Bulletin of the Seismological Society of America, Vol. 93, No. 4, pp. 1573–1605, August 2003

Earthquakes and Associated Deformation in Northern Baluchistan 1892–2001

by Nicholas Ambraseys and Roger Bilham

Abstract We examine a century of seismicity and earthquake-related deformation on the western margin of the Indian plate in the Pakistan region of northern Baluchistan. Several catalogs of earthquakes for this region currently exist, but early catalogs in particular suffer from errors, incompleteness, inhomogeneity, and location bias. We form a new catalog of more than 1000 earthquakes using original sources to confirm macroseismic locations and assign M_S magnitudes to earthquakes since 1892. In doing so we reveal a systematic east-northeast bias in locations caused largely by the uneven global distribution of seismic stations used in their determination. An appendix provides narrative accounts and historical references to 34 significant earthquakes in the region.

The pattern of seismicity in the past century shows activity over a 700-km-long, 200-km-wide segment of the plate boundary with predominantly strike-slip faulting to the west and thrust faulting to the east. At its narrowest near 29° N, transpression of the plate boundary is partitioned into reverse and strike-slip components separated by approximately 100 km. The *M* 7.3 1931 Mach earthquake (slip 1.1 m on a 40° east-southeast–dipping reverse fault) released fault-normal stresses that may have "unclamped" the subsequent *M* 7.7 left-lateral Quetta earthquake 4 years later. The northern Chaman fault system in the past century has been largely inactive, suggesting that this time period is not representative of long-term activity in the region and that up to 4 m of potential slip is currently available to drive one or more future $M > 7$ earthquakes. Despite triangulation installed in the late nineteenth and early twentieth centuries, no recent geodetic data are available to permit plate boundary velocities to be measured directly.

Introduction

The northern Baluchistan region of Pakistan (Figs. 1–3; 27° to 32° N, 65° to 70° E) includes the Chaman fault system, a left-lateral transform plate boundary that separates the Indian and Eurasian plates. The width of the region of deformation across the plate boundary varies from 150 km at its narrowest to more than 300 km in the Sulaiman Ranges, where a fold and thrust system is thrust southward over the Indian plate. The western edge of the Chaman fault system is terminated abruptly by the Chaman fault, whose strike varies from approximately parallel to the NUVEL-1 inferred India/Eurasia slip velocity to an oblique strike of 20° in a transpressional sense. The fold and thrust belt is most prominently developed where transpression attains its maximum obliquity.

Relative plate motions between India and Eurasia in the past decade show a wide region of distributed deformation north of an apparently rigid Indian Plate moving northeast at roughly 47 mm/yr (Wang *et al.*, 2001). In contrast to well-determined velocity fields in parts of the Himalaya, there is currently no Global Positioning System (GPS) geodetic control across the Chaman Transform boundary and important questions remain concerning the slip rate between Baluchistan and the Indian plate. If central Baluchistan is part of the Euroasian plate, it is possible that the slip velocity along the Chaman system may be as high as 41 mm/yr, yet seismicity in the mountains of northern Afghanistan suggests that some convergence may be occurring there, which would reduce this velocity. The absence of conventional GPS geodesy in Afghanistan frustrates indirect calculations of the slip velocity of the transform boundary. Moreover, it has been suggested (Stein *et al.*, 2002) that the western margin of the Indian plate may be deforming and may be responsible for historic seismicity in the Rann of Kachchh. This also, were it occurring, would reduce the slip rate on the transform boundary.

Although subsurface creep processes prevail in parts of the region as result of salt-detachment processes, especially in the Sulaiman Range and other ranges east of the main

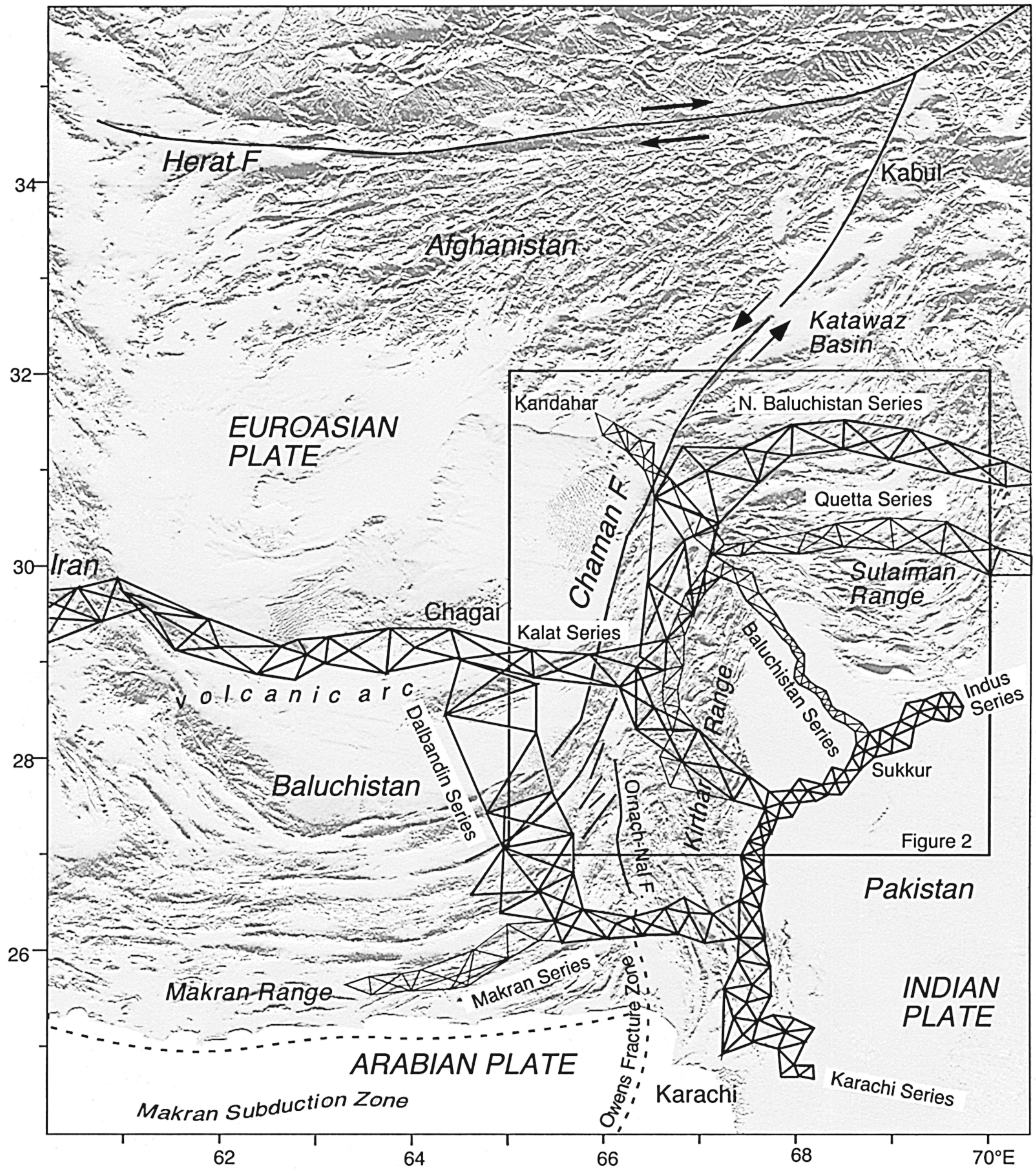

Figure 1. Location map showing principal structural units, major faults, and historic triangulation in the region. The box indicates the study region.

left-lateral surface faults, we are unaware of reports of surface creep on any the left-lateral faults of the Chaman system. Thus, the slip rate along the Chaman fault system dictates the productivity of seismicity in Baluchistan. In the absence of direct measurements of this slip rate, we attempt the reverse: to estimate the slip rate of the Chaman fault system from the seismic productivity over a period as long as macroseismic information allows (150 years).

We provide a more complete account of the background macroseismic and early instrumental information than has been available previously. Our task is rendered difficult because existing regional and global earthquake catalogs are not complete or homogeneously compiled in terms of earthquake location and magnitude, particularly for the period before the mid-1970s, which makes it difficult to associate seismicity with active tectonics over periods longer than the last few decades. Few of the regional or national catalogs we know of are uniformly compiled and transparent regarding primary macroseismic data and instrumental procedures, and much of the seismic information that is used to quantify tectonic activity is either incomplete or assumed.

The importance of knowing the quality of epicenters and magnitudes in parametric catalogs for the last 100 years is obvious. Completeness for historical events is difficult and almost impossible to assess. Uniformity in magnitude is important for the derivation of reliable regional $\log(M_0)$–M_S

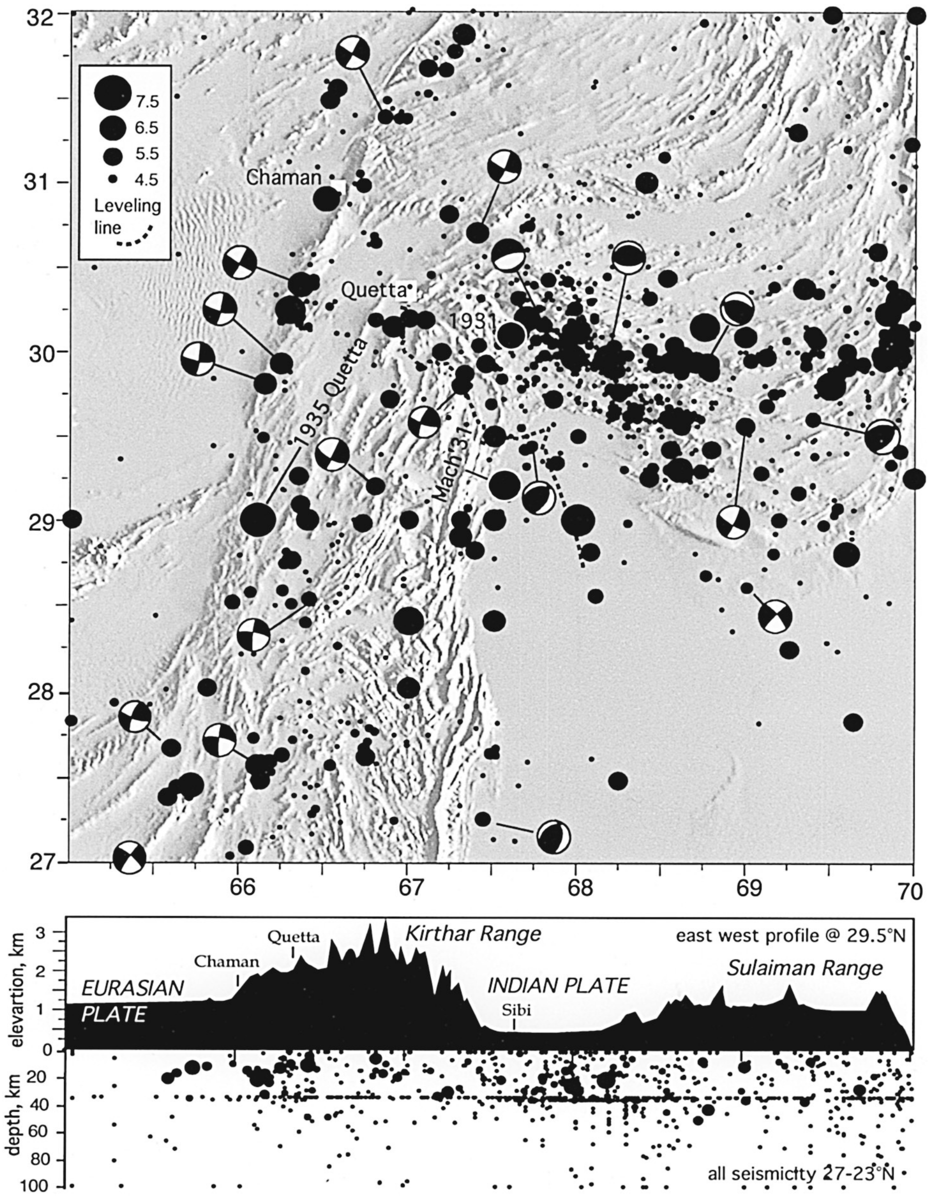

Figure 2. Study region showing relocated epicenters and focal mechanisms for selected events from 1978 to 1997 (from Centroid Moment Tensor [CMT] Catalog and Quittmeyer and Jacob [1979]). Beach balls show lower hemisphere projection with black quadrant for compressional first *P* arrivals containing the *T* axis, and open quadrants the *P* axis. The path of the leveling line is indicated (see Fig. 11).

relationships that are needed to estimate seismic moments for the majority of historical events. They are equally important for the derivation of long-term frequency–magnitude relationships, that are required for the estimation of the total moment release and for the comparison of tectonic motions, including aseismic creep, with the rate that is known from GPS measurements. Also the development of predictive relationships of ground motions for engineering purposes requires reliable location of seismic sources and magnitudes.

A result from our study is that in the process of summing seismic moment release along the transform boundary to infer its mean slip rate, we reveal a decrease in moment release north of latitude 31° N. We interpret this to indicate that the 100-year length of the seismic record in Baluchistan is not representative of long-term behavior of the plate boundary. A second result from our study is that we infer a slip rate south of 31° N that is close to that estimated from NUVEL-1 plate motions. With the important caveat that this may not be representative of the long-term behavior of the plate boundary, it has important implications for the absence of significant deformation across the mountains of Afghanistan and the consequent presence of high convergence

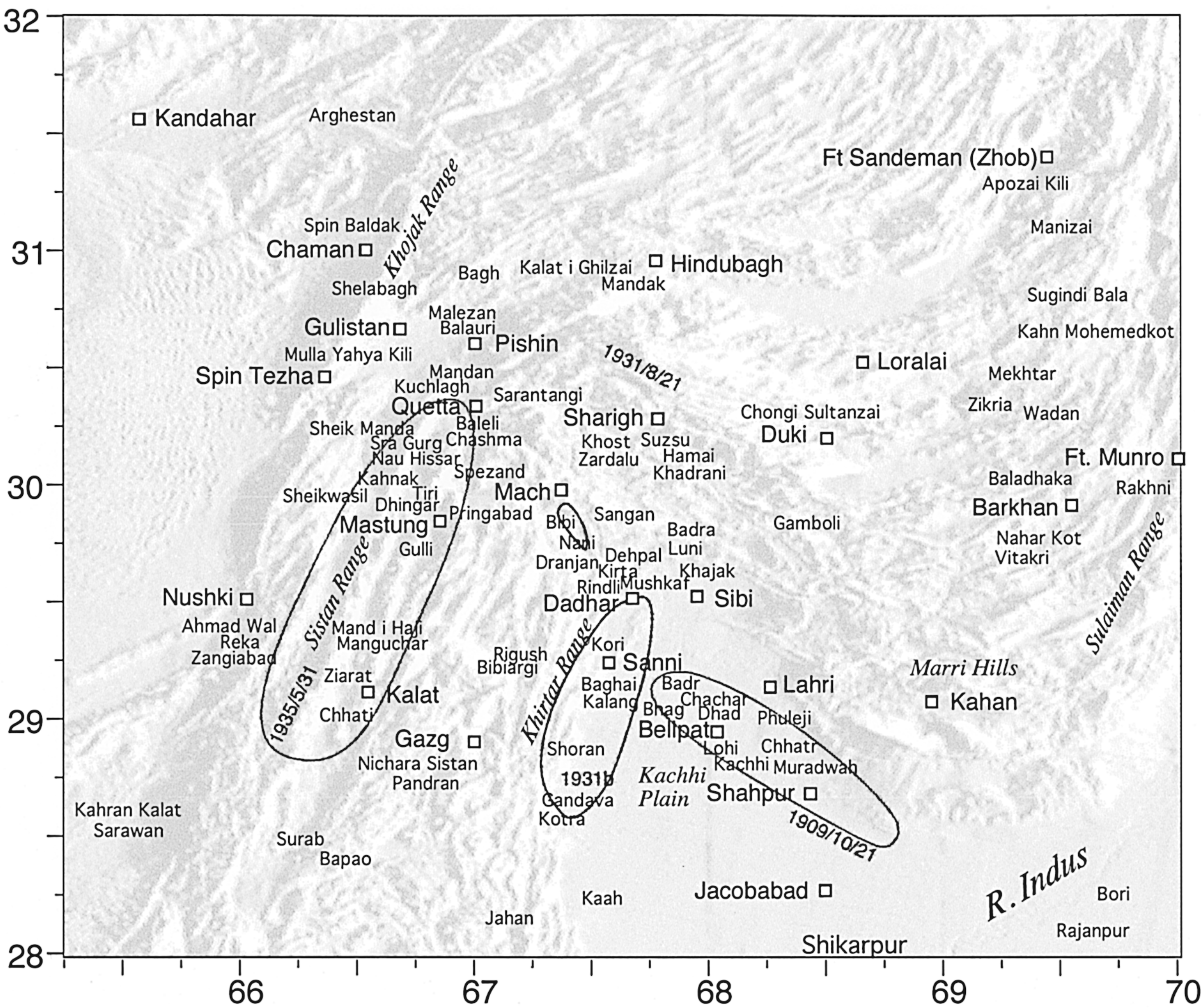

Figure 3. Map showing the locations of the principal places mentioned in the text. Rossi–Forel intensity VIII isoseismal contours for the 1909 Kachhi (Heron, 1911) and 1935 Quetta (West, 1936) earthquakes are shown, with our revaluated FSK intensity VIII contours for the 1931 Mach earthquake. The shapes of the contours are considered very approximate, and possibly misleading, because of the imperfect spatial coverage of postseismic investigations and because local construction methods result in the Rossi–Forel scale saturating at intensities greater than VIII.

rates between Baluchistan and the Arabian plate across the Makran.

Available Data

Macroseismic Information

The peculiar physical characteristics of this region, its inaccessiblity, lack of large urban centres, and low level of literacy, are responsible for a poorly documented history, in which few earthquakes before the end of the nineteenth century are mentioned, primarily in standard Arabic and Persian histories. Allusions to earthquakes in Baluchistan before 1870 are vague and of little use, except for confirming the obvious seismic activity to be expected in this area (McMahon, 1897). Detailed information about earthquakes is available only after the establishment of Quetta as a military center, the building of a railroad in Baluchistan, and geodetic surveys of the region starting in the 1880s. Indeed, incomplete identification of small and perhaps a few moderate shocks (M_S <5.5) may have persisted to the early part of the twentieth century. It is very probable, however, that most moderate and all large earthquakes have been noted, although not necessarily fully identified. It is reasonable to suppose, therefore, that the available twentieth-century data for the whole region are complete only for moderate earthquakes or greater. This is illustrated in Figure 4, which shows the number of earthquakes in 5-year intervals, and in Figure 5, which shows the standard deviation of the estimate of the mean of the annual number of events as a function of sample length (Stepp, 1971).

With the paucity of data available for this region we can devise no formal methods to test completeness, other than

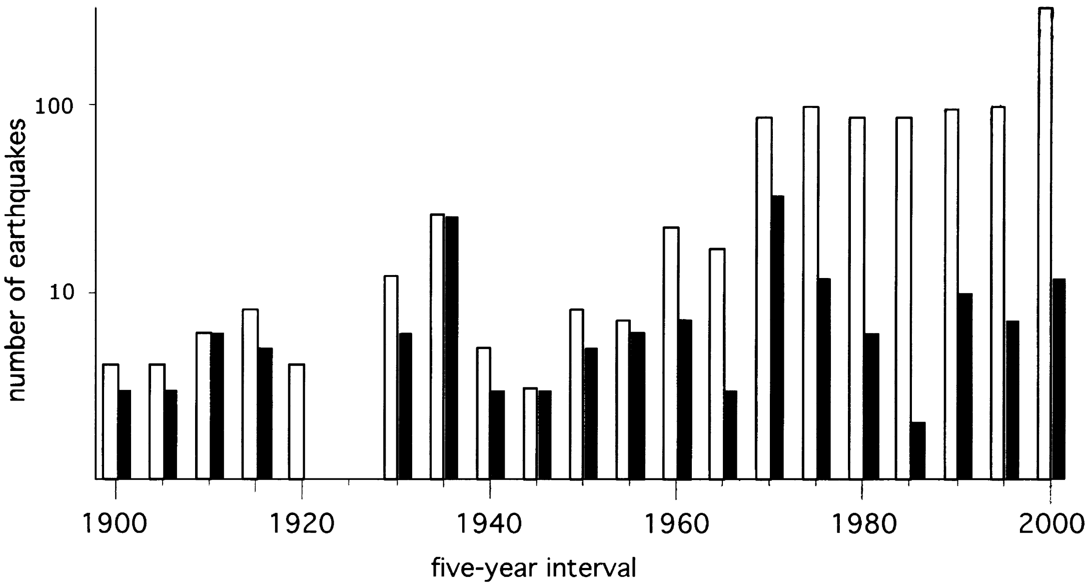

Figure 4. Distribution per quinquennium of the number of earthquakes in the full dataset. Open bars are for events of all magnitudes ($N = 1035$), whereas solid bars are for $M_S \geq 5.0$ ($N = 157$). For the most recent 5 years, the total number of events (open bar) is 355 (not shown fully).

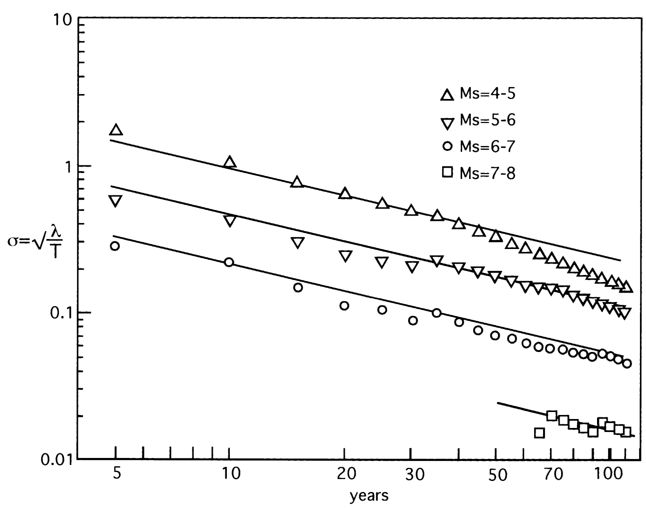

Figure 5. Variation in the standard deviation of the mean annual number of earthquakes in Baluchistan as a function of sample length (Stepp, 1971). T is the total time in years, and λ_T is the mean rate of occurrence.

by testing their implications. Statistical techniques are inappropriate, because the data may contain both peculiarities of the geophysical process and peculiarities of the process by which the events were recorded (Vere-Jones, 1987). With short-term, 100-year-long datasets it is unreasonable to ignore the possibility that for a particular region much or all of our record of large events may be from a quiescent or active period in the seismic activity. Indeed, we identify later in this article an apparent deficiency in earthquake activity north of 31° N along the transform boundary.

