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A Moment Magnitude Seismicity Catalog for the United States East of the Rocky Mountain Front

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ABSTRACT

The creation of a uniform moment magnitude (M_w) seismicity catalog for the central and eastern United States (CEUS) is an essential but not straightforward task. Event locations (ranging from precise in the current well-instrumented era to qualitative but with uncertainty fairly well characterized in the pre-instrumental era) and modern instrumental magnitudes are not the problem. The controversial difficulty and the focus of this research is with magnitudes of the pre-instrumental and early instrumental events because this is where the large earthquakes that represent the maximum earthquakes (M_{max}) of the CEUS are found. These are the events that dominate CEUS seismic hazard estimates: 1811-12 New Madrid (3-5 events); 1886 Charleston, SC; 1895 Charleston, MO. If you accurately characterize the magnitudes of the hundreds of $M_w \leq 5$ events in the catalog but mis-characterize the size of New Madrid or the two Charlestons, then you've done little to improve hazard estimation.

Here we present the results of an extensive investigation (Dockter, 2001) of the best means to extract an M_w estimate from MMI data for large pre-instrumental CEUS earthquakes such as New Madrid or Charleston. This effort was redirected in mid-project by the occurrence of the 2001 M_w 7.6-7.7 Bhuj, India, earthquake. Bhuj was the ideal analog for the 7 Feb 1812 New Madrid thrust earthquake (Johnston, 2001). Its MMI data across the India subcontinent made possible a recalibration of the M_w – MMI CEUS regressions for large CEUS events. Utilizing point MMI data with large M_w constraints from Bhuj allows a robust MMI to M_w regression that avoids the uncertainty and assumptions associated with contoured MMI data (Johnston 1996 b,c; Hough *et al.*, 2000) and lack of large M_w regression control (Bakun *et al.*, 2003; Bakun and Hopper, 2004).

A CEUS UNIFORM MOMENT MAGNITUDE CATALOG: THE SCIENTIFIC CHALLENGE

The catalog of CEUS earthquakes M ≥ 3.0 (Mueller *et al.*, 1997) is extremely uneven in terms of event completeness and uniform magnitude (M_w) assignment. The problem is summarized in Figure 1, which plots the number of events per decade in the 1996 NEHRP CEUS catalog. The

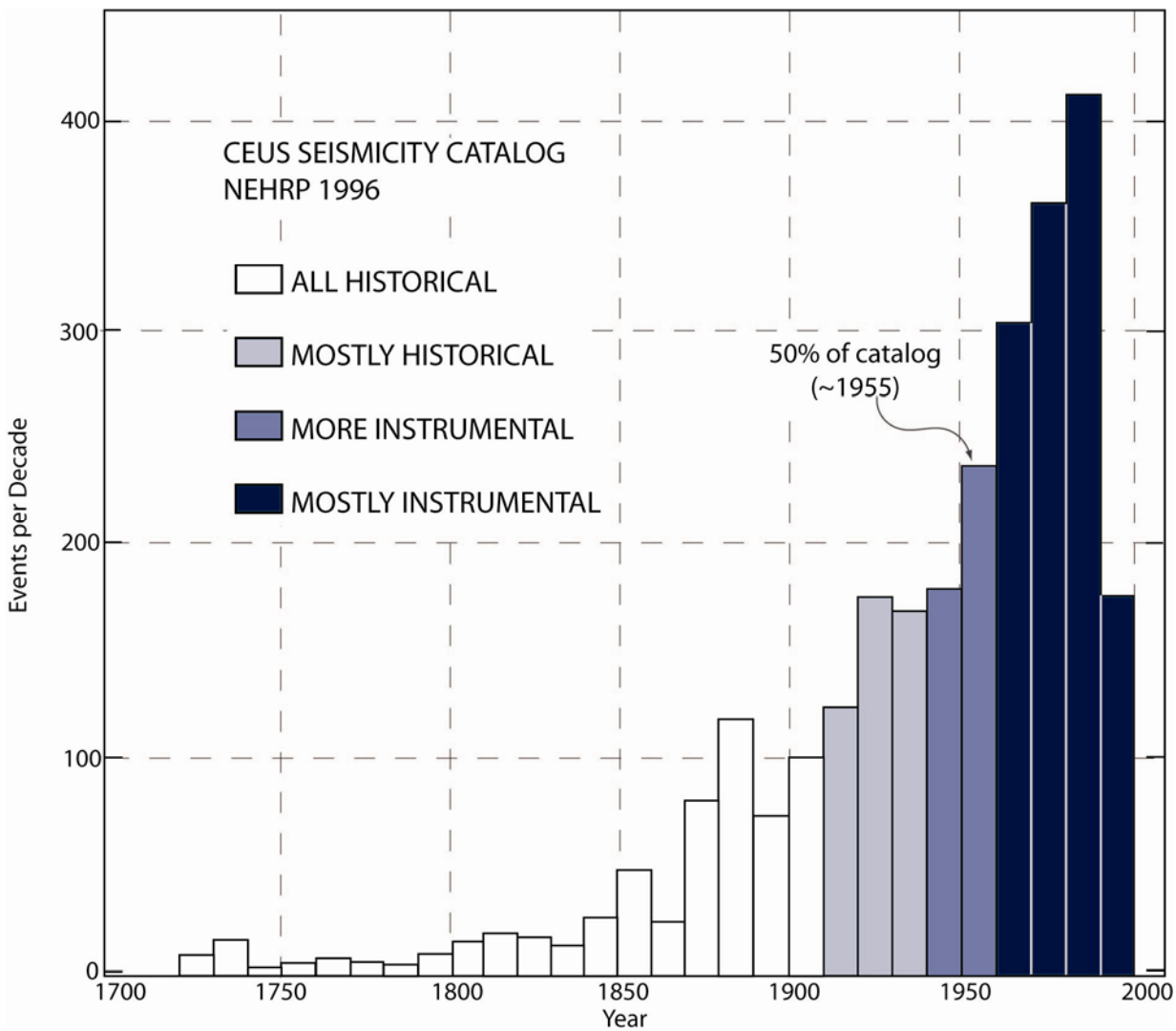


Figure 1. Data type distribution per decade in the NEHRPP 1996 catalog for the National Seismic Hazard Mapping Project

figure implies a steep increase in CEUS seismic activity from the pre-instrumental (historical) era (~1720 - ~1910) to the modern instrumental era (~1960 -2000 (note the 1990s decade is incomplete)). If you assume the seismic activity level during this nearly three-century time

period has been roughly constant (an assumption we believe is a good one) then it is clear that the catalog is incomplete at the M3 level for all but the modern instrumental era. It is probably not complete at the M4.0-4.5 level until the early instrumental era, ~1920. Thus the pre-instrumental era is the most poorly characterized, not only in terms of completeness, but also and more importantly in terms of uniform M_w estimation. In hazard assessments there are various techniques to compensate for incompleteness in the catalog. Therefore, in this project we focus on the latter problem, that of M_w estimation for pre-instrumental earthquakes, in particular the large M ≥ 6.0 events that contribute most of the CEUS hazard.

