Bulletin of the Seismological Society of America, Vol 71, No 2, pp. 477–489, April 1981

SEISMICITY OF THE IRANIAN PLATEAU AND BORDERING REGIONS

By Jafar Shoja-Taheri and Mansour Niazi*

ABSTRACT

Seismicity of the Iranian Plateau and bordering regions during the past 22½ yr from 1 July 1957 through December 1979 is investigated in four successive time intervals by analyzing close to 4000 earthquakes in the region. This tectonically active part of the Alp-Himalayan belt is defined by a broadband of diffuse seismicity and contains several mobile belts surrounding small, relatively stable blocks. The major zones of mobility in decreasing order of activity are, Hindukush, Zagros, Elborz, Chaman fault system, east-central Iran, and the Caucasus and eastern Turkey. The most conspicuous aseismic block is that of western Afghanistan, but smaller blocks in central Iran, Azarbayejan, and the southern Caspian Sea also show noticeable stability.

The *a* and *b* parameters of the frequency-magnitude recurrence curve during successive time intervals in three of the mobile zones which are located in Iran show an increasing trend to stabilized levels at the end of the period. The annual average of seismic moment rates in Zagros during the past 22½ yr requires nearly a two order of magnitude increase to account for the relative plate motion between the Arabian and central Iran plates.

Introduction

Seismicity of the Iranian Plateau and the surrounding regions has been the subject of numerous investigations (Wilson, 1930; Niazi and Basford, 1968; Nowroozi, 1971; Seyed-Nabavi, 1977, 1979). Here we present the seismicity of the region as derived from the instrumental data compiled by the USGS and its predecessors during the 22½-yr period from the beginning of July 1957 to the end of December 1979. (This study was initially planned to analyze 20-yr seismicity, but because of several strong earthquakes which occurred in 1978 and 1979, the period was extended 2½ yr). This work is, therefore, an extension of Niazi and Basford (1968), herein referred to as Paper I, in which the seismicity of the same region during the period 1957 through June 1967, was compiled, and the frequency of earthquake recurrence was examined for the subregion covering Iran. Because of better coverage provided by additional regional and teleseismic recording stations in recent years, the available data for the second decade, 1967 to 1977, are expected to be more complete. Consequently, the threshold magnitude of detection has been lowered in some subregions.

Method of Analysis

The region covers from 20° to 44°N latitude and from 40° to 76°E longitude. The method of computation is essentially the same as described in Paper I. The same area was divided in Paper I into quadrangles each covering half a degree of latitude and longitude, and the seismic energy and associated strain release ($E^{\frac{1}{2}}$) of the earthquakes which occurred within each quadrangle in different periods were computed and combined. The following minor modifications are here introduced.

* Present address. Tera Corporation, 2150 Shattuck Avenue, Berkeley, California 94704.

(a) Seismic energy is calculated from body wave magnitude using the relation (Richter, 1958, p. 365)

$$\log E = 5.8 + 2.4\, m_b.$$

(b) The calculated strain release in each quadrangle is here convolved with a low-pass filter. The filter is so constructed that the following normalized weights are assigned to the quadrangles at and around the instrumental epicenters

37.5 per cent to the main quadrangle;
37.5 per cent to the four immediately adjacent quadrangles; and
25.0 per cent to the four diagonally adjacent quadrangles.

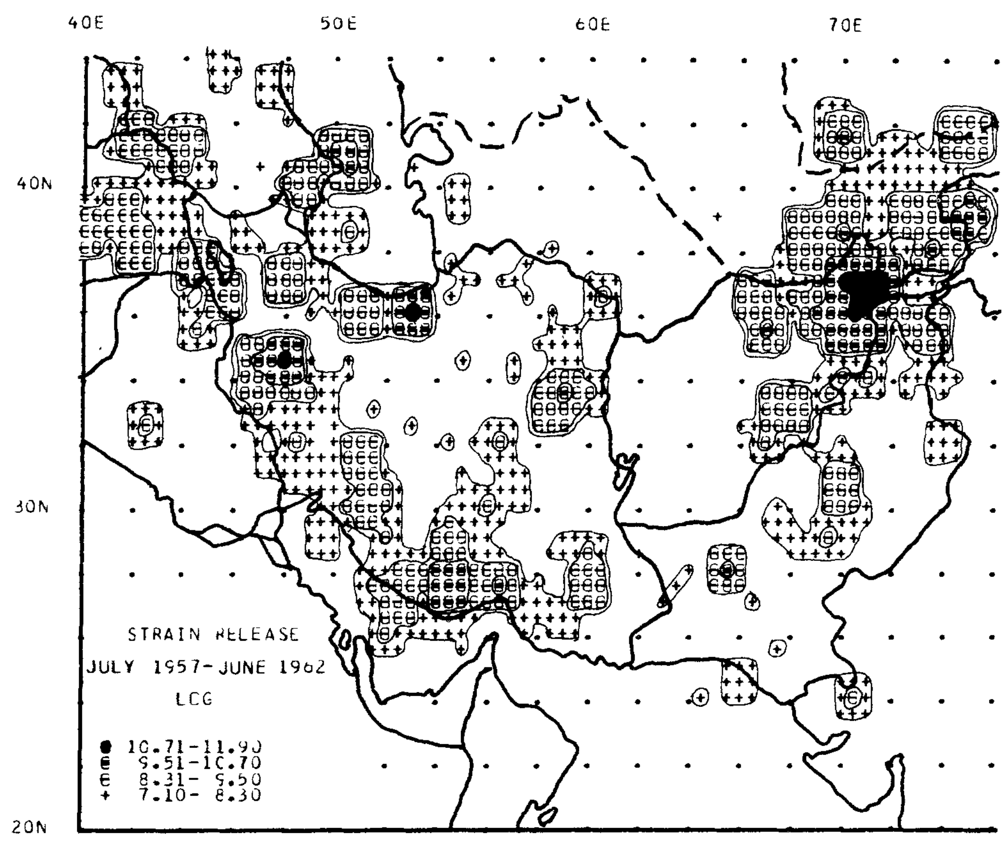

FIG. 1. Seismic activity during the 5-yr period from 1 July 1957 through 30 June 1962

Allen *et al.* (1965) have used a slightly different filter, more appropriate to the relatively better determined epicentral locations in southern California.

