

# The 21 May 2014 $M_w$ 5.9 Bay of Bengal Earthquake: Macroseismic Data Suggest a High-Stress-Drop Event

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*Online Material:* Tables of locations and associated intensity values.

## INTRODUCTION

A modest but noteworthy  $M_w$  5.9 earthquake occurred in the Bay of Bengal beneath the central Bengal fan at 21:51 Indian Standard Time (16:21 UTC) on 21 May 2014. Centered over 300 km from the eastern coastline of India (Fig. 1), it caused modest damage by virtue of its location and magnitude. However, shaking was very widely felt in parts of eastern India where earthquakes are uncommon. Media outlets reported as many as four fatalities. Although most deaths were blamed on heart attacks, the death of one woman was attributed by different sources to either a roof collapse or a stampede (see © Table S1, available in the electronic supplement to this article). Across the state of Odisha, as many as 250 people were injured (see © Table S1), most after jumping from balconies or terraces. Light damage was reported from a number of towns on coastal deltaic sediments, including collapsed walls and damage to pukka and thatched dwellings. Shaking was felt well inland into east-central India and was perceptible in multistoried buildings as far as Chennai, Delhi, and Jaipur at distances of  $\approx 1600$  km (Table 1).

In the days following the earthquake, we collected accounts from conventional news outlets as well as social media. Using these accounts, we assigned intensities in keeping with practices described by Martin and Szeliga (2010). The earthquake was reported as “felt” at 310 locations in the eastern and central Indian subcontinent (Fig. 2a; © Table S1). In contrast to available data from the U.S. Geological Survey Community Internet Intensity Map (“Did You Feel It?” [DYFI]) site (Fig. 2b), our intensity map for the 21 May 2014 earthquake (Fig. 2a) confirms initial impressions that the event was remarkably widely felt for an  $M_w$  5.9 earthquake.

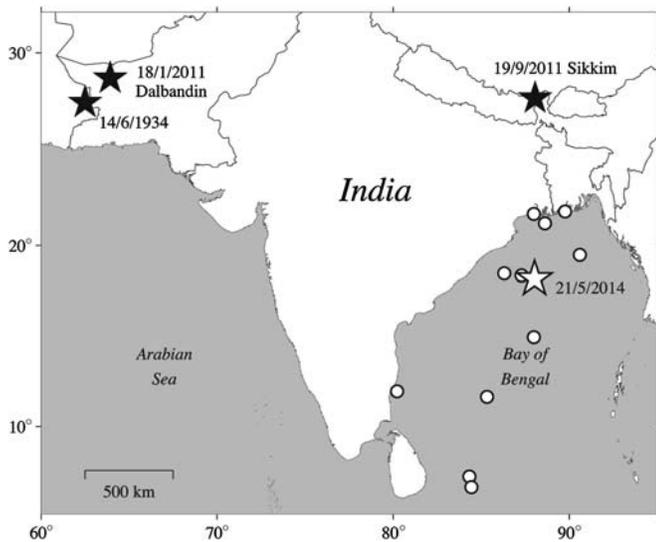
The purpose of this report is to make available the newly collected intensity dataset and to present preliminary analysis of this noteworthy recent earthquake. We further show that the intensity distribution provides evidence for a high-stress-drop source. These results bear out the observation made two

decades ago by Hanks and Johnston (1992, p. 20): “[Our] results suggest that it should be a fairly simple matter to infer a high-stress-drop event from intensity data alone, provided that an instrumental  $M_0$  or  $M_w$  value is known separately.” Our study illustrates the potential value of carefully determined intensity data for investigations of earthquake source properties, especially when instrumental recordings are sparse. We suggest it may in fact be a more robust way to estimate stress drop than conventional approaches, which require correction of attenuation to estimate pulse width or corner frequency (e.g., Anderson, 1986); the estimate is then cubed to estimate stress drop (Madariaga, 1976). Lastly, we discuss potentially important implications of our results for efforts to characterize probabilistic seismic hazard in the Himalayan region.

## OBSERVED INTENSITY DISTRIBUTION

The  $M_w$  5.9 Bay of Bengal earthquake was reported as “felt” at 310 locations in the eastern and central Indian subcontinent, of which 223 contained sufficient information to assign intensities (Fig. 2a; © Table S1). These were interpreted in terms of the European Macroseismic Scale 1998 (EMS-98; Grünthal, 1998), a successor to the Medvedev–Sponheuer–Kárník (MSK) scale (Medvedev and Sponheuer, 1969). Both of these scales are based on the original formulation of the modified Mercalli intensity (MMI) scale (Wood and Neumann, 1931), the Mercalli–Cancani–Sieberg (MCS) scale (Sieberg, 1930), and the Geophysics Institute of the Academy of Sciences (GEOFIAN) scale (Medvedev, 1953), with modified and expanded criteria that include six vulnerability classes to assist in distinguishing between effects to different building types and discrimination between structural and nonstructural damage.

In practice, the differences between EMS and MMI values are minor (e.g., Musson *et al.*, 2010). For this study, we assign EMS intensities following the practice of Ambraseys and Douglas (2004) and Martin and Szeliga (2010). We use multiple press accounts from some larger cities to distinguish site response between fluvial and hard rock sites (Hough *et al.*, 2000). To each intensity value, we also provide a quality weighting



▲ **Figure 1.** The white star represents the location of the 21 May 2014 earthquake. Open circles mark the locations of  $M_w > 5.0$  instrumentally recorded earthquakes in the Bay of Bengal basin since 1964. Locations and dates of other events are also indicated (black stars): 2011 Dalbandin, 2011 Sikkim, and the 1934 Balochistan earthquake near the Iran–Pakistan border. Source depth estimates for the 2014 event range from 50 km (U.S. Geological Survey [USGS] monthly *Preliminary Determination of Epicenter Bulletin*) to 60–85 km (Singh *et al.*, 2015).

(Musson, 1998) identifying location and or reliability errors in the raw data.