With few exceptions, macroseismic data in Baluchistan are scarce. However, for the larger events before the 1950s they provide an approximate indication of the location of an earthquake. For shallow, well-reported earthquakes they are defined as the center of the area mostly affected by the shock. Excluding epicenters in sparsely populated areas, they can be assessed with an error of 5–15 km depending on the available information and magnitude of the earthquake. Good-quality macroseismic epicentres for shallow-depth earthquakes of $M_S < 6.5$, before the early 1960s, are less variable, and many of them are more reliable than instrumental locations.

For shallow events of $M_S > 6.5$ of that period in this part of the world, the location uncertainty of macroseismic epicenters increases to a few tens of kilometers with increasing magnitude. At these magnitudes this is understandable, even for teleseismic locations, since the earthquake will have ruptured faults tens of kilometers or more in length.

Instrumental Locations

After 1899 epicentral locations are available from bulletins of international agencies such as the British Association for the Advancement of Science (BAAS), the International Seismological Summary (ISS), the International Seismological Centre (ISC), and the U.S. Geological Survey (USGS).

For the early period 1899–1910, BAAS (1912, 1913) published a considerable number of epicenters of the larger shocks, for some of which macroseismic information was used to determine approximate positions and origin times, whenever it was possible. When macroseismic information was not available, as is the case with our region, epicenters are often associated with location errors of tens to hundreds of kilometers (Ambraseys, 2001). Another set of BAAS epicenter determinations covers the period 1913–1917 and is marginally more reliable. However, in this 18-year-long period only 17 events have been recorded and located by the Milne network in our region.

ISS determinations of epicenters, which begin in 1918 and continued to 1962, vary in accuracy, and they must be used with great caution. ISS locations may be divided into three categories: (a) epicenters properly calculated by ISS; (b) the so-called adopted epicenters, that is positions adopted by ISS from old locations, without calculation on the assumption that they must have the same origin; and (c) epicenters assessed from macroseismic locations. Of these, categories (b) and (c) are not instrumental positions and can be in error, while category (a) may be used only in the absence of better relocations. In total only 86 earthquakes, of all magnitudes, have been located by ISS in our region.

ISC locations are available from 1964 onward. These provide 878 events of all magnitudes located by ISC which supersede positions given by the U.S. Coast and Geodetic Survey (USCGS)/USGS. Under the agency code LAO, from 1967 to 1970 ISC published locations from the Large Aperture Seismic Array (Ambraseys and Adams, 1986). These locations are not reliable, and they were disregarded as well as locations from the Bureau Central de l'Association de Sismologie (BCIS), the Delhi Meteorological Department and the Quetta Geophysical Centre, Pakistan Meteorological Department.

In addition to these catalogs new earthquakes have been located and old ones relocated routinely by different authors using different procedures. Epicenters given by Gutenberg and Richter (1965) are crude and include very few events of $M_S > 5.5$ before 1954. Nowroozi (1971), using Bolt's program (Bolt, 1960), relocated events between 1950 and 1965 that were recorded by 10 or more stations. Quittmeyer and Jacob (1979) used the same location procedure to relocate earthquakes between 1914 and 1965 that had preliminary hypocentral positions calculated by ISS. Ambraseys (2000) located a few new and relocated known events in the early period using the present procedures at the ISC. Most recently Engdahl *et al.* (1998, unpublished additions in 2001) relocated a large part of the whole ISS/ISC catalog using an improved velocity model and also including the arrival times of additional phases, particularly teleseismic depth phases to supplement the direct P arrival times in the relocation procedure. Recently their dataset has been extended back to 1918, which adds an additional three relocated earthquakes in our region. This and earlier procedures, however, cannot overcome location uncertainties arising from poor input data and azimuthal distribution of stations.

Other catalogs are available that are derivative of the previously mentioned works, and as such they are of little interest. Locations given by Rothé (1969) for the period 1953–1959 are in fact ISS positions, while for the period 1960–1965 they are positions determined by USCGS. Also the recent data file made available through the Internet by the Global Seismic Hazard Assessment Program (GSHAP, 2000) is a recompilation of earlier determinations without refinement or recalculation and contains only 25 events in our region in the period 1909–1985. Bapat's catalog is also a derivative work that is based entirely on earlier compilations, adopted without revision (Bapat *et al.*, 1983).

For events after 1963 in our scheme, with a few exceptions, we adopted locations recalculated by Engdahl, which are superior to and supersede ISS and ISC estimates (Engdahl *et al.*, 1998).

Procedure

We reappraised locations and surface-wave magnitudes of earthquakes from 1892 to 2000 in an area that extends between 27° and 33° N and from 65° to 70° E (Table 1).

Location

By merging all the datasets available into a single file, we compared locations and magnitudes, starting with the retrieval of macroseismic information from various published and unpublished sources, chiefly for events before 1963. We found reliable macroseismic information to define the locations of 34 events, which were also used as initial positions for relocation using present ISC procedures, with formal errors of not more than about 25 km. Macroseismic locations were thought to be preferable to poorly determined instrumental locations that could not be improved, and they were retained.

In the next stage we examined the location of 74 ISS and 416 ISC events and recalculated at random a number of ISS locations, with good agreement with those calculated by Nowroozi (1971) and Quittmeyer and Jacob (1979). Using the amplitude of these residuals as a selection criterion, we adopted 489 locations from ISS/ISC, 4 from Nowroozi (1971), and 59 from Quittmeyer and Jacob (1979). However, for earlier events reappraisal and refinement of epicentral positions becomes hardly practicable, chiefly because of the absence of reliable input data, for which there is no foreseeable solution.

Next we compared 384 ISC positions in the region, of predominantly small events, with those relocated by Engdahl *et al.* (1998) using much improved relocation procedures. This comparison is given in Figs. 6–10, which show that relocation has systematically shifted ISC epicenters to the west by about 10 km on average. This shift is very similar in average direction and magnitude to the shift of ISC locations from their macroseismic positions found in the eastern Mediterranean and in the Middle East, an effect influenced by the regional grouping of stations (Ambraseys, 2001). Figure 8 suggests that, with the exception of the small aftershocks of the large shocks of 1966 and 1997, average shifts are on average less than about 15 km and are independent of the year of the earthquake. The concentration of

Table 1
Significant Events (M >5.9) 1892–2000 between 27° and 32° N and between 65° and 70° E

No.	Date (yyy mm dd)	OT (GMT)	N°	E°	R	M_S	h (Km)	logM_{os} (dyne cm)	logM_0 (dyne cm)
1	1892 12 20	0020	30.90	66.50	3	6.5	00	26.0	
2	1893 02 13	0400	30.70	67.40	3	5.9	00	25.2	
3	1901 10 07	0557	31.00	68.40	3	6.1	00	25.5	
4	1903 12 23	0300	29.50	67.50	3	5.9	00	25.2	
5	1905 09 26	0128	30.30	69.90	3	6.4	00	25.8	
6	1908 03 05	0220	30.20	67.70	3	6.4	00	25.8	
7	1908 06 03	1556	28.00	67.00	1	6.2	00	25.5	
8	1909 09 07	0033	33.00	70.00	1	6.0	00	25.3	
9	1909 10 20	2341	29.00	68.00	3	7.1	00	26.8	
10	1910 08 17	1158	28.40	67.00	4	6.3	00	25.7	
11	1918 11 29	1041	32.70	67.70	3	6.2	00	25.5	
12	1923 10 01	0816	29.00	67.50	4	6.1	00	25.4	
13	1928 09 01	0609	28.77	69.57	6	6.5	33	25.9	
14	1928 10 15	1419	28.50	67.40	4	6.8	33	26.4	
15	1931 08 24	2135	30.10	67.60	3	6.8	00	26.4	
16	1931 08 27	1527	29.20	67.60	4	7.3	33	27.1	
17	1935 05 15	0201	28.40	67.50	3	6.0	33	25.3	
18	1935 05 30	2133	28.87	66.40	6	7.7	33	27.8	28.2
19	1935 06 02	0916	30.14	66.93	6	6.0	13	25.4	
20	1945 10 01	0516	28.95	67.28	6	6.0	33	25.3	
21	1952 10 10	1847	30.37	69.34	3	6.1	02	25.5	
22	1952 12 25	2222	29.25	70.00	4	6.0	33	25.1	
23	1956 05 13	0750	30.00	69.90	3	5.9	33	25.2	
24	1966 02 07	0426	29.80	69.50	3	6.7	17	26.0	
25	1966 02 07	2306	30.22	69.84	7	6.4	16	25.8	
26	1966 08 01	1909	29.94	68.70	3	6.1	19	25.3	25.5
27	1966 08 01	2102	30.15	68.75	3	6.9	09	26.5	
28	1975 10 03	0514	30.24	66.29	7	6.8	01	26.3	
29	1975 10 03	1731	30.39	66.35	7	6.5	02	25.9	
30	1978 03 16	0159	29.93	66.24	7	5.9	12	25.2	25.3
31	1990 03 04	1946	29.00	66.40	3	6.2	10	25.5	25.2
32	1990 06 17	0451	27.42	65.71	7	6.3	12	25.4	25.3
33	1992 04 24	0707	27.54	66.10	7	6.2	21	25.5	25.1
34	1997 02 27	2108	29.96	68.18	7	6.9	21	26.5	26.7

OT indicates origin time, and N° and E° are epicentral latitude and longitude. R indicates derivation history:1, ISS/ISC estimates; 3, macroseismic locations; 4, positions recalculated in this article; 6, locations recalculated by Quittmeyer *et al.* (1979); 7, recalculated by Engdahl et al. (1998, 2000). M_S is surface-wave event magnitude, h is estimated focal depth, logM_{os} is seismic moment M_{os}, calculated from M_S and equations (1a–c). LogM_0 is seismic moment M_0, from the Harvard solution (CMT catalog).

many of the reporting stations reporting events of $M_S < 5$ are in the northwest quadrant, in Europe, with little control from stations in other quadrants, causing systematic location errors. Procedures used to recalculate epicenters cannot overcome uncertainties of location arising from poor input data or the bias caused by this uneven azimuthal distribution of stations. In addition Figure 8 suggests that, with the exception of the two relatively large earthquakes before 1940, shifts are larger for the smaller events.

Finally, we adopted six USGS locations and one from BCIS, with another seven events given assumed locations. Thus the full dataset consists of 1045 earthquakes of all magnitudes (Fig. 6).

Depth

Earthquakes relocated by Engdahl *et al.* (1998) include much improved accuracy on hypocentral depth compared to those routinely calculated by ISC, as demonstrated by seismic sections in several subduction zones where improved locations clearly show the descending slabs. However important errors in depth may still remain for shallow crustal earthquakes (Maggi *et al.*, 2000). Where these were available we adopted depths from Engdahl *et al.* (1998). Depths for other events such as from earlier relocations made by others, and from ISC solutions, shown in Figure 2, are consequently uncertain. Although depths vary from the surface to more than 100 km, data from *P*/*SH* body-wave modeling suggest that seismicity in this region is restricted to the upper 30 km of the crust.

Magnitudes

Where information is available in station bulletins and other sources, we used reports of amplitudes and periods at stations with intermediate- and long-period instruments to

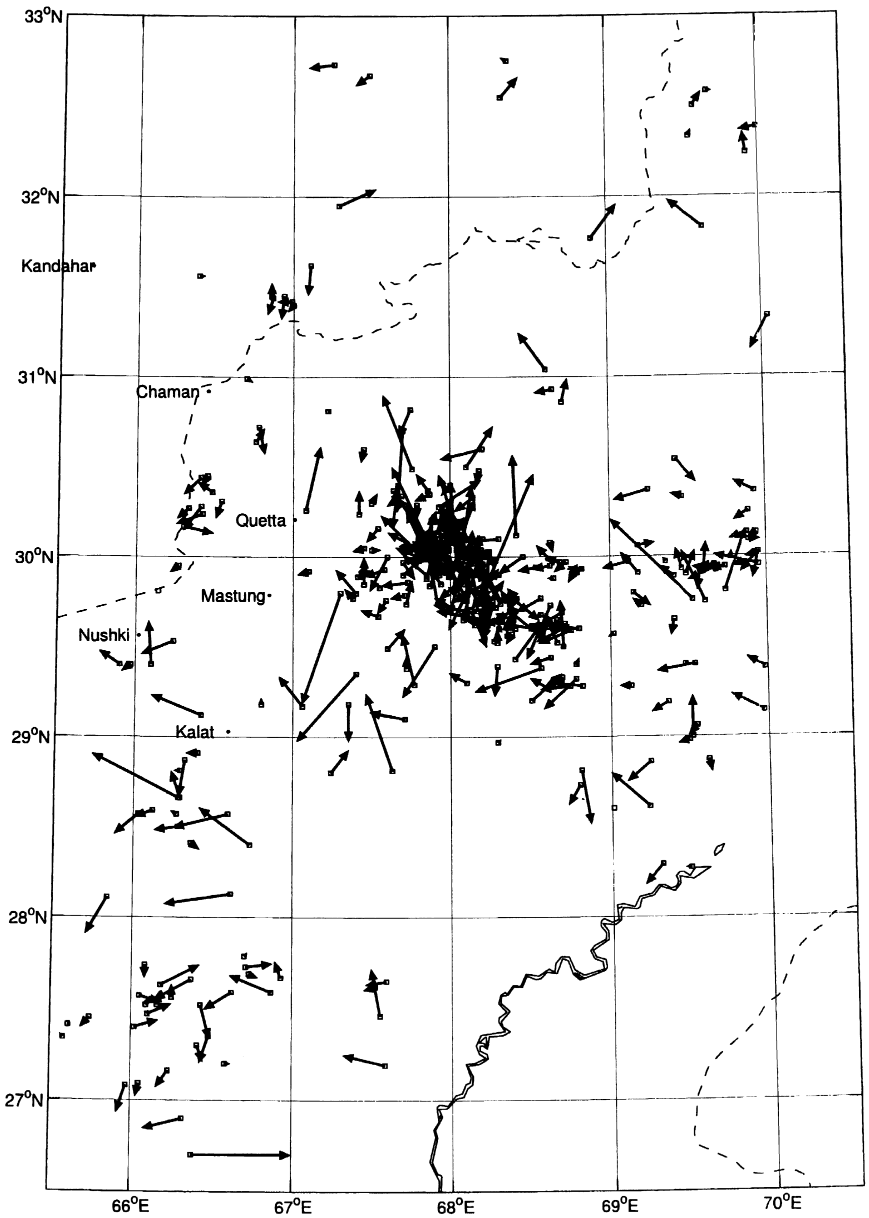

Figure 6. Comparison of 377 ISC original positions with epicenters relocated by Engdahl *et al.* (1998). The pointed end of the arrow is the Engdahl location, and the origin of the arrow the ISC location. The figure also shows a few gross ISC mislocations.

determine reliable M_S values for 315 events according to the Prague formula (Willmore, 1979) with distance and depth corrections (Ambraseys and Free, 1997). This required culling about 4000 ratios of surface-wave maxima and their corresponding periods from station bulletins, which allowed estimation of M_S with an average standard deviation of ± 0.25. In Appendix B we show as an example the summary worksheet for the calculation of M_S of the earthquake of 27 August 1931.

We used the same method to calculate M_S for another 639 small events for which we had no more than two station magnitudes. For 18 very early events, equivalent M_S values were calculated from reading from Milne instruments (Ambraseys, 2001), while for 24 shocks no magnitude could be determined.

For the period before 1978 surface-wave magnitudes are scarce. Gutenberg and Richter (1965) estimated a unified magnitude m_B for nine of the larger events. Quittmeyer and Jacob (1979) calculated from the Prague formula the M_S of another 15 events between 1923 and 1952, using readings from De Bilt and Uppsala, but for the rest of the earthquakes in their catalog they adopted estimates from Gutenberg and Richter, Rothé, and others. A comparison of their M_S estimates with those in this study is shown in Figure 10, in

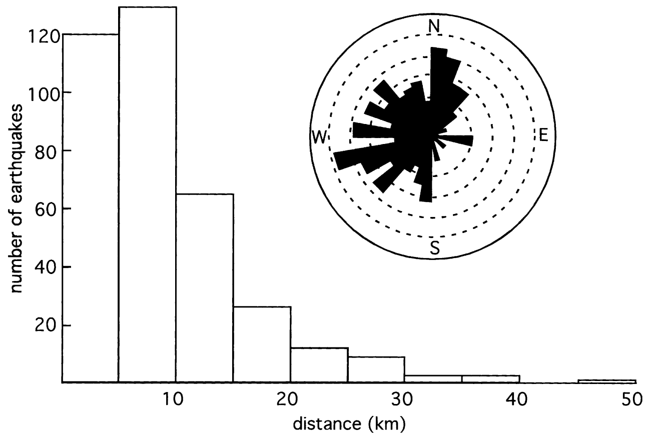

Figure 7. Azimuthal distribution of average shift of epicenters in each 10° sector. Relocation has systematically shifted ISC epicenters to the west by an average distance of ≈10 km, shown by the histogram.

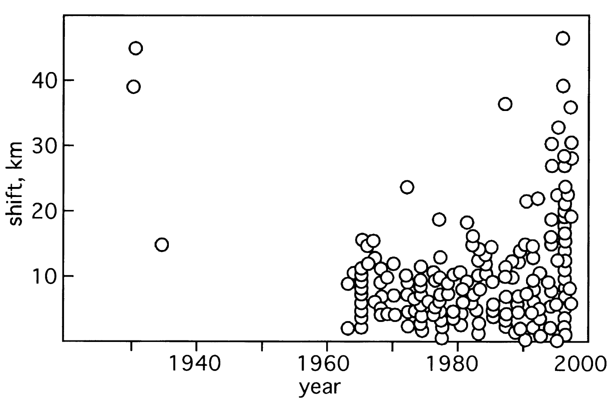

Figure 8. Distribution of epicentral shift between ISS/ISC locations and those recalculated by Engdahl *et al.* (1998) with time. The large shifts in 1997 are for relatively small aftershocks.

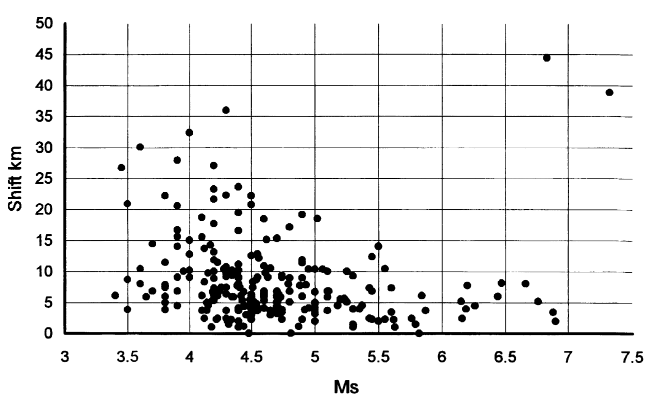

Figure 9. Epicentral shift of ISS/ISC positions versus M_S after recalculation by Engdahl *et al.* (1998).

which open circles indicate those that are calculated from the Prague formula and crosses indicate those that were adopted from earlier estimates.

For the period after 1977, ISC provided M_S values for 177 events calculated from the Prague formula with period restrictions. These we compared with the recomputed M_S values in this work, and as Figure 11 shows, with very few exceptions, the agreement is very good.

For the same period ISC provided body-wave magni-

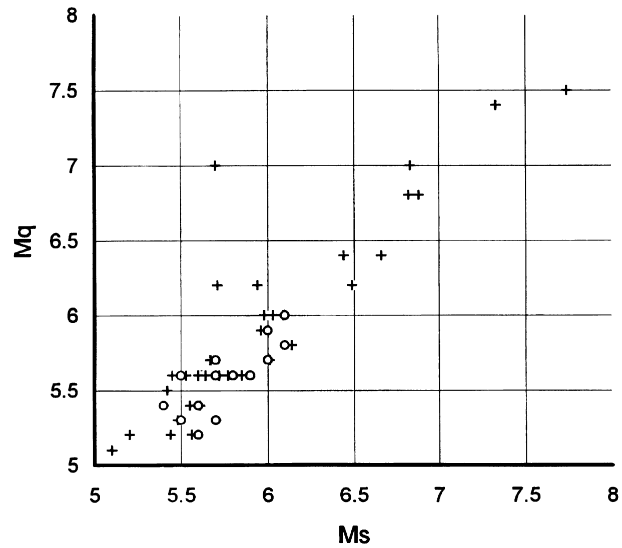

Figure 10. Comparison of surface-wave magnitudes M_q calculated by Quittmeyer and Jacob (1979) from the Prague formula (open circles) and of adopted values (crosses) with those calculated in this study, M_S. The outlier at M_q 7.0 is in fact an m_B value estimated by Gutenberg and Richter (1965) for the earthquake of 6 February 1914, which they consider to be an intermediate depth event (100 km).

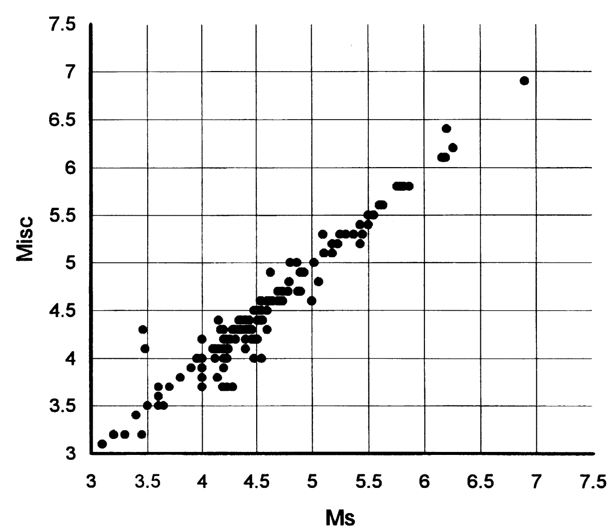

Figure 11. Comparison of the surface-wave magnitude M_{ISC} of 177 earthquakes after 1977, calculated by ISC, with reassessed estimates of M_S.

tudes m_b for 598 events, for which we reassessed M_S. We examined the regional relation between m_b and M_S, which is often used to estimate M_S from m_b. Figure 12 confirms the weakness of such a correlation and the saturation of m_b with increasing M_S. We invoke the absence of a quantifiable relationship as justification for avoiding this method.

Seismic Moment and Moment Magnitude. Ekström and Dziewonski (1988) derived global average relationships between M_S and $\log M_0$, in which the independent variable is $\log M_0$. Relationships were then determined, which when solved for $\log(M_0)$ gave

$$\log M_0 = 19.24 + M_S \quad \text{for } M_S < 5.3 \quad (1a)$$

$$\log M_0 = 30.20 - [92.45 - 11.40 M_S]^{0.5} \quad \text{for } 5.3 \le M_S \le 6.8 \quad (1b)$$

$$\log M_0 = 16.14 + 1.5 M_S \quad \text{for } M_S > 6.8 \quad (1c)$$

on the assumption that the slope of the regression is unity for $\log M_0 < 24.5$ and 3/2 for $\log M_0 > 26.4$.