(c) Strain release maps are presented in the form of contours through the points of equal flux.

(d) The magnitude frequency curves are derived for different seismotectonic provinces, and their respective parameters are compared for the successive time intervals. The tectonic significance of the rates of the strain release in some subregions is also discussed.

Strain Release Maps

The $22\frac{1}{2}$-yr coverage is divided into three 5-yr intervals, the first two of which were initially dealt with in Paper I, and one $7\frac{1}{2}$-yr interval. As shown in Paper I, there is considerable scatter of data during 1957 to 1962, with Hindukush appearing as the most prominent seismic feature to the northeast of the region. During the same interval, there is also noticeable seismic activity in Zagros, markedly around

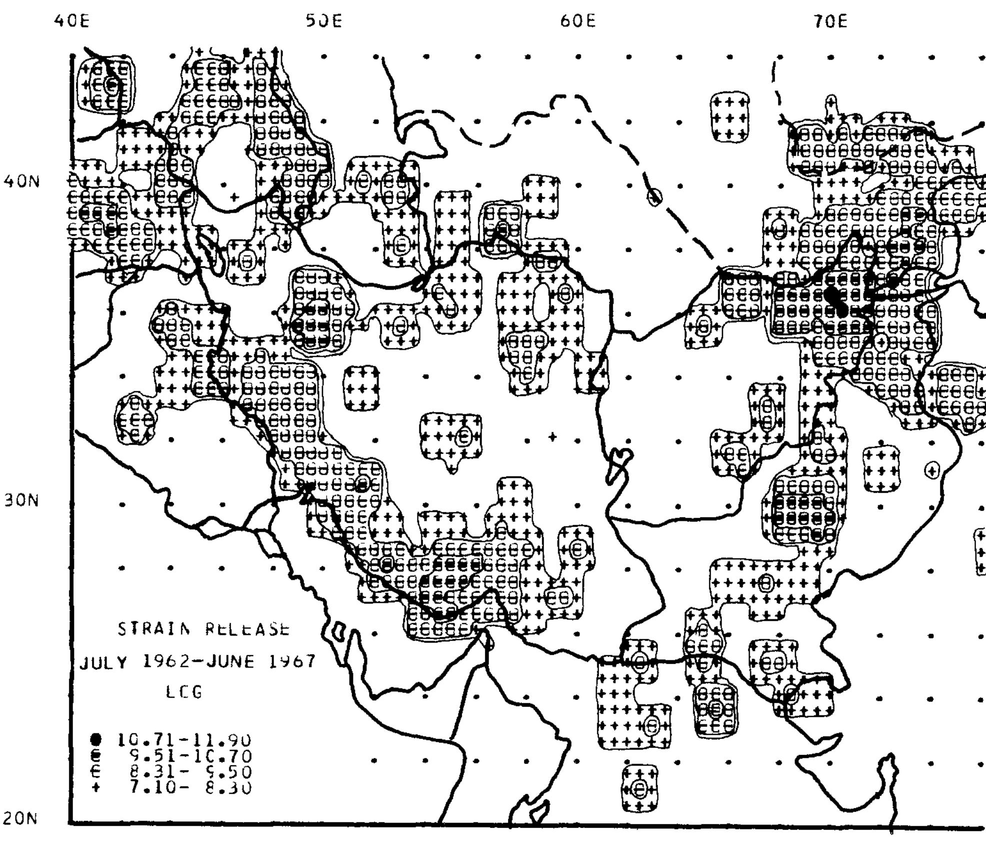

FIG. 2. Seismic activity during the 5-yr period from 1 July 1962 through 30 June 1967

the two ends of the belt, and in Elborz [(Figure 1) The correct local name for this mountain range in northern Iran is Alborz (see abbreviation in Figure 7), however Elborz and Elburz spellings are frequently used in western literature.]. Figure 2 displays a more uniform distribution of activity in Zagros and more intense seismicity in eastern Turkey in the second 5-yr period. A westward migration of activity in Elborz is observed in this period. Hindukush also continues to be the center of intense seismic activity.

During the third 5-yr period, 1967 to 1972, major seismic activity initiates in eastern Iran, with the occurrence of the Dasht-e Bayāz earthquake, $M_S = 7.3$, in August 1968. The activity in Elborz is concentrated around the southeast corner of the Caspian Sea. The Hindukush center is relatively calm, and the high seismicity center of the eastern Turkey moves slightly westward. The southern portion of Zagros is also widely active during this period (Figure 3).