We began by working with Bill Bakun of the USGS to adapt to the CEUS his successful point MMI regression technique applied in California (Bakun and Wentworth, 1997). The point MMI technique has many potential advantages over the contouring MMI data for isoseismal areas utilized by Johnston (1996 b,c) and Hough *et al.* (2000). In particular, it completely avoids the potentially large uncertainty associated with just how you draw the contour. However, differences of opinion arose over the proper application of the point MMI method. As detailed in a later section, there were three main areas of disagreement: (1) application of California regression coefficients to the CEUS (Bakun and Hopper, 2004); (2) combining all MMI levels into one regression equation (Bakun *et al.*, 2003; Bakun and Hopper, 2004); this seemed to be an oversimplified approach for this project and led to our developing our own regressions with CEUS-specific coefficients for each MMI level (Dockter, 2001). Therefore, we proceeded independent from the Bakun approach even before the 2001 Bhuj, India, earthquake occurred. The final disagreement with Bakun and co-workers was over (3) incorporating the 2001 Bhuj MMI data into the training set regression events for the CEUS. Bakun and co-workers did not include Bhuj, citing differences in attenuation between the India subcontinent and the CEUS. We counter those arguments in Dockter (2001) and this report and use the Bhuj earthquake data to constrain our large pre-instrumental regressions to estimate M_w for large CEUS historical earthquakes. In contrast the regression used in Bakun and Hopper (2004) is largely unconstrained for events M_w > 6.5-7.0.

For the remainder of this report we will document and justify our approach to CEUS MMI to M_w regression analysis in terms of the above points (1)-(3). Our conclusions will be a set of CEUS-specific MMI regressions with large earthquake constraint supplied by the high-quality data set of the CEUS analog, the M_w 7.7 Bhuj, India, earthquake of 2001.

DEVELOPMENT OF REGRESSIONS TO RECOVER M_w FROM CEUS-SPECIFIC INSTRUMENTAL MAGNITUDES OR POINT MM INTENSITY DATA

Instrumental Magnitudes. For earthquakes of the early instrumental or modern instrumental era, robust regressions already exist to recover M_w; further development in this project would add little if any to reduction of hazard uncertainty and therefore were not attempted. Since the National Seismic Hazard Mapping Project (Mueller *et al.*, 1997) used the regressions of Johnston (1996a), especially for recovering M_w from m_{bLg}, we simply show the quoted uncertainties on M_w from the regressions for reference. A number of other regressions with very similar results exist, although often without formal uncertainties quoted.

Independent Variable	Predicted M_w value ± 1 standard deviation	
M_0 (scaler seismic moment)	M_w (M_0)	± 0.16
M_s (teleseismic surface wave)	M_w (M_s)	± 0.19
m_{bLg} (regional *Lg* wave)	M_w (m_{bLg})	± 0.23
m_n (Canadian m_{bLg})	M_w (m_n)	± 0.23
m_b (teleseismic body wave)	M_w (m_b)	± 0.26
M_L (various regional, local)	M_w (M_L)	± 0.35

CEUS-Specific MMI to M_w Regressions. In this section we summarize the results presented in Dockter (2001) up to the occurrence of the January 2001 M_w 7.7 Bhuj earthquake. A following section then examines the effect of inclusion of Bhuj data on the final MMI- M_w regressions, which are then presented in the *Conclusions* section as the final research product of this project.

The basic format for relating M_w (or logM_0) to MMI (eg, Frankel, 1994) is:

$$M_w = A_0 + A_1(\text{MMI}) + A_2(\Delta) + A_3\log(\Delta)\ , \qquad (1)$$

Where A_0- A_3 are the regression coefficients, Δ is the source-receiver distance in km, and MMI is a point intensity observation, ranging from 1(I) to 12(XII) on the Modified Mercalli scale. The problem with equation (1) is it is underdetermined – there are too many degrees of freedom for stable solutions. To address this problem Bakun and Hopper (2004) [designated BH04] and Bakun *et al.* (2003) assume California values for A_0 and A_1 (derived in Bakun and Wentworth (1997)), reducing equation (1) to A_2 and A_3 coefficients to be determined from the independent variables MMI and Δ.

Not willing to use California values for the A_0 and A_1 coefficients for the CEUS, Dockter (2001),

as slightly modified by ACJ for this report [designated DJ01], employed a different strategy. Rather than lumping all MMI observations into one master regression, DJ01 developed a different regression for each MMI value (only II ≤ MMI ≤ VI had sufficient data for a successful regression). By designating a given MMI value specific to each MMI- M_w relation, the A_1 (MMI) term in equation (1) becomes a constant that can be combined with A_0 and create a new, single coefficient. The resulting comparison will aid in evaluating the advantages and disadvantages of the two approaches.

BH04: $M_w = [-0.830 + 0.595(\text{MMI})] + A_2(\Delta) + A_3\log(\Delta)$ II ≤ MMI ≤ X

DJ01: $M_w = [\quad A_1 \quad] + A_2(\Delta) + A_3\log(\Delta)$ *for each MMI* II ≤ MMI ≤ VI

In BH04 all MMI values are used with the same regression coefficients; only MMI varies according to its assigned value. Note the square bracket term. Instead of two additional coefficients to be determined (A_0 and A_1), BH04 uses the constants -0.83 and 0.595. These were determined from California data in Bakun and Wentworth (1997) and used without modification in BH04 for the CEUS. DJ01 reduce the theoretically necessary 4 regression coefficients to 3 by removing the MMI term from the regression altogether. This is done by computing separate regression relation (different A_1, A_2, A_3) for each MMI level, II through VII. The cost is a series of regression relations rather than one master relation; the benefit is that there is no arbitrary assumption of A_0 and A_1 values imported from an active tectonic region. Both BH04 and DJ01 found it necessary to reduce the 4 regression coefficients (to 2 and 3 respectively) in order to achieve acceptable stability and convergence of the regressions.

