Master “blind” thrust faults hidden under the Zagros folds: active basement tectonics and surface morphotectonics

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Abstract

The basement-involved active fold-thrust belt of the Zagros in southwest Iran is underlain by numerous seismogenic blind basement thrust faults covered by the folded Phanerozoic sedimentary rocks. Meizoseimal regions of moderate- to large-magnitude earthquakes in the Zagros are localized and concentrated along particular structural–geomorphological features and topographic fronts at the surface. The study reveals at least four active SW-vergent segmented master blind thrusts in the Zagros collisional belt, along which different morphotectonic units are thrusting over the deforming regions. These boundary thrusts, which make contiguous frontal asymmetric anticlines, prominent escarpments and Quaternary deformation, mark topographic fronts at the surface, and have vertically displaced geologic marker beds for more than 6000 m, include: the High Zagros (with a maximum recorded historic earthquake of $M_s = 6.0$ at Daryan); the Mountain Front ($M_s = 7.0$ at Khurgu); the Dezful Embayment ($M_s = 5.7$); and the Foredeep ($M_s = 6.5$ at Ahwaz) thrusts. Three other seismogenic blind thrusts responsible for the Qir ($M_s = 6.9$), the Lar ($M_s = 6.5$) and the Beriz–Dehkuyeh ($M_s = 5.7$) earthquakes are also documented in this study. The master faults, as evidenced by deformation of the asymmetric anticlines in the hanging wall of the blind thrusts, are segmented and discontinuous, and are separated by gaps in faulting that have presumably controlled the extent of rupture and the magnitude of earthquakes. The master seismic thrusts are displaced right-laterally by deep-seated active transverse faults of Kazerun ($I_o = \text{VIII}$), Sarvestan ($M_s = 6.4$) and Sabz Pushan. The study shows that active deformation in the Zagros is dominated by: (1) prevalent subsurface blind thrusting; (2) occasional surface strike-slip faulting; (3) coseismic asymmetric folding and uplift of sedimentary cover; and (4) surface thrusting ramping up from at least two regional upper (Miocene Gachsaran) and lower (Lower Cambrian Hormoz) décollement detachments.

The active master thrust faults have implications for seismic hazard assessment that were not previously appreciated. The possibility of large compressive earthquakes ($M_s \sim 7.0$) along the introduced blind thrusts must be considered. Locations of other unknown segmented blind thrusts in the belt, which have distinct effects on the surface morphotectonics and topography, and on the structures at depth, could be easily based on meizoseismal maps of the earthquakes combined with active morphotectonic features, morphometric analyses and accurate aftershock sequence studies.
1. Introduction

Seismic risk evaluation requires a thorough knowledge of seismogenic faults. In the areas where seismicity is related to exposed surface active faults, like central Iran (Tchalenko and Berberian, 1975; M. Berberian, 1981; M. Berberian et al., 1984), Alborz (M. Berberian, 1983; M. Berberian et al., 1992) or some parts of the western United States (Allen, 1975; Wallace, 1981; Sieh, 1981, 1987; Wenousky, 1986), capable faults are easily recognized on the surface, in aerial photographs and in satellite imagery. In areas like the Zagros (Fig. 1), where seismicity has a diffuse pattern and active basement faults are covered by Phanerozoic sedimentary cover (M. Berberian, 1976, 1981; M. Berberian and Tchalenko, 1976a,b; M. Berberian and Papastamatiou, 1978), recognition of seismogenic faults is elusive. Using field topographic observations, together with morpho- and seismo-tectonic information, and regional geology, tectonics and stratigraphy, this paper will address the relationship between surface and active basement tectonic processes, and will demonstrate the existence of a number of major segmented active blind thrusts—and basement to surface transverse faults—responsible for some of the hidden (Zagros-type) earthquakes in the active Zagros fold-thrust belt.