In the $7\frac{1}{2}$-yr period, from July 1972 through December 1979, the general picture stays more or less the same, with a continuation of intense seismic activity in eastern Iran, culminating in two major shocks, the Tabas earthquake (Mohajer-Ashjai and Nowroozi, 1979; Berberian *et al.*, 1979) of 16 September 1978. $M_S = 7.8$ (BRK) and the Qainat earthquakes of November 1979 (Haghipour and Amidi, 1980), the main shock of which had $M_S = 7.1$. There is also some major but isolated seismic activity

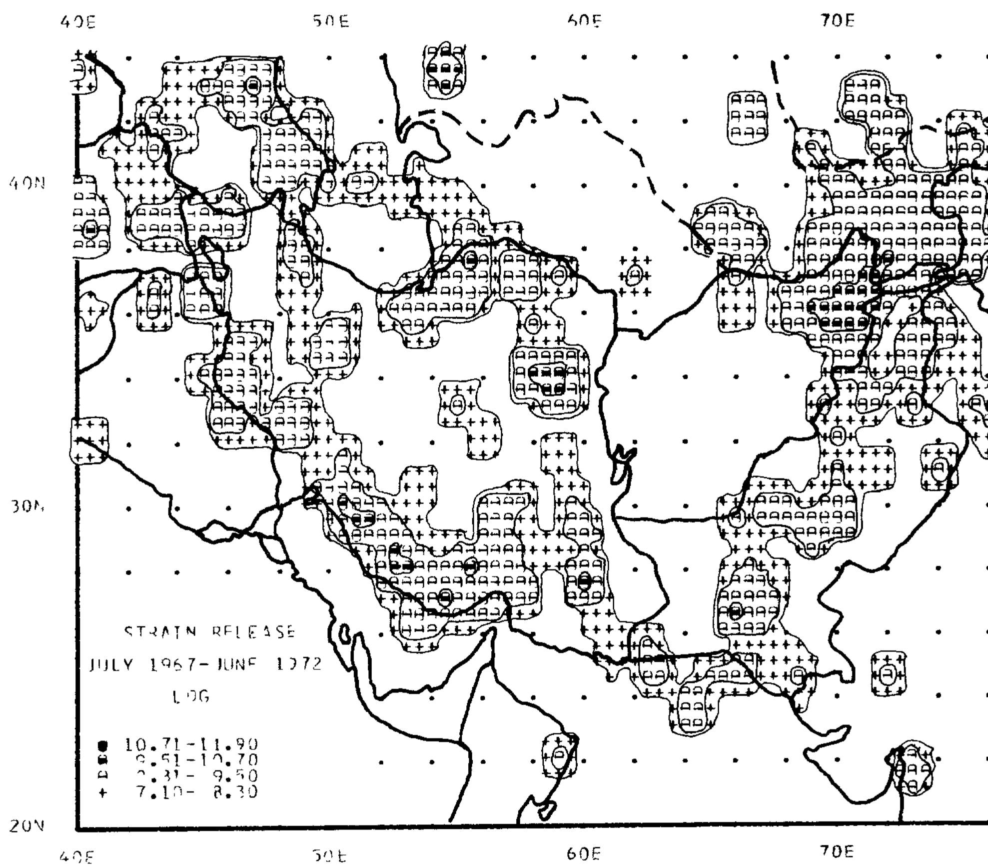

FIG 3 Seismic activity during the 5-yr period from 1 July 1967 through 30 June 1972

recorded in Uzbek, USSR, with the occurrence of the two Gazli earthquakes of 8 April and 17 May 1976 (Kristy *et al.*, 1980; Hartzell, 1980). Eastern Turkey remains active on either side of the 1966 Varto epicenter (Wallace, 1968). Zagros also continues to be active, particularly at the southeast end to the north of the Hormuz Strait, where studies to evaluate the feasibility of installation of one or more nuclear power plants were being conducted during this period (Figure 4). In contrast, little activity is exhibited in Elborz. Because of the establishment of a number of local seismographic networks in the region, a relatively higher number of smaller earthquakes (m_b 4 to 5) have been located in some areas.

The total strain release during the period from mid-1957 through 1979 is shown in Figure 5. Although the whole region exhibits a broad belt of diffuse seismic activity, several highly mobile systems appear to surround relatively smaller stable blocks. The most conspicuous aseismic block is that of western Afghanistan (Sistan Block of Stöcklin, 1977), which separates seismic zones of eastern Iran from Chaman-Hindukush zones. Despite the reported historical seismicity along the Herat fault system of northern Afghanistan (Quittmeyer and Jacob, 1979) during the $22\frac{1}{2}$ yr of this study, the quiet zone has extended northward across this structure to join the

