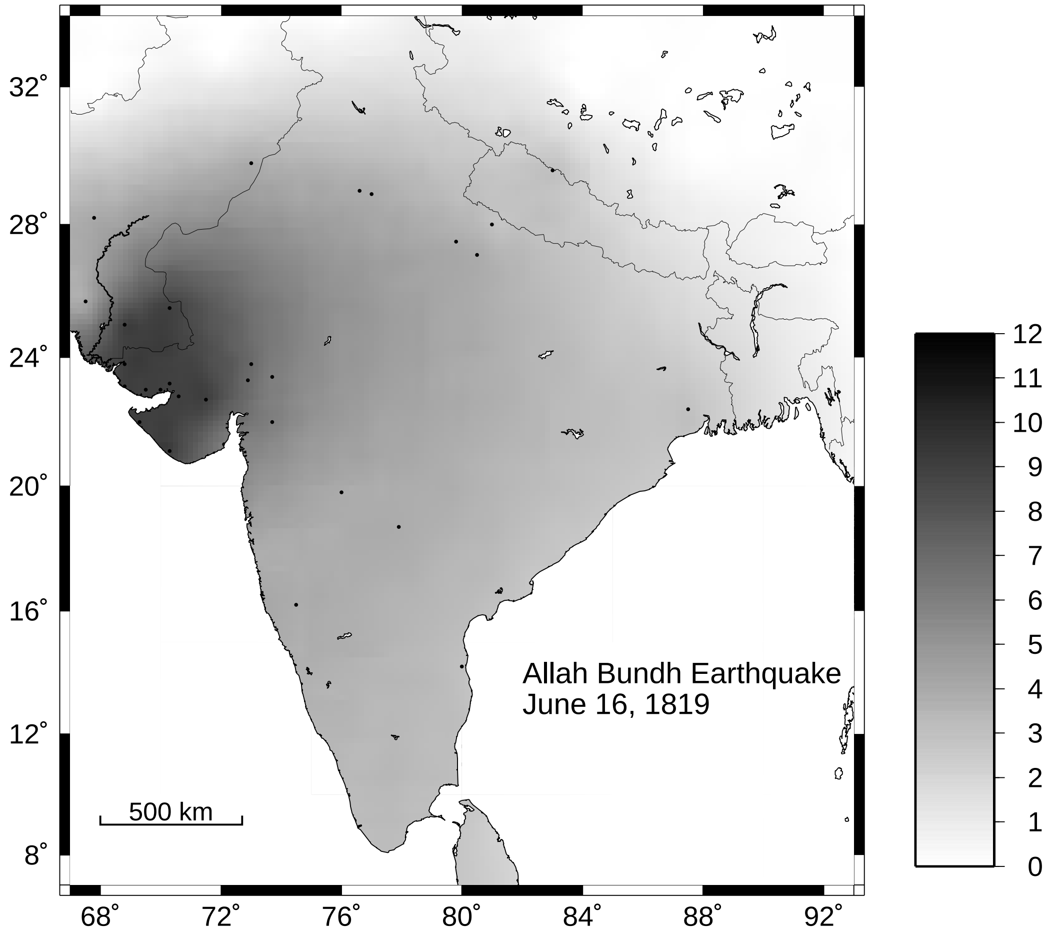

Figure 8. Distribution of shaking effects from the 1819 Allah Bund earthquake, from Bilham (1999) compared to those determined in this study for the 2001 Bhuj earthquake.

of the felt areas of the 1819 event with those of the 1905, 1934, and 1950 Indian earthquakes for which he had derived surface wave magnitudes. Recent recalibrations of these magnitudes suggest that many are inflated (Ambraseys and Bilham 2000; Chen and Molnar 1983).

Attempts to quantify the magnitude of the 1819 event from Oldham's isoseismal data were subsequently attempted by Johnston and Kanter (1992) and by Bilham (1998). Magnitude estimates varied from 7.6–7.9. A geologic estimate of the magnitude has been proposed by Rajendran and Rajendran (2001) based on the estimated rupture length and a surface slip estimate of 3 m. Bilham (1998) used Baker's profile to derive a geodetic moment magnitude of 7.7 ± 0.2

The 2001 Bhuj earthquake stands to provide important new constraint on the magnitude of the 1819 event in that the mechanisms and locations of the two events are very similar. In many cases, local construction practices have not changed. In some cases, the same historic structures were damaged by both events (e.g., the forts and town walls of Bhuj and Anjar). Yet there are important differences in that some earthquake resistant structures have been built in recent years; also, no concrete frame buildings existed in 1819.