Several large earthquakes indicate that the amplitude of folds may increase during earthquakes. Work on the Tabas-e-Golshan (Iran) earthquake of 1978.09.16, $M_s = 7.4$ (King et al., 1981), and the El Asnam (Algeria) earthquake of 1980.10.10, $M_s = 7.3$ (King and Vita-Finzi, 1981; Yielding et al., 1981) demonstrated that surface anticlines associated with active thrust faults increased in amplitude synchronously with seismic fault motion at depth. The New Idria, CA, earthquake of 1982.10.25, $M_w = 5.4$ (Ekstrom et al., 1992; Stein and Ekstrom, 1992), the Coalinga, CA, earthquake of 1983.05.02, $M_s = 6.5$, $M_w = 6.5$ (Clark et al., 1983; Stein and King, 1984; Eaton, 1985; Rymer et al., 1985; Eberhart-Phillips, 1989), the Kettleman Hills, CA, earthquake of 1985.08.04, $M_w = 6.1$ (Ekstrom et al., 1992; Stein and Ekstrom, 1992), and the Whittier Narrows, CA, earthquake of 1987.10.01, $M_s = 5.9$ (Hauksdon and Jones, 1989; Lin and Stein, 1989), focused more attention on active folds and the relationship between folds, faults and earthquakes, and showed that folds can grow suddenly by repeated earthquakes rather than by steady progressive deformation. These earthquakes [including the 1964, $M_s = 7.5$, Niigata, Japan (Kawasumi, 1973), and the 1985.10.05, $M_s = 6.6$ and 1985.12.23, $M_s = 6.9$, Nahanni, Canada, earthquakes (Wetmiller et al., 1988)] were produced by “blind” structures whose presence and seismic potential could have been, but were not, appreciated before the earthquakes. The 1994.01.17 Northridge, CA, earthquake prompted more awareness on this issue. The earthquakes signaled the importance of concealed thrust faulting in regions of continental compression.

The active Zagros fold-thrust belt lies on the northeastern margin of the Arabian plate, on Precambrian (Pan African) basement (Fig. 1). This is a young (Pliocene) fold-thrust belt currently undergoing 20 mm/yr shortening (Jackson and McKenzie, 1984; De Mets et al., 1990) and thickening as a result of collision of the Arabian and central Iranian plates (M. Berberian and King, 1981; F. Berberian et al., 1982; M. Berberian, 1983).

Although the entire active Zagros fold-thrust belt in southwestern Iran, northern Iraq, southern Turkey and northern Syria has been mapped geologically and extensively drilled for oil and gas, little effort has been focused on understanding the active and seismogenic faults of the belt. The exact locations of the faults that produced most of the major earthquakes in the Zagros are poorly constrained (M. Berberian and Papastamatiou, 1978).

Because of the presence of several ductile layers in the Zagros, decoupling of the Phanerozoic sedimentary cover from the Precambrian metamorphic basement, has occurred along the Lower Cambrian Hormoz Salt (“lower Hormoz detachment zone”), and above the Eocene–Oligocene Asmari Limestone along the Miocene Gachsaran Evaporites (“upper Gachsaran detachment zone”), large-magnitude earthquakes fail to rupture the near-surface deposits in the Zagros (M.
Fig. 1. Major morphotectonic features and units of the Zagros active fold-thrust belt of southwestern Iran and northern Iraq, along the northeastern part of the Arabian Platform, as defined in this study. The units from top (north) to bottom (southwest) are: the High Zagros; the Simple Fold Belt; the Foredeep (including the Dezful and the Karkuk embayments); the Coastal Plain; the Persian Gulf-Mesopotamian lowland. See also Figs. 3, 4 and 5. Anticlinal axes are shown by thin lines, and faults (mainly longitudinal thrusts and transverse strike-slip) by heavy barbed lines. In order to show the overall continuity of the longitudinal reverse faults, each fault is shown by a special barbed line. Major longitudinal reverse faults introduced here are: DEF = Dezful embayment fault; HZF = High Zagros fault; KEF = Karkuk embayment fault; MZF = Zagros Mountain Front fault; MZRF = Main Zagros reverse fault (the geosyncline); ZFF = Zagros Foredeep fault. Major longitudinal right-lateral strike-slip faults: MBF = Main Recent fault. Major transverse right-lateral strike-slip faults are: B = Borazian fault; K = Kazerun fault; KB = Kisch Bush; S = Sarvestan fault; SP = Sabo Pahsan fault zone; BB = Balutal left-lateral shear zone northwest of the Dezful Embayment.

Recent folding and uplifting of the belt is already evident in the deep river valleys cutting the anticlines (Oberlander, 1965), raised beaches, the height of Quaternary alluvial terraces and uplift of historical canals. Historical evidence in the Zagros indicates that uplift of about 1mm/yr has occurred in the Shaur anticline (in the Dezful Embayment in the Zagros Foredeep) since the Late Pliocene (Lees and Falcon, 1952; Lees, 1955; Falcon, 1974; Vita-Finzi, 1979). Holocene uplift rates of 1.8–6.6 mm/yr, indicate a shortening by folding of 29 mm/yr, have been obtained from the fossil shorelines in the Zagros coastal plain southwest of Bandar Abbas (Vita-Finzi, 1978).