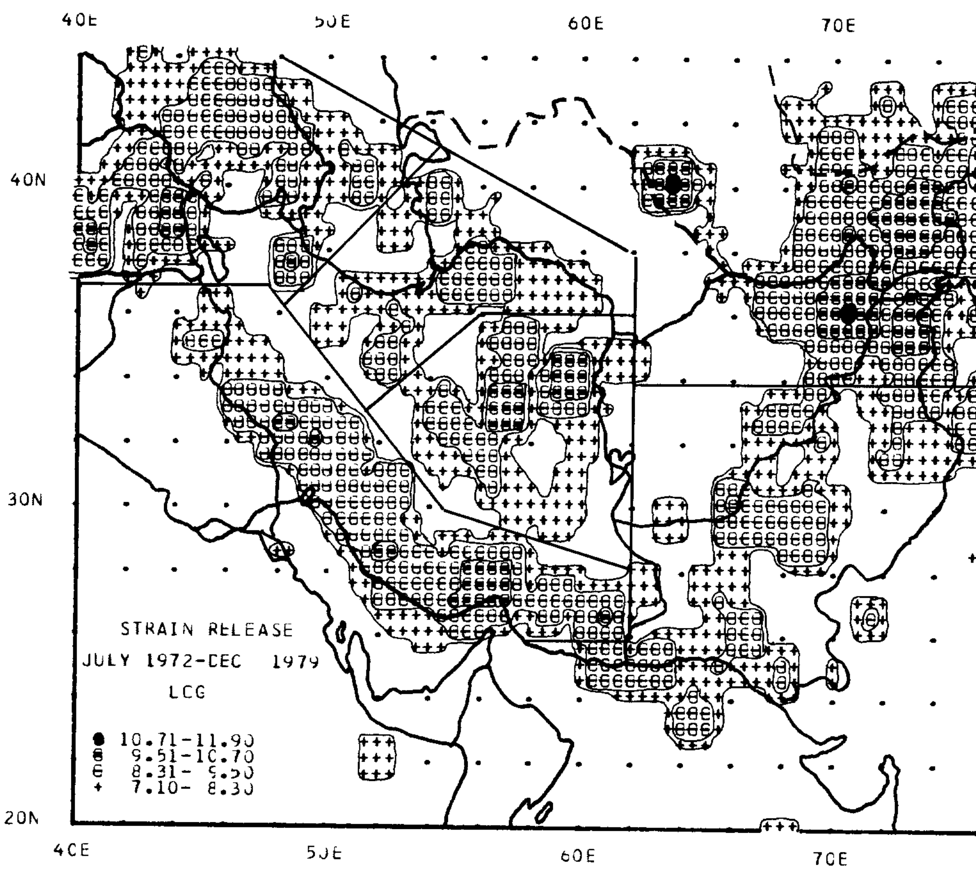

FIG. 4 Seismic activity during the $7\frac{1}{2}$-yr period from 1 July 1972 through 31 December 1979 The straight line segments show the approximate boundaries of the seismotectonic provinces of Caucasus and eastern Turkey, Hindukush, the Chaman fault system of Pakistan, Zagros, Elborz, and east-central Iran as defined in this study

central Asian platform. Other stable blocks are located in central Iran, the southern Caspian Sea, and Azarbayejan. The Zagros and Elborz ranges constitute two sides of a triangle, the third side of which is rather irregular and appears to follow the northern and western boundaries of the Lut Block (Stocklin, 1974).

FREQUENCY OF RECURRENCE

Nearly 3850 earthquakes of magnitude 4 and above occurred in the region during the 20-odd yr period covering this study. Table 1 shows the number of earthquakes in each of the six major tectonic provinces of the region in the successive periods. These provinces are: Zagros, Elborz, east-central Iran, Hindukush, the Chaman fault system in Pakistan, and the Caucasus and eastern Turkey. The boundaries of these six zones are shown in Figure 4. Approximately one-third of the epicenters are located in Iran, i.e., subregions 1, 2, and 3. To see how the recurrence parameters may have changed during the $22\frac{1}{2}$ yr, regression lines are fitted to the frequency-magnitude variations for each of the three subregions during each interval. The

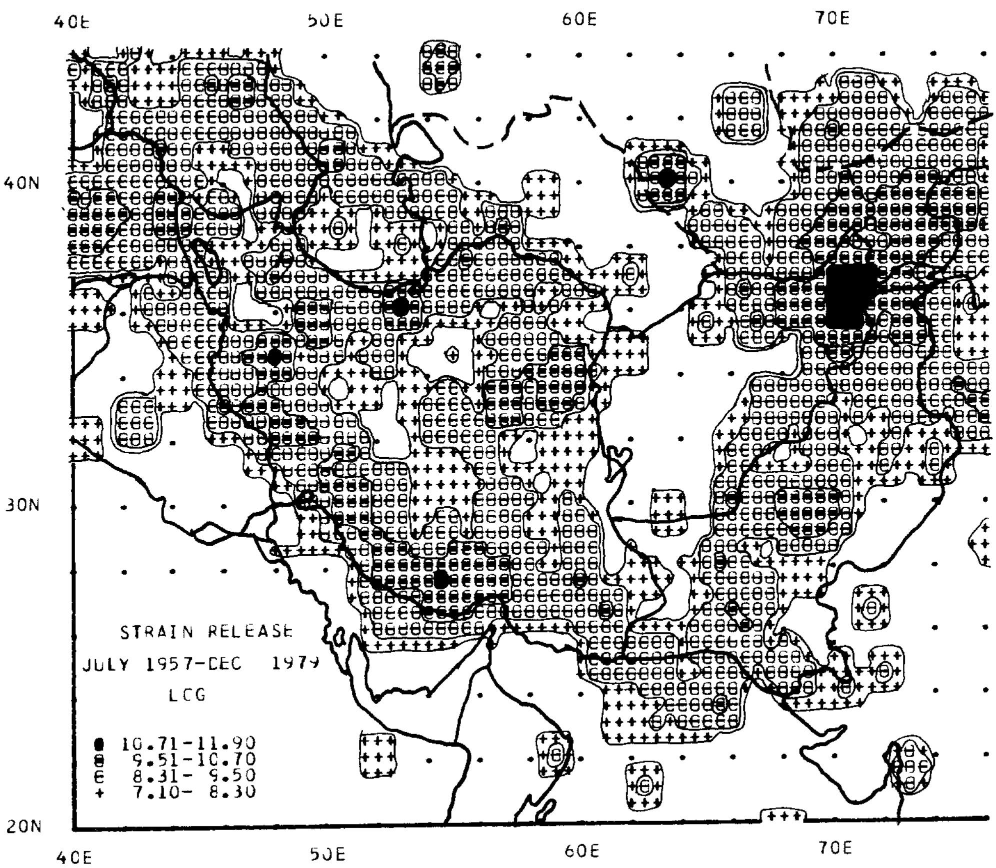

FIG. 5. Cumulative regional seismicity during the $22\frac{1}{2}$-yr period from June 1957 through December 1979. A number of highly mobile belts can be recognized, in the otherwise diffuse pattern, to surround relatively more stable blocks of west Afghanistan, Lut, Central Kavir, southern Caspian, and Azarbayejan Note that the low level of seismicity shown by the plus signs, could be produced by weak, mislocated earthquakes or introduced by the low-pass filtering of the data

estimated parameters, a and b, and the standard deviations of estimate are listed in Table 2.