For the region between the eastern Mediterranean and Pakistan we derived a regional $\log(M_0)$–M_S relation by fitting a set of bilinear relationships to the full dataset, with M_S as the independent variable, using CMT or *P/SH* moments and the corresponding uniformly revaluated M_S values of 577 shallow earthquakes, in the $\log M_0$ range 22.4–27.3. Allowing for the theoretical and observed variation in slope in the $\log(M_0)$–M_S relationship, from unity, for small events, to 3/2 for all but the largest earthquakes (Kanamori and Anderson, 1975; Geller, 1976), we find that

$$\log(M_0) = 19.08 + M_S \quad \text{for } M_S < 6.0 \quad (2a)$$

and

$$\log(M_0) = 16.07 + 1.5 M_S \quad \text{for } M_S > 6.0. \quad (2b)$$

The constants in equation (2) were determined from the reduced dataset of events of uniformly recalculated M_S from the Prague formula and M_0 (CMT), in which M_S and $\log M_0$ were averaged in narrow bins of 0.2 units, a bin width smaller than the error with which these values are known (Ambraseys, 2001).

Figure 13 shows a similar $\log(M_0)$–M_S plot of CMT seismic moments for 42 shallow events in the Baluchistan region. The data, although limited, fit almost exactly equation (2) with *a*-values in equations (2a) and (2b) of 19.08 and 16.19, respectively. For $M_S < 6.8$ Geller's constants for equations (2a) and (2b), which have been derived for average global conditions and a stress drop of 50 bar, are 18.89 and 15.51, respectively (Geller, 1976). In the figure data point (a) is from surface waves of the 1935 earthquake (Singh and Gupta, 1980), and point (b) is from CMT inversion of the

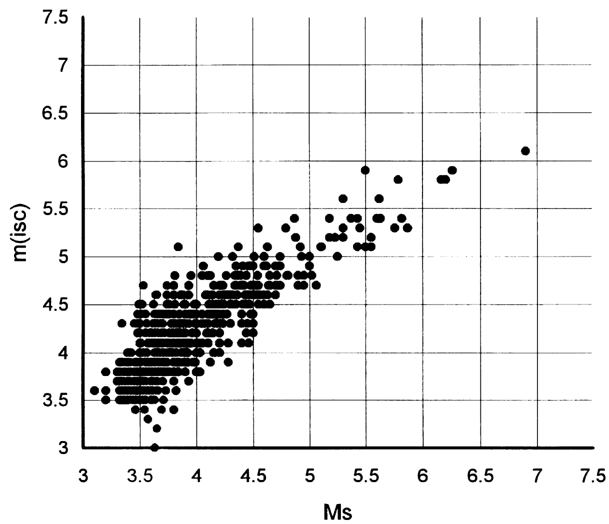

Figure 12. Comparison of the body-wave magnitude m_{ISC} of 593 earthquakes after 1977, calculated by ISC, with reassessed estimates of M_S.

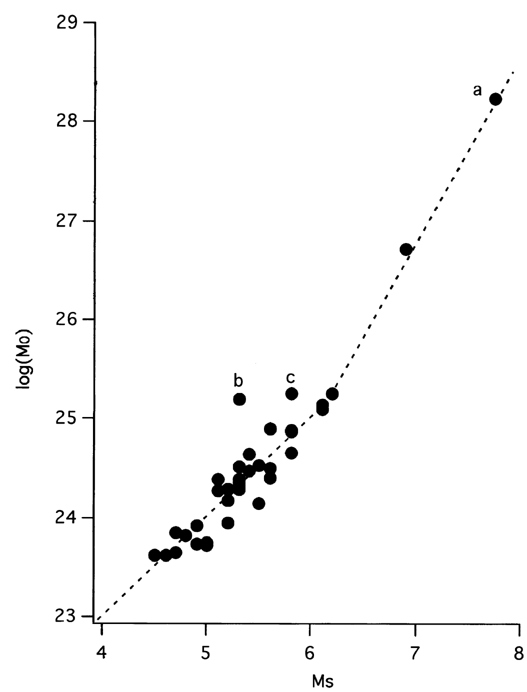

Figure 13. Regional $\log(M_0)$–M_S scaling from 42 shallow earthquakes in the study area; $\log(M_0) = 19.08(\pm 0.3) + M_S$ for $M_S \ge 6.0$, and $\log(M_0) = 16.19(\pm 0.3) + 1.5M_S$ for $M_S > 6.0$. Data point (a) is from surface waves of the 1935 earthquake. Point (b) is from CMT inversion of the earthquake of 27 February 1977 (CMT catalog). Point (c), which was not used in the regression, belongs to the earthquake of 5 August 1988, an event probably deeper than normal, and if so its magnitude should be larger.

earthquake of 27 February 1977. The outlier, point (c), which was not used in the regression, belongs to the earthquake of 5 August 1988, an event probably deeper than normal, and if so its magnitude should be larger.

Dataset. The full dataset of 1045 earthquakes of all magnitudes is homogeneous for the entire period, but incomplete for $M_S < 5.0$ (Ambraseys, 2001). From this reevaluated dataset we select 34 significant earthquakes ($M_S \geq 5.9$) for tectonic evaluation.

For those events in the full dataset that we have assigned a surface-wave magnitude, we infer a seismic moment, M_0. We recognize that in the absence of directly determined values of M_0 this procedure must be used with caution; however, in our case we have derived a local $\log M_0$ versus M_S scaling law (equations 2a and 2b) and are persuaded that the method is viable. The resulting catalog provides us with more than 105 years of seismic moment estimates from which we may calculate a plate boundary velocity for this same period of time (Brune, 1968). In a later section we compare this estimate with reported geological fault slip rates and with geodetic estimates of plate motions.

Regional Frequency–M_S *Magnitude Distribution.* The annual cumulative rate, n, of occurrence of earthquakes of magnitude equal to or greater than M_S for a homogeneous region or a single fault zone is expressed usually by

$$\log(n) = a - bM_S, \tag{3}$$

in which a is a measure of the level of seismic activity and b is the rate of occurrence of events below a specified M_S, above which the self-similarity relation is no longer apparent due to saturation effects (Okal and Romanowicz, 1994). For inhomogeneous regions containing active faults, equation (3) becomes log bilinear, with a change in slope that may be compared with the break in slope of the $\log(M_0)$–M_S relationship, an indication of a change of self-similarity.

Figure 14 shows plots of the logarithm of the annual cumulative frequency (n) as a function of M_S for three time periods: for the ISC period 1964–1999, for the period 1892–1964, and for the whole period 1892–1999. These plots show that the annual rate at which events of $M_S > 5.5$ occur is similar for each time window and also that the catalog, for all practical purposes, is complete in the range $5.5 < M_S < 7.5$.

The 35-year-long ISC dataset is often used for hazard assessment because of its completeness and availability, and it displays an activity rate of $b = 0.89$ to $M_S \leqq 6.4$ and an increasing rate near its upper limit of $M_S \approx 7.0$.

For the 107-year-long period 1892–1999, a bilinear set of equations (equation 3) fitted to the data suggests a break at $M_S > 6.6$, where the rate of activity changes with increasing M_S from $b = 0.85$ to 1.18 (Fig. 14). This change in slope is similar to that of the $\log(M_0)$–M_S relationship, and it is consistent with the magnitude-moment scaling law

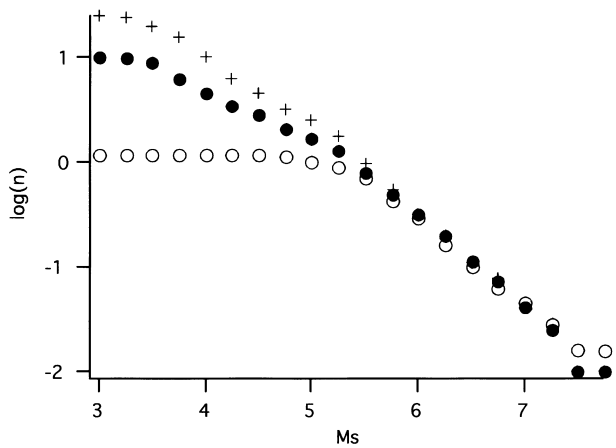

Figure 14. Plot of the logarithm of the annual cumulative number of earthquakes for three different time periods of observation. Solid circles are for the whole dataset, from 1892 to 1999, whereas open circles are for the set from 1892 to 1964 and crosses are for the ISC period 1964–1999. The spread of the data points at high magnitudes suggests that the preparation time for $M_S > 7.0$ is more than one century.

changing, being different for small events for which $\log(M_0)$ and M_S have a 1:1 relation, while for earthquakes of intermediate size that rupture the whole depth of the seismogenic layer, the ratio decreases to 1:1.5, departing yet further from unity for very large earthquakes (Okal and Romanowicz, 1994). This bilinear distribution is also compatible with the frequency of occurrence of events in regions containing many active faults of different length and mobility. It is different from the distribution for a single fault or for a relatively small area where the larger earthquakes will be regarded as likely to occur more frequently than expected from the extrapolation of the small event size. Such an extrapolation will underestimate seismic hazard (e.g., Scholz, 1982, 1997).

Intensity. For most of the earthquakes for which macroseismic information is available, it is possible to assess the extent of the epicentral area and the associated maximum observed intensity, which may be considered to be the epicentral intensity, I_0, if observed at a number of localities. The few field studies in our region show that epicentral intensity in rural areas "saturates," that is, it appears to be effectively the same at intensity of about VIII MSK (Medvedev *et al.*, 1981), because at this level all rural houses are destroyed and any village or town would thus appear equally but no more damaged at so-called higher intensity. It may be argued that in the MSK scale the destruction of all very weak structures corresponds to intensity IX and not to VIII. However, the scale does not specify what is meant by "destruction" and what is "collapse"; for example, heavily fractured walls and dislodged lintels cause destruction of an adobe dwelling but cause "damage" to an engineered kiln brick house. As a consequence any attempt to assess intensities larger than VII+, particularly in rural areas, becomes judgemental and is quite often unduly subjective. Our intensity data at present are insufficient to allow correlation with magnitude.

Historic Geodesy in Baluchistan

Four triangulation networks cross the Eurasia/India plate boundary westward into Baluchistan from the Great Indus Series (1853–1861) of the Great Trigonometrical Survey of India (Walker, 1874) (Fig. 1). The first of these, the Makran Longitudinal Series, was measured in 1895 and crosses 300 km of the plate boundary at 26°–27° N (Strahan, 1899). The second, the Kalat Longitudinal Series (1904–1908), extends 700 km to the Iran border between 27° and 30° N. A northern network (1908–1910) links the Kalat Series to Quetta northward and crosses the southern Katawaz Basin and Sulaiman Range to join the Indus Series at 31° N. The northwest-trending Baluchistan Series (Burrard, 1912) starts at Sukkur on the Indus series and follows a first-order leveling line through Quetta to Chaman, terminating just short of Kandahar. The date of this secondary survey, and of another that emanates due east from Quetta (the Quetta Series), is uncertain but may have been measured as early as 1908. In 1932–1933 the Makran and Kalat networks were linked by the north–south Dalbandin network at longitudes 64° to 66° E (Bomford, 1933). Finally, in 1941–1944 the survey networks of Iraq and Iran were linked to the western extremity of the Kalat network (De Graaff-Hunter and Gulatee, 1946; Thomas, 1946).

The first-order geodetic triangulation in Baluchistan was undertaken to an angular accuracy of the order of 1–7 μrad so that on typical 10- to 30-km-long lines a displacement accuracy of the order of 10–200 mm is available (Bomford, 1933). Due to the prevalence of clear sighting conditions and favorable relief, some of the line lengths were long, and a 128-km/line in the Dalbandan Series is distinguished as the longest sight line in the entire Survey of India. Despite the lengths of the lines in this series, the closure errors observed in linking the earlier Kalat and Makran Series (a distance of 300 km) were 3.05 m in latitude and 2.4 m in longitude.

The remeasurement of segments of these east–west triangulation lines would be of considerable value in constraining the plate boundary velocity in the past century, but to our knowledge no systematic remeasurements have been published. We have found mention of the Secondary Baluchistan and Quetta Series only in the Synoptical summaries of the Survey of India, yet these cross the epicentral tracks of the three largest earthquakes in the region and the Chaman fault at Chaman. The Primary North Baluchistan Series follows the Chaman fault, and although all its control points lie to the east of the fault, several of its points are strategically placed to have detected deformation in the 1935 Quetta earthquake. Surveyors were active in the mountains surrounding Quetta at the time of the 1935 earthquake and participated in the rescue operations following the event.

Space geodesy has yet to be applied to the tectonics of the Baluchistan/Afghanistan region. The closest GPS measurement points currently lie in Pakistan (Peshawar and Kachchh), in Iran, in the Tien Shan, and in Oman, all with one exception outside the overview map (Fig. 1), and they do not sample the intervening crustal blocks of central Baluchistan. The one exception is a single GPS measurement near the Iran border whose velocity is close to that of the Eurasian plate (D. Hatzfeld, personal comm., 2001). The transform slip velocities across the Chaman fault system, and the convergence rate in the Makran Range, may be inferred from Eurasia/India/Arabia relative motions only in the absence of independent rotation of south and central Baluchistan.

Quittmeyer and Jacob (1979) estimated plate closure velocities in the region, and their estimates, despite being made with early plate motion models, cannot be much improved on today. NUVEL-1 estimated relative motions between the Eurasian plate and the Arabian plate south of Baluchistan (27° N, 66° E) are 42.1 mm/yr at 9° E and between the Indian plate and the Eurasian plate (30° N, 66° E) are 40.2 mm/yr at N5° E. The inferred relative velocity between India and Arabia on the Owens Fracture Zone south of the triple junction near Karachi is less than 2 mm/yr at approximately N40° E. Allowing for minor convergence in the Afghan mountains would suggest that the relative velocity between east Baluchistan and west India is less than the Eurasia/Indian plate velocity and more than that estimated from geological offsets on faults with recent surface expression.

Slip rates within the Chaman fault system estimated from geological offsets are 19–24 mm/yr for the past 20–25 Myr (Lawrence *et al.*, 1992) and 25–35 mm/yr for the past 2 Myr (Beun *et al.*, 1979), but these do not sample distributed shear and underestimate the contribution from block rotation should this be occurring.

Vertical Deformation in the 1931–1935 Earthquake Sequence

In contrast to the absence of horizontal geodetic constraints of deformation in the region, vertical deformation between 1909 and 1936 is known precisely across part of the plate boundary at 29° to 30.5° N (Fig. 1). The 432-km distance between Sukkur and Quetta is linked by a first-order leveling line for which relative heights of 164 benchmarks at 2- to 5-km intervals were measured to millimeter accuracy in 1909 (Lenox-Conyngham, 1916). The route follows the road, and in places, the railroad (Table 2). Random errors were estimated to increase as $k\sqrt{L}$ (mm) where $k = 0.65$ and L is the distance in kilometers. Maximum random errors along the entire line amount to 19 mm, but where the line crosses geologically active structures with dimensions of less than 35 km, errors are typically less than 5 mm. The southernmost 96 km of the line was leveled in 1909, and the

Table 2
Height Changes 1914–1936 of 167 Geodetic Benchmarks Between Quetta and a Point South of Sibi (Wilson, 1937)

BM#	Map#	Lat. N°	Long. E°	Q (km)	Ht. (m)	Δ (mm)	± mm	Benchmark Type
343	40A	27.58	68.42	391.3	59.034	0	19.8	Shikarpur iron plug
89	39D/1	28.7536	68.0756	272.2703	60.9232	−80.5	10.7	Nuttal p. 17
91	39D/1	28.7653	68.0731	270.4747	60.9347	−85.4	10.7	Stone pillar
93	39D/1	28.7828	68.0689	268.4155	61.1054	−101.5	10.6	Stone pillar
94	39D/1	28.7864	68.0681	268.0037	61.1495	−104.3	10.6	Stone pillar
95	39D/1	28.7930	68.0673	267.18	61.243	−105.5	10.6	Stone pillar
96	39D/1	28.8003	68.0656	266.3564	61.3674	−105.8	10.6	Stone pillar
97	39D/1	28.8061	68.0640	265.5162	61.5531	−110.4	10.6	Flooring
98	39D/1	28.8171	68.0623	263.8689	61.4281	−103.1	10.6	Stone pillar
99	39D/1	28.8251	68.0606	263.457	61.5039	−114.6	10.6	Stone pillar
100	39D/1	28.8280	68.0598	263.0452	61.5179	−104.6	10.5	Stone pillar
104	39D/1	28.8499	68.0556	260.5742	61.7088	−106.1	10.5	Stone pillar
105	39D/1	28.8571	68.0540	259.7505	61.7798	−108.9	10.5	Stone pillar
108	39D/1	28.8732	68.0507	258.0043	62.0945	−129.3	10.4	Flooring
107	39D/1	28.8739	68.0498	257.9549	61.8513	−124.7	10.4	Chuckra IBM Type A
109	39D/1	28.8863	68.0473	256.3734	62.0116	−136.9	10.4	Stone pillar
110	39D/1	28.8943	68.0457	255.5498	62.1175	−123.8	10.4	Stone pillar
112	39D/1	28.9162	68.0382	253.4741	62.2223	−124.7	10.3	Stone pillar
113	39D/1	28.9176	68.0374	253.0623	62.2204	−129.6	10.3	Stone pillar
116	39D/1	28.9322	68.0316	250.9866	62.4529	−116.2	10.3	Flooring
121	39D/1	28.9913	68.0091	243.8536	62.6435	−101.2	10.2	Flooring
122	39D/1	28.9942	68.0083	243.7054	62.3784	−75.3	10.1	Bellpat
1	39C/4	29.0010	68.0010	241.3002	62.6068	−79	10.1	Stone pillar
2	34O/16	29.0150	67.9953	238.4009	62.7747	−76.2	10	Stone pillar
3	34O/16	29.0300	67.9907	237.1654	62.7731	−57.3	10	Stone pillar
4	34O/16	29.0450	67.9860	236.3417	62.7875	−67.7	10	Stone pillar
6	34O/16	29.0600	67.9813	235.1062	62.7798	−63.7	10	Stone pillar
7	34O/16	29.0750	67.9767	233.8872	62.9292	−122.6	9.9	Bridge
10	34O/16	29.0900	67.9720	231.6633	63.0281	−63.1	9.9	Flooring
9	34O/16	29.0911	67.9718	231.5974	62.788	−47.9	9.9	Damboli Type A
11	34O/16	29.1035	67.9656	229.9994	62.8655	−73.5	9.9	Stone pillar
12	34O/16	29.1086	67.9635	229.5876	62.8979	−62.5	9.8	Stone pillar
13	34O/16	29.1276	67.9568	228.7639	62.9377	−59.8	9.8	Stone pillar
16	34O/16	29.1436	67.9502	225.2386	63.1291	−64.4	9.8	Lashari flooring
20	34O/16	29.1968	67.9302	218.7975	63.2251	−16.5	9.6	Tone pillar
22	34O/16	29.2172	67.9228	216.4912	63.38	−31.1	9.6	Flooring
21	34O/16	29.2179	67.9236	216.4418	63.2837	−13.1	9.6	Lindsay Type A
30	34O/15	29.2981	67.8862	204.6303	64.0804	−33.6	9.3	Stone pillar
33	34O/15	29.3389	67.8754	201.698	64.4025	−30.5	9.2	Stone pillar
34	34O/15	29.3455	67.8729	200.4625	64.5032	−28.4	9.2	Stone pillar
35	34O/15	29.3513	67.8704	200.0507	64.526	−29	9.2	Stone pillar
36	34O/15	29.3659	67.8663	198.3045	64.6633	−25.6	9.2	Bridge
38	34O/15	29.3783	67.8605	196.8713	64.8357	−24.7	9.1	Stone pillar
39	34O/15	29.3797	67.8588	195.85	64.7462	−16.2	9.1	Mithri type A
40	34O/15	29.3870	67.8580	195.6688	64.9946	−25.3	9.1	Flooring
44	34O/15	29.4206	67.8467	191.7151	65.111	−15.9	9	Stone pillar
47	34O/15	29.4227	67.8372	189.6395	65.2887	51.2	9	Stone pillar
56	34O/14	29.5503	67.8704	175.983	66.3425	68.8	8.6	Sibi Type B
63	34O/14	29.5255	67.8115	168.9653	66.0186	154.2	8.4	Bridge
64	34O/14	29.5233	67.8040	168.1251	66.1828	162.7	8.4	Bridge
65	34O/14	29.5226	67.7899	167.2356	66.3366	173.4	8.4	Masonry tank
71	34O/11	29.4883	67.6894	153.4802	67.3095	145.3	8.1	Mushkaf Type B
75	34O/11	29.4913	67.5814	142.0477	71.2222	356.9	7.7	Boulder p. 19
76	34O/11	29.4971	67.5739	140.8122	72.4303	428.5	7.7	Bridge
77	34O/10	29.5029	67.5664	139.7908	72.4912	474.2	7.7	Bridge
79	34O/11	29.4956	67.5399	136.9903	73.759	452	7.6	Bridge
81	34O/11	29.4708	67.5249	133.5638	74.9196	418.4	7.5	Bridge
82	34O/11	29.4650	67.5183	132.5754	75.2051	431.6	7.5	Bridge
83	34O/11	29.4621	67.5033	131.0104	76.057	440.4	7.4	Bridge
84	34O/7	29.4563	67.5000	130.4998	76.2738	438.9	7.4	Culver
85	34O/7	29.4606	67.4934	128.9677	77.143	468.7	7.4	Boulder

(*continued*)

Table 2
(*Continued*)