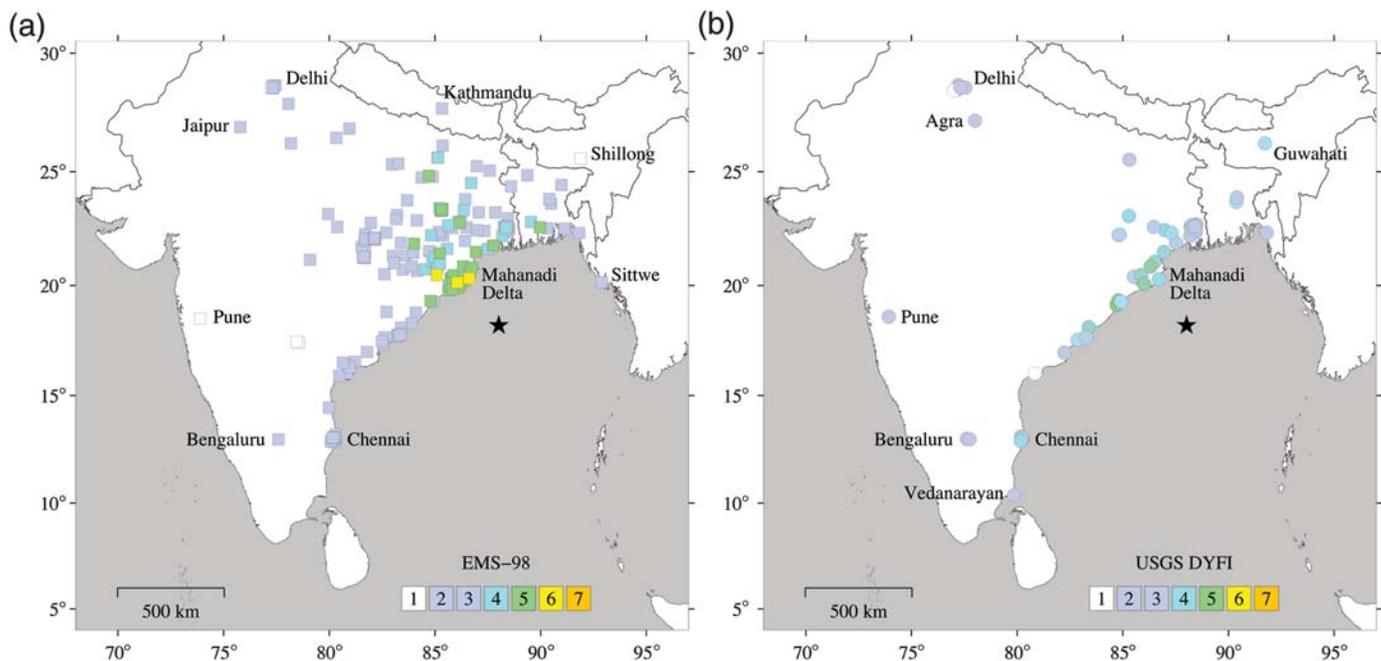
Despite being centered  $\approx 270$  km offshore, with a modest moment magnitude, this earthquake produced strong shaking

in the Mahanadi delta region, with significant suggested amplification by fluvial sediments. Damage was reported from many villages and towns including reports of collapsed walls and thatched houses (see Table S1).

Toward the west and north of the delta region, felt shaking was reported in many locations at distances up to  $\approx 1000$  km, with a sprinkling of accounts from greater distances. The extent of the felt area to the east and northeast is poorly constrained; the easternmost felt report shown on Figure 2a is from the city of Sittwe in western Myanmar. To the south, the shock was perceived in many places along the coast and in multistoried buildings as far south as Chennai.

One striking feature of the macroseismic field, given the magnitude and location of the earthquake, were the isolated reports from such distant places as Delhi, Jaipur, and Kathmandu, Nepal, among others. Felt shaking was reported from 17 locations at distances greater than 1000 km, including 6 locations at distances greater than 1500 km. At the largest distances, most documented accounts come from observers on the upper floors of multistoried buildings.

The U.S. Geological Survey (USGS) DYFI map for this earthquake (<http://earthquake.usgs.gov/earthquakes/eventpage/usb000qy82#dyfi>; last accessed January 2014) displays felt reports from 60 cities received using the DYFI questionnaire (Wald *et al.*, 1999). In contrast to recent significant earthquakes in the United States, the DYFI response was not extensive, with only a single response from most of the reporting cities. The available DYFI data (Figs. 2b and 3b) show that although the earthquake was widely felt along the east coast of India, felt reports were only available from a few cities away from the coast. We were able to extract considerably more information from Indian media sources in the aftermath of the earthquake, which received



▲ **Figure 2.** (a) European Macroseismic Scale 1998 (EMS-98) intensities for the 21 May 2014 earthquake, estimated by the authors from media accounts, plotted using the color scale shown. (b) Modified Mercalli intensities from the USGS “Did You Feel It?” (DYFI) system.

widespread media attention in spite of concurrent media focus on a landmark general election.

## INTERPRETATION OF OBSERVED INTENSITY DISTRIBUTION

The media-based EMS data determined in this study are generally consistent with the DYFI data, with three key differences: (1) The media-based data are significantly more spatially rich, in particular for locations away from the coast; (2) media accounts stated that shaking was not felt in Pune (southeast of Mumbai), at a distance of 1485 km, while a single report submitted to DYFI reported felt shaking there; and (3) the highest DYFI intensity is 5.0, whereas EMS values of 6.0 were assigned at four locations based on media accounts. We discuss each of these in turn below.

The spatial richness of the media-based intensity map reveals the continuing value in undertaking traditional media surveys in countries where the DYFI system is not well known and/or Internet access is simply not widespread. The inland extent (> 500 km) of the felt area deduced from the media-based map (Fig. 2a) rules out the possibility that macroseismic effects were restricted to coastal areas as suggested by the DYFI map. The more detailed view of the shaking distribution rules out a possibility suggested by the DYFI map, namely that unusually strong shaking along the eastern coast of India was a consequence of converted  $T$ -phases (e.g., Krivoy and Eppley, 1964; Talandier and Okal, 1997; Leonard, 2004). Leonard (2004) proposed that unusually strong  $T$ -phase generation accounted for isolated instances of felt shaking in Australia,  $\approx$ 1800 km northwest of an  $M_w$  7.1 earthquake in New Zealand in 2003.

On the other hand, even where DYFI responses are sparse, a plot of DYFI intensities versus distance commonly reveals long, flat tails at large distances, because if even a single person reports felt shaking, that defines an intensity value of 2.0 (Boatwright and Phillips, 2013). Indeed, at distances above 1000 km, the DYFI intensities reveal a more gradual decay than do the media-based intensities. A reasonable interpretation of the two intensity values for Pune is that very weak shaking might have been felt by a very small number of individuals who were especially well situated to feel shaking in multistoried buildings. As suggested by Boatwright and Phillips (2013), shaking on the very ragged edge of perceptibility could reasonably be characterized by an intensity value between 1 and 2, although by convention such values are never assigned by either the DYFI system or traditional practice.