Although there are minor inconsistencies in the parameter estimates of Table 2, for instance the low values obtained for the first 5-yr interval and in the subregion 2 in the second interval, they can be justified by the incompleteness of the data at the low magnitude end in those periods. An apparent trend in the direction of progressive increase for both a and b values established in the first 10 yr is thus stabilized for the latter half in all of the subregions. The stabilized b value for Elborz and east-central Iran is between 0.9 to 1.0, and for Zagros from 1.1 to 1.2, indicating fewer larger earthquakes relative to smaller ones in the latter region.

Tectonic Implication of Strain Rates

The cumulative strain release in the six distinct tectonic subregions are plotted in Figure 6 for comparison. Several interesting features may be noted in Figure 6.

(a) Hindukush and Zagros are producing a relatively regular pattern of seismicity, with many more earthquakes of moderate magnitude relative to the number of strong earthquakes. These two subregions representing the most recent active plate boundaries of the region, are also the most active zones.

TABLE 1

The Number of Earthquakes with $M_b \geqq 4$ in Different Subregions During the Successive Time Interval

Zone	Location	1957–1962	1962–1967	1967–1972	1972–1979	1957–1979
1	Zagros	193	162	185	436	975
2	Elborz	27	24	33	47	131
3	East-central Iran	31	19	39	108	197
4	Hindukush	255	349	283	920	1807
5	Pakistan	50	77	47	116	290
6	The Caucasus and eastern Turkey	72	87	84	199	442
Total		628	718	671	1826	3842

(b) The remaining four subregions exhibit a less regular pattern, with sporadic bursts of activity at irregular intervals. Although the Caucasus and eastern Turkey may not fall into the definition of a complete seismic region, its temporal variation of seismicity resembles those of Pakistan (Ornach Nal-Chaman fault system) and east-central Iran. The coincidence of discontinuities in the strain release curves for these three subregions indicates a certain degree of clustering of earthquake activity in the region as a whole. Although the strain release curve of east-central Iran falls below those of the other subregions due to relative quiescence in the first 10 yr of this period, the cumulative strain flux reaches nearly the same value in all the four subregions

TABLE 2

Estimates of a and b Parameters of the Magnitude Frequency Distribution in the Three Seismotectonic Provinces of Iran During Different Periods

Date	Zagros		Elborz		Eastern and central Iran	
	a	b	a	b	a	b
1957–1962	5.21 ± 0.28	0.74 ± 0.05	2.43 ± 0.30	0.40 ± 0.06	3 64 ± 0 55	0.60 ± 0 11
1962–1967	7.27 ± 0.60	1.13 ± 0 11	4 22 ± 0.50	0 67 ± 0 09	5.47 ± 0.00	0.95 ± 0 00
1967–1972	7 47 ± 0 55	1.17 ± 0.11	6.39 ± 0 87	1 10 ± 0.17	6.30 ± 0 74	1.04 ± 0.14
1972–1979	7 71 ± 0.09	1 16 ± 0 02	5.41 ± 1 31	0.94 ± 0.25	5 92 ± 0.24	0.91 ± 0 04
1957–1979	8 10 ± 0.31	1.15 ± 0.05	5 98 ± 0 06	0 92 ± 0 01	6 93 ± 0.26	1.06 ± 0.05