There is a close relation between the Lower Cambrian Hormoz Salt domes and structures in the Zagros. The Salt is either intruded along deep-seated faults cutting the Lower Cambrian Hormoz Salt and the Phanerozoic sedimentary cover, or it cuts the anticlinal axes. Most of the anticlines in the Zagros, especially those in the Fars arc east of the Kazerun–Borazjan transverse strike-slip active fault (and the boundary fault planes, or thrust faults cutting the southwestern inverted limbs of anticlines), are pierced by salt domes or have unbreached salt domes. This geometry may indicate that the Zagros anticlines are cored by active blind faults, which facilitated the salt migration into cores of anticlines (Falcon, 1961, 1969, 1974; Huber, 1977; Jackson et al., 1981).

Seismological and paleogeographic observations in the Zagros are consistent with shortening and imbrication of the metamorphic basement by the reactivation of old normal faults as thrust faults along the previously thinned passive continental margin of the underthrusting Arabian plate coupled with the vertical expansion (folding and uplifting) of the Phanerozoic sedimentary cover (Jackson, 1980; Jackson et al., 1981; M. Berberian, 1981; 1983; Jackson and McKenzie, 1984; Ni and Barazangi, 1986).

Reliable fault plane solutions and focal depths of the earthquakes in the Zagros using long-period WWSSN P-waveforms show that most earthquakes occur on high-angle thrust faults (40–50°) at centroid depths of 8–12 km in the uppermost part of the metamorphic basement beneath the Hormoz Salt and the top sedimentary cover on large number of faults distributed across the belt that are concealed by the folded shallow sedimentary cover (McKenzie, 1972; Jackson, 1980; Jackson and Fitch, 1981; Kading-Cade and Barazangi, 1982; Jackson and McKenzie, 1984; Ni and Barazangi, 1986). No focal mechanism indicating slip along a shallow-dipping detachment surface has been obtained from the Zagros; if slip takes place between the metamorphic basement and the top sedimentary cover above the Lower Cambrian Hormoz Salt, it should therefore be aseismic. The slip vectors indicate consistent motion at azimuths of north to northeast (30–40°) (Jackson and McKenzie, 1984). Despite the argument developed by Kidder and Duncan (1992), no evidence of intermediate earthquakes with depths ranging from 30 to 100 km and brittle deformation in the upper mantle, associated with lithospheric delamination, has been found in the Zagros.

As it was before the Coalinga earthquake of 1983.05.02 in the USA, earthquake hazard estimation in Iran is still focused exclusively on the identification and study of surface faults, whereas active folds, and the faults they may conceal, remain largely unassessed in areas such as the Zagros (in southwestern Iran), Kuh Banan–Lakar Kuh (in southeastern Iran) and central Kavir (north-central Iran). A principal source of future earthquakes in the Zagros (as well as the Kuh Banan–Lakar Kuh Mountains, and the central Kavir of Iran) is basement “blind” (buried) thrusts that are intimately coupled to the development of the surface folds. Macroseismic data and morphotectonic patterns and analyses, together with topography and deep structures, are thus important data sources for assessing the long-term modes of deformation and thus the likelihood
and characteristics of future earthquakes in regions such as the basement-involved active fold-thrust belt of the Zagros.

2. Morphotectonic units of the Zagros; methodology

The present morphology of the Zagros active fold-thrust belt (Fig. 1) is the result of its structural evolution and depositional history: a platform phase during the Paleozoic; rifting in the Permian Triassic; passive continental margin (with sea-floor spreading to the northeast) in the Jurassic–Early Cretaceous; subduction to the northeast and ophiolite-radiolarite emplacement in the Late Cretaceous; and collision-shortening during the Neogene (Falcon, 1974; M. Berberian and King, 1981; F. Berberian et al., 1982; M. Berberian, 1983). The Phanerozoic top sedimentary cover of the Zagros was warped into elongate, open folds and thrusts during the Neogene collisional orogenies. Landforms in the Zagros are largely structural, and, because the folds are asymmetrical with axial planes dipping to the northeast and north, NE- and N-facing slopes are gentle whereas southwestern and southern slopes are steep and in some cases nearly vertical, overturned or faulted.

In this study the belt is subdivided from northeast to southwest into five morphotectonic units which step down as five prominent levels to the southwest with different degrees of thrusting, folding, uplift, erosion and sedimentation (Figs. 1–3). Each unit has its own characteristics and deformation style which will be discussed in the following sections. Structural geology, morpho- and seismo-tectonics of the Zagros are therefore, dominated by these five compressional uplift units which make five parallel trends south of the Main Zagros Reverse fault line (the Zagros suture, Figs. 1–3): (1) the High Zagros Thrust Belt; (2) the Simple Fold Belt; (3) the Zagros Foredeep; (4) the Zagros Coastal Plain; and (5) the Persian Gulf–Mesopotamian lowland.