A final observation is that combining all MMI levels into one regression has the potential to introduce an unknown level of systematic error. This is because to combine MMI levels requires the implicit and probably inaccurate assumption that the level of ground velocity or acceleration (whichever best correlates with MMI) increases linearly and regularly with MMI. There is no theoretical reason this should be the case and very little if any empirical evidence. If this assumption is not true, a systematic bias among analyzed events will be introduced depending on the portion of MMI point data available at each MMI level. The approach of DJ01 removes this potential source of systematic error.

The third point of divergence between DJ01 and BH04 – incorporation of data from the 2001 Bhuj, India, event to constrain the large earthquake behavior of the regressions – is perhaps the most important difference in our approaches in that it has the greatest effect on estimated CEUS seismic hazard. We therefore devote a separate section to this point in order to develop it more thoroughly.

INCLUSION OF DATA FROM THE 2001 BHUJ, INDIA (M7.7) DATA AND FINAL REGRESSIONS

The M_w 7.7 [8 different M_0 determinations for Bhuj average to M_w 7.65; generally in discussion we round this to 7.7, others round to 7.6] Bhuj earthquake occurred on 26 January 2001 in the Kutch (Kachchh) rift zone, westernmost India near the Pakistani border. This was about one-half year into the award period for this project. Prior to Bhuj we had struggled to constrain the large magnitude ($M_w > 7 \pm 0.5$) portion of our CEUS MMI – M_w regressions. The only available North American $M_w > 7$ event was the 1927 M_w 7.2 Grand Banks, Newfoundland earthquake, far offshore and perhaps even in ocean crust. This meant that in Dockter (2001) most of the higher value MMI data were either missing (located at sea) or tended to have high on-land values because of the abnormally high quality factor Q (high Q = low attenuation, attenuation proportional to Q^{-1}) of the eastern Canadian crust. In summary, the Grand Banks earthquake was an unsuitable anchor for the large magnitude portion of our CEUS regressions.

But was the Bhuj earthquake a more viable large magnitude anchor? Before we could accept it as such, two main questions needed affirmative answers: (1) Was the Bhuj earthquake a valid stable continental region (SCR) analog event for CEUS regressions? And (2) Was the seismic attenuation (Q) of the Indian sub-continent comparable to the CEUS (BH04 and companion papers argued it was not)? For question (1) we reproduce on the next page a table from Johnston (2001), one of the publication products of both this project and the Mid-America Earthquake (MAE) Center. It documents a remarkable correspondence between the Bhuj earthquake and the culminating event of the 1811-12 New Madrid sequence – the 7 February 1812 earthquake – both in terms of its source characteristics and its geologic/tectonic setting.

There are those who argue because of its proximity to the Chaman transform plate boundary in Pakistan (~300-400 km distance), Bhuj is not a valid SCR earthquake. The Kutch rift may well be subject to higher tectonic stresses because of this proximity; that may shorten the intra-rift large earthquake recurrence interval, but that does not invalidate the abundant evidence of Table 1 that not only is Bhuj a valid CEUS SCR analog event but it bears many remarkable similarities to the 7 February 1812 third principal New Madrid shock.

Question (2) focuses on comparing the regional (not local within the Reelfoot and Kutch rifts) attenuation of the Indian sub-continent and the CEUS. We sharpen the question with two figures from Dockter (2001). Figure 2 maps the distribution of intensity data points across India, the Himalayan front and adjacent Pakistan. These data were collected by the USGS's Susan Hough and posted on her web site. Intensity data in addition to Hough's in Figure 2 are courtesy of B. K. Rastogi of NGRI, Hyderabad, India. We acknowledge with gratitude both of these sources that made possible the high quality point intensity data set of Figure 2.

Table 1: Comparison of Attributes of the Bhuj and New Madrid Earthquakes

Attribute	New Madrid, USA 7 February 1812	Bhuj, India 26 January 2001
Host geologic structure	Failed intracontinental rift: **Reelfoot rift**	Failed intracontinental rift: **Kutch rift** or graben
• Age of rifting	Precambrian (with major re-activation in the Mesozoic)	Mesozoic (Jurassic)
• Rift orientation to regional tectonic stress regime	Oblique, angle ~30° - 40°	Perpendicular, angle ~90°
• Regional crustal class	Stable Continental Region	Stable Continental Region
• Crustal thickness	~40 km	~40 km
• Regional crustal age	Proterozoic (0.9 – 1.6 b.y.)	Proterozoic (0.9 – 1.6 b.y.)
• Distance from plate boundary or ATR	1,200–1,500 km to Rocky Mts. or Caribbean P.B.	300 – 400 km to Chaman transform (Asia-Pakistan)
Source Fault: type	**Reelfoot fault**: thrust	**Unnamed**: blind thrust
• Orientation to regional stress	~ Perpendicular (see Fig. 1)	~ Perpendicular (see Fig. 1)
• Length	70 – 90 km	35 – 55 km†
• Dip/down-dip width	30° – 40°/45 km#	40° - 50°/30 – 45 km†
• Surface rupture	Probably (3-7 m, sharp fold)	Probably not
• Prior large earthquakes	Yes, at least two	Unknown
• Prior large earthquakes in the rift fault system	Yes, ~1400 AD, 900 AD, and 500 AD	Yes, in 1819 (Allah Bundh) and ~1100 AD
Mainshock: Seismic Moment	10×10^{27} dyn-cm (M_w 8.0)#	4×10^{27} dyn-cm (M_w 7.7)
• Body-wave magnitude	$m_b = 7.4$ (estimated)	$m_b = 6.9$
• Liquefaction field	Large and severe	Large and severe (see chpt. 3)
• Maximum intensity (MMI)	XI –XII	XI – XII
• Intensity felt limit	> 2000 km	> 2000 km
• Aftershock sequence	Robust, at least 4 $M_w = 6.5$	Weak, $M_w = 5.8$ largest

† from aftershock hypocenter locations # modeled or estimated in Johnston (1996)

The efforts of CERI after the occurrence of the Bhuj earthquake were focused on transporting a portable seismic array from Memphis to the Bhuj epicentral region and recording thousands of its aftershocks (MAE Center, 2001). This effort provided the evidence for a Bhuj mainshock source scaling much more consistent with SCR as opposed to ATR (active tectonic region) source events (Johnston, 2001). Moreover the depth of faulting of the Bhuj mainshock extended through the seismogenic upper crust to deep within (perhaps through?) the previous believed aseismic lower crust. Both the Bhuj mainshock's unexpected source scaling and depth of faulting as established from the aftershock data were essential in establishing Bhuj as a valid SCR event (Table 1 and Johnston, 2001).