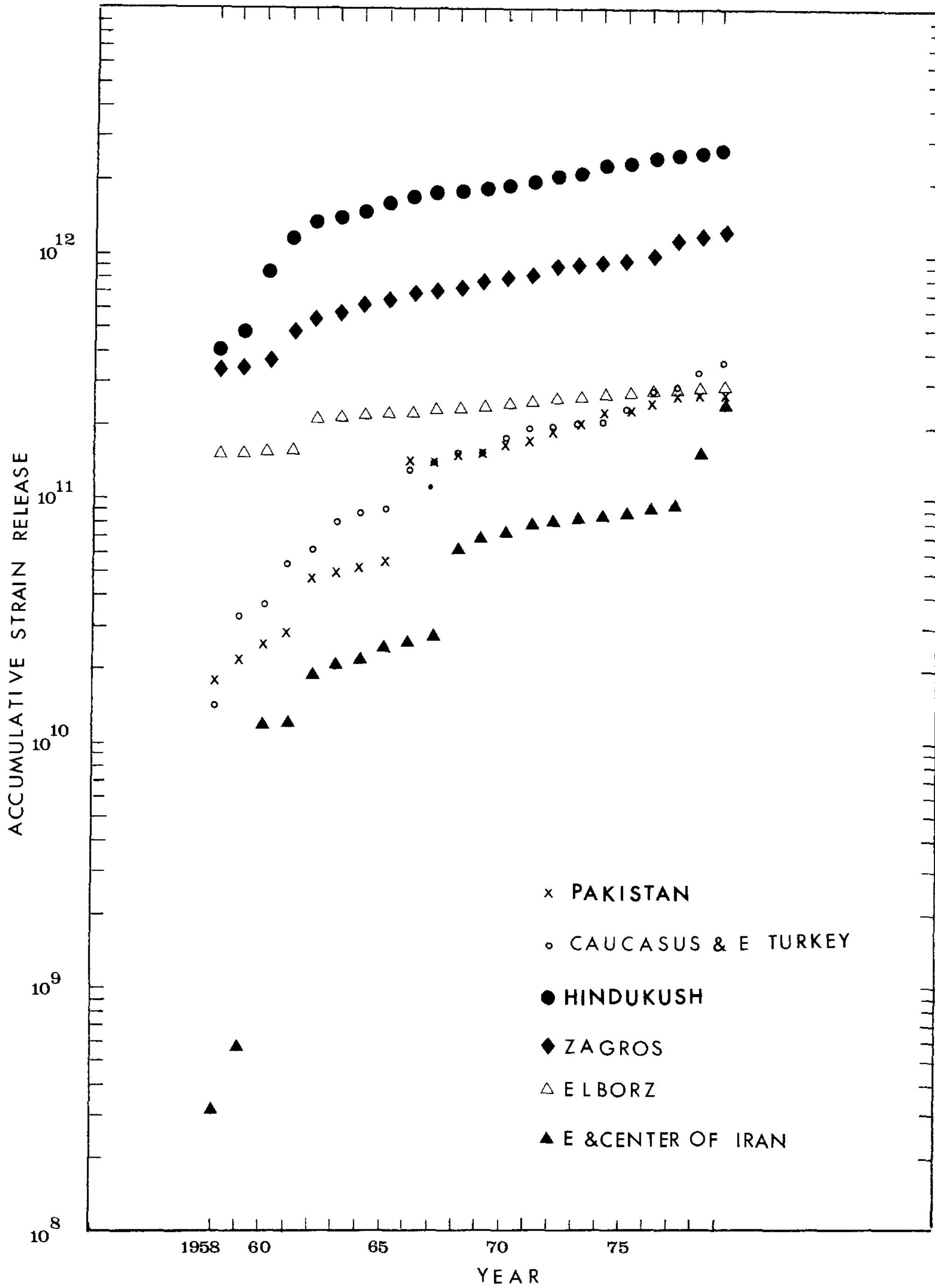

FIG 6. The cumulative annual strain release within each of the six seismotectonic provinces defined in Figure 4.

of Pakistan, Elborz, the Caucasus and eastern Turkey and east-central Iran at the end of the study period. The seismicity pattern of each of these four intraplate subregions is diffuse, and the cumulative strain release is about one order of magnitude below the two interplate boundaries representing Zagros and Hindukush.

(c) The variation of seismicity in Elborz clearly differs in two respects from the other three intraplate zones. One difference is the high initial value which consequently assigns a high overall seismicity to this zones throughout the study period. This high initial jump in the strain release curve is due to an earthquake of M_S = 7.4 (PAS), which occurred on 2 July 1957, in eastern Elborz. The second difference is the lack of significant variation except in 1962, during which the Buin-Zahra earthquake (M_S = 7.2) occurred (Ambraseys, 1963). Whether or not these differences are due to the sampling window is difficult to ascertain. If, as seems reasonable, we are to expect similar behavior over a longer observation period, an immediate conclusion may be to designate this zone as the subregion in which intensive future seismic activity is most probable. There is ample historical evidence to back up this expectation (Ambraseys, 1968). As seen in Figures 1 and 5, the western segment of the gap in seismicity which developed in central Elborz since 1957 has been partially filled by the 1962 sequence. The recognition of the fact that Tehran, a city with a population of nearly 5 million and few structures of adequate engineering design, is situated in the heart of the remaining unfilled section is very alarming.

TABLE 3

THE AVERAGE ANNUAL STRAIN RELEASE IN EACH SUBREGION

Zone	Location	Strain release rate [(ergs)$^{1/2}$/yr]	Moment rate (erg/cm/yr)
1	Zagros	5.2×10^{10}	5.5×10^{25}
2	Elborz	1.1×10^{10}	1.1×10^{25}
3	Eastern and central Iran	1.0×10^{10}	1.8×10^{24}
4	Hindukush	$1 2 \times 10^{11}$	6.4×10^{25}
5	Pakistan	$1 2 \times 10^{10}$	7.0×10^{23}
6	The Caucasus and eastern Turkey	1.4×10^{10}	7.2×10^{23}

It is generally accepted that Zagros suture zone is a major plate boundary, where the Arabian Plate has been in collision with Eurasia since the late Miocene (Takin, 1972; McKenzie, 1972; Hynes and McQuillan, 1974). The fact that the tectonic flux along the Elborz ranges and in east-central Iran during the $22\frac{1}{2}$-yr period has remained lower than in Zagros by about one order of magnitude may indicate that the deformation in the former subregions is merely a by-product of the collision along Zagros. Furthermore, the accumulation of strain and its release in the former subregions may be coupled through the complex network of the horst and graben block structure in central Iran (see Stocklin, 1974).

SLIP RATE IN ZAGROS

The average annual strain release in each of the six subregions is given in Table 3. From this table, we see that the rate of elastic deformation in Hindukush exceeds Zagros by a factor of about 2. This rate decreases successively for the Caucasus and eastern Turkey, Pakistan, east-central Iran, and Elborz.

A somethat different deformation rating may be assigned by the average annual moment associated with seismic sources within each zone. Still, Hindukush and Zagros rank higher by one order of magnitude. However, earthquake moment rate in Elborz, being dominated by the 1957 earthquake, ranks third after Hindukush and Zagros.

Among the six zones of Table 3 the geometry of the Zagros boundary, along which the Iranian segment of the Eurasian Plate (assuming Iran is part of the Eurasian Plate) and the Arabian plate coverage, is relatively simple. The seismic boundary can be roughly modeled as a prism of about 1750 km in length, 150 km in width, and 50 km in depth, at a uniform compression in the horizontal plane perpendicular to its length. The faulting associated with Zagros earthquakes seldom ruptures the surface, and in contrast to the Main Zagros Thrust, which is nearly vertical (Stocklin, 1974), is thought to have a predominantly shallow dipping thrust mechanism. If the average dip is taken to be $\alpha = 30°$, from geometrical consideration and projection of the relative motion between the two plates onto the fault plane, the annual moment ($\dot{M}_0$) and convergence rate ($\dot{d}$) can be related by

$$\dot{M}_0 = 2\mu \frac{Lh\,\dot{d}}{\sin 2\alpha} \quad (1)$$

in which L and h are the length and depth of the seismic zone and μ is the modulus of rigidity. By substitution of the estimated numerical values (μ is taken 3×10^{11} dyne/cm^2) in (1), $\dot{d}$, the annual rate of convergence along the Zagros plate boundary estimated from the most recent $22\frac{1}{2}$-yr data, turns out to be 0.15 cm/yr. This is less than 4 per cent of the relative long-term value from the observations of plate motion (McKenzie, 1972; Minster and Jordan, 1978).