The boundaries of the units in this study are
defined on the basis of: (1) surface topography and morphotectonic features; (2) style of deformation; (3) subsurface geologic–tectonic data; and (4) the regional seismicity [mainly macroseismic location of earthquakes which are more accurate than the instrumental locations; the Iranian teleseismic data have large location errors, see M. Berberian (1979) for discussion]. The crustal thickness (Dehghani and Makris, 1983, 1984; Giese et al., 1983; Snyder and Barazangi, 1986), topography, intensity of deformation (Falcon, 1961, 1969, 1974), fold amplitude, reverse fault displacement, relative shearing along the Hormoz décollement detachment and age of the folded and faulted sedimentary rocks decrease from the High Zagros and the Zagros suture (the Main Zagros reverse fault) in the north and northeast toward the Zagros Foredeep in the south and southwest (Fig. 3). Neogene and Quaternary folding in these units become younger from northeast to southwest demonstrating that the deformation front is migrating from the suture towards the foredeep (Figs. 1–3).

The five morphotectonic units of the Zagros are separated by “deep-seated and discontinuous master thrust faults” that:

(1) make asymmetric topographic patterns (prominent escarpments and topographic fronts) with special morphotectonic features (such as changes in stream sinuosity, slope, incision and profile) at the surface, indicating increased rate of Quaternary deformation along the margins of each unit;

(2) show higher rate of Quaternary deformation (terrace warping, tilting and uplifting) and asymmetric anticlines at the surface (with steeper, overturned, or thrusted flanks on the southern and southeastern side) along the margins of each unit;

(3) have higher concentrations of macroseismic regions of moderate- to large-magnitude earthquakes aligned along the hanging-wall margins of each unit at the surface;

(4) delimit the main structural style and deformation in each unit;

(5) are responsible for formation of elongated narrow marginal depressions and sedimentary basins along the foot-wall edges of each unit;

(6) are responsible for large displacements of geologic marker beds at depth along the margins of each unit; and

(7) are responsible for uplift, erosion, exposure, subsidence, sedimentation, or coverage of the Paleozoic, Mesozoic and Paleogene formations in different units (Figs. 1 and 3).

The lower Paleozoic rocks cropping out in the High Zagros Thrust Belt, are covered in the other units to the southwest (Fig. 3). Moreover, due to higher rate of uplift, deformation and erosion, the Eocene–Oligocene Asmari Formation is eroded from most part of the High Zagros Thrust Belt. The Mesozoic and Eocene–Oligocene formations exposed in the Simple Fold Belt are covered by Neogene deposits in the Zagros Foredeep (with Miocene salt tectonics) and Coastal Plain, and the latter is covered by Quaternary alluvial deposits (Fig. 3). Although earthquakes are distributed across the entire Zagros belt, seismoseimal regions of moderate- to large-magnitude earthquakes in the Zagros are localized along particular structural–geomorphological features and topographic fronts at the surface (Figs. 1–3). The deep-seated master thrust faults bordering the morphotectonic units of the Zagros are:

(1) the Main Zagros reverse fault (MZRF: the Zagros suture) and the Main Recent fault (MRF; exposed at the surface);

(2) the High Zagros fault (HZF; partly exposed at the surface);

(3) the Zagros Mountain Front fault (MFF);

(4) the Dezful Embayment fault (DEF);

(5) the Zagros Foredeep fault (ZFF); and

(6) the Zagros–Arabia boundary (southern limit of the Zagros active fold-thrust belt).

In spite of decoupling between basement and cover sediments by salt layers (along the lower and the upper detachment zones), these major basement features have major localized morphotectonic effects on the surface geomorphology and topography, and have drastic structural influence at depth. Boundary faults 2 through 5 are master blind thrusts in the Zagros that can be identified at the surface.