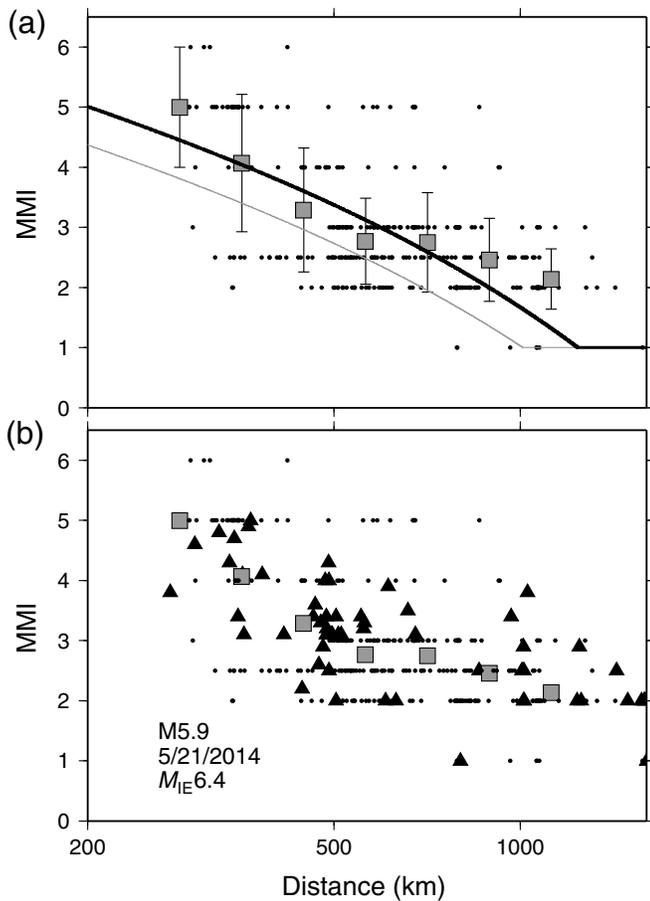
Lastly, the difference between the highest estimated values in the two datasets is consistent with the results of Hough (2013, 2014a), who consider traditional media-based versus DYFI intensities. These studies conclude that, even when intensities are assessed subjectively from archival accounts using modern conservative practices, they tend to be controlled by relatively dramatic effects, whereas, by design, the DYFI system reports representative values within a given spatial footprint. To facilitate a comparison of the intensities of the 2014 earth-

quake with those of other events analyzed by Martin and Szeliga (2010), who, barring a few exceptions, considered media-based intensities, we will focus on analysis of media-based intensities in this study rather than including any of the DYFI values.

Using the intensity database compiled by Martin and Szeliga (2010), Szeliga *et al.* (2010) developed separate interplate and intraplate intensity-prediction equations for the Himalayan region and for peninsular (cratonic) India, respectively. Following the Bakun and Wentworth (1997) approach, one can use these relationships to estimate intensity magnitudes ( $M_I$ ), for historical earthquakes in the Indian subcontinent (Szeliga *et al.*, 2010). If the intensity-prediction equations are developed using moment magnitude ( $M_w$ ), the expectation is that the intensity magnitude  $M_I$  inferred for historical events will correspond to  $M_w$ . We will discuss the validity of this assumption in the [Implications for a High Stress Drop](#) section. In the absence of equations developed specifically for offshore events, we assume that the cratonic model developed by Szeliga *et al.* (2010) provides the best calibration for the 2014 earthquake. In Figure 3, we show the media-based intensities for the 2014 earthquake together with predicted intensities using the cratonic model for  $M_I$  5.9 and 6.4.

Using the cratonic model of Szeliga *et al.* (2010), intensity data for the 2014 earthquake are best fit assuming  $M_I$  6.4, with a  $1-\sigma$  uncertainty of 0.7. Following Hough (2014a), we refer to this as the effective intensity magnitude ( $M_{IE}$ ); that is,  $M_{IE}$  is the magnitude that best fits available intensity data, given an established regional intensity-prediction relation. Although the instrumentally determined moment magnitude lies within the  $1-\sigma$  uncertainties, Figure 3 reveals that, in keeping with the overall impression of the felt extent, observed intensities are significantly higher than predicted values for  $M_w$  5.9. (The difference between the light and dark curves in Figure 3a illustrates the significance of the difference between the two magnitude values.) We further note that, as discussed by Hough *et al.* (2013), one expects that attenuation for hybrid oceanic-stable continental region (SCR) paths will be somewhat higher than attenuation within a pure SCR, or cratonic, environment. Although the cratonic model of Szeliga *et al.* (2010) provides the best available calibration, our  $M_{IE}$  estimate is thus likely to be conservative.

Our results can be compared to analysis of instrumental data. Using data from 38 broadband stations in India, Singh *et al.* (2015) considers both peak ground acceleration (PGA) and peak ground velocity (PGV) and shows that PGA values are comparable to those from the  $M_w$  6.5 Chamoli earthquake, although PGV values are smaller. At comparable distances, the velocity spectrum of the Bay of Bengal event exceeds that of the larger Chamoli earthquake for frequencies above roughly 1 Hz (frequencies that control both intensity and PGA; Trifunac and Brady, 1975; Sokolov and Chernov, 1998). Analyzing data from seven broadband stations around the rim of the Bay of Bengal, Rao *et al.* (2015) also document unusually strong high-frequency radiation.

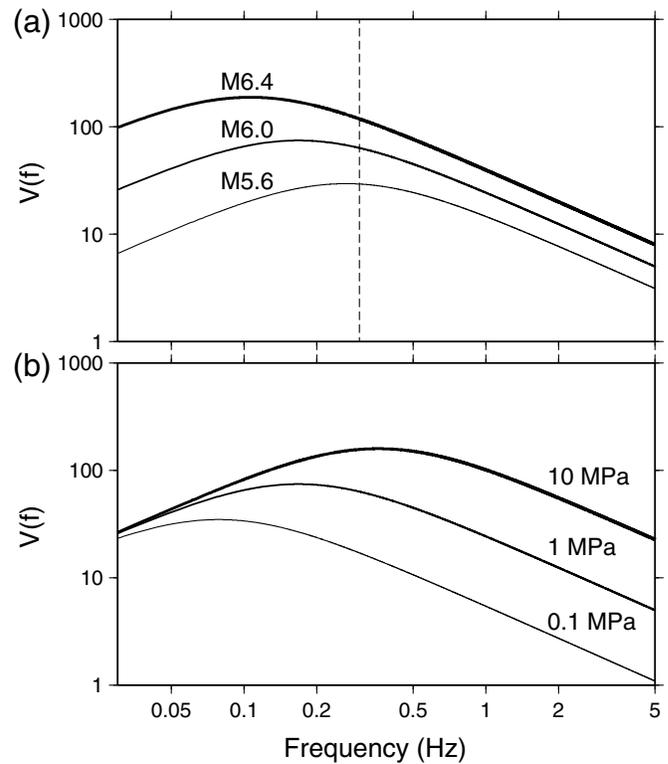


▲ **Figure 3.** (a) Media-based intensities determined in this study as a function of epicentral distance (black dots), and bin-averaged values (gray squares) with  $1-\sigma$  uncertainties. The lines indicate predicted intensities using the cratonic model of [Szeliga et al. \(2010\)](#) for  $M_I$  5.9 (light line) and 6.4 (heavy line). (b) Same intensity dataset, but replotted with DYFI intensities (black triangles).