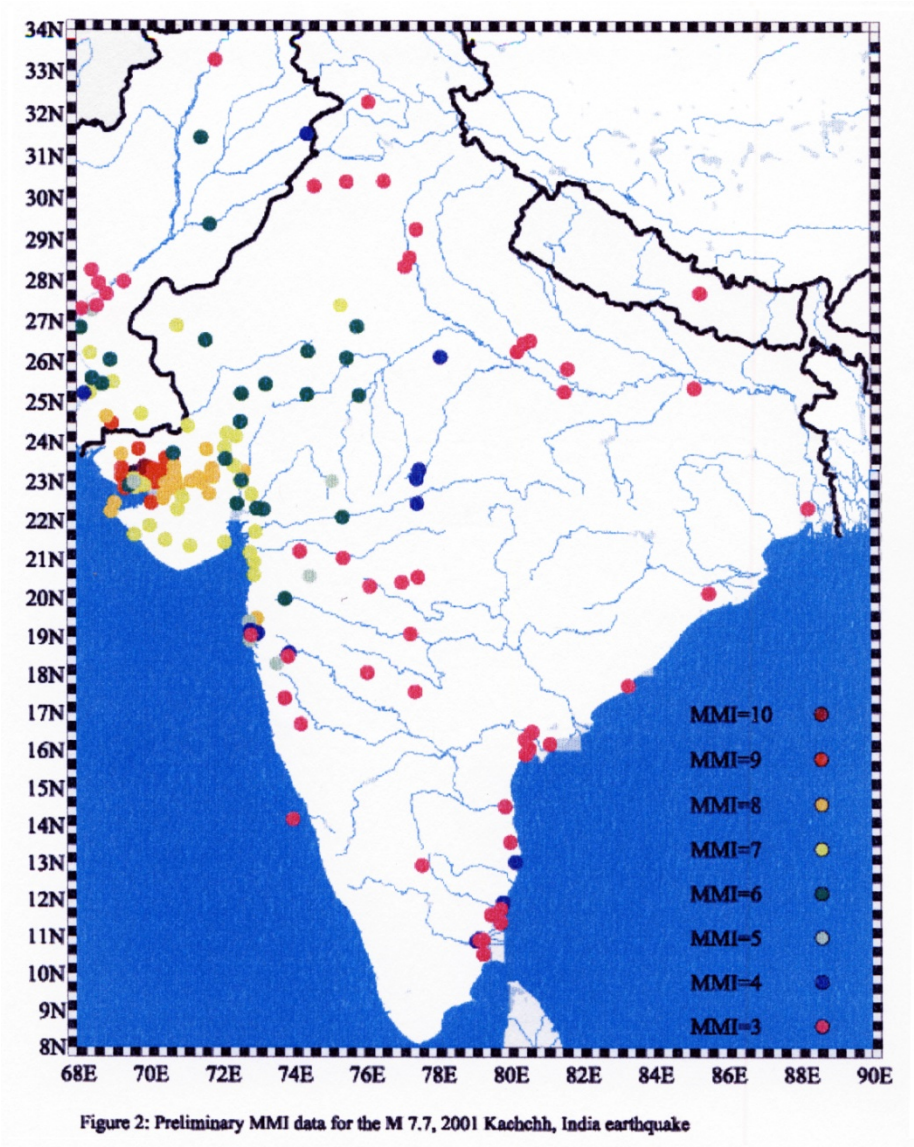


Figure 2. The distribution of intensity data points throughout the Indian sub-continent and adjacent regions (from Dockter, 2001). See text for data sources.

Figure 3 compares the Figure 2 Bhuj point intensity data (versus distance from epicenter) with a similar data set for the first New Madrid earthquake, 16 December 1811 (for the others of the sequence the intensity data were too sparse) (Dockter, 2001). There are three ways to interpret this graph: (1) New Madrid and Bhuj were of comparable size (M_w) with New Madrid, perhaps, slightly larger; (2) the Indian sub-continent Q is higher than that of the CEUS (lower attenuation); thus with roughly the same intensities at a given distance, Bhuj is resolvably smaller than New Madrid; the India sub-continent Q is smaller than that of the CEUS (higher

attenuation). Thus for roughly the same intensity at a given distance Bhuj is resolvably larger than New Madrid. These three outcomes are key to the following attenuation debate.