Segments of some of these boundary faults have partially reached the surface (therefore, are
Fig. 4. Regional neotectonic features of different segments of the active Main Recent fault (MRF) along the northeastern edge of the western Zagros active fold-thrust belt. Note right-lateral offset of the Main Zagros reverse fault (MZRF) along the Dorud, Nahavand, Sahneh and Dinevar segments of the MRF which were activated during different earthquakes of the 20th century. These segments, which offset the MZRF, show more seismic activity than the other segments of the MRF. There appear to be seismic gaps towards northwest (i.e., along the Sartakht, Morvarid and Piranshahr segments of the MRF. The top figure is the northwestward continuation of the bottom figure. See also caption for Fig. 1. Legend (for Figs. 4-14): 1 = macroseismic epicentre of historical earthquakes (mainly based on M. Berberian, 1976, 1977, 1981, 1983, 1986; M. Berberian and Tchalenko, 1976a,b; Ambraseys and Melville, 1982; this study). Only selected data related to the topics of this study are shown. 2 = ISC instrumental epicentres. 3 = relocated epicentres of the 1977 Khurgu (and 1972 Qir in Fig. 5) aftershock sequence relative to the main shock of 1977.03.21 of $M_s = 7.0$, $I_o = VIII$ (Jackson et al., 1981). The relocation pattern is positioned here by setting the Khurgu mainshock on the ISC location. 4 = meizoseismal area of earthquakes (mainly based on M. Berberian, 1976, 1977, 1981; Ambraseys and Melville, 1982; this study). 5 = italic numbers in or outside fault plane solutions are surface wave magnitudes ($M_s$); $b$ = bodywave magnitude. 6 = intensities (MMI) are given in Roman numbers. Darkened regions in fault plane solutions (Figs. 3–14) indicate compressions. The numbers with no decimals inside the fault plane solutions are focal (centroid) depths in km determined by waveform modelling. Solutions in Figs. 3–14 are from: AAN (Nowroozi, 1972); BJP (Baker et al., 1993); C (Chandra, 1984); CMT (centroid-moment tensor solution (HRVD)); JF (Jackson and Fitch, 1981); JM (Jackson and McKenzie, 1984); KB (Kadinsky-Cade and Barazangi, 1982); KM (Kim and Nuttli, 1977); M (McKenzie, 1972); NB (Ni and Barazangi, 1986); S (Shirokova, 1962) (short-period solution). For abbreviations used for the major deep-seated longitudinal reverse faults in Figs. 4–14 see Fig. 1. BA = Bandar Abbas; F = Faraghan; G = Gahkom; H = Hajiabad. For locations of Figs. 4–13 see Fig. 2.
not fully blind) and usually the Hormoz Salt is intruded along parts of them indicating the faults are deep seated, cutting at least the entire Phanerozoic section of the sedimentary cover. Despite a greater length and continuity of the master blind thrusts in the Zagros (Fig. 1), the fault segments are rarely continuous for more than 110 km, and the segments are separated by gaps at depth (corresponding to the gaps between anticline trains at the surface). These have presumably controlled the extent of rupture and the magnitude of earthquakes at depth, as well as surface geomorphic features (i.e., gaps between anticlines and lack of Quaternary deformations). Structural–stratigraphic evidence, based on the position of the geologic marker beds (James and Wynd, 1965; Falcon, 1961, 1969, 1974), demonstrates the vertical displacements along these thrust faults being more than 6 km (see cross sections in Huber, 1977; Fig. 3). By using a more detailed morpho- and seismo-tectonic investigations and analyses, evidence for more basement structures could be revealed along the belt.

2.1. The Main Zagros reverse fault (MZRF: the Zagros suture)

The MZRF indicates a fundamental change in sedimentary history, paleogeography, structure, morphology and seismicity (Figs. 1 and 3). It marks the suture between the two colliding plates of the central Iranian active continental margin (to the northeast) and the Afro-Arabian passive continental margin (the Zagros fold-thrust belt to the southwest). It has a NW–SE strike from western Iran to the area north of Bandar Abbas, where it changes to a N–S trend (Minab) and marks the boundary between the Zagros belt (to the west) and the Makran accretionary flysch and the active subduction zone (to the east) (Figs. 1–3). There is no documented surface evidence of historical rupturing or seismosismal areas of large earthquakes along the MZRF, where the seismicity of the Zagros mountains stops. However, two sets of fresh slickensides were observed and documented on the fault plane (M. Berberian, 1976, 1981).

2.2. The Main Recent fault (MRF)

The MRF (Tchalenko and Braud, 1974) is a major seismically active right-lateral strike-slip fault with a NW–SE trend which more or less follows the trace of the MZRF (Figs. 1, 3 and 4). A right-lateral displacement of 10–60 km of a geological marker bed by the Nahavand and Dorud segments of the MRF (Fig. 4) is reported in the northwestern Zagros (Gidon et al., 1974). However, an overall missing and right-lateral shift of the MZRF trace of 197 km is present in the Dorud–Nahavand region (Figs. 1 and 4). If slip began around Pliocene times (5 Ma) it yields an average slip rate of 40 mm/yr. Interestingly those segments of the MRF that right-laterally offset the MZRF (i.e., the Dorud, Nahavand, Sahneh and Dinevar segments of the MRF) produce more seismic activity than the other segments of the MRF (i.e., Sartakht, Morvarid, Marivan and Piranshahr) which show relative seismic quiescence (Fig. 4). The MRF is morphologically and structurally distinct along its entire length, and the component of right-lateral strike-slip motion between Arabia and central Iran is taking place preferentially along different segments of the MRF in western Iran (Jackson, 1992).