## IMPLICATIONS FOR A HIGH STRESS DROP

Shaking intensities from the 2014 Bay of Bengal earthquake were thus significantly higher than predicted by well-calibrated intensity- and ground-motion prediction equations, a result that is corroborated by assessment of PGA values ([Singh et al., 2015](#)) and spectral energy ([Rao et al., 2015](#)). One can discount the possibility that the discrepancy is due to inconsistency in intensity assessment; intensity values for both the 2014 earthquake and the calibration events were consistently interpreted by the first author ([Martin and Szeliga, 2010](#)). The two remaining explanations are that path effects and/or source properties accounted for the anomalous high-frequency radiation.

[Singh et al. \(2015\)](#) point out that the deep source depth of the Bay of Bengal earthquake can explain its relative depletion of low-frequency energy and enrichment of high-frequency energy compared to the 1999 Chamoli earthquake, which occurred at a depth of 21 km and generated much stronger surface waves. They note, however, that the full effects of source



▲ **Figure 4.** (a) Theoretical relative velocity spectra for a stress drop of 1 MPa and  $M_w$  5.6, 6.0, and 6.4. The dashed vertical line indicates a frequency of 0.3 Hz. (b) Theoretical velocity spectra for an  $M_w$  6 earthquake for stress drop values 0.1, 1, and 10 MPa. Spectral amplitudes are relative; that is, absolute amplitudes are not physically meaningful.

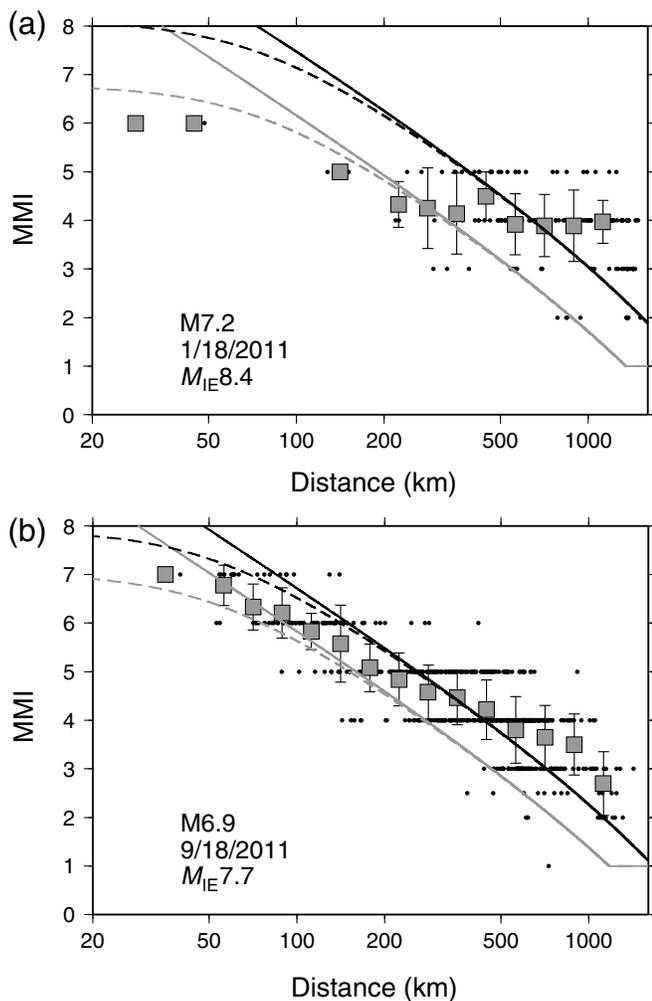
depth on high-frequency radiation are difficult to quantify and suggest that relative high-frequency enrichment of the 2014 earthquake may be partially attributable to a source effect, in particular, a high stress drop. [Rao et al. \(2015\)](#) estimate a high dynamic stress drop, 94 MPa.

As discussed by [Hanks \(1979\)](#), [Boore \(1983\)](#), and [Hanks and Johnston \(1992\)](#), first principals can be used to demonstrate that high-frequency radiation depends quite strongly on stress drop. As discussed by [Hough \(2014b\)](#), this dependence can be illustrated simply with theoretical omega-square velocity source spectra using standard equations; for example,

$$\Delta\sigma = M_0(f_c/0.42\beta)^3,$$

in which  $\Delta\sigma$  is stress drop,  $f_c$  is corner frequency, and  $\beta$  is the shear-wave velocity near the source ([Madariaga, 1976](#)). In Figure 4, we show theoretical velocity spectra for an  $M_w$  6 earthquake with a range of stress-drop values (Fig. 4a) and for a range of magnitude values between 5.6 and 6.4 with a single stress drop (1 MPa; Fig. 4b). Using a random approach to relate PGV to  $M_w$  and  $\sigma$ , [Boore \(1983\)](#) shows that  $\log(\text{PGV})$  is  $\sim 0.55 M_w + 0.64 \log(\Delta\sigma)$ .

As noted, while it is not known precisely which frequencies control observed shaking intensities, felt ground motions



▲ **Figure 5.** (a) EMS intensities for the 2011 Dalbandin earthquake, together with predicted curves (Szeliga *et al.*, 2010) for  $M_l$  7.2 (light line),  $M_l$  8.4 (dark line), and the same magnitude values, assuming a depth of 70 km (dashed lines). (b) EMS intensities for the 2011 Sikkim earthquake, together with predicted curves for  $M_l$  6.9 (light line) and 7.7 (dark line), and with both magnitudes assuming a source depth of 50 km (dashed lines).

are generally associated with frequencies of 1 Hz and above (Trifunac and Brady, 1975; Frankel, 1994; Sokolov and Chernov, 1998). We assume, based in part on personal experience of the authors, that frequencies as low as 0.3 Hz can generate weakly felt shaking from large distant earthquakes. Figure 4a illustrates the point made by Hanks and Johnston (1992), namely that, for a moderate earthquake, shaking at these frequencies depends relatively weakly on moment or moment magnitude. In contrast, Figure 4b shows how strongly high-frequency shaking levels depend on stress drop. For the 2014 earthquake, the effective intensity magnitude is 0.5 units larger than the moment magnitude. This suggests a stress-drop value that is a factor of  $\approx 3$  higher than the average stress-drop value of the calibration events used by Szeliga *et al.* (2010). Given that intraplate and, specifically, intermediate-depth and intraplate oceanic events are

expected to be generally characterized by relatively high stress-drop values (e.g., Scholz *et al.*, 1986; Choy and Boatwright, 1995; Allmann and Shearer, 2009), our results suggest that the 2014 earthquake was a notably high-stress-drop event.