BM#	Map#	Lat. N°	Long. E°	Q (km)	Ht. (m)	Δ (mm)	± mm	Benchmark Type
86	34O/7	29.4687	67.4925	128.3417	77.4116	480.6	7.4	Rock in situ
87	34O/7	29.4745	67.4917	127.4522	77.9422	494.3	7.3	Bridge
88	34O/7	29.4920	67.4849	126.0025	78.6803	509.3	7.3	Culvert
91	34O/7	29.4934	67.4817	122.8726	81.9207	541.9	7.2	IBM Type B
95	34O/6	29.5394	67.4815	117.5846	83.1436	504.7	7	Rock in situ
96	34O/6	29.5466	67.4768	116.9915	83.016	466.6	7	Rock cut Type C
98	34O/6	29.5744	67.4725	115.1136	84.1236	388.6	7	Ms
99	34O/6	29.5728	67.4627	113.3674	86.4293	327	6.9	Bedrock
100	34O/6	29.5829	67.4354	112.1154	87.0228	280.7	6.9	Rock
101	34O/6	29.5924	67.4412	110.1715	88.3745	144.4	6.8	Rock in situ
102	34O/6	29.5982	67.4346	109.2655	89.1604	21	6.8	Boulder
104	34O/6	29.6127	67.4222	106.8439	90.9609	−82.6	6.7	IBM Type B
105	34O/6	29.6273	67.4131	105.1306	92.8704	−114.3	6.7	Rock in situ
106	34O/6	29.6323	67.4123	104.2905	93.5604	−111.6	6.6	Bridge
107	34O/6	29.6440	67.4106	103.2362	94.8388	−117.4	6.6	Bridge
108	34O/6	29.6490	67.4106	102.7255	95.3902	−115.9	6.6	Bridge
110	34O/6	29.6657	67.4040	100.5181	97.8907	−97	6.5	Rock in situ
111	34O/6	29.6694	67.4023	99.94151	98.928	−98.5	6.5	Bridge
112	34O/6	29.6926	67.3891	97.17397	103.752	−89.3	6.4	Bedrock
113	34O/6	29.6948	67.3874	96.46561	103.861	−84.8	6.4	Rock-cut Type C
114	34O/6	29.7064	67.3808	95.14773	105.938	−73.2	6.3	Bedrock
115	34O/6	29.7101	67.3808	94.53821	107.045	−62.8	6.3	Rock
116	34O/6	29.7217	67.3791	93.38507	109.037	−50.9	6.3	Rock in situ
117	34O/6	29.7268	67.3775	92.84145	109.991	−47.3	6.3	Boulder
118	34O/6	29.7340	67.3758	91.90246	111.452	−30.8	6.2	Rock in situ
119	34O/5	29.7483	67.3729	90.22217	114.182	−36.6	6.2	IBM Type B
120	34O/5	29.7541	67.3723	89.54676	115.27	−18	6.2	Bridge
121	34O/5	29.7621	67.3691	88.55835	117.052	−22.6	6.1	Ms
122	34O/5	29.7759	67.3616	86.87806	120.448	−30.2	6.1	Ms
123	34O/5	29.7912	67.3555	85.9226	122.866	−26.3	6	In situ rock
124	34O/5	29.7912	67.3475	83.56689	129.66	−35.1	5.9	ms
125	34O/5	29.7912	67.3455	83.03974	131.375	−36.9	5.9	In situ rock
126	34O/5	29.8116	67.3380	81.5736	136.659	−56.4	5.9	In situ rock
127	34O/5	29.8196	67.3284	80.28867	135.968	−165.8	5.8	Bridge
128	34O/5	29.8290	67.3256	79.18495	140.244	−68.3	5.8	In situ rock
129	34O/5	29.8356	67.3198	78.22949	142.412	−69.8	5.7	In situ rock
130	34O/5	29.8494	67.3173	76.33505	146.697	−58.9	5.7	In situ rock
132	34O/5	29.8647	67.3131	73.81461	155.358	−111.3	5.6	Boulder
133	34O/5	29.8683	67.3106	73.04035	155.812	−54.6	5.6	Boulder
134	34O/5	29.8778	67.3040	71.85427	159.098	−83.6	5.5	Old Mach IBM type B
136	34O/5	29.8727	67.2869	70.20692	163.339	−94.2	5.4	Bridge
137	34O/5	29.8887	67.2743	68.5431	171.143	−100	5.4	Ms
138	34O/5	29.8916	67.2636	67.09344	177.962	−93.6	5.3	Bedrock
139	34O/5	29.8967	67.2650	65.8744	176.095	−80.8	5.3	Bridge
140	34O/5	29.9021	67.2626	65.05073	177.401	−76.2	5.2	Bridge
141	34O/5	29.9127	67.2550	63.68343	182.56	−64	5.2	Rock
142	34O/5	29.9146	67.2533	63.2057	183.616	−61.6	5.2	Rock
144	34O/1	29.9089	67.2095	61.6572	188.896	−43.6	5.1	Bed rock
145	34O/1	29.9109	67.2000	60.73468	191.514	−46.4	5.1	Bed rock
146	34O/1	29.9131	67.1956	60.15811	193.167	−45.8	5	Bed rock
147	34O/1	29.9157	67.1912	59.76275	194.69	−43.3	5	Bed rock
149	34O/1	29.9207	67.1854	58.09893	200.09	−40	5	Bed rock
150	34O/1	29.9216	67.1796	57.85183	201.215	−40	4.9	Bed rock
151	34O/1	29.9241	67.1766	57.3741	203.901	−40.3	4.9	Bed rock
152	34O/1	29.9266	67.1759	57.04463	205.849	−37.2	4.9	Bed rock
355(153)	34O/1	29.9283	67.1752	56.79753	206.064	−33.9	4.9	IBM type b
155	34O/1	29.9283	67.1715	56.20448	207.358	−30.5	4.9	Bridge
156	34O/1	29.9308	67.1642	55.69381	209.052	−29.9	4.9	Rock in situ
157	34O/1	29.9241	67.1591	54.87013	211.724	−17.7	4.8	Bridge
158	34O/1	29.9258	67.1489	54.54066	212.529	−12.8	4.8	Rock in situ
159	34O/1	29.9241	67.1458	53.93115	214.037	−12.5	4.8	Rock in situ

(*continued*)

Table 2
(*Continued*)

BM#	Map#	Lat. N°	Long. E°	Q (km)	Ht. (m)	Δ (mm)	± mm	Benchmark Type
160	34O/1	29.9207	67.1416	53.48636	216.057	−7.7	4.8	Rock in situ
162	34O/1	29.9182	67.1365	51.85549	220.596	11.2	4.7	Bedrock
163	34O/1	29.9072	67.1314	51.09771	222.553	28.9	4.6	Boulder
165	34O/1	29.9072	67.1314	50.05988	226.027	3.9	4.6	Bedrock
166	34O/1	29.9030	67.1292	49.54921	226.291	17.6	4.6	Bedrock
167	34O/1	29.8988	67.1248	48.74201	227.25	19.8	4.5	Bedrock
170	34O/1	29.8853	67.1153	46.88051	231.927	28.9	4.5	Bedrock
171	34O/1	29.8819	67.1131	46.51809	232.893	24.7	4.4	Bedrock KOLPUR
172	34O/1	29.8870	67.1066	45.69442	230.945	25	4.4	Bedrock
372(173)	34O/1	29.8954	67.0993	44.34359	230.112	22.5	4.3	Bridge
373(174)	34O/1	29.9005	67.0920	43.38813	230.071	19.5	4.3	Ms
175	34O/1	29.9123	67.0818	42.13615	230.196	40.2	4.2	Bedrock
176	34O/1	29.9114	67.0818	41.27953	230.632	37.1	4.2	Bridge
177	34O/1	29.9207	67.0657	39.97813	231.252	40.8	4.1	IBM type b
178	34O/1	29.9334	67.0584	38.11663	231.766	61.5	4	Bridge
179	34O/1	29.9460	67.0438	36.25513	231.984	53.3	3.9	Bridge
181	34O/1	29.9730	67.0058	30.81889	231.502	57	3.6	Bridge
3	34k	29.9764	67.0000	30.01169	231.503	55.7	3.6	Platform
4	34k	29.9831	66.9942	29.58338	231.48	57	3.5	Bridge
1	34k	29.9916	66.9898	28.52908	231.471	50.6	3.5	Bridge
2	34k	29.9966	66.9883	27.35946	231.534	52.7	3.4	Bridge
1	34j	30.0067	66.9825	26.30516	231.606	44.5	3.3	Bridge
2	34j	30.0202	66.9788	25.05318	231.669	32	3.3	Bridge
3	34j	30.0354	66.9803	23.76825	231.194	26.2	3.2	Bridge
4	34j	30.0430	66.9876	22.30211	233.526	23.4	3.1	IBM type b
5	34j	30.0725	66.9839	18.99095	228.608	4.8	2.8	Bridge
6	34j	30.0835	66.9869	18.18375	227.964	−3.4	2.8	Bridge
7	34j	30.0911	66.9876	17.44244	227.352	−16.5	2.7	Bridge
8	34j	30.0978	66.9869	16.7835	226.811	−25.6	2.7	Bridge
9	34j	30.1113	66.9854	15.67978	226.344	−42.7	2.6	Bridge
10	34j	30.1164	66.9853	14.93848	225.967	−53.7	2.5	Bridge
11	34j	30.1282	66.9854	13.57118	225.62	−75.9	2.4	Bridge
12	34j	30.1392	66.9857	12.71456	224.99	−85.1	2.3	Bridge
13	34j	30.1468	66.9861	11.98973	224.653	−89	2.3	Bridge
14	34j	30.1577	66.9861	10.77069	224.039	−104.3	2.1	Bridge
39(16)	34j	30.1881	66.9927	7.723103	222.405	−79.6	1.8	Culvert
39(17)	34j	30.2041	66.9949	5.894549	221.052	−76.2	1.6	IBM type b
19(3)	34n	30.2244	67.0007	3.818894	220.769	−60.4	1.3	Bridge
20	34j	30.2294	67.0015	3.489425	220.518	−63.7	1.2	Step
46(PP)21	34n	30.2379	66.9591	−2.128024	225.066	276.1	0.9	Rockcut type C
23(5)	34n	30.2277	67.0088	2.830487	221.237	−54.6	1.1	Platform
25(PP)8	34n	30.2379	67.0131	1.907973	221.081	−43.9	0.9	Quetta SBM
31(11)	34n	30.2446	67.0197	−0.315943	223.64	−6.7	0.4	Flooring
38(16)	34n	30.2	67.0	−4.467254	231.729	−14.1	1.4	Step
40(17)	34n	30.2	67.0	−7.613684	238.234	−12.2	1.8	Rockcut type C

Several types of subsurface (interred = IBM) benchmarks and rock-cut markers were used (Lenox-Conyngham, 1916), numbered sequentially (BM#) on each quadrangle map (Map#). ms = milestones, now lost as a result of their replacement by kilometer markers after 1947. Q is along-line distance from Quetta. Ht. = height assuming the orthometric height of the iron plug at Shickarpur is 59.034 m (Burrard, 1910). Δ is the height change 1936–1914 relative to Shikarpur, and ± mm is the random error estimated from Quetta assuming an error growth of 0.65 mm per square kilometer (Lenox-Conyngham, 1916). Raw data from Wilson (1937), using a conversion factor of 1 Indian inch = 25.399772 mm. Coordinates in column 2 were identified on inch-to-the-mile sheets, and relative positions are estimated accurate to approximately 20 m (Burrard, 1919; Couchman, 1935a–f, 1936; Gore, 1901; Hamilton, 1935; Tandy, 1928a–c; Thomas, 1929a,b). The locations of the last two benchmarks are approximate since they could not be located on available maps.

entire line was measured between 1913 and 1914 and again between 1935 and 1936 (Wilson, 1938).

Although the 1935 and 1936 measurements were specifically to determine possible height changes associated with the Quetta 1935 earthquake, the leveling line terminated on the western outskirts of Quetta, too far east to reveal details of surface deformation across the fault zone responsible for this earthquake. Points in the town of Quetta showed no significant uplift, but two points on rock near the brewery on the hill west of Quetta were raised 20 cm, presumably by slip on a shallow fault at the foot of the south-southeast–trending Chiltan range. Contemporary reports describe surface fractures near the rail line that crosses the range front 20 km to the south. The leveling line appears to have been measured to Chaman beyond Quetta in 1936/7 (Wilson, 1938), but these results were not published with the data, with the exception of ties to trigonometrical points near the Khojak Range, presumably because no significant deformation was detected in this region. Additional data have almost certainly been obtained in subsequent years, but these are not publicly available. In their absence the leveling data prevent clear conclusions from being derived about the 1935 rupture.

The leveling line may also have sampled minor deformation in the Kachhi event of October 1909 (Heron, 1911) in the Kachhi Plains southeast of the Sulaiman Range, although there is some doubt whether the measurements predated the earthquake since they were underway in the same year. Subsidence in 1909–1936 along the line was less than 10 mm in the 50 km near Kachhi.

The 1931 Mach/Sharigh sequence, however, produced large and incontestable deformation between Sibi and Quetta in the form of three broad regions of uplift. Two regions of minor uplift (10–20 cm) occur northwest of Mach, and a region of pronounced uplift (>65 cm) is encountered southeast of Mach and south of Sharigh. These uplift features have wavelengths of 30–60 km, and uplift greatly exceeds anticipated errors in the leveling process (Fig. 15c). Moreover, since the topography along the leveling line between Quetta and Sukkur shows no correlation with the reported height changes, systematic errors are insignificant (Fig. 15c).

Although it is clear that subsurface slip occurred beneath the leveling line, attempts to estimate geometry and slip uniquely for the Sharigh and Mach ruptures are frustrated by the absence of 3D coverage of the deformation field and by the absence of independent geometric constraints of possibly active subsurface structures. Surface folds rotate from northwest-trending to South-southwest–trending between Sharigh and Mach within 10 km of the leveling line. We chose to project the leveling data at N110° E on a line normal to the trend of fold axes south of the Bolan Pass. Weakly supportive of this projection azimuth is the observation that with this projection the deformation field varies smoothly across the ranges, whereas with other azimuths the deformation field is more complex.

The 65-cm Bolan Pass uplift signal, the largest of the deformation fields crossed by the leveling line, has the deformation asymmetry associated with reverse slip on a buried rupture (Fig. 15c). Elastic deformation fields of simple planar dislocation models that reproduce the long wavelength of the observed deformation share three attributes: they dip at 35° to 45° to the southeast, they rupture from near the surface to the base of the seismogenic layer at 35–40 km, and average slip is 1.1 ± 0.1 m. Best-fitting models stop short of the surface at depths of 3–5 km. Our models assumed an elastic half-space and used a 2D dislocation calculation (Savage, 1988). Alternative interpretations based on variable slip, a 3D geometry, and slip on additional faults are possible that would fit the data better than those shown in Figure 15c; they are unwarranted given the absence of detailed structural information available to us. The southeasterly dip, and downdip width of the rupture, has important implications for the tectonics in the region. The relocated Mach epicenter coincides with maximum uplift in the Bolan Pass extending west toward the Kachhi Plain. Although maximum intensities of shaking in the Mach event occur in the hanging wall of the reverse fault, high accelerations also occur near Mach. These may be a result of directivity in the rupture, combined with local site conditions in the valley floors where most of the observations of shaking were derived.

The geometric seismic moment associated with these simple models is consistent with a M_w 7.3 earthquake if its along-strike length is limited to 60–80 km. The isoseismals for the Mach earthquake include a south-southwest lobe that follows the inferred rupture zone, but extends 20–40 km further south-southwest, suggesting either that the earthquake was larger than indicated by the teleseismic data (Appendix B) or that the downdip width and/or slip reduces to the south-southwest. Because the leveling data are largely insensitive to strike-slip displacement except near the ends of the rupture, the Mach event could also have included a strike-slip component, as suggested by one recent focal mechanism near our relocated epicenter. However, the amount of strike slip cannot have been significant (<1 m) for it to be compatible with its estimated seismic moment and inferred along-strike and downdip width.

The smaller magnitude, and inferred distance from the Bolan Pass, of the 1931 Sharigh earthquake suggests that this is unlikely to have generated significant deformation near the Bolan Pass, and recent focal mechanisms and the strike of structural trends suggest that this event may have thrust to the south or southwest. We note that the Bolan Pass hosts one of two railroads crossing the range front near Sharigh and that independent leveling data may exist on this line that might in the future provide a 2D view of the deformation in the two earthquakes.

The mechanism of the Mach and Quetta earthquakes suggests that strain partitioning prevails on the Chaman plate boundary, with strike-slip faults near the Chaman fault absorbing left-lateral slip and reverse faults to the east absorbing transpressional fault-normal convergence. The close association of the Mach M 7.3 and Quetta M 7.7 earthquakes geographically (100 km) and in time (4 years) leaves little doubt that the first event resulted in conditions favorable for slip of the second. Fault planes in the two earthquakes are approximately parallel, of similar length, and spaced approximately one fault dimension apart. By reducing fault-normal stress, the Mach earthquake may have "unclamped" the left-lateral fault that slipped in the Quetta earthquake. The delay between the two events is presumably the result of viscous or poroelastic processes in the crust and upper mantle.

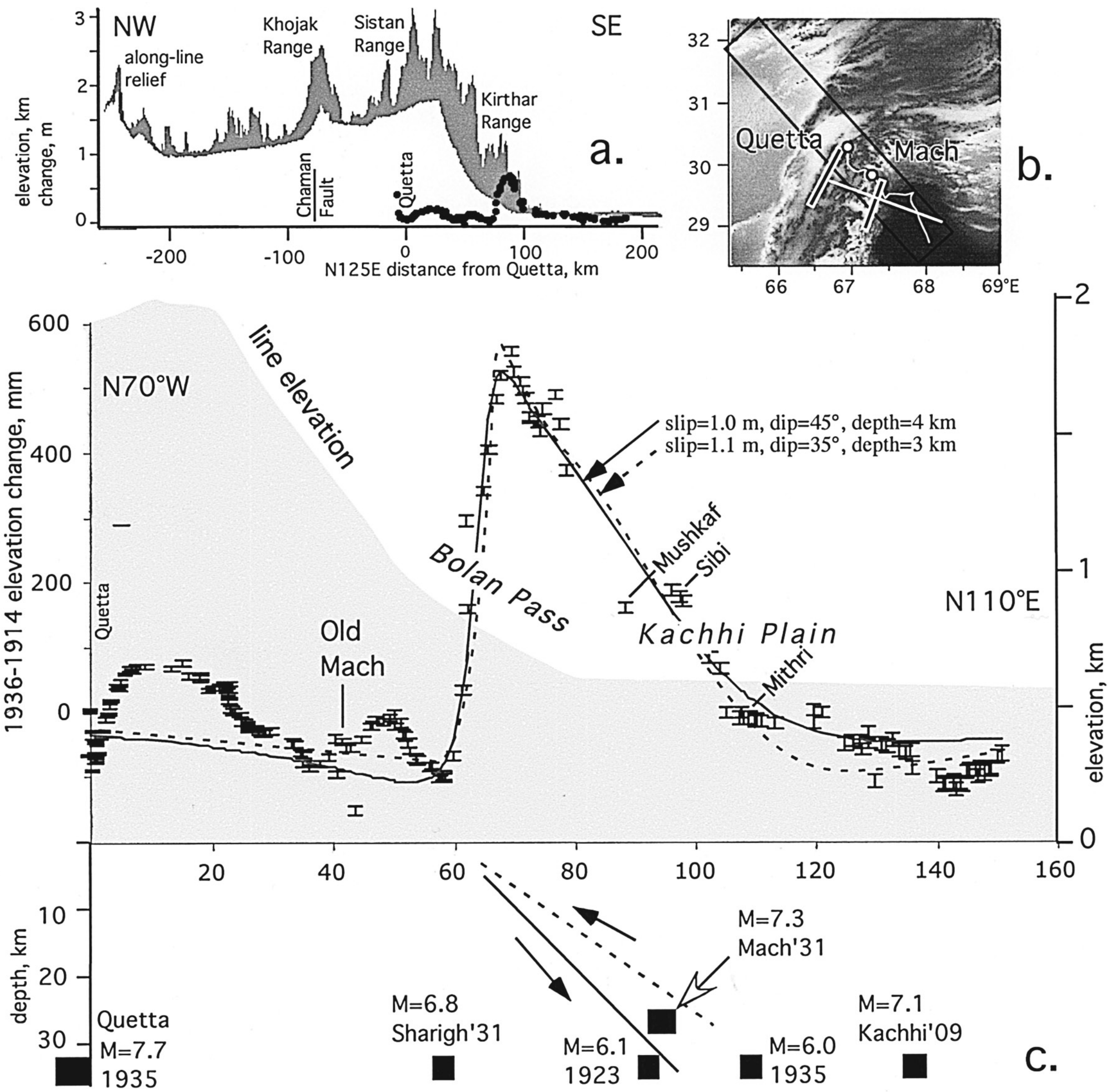

Figure 15. (a) Height changes 1914–1936 (black line), leveling-line profile, and vertical relief from the plains of India to Kandahar, Afghanistan, through the Bolan Pass (gray). (b) Baluchistan relief, and path of leveling line and leveling-line projection azimuth (white line), through the mountains of Baluchistan. The inferred causal faults of the Quetta and Mach earthquakes are indicated. The box indicates the path included in profile (a). (c) Leveling-line profile (gray) and height changes relative to an arbitrary datum at Shikarpur. Bars indicate error growth as a function of distance from Quetta. Elastic half-space dislocation models require a 40- to 50-km-wide fault dipping to the southeast beneath the eastern edge of the Kachhi Plain. The projected location of large earthquakes within ±30 km of the leveling line are indicated at arbitrary depth.

Estimates of Deformation from Seismic Moment Release

Seismic moment release as a function of depth in the full catalog suggests that significant moment release occurs below 20 km, even when default depth locations at 0 and 33 km are ignored. Our dislocation model for the Mach earthquake also indicates that rupture penetrated to depths of more than 30 km. In the better-located depths from the shorter Engdahl *et al.*, catalog (1998), we note that 28% of the moment release occurs below 20 km depth, but only 8% occurs below 30 km.

Recent earthquakes within 60 km and east of the Chaman fault have predominantly left-lateral mechanisms, whereas earthquakes more than 120 km from the fault in the Kirthar and Sulaiman Ranges possess largely reverse-faulting mechanisms (Fig. 2). To obtain an estimate of the average plate slip velocity (Brune, 1968) from this subset, we sum the seismic moment within a strip 60 km wide and assume a value for the rigidity modulus (3×10^{11} dyne cm^{-2}) and a seismogenic thickness of 30 km. A summation of earthquakes within 60 km of the Chaman fault results in a cumulative seismic moment along the 600-km plate boundary in Figure 12a of 8.2×10^{27} dyne cm (1.0×10^{28} dyne cm allowing for the contribution from earthquakes smaller than M_S 5.9). The mean velocity for this 600-km segment of plate boundary given these assumptions is 13.2 mm/yr.

Inspection of Figure 16 reveals that the Quetta earthquake contributes most of this moment release and that 90% of the moment release occurs between 28° and 31° N. For this 300-km segment of the plate boundary a mean slip velocity of 26.4 mm/yr can be calculated to have occurred in the past century, although this is unlikely to represent the true long-term slip rate in the region. North of 31° N a significant slip deficit currently exists. Bernard *et al.* (2000) formed a similar conclusion. The absence of either a complete cycle of earthquake recurrence, or contiguous rupture along the plate boundary, indicates that the 100-year time interval investigated is inadequate to form general conclusions concerning the mean slip velocity of the plate boundary.