The mechanism of earthquakes and seismic potential of the MRF is quite different from those of the earthquakes of the Zagros fold-thrust belt. Earthquakes of larger magnitudes than those in the Zagros have taken place along the MRF. The fault ruptured almost along its length from Dinevar in the northwest (with the 1957.12.13 event, \( M_s = 6.7 \)) to Lake Gahar in the southeast (with the 1909.01.23, \( M_s = 7.4 \), and the pre-historic Lake Gahar earthquakes) in a series of large earthquakes from 1909 to 1963 (Fig. 4).

2.3. The High Zagros thrust belt

The High Zagros is a narrow thrust belt up to 80 km wide, with a NW–SE trend between the MZRF (the Zagros suture) to the northeast and the High Zagros fault (HZF) to the southwest (Figs. 1–10). The High Zagros has the highest rate of topography, uplift and rainfall. It reaches elevations of 4000 m and contains higher moun-
tains and deeper exposures (with lower Paleozoic outcrops in the cores of thrusted anticlines) than the other morphotectonic units of the Zagros Mountains. The belt is strongly dissected by numerous reverse faults and is upthrusted to the southwest along different segments of the High Zagros fault (Figs. 1–10).

The High Zagros is characterized by extensively deformed overthrust anticlines mainly composed of autochthonous Jurassic–Cretaceous outcrops with Paleozoic cores along the reverse faults, allochthonous Jurassic–Cretaceous limestone of the Bisutun seamount, obducted Upper Cretaceous radiolarite-ophiolite nappes, Upper Cretaceous to Eocene–Oligocene flysch and longitudinal reverse faults. The belt was affected by the Late Cretaceous (subduction) and the Pliocene (continent–continent) collisional orogenies (Stocklin, 1968; Falcon, 1969, 1974; Huber, 1977; M. Berberian, 1976, 1977, 1981, 1983; M. Berberian and King, 1981; F. Berberian et al., 1982).

2.4. The High Zagros fault (HZF)

The HZF (the southern boundary of the thrust zone of M. Berberian and Tchalenko, 1976a,b) separates the thrust belt of the High Zagros (in the northeast) from the Simple Fold belt (in the southwest) (Figs. 1–3). The High Zagros is upthrusted to the southwest along discontinuous different segments of the HZF (Figs. 3, 5–10; M. Berberian and Qorashi, 1986). The geological evidence based on the present position of the Paleozoic and deeper exposures (with lower Paleozoic outcrops in the cores of thrusted anticlines) than the other morphotectonic units of the Zagros Mountains. The belt is strongly dissected by numerous reverse faults and is upthrusted to the southwest along different segments of the High Zagros fault (Figs. 1–10).

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Fig. 6. Regional neotectonic features of the western Fars province of the Zagros active fold-thrust belt. PPPP shows location of the lower Paleozoic core along the Surmeh thrust anticline, west of Qir. Relocated epicentres of the 1972.04.10 Qir ($M_s = 6.9$, $I_o = IX$) and the 1968.09.14 Tang-e-Ra'in and Mobarakabd ($M_s = 5.9$, $I_o = VII^{+}$) sequence (small circles) relative to the main shock of 1972.04.10 is after Jackson and Fitch (1981), and Jackson et al. (1981). As with fig. 7 in M. Berberian (1981), the relocation pattern is positioned here by setting the 1968.09.14 event over the localized damaged zone. Both buried thrusts of Lar and Beriz are associated with Hormoz Salt domes at Kuh-e-Gach (Gypsum Mt.) southeast of Lar (few kilometres south of the 1911 epicentre), and Kuh-e-Parak–Dehkuveh (southwest of the 1677 epicentre to the eastern area between meizoseismal regions of the 1960 and the 1970 earthquakes). See also captions for Figs. 1 and 4.

Phanerozoic rocks (Huber, 1977) demonstrates the vertical displacement along the HZF to be more than 6 km (Fig. 3). The Hormoz Salt is intruded along different segments of the HZF, reaching the surface. This indicates that the HZF is a deep-seated fault, cutting the Lower Cambrian Hormoz Salt horizon, and its activity extends through the Phanerozoic sedimentary cover (M. Berberian, 1981).

Wedging of the post-Asmari deposits (Miocene Gachsaran evaporites together with the Lower Miocene to Pleistocene Aghajari–Bakhtiar syn-
orogenic molasse) towards the High Zagros (James and Wynd, 1965; Falcon, 1974; Huber, 1977), suggest uplift of the High Zagros along the HZF since the Early Miocene, contemporaneous with the relative subsidence of the Zagros Foredeep and southward migration of the Zagros basin and deformation.