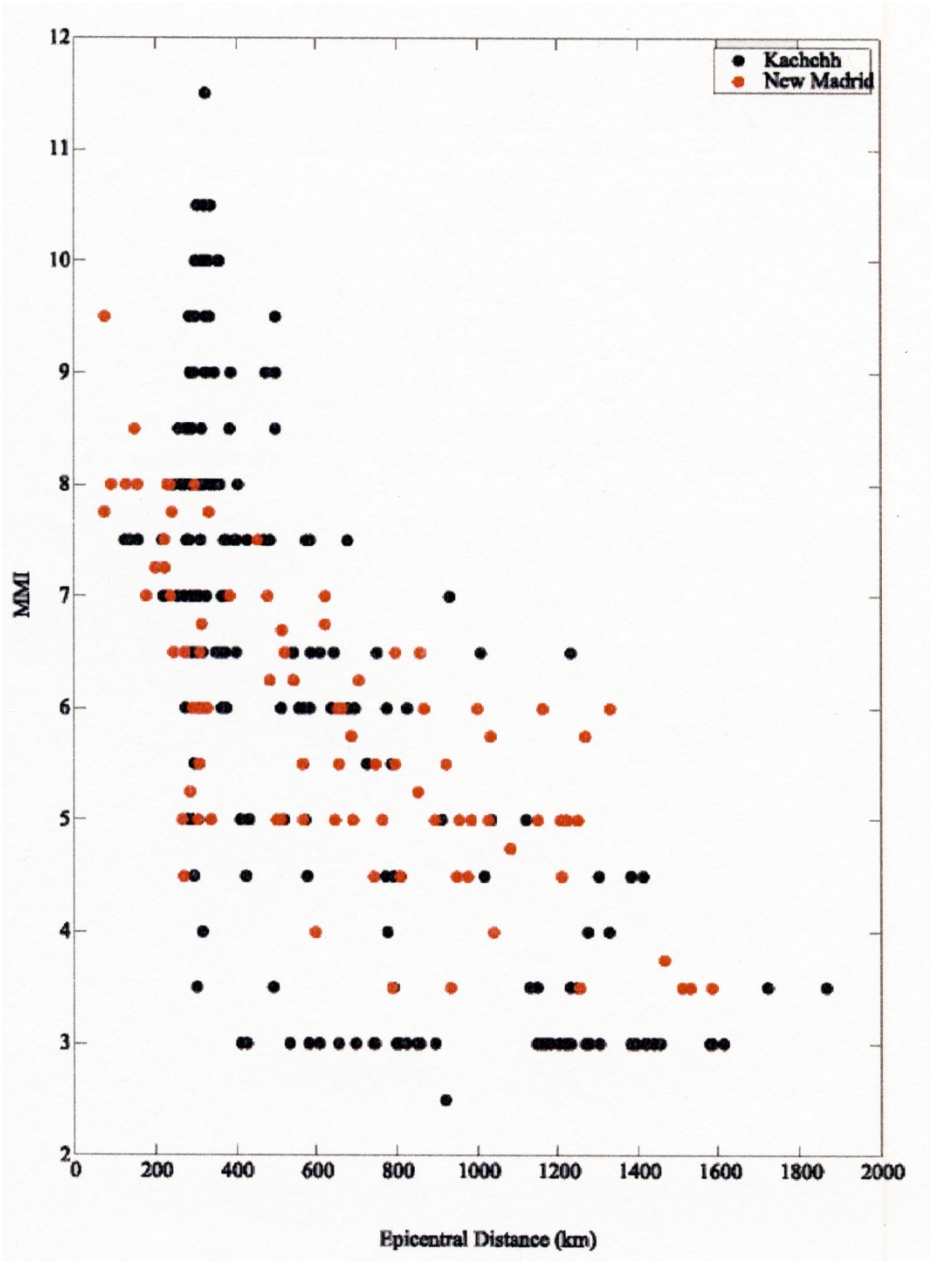


Figure 3. MMI versus epicentral distance for the 2001 Bhuj, India, Mainshock and the 16 Dec. 1811 New Madrid earthquake, of the CEUS (from Dockter, 2001).

BH04 reject the use in CEUS regression relations of any earthquake that does not originate in North American SCR crust. In Dockter (2001) and this report we embrace the use of such data

as rare and invaluable. The M_w 7.7 Bhuj earthquake is the classic example. An analysis of the Bhuj intensity data following the BH04 method results in a large underestimate of its size: M_w 7.1-7.2 versus the instrumental M_w 7.6-7.7. By eschewing the use of Bhuj for large earthquake regression control, BH04 leaves its large- M_w extrapolation essentially unconstrained, simply because Bhuj is not a North American SCR event. The BH04 reasoning is that inter-SCR continental-scale differences in attenuation are too great to use events such as Bhuj in their CEUS regression analysis and specifically that CEUS crustal attenuation is significantly less (higher *Q*) than for any other continental SCR.

Brian Mitchell of St. Louis University is referenced by BH04 to support their position but only in an early abstract-only citation (Mitchell *et al.*, 1993). Subsequent published work by Mitchell (eg, Baquer and Mitchell, 1998) and others (eg, Mitra *et al.*, 2006) show that this is not the case, at least so far as India and the CEUS are concerned. Figure 4, from Mitra *et al.* (2006) is a summary figure of their *Lg Q* analysis. They show that India at a full sub-continental scale has

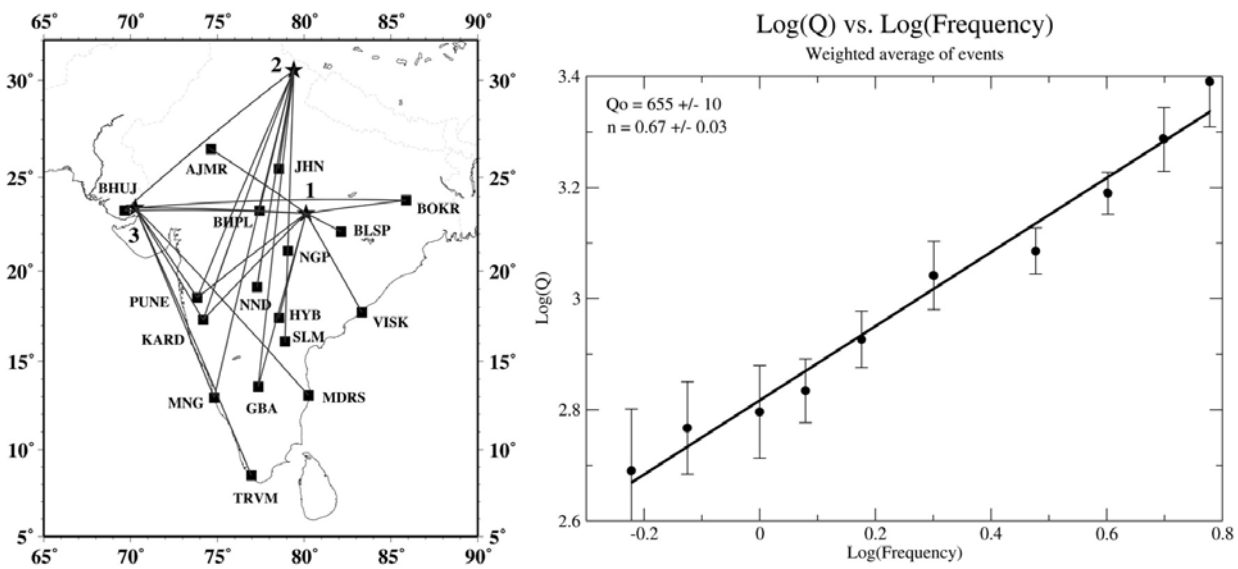


Figure 4. From Mitra et. al (2006). An average Q_0 (1 Hertz) of 655 ± 10 (right panel) is obtained for raypaths throughout the Indian sub-continent from three large, recent earthquakes.

an average 1 Hertz *Q* of 600-700; breakdown of this average reveals a *Q* of 300-500$^+$ from the Himalayan front/Ganges plain into central India, increasing to the south to a *Q* > 850 in the southern portion of the sub-continent. These *Q*-values are very comparable to those reported by Baquer and Mitchell (1998) for the CEUS: *Q* increases from 300-500 in the coastal plain regions to 500-~650 in the central U.S. to >700 in the U.S. northeast. Other work (eg, Shi *et al.* ,

1996) found *Q*-values to exceed 900 in restricted regions of the northeast and increasing still further into the eastern Canadian craton. Therefore we conclude that the *Q*-values of the India sub-continent and the CEUS SCR are not only broadly similar when averaged over their respective continental-scale areas, but also they exhibit a similar range of *Q* variation within their respective boundaries. Within the individual SCR regions, attenuation (Q^{-1}) varies to a greater degree than the overall *Q* differences exhibited by independent SCRs. This point and others of this section will be summarized in the final, concluding section.