We identify two other recent events in and near India for which there is macroseismic and/or instrumental evidence of high stress drop: the 18 January 2011  $M_w$  7.2 Dalbandin earthquake and the 18 September 2011  $M_w$  6.9 Sikkim earthquake. The 2011 Dalbandin earthquake, which occurred on a normal fault within the subducting Arabian–Ormara plate had an energy magnitude,  $M_e$  7.3 (P. Earle, written comm., 2014), implying a somewhat high apparent stress. (There has been some inconsistency in the reporting of  $M_E$  for this event. Martin and Kakar [2012] cite a value of 7.9, the value given by National Earthquake Information Center [NEIC] at the time. As of 27 October 2014, the NEIC listed 8.2.) Moreover, although the earthquake was located within the active plate boundary zone, the intensity distribution determined by Martin and Kakar (2012) from field observations and media accounts reveals that intensities at regional distances are significantly above the Szeliga *et al.* (2010) Himalayan model.

The intensity distribution of the 2011 Dalbandin earthquake (Fig. 5a) is also enigmatic: the overall felt extent is larger than expected for  $M_w$  7.2, but, at distances within 200–300 km, intensities are commensurate with or lower than predicted values for the event magnitude. If one uses the intensity-prediction equations of Szeliga *et al.* (2010) with an assumed source depth of 70 km, predicted intensities are lowered somewhat for distances within 200 km (Fig. 5a, dashed line), but observed intensities still fall below this curve. We note that the epicentral region of this earthquake was both sparsely populated and not conducive to fieldwork due to political unrest; thus only ten of 200 intensity values are for locations within 200 km. It is therefore possible that more severe shaking is not documented by available intensity data. It is also possible that direct field surveys revealed generally lower intensity levels than would have been inferred from media accounts, as Hough and Pande (2007) conclude was the case for the 2001 Bhuj, India, earthquake. Lastly, however, it is possible that, for unknown reasons, near-field intensities for relatively deep earthquakes are lower than predicted given the traditional intensity-prediction equation characterization, even accounting for source depth. The key point for this study, however, is that the felt extent of the earthquake was extremely large given the constrained  $M_w$  of 7.2. Again, the deep depth of the event likely contributed to some extent to the large felt area, but together with the high instrumentally determined  $M_E$  value, the large felt area provides evidence for a high-stress-drop event.

The 2011 Sikkim earthquake, which occurred in the greater Himalayas near the India–Nepal border region, had a notably high  $M_E$  value, 7.7, relative to the moment magnitude, 6.9 (NEIC). The purely media-based intensity distribution determined by the first author reveals intensity values that are higher than predicted from the Szeliga *et al.* (2010) Himalayan model (Fig. 5b; ⊕ Table S2), again in particular at dis-

tances greater than  $\approx 200$  km. The reported depth of this earthquake varied from a reported value of  $\approx 20$  km (USGS) to 47.4 km (Global Centroid Moment Tensor [Global CMT] catalog). The near-field intensities are less anomalous than for the Dalbandin earthquake, but they do fall below the predicted curve, given the  $M_{IE}$  value that best fits data at distances greater than 200 km. In this case, the observed near-field intensities are well characterized using the Himalayan model of [Szeliga \*et al.\* \(2010\)](#) and assuming a source depth of 50 km. Once again, both the high  $M_E$  value and the large overall felt extent provide evidence for a high-stress-drop event.

The conclusion that the 2014 Bay of Bengal earthquake was characterized by a high stress drop is consistent with expectations given a body of evidence that oceanic intraplate earthquakes are characterized by high stress drop (e.g., [Choy and Boatwright, 1995](#); [Choy and McGarr, 2002](#)). High-stress-drop events are also not unexpected within India and the surrounding region, given the compressional environment and the occurrence of lower crustal, intraplate earthquakes, which [Bilham \*et al.\* \(2003\)](#) suggest is associated with the flexure of the Indian plate.

As discussed, it is possible that both source depth and stress drop contribute to the relative enrichment of high-frequency energy for deeper crustal events. Regardless of the interpretation, the conclusion that some events generate anomalously high-frequency radiation has important implications for analysis of historical earthquakes, which we discuss briefly here and in the following section. In the absence of instrumental data, intensity data for a historical earthquake will reflect the effective intensity magnitude,  $M_{IE}$ . It will thus not generally be possible to identify a high-stress-drop event (or source depth) from intensity data alone, because there is no independent constraint on  $M_w$ . One potentially interesting event is the 14 June 1934  $M_{GR}$  7.0 Balochistan earthquake that is believed to have originated within the lower crust at a depth of 80 km along the Iran–Pakistan border (⊕ Table S3). The cratonic model of [Szeliga \*et al.\* \(2010\)](#) yields an  $M_{IE}$  of  $7.6 \pm 0.7(1\sigma)$ , assuming the hypocentral depth of 80 km ([Gutenberg and Richter, 1954](#)), whereas the Himalayan model ([Szeliga \*et al.\*, 2010](#)) gives an  $M_{IE}$  of  $8.6 \pm 0.7(1\sigma)$ . There is no moment magnitude estimate for this event, but as discussed by [Martin and Kakar \(2012\)](#), the felt area was almost as large as that of the 19 January 2011  $M_w$  7.2 Dalbandin earthquake, which we conclude was likely to have been a high-stress-drop event.

## DISCUSSION

We have presented evidence that the 2014 Bay of Bengal earthquake, along with two other recent events in the region, were high-stress-drop events. It is possible that inferred high stress drops of the earthquakes analyzed in this study are in part a consequence of source depth. The estimated source depth of the 2014 earthquake is 60–85 km ([Singh \*et al.\*, 2015](#)); the estimated depths for the Dalbandin and Sikkim earthquakes in 2011 were, respectively,  $\approx 70$  and  $\approx 50$  km. However, an as-

sociation of deep source depth with high stress drop is complicated by the fact that the depth dependence of stress drop has been a matter of considerable debate. A number of past studies have inferred a trend of increasing stress drop with distance (e.g., [Jones and HelMBERGER, 1988](#); [Hardebeck and Hauksson, 2001](#); [Mori \*et al.\*, 2003](#); [Allmann and Shearer, 2009](#)), while others have found no depth dependence (e.g., [Houston and Williams, 1991](#), and [Jin \*et al.\* 2000](#) found stress drop to be constant with depth). Moreover the inferred depth dependence is weak; for example, [Allmann and Shearer \(2009\)](#) conclude that, over the depth ranges at which most earthquakes in California occur (5–20 km), median stress drop increases by less than a factor of 2). However, while the issue clearly remains open, our results and those of a number of past studies suggest that deep intraplate Indian events might be characterized by relatively high stress drop and, therefore, high ground motions at regional distances.