In the Khurgu area, north of Bandar Abbas (the southeastern Zagros), the HZF reaches the Mountain Front fault (MFF, Figs. 3 and 5) and it

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Fig. 7. Regional neotectonic features of the Kazerun–Borazjan, Kareh Bas, Sabz Pushan and Sarvestan transverse right-lateral strike-slip faults in the western Fars province of the central Zagros. Centroid depths (Baker et al., 1993) are added to the Harvard centroid moment tensor (CMT) solutions. See also captions for Figs. 1 and 4. K = Kazerun; Sh = Shiraz.
follows the 1000–1500 m contours at the surface. To the northwest of this intersection (Fig. 5), it diverges from the MFF and becomes parallel to the Zagros suture (MZRF) following the 1500 and 2000 (northwestern Darab, Figs. 5–7) to 3000 m (Dena) contours (Fig. 8). Presumably, the southeastern segments of the HZF were associated with several earthquakes (see Fig. 5). The northern and northeastern nodal planes of the fault plane solutions of these events, are consistent with strike and dip of segments of the HZF (Fig. 5), but very few of these fault-plane solutions have been constrained by SH waves. The ISC epicentre of the 1970.02.28 earthquake ($M_s = 5.2$, $M_b = 5.5$, Figs. 5–11) is located near the Faraghun segment of the HZF, but the fault-plane solution (Jackson and McKenzie, 1984) yields a nearly E–W trend. Apparently, this event took place in the Simple Fold Belt near the HZF (Fig. 11). Fault-plane solution of the Sarchahan earthquake of 1974.12.02 (M. Berberian and Tchalenko, 1976b) yields nodal planes (Jackson and McKenzie, 1984; Chandra, 1984) that neither match with the HZF, nor with the structures in the Simply Fold Belt (Fig. 5). The first nodal plane (dipping southwest) is roughly parallel to

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**Fig. 8.** Regional neotectonic features of the Behbahan–Dena region of the Zagros Mountains. Note the right-stepping of the MFF and the ZFF towards the west. The normal centroid moment tensor (CMT) solution (HRVD) of the 1985.03.27 ($M_b = 5.2$, $M_s = 4.6$) earthquake with $h = 83$ km (ISC $h = 41$ km, NEIC $h = 53$ km; number of observations, ISC = 308, NEIS = 198) is doubtful. See also captions for Figs. 1 and 4.
2.5. The Simple Fold Belt

The Simple Fold Belt of the Zagros (Figs. 1 and 3) is limited to the northeast by the High Zagros fault (HZF) and to the southwest by the Mountain Front fault (MFF). It has an average width of about 250 km to the southeast (Fig. 5), 120 km to the northwest (Figs. 9 and 10), and a length of 1375 km in Iran. The belt is only 50–60 km wide in the Bakhtiar Mountains (the Bakhtiar culmination) with more thrusting and tight folds, shorter wavelengths and steeper surface slopes (Fig. 9).

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The HZF but it dips southwest and the slip vector is not in the N- to NE-striking overall regional slip vector of the Zagros.

Except for two earthquakes in 1865 (Daryan, 260 km NW of Furg) and 1894 (Kherameh, 225 km nNW of Furg, Fig. 7), there is a gap in seismicity of about 440 km along the HZF from the epicentral region of the Furg earthquake of 1990.11.06 (Ms = 5.7) in the southeast (Fig. 5) to the 1934.03.13 (Ms = 5.3), the 1975.05.09 (Ms = 4.9), the 1975.09.21 (Ms = 5.2) and the 1989.10.01 (Mb = 5.2) earthquakes along the Dena segment of the HZF to the northwest (Figs. 5–8).

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Fig. 9. Regional neotectonic features of the Khuzestan–Bakhtiar region of the Zagros Mountains. Right-stepping and left-stepping of the MFF is clear in the east and the west, respectively. The Zagros Foredeep in Khuzestan (west) is widened and the Simply Fold Belt at Bakhtiar (centre) is shortened. Meizoseismal regions of at least six earthquakes are located along the Ardal deep-seated reverse fault with Hormoz Salt intrusion in the High Zagros. The normal centroid moment tensor (CMT) solution (HRVD) of the 1985.03.27 (Mb = 5.2, Ms = 4.6) earthquake with h = 83 km (ISC h = 41 km, NEIC = 53 km; number of observations: ISC = 308, NEIC = 198) is doubtful. See also captions for Figs. 1 and 4. B = Borujen; DP = Dopolan; G = Gandoman; Go = Gotvand; Gz = Gazulak.
The Simple Fold Belt contains huge, elongated hogback or box-shaped anticlines, penetrated by salt plugs from the Hormoz Salt in the Zagros mountainous terrain where calcareous ranges of the Eocene–Oligocene Asmari Limestone and Mesozoic formations dominate the topography. Structures are NW–SE trending in Lorestan and Fars, E–W trending in Larestan, and ENE–WSW trending in the northern Bandar Abbas area (Figs. 1–3).