By summing the moment release in segments parallel to the Chaman fault (Fig. 16) we gain some insight into the slip deficit in each segment. The fault system follows a curved path between 28° N and 33° N that we divide into three 60-km-wide bands approximately parallel to the Chaman fault. We divide these in turn into 150-km-long, along-strike segments. For each segment we sum the moment re-

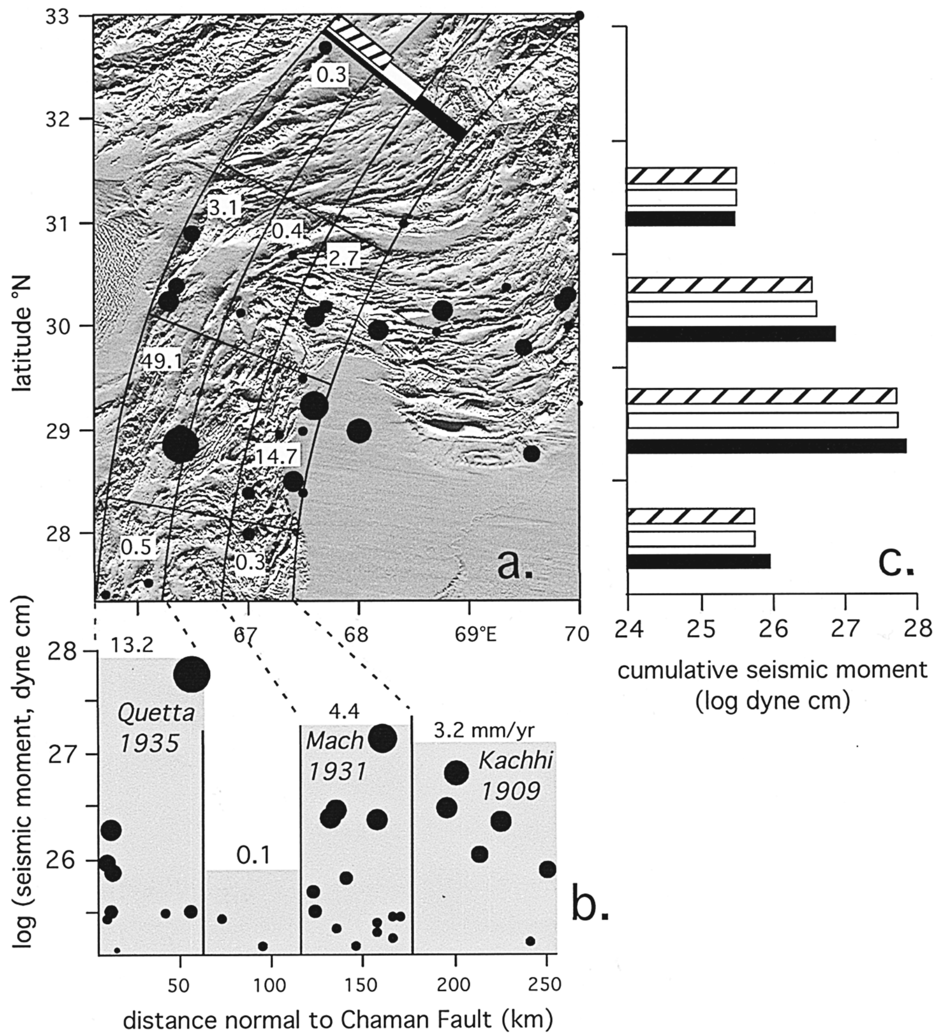

Figure 16. (a) Geographic distribution of moment release in Baluchistan, showing segments summed for moment release. Dot size is proportional to moment as in Figure 13b. Numbers indicate equivalent slip rate in millimeters per year. (b) Rate of reduction in moment release eastward, normal to the Chaman Fault with largest events indicated. Gray area indicates cumulative moment release in 60-km-wide swaths from fault, and numbers indicate equivalent mean slip rate. (c) Cumulative moment release (1892–2002) in segments along the plate boundary corresponding to 60-km-wide (striped), 120-km-wide (white), and 180-km-wide (black) strips parallel to the Chaman fault.

lease and calculate an equivalent slip velocity with the assumptions given before. The values derived fall far short of the estimated Euroasian plate boundary velocity (≈40 mm/yr) except in the segment that includes the Quetta earthquake.

Of interest in Figure 16 is the apparent absence of significant moment release between 60 and 120 km of the fault and the significant moment release from reverse faulting beyond this region. The brevity of the seismic record may be responsible for the apparent separation between these two processes. Although the data suggest an apparent eastward decrease in moment release, and moment release per event, with increasing distance from the Chaman fault (Fig. 16b), we note that had this time interval not included the Chaman and Mach events, this pattern of energy release would not exist.

Discussion and Conclusions

Many of the existing regional and global parametric earthquake catalogs of the last 100 years do not fulfill the condition of transparency. Transparency requires clear statements indicating the procedures followed to locate macroseismic or instrumental epicenters, the scales used to calculate magnitude and intensity and their methods of calculation, and, if these parameters were not calculated by the author, the sources from which they were taken.

The example shown in Figure 10, in which we compare uniformly recalculated M_S with magnitudes estimated by Quittmeyer and Jacob (1979) and Gutenberg and Richter (1965), demonstrates, for example, that for $M_S \geq 7.0$ an overestimation of magnitudes by 0.3–0.5 units is possible and sufficiently large to obscure or to eliminate the break in the regional frequency relation, to blur scaling laws, and to exaggerate grossly early twentieth-century seismicity (Satyabala and Gupta, 1996).

Instrumental locations before the early 1970s are of low accuracy. For the Middle East to Pakistan we find that ISS/ISC locations are systematically 10–30 km to the north or northeast of their macroseismic epicenters, a bias that is unlikely to be due to systematic errors in the macroseismic positions (Ambraseys, 2001). A similar trend is shown in Figures 6 and 9, in which ISC locations average 10 km east of Engdahl's relocated positions.

We find that good macroseismic evidence is by far the most reliable indicator of epicentral location, particularly for events of $M_S < 6.5$ of the first half of this century when instrumental positions were more uncertain, and we give macroseismic locations more weight. Macroseismic epicenters are good enough for the association of earthquakes with local tectonics as well as for the calculation of the magnitude of early events; a location error of as much as 50 km would correspond only to a second decimal place error in magnitude. While there can be no objection to calculating epicenters whose accuracy is greater than that actually required, there is a degree of precision beyond which refinement becomes pointless.

Present-day activity in continental zones is not restricted to junctions between plates or along important elements in the geological history of the region; it extends over wide zones that accommodate relative motion between them (Quittmeyer *et al.*, 1979; Lawrence *et al.*, 1981, 1992). This is clearly seen in the seismicity of this century shown in Figures 2 and 16, which give a 100-year-long image of the seismic potential of the region. Notwithstanding the brevity of this time interval, we find that slip at the plate boundary is partitioned between strike-slip and fault-normal faulting as exemplified by the 1935 Quetta and 1931 Mach faults, respectively. That the Mach earthquake occurred only 4 years prior to the Quetta event in an area parallel to, and 100 km from, the Quetta rupture suggests that the Mach event released fault-normal stresses on the Quetta fault, which permitted the Quetta fault to rupture.

The best constrained depths of recent earthquakes in the region indicate that significant seismic moment release occurs to depths of 30 km (Engdahl *et al.*, 1988). Leveling data from the 1931 Mach epicenter is interpreted to indicate that rupture occurred to depths as much as 37 km. The Mach rupture thus has similarities to the 1897 Shillong (Bilham and England, 2001) and 2001 Bhuj earthquakes (Bendick *et al.*, 2001), in that a steeply dipping rupture penetrated to the base of the continental crust but failed to rupture to the surface.

Assuming that 30 km is representative of the seismogenic thickness, we derive a mean slip rate for the 700-km length of the plate boundary of 13 mm/yr. This is clearly too low since a summation of seismic moments north and south of latitude 31° N reveals an order-of-magnitude difference in mean seismic-slip rate in the past century. Rates north of 31° N are significantly less than the anticipated plate boundary transform velocity between Eurasia and India, suggesting that the slip deficit north of 31° N may be as much as 4 m, sufficient to drive one or more $M > 7$ earthquakes.

The recent $M_w = 7.6$ earthquake in Bhuj (Bendick *et al.*, 2001) and its antecedents in the previous two centuries have raised concern that incipient fragmentation of the western edge of the Indian plate between Baluchistan and the Gujarat region may be occurring as a result of stresses near the Makran–Chaman–Carlsberg triple junction (Stein *et al.*, 2001). We note that there is no morphological evidence for, nor recent seismological expression of, an incipient plate boundary crossing the Indus Valley obliquely from Gujarat toward northern Baluchistan. Significant eastward-directed stresses that prevail normal to the Chaman fault are sufficient to fracture through the crust, but these stresses are released quite close to the Chaman fault, as demonstrated by the 1931 Mach earthquake.

Acknowledgments

We would like to thank George Hallows, who organized the retrieval of press reports from repositories in Lahore, and Charles Melville and Dominic White, for their help with unpublished information from the Foreign and India Offices in London. Klaus Jacob, Emil Okal, and Pradeep Talwani reviewed the text, and their written comments have improved it substantially. We thank the staff of the Indian Institute of the Bodleian Library in Oxford for their assistance in making available maps and documents related to Indian earthquakes. We are grateful to the ISC, where computer relocation has been carried out over the last decade. Stacey Martin kindly provided plates depicting aspects of the Quetta earthquake. Part of this study (R.B.) was supported by the National Science Foundation (EAR-0003449) and by a Guggenheim Fellowship.

References

Abe, K. (1994). Instrumental magnitudes of historical earthquakes 1892 to 1898, *Bull. Seism. Soc. Am.* **84,** 415–425.

Abe, K., and S. Noguchi (1983a). Revision of magnitudes of large shallow earthquakes 1897–1912, *Phys. Earth Planet Interiors* **33,** 1–11.

Abe, K., and S. Noguchi (1983b). Determination of magnitude for large shallow earthquakes 1898–1917, *Phys. Earth Planet. Interiors* **32,** 45–59.

Ahmed, M. (1954). The earthquake of February 6, 1953, near Karachi, in *Proc. of the 6th Pakistan Scientific Congress*, Lahore, Pakistan.

Ambraseys, N. (2000). Reappraisal of north-Indian earthquakes at the turn of the 20th century, *Current Sci.* **79,** 101–114.

Ambraseys, N. (2001). Reassessment of earthquakes, 1900 to 1999, in the Eastern Mediterranean and the Middle East, *Geophys. J. Int.* **145,** 471–485.

Ambraseys N., and R. D. Adams (1986). Seismicity of Africa, *Ann. Geophysicae* **4,** 691.

Ambraseys, N., and M. W. Free (1997). Surface-wave magnitude calibration of European region earthquakes, *J. Earthquake Eng.* **1,** 1–22.

Ambraseys, N., and J. Jackson (1998). Faulting associated with historical and recent earthquakes in the Eastern Mediterranean region, *Geophys. J. Int.* **133,** 390–406.

Anonymous (1872). *Times*, 30 December 1872, London.

Anonymous (1931). Seismological Bulletin of Osaka, Osaka.

Anonymous (1936). Materiaux pour l'etude des calamites, Vol. 37, 64, Geneva.

Anonymous (1952). *Quetta Monthly Seismological Bulletin*, Quetta.

Anonymous (1955). Geophys. Rev. Pakistan Meteorological Service, Vol. 1, Quetta.

Armbruster, J., L. Seeber, R. Quittmeyer, and A. Farrah (1979). Seismic network data from Quetta Pakistan, *Records Geol. Surv. Pakistan* **49,** 1–5.

Armbruster J., L. Seeber, R. Quittmeyer, and A. Farrah (1980). Seismic network data from Quetta Pakistan: the Chaman fault and the fault related to the 30 May 1935 earthquake, *Geol. Bull. Univ. Peshawar* **13,** 129–142.

Baluchistan District Gazetteer (1907). Government of India, Bombay.

Bapat, A., R. Kulkarni, and S. Guha (1983). *Catalogue of Earthquakes in India and Neighbourhood from Historical Period up to 1979*, Indian Society of Earthquake Engineering, Roorkee.

Bendick, R., R. Bilham, E. Fielding, V. K. Gaur, S. Hough, G. Kier, M. N. Kulkarni, S. Martin, K. Mueller, and M. Mukul (2001). The January 26, 2001 "Republic Day" Earthquake, India, *Seism. Res. Lett.* **72**(3), 328–335.

Bernard, M., B. Shen-Tu, W. Holt, and D. Davis (2000). Kinematics of active deformation in the Sulaiman Lobe and range, Pakistan, *J. Geophys. Res.* **105,** 13,253–13,280.

Beun, N., P. Border, and I. Carbonnel (1979). Premières données quantitatives relative au coulissage du décrochement de Chaman, Afghanistan du sud-est, Comptes Rendus Séances de l'Academie des Sciences, Paris *D* **288,** 931–934.

Bilham, R., and P. England (2001). Plateau pop-up during the great 1897 Assam earthquake, *Nature* **410,** 806–809.

Bolt, B. (1960). The revision of earthquake epicentres, focal depths, and origin-times using a high-speed computer, *Geophys. J. Int.* **3,** 433–440.

Bombay Times, 13 March 1852.

Bombay Times, 12 October, 25–27 December 1952.

Bombay Times, 8–20 February 1955.

Bomford, G. (1933). Dalbandin Triangulation, in *Survey of India Geodetic Report 1931–1932*, R. H. Thomas (Editor), Vol. 8, 66–70, Suney of India, Dehra Dun.

British Association for the Advancement of Science (BAAS). (1911) Seismological Investigations, 16th Report, 26–36, Portsmouth.

British Association for the Advancement of Science (BAAS). (1912). Seismological Investigations, 17th Report, 2–22, Dundee.

British Association for the Advancement of Science (BAAS). (1913). Seismological Investigations, 18th Report, 2–7, Birmingham.

Brune, J. N. (1968). Seismic moment, seismicity, and rate of slip along major fault zones, *J. Geophys. Res.* **73,** 777–784.

Bureau Central International Seismologie (1921–1969), Strasbourg Files, J-P Rothe Ficmer Macroseismique, Collection of unpublished material, Strasbourg.

Burrard, S. G. (1910). *Levelling of Precision in India (1858–1909)*, in *Account of the Operations of the Great Trigonometrical Survey of India*, Vol. 19, Survey of India, Dehra Dun, India.

Burrard, S. G. (1912). Annual Reports 1909–1910, Records of the Survey of India, Superintendent Government Printing, Calcutta, Vol. 1, 24–25.

Burrard, S. G., (1919). Kalat State, 1:63360, Map 34K/13.

Centroid Moment Tensor (CMT) Catalog, www.seismology.harvard.edu/CMTsearch.html (last accessed May 2003).

Couchman, H. J. (1935a). Bolan Pass and Kalat State, Map 34 O/1, Scale 1:63,360.

Couchman, H. J. (1935b). Bolan Pass and Sibi District, Kalat State and Tribal Territory, Map 34 O/14, Scale 1:63,360.

Couchman, H. J. (1935c). Bolan Pass District and Kalat State, Map 34 O/6, Scale 1:63,360.

Couchman, H. J. (1935d). Quetta, Pushin District and Kalat State, Map 34J/16, Scale 1:63,360.

Couchman, H. J. (1935e) Quetta, Pushin District, Map 34 J/15, Scale 1:63,360.

Couchman, H. J. (1935f). Quetta District, Map 34 N/4, Scale 1:63,360.

Couchman, H. J. (1936). Bolan Pass and Sibi Districts and Kalat State, Baluchistan, Map 34 O/5, Scale 1:63,360.

Davison, C. (1893). Note on the Quetta earthquake of December 20th, 1892, *Geol. Mag.* **350,** 356–361.

De Graaff-Hunter, J., and B. L. Gulatee (1946). *The Trans-Persia Triangulation 1941–44 Linking Iraq and India*, War Research Series Pamplet 9, Survey of India Geodetic Branch, Dehra Dun, India.

Denikaev, S., and A. Kafarski (1973). Recent movements of the Tsaman fault in Afghanistan, Report Tekhnoimport, Department of Geology, Kabul, Afghanistan.

Duda, S. (1965). Secular seismic energy release in the circum-Pacific belt, *Tectonophysics* **2,** 409–452.

Eastern Times, 11–14 October 1952, Lahore, Pakistan.

Egerton, R. W. (1893). Effects of earthquakes on North-Western railway, India, *Engineering* **(May 19),** 698–699.

Ekström, G., and A. Dziewonski (1988). Evidence of bias in estimations of earthquake size, *Nature* **332,** 319–323.

Engdahl, R., R. van der Hilst, and R. Buland (1998). Global teleseismic earthquake relocation with improved travel times and procedures for depth determination, *Bull. Seism. Soc. Am.* **88,** 722–743.

Farah, A. (1976). Study of recent seismotectonics in Pakistan, Rep. CENTO Working Group on Recent Tectonics, Istanbul, Turkey.

Fuchs, C. W. (1886). Earthquake statistics 1865–1885, Session reports of the Royal Academy of Sciences, Vienna (in German), Vol. 92, 215–625.

Geller, R. (1976) Scaling relations for earthquake source parameters and magnitudes, *Bull. Seism. Soc. Am.* **66,** 1501–1523.

Global Seismic Hazard Assessment Program (GSHAP) (2000). seismo.ethz.ch/GSHAP/index.html (last accessed 2002).

Gore, G. C. (1901). Upper Sind Frontier District Sind, Map 39 D/8, Scale 1:63,360.

Government of India Bureau in Simla (1935). Archivers, Situation Reports, 31 May 1935–13 August 1935, files 1–73.

Griesbach, C. L. (1893). Notes on the earthquake of Baluchistan on the 20th December 1892, *Rec. Geol. Surv. Ind.* **26,** 57–64.

Gutenberg, B., and C. Richter (1965). *Seismicity of the Earth and Associated Phenomena*, Princeton University Press, Princeton, New Jersey, 310.

Hamilton, S. W. S. (1935). Bolan Pass and Sibi Districts and Kalat State, Map 34 O/10, scale 1:63,360.

Haq, A. F. M. and S. A. H. Naqvi (1957). Earthquakes in Pakistan during the year 1955, Pakistan Met. Service, Quetta, *Monthly Rept. Geophys. Obs.* 14–15.

Heron, A. (1911). The Baluchistan earthquake of the 21st October 1909, *Rec. Geol. Surv. India* **41,** 22–35.

Heuckroth, L. and R. Karim (1970). *Earthquake History, Seismicity, and Tectonics of the Regions of Afghanistan*, Seism. Centre, Univ. of Kabul, Kabul, Afghanistan.

Inqihab (1931), Lahore. 27 August 1931 and subsequent days (newspaper in Urdu).

Jackson, R. (1960). *Thirty Seconds at Quetta*, Evans, London.

Jones, A. G. (Editor) (1960). *Reconnaissance Geology of Part of West Pakistan*, Colombo Plan Co-operative Project Report, Toronto, Canada, 365–374.

Kanamori, H., and D. L. Anderson (1975). Theoretical basis of some empirical relations in seismology, *Bull. Seismol. Soc. Am.* **65,** 1073–1095.

Kazmi, A. H. (1979). Active fault systems in Pakistan, in *Geodynamics of Pakistan*, A. Farah and K. A. De Jong (Editors), Geologic Survey Pakistan, Quetta, 285–294.

Kazmi, A. H. and R. A. Rana (1982). Tectonic map of Pakistan, Geological Survey of Pakistan, Kabul, Afganistan, scale 1:2,000,000.

Khan, A. Q. (1956). Earthquake and aseismic design in Pakistan, *Proc. 1st World Conf. on Earthquake Engineering*, Berkeley, California, Vol. 19, 1–9.

Kumar, S. L. (1933). Theory of earthquake resistant design with a note on earthquake resisting construction in Baluchistan, paper 165, *Proc. Punjab Engineering Congress*, 1933, Lucknow, India.

Lawrence, R. D., and R. S. Yeats (1979). Geological Reconnaissance of the Chaman Fault in Pakistan, in *Geodynamics of Pakistan*, A. Farah and K. A. De Jong (Editors), Geol. Surv. Pakistan, Quetta, 351–357.

Lawrence, R. D., S. H., Khan, K. A. De Jong, A. Farah, and R. S. Yeats (1981). Thrust and strike-slip fault interaction along the Chaman transform zone, Pakistan, in *Thrust and Nappe Tectonics*, Spec. Publ. Geol. Soc. London, 363–370.

Lawrence, R. D., S. H. Khan, and T. Tanaka (1992). Chaman Fault, Pakistan–Afghanistan, in *Major Active Faults of the World*, Results of IGCP project 206, R. Buckham and P. Hancock (Editors), *Annales Tect.* **6** (Suppl.), 196–223.

Lenox-Conyngham, G. P. (1916). Leveling of precision in India, Addendum, Heights of bench marks, Sheet 39, Dehra Dun, India.

Mackey, J. N. (1962). *Regimental History of the 7th Duke of Edinburgh Gurkha Rifles*, W. Blackwood, London.

Maggi A., J. Jackson, K. Priestley, and C. Baker (2000). A re-assessment of focal depth distribution in southern Iran, the Tien Shan, and northern India: do earthquakes really occur in the continental mantle? *Geophys. J. Int.* **143,** 629–661.

McMahon, A. H. (1897). The southern borderlands of Afghanistan, *Geogr. J.* **9,** 393–415.

Medvedev, S., W. Sponheur, and V. Karnik (1981). Report of the ad hoc panel meeting of experts on updating the MSK64 seismic intensity scale, *Gerlands. Beitr. Geophys.* **90,** 261–268.

Methewether, W. (1852). A report of the disastrous consequences of the severe earthquake felt on the frontier of Upper Sinde on the 24th January 1852, *Trans. Geogr. Soc. Bombay* **4,** 284–286.

Middlemiss, C. (1910). The Kangra earthquake of 4 April 1905, *Mem. Geol. Soc. India* **38,** Calcutta.

Montessus de Ballore, F. (1924). *La géologie sismologique*, A. Colin, Paris.

Montessus de Ballore, F. (1906). *La géographie séismologique*, A. Colin, Paris.

Nature (1889). **42,** 232.

Nature (1893). **48,** 348–349.

Nowroozi, A. A. (1971). Seismotectonics of the Persian plateau, eastern Turkey, Caucasus, and Hindu Kush regions, *Bull. Seism Soc. Am.* **61,** 317–341.

Okal, E., and B. Romanowicz (1994). On the variation of *b*-value with earthquake size, *Phys. Earth Planet. Interiors* **87,** 55–76.