Taking into account the slip increments which would have been produced by the earthquakes with $M \geqq 5.5$ during the 60 yr from 1910 to 1970, North (1974) concluded that only about 6 per cent of the shortening predicted by the plate tectonics models can be accounted for by such earthquakes. His short-term value estimated from 1963 to 1970 data accounts for nearly 1 per cent. Although different magnitude-moment conversion schemes were used in this work [North also takes $\alpha = 45°$, but has used $\sin \alpha$ instead of $\sin 2\alpha$ in (1)], the similarity of the conclusions as to the small role seismic activity plays in releasing the strain induced by plate convergency along the Zagros plate boundary by the two investigations are inescapable.

Discussion

Because of the slow nature of tectonic processes, a $22\frac{1}{2}$-yr observation is too short for specific, detailed inferences. As more data for longer periods of observation are compiled, a more coherent and representative picture is expected to emerge. Certain general remarks can be made, however, on the basis of the present analysis, regarding the distribution of the prominent seismic features of the region as displayed in Figure 5. In particular, some of the more conspicuous gaps in eastern Iran, in central Elborz, and in central Zagros are expected to be filled in the future.

Despite the diffuse pattern of seismicity in Iran and bordering regions, the areas in which seismic activity during the past $2\frac{1}{2}$ decades has been relatively high, follow for the most part the Alpine mobile belts which border the Arabian and Indian shield masses to the south and the Hercynian realm of central Asia to the north, as can be seen from comparison of Figures 5 and 7. Internally this marginal strip contains a number of median-masslike rigid blocks, such as western Afghanistan, central Iran, Lut and Azarbayejan, which have remained stable during the later phases of Alpine orogeny (Stöcklin, 1977). Except for Zagros, most of the regional stresses which are currently produced as a result of relative plate motions in the

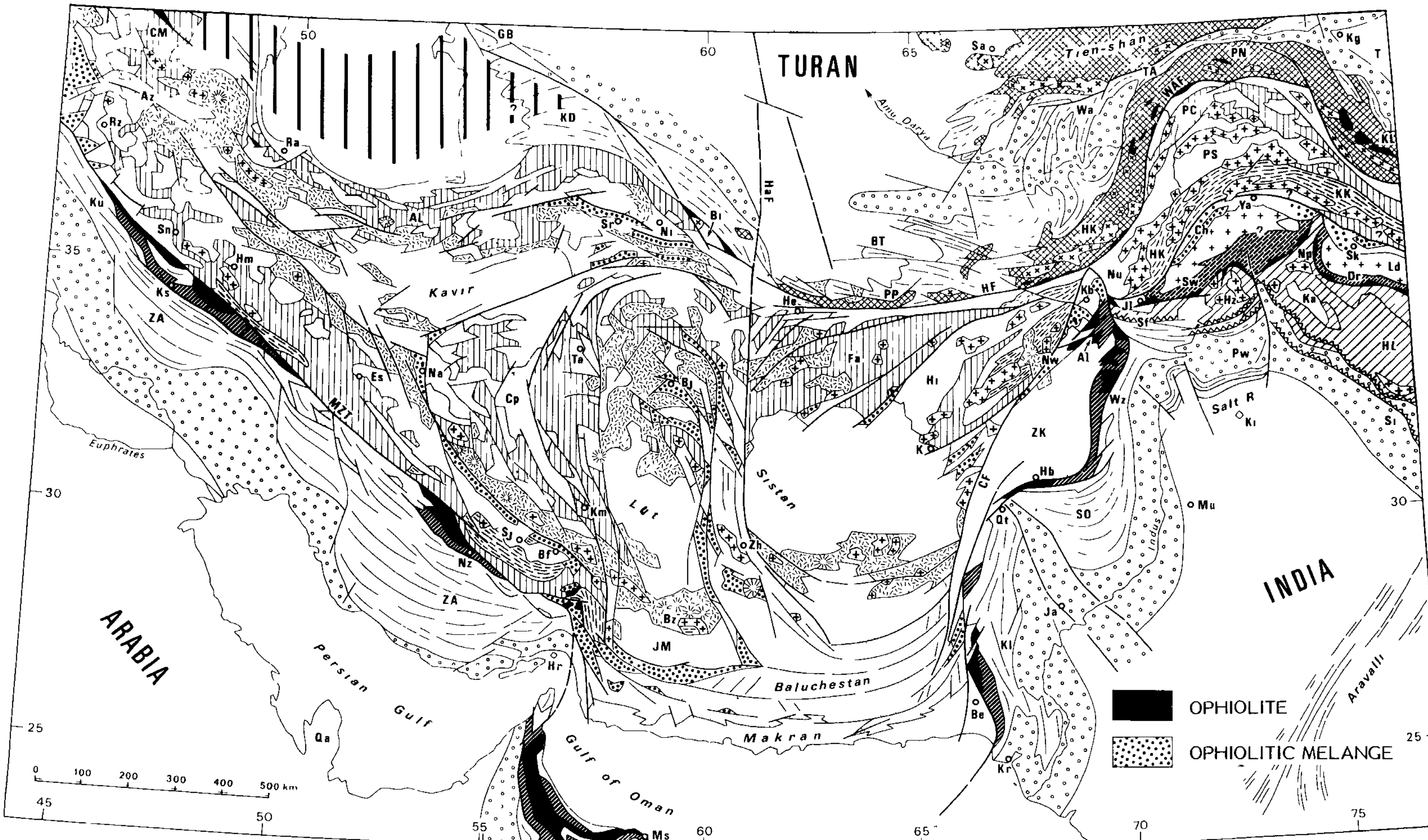

FIG 7 General tectonic features of the region as given by Stocklin (1977) Most of the names referred to in the text are seen in the map in an abbreviated form.

region appear to be released by marginal readjustment along preexisting structural weaknesses surrounding these blocks, rather than causing internal deformation.