CONCLUSIONS AND PROJECT RESULTS: THE FINAL MMI-MW REGRESSIONS FOR UNIFORM CEUS MOMENT MAGNITUDE ESTIMATION

The scope of this project was considerably expanded by the occurrence of the M_w 7.7 Bhuj, India, earthquake during the project period. It offered the unique opportunity to constrain the large magnitude portion of the MMI to M_w regressions because it had a robust, modern instrumental determination of seismic moment M_0 and a rich data set of intensity observations well distributed across the India subcontinent (courtesy of S. Hough and B. K. Rastogi). Our three principal conclusions for this project all support our selected strategy for generating the final MMI to M_w regressions that complete this section.

Conclusion A. It is valid to include the Bhuj intensity data in the final CEUS MMI regressions because the Bhuj mainshock was indeed a stable continental region (SCR) earthquake from within the India SCR. Arguments supporting this conclusion are summarized in Table 1. Essentially the Bhuj mainshock exhibits SCR source scaling, which is distinct from ATR (active tectonic region) scaling (Johnston, 2001), and the geologic/tectonic setting of the hypocenter is within rifted Proterozoic Indian cratonic crust currently under compressional tectonic stress, a hallmark of SCR crust.

Conclusion B. The MMI observations that constitute the data from which our final regressions are derived, all lie within the CEUS SCR, or the Indian subcontinent SCR. We have demonstrated (Figures 2. and 3. and their discussion) that the CEUS and India exhibit broadly similar Q-values and attenuation characteristics, both in terms of average *Q* (attenuation) across the respective regions and the pattern and range of variation of *Q* within the respective regions. This conclusion was reinforced at the 2008 CEUS M_{max} Workshop, sponsored by the USGS and NRC at Golden, Colorado (Wheeler, 2009). There the participants were polled to see which of over a dozen techniques they favored to estimate the size of the maximum earthquake (M_{max}) in CEUS domains. A strong majority favored using <u>global</u> analog regions to the CEUS SCR in large part because of the observation that variation of crustal properties, mainly attenuation (*Q*), within a given SCR, exceeds the variation observed between or among different SCRs at continental

scale. Since the intensity data field for large SCR earthquakes (eg, New Madrid and Bhuj) extends to continental scale this endorsement by the M_{max} workshop participants strongly supports including Bhuj MMI data in the CEUS regressions.

Conclusion C. Conclusion C. concerns regression strategy as discussed in the regression development section. The two innovations that we introduced and justified there were: (1) development of a separate regression relation for each MMI level; (2) deriving all regression coefficients as CEUS-specific, rather than importing coefficient values derived in California. Indeed, it was only by implementing separate regressions for each MMI level that we could reduce the number of degrees of freedom so that CEUS-specific coefficients could be derived, not assumed.

To calculate moment magnitude (M_w) from a set of MMI point data for an individual earthquake, the epicentral radius for each data point is applied to the appropriate equation based on its assigned MMI value. This yields a set of calculated moment magnitudes, the median of which is taken for a final estimated M_w at that particular level. A median rather than mean magnitude is considered a better estimate for the same reason median epicentral distance is used: medians minimize any undue influence of outliers or biased data.

The final MMI- M_w regression results were performed using the *Conclusion C* strategies and with inclusion of the Bhuj MMI for large earthquake control, per *Conclusion A* and *B*. The many trial runs, both with and without Bhuj, and the extensive statistical analyses of the weighted least squares fits to the data may be found in Dockter (2001) and will not be repeated here.

We present as our final project results the final MMI- M_w regressions for MMI II-VI. Using the individual MMI level approach, the data are too few for regressions on MM VII and above, but that has negligible effect because the CEUS seismicity catalog contains so few of the higher MMI values.

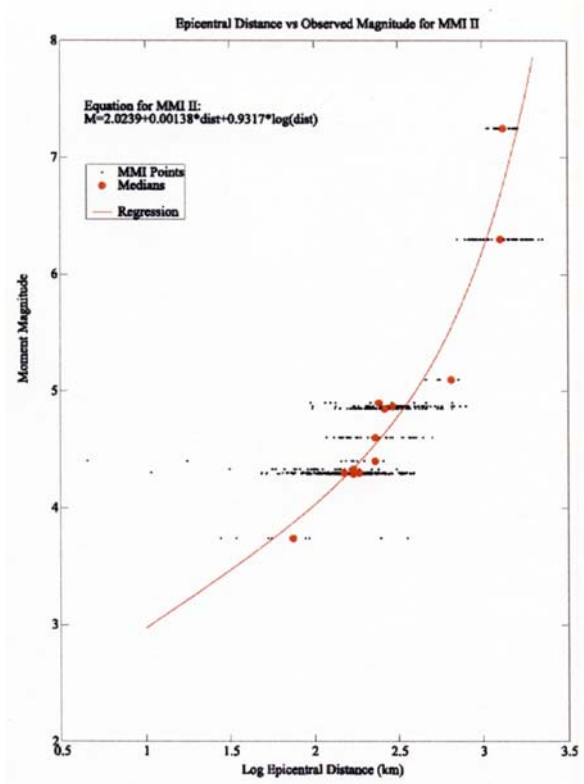
MMI II: $M_w = 2.024 + 0.0014(\Delta) + 0.932 log(\Delta)$

MMI III: $M_w = 2.585 + 0.0023(\Delta) + 0.648 log(\Delta)$

MMI IV: $M_w = 3.70 + 0.0044(\Delta) + 0.072 log(\Delta)$ (2)