A detailed intensity map for the 1819 earthquake is unavailable. However, Bilham (1998) does map out sites that experienced severe and light damage, as well as sites at which the event was reportedly felt. We make crude MMI assignments of IX, VI, and III for these shaking levels, respectively (figure 8). A comparison of the isoseismal distribution of the 1819 and 2001 earthquakes shows that they are virtually indistinguishable in overall characteristics. Both events were felt lightly on the eastern coast of India; both caused light damage to distances of 500–600 km; and both caused heavy damage to distances of approximately 100 km (figure 8). (The extent of the high-intensity region is larger for the 1819 earthquake than it is for the Bhuj earthquake but we attribute this to the sparsity of the 1819 data and our inability to assess precise MMI values for each site where "severe" damage occurred.)

We therefore conclude that the magnitude of the 1819 Allah Bund earthquake was also likely to have been very close to 7.6. This value is within the uncertainties of previous estimates, but suggests that rupture dimensions and/or slip in 1819 may have been somewhat smaller than the values permitted by the higher geologic and geodetic estimates.

5. Discussion and conclusions

We have compiled media-based intensity maps for the January 26th, 2001, Bhuj earthquake. These maps, based only on news accounts of the event, allow us to map out the general distribution of shaking effects; they will also ultimately provide insight into the potential biases associated with determination of intensities based solely on media accounts. Such results are expected to be very useful, as the 2001 Bhuj earthquake has important implications for earthquake hazard in not only India, but also in other parts of the world where the source zones and/or the wave travel paths are similar. Based on our results and the similarity between their intensity distributions, we conclude that the 1819 Allah Bund earthquake had a magnitude very close to that of the 2001 Bhuj event: 7.6 ± 0.1.

Our results show that, especially in the absence of modern instrumentation, MMI data can provide important information about the distribution of ground motions. As discussed earlier, site response patterns are quite evident in the intensity distribution at both near and far distances. The overall felt distribution of the event also provides insights into the nature of *Lg* wave propagation. Hanks and Johnston (1992) showed that the far-reaching effects of central/eastern U.S. earthquakes can be explained by the efficient propagation of *Lg* waves (i.e., higher mode surface waves) within cratonic north America. Kennett (1989) showed that *Lg* waves will propagate efficiently within a waveguide, but will be disrupted when they encounter complexity such as crustal thickening. The felt area of the Bhuj earthquake is contained almost entirely within the Indian subcontinent. Our results therefore provide observational confirmation of the modeling results of Kennett (1989), that *Lg* waves are significantly disrupted by large-scale crustal complexity.

Our finite-fault modeling results show that our estimated MMI values provide a good indication of the *distribution* of ground motions (peak ground acceleration). Although the predicted hard-rock shaking level is lower than that inferred from macroseismic observations, we conclude that site response can explain most of the discrepancy. We have discussed three additional possible factors that might also contribute to the discrepancy:

- extreme vulnerability of buildings in the Kachchh region,
- a tendency of news accounts to focus on the most dramatic damage, and
- the nature of the ground motions in intraplate crust.

Although the first factor has been widely discussed, it is unlikely to account for the discrepancy in regions that experienced moderate (MMI IV–VI shaking). We also note that the discrepancy is no larger in the epicentral region than at regional distances, which perhaps suggests that building vulnerability was not an important factor at close distances. This would not be an altogether surprising result, as building type and vulnerability are taken into account when MMI values are assigned.

At present it is difficult to assess the effect of a possible "media bias," although we consider it likely that such a bias did contribute to the discrepancy. A comparison with a survey-based intensity map will ultimately allow us to constrain the magnitude of this effect. This result will have implications for the interpretation of historic earthquakes for which the only available information is from printed media sources.

The final possibility, that the Bhuj ground motions were unusually damaging because of their high levels of high-frequency energy, is interesting to consider. To compare predicted and estimate MMI values we have used a relationship between MMI and peak ground acceleration determined from recent large earthquakes in California. However, it has been suggested that ground motions from large intraplate earthquakes might be more damaging than their interplate counterparts (e.g., Greig and Atkinson 1993; Atkinson 2001). We therefore also compared predicted and estimated MMI values using a relationship between MMI and response spectral amplitudes (Atkinson and Sonley 2000). Although also developed for California earthquakes, Atkinson (2001) concludes that the relationship is appropriate for earthquakes in eastern north America, at least for distances of 150 km or less. Our results show that using the response spectral regressions, our predicted ground motions imply rock MMI values approximately one unit higher than those estimated from the MMI-PGA relationship. For soil sites, the predicted MMI values would be about 1 unit higher than for rock sites. Thus there would be no significant discrepancy between observed and predicted MMI values.

Although much work remains to be done, the Bhuj earthquake provides important information to better understand the hazard posed by earthquakes that occur in and/or affect intercratonic regions. In addition to insights into the nature of source zones in low strain-rate environments, the event provides invaluable new information with which the ground motions from past and future large intracratonic earthquakes can be better understood.

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