Oldham, T. (1883). A catalogue of Indian earthquakes, *Mem. Geol. Surv. India* **19,** 163–215.

Panza, G., S. Duda, L. Cernobori, and M. Herak (1989). Gutenberg's surface-wave magnitude calibrating function: theoretical basis from synthetic seismograms, *Tectonophysics* **166,** 35–43.

Paterson, J. (1910). The Simla seismograms obtained between June 1905 and November 1908, *Memoirs Indian Meteor. Dept.* **10,** 33–52.

Perrey, A. (1853). Tremblements de terre ressentis en 1852, *Bull. Acad. R. Sci. Bruxelles* **20**(2), 40.

Pinhey, L. A. (1938). *The Quetta Earthquake of 31 May 1935*, Govt of India, New Delhi.

Political and Secret Correspondence, India Office, London, IO.L/P&S/10/1084/10/11, Baluchistan Agency, Confidential Diary ending 15 June 1927.

Political and Secret Correspondence, India Office, London, IO.L/P&S/10/1084/18, Baluchistan Agency, Kalat Confidential Diary ending 15 December 1925.

Political and Secret Correspondence, India Office, London, IO.L/P&S/10/1084/20, Baluchistan Agency, Kalat Confidential Diary.

Political and Secret Correspondence, India Office, London, IO.L/P&S/10/1084/20-23, Baluchistan Agency, Kalat Confidential Diary ending 15 December 1925.

Political and Secret Correspondence, India Office, London, IO.L/P&S/10/1084/7, Baluchistan Agency, Kalat Confidential Diary.

Political and Secret Correspondence, India Office, London, IO.L/P&S/10/1084/8, Baluchistan Agency, Kalat Confidential Diary.

Political and Secret Correspondence, India Office, London, IO.L/P&S/10/1084/annex, Baluchistan Agency, Kalat Confidential Diary.

Political and Secret Correspondence, India Office, London, IO.L/P&S/10/813, Baluchistan Agency, Confidential Diary.

Political and Secret Correspondence, India Office, London, IO.L/P&S/10/814, Baluchistan Agency, Kabul Confidential Diaries for the month ending 15 December 1912.

Political and Secret Correspondence, India Office, London, IO.L/P&S/10/814/17, Baluchistan Agency, Confidential Diaries ending 30 November 1918.

Political and Secret Correspondence, India Office, London, IO.L/P&S/10/814/4, Baluchistan Agency, Confidential Diaries up to April 1914.

Political and Secret Correspondence, India Office, London, IO.L/P&S/10/814/5, Baluchistan Agency, Confidential Diaries (General).

Political and Secret Correspondence, India Office, London, IO.L/P&S/10/814/6, Baluchistan Agency, Confidential Diaries ending July 1914.

Political and Secret Correspondence, India Office, London, IO.L/P&S/10/814/9, Baluchistan Agency, Confidential Diaries up to 15 September 1913.

Political and Secret Correspondence, India Office, London, IO.L/P&S/10/815/1, Baluchistan Agency, Confidential Diaries up to May 1913.

Political and Secret Correspondence, India Office, London, IO.L/P&S/10/890, Baluchistan Agency, Confidential Diaries (numbers 9 and 23) ending 15 December 1920.

Political and Secret Correspondence, India Office, London, IO.L/P&S/12/3403, Diary of Political Agents in Sistan & Kain (with extension to 7 August 1931 in the collection annex 28/8).

Political and Secret Correspondence, India Office, London, IO.L/P&S/7/230–231, Diary of Political Agents in Kabul 17 July to 30 November 1909.

Postens, B. A. (1843). Map of the route from Sukkur to Dadur and Kahun in the Murree country, *J. Asiat. Soc.* **12,** 44.

Purtaap (1931), Lahore. 27 August 1931 and subsequent days (Urdu newspaper).

Quetta Meteorological Service (1915). Earth Tremors, File 005, 1914–1915, Quetta, Pakistan.
Quittmeyer, R. C., and K. H. Jacob (1979). Historical and modern seismicity of Pakistan, Afghanistan, northern India, and southeastern Iran, *Bull. Seism. Soc. Am.* **69,** 773–823.
Quittmeyer, R. C., A. Farah, and K. Jacob (1979). The seismicity of Pakistan and its relation to surface faults, in *Geodynamics of Pakistan*, A. Farah and K. De Jong (Editors), Geologic Survey of Pakistan, Quetta, Pakistan.
Ramanathan, K., and S. Mukherji (1938). A seismological study of the Baluchistan, Quetta, earthquake of May 31, 1935, *Rec. Geol. Surv. India* **73,** 483–513.
Rebeur-Paschwitz, E. (1893). Über die Aufzeichnung der Fernewirkung von Erdbeben, *Peterm. Geogr. Mitteil.* **19,** 201–212.
Rebeur-Paschwitz, E. (1895). Horizontalpendel-Beobachtungen auf der Kaiserlichen Universitäts Sternwarte zu Strassburg 1892–1894, *Beitr. z. Geophys.* **2,** 452–454.
Robertson, R. G. (1948). Earthquake-resistant structures, the seismic factor and the use of reinforced brickwork in Quetta civil construction, Paper no. 5381, *J. Inst. Civil Eng.* 171–187, London, England.
Rothé, J. P. (1969). The seismicity of the earth 1953–1965, pub. 336, UNESCO, Paris, France.
Satyabala, S. P., and H. K. Gupta (1996). Is the quiescence of major earthquakes ($M \geq 7.5$) in the Himalaya and northeast India real? *Bull. Seism. Soc. Am.* **86,** no. 6, 1983–1986.
Savage, J. (1998). Displacement field for an edge dislocation in a layered half-space, *J. Geophys. Res.* **103,** 2439–2446.
Scholz, C. (1982). Scaling laws for large earthquakes: consequences for physical models, *Bull. Seism. Soc. Am.* **72,** 1–14.
Scholz, C. (1997). Size distribution for large and small earthquakes, *Bull. Seism. Soc. Am.* **87,** 1074–1077.
Shabaz (1372). 25 December 1952 (Muslim year 1372) (in Urdu).
Sieberg, A. (1917). Catalogue des tremblements de terre ressentis pendant l'année 1908, Publ. Bureau Central de l'Association Internationale de Sismologie, Strasbourg, France.
Singh, D. D., and H. K. Gupta (1980). Source dynamics of two great earthquakes of the Indian subcontinent, the Bihar-Nepal earthquake of January 15, 1934 and the Quetta earthquake of May 30, 1935, *Bull. Seism. Soc. Am.* **70,** 757–773.
Skrine, C. P. (1936). The Quetta earthquake, *Geogr. J.* **88,** 414–430.
Spate, O. H. K. (1954). India and Pakistan, Methuen, London, England.
Stein, S., G. Sella, and E. A. Okal (2002). The January 26, 2001, Bhuj earthquake and the diffuse boundary of the Indian Plate, *American Geophysical Monograph* **30,** 243–254.
Stenz, E. (1945). Strong earthquakes in Afghanistan, *Q. Bull. Polish Inst. Arts Sci.* **(Jan.)**.
Stepp, J. C. (1971). An investigation of earthquake risk in the Puget Sound area by use of the type I distribution of the largest extremes. *Ph.D. Thesis*, Pennsylvania State University.
Strahan, C. (1899). General Report on the Operations of the Survey of India Department 1897–1898, Survey of India, Dehra Dun, India.
Szirtes, S. (1909). Katalogue der im Jahre 1905 registrierten seismichen Storungen, *Publ. Bur. Centr. Assoc. Intern. Sism.* A 13–14.
Tandy, E. A. (1928a). Kalat State and Sibi District, Baluchistan, Map 34 O/15, scale 1:63,360.
Tandy, E. A. (1928b). Kalat State, Baluchistan, Map 39 D/1, scale 1:63,360.
Tandy, E. A. (1928c). Kalat State, Baluchistan, Map 39 D/2, scale 1:63,360.
Thomas, R. H. (1929b). Kalat State, Baluchistan, Map 34 O/16, scale 1:63,360.
Thomas, R. H. (1929a). Bolan Pass District and Kalat State, Baluchistan, Map 34 O/11, scale 1:63,360.
Thomas, P. A. (1946). The Persia India Connection, War Research Series Pamphlet 9, Survey of India Geodetic Branch.
Thomson, R. O. C. (1936). Notes on the Quetta earthquake, Technical paper 307, Railway Board, Lucknow, India.
UNESCO (1966). Annual summary of information on natural disasters for 1966, Vol. 1, Paris, 23.
United Kingdom Foreign Office. India Correspondence and Dispatches, 1890–1955, unpublished files.
Vere-Jones, D. (1987). Statistical aspects of the analysis of historical earthquake catalogues, in *Proc. Workshop on Historical Seismicity*, C. Margottini and L. Serva (Editors), 271–295.
Walker, G. (1908). Monthly Weather Review, Calcutta, Survey of India, Dehra Dun, India.
Walker, J. T. (1874). *Descriptions and Coordinates of the Stations and Other Fixed Points of the Great Indus Series: Synopsis of the Results of the Operations of the Great Trigonometrical Survey of India*, Dehra Dun, India.
Wang, Q., P.-Z. Zhang, J. T. Freymueller, R. Bilham, K. M. Larson, X. Lai, X. You, Z. Niu, J. Wu, Y. Li, J. Liu, Z. Yang, Q. Chen (2001). Present day crustal deformation in China constrained by global positioning measurements, *Science* **294,** 574–577.
Wellman, H. W. (1965). Active wrench faults in Iran, Afghanistan, and Pakistan, *Geol. Rundschau* **55,** 25–27.
West, W. D. (1934). The Baluchistan earthquakes of 25th and 27th August 1931, *Mem. Geol. Surv. India* **67,** 1–82.
West, W. D. (1936). Preliminary geological report on the Baluchistan (Quetta) earthquake of May 31st, 1935, *Rec. Geol. Surv. India* **69,** 204–241.
West, W. D. (1937). Earthquakes in India, *Proc. Indian Sci., Congress*, Delhi, Vol. 24, 189–225.
Willmore, P. (1979). *Manual of Seismological Observatory Practice*, World Data Centre A for Solid Earth Geophysics, Boulder, Colorado.
Wilson, C. A. (1938). Leveling operations, Technical Report 1937, Survey of India, Dehra Dun, India.
Yeats, R., K. Sieh, and C. Allen (1997). *The geology of earthquakes*, Oxford Univ. Press, New York.
Yeats, R. S., R. D. Lawrence, S. Jamil-ud-Din, and S. H. Khan (1979). Surface effects of the 16 March 1978 earthquake, Pakistan–Afghanistan border, in *Geodynamics of Pakistan*, A. Farah and K. A. De Jong (Editors), Geologic Survey of Pakistan, Quetta, Pakistan.

Appendix A

Case Histories

In what follows we present a summary of macroseismic information for earthquakes with $M_S \geq 5.9$ and brief descriptions of events with magnitudes possibly close to 5.9 but for which we found insufficient instrumental or macroseismic information to assess location or magnitude. M_S is the surface-wave magnitude calculated in this study from the Prague formula. Dates and times for events recorded instrumentally are GMT.

24 January 1852 (Kahan). This locally destructive shock in the Murree (Marri) hills was preceded by a foreshock on 13 December 1851. The mainshock destroyed the principal fortified town of Kahan (Kahun), killing 340 people, including the son of the leader of the tribe. To the north of Kahan a cave in which a part of the tribe lived with their cattle collapsed, killing all within it.

The road by Nufusk (Guchi?) to Kahan was completely closed by the collapse of a hillside. As a result of the earthquake, the flow of water in the Lahri (Tratani) river increased and extended its course into the Kachhi plain. There is no evidence of damage beyond the Marri hills.

The shock was felt along the east edge of the Kachhi plain to the west of the hills, at Lahri, Phuleji, Chhatr, and

Shahpur and further west in the plain at Dadhar, Bagh, and Gundava. These latter villages apparently were presumably little damaged, as they were chosen by the surviving members of the tribe from Kahun to emigrate to after the earthquake.

There are no accounts from Kalat or western Baluchistan of the earthquake having caused any damage to any of the large villages in those hills (Methewether, 1852; *Bombay Times*, 13 March 1852). For the political situation in this area just before the earthquake, see Postens (1843). There is no evidence to justify Perrey's statement that the damaging effects of this event extended to Gujarat, 700 km to the south of Kahan (Perrey, 1853).

25 August 1858 (Jacobabad). A slight shock was felt at Jacobabad (Oldham, 1883).

15 December 1872 (Sibi). A damaging earthquake in the region of Sibi, Lahri, and Shikarpur killed about 500 people (Fuchs, 1886; Anonymous, 1872).

28 December 1888 (Quetta). This is the first damaging shock in Quetta for which we could find some information. It destroyed a few shops in the town without casualties and was followed by aftershocks until the end of the month. The epicentral area of this event is not known (*Nature*, 1889).

20 December 1892, M 6.5 (Chaman). The event occurred about 90 km northwest of Quetta, near the Pakistan–Afghanistan border. Aftershocks continued to be felt until the end of February 1893.

Old Chaman, the only large settlement and the head of the North-Western Railway line, which was at the time under construction, was almost totally destroyed without loss of life. The stations of Sanzal and Shalabagh, situated on either side of the 3.8-km-long Khojak tunnel and about 5 and 8 km from Old Chaman, were damaged. However, no locomotives and carriages at these places were overturned or derailed by the shock, and no water supply tanks along the track were destroyed. The tunnel itself was undamaged, but workmen engaged on the roofing were thrown from their scaffolds and the upper crenulations of the tunnel's blockhouse were cracked. At Shalabagh and its vicinity the shock was strong enough to throw down several local houses, making many of them unsafe.

Spin Baldak, a small fortified station in Afghanistan, about 20 km northwest of Chaman, was probably damaged. The country to the east of Old Chaman was very sparsely inhabited, and hence the limits of the damage area must probably remain unknown. After the earthquake, Chaman was relocated to its present position about 10 km further to the northwest of its old site.

The shock was not felt over great distances; it was rather strong at Quetta, 90 km to the southeast, and probably it was also felt at Kandahar in Afghanistan, 115 km northwest of Old Chaman. We could find no evidence that the shock was felt along the Shalabagh section of the North-Western Railway, at Sibi, Jacobabad, or Sukkur.

The earthquake was associated with surface faulting, with Old Chaman located directly on the active trace of the Chaman Fault. At a place outside of the Khojak tunnel, near the Chaman end, where the line emerges on the plain of Kandahar, the fault break crossed the railway track at 25° and followed the Khojak Range (north-northeast–south-southwest), about 4.8 km to the west of the southward continuation of the railway line. Where they crossed the fault, both the tracks and with their sleepers were buckled in the same manner, suggesting an oblique thrust with 60–75 cm left-lateral motion combined with 20–30 cm downthrow of the west block (Griesbach, 1893; Davison, 1893). From the length of the rail removed and from the obliquity of the fault trace, Griesbach (1893) estimated 75 cm of left-lateral slip, although from the numerical shortening of the rails and the obliquity in the photograph it is possible to derive a fault slip of just over 80 cm. The two nearest benchmarks on either side of the fault break that were checked by Egerton (1893), the location of which are not given, show a difference of 4.3 m more than before the earthquake, indicating that either the western side was downthrown or the eastern side was raised, but it is not stated which side is relatively the higher. Conflicting with this observation, Davison pointed out that a revision of these levels shows the actual difference was not more than 5 cm (Davison, 1893).

Egerton traced the fault break for several miles in both directions from its crossing with the railway lines, but it was not possible to trace the break to its end in either direction. To the north it passed from British territory into Afghanistan, and to the south it was lost in the snow of the Khowaja Amran peak, a distance that, measured on the map that accompanies his article, is approximately 16 km (Egerton, 1893). However, Griesbach stated that the fault break was 32 km long, with displacement continuing out of sight to both the north and south (Griesbach, 1893). He did not indicate on what he based this estimate.

Attempts in recent years to identify in the field the 1892 rupture are inconclusive. The fault in Afghanistan north of Chaman, mapped in the early 1970s by Denikaev and Kafarski (1973), is shown on copies of the geological map of eastern Afghanistan. They could find no evidence that this segment of the fault was activated in 1892, nor in the recent past. An minimum surface rupture length of 60 km was inferred by Lawrence *et al.* (1992). This they deduced from a single very young scarp of low relief and great continuity, which includes Egerton's reported rupture.

This is the earliest event for which we have scant, but reasonably good, instrumental data. We used Abe's (1994) method to calculate its magnitude from trace amplitudes recorded by undamped instruments other than Milne recorders, that is, by Rebeur-Paschwitz undamped seismographs at Nikolaiev and Strasbourg (Rebeur-Paschwitz 1893, 1895). Using Abe's method we calculate a magnitude of 6.7, which is considerably larger than the value of 6.2 assessed by Abe for this earthquake.

Although not confirmed by contemporary corroborating evidence, the following estimates of rupture parameters are available: Montessus De Ballore (1906), $L = 20$ km, $H = 80$ cm, $V = 20$–30 cm; Montessus de Ballore (1924), $L = 24$ km, $H = 60$–75 cm; Quittmeyer and Jacob (1979), $L > 30$ km, $H = 75$ cm; and Lawrence *et al.* (1992) and Yeats *et al.* (1997), $L = 60$ km, $H = 60$–75 cm, $V = 20$–30 cm. As a check on the instrumental estimate of magnitude we calculated M_S using the empirical formula of Ambraseys and Jackson (1998), using the maximum length (60 km) and slip (75 cm) inferred for this event. The derived value of M_S 6.8 is close to the instrumental value. This magnitude is smaller than earlier estimates by previous investigators but is consistent with the relatively small area from which the shock was reported felt.

13 February 1893, M 5.9 (Chaman). This earthquake caused some concern at Chaman but no damage. In Quetta it was much stronger than the shock of 20 December 1892, which implies that this was not an aftershock but a separate event not far from the town. It may be the shock that is said to have caused damage at Pishin and Baghihindu sometime in early 1893 (*Nature*, 1893). The earthquake was recorded at Strasbourg (Rebeur-Paschwitz 1893, 1895), and if it is assumed that it occurred somewhere near Quetta, its magnitude should be about 5.9.

1900 (Pishin). In the Quetta–Pishin district a severe earthquake was felt in 1900, causing a spring to appear in the Sraghurgi village on the slopes of Takatu, which gave a good supply of water for irrigation for some time, but later decreased (*Baluchistan District Gazetteer*, 1907).

17 October 1901, M 6.1 (Loralai). Little macroseismic information is available for this earthquake in the Loralai district, which destroyed several houses in the villages of Bori, Mula Sadik, and Surgundi Bala; the location of the last two sites is not certain. Fissures are said to have been formed in the mountains (*Baluchistan District Gazetteer*, 1907).

1902 (Pishin). A severe shock caused much damage to the buildings in Pishin, Kila Abdulla, and Gulistan. The date is not given (*Baluchistan District Gazetteer*, 1907), and the event cannot be associated with shocks recorded instrumentally during that period. However, it must be the earthquake that, although felt at Chaman and Quetta, caused some unspecified damage to the single track of the railway that crosses the Pishin Lora plain.

23 December 1903, M 5.9 (Dhadar). A damaging earthquake south of the Bolan Pass in the Kachhi plain caused the total collapse of about 60 houses in Dhadar, and many more were damaged, with loss of life. Damage extended to Sibi and to railway stations of the line to the Bolan Pass in the north and to Dingri in the south. The loss of property was estimated at about Rs 15,000 (*Baluchistan District Gazetteer*, 1907). The earthquake was well recorded by Milne seismographs, but the readings can only confirm the general area.

26 September 1905, M 6.4 (Khan Mahomedkot). For this earthquake we have relatively good macroseismic and instrumental data that place the event in the Sulaiman mountains. The shock caused severe damage in the region of Rakhni and Khan Mahomedkot. Minor damage was reported from Loralai, Barkhan, Dera Ghazi Khan, and Multan (Middlemiss, 1910).

Szirtes (1909) and BAAS (1913) mislocated the event by about 440 and 300 km, respectively, east of its macroseismic position, and Duda (1965) assigned to it a magnitude of 7.1, for which we can find no justification.

5 March 1908, M 6.4 (Sharigh). Preceded and followed by strong shock, an earthquake occurred in the Harnai valley, east of Quetta. Sharigh and villages to the southeast in the valley were ruined (Walker, 1908; Patterson, 1910; Sieberg, 1917). This event is often mislocated near Manila in the Philippines (Anonymous, 1931).

3 June 1908, M 6.2. The only macroseismic information we have for this earthquake is that it was felt in Quetta and in much of northeastern Baluchistan. This earthquake was widely recorded instrumentally, but the data are not enough to establish the epicentral region, even approximately. We adopt the crude location given by BAAS (1913), Bureau Central International Seismologie (1921–1969), and Patterson (1910).

7 September 1909, M 6.0. The position of this earthquake given by BAAS (1913) is poorly determined, but cannot be improved. There are no felt reports.

20 October 1909, M 7.1 (Kachhi). This earthquake caused extensive damage in the plain of Kachhi. The field study of the event was carried out by Heron (1911), who did not visit the hilly tract surrounding the plain, where he said that no damage occurred and that the shock there passed almost unnoticed. He added that the shock does not seem to have been felt outside Baluchistan and the immediate contiguous portions of Sind and that no reports were received from any seismological stations in India. However, additional, but not very detailed, official information suggests that, in fact, the shock was widely felt, causing considerable concern and probably small damage over an area larger than that considered by Heron (U.K. Foreign Office; Political and Secret Correspondence, India Office, London [IO.L/P&S/7/230–231; IO.L/P&S/10/814]) and that all three seismological stations operating at the time in India, Bombay, Kodaikanal, and Calcutta, recorded the event with large ground amplitudes (BAAS, 1909). Maximum damage was reported from the Kachhi plain.

In Bagh most of the rural adobe houses were destroyed, and 66 people were killed. Here the shock triggered flow slides and spreading of the ground, with some evidence of liquefaction. Bellpat was ruined, and 26 people were killed, 25 of whom perished in the railway station building, which collapsed.

Muradwa was leveled with the ground, and 20 people were killed, including those in neighboring settlements. Shahpur was totally destroyed, with the loss of 102 lives. However, the tomb of Saiyd Hasan, a massive old construction made of kiln bricks, suffered little damage. Also better-built houses and corrugated iron sheds throughout the area were quite undamaged.

Damage was widespread, but apparently not serious, in the Kachhi plain and further northwest and west of Sibi, in the region of Gugurt and Dadar. Damage in the form of wall cracks and fallen flat clay ceilings was reported from villages quite some distance from the epicentral area. The shock was strong at Quetta, Nushki, Khunzdar, and Dadar, and it was felt at Multan and Dera Ismail Khan, as well as in much of Baluchistan and in northern Sind, but details are lacking. The railway line that traverses the Kachhi Plain for a considerable distance suffered no damage.