MMI V: $M_w = 4.237 + 0.0077(\Delta) - 0.207 log(\Delta)$

MMI VI: $M_w = 4.50 + 0.0009(\Delta) - 0.155 log(\Delta)$



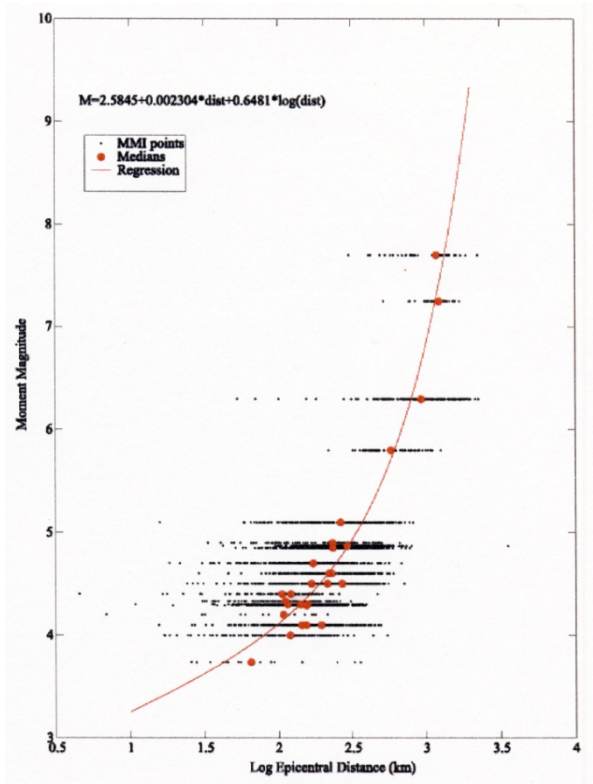
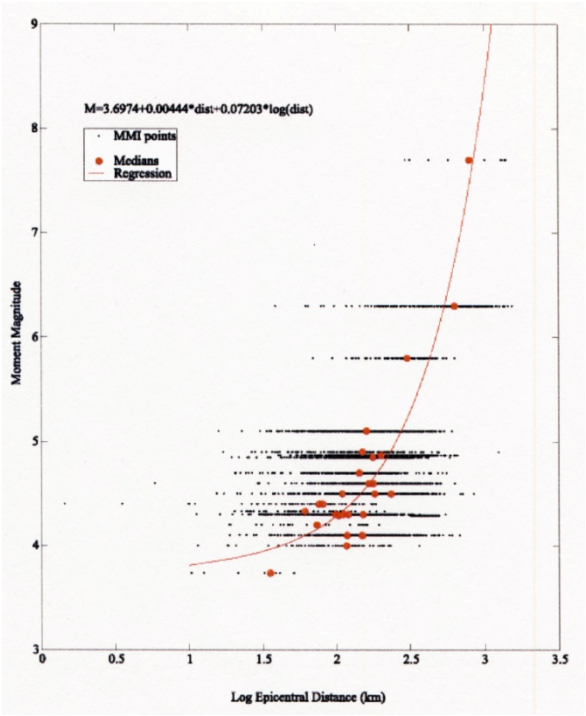