Regardless of the interpretation, the primary result of this study is that the 2014 Bay of Bengal earthquake had higher shaking intensities at regional distances than expected given the instrumentally determined  $M_w$ , with observed shaking intensities commensurate with  $M_{IE}$  6.4. The two other examples discussed—the 2011 Dalbandin and 2011 Sikkim earthquakes, which have even more anomalous regional shaking distributions—suggest that high-stress-drop earthquakes are not uncommon, both in intraplate regions and along the Himalayan arc. Past investigations of intraslab events in oceanic subduction zones have also found generally high stress drops (e.g., [Choy and Boatwright, 1995](#); [Choy and McGarr, 2002](#); [Strasser \*et al.\*, 2010](#)).

It is thus virtually certain that other high-stress-drop earthquakes are lurking in the historical catalog, including events along the Himalayan arc. Because of the trade-off between magnitude and stress drop discussed in this report, when only intensity data for a historical earthquake are available, the inferred  $M_I$  value will not necessarily provide a reliable indication of  $M_w$ . As the Dalbandin and Sikkim earthquakes illustrate, intensity data from regional distances can imply a significantly higher  $M_I$  than the true  $M_w$ . The opposite bias would hold for anomalously low-stress-drop events, but little evidence has been found for such events within the intraplate or compressional Himalayan environment. We therefore expect that  $M_w$  of large historical Indian earthquakes has been overestimated more frequently than underestimated, due to the occurrence of high-stress-drop events, many of which would have been assumed to be interplate earthquakes due to their locations. For example, had an equivalent of the 2011 Sikkim earthquake occurred during historical times, it would likely be in the historical catalog as a high-magnitude-7 earthquake. This suggests that known historical earthquakes have released less overall moment than has been estimated, given the conventional assumption that  $M_I$  values indicate  $M_w$ . To the extent that historical  $M_w$  values have been used to estimate the long-term moment accrual rate for the Himalayan arc, the rate could be biased high. It further suggests that, to the extent that historical  $M_w$  values have been used to identify slip deficits

Table 1 Magnitude Types Used in This Report		
Type	Sym	Reference
Moment	$M_w$	Kanamori (1977)
Intensity	$M_I$	Bakun and Wentworth (1997)
Gutenberg–Richter	$M_{GR}$	Richter (1958)
Energy	$M_E$	Choy and Boatwright (1995)
Effective intensity	$M_{IE}$	Hough (2014b)

(e.g., Bilham and Ambraseys, 2005), estimates of slip deficits could potentially be biased low.

## CONCLUSIONS

We present intensity data for the 2014  $M_w$  5.9 Bay of Bengal earthquake determined from an exhaustive search of Indian media accounts following the earthquake. EMS intensities are assigned for each account using the modern conservative practices (e.g., Ambraseys and Bilham, 2003; Ambraseys, 2004); of particular note, these assignments are consistent with those of Martin and Szeliga (2010), who undertook a comprehensive reinterpretation of the Indian historical catalog. In this study, we show that intensities for the 2014 earthquake are significantly higher than predicted using the intensity prediction equations developed by Szeliga *et al.* (2010) for peninsular India. The intensities are consistent with an effective intensity magnitude,  $M_{IE}$ , of 6.4. We show that the difference between  $M_w$  and  $M_{IE}$  suggests that the 2014 earthquake was a high-stress-drop event, with a stress drop higher by a factor of roughly 3 than the average stress drop of the calibration events used by Szeliga *et al.* (2010). Our results bear out the observation made by Hanks and Johnston (1992) that stress drop can be estimated relatively robustly from intensity data, if an instrumental magnitude is available.

Our results have potentially important implications for probabilistic seismic-hazard assessment in India. With intensity data alone, one can only estimate  $M_I$ , which for high-stress-drop events such as those discussed in this study can be larger than the true  $M_w$ , potentially by a full magnitude unit or more.

The results of this study also have important general implications for efforts to characterize and predict earthquake ground motions at frequencies of engineering concern, an issue discussed by Bormann and Di Giacomo (2011). Although moment magnitude is assumed to be the preferred magnitude estimate in the modern catalogs used to develop ground-motion prediction equations, shaking at frequencies of engineering concern for a given magnitude depends on stress drop, which cannot be predicted in advance and is difficult to estimate precisely for past earthquakes. Moreover stress-drop values are known to vary significantly. Hough (1996) suggests that stress-drop variability is higher for small earthquakes than for  $M_w > 6$  events, but is at least a factor of 10 for large events.

Thus, the range of stress-drop variability will potentially give rise to shaking intensity differences commensurate with  $\approx 0.8$  magnitude units. In other words, an  $M_w$  6 earthquake might potentially have shaking intensities commensurate with magnitude values ranging from 5.6 to 6.4. Several studies have concluded that ground-motion-prediction equation variability is smaller than the predicted variability associated with stress drop (Strasser *et al.*, 2010; Oth and Bindi, 2013). Nonetheless, these results provide a further explanation why ground-motion prediction equations are ubiquitously characterized high event-to-event uncertainty: no matter how carefully other effects (such as hanging wall/footwall shaking differences) are characterized, unless stress drop is accounted for, ground motions predicted from moment magnitude will be characterized by substantial uncertainty. One alternative, as suggested by a number of past studies (e.g., Choy and Boatwright, 1995; Boatwright *et al.*, 2002; Bormann and Di Giacomo, 2011) might be to move away from moment magnitude as the preferred magnitude value for development of ground-motion prediction equations, instead adopting an energy magnitude that more directly reflects the level of shaking at frequencies of engineering concern. However, a fundamental limitation would remain for probabilistic seismic-hazard analysis: scaling relationships can be used to predict  $M_w$  for a hypothetical future rupture, while energy magnitude is less predictable. Fundamentally, the dependence of shaking on stress drop poses a challenge for efforts to predict in advance the severity of felt and damaging shaking from future events.