The shock had no effect on the yield of springs and underground (qanat) water in the valley, but it did cause an increase in qanat water in the Mastung valley 100 km to the northwest of the region, where the shock was rather strong. Aftershocks continued to be felt in the region until April 1910.

The shock caused extensive fissuring of the dry clay-surfaced ground around Shahpur and beyond within a narrow zone for a few miles. The tectonic origin of these features cannot be substantiated. The large magnitude of the earthquake and the elongated shape of its epicentral area (Fig. 3) suggest a shallow event possibly associated with surface faulting; however, there is no conclusive information for this, and Heron specifically asserted that there was none. This is either because there was no faulting or probably because, in this sparsely populated part of Pakistan, it was not found or reported.

Heron's isoseismal map for this earthquake is drawn on the Rossi–Forel (RF) scale for the Kachhi plain where, due to adverse soil conditions, apparent damage was maximum. For 45 sites for which we could find sufficient information, we reassessed intensities in the MSK scale and have assessed a new set of isoseismals (Fig. 3). Gutenberg and Richter (1965) and Abe and Noguchi (1983a;b) assigned to this event magnitudes of 7.2, 7.0, and 7.1, respectively.

17 August 1910, M 6.3. The only macroseismic information we have for this earthquake is from Shikarpur in the Sind where it was felt. The earthquake was well recorded at Milne seismograph stations and by other instruments in Europe. The readings are not particularly consistent, however, and the error could be 100 km (Political and Secret Correspondence IO.L/P&S/10/813).

1 November 1912. A severe shock that lasted 30 sec and followed by aftershocks was felt at Bhag at 20 h (Political and Secret Correspondence IO.L/P&S/10/814).

27 March 1913, M 5.6. The facts about this earthquake are not clear. The shock was reported from Dhadar, Bhag Rindhli, and probably from Kalat, where it caused no damage. A later report mentions rockfalls and damage to Rigush in the Nagau mountains, triggered by an undated shock early in 1913. Many other shocks were reported during the year from various parts of Baluchistan (Political and Secret Correspondence IO.L/P&S/10/814/5 and 815/1).

7 August 1913. Several shocks were felt around Quetta and Pishin from 7 to 9 August (Political and Secret Correspondence IO.L/P&S/10/814/9). We could find no record of this event in station bulletins.

6 February 1914. This earthquake occurred outside our study area in the sparsely populated region of southwest Baluchistan. The shock was felt at Chagai and Kharan (*Civil and Military Gazette*; Quetta Meteorological Service, 1952). There is no evidence in the contemporary British consular correspondence from the area that the shock was felt at great distance. It was not felt at the nearest large center of population at Quetta, 200 km distant.

Gutenberg's worksheets (B. Gutenberg, unpublished worksheets, pad 82/887) gave an epicenter close to our macroseismic location, with 100 km depth and a long-period body-wave m_B magnitude of 6.8. Gutenberg and Richter (1965) rounded off this value to 7.0.

The earthquake was well recorded and, assuming that it was shallow, we calculated its surface-wave magnitude from 14 stations as M_S 5.7. However, the large number of stations at which it was recorded, the small surface-wave amplitudes relative to those of p and s, and the lack of any known aftershocks suggest an event in the lower crust. If we assume a depth of 100 km, the corresponding M_S would be 6.9 (Panza *et al.*, 1989).

8 March 1914. Earthquake shocks were reported from Dadhar (Political and Secret Correspondence IO.L/P&S/10/814/4).

4 May 1914. There was a slight shock at Ziarat on the night of 4 May (Political and Secret Correspondence IO.L/P&S/10/814/6).

24 March 1918. A severe earthquake was felt at Quetta at about 10 h 30 m, but no serious damage was reported (Political and Secret Correspondence IO.L/P&S/10/814/5).

29 November 1918. M 6.2. This was a violent earthquake in Afghanistan; between Kalat-i Ghilzai and Ghazni, the earthquake caused many deaths and the collapse of many houses. It is said to have caused increased flow of water in springs and qanats and the reactivation of hitherto dry springs and qanats (Political and Secret Correspondence IO.L/P&S/10/814/17).

26 April 1920. A slight shock lasting half a second was felt at 13 h 35 m at Sibi (Political and Secret Correspondence IO.L/P&S/10/890).

15 December 1920. A very strong earthquake was felt at Harnai at 07 h 45 m. No important damage was reported (Political and Secret Correspondence IO.L/P&S/10/890).

1 October 1923, M 6.1. The facts about this earthquake in the Kachhi area are not clear. We know that sometime in the autumn of 1923 an earthquake caused considerable damage to settlements on the Nagau range and at Sanni and also that a slight shock of earthquake was felt at Lehri at 12 noon local time on 1 October 1923 (Political and Secret Correspondence IO:L/P&S/10/1084/20-3, Kalat). This is the only event from this area that was widely recorded in October 1923. Our instrumental position, a relocation using *P* waves from 38 stations, and 1975 ISC procedures, place it in the Kachhi area with a location error of about 50 km.

13 September 1926. An earthquake was felt at Mach (Political and Secret Correspondence IO.L/P&S/1084/18).

4 May 1927. A severe earthquake on the night of 4/5 May was felt at Pishin. Several buildings, including the political bungalow, were damaged (Political and Secret Correspondence IO.L/P&S//1084/10).

21 May 1927. A number of earthquakes were reported from the Shahpur region and Kachhi (Political and Secret Correspondence IO.L/P&S/1084/11).

1 September 1928, M 6.5. There is no macroseismic information to improve our instrumental position for this earthquake, which is very close to that of Quittmeyer and Jacob (1979).

15 October 1928, M 6.8 (Katra). Little macroseismic information has been found for this event, except that settlements around Katra were destroyed. The shock was reported from stations along the railway line between Jacobabad and Sibi, and it was probably felt at Kalat (Political and Secret Correspondence IO.L/P&S/1084/8). The earthquake was widely recorded instrumentally, and the readings are consistent with a location on the central Brahui range.

12 March 1930. An earthquake occurred in the Barkhan District at Chuharkot and Loralai; it caused no damage (Political and Secret Correspondence IO.L/P&S/1084/7).

28 September 1930. Earthquakes were reported from Khozdar; it is not known whether they caused any damage (Political and Secret Correspondence IO.L/P&S/1084/20).

10 October 1930. An earthquake caused some damage at Mastung and to the Sheikhwasil levy post (Political and Secret Correspondence IO.L/P&S/1084/20).

24 August 1931, M 6.8 (Sharigh). In this earthquake, the first of two in 3 days east of Quetta, maximum damage was not very serious and occurred in villages along a distance of about 30 km near the Sibi–Zardalu railway line, which runs in an east-northeast–west-southwest direction: Khost was considerably damaged Sharigh was half destroyed and two persons were killed. The bazaar, poorly built mostly of unbaked mud, was completely ruined, while other buildings, such as the dispensary and some of the railway quarters, built of sun-baked brick and mud mortar, were severely damaged. The railway station was rather badly cracked and had its chimney pots overturned. The old locomotive shed, which had a heavy roof, was half demolished. Two buildings for railway workers, which were of adobe construction, were only slightly damaged. Nakus, 14 km east-southeast of Sharigh, suffered similar damage. Between Sharigh and Nakus one of the two railway bridges was damaged to the extent of holding up traffic for a few days. Damage to the railway extended well beyond Harnai (Kumar, 1933).

Away from the Khost–Nakus segment of the railway, the country is sparsely inhabited and it is difficult to assess the extent of the epicentral region. However, along the line to the South East, the effects of the shock diminished rapidly. At Harnai, about 10 km from Nakus, only two houses collapsed; the rest were damaged, but the railway station was undamaged. About 20 km to the north of Khost a good deal of damage was done to Ziaret by this shock and the shock of 27 August 1931. About 30 km to the south of Sharigh, Sangan was badly damaged and half the houses were demolished. Along the Bolan River this earthquake was felt very much less than the later earthquake of the 27th.

Localized damage was reported from other places further away from Mach, where a few local houses were ruined. In Quetta dwellings including the Town Hall cracked, and damage was reported from Dadhar, Pishin, Bagh, and Kila Abdula, up to epicentral distances of about 100 km. Far-field information comes almost exclusively from the southeast quadrant defined by the Kachhi plain and the Indus valley. The limits of the felt area are at Radan, Rajanpur, and Dehra Ismail Khan, which define a radius of perceptibility of 310 km.

This earthquake, the so-called Sharigh, of magnitude M_S 6.8 calculated from 136 station magnitudes, was followed within 66 hr by the Mach earthquake of M_S 7.3. Because in most places the second shock was the more destructive of the two, information as to the effect of the first was difficult to obtain. This was particularly the case at places where the effects of the second shock were serious: such damage as was done by the first shock was in many cases obscured by the more severe damage caused by the second shock. West (1934), who surveyed the damage and drew isoseismals for the two earthquakes in the RF scale (Fig. 3), pointed out that the information available to construct the intensity distribution map for the Sharigh earthquake was incomplete. His isoseismals for this event are incompatible for those anticipated from a shallow M_S 6.8 event but might be consistent with a lower crust or subcrustal event that might not be expected to exhibit a recognizable epicentral region.

The macroseismic position of the event is difficult to assess and is estimated at 30.10° N, 67.60° E. The shock was well recorded instrumentally with good agreement between instrumental and macroseismic positions. Our location is 15 km southwest of the ISS position and 33 km south of the location recomputed by Quittmeyer and Jacob (1979) but 44 km northeast of the epicenter reappraised by Engdahl *et al.* (1998) on the Bolan Pass, which, although not corroborated by macroseismic data, is compatible with significant vertical deformation recorded there by leveling crews. Table 3 itemizes locations for which an MSK isoseismal intensity could be evaluated for the Sharigh earthquake.

27 August 1931, M 7.3 (Mach). The Mach earthquake resulted in approximately 120 deaths and was felt over a large part of Baluchistan and Sind, covering an area of 550 km radius. West (1934, 1937) visited the region shortly after the earthquake, and judging from the damage done, he defined its epicentral region as a narrow, boomerang-shaped zone concave to the west, about 140 km long and not more than 15 km wide, following the Bolan Pass and the western foothills of the Kachhi plain (Fig. 3), in which the maximum intensity did not exceed VIII RF.

In the northern part of this 40-km-long northwest–southeast zone, damage was mostly confined from a short distance from Mach along the Bolan Pass, to the alluvial plain that borders the hills to the southwest of Sibi. This part of the zone is traversed by the railroad, which runs along the northeast margin of the zone, and by the trunk road, which follows the southwest margin, the two converging at Sibi.

The southern part of West's epicentral zone extends from Dadhar to Katra, a distance of 100 km through a sparsely inhabited region, and runs along the border of the Kachhi floodplains of Badra and Bolan, with the hills to the west. The few villages in this region were badly damaged and suffered some loss of life. West did not visit this area owing to the fact that the roads were impassable, and for his report he had to rely on information from the political agent in Kalat (West, 1934; Political and Secret Correspondence IO.L/P&S/1084/7; IO.L/P&S/12/3403).

It was at Mach, at the northern extremity of the zone, that the most costly damage occurred. New Mach was both the headquarters of the civil administration and the railway authority. Here all the buildings were damaged to some extent, while many houses, built of unbaked mud bricks or stone with mud mortar, were completely ruined, along with two rest houses, the bazaar, some of the railway quarters at New Mach, and the outlying village of Old Mach. At the time of the earthquake the train stationed at Mach swayed from side to side and the driver was thrown from the engine, but this train and another eight or nine engines at the station did not overturn or derail. The new jail, completed only 18 months before and containing over 400 prisoners (who escaped and were subsequently reinterred), was considerably damaged, but the powerhouse was left undamaged. In Old Mach damage was more complete and most of public buildings were totally ruined. In all five people were killed, and the total damage to the inhabitants was not more than Rs 70,000 (£4,700 in 1930). Overall damage was considerable, although not as serious as reported by the press.

None of the tunnels along the Bolan River were damaged directly by the earthquake, although in one or two cases the entrances to the tunnels were damaged by falling boulders. The shock triggered large rockfalls from the mountains north of Mach, raising enormous clouds of dust, which gave rise to rumours of a volcanic eruption. The 140-m-long railway bridge located just above Mach was not damaged. It consisted of four spans on three 14-m-high brick piers, and its axis bears N150°E. The general effect of the earthquake on the bridge was to compress it end-on and shorten it by 20 cm. Surveyed after the earthquake, the piers were found to have remained vertical, which suggests that the bed of the river had contracted uniformly in width. The track immediately southeast of the bridge, which was on level ground, settled, and tracks had to be repaired along some of their length. This settlement was caused by a gradual lowering of the southeast segment of the track by about 60 cm (West, 1934, 1937). The reported contraction occured close to the region of uplift recorded by subsequent leveling (Wilson, 1938).

Following the railway to the south, the station of Ab-i-Gum was damaged and that of Peshi partly collapsed. Here the railway line down the Bolan was considerably damaged by falling rocks. At Panir the station and surrounding buildings were damaged, but the postmaster's brick house was practically undamaged. The station at Ocepur was also badly damaged, but beyond this place to the southeast the effects of the earthquake rapidly diminish. At Sibi only a few mud walls and one of the four minarets fell, the earthquake enhancing the overall damage to houses sustained by the Sharigh earthquake of 25 August.

The trunk road to the south from Mach in the 1930s was thinly inhabited; the stage posts of Bibi Nami, Dranjan, and Gokurth were damaged. Just north of Gokurth, Kirta was badly damaged. Further south, at Kundalani, the rest house was practically undamaged. Below Gokurth the bed of the river was full of small cracks, running parallel to the river, and it was along here that the road itself was most severely damaged. The road here runs along the west side of the riverbed and is cut into steep slopes at some height above the riverbed. Between miles 68.5 and 71.0 the road was very seriously damaged by landslides, in places being completely obliterated. It appears that this section has frequently given trouble during bad weather owing to landslides. We note that locations between Bibi and Sibi, and others mentioned in the next two paragraphs, lie in the hanging wall of the fault we infer to be responsible for uplift of the Bolan Pass.

Rindli, a few kilometers east of the entrance to the Bolan Pass fronting the Kachi Plain, was practically undamaged, but Dadhar in the valley floor was badly damaged. This village, like many others in the Kachhi plain, was built on an artificial mounds of soil designed to raise structures above periodic flash floods. Of 946 houses, 567 collapsed and 316 were badly cracked, and seven people were killed. The covered bazaar, which was supported internally by wooden posts and had wooden beams across in all directions, was practically unaffected. Mushkaf suffered worse than Dadhar, as every one of the 300 houses collapsed and one person was killed. In nearby villages in the plain, such as Naoshera

Table 3
Reevaluated MSK Intensities for the Shiragh (24 August 1931) and Mach (27 August 1931) Earthquakes

Location	Lat.	Long.	Mach MSK	Shiragh MSK
Ab-i-Gum	29.82	67.39	7	
Ajmer	26.45	74.64	1	
Bagh	29.04	67.81	6	5
Bahawalpur	29.39	71.67	3	
Barkhan	29.91	69.51	5	
Belpat	28.98	68	6	4
Bibi-Argi	29.22	67.17	7	
Bibi-Nani	29.7	67.38	6	
Bikaner	28.02	73.32	1	
Bolan	29.9	67.12	7	5.5
Bostan	29	66	4	
Chaman	30.92	66.44	4	2
Chawan	26	73	1	
Churu	28.3	74.97	2	
Dadhar	29.48	67.64	8	5
Dadu	26.73	67.77	5	1
Dera-Ghazi	30.06	70.64	3	
Dera-Ismail	31.83	70.91	3	2.5
Dodapur	28.05	68.17	5	
Dranjan	29.6	67.42	7	
Ferozepore	30.92	74.61	1	
Gandava	28.62	67.47	8	4
Gazkh	28.94	67.01	7	
Gokurth	29.53	67.47	7	
Goru	27.8	66.83	4	
Harnai	30.1	67.93	6	6
Hindu-bagh	30.82	67.75	4	4.5
Hirok	29.93	67.21	7	
Hyderabad	25.37	68.36	3	
Jacobabad	28.28	68.43	5	3
Jahl	28.28	67.47		4.5
Jaipur	26.91	75.8	3	
Jaisalmer	26.91	70.92	2	
Jampur	29.64	70.59	4	1
Jodhpur	26.28	73.02	3	
Johan	29.33	66.96	8	
Johi	26.7	67.61	3	1
Kalat	29.03	66.58	4	1
Karachi	24.85	67.01	3	
Khairpur	27.53	68.75	4	
Khari	28.58	67.37	8	
Khost	30.22	67.58	6	
Kila-Abdula	30.72	66.63		4.5
Kila-Saiful	30.71	68.37	5	4.5
Kirta	29.6	67.49	8	
Kotra	28.55	67.38	8	
Kundalani	29.45	67.5	6	
Lahore	31.56	74.35	2	
Lahri	29.18	68.18	6.5	3
Larkana	27.56	68.21	5	2
Las-Bela	26.23	66.3	3.5	
Leiah	30.96	70.93	3	
Loralai	30.37	68.6	4	
Lunkarabdar	28.49	73.75	2	
Mach (N)	29.87	67.33	7	5
Mach (O)	29.87	67.34	9	
Mahmudkot-Multan	30.19	71.02	3	
Mastung	29.8	66.85	5	3
Mehar	27.18	67.82	5	
Mianwali	32.59	71.54	1	
Multan	30.2	71.46	4	
Mushkaf	29.5	67.68	9	
"Nakus,"	30.15	67.83		7
Naoshera	29.37	67.58	9	
Nasirabad	26.3	74.72	1	
Naushahr	26.84	68.13	2.5	
Nichara	28.87	66.75	5	
Nighari	29.4	67.63	8	
Nushki	29.55	66.01	5	
Ocepur	29.63	67.63	7	
Pali	25.78	73.34	2	
Pandran	28.73	66.73	6	
Panir	29.67	67.53	7	
Peshi	29.72	67.48	7	
Pir-Chuttar	28.47	67.28	6	
Pishin	30.57	66.99	5	5
Quetta	30.21	67.01	6	6
Radhan	27.2	67.95		2.5
Rajanpur	29.1	70.32	4	2.5
Rani	25.37	73.3	2	
Ratangarh	28.08	74.62	2	
Rindli	29.49	67.63	6	
Sangan	29.87	67.65		8
Sanjawi	30.28	68.35	5	
Sanni	29.15	67.57	9	5
SariBollan	29.94	67.17	7	
Sarwar	26.07	75	2	
Sehwan	26.43	67.85	3	
Shahdakot	27.84	67.9	5	
Shahdadpur	25.92	68.61		4
Shahpur	28.73	68.41	4.5	
Sharig	30.2	67.7	6	
Shergarh	26.33	72.29	1	
Shershah	30.1	71.35	3	
Shikarpur	27.96	68.64	5	3
Shoran	28.87	67.43	9	4.5
Sibi	29.55	67.88	6.5	1
Sirsa	29.53	75.03	1	
Spezand	29.98	67	6	
Sukkur	27.69	68.85	4	
Surab	28.49	66.26	5	
Taunsa	30.7	70.63		1
Udaipur	24.58	73.69	1	
Uthal	25.81	66.62	3	
Washuk	27.73	64.7	3	
Ziarat	30.38	67.72		6.5

and Nighari, most of the houses collapsed, with loss of life.

Further south, along the remaining 100 km of the epicentral area defined by West, Sanni was most seriously damaged and 42 people were killed, and in Shoran all the houses collapsed, 46 people were killed, and about 300 cattle were destroyed. The southernmost limits of the epicentral region are defined by a group of villages: Gandava, where 77 houses collapsed but there was no loss of life; Kotra, where out of 385 houses 86 collapsed and three persons were killed; and Khari, where 297 out of 376 houses collapsed, killing 13 people. These villages are in the floodplain about 10 km east of the foothills of the Nagau Range. In contrast, Pir, situated on high ground on the track to Khuzdar, suffered little damage.

Although not visited by West, there is considerable evidence of equally severe shaking west of the epicentral area defined by West, an almost uninhabited region, which enlarges the epicentral area to the west of the Kachhi plain well into the Nagau and Brahui hills. Most of the roads and tracks across these ranges were blocked by rockfalls, and the few levy posts and small, semiabandoned villages were ruined, but details are lacking. The settlements of Jahan and Bibi Argi were totally destroyed, and the route to the east was obliterated at its crossing with Sarawan. The collapse of a mountainside at Gazkh killed flocks of sheep along with two shepherds. At Pandran, 35 km southeast of Kalat, several houses partly collapsed, killing one person, and large falls of rock at Nichara caused large clouds of dust (Political and Secret Correspondence IO.L/P&S/10/1084/7; IO.L/P&S/12/3403).

Alleged catastrophic damage at Mach in the Bolan Pass was responsible for the name of the earthquake, and while damage was undoubtedly considerable, newspaper accounts appear exaggerated (Inqilab; Purtaap). Villages in the Kachhi plain southwest of Sibi bordering the hills sustained considerable damage, aggravated by adverse site construction practices (building on artificial mounds in the floodplains) and the collapse of adobe buildings into narrow alleyways. Although 120 people were killed in the earthquake, the earlier earthquake at Sharigh and its aftershocks had caused many of the inhabitants to sleep out of doors, which is almost certainly responsible for the death toll not being higher.

Outside this enlarged epicentral area, damage was minor but widespread over a large area with considerable irregularity. In Quetta, 50 km northeast of Mach, nonstructural damage was so serious that an official report attributed excessive damage to the fact that the majority of houses in the city were built with exceptionally poor quality construction (BAAS, 1935). For some days Quetta was cut off from road and rail communication with the rest of India, and the military road suffered in a similar way, badly damaged by landslides particularly between miles 68.5 and 71 (measured from the Quetta rail station). Repairs of the road and railway link between Quetta and Sibi were completed in 9 days. Also, telephone and road communications with Kalat and Persia were interrupted for some time.

The shock was perceptible as far as Wishek in the southwest, at Karachi in the south, and Jaipur, Lahore, and Srinagar in the east and northeast, with no data for the other quadrants in Baluchistan and Afghanistan. The felt area thus was a circle with a radius of about 570 km.

This event and the Sharigh earthquake were responsible for the introduction of compulsory earthquake-resistant design of railway structures and public buildings in Baluchistan and in the Indian subcontinent (Khan, 1956), a measure that caused the survival of many public buildings in the Quetta earthquake that followed 4 years later and in more recent events.