The saturation of body wave magnitude, m_b (Kanamori, 1977), selected here for estimation of strain release, has caused relative flattening of the high seismicity ridges of Figures 1 to 5. Thus, because of a low assigned m_b of 6.5, the Tabas earthquake of 16 September 1978, which by most estimates ranks as the strongest continental earthquake of this century in and around Iran, does not produce a sharp maximum. The surface wave magnitude of this earthquake ranges from 7.4 (USGS) to 7.8 (BRK).

The Kopeh-Dagh folded belt of northeast Iran which produced several major earthquakes, including those of 1929 and 1948, in the 50 yr preceding this period showed a relatively low level of activity during this time.

The coseismic deformation of the region in general, and the Zagros folded belt, in particular, is probably two orders of magnitude below what would be expected from the inferred relative plate motions, thus confirming North's (1974) suggestion that most of the regional tectonic deformation takes place aseismically.

ACKNOWLEDGMENTS

This study was partially supported by the Research Council of Mashad University, and was completed during the period in which one of the authors (MN) was working at the Department of Geology and Geophysics, University of California, Berkeley. We wish to acknowledge the assistance of the Mashad University Computer Center. The assistance of Miss F. Sadighzadeh in punching the data and of Ms. Joan Bossart in typing the manuscript is appreciated. We also thank an anonymous reviewer for a number of helpful suggestions

REFERENCES

Allen, C. R., P St. Amand, C. F Richter, and J M Nordquist (1965). Relationship between seismicity and geologic structure in southern California, *Bull. Seism. Soc. Am.* **55**, 753–798.

Ambraseys, N N. (1963). The Buyin-Zara (Iran) earthquake of September, 1962 a field report, *Bull Seism Soc. Am.* **53**, 705–740.

Ambraseys, N. N. (1968). Early earthquakes in north-central Iran, *Bull. Seism. Soc Am* **58**, 458–496.

Berberian, M., I Asudeh, R. G. Bilham, C. H. Scholz, and C. Soufleris (1979). Mechanism of the main shock and the aftershock study of Tabas-e Golshan (Iran) earthquake of September 16, 1978, *Bull. Seism. Soc. Am* **69**, 1851–1860

Haghipour, A. and M. Amidi (1980). The November 14 to December 25, 1979 Ghaenat Earthquakes of Northeast Iran and their tectonic implications, *Bull Seism. Soc Am.* **70**, 1751–1757.

Hartzell, S. (1980). Faulting process of the May 17, 1976, Gazli, USSR, earthquake, *Bull. Seism. Soc Am* **70**, 1715–1736.

Hynes, S. J. and H. McQuillan (1974). Evolution of the Zagros suture zone, southern Iran, *Bull Geol. Soc. Am.* **85**, 739–744

Kanamori, H. (1977). The energy release in great earthquakes, *J. Geophys. Res.* **82**, 2981–2987.

Kristy, M J., L. J Burdick, and D. W. Simpson (1980). The focal mechanisms of the Gazli, USSR, earthquakes, *Bull. Seism. Soc. Am.* **70**, 1737–1750.

McKenzie, D. P. (1972). Active tectonics of Mediterranean region, *Geophys. J.* **30**, 109–185

Minster, J. B. and T. H. Jordan (1978). Present-day plate motions, *J Geophys. Res* **83**, 5331–5354.

Mohajer-Ashjai, A. and A A. Nowroozi (1979). The Tabas earthquake of September 16, 1978 in East-Central Iran, *Geophys. Res. Letters* **6**, 689–692

Niazi, M. and J. R. Basford (1968). Seismicity of Iranian Plateau and Hindukush region, *Bull. Seism. Soc Am* **58**, 417–426.

North, R. (1974) Seismic slip rates in the Mediterranean and Middle East, *Nature* **252**, 560–563.

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

Quittmeyer, R. C. and K. H Jacob (1979). Historical and modern seismicity of Pakistan, Afghanistan, northwestern India and southeastern Iran, *Bull Seism Soc. Am* **69**, 773–823.

Richter, C. F. (1958). *Elementary Seismology,* W. H Freeman, San Fransisco, 768 pp.

Seyed-Nabavi, M. (1977). Seismic activity in Iran 1971–1976, *J Earth Space Phys* (Tehran University) **6,** 38–86.

Seyed-Nabavi, M (1979). Seismic activity in Iran 1963–1976, *J. Earth Space Phys.* (Tehran University) **8,** 13–64.

Stocklin, J. (1974). Possible ancient continental margins in Iran, in *Geology of Continental Margins,* C A Burk and C. L. Drake, Editors, Springer-Verlag, New York, 873–887.

Stocklin, J. (1977). Structural correlation of the Alpine ranges between Iran and Central Asia, *Société Géol. France, Mém. h. sér.* **8,** 333–353.

Takin, M. (1972). Iranian geology and continental drift in the Middle East, *Nature* **235,** 147–150.

Wallace, R. E. (1968). Earthquake of August 19, 1966, Varto area, eastern Turkey, *Bull Seism. Soc Am.* **58,** 11–46.

Wilson, A. T. (1930) Earthquakes in Persia, *Bull. School Orient Studies* **6,** 103–131.

DEPARTMENT OF GEOPHYSICS
UNIVERSITY OF MASHAD
MASHAD, IRAN (J.S.T.)

DEPARTMENT OF GEOLOGY AND GEOPHYSICS
UNIVERSITY OF CALIFORNIA
BERKELEY, CALIFORNIA 94720 (M N)

Manuscript received July 22, 1980