## DATA AND RESOURCES

U.S. Geological Survey (USGS) “Did You Feel It?” data are available at <http://earthquake.usgs.gov/earthquakes/dyfi/events/us/b000qy82/us/index.html> (last accessed October 2014). © Intensity data assigned by the authors for the 2014 Bay of Bengal earthquake, the 14 June 1934 Balochistan earthquake, and the 19 September 2011 Sikkim earthquake are available in the electronic supplement. The  $M_E$  estimates for the Dalbandin and Sikkim earthquakes are from the USGS/National Earthquake Information Center (NEIC) at [http://comcat.cr.usgs.gov/earthquakes/eventpage/pde20110118202323480\\_68#summary](http://comcat.cr.usgs.gov/earthquakes/eventpage/pde20110118202323480_68#summary) (last accessed October 2014) and [http://earthquake.usgs.gov/earthquakes/eqinthenews/2011/usc0005wg6/neic\\_c0005wg6\\_e.php](http://earthquake.usgs.gov/earthquakes/eqinthenews/2011/usc0005wg6/neic_c0005wg6_e.php) (last accessed June 2014). ✉

## ACKNOWLEDGMENTS

We thank Annemarie Baltay, David Boore, an anonymous reviewer, and Zhigang Peng for constructive reviews that improved the manuscript; and we thank Paul Earle and S. K. Singh for helpful discussions. Figures were generated using the Generic Mapping Tools package (Wessel and Smith, 1991).

## REFERENCES

- Allmann, B. P., and P. M. Shearer (2009). Global variations of stress drop for moderate to large earthquakes, *J. Geophys. Res.* **114**, 1978–2012, doi: [10.1029/2008JB005821](https://doi.org/10.1029/2008JB005821).
- Ambraseys, N. N. (2004). The state-of-the-art and practice of long-term seismicity, *Ann. Geophys.* **47**, 335–338.
- Ambraseys, N., and R. Bilham (2003). Reevaluated intensities for the great Assam earthquake of 12 June 1897, Shillong, India, *Bull. Seismol. Soc. Am.* **93**, 655–673.
- Ambraseys, N., and J. J. Douglas (2004). Magnitude calibration of north Indian earthquakes, *Geophys. J. Int.* **159**, no. 1, 165–206, doi: [10.1111/j.1365-246X.2004.02323.x](https://doi.org/10.1111/j.1365-246X.2004.02323.x).
- Anderson, J. G. (1986). Implication of attenuation for studies of the earthquake source, *Earthquake Source Mechanics*, American Geophysical Union, Washington, D. C., 311–318.
- Bakun, W. H., and C. M. Wentworth (1997). Estimating earthquake location and magnitude from seismic intensity data, *Bull. Seismol. Soc. Am.* **87**, 1502–1521.
- Bilham, R., and N. Ambraseys (2005). Apparent Himalayan slip deficit from the summation of seismic moments for Himalayan earthquakes, *Curr. Sci.* **88**, 1658–1663.
- Bilham, R., R. Bendick, and K. Wallace (2003). Flexure of the Indian plate and intraplate earthquakes, *J. Earth Syst. Sci.* **112**, no. 3, 315–329.
- Boatwright, J., and E. Phillips (2013). Exploiting the demographics of “Did You Feel It?” responses to estimate the felt area of moderate earthquakes (abstract), *Seismol. Res. Lett.* **84**, 149.
- Boatwright, J., G. L. Choy, and L. C. Seekins (2002). Regional estimates of radiated seismic energy, *Bull. Seismol. Soc. Am.* **92**, 1241–1255, doi: [10.1785/0120000934](https://doi.org/10.1785/0120000934).
- Boore, D. M. (1983). Stochastic simulation of high-frequency ground motions based on seismological models of the radiated spectra, *Bull. Seismol. Soc. Am.* **73**, 1865–1894.
- Bormann, P., and D. Di Giacomo (2011). The moment magnitude  $M_w$  and the energy magnitude  $M_e$ : Common roots and differences, *J. Seismol.* **15**, 411–427, doi: [10.1007/s10950-010-9219-2](https://doi.org/10.1007/s10950-010-9219-2).
- Choy, G. L., and J. Boatwright (1995). Global patterns of radiated seismic energy and apparent stress, *J. Geophys. Res.* **100**, 18,205–18,228.
- Choy, G. L., and A. McGarr (2002). Strike-slip earthquakes in the oceanic lithosphere: Observations of exceptionally high apparent stress, *Geophys. J. Int.* **150**, no. 2, 506–523.
- Frankel, A. (1994). Implications of felt area-magnitude relations for earthquake scaling and the average frequency of perceptible ground motion, *Bull. Seismol. Soc. Am.* **85**, 462–465.
- Grünthal, G. (Editor) (1998). European Macroseismic Scale EMS-98, in *Cahiers du Centre Européen de Géodynamique et de Séismologique*, Vol. 15, Centre Européen de Géodynamique et de Séismologie, Luxembourg, 101 pp.
- Gutenberg, B. U., and C. F. Richter (1954). *Seismicity of the Earth and Related Phenomena*, Princeton University Press, Princeton, New Jersey, 310 pp.
- Hanks, T. C. (1979).  $b$ -values and  $\omega^{-V}$  seismic source models: Implications for tectonic stress variations along active crustal fault zones and the estimation of high-frequency strong ground motion, **84**, 2235–2242, doi: [10.1029/JB084iB05p02235](https://doi.org/10.1029/JB084iB05p02235).
- Hanks, T. C., and A. Johnston (1992). Common features of the excitation and propagation of strong ground motion for North American earthquakes, *Bull. Seismol. Soc. Am.* **82**, 1–23.
- Hardebeck, J., and E. Hauksson (2001). Crustal stress field in southern California and its implications for fault mechanics, *J. Geophys. Res.* **106**, 21,859–21,882.
- Hough, S. E. (1996). Observational constraints on earthquake source scaling: Understanding the limits in resolution, *Tectonophysics* **261**, 83–95.
- Hough, S. E. (2013). Spatial variability of “Did You Feel It?” intensity data: Insights into sampling biases in historical earthquake intensity distributions, *Bull. Seismol. Soc. Am.* **93**, 2767–2781, doi: [10.1785/0120120285](https://doi.org/10.1785/0120120285).
- Hough, S. E. (2014a). Earthquake intensity distributions: A new view, *Bull. Earthq. Eng.* **12**, 135–155.
- Hough, S. E. (2014b). Ground motions from injection-induced earthquakes in the central and eastern United States, *Bull. Seismol. Soc. Am.* **104**, 2619–2626, doi: [10.1785/0120140099](https://doi.org/10.1785/0120140099).
- Hough, S. E., and P. Pande (2007). Quantifying the “media bias” in intensity surveys: Lessons from the 2001 Bhuj, India, earthquake, *Bull. Seismol. Soc. Am.* **97**, 638–645.
- 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**, 23,839–23,864.
- Hough, S. E., J. Munsey, and S. N. Ward (2013). A significant, tsunami-generated historical earthquake offshore the Carolina coast, *Seismol. Res. Lett.* **84**, 891–898, doi: [10.1785/0220120152](https://doi.org/10.1785/0220120152).
- Houston, H., and Q. Williams (1991). Fast rise times and the physical mechanism of deep earthquakes, *Nature* **352**, 520–522.
- Jin, A., C. A. Moya, and M. Ando (2000). Simultaneous determination of site responses and source parameters of small earthquakes along the Atotsugawa fault zone, central Japan, *Bull. Seismol. Soc. Am.* **90**, 1430–1445.
- Jones, L. E., and D. V. Helmberger (1998). Earthquake source parameters and fault kinematics in the eastern California shear zone, *J. Geophys. Res.* **88**, 1337–1352.
- Kanamori, H. (1977). The energy release in great earthquakes, *J. Geophys. Res.* **82**, 2971–2987.
- Krivoy, H. L., and R. A. Eppley (1964).  $T$ -phase of May 11, 1962, recorded in Hawaii, Geological Survey Research 1964: *U.S. Geol. Surv. Profess. Pap.* 501-B, B105–B107.
- Leonard, M. (2004).  $T$ -phase perception: The August 2003,  $M_w$  7.1, New Zealand earthquake felt in Sydney, 1,800 km away, *Seismol. Res. Lett.* **75**, 475–480, doi: [10.1785/gssrl.75.4.475](https://doi.org/10.1785/gssrl.75.4.475).
- Madariaga, R. (1976). Dynamics of an expanding circular crack, *Bull. Seismol. Soc. Am.* **66**, 639–666.
- Martin, S. S., and D. M. Kakar (2012). The 19 January 2011  $M_w$  7.2 Dalbandin earthquake, Balochistan, *Bull. Seismol. Soc. Am.* **102**, 1810–1819, doi: [10.1785/0120110221](https://doi.org/10.1785/0120110221).
- Martin, S., and W. Szeliga (2010). A catalog of felt intensity data for 589 earthquakes in India, 1636–2009, *Bull. Seismol. Soc. Am.* **100**, 536–569.
- Medvedev, S. V. (1953). A new seismic scale, *Tr. Geofiz. Inst., Akad. Nauk, SSR* **21**, no. 148.
- Medvedev, S. V., and W. Sponheuer (1969). Scale of seismic intensity, in *Proc. World Conf. Earthquake Eng.*, 4th, Santiago, Chile, Vol. A2, 143–153.
- Mori, J., R. E. Abercrombie, and H. Kanamori (2003). Stress drops and radiated energies of aftershocks of the 1994 Northridge, California, earthquake, *J. Geophys. Res.* **108**, 2545, doi: [10.1029/2001JB000474](https://doi.org/10.1029/2001JB000474).
- Musson, R. (1998). Intensity assignments from historical earthquake data: Issues of certainty and quality, *Ann. Geofisc.* **41**, no. 1, 79–91.
- Musson, R. M. W., G. Grünthal, and M. Stucchi (2010). The comparison of macroseismic intensity scales, *J. Seismol.* **14**, 413–428, doi: [10.1007/s10950-009-9172-0](https://doi.org/10.1007/s10950-009-9172-0).
- Oth, A., and D. Bindi (2013). Stress drop variations and their relevance for ground motion prediction: Case study of Japan, *Eos Trans. AGU* (Fall Meet. Suppl.), Abstract S51F-01.
- Rao, N. C., P. N. Rao, R. M. Kumar, S. Prasanna, and D. Srinagesh (2015). Structure and tectonics of the Bay of Bengal through waveform modeling of the M 6.0 21 May 2014 earthquake *Seismol. Res. Lett.* **86**, no. 2A, doi: [10.1785/0220140166](https://doi.org/10.1785/0220140166).
- Richter, C. F. (1958). *Elementary Seismology*, W. H. Freeman, San Francisco, 768 pp.