The Mach earthquake was a relatively large event. Its surface-wave magnitude calculated from the Prague formula from 22 stations is M_S 7.3 $\pm$ 0.25, and its ISS location is on the Bolan Pass, consistent with deformation data available to us (Appendix B). A leveling line through the Bolan Pass shows the range through which it cuts to have been uplifted 65 cm relative to the Mach region, with minor uplift northwest of Mach (Fig. 11). In spite of its large magnitude, there is no field evidence for surface faulting in this earthquake, and the deformation field is suggestive of slip on a blind thrust dipping east-southeast beneath the range. The location of this thrust is some 20–40 km to the southeast of the Mach epicentral location and a similar distance south of the Sharigh epicenter. Kazmi (1979) indicated three recently active surface faults in the region with northerly, northeasterly, and northwesterly strike but gave no further information with which we might base deformation models of the Mach–Sharigh sequence.

Quittmeyer and Jacob (1979) relocated the earthquake about 15 km to the northwest of Hirok, just outside the epicentral area, where we know damage was minor. A more likely location, however, would be close to that computed by Engdahl *et al.* (1998), which is about 30 km west of the trunk road in the north part of the Brahui Range, or close to our relocation, which is further southeast and which has formal errors of about 20 km, although due to the station bias discussed earlier the true position could be further northwest. These two locations are outside West's but well inside our reappraised epicentral region. This interpretation, however, would require the Bolan Pass uplift to be associated with secondary faulting from the Mach event, which may have been primarily strike slip, or faulting associated with the Sharigh earthquake (see discussion in text).

Table 3 itemizes locations for which an MSK isoseismal intensity was evaluated for the Mach 1931 earthquake.

16 October 1933. M 5.7 (Uruzgan). This event was a damaging earthquake in the small and sparsely populated districts of Uruzgan and Deh Chopan of Afghanistan. The shock destroyed three fortified places, which are not named, and caused rockfalls and the collapse of a mountain face (Heuckroth and Karim, 1970). There is no evidence that the shock, which had a magnitude of 5.7, was felt in Chaman or in Quetta.

15 May 1935, M 6.0 (Kotra). There is little macroseismic information about this earthquake in the south parts of the Kachhi plain. The shock, allegedly, did some damage in the Kotra region (Political and Secret Correspondence IO.L/P&S/10/1084/annex) and was strong at Jacobabad (West, 1936).

30 May 1935, M 7.7 (Quetta). Although Baluchistan in 1935 had one of the lowest population densities on the subcontinent of India, this earthquake occurred where most of the population lived. For this reason, and despite the initiation of earthquake-resistant design triggered by the nearby 1931 sequence, the 1935 Quetta earthquake resulted in the largest number of fatalities of any earthquake on the Indian plate or its boundaries in the past two centuries.

Quetta was ceded to the British in 1877. Before then Quetta was a station that controlled the trade route from India to Kandahar, as well as the Bolan Pass to the south and the road to Kalat and to Persian Baluchistan. Although a sketch of the fort at this time looks quite imposing, an 1839 report describes Quetta as "a most miserable mud town with a small castle on a mound having one small gun on a rickety carriage" (Spate, 1954, p. 430). Photographs of the town just before, and after, the 1935 earthquake reveal a busy frontier town that was severely damaged by the event.

Detailed information survives for the Quetta earthquake (Government of India Bureau in Simla, as well as West [1936], Jackson [1960], Skrine [1936], and Pinhey [1938]). Most of the damage to rural and urban houses, chiefly of mud brick construction, was enclosed within a narrow zone, with Baleli and Quetta in the north extending in a southwesterly direction into the Harboi Hills, about 160 km long and 25 km broad. A great deal of the land in the zone is unproductive, containing only a few large villages where water could be found in underground irrigation and water supply conduits (qariz, qanat). In addition to the towns of Quetta and Mastung, at least 100 villages in the Quetta subdivision and Kalat state were totally destroyed.

Starting from the north, Baleli was totally destroyed; 108 people were killed, and 23 were injured. At Kuchlagh all houses were ruined and the railway depot collapsed, with the loss of eight lives and nine injured. Further south, Sheik Manda was razed to the ground, and in nearby Nauhissar 77 people were killed and 28 injured.

Quetta, a military garrison town with a population of about 40,000 (summer population 65,000), is built on a slope crossed by two nullahs (watercourses). The Habib Nullah separated the civil lines and town from the cantonment, and the Durani Nullah, a kilometer further north, ran parallel to it for most of its length. Both nullahs were crossed by bridges at several points. The civil lines was the more densely populated part of the town. It occupied an area of about 4 km^2, and it was located south of Habib Nullah, an area with a high water table in the spring. This low-lying part of Quetta was utterly destroyed, and about 15,000 people lost their lives (Pinhey, 1938). The police lines, the durbar hall, the civil and mission hospitals, and the club were ruined, and the residency was damaged. The only buildings that survived the earthquake with minor damage were the few reinforced concrete structures and the new railway quarters, constructed after the 1931 earthquake using earthquake-resistant principles and situated in the most damaged part of the civil station.

North of the Habib Nulla, on higher ground, the cantonment was much less affected and only a few houses collapsed. The garrison church and the British and Indian military hospitals were undamaged. The only serious damage done to the cantonments was a belt about 1 km wide immediately adjoining the Durani watercourse and the civil lines, damage decreasing rapidly toward the northeast. Here a good deal of damage was done to the fort, and some of its buildings collapsed.

The airfield, with its modern hangars and barrack blocks, stood to the northwest, apart from the city and cantonment. In the Royal Air Force lines the hangars were left standing but little else. Every aircraft was so damaged that it was unsafe to fly. The earthquake caused no serious damage to the piped water supply or to the power stations, which continued to work on restricted load.

South of Quetta, Kansi was totally destroyed; 1010 people were killed, and 370 were injured. Also, Sariab was razed to the ground with the loss of 1206 lives and 641 injuries. At Durani 101 people were killed and 114 were injured. At Spezand, Dingar, and Mand-i Haji local houses were flattened, but the railway station at Spezand was not destroyed. Tiri was utterly destroyed, with the loss of 710 lives and 275 injuries. Mastung, 65 km south of Kuchlagh, was flattened by the shock together with the Khan's palace, killing altogether 1736 people and injuring 716.

Southwest of Mastung, small settlements in the Shirinab valley, which extends from Kuhnak to Manguchar along a distance of 90 km by road, were destroyed. This region was within the thinly populated tribal territory belonging to the Khan of Kalat, and damage details are lacking. Pringabad, the only large settlement in this region, was destroyed; 369 people were killed, and 234 were injured. Manguchar, 100 km south of Kuchlagh, was also destroyed; 185 people were killed and 185 were injured.

Destruction extended south into the state of Kalat, 155 km from Kuchlag. Kalat itself was ruined, with 120 people killed and 50 injured. In Kalat state, out of a population of 10,000, 2900 were killed and 5000 injured. It was estimated that all villages between Quetta and Kalat were destroyed, with 70% of the population either dead or injured.

Outside the epicentral region, damage was widespread to dilapidated rural houses, particularly in many places in the Indus valley and in the Spin Baldak (Qla-i Jadid) and the Kandahar regions of Afghanistan (Stenz, 1945).

Liquefaction of the ground and mud volcanoes were reported in the valley northwest of Quetta. Some 20 km south of Kalat on the main road to Surab, about 5 km east off the road near the village of Thok (28.333 °N, 66.517 °E), large quantities of liquid mud were observed coming out from the top of an old mud volcano at the time of the earthquake, the eruption lasting 9 hr. None of the local inhabitants could recall any similar event in the past. The new flows had spread out beyond the limits of the old, occupying an area of radius 140 m.

Official figures for the loss of life in the earthquake are no more than estimates (Pinhey, 1935). In Quetta about 26,000 people were killed, of which a few thousand bodies were left buried in the ruins of the town. Outside Quetta numbers are even more uncertain, particularly in the Kalat tribal area, where more than 8410 deaths were recorded. Altogether, the earthquake could have killed about 35,000 people, but reliable figures are lacking.

The telegraph lines from Kalat and Quetta to Chaman and Jacobabad were broken, but communication with the government of India at Simla was established by radio. The railways and roads, including the section through the Bolan Pass, were not badly damaged. Several small road bridges suffered slumping of their abutments, and five segments of the Quetta–Nushki rail track had to be replaced at its crossing with the zone of ground fissures (Thomson, 1936).

Administration became difficult owing to the fact that nearly all the subordinate civil officers and police had been killed. However, the fact that the troops escaped with few casualties allowed a quick rescue and evacuation of survivors, the disposing of thousands of dead by burial or by burning, sealing the town to prevent looting and the outbreak of epidemic disease, protecting and salvaging of property, and controlling the rehabilitation of the region. Two battalions of the Seventh Gurka Rifles, who were posted in Zhob and Chaman at the time of the earthquake, felt the earthquake and returned to find their regimental institute damaged beyond repair (Mackey, 1962).

Following the earthquake new laws were enacted for regulation of the distribution to relatives of property salvaged in the earthquake, for settlement of property claims, and for the compulsory application of earthquake-resistant design for all new public buildings and engineering structures (Robertson, 1948; Khan, 1956). Priority was given to the repair and reconstruction of destroyed qanats (underground irrigation channels) throughout the affected area to secure the next harvest.

Contrary to what has been said by a number of authors, that the shock was felt within a radius of only 280 km, Urdu and Hindi press reports confirm that the shock was felt over a large area, as far as Amritsar, Sultanpur, and Simla to the east (1000 km), to Jatti (610 km) on the mouth of the Indus to the south, Dera Ismail Khan (500 km) to the north, and Chagai (250 km) to the east; in the last two directions, information is lacking beyond these points into Afghanistan.

The earthquake was followed by a long sequence of relatively small magnitude earthquakes, the largest of which in the south part of the epicentral area did not exceed a magnitude M_S 6.0. Shocks continued to be felt until the beginning of October. No shocks were reported before the earthquake, but a bright orange glow was seen over Quetta to the west, and further south, near Kalat, flashes of light were reported along the flanks of the mountains on both sides of the valley.

Following the earthquake a survey of the northwest-dipping thrust faults southwest of Quetta, which run for a few kilometers along the northern flanks of Chiltan, showed no signs of any movement, although 20 cm of uplift was subsequently recorded on bedrock benchmarks near the Quetta brewery that lies 5 km west of the town on the hanging wall of the fault. Ground deformations extended discontinuously for about 105 km along the south side of the Chiltan Range toward Kalat, striking N15°E. Over the greater part of this distance they took the form of strands of open cracks, 2–20 cm wide, mostly in alluvium. About 8 km west of Mastung the ground of the west side of these cracks was downthrown on average by about 80 cm, although a little further south the sense of vertical movement was reversed. In some places, instead of a throw or open cracks, the ground had been heaved up, the uplifted portion being 30 cm or more high and several meters wide.

Where the locus of ground deformation crossed the railway that runs from Spezand to Nushki, about 3 km west of the Mastung Road station, the track had been uplifted and the rails buckled. Where bedrock intervened along these zones of fissures in alluvium, the cracks died out, with rockfalls and shattered rock taking the place of fissuring along the same line. This was well seen to the northwest of Mastung Road, on the southern flanks of the Chiltan Range. The zone of fissures extended further south, past Kalat. A few kilometers southwest of the village, ground cracks passed beneath an adobe house, displacing its walls but leaving them standing.

It appears, therefore, that the earthquake was associated with the zone of faults that lies along the east edge of the Chiltan range and that this zone extends to the south, passing near the towns of Mastung and Kalat. Leveling data confirm abrupt uplift of the foot of the range, but triangulation data that would reveal the extent and sense of strike-slip motion have yet to be released. The first-order North Baluchistan Series of the Survey of India measured in 1909 (Burrard, 1912) passes southward through Quetta and along the Chiltan range. Remeasurements of some of these stations were in progress during the earthquake.

Our instrumental position, a relocation using *P* waves from 231 stations and present ISC location procedures, is 160 km south of Quetta, about 40 km west of Kalat and close to the locations computed by Engdahl *et al.* (1998) and Ramanathan and Mukherji (1938). The formal errors are about 15 km, but as most of the stations are grouped to the northwest, the true position could be further to the northwest. The surface-wave magnitude calculated from 25 station magnitudes is 7.7, to which corresponds a seismic moment of 17.0×10^{27} dyne cm, estimated by Singh and Gupta (1980).

Lawrence *et al.* (1992) and Yeats *et al.* (1997) associated these ruptures with the Ghazaband fault zone, one of a series of large north–south left-lateral strike-slip systems that accommodate plate boundary shear. A temporary seismic network operated in the region in 1978 suggests that microseismicity was at that time concentrated near the ends of the 1935 rupture (Armbruster *et al.*, 1980). Fault-plane solutions in the area confirm left-lateral faulting on this trend, and, in spite of the lack of reported observations of strike-slip offsets at the time, this is the most likely mechanism for the 1935 earthquake.

2 June 1935, M 6.0 (Quetta). This was the largest aftershock of the 1935 sequence, and it added to the damage at Kalat, Maguchar, and Mastung but not in Quetta. Had it occurred by itself, it would have been considered a severe earthquake, and had there been any houses in the lower part of Quetta left to damage, the shock would certainly have damaged them. The aftershock triggered more slides in the Shirinabad valley and rockfalls from the sides of the Chiltan Range, southwest of Quetta, the dust rising 500 m above the mountain. Some damage reported from Nushki could be due to this aftershock.

17 January 1936. This shock ruined several houses in Quetta (Anonymous, 1936).

8 August 1938. Nothing is known about this event, except that it caused significant damage in the district of Arghestan in Afghanistan (Heuckroth and Karim, 1970).

29 September 1941. This shock was strong at Spin Baldak across the Afghan borders (Heuckroth and Karim, 1970).

1 October 1945, M 6.0. The position of this event in the Nagau Range is given by Quittmeyer and Jacob (1979) and cannot be improved. There are no felt reports.

10 October 1952, M 6.1. This was an earthquake west of the Sulaiman Range. The shock ruined a few villages, including Mekhtar, Zikra, Wadan, and Malezan, where a number of people were killed. The shock was strong in the regions of Fort Sandeman, Loralai, and in the Indus valley, where it caused slumping and spreading of the ground. It was felt in Multan and Quetta (Anonymous, 1952; *Bombay Times*, 1952; *Eastern Times*, 1952). Worldwide instrumental recordings confirm the macroseismic position.

25 December 1952, M 6.0. Little is known about the macroseismic effects of this earthquake in the Sulaiman Range, except that the shock was felt at Sui, Kaah, and Multan (Shabaz, 1372; Anonymous, 1952; *Bombay Times*, 1952).

18 February 1955, M 5.7. This was an earthquake in Baluchistan with an epicenter close to Quetta. Damage was confined within a small area of only 7 km radius, about 15 km north of Quetta, that included Chashma and a few small settlements such as Sragurgi and Sarantangi, already damaged by the foreshock of 12 February. Quetta itself suffered considerable damage. Many adobe houses were ruined, but modern buildings, designed to resist earthquakes, suffered less. Altogether, 10 people were killed in outlying villages and 50 were injured. The shock was strong at Chaman, and it was felt within a radius of about 120 km (*Bombay Times*, 1955; Pakistan; Haq and Naqvi [1957]; Khan [1958].) Kazmi (1979) reported a ground rupture in alluvium, about 1 km long. He gave no details about the exact location and azimuth of this feature, which he said was on an extension of the Chiltan fault. We consider this somewhat unlikely since the epicentral area of this M_S 5.7 earthquake is some distance from the extension of the Chiltan fault.

13 May 1956, M 5.9 (Baladhaka). This was an earthquake on the Sulaiman Range. The shock demolished Baladhaka, where a number of people were killed, and damaged Barkhan, Fort Munro, and Rakhni, with many injured but no loss of life. It was felt at Kahan, Loralai, Dera Ghazi Khan, and Multan (Ahmed, 1954).

7 February 1966, M 6.7 (Barhhan). A damaging earthquake on the foothills of the Sulaiman mountains, it was preceded by a strong foreshock on 24 January (07 h 23 m), which was widely felt in the region. The mainshock and the aftershock, which were of almost the same magnitude separated by 16 hr, affected the Barkhan region, where 4860 houses in neighboring villages, particularly Baladhaka, Naharkot, and Vitakri, were destroyed. Collapsed houses and rockfalls killed 12 and injured 100 people. The shock was strong in Loralai and Fort Munro and was perceptible at Quetta, Bahawalpur, Multan, Lahore, and Sargodha, 480 km away (QUE). The high observed intensities make the macroseismic position preferable to the position determined instrumentally.

7 February 1966, M 6.4. This was the strongest aftershock, occurring about 16 hr after the mainshock. It was strong throughout the Loralai district, and it was felt at Fort Munro, Multan, and Bahawalpur (UNESCO, 1966).

1 August 1966, M 6.2. This was the strongest foreshock of the earthquake at 21 h 03 m in the Duki region.

1 August 1966, M 6.9. A damaging earthquake in the Loralai district on the foothills of the Sulaiman mountains, it was preceded by two large foreshocks at 19 h 10 m and 20 h 31 m that did some small damage and forced people out of their houses. In the mainshock 1300 houses in 45 villages in the Duki and Manza (30.12° N–68.87° E) districts were destroyed; at least 2 people were killed, and 15 were injured. Damage extended to Loralai. The shock was very strong at Barkhan and was felt at Quetta. The earthquake was followed by many strong aftershocks well into September (UNESCO, 1966).

3 October 1975, M 6.8 (Spin Tezha). This earthquake on the Chaman fault was felt in northwest parts of Baluchistan and severely felt at Quetta. Along a 5-km-long strip of the Chaman fault zone, south of Spin Tezha, at least 30 ground cracks were found in alluvium. They were 0.5–10 m in length, with about 4 cm of left-lateral offset and a few centimeters up to the west dip-slip motion (Farah, 1976; Lawrence *et al.*, 1992). The position given by Engdahl *et al.*, (1998) is close to Spin Tezha.

3 October 1975, M 6.5 (Spin Tezha). This was an aftershock, 12 hr after the main earthquake, of almost equal magnitude, 18 km north of the previous event. It was felt severely at Quetta and in northwest parts of Baluchistan.

16 March 1978, M 5.9 (Nushki). This was a damaging earthquake on the Chaman fault with an epicentral area along the border of Pakistan and Afghanistan. This area probably extended north of Nushki into Afghanistan closer to the instrumental location of the event, an area that was not visited. Damage was limited to the pressure ridges and the alluvial fan west of the Chaman fault. Nushki itself, which is situated just east of the Chaman fault, was not damaged. However small villages west and south of the town suffered different degrees of damage, with no loss of life due to the earthquake. North of Nushki, the settlement of Siah

Koh was slightly damaged. More damage was reported from west of Nushki from Mohammad Ali Khan and a dozen settlements within a radius of 7 km from Nushki. To the south, damage decreased rapidly from Ahmad Wal, Reka or Zangiabad, Rahmat Duni to Kharan Kalat, where damage was negligible. The shock was felt at Spin Tezha, Quetta, and Chaman, 140 km to the north of Nushki (Yeats *et al.*, 1979). First-motion data indicate left-lateral strike-slip on the Chaman fault (Armbruster *et al.*, 1979, 1980).

4 March 1990, M 6.2 (Kalat region). The shock killed 11 and injured 40 persons, destroying hundreds of rural houses and government buildings. The earthquake was very strong at Kalat and was felt at Surab, Khuzdar, Mastung, and Quetta. First-motion data show reverse faulting with strike slip.

17 June 1990, M 6.3 (Central Makran Range). Heavy damage was reported from the Maskhai–Jebri region, where many local houses collapsed, injuring a number of people. In places cracks opened in the ground, allegedly to a depth of 13 m, and the yield of springs was temporarily reduced. The shock was felt at Khuzdar and Surab. The source mechanism shows strike-slip faulting with a moderate reverse component.

24 April 1992, M 6.2 (Central Makran Range). This occurred northeast of the shock of 17 June 1990; it affected settlements between Gwani Kalat and Nal. The shock was strong at Khuzdar. The mechanism of the event shows strike slip with a large reverse component.

27 February 1997, M 6.9 (Sibi region). Maximum damage occurred along a northwest–southeast sparsely inhabited zone about 70 km long that includes Suzsu, Harnai, Badra, Mandal, and Gambuli. In all about 500 houses collapsed, killing 57 people and hundreds of livestock and making thousands homeless. The shock damaged the railroad between Shashrig and Badra, and near Harnai it was blocked by rockfalls. Some damage was also reported from further away, from Mach, Sharigh, Duki, and Sibi. Less serious damage extended to the Mastung and Quetta areas, where three people were killed. The shock was felt throughout much of Baluchistan, in eastern Sind and in southwest Punjab. The earthquake was followed by damaging aftershocks: on 4 March, when a few people were injured with additional damage at Sibi and Harnai, and on 20 March, when it was felt in Quetta, Harnai, and Sibi with slight damage in Harnai and Sibi.

Appendix B

Example Worksheet Summarizing M_S Calculations for the Mach Earthquake of 27 August 1931 (Time 15:27:20, Location 29.20° N, 67.60° E)

Station	T_a (sec)	A_a (μm)	T_b (sec)	A_b (μm)	$\Delta°$	M_S
BOM	20.0	816.0	14.0	305.0	11.3	6.76
ANR	2	95	0	0	11.6	6.84
KUC	22.0	159.0	0	0	33.9	6.80
IRKz	14.0	82.0	0	0	35.5	6.64
PULz	14.0	199.0	0	0	39.5	7.10
BUD	18.0	309.0	18	222	41.4	7.31
VIE	16.0	210.0	0	0	42.9	7.23
UPP	15.0	466.0	0	0	45.3	7.64
POT	16.0	420.0	0	0	45.9	7.58
ZKW	18.0	399	0	0	46.2	7.51
LEI	15.0	300.0	14.0	135.0	46.2	7.42
JEN	20.0	100.0	19.0	210.0	46.7	7.15
GTT	15.0	190.0	0	0	47.9	7.29
KRL	14.0	200.0	13.0	140.0	48.6	7.36
STR	14.0	148.0	14.0	173.0	48.6	7.31
DBN	15.0	485.0	16.0	286.0	50.7	7.69
UCC	13.0	130.0	14.0	135.0	51.2	7.28
BER	12.0	150.0	12.0	200.0	51.3	7.46
PAR	14.0	250.0	0	0	52.0	7.50
ALG	16.0	25.0	18.0	70.0	53.4	6.81
KEW	16.0	230.0	16.0	220.0	54.1	7.48
LPZ	30.0	138.0	0	0	137.6	7.61

Average M_s magnitude and standard deviation = 7.26 ± 0.07.

A_a and A_b are maximum ground amplitude (μm) at the observed periods T_a and T_b seconds for orthogonal horizontal components. $\Delta°$, epicentral distance in degrees.

Department of Civil Engineering
Imperial College
London, UK
(N.A.)

CIRES and Department of Geological Sciences
University of Colorado
Boulder, Colorado 80309-0399
(R.B.)

Manuscript received 24 January 2002.