Figure 5 a. & b. The MMI II and III regressions



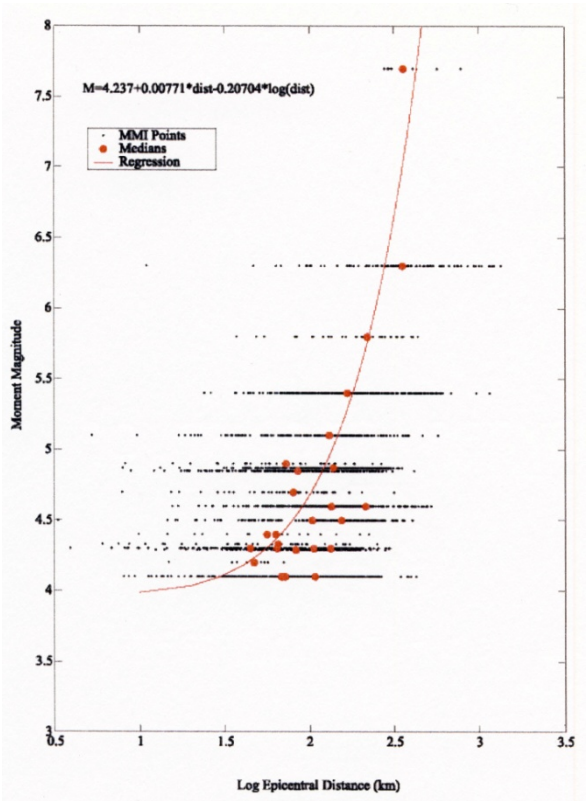


Figure 5 c. & d. The MMI IV and V regressions

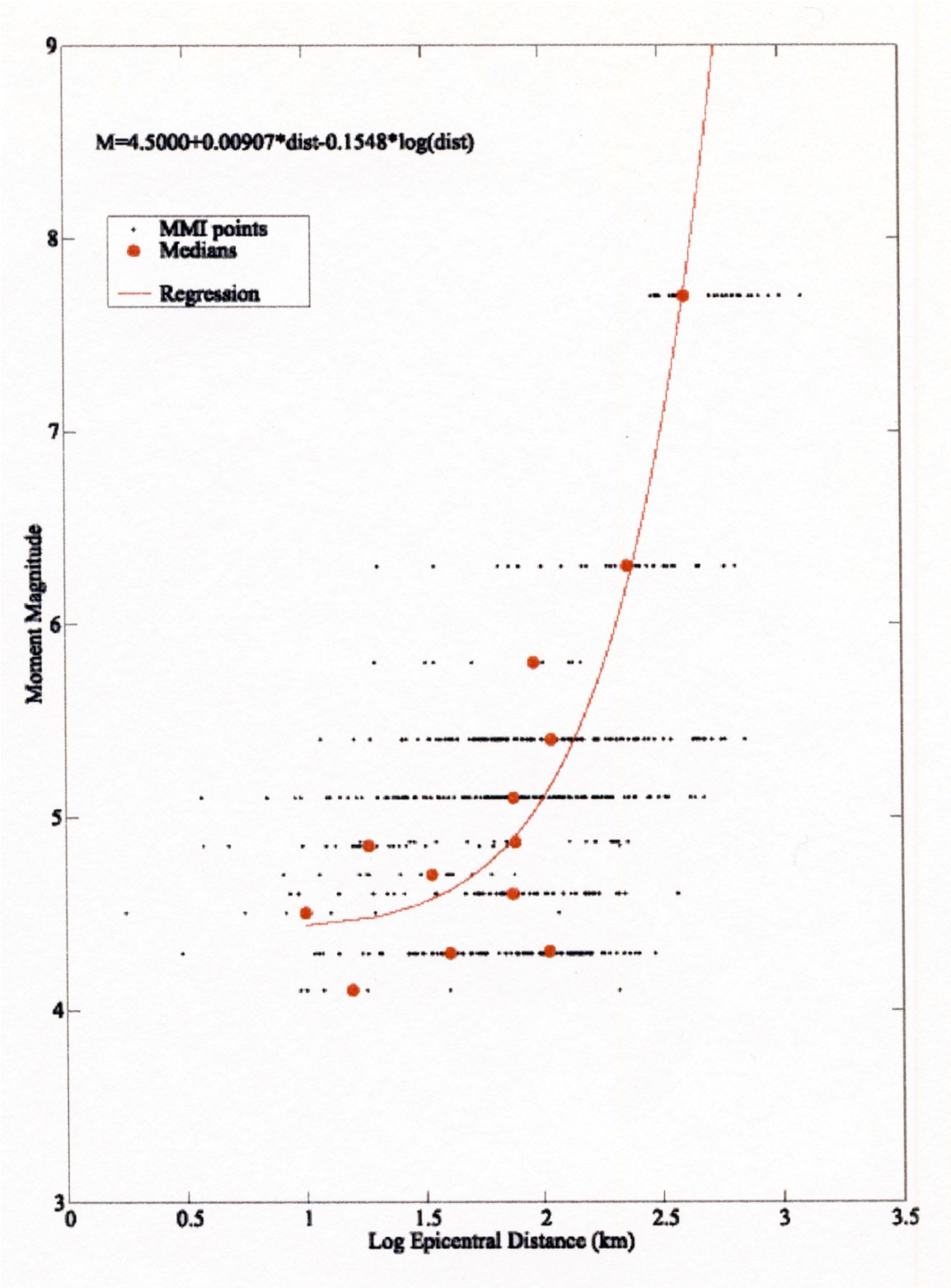


Figure 5e. The MMI VI regression

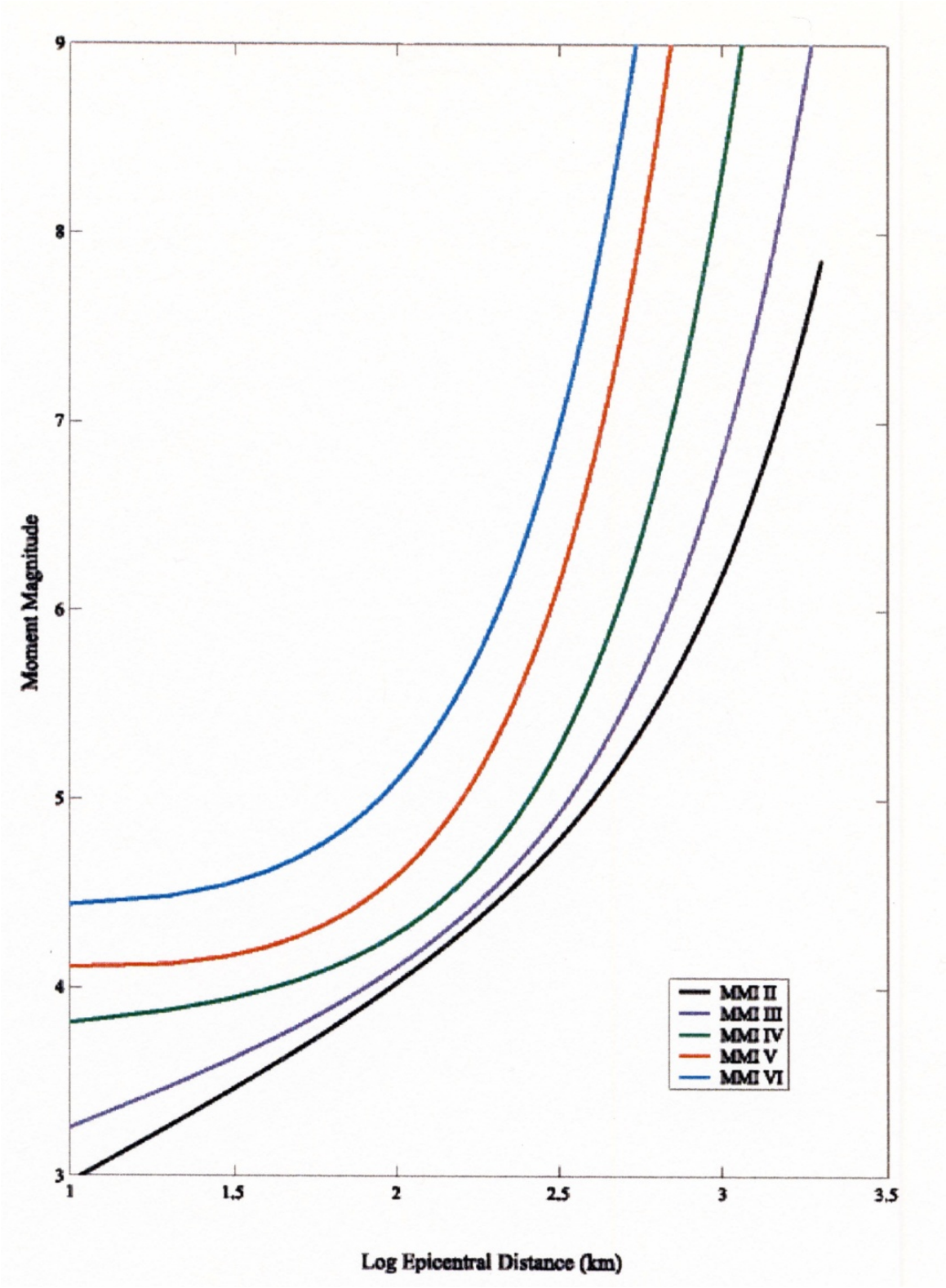


Figure 6. MMI II-VI final regressions (Dockter 2001)

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We are indebted to S. Hough and B. K. Rastogi for access to their Bhuj MMI data sets and to C. Cramer for helpful advice on statistical analyses and to all those too numerous to name here who made possible a difficult deployment to the Bhuj aftershock region just two weeks following the mainshock.

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