- Scholz, C. H., C. A. Aviles, and S. G. Wesnousky (1986). Scaling differences between large interplate and intraplate earthquakes, *Bull. Seismol. Soc. Am.* **76**, 65–70.
- Sieberg, A. (1930). Geologie der Erdebeben, in *Handbuch der Geophysik*, B. Gutenberg (Editor), Borntraeger, Berlin, 550–554.
- Singh, S. K., V. Hjorleifsdottir, G. Suresh, D. Srinagesh, R. K. Chadha, and X. Perez-Campos (2015). Bay of Bengal earthquake of 21 May 2014 ( $M_w$  6.1): Source depth and ground motions, *Seismol. Res. Lett.* **86**, doi: [10.1785/0220140238](https://doi.org/10.1785/0220140238) (in review).
- Sokolov, V. Y., and Y. K. Cherov (1998). On the correlation of seismic intensity with Fourier amplitude spectra, *Earthq. Spectra* **14**, 679–694, doi: [10.1193/1.1586022](https://doi.org/10.1193/1.1586022).
- Strasser, F. O., M. C. Arango, and J. J. Bommer (2010). Scaling of the source dimensions of interface and intraslab subduction-zone earthquakes with moment magnitude, *Seismol. Res. Lett.* **81**, 941–950, doi: [10.1785/gssrl.81.6.941](https://doi.org/10.1785/gssrl.81.6.941).
- Szeliga, W., S. E. Hough, S. Martin, and R. Bilham (2010). Intensity, magnitude, location, and attenuation in India for felt earthquakes since 1762, *Bull. Seismol. Soc. Am.* **100**, 570–584.
- Talandier, J., and E. A. Okal (1997). Human perception of *T* waves: The June 22, 1977 Tonga earthquake felt on Tahiti, *Bull. Seismol. Soc. Am.* **69**, 1475–1486.
- Trifunac, M. D., and A. G. Brady (1975). A study on the duration of strong earthquake ground motion, *Bull. Seismol. Soc. Am.* **65**, 581–626.
- Wald, D. J., V. Quitoriano, L. Dengler, and J. W. Dewey (1999). Utilization of the Internet for rapid community intensity maps, *Seismol. Res. Lett.* **70**, no. 6, 680–697.
- Wessel, P., and W. H. F. Smith (1991). Free software helps map and display data, *Eos Trans. AGU*, **72**, 441, 445.
- Wood, H., and F. Neumann (1931). Modified Mercalli intensity scale of 1931, *Bull. Seismol. Soc. Am.* **21**, 277–283.

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Published Online 18 February 2015