The sedimentary column in the belt is estimated to be up to 12 km thick (James and Wynd, 1965; Falcon, 1974; Huber, 1977); it includes most of the Phanerozoic without visible angular unconformities. The belt was folded during Miocene–Pliocene continent–continent collision. The Cambrian–Miocene strata were folded competently (into open folds), while the Miocene Gachsaran Evaporites have been affected by flowage and diapirism producing disharmonic folding. The Hormoz Salt and the Miocene Gachsaran Evaporites have facilitated décollement in the lower and the upper parts of the Phanerozoic sedimentary cover (Stocklin, 1968; Falcon, 1961, 1969, 1974; Huber, 1977; M. Berberian, 1976, 1977, 1981, 1983).

Fig. 10. Regional neotectonic features of the Ilam–Lorestan province of the Zagros Mountains. Both the \textit{MFF} and the \textit{ZFF} have a right-stepping pattern towards the Karkuk Embayment near the Iran–Iraq border in the west. Inset is the westward continuation of the figure in northern Iraq (historical earthquakes of this area are taken from Ambraseys, 1988, 1989). See also captions for Figs. 1 and 4.
The Qir earthquake and the thrusted Surmeh Anticline

Based on the occurrence of five destructive to damaging earthquakes along strike (with no surface faulting), together with an aftershock sequence and the fault-plane solutions, M. Berberian (1981) suggested existence of the “Qir basement fault”, which lies along the transition zone between the Lower Miocene Razak red beds to the north and northeast, and the Miocene Gachsaran Evaporites to the south and southwest (Figs. 6 and 12). The 1985.02.02 Fathabad (southeastern Qir) earthquake is the most recent event that took place in the Qir region (Fig. 12).

It is of great interest that the meizoseismal regions of these six earthquakes closely follow the eastern extension of the Surmeh anticline with a southern thrust limb and lower Paleozoic core (which is the only exposure of Paleozoic rocks in the entire Zagros Simple Fold Belt from the Strait of Hormoz to northern Iraq) thrust southward over the Pliocene Bakhtiari conglomerate (Fig. 12). The anticlinal axes plunge eastward (towards Qir) and together with this plunge, the elevation of the Surmeh Mountains decrease to about 1000 m (Fig. 6). Towards the west, the elevation of the Surmeh Mountains increases about 2000 m, and the thrust fault together with

![Fig. 11. Regional neotectonic features of the Khurgu region in the southeastern Zagros. Anticlinal axes are shown by thin lines with arrows showing the plunge of the folds. Note the easternmost aftershock of the Khurgu sequence (1977.03.24, $M_b = 5.3$) which shows NW–SE-trending nodal planes following the HZF trend; this is different from the E–W-oriented nodal planes of the sequence (1977.03.21a,b, 22, 23, 24). Note left-stepping of the MFF towards the HZF in the east. Although meizoseismal regions of earthquakes show a N–S trend, they are located along the MFF and the ZFF where both converge. See also captions for Figs. 1 and 4.](image-url)
the lower Paleozoic core appear at the surface by approaching the Kareh Bas right-lateral transverse fault (Figs. 6 and 12). The prominent escarpment and topographic drop is clearly visible on the ground, aerial photographs and satellite imagery.

Although the longest individual anticline exposed in the Zagros, the Kabir Kuh (the Great Mt.) anticline, has a length of more than 200 km (Fig. 10), it is not proposed that the Qir blind thrust continues over hundreds of kilometres (M. Berberian, 1981). If it continues to the east or west, there should be several discontinuous segments with gaps. The two Farashband earthquakes of 1976.04.22 ($M_b = 5.9$) and 26 ($M_b = 5.2$), took place to the west of the Kareh Bas right-lateral strike-slip fault, were possibly originated along the western displaced segment of the Surmeh–Qir fault (Fig. 12).

2.6. The Mountain Front fault (MFF)

The MFF [approximately the mountain front flexure of Falcon (1961) and the Mountain Front of M. Berberian and Tchalenko (1976a,b)], which delimits the Zagros Simple Fold Belt and the Eocene–Oligocene Asmari limestone outcrops to the south and southwest, is a segmented master blind thrust fault with important structural, topographic, geomorphic and seismotectonic characteristics (Figs. 1 and 3). It is important to note that no outcrop of the Eocene–Oligocene Asmari

![Fig. 12](image-url)
Formation and/or the Mesozoic rocks occurs southwest of this major topographic–morphologic front in the Zagros Foredeep where a thick sequence of the Miocene Gachsaran Evaporites were deposited (Fig. 3). Erosion of the uplifting Zagros Mountains northeast of the MFF (the Simple Fold Belt and the High Zagros) provided detrital material to be deposited in the Zagros Foredeep southwest of the MFF. Pronounced subsidence of the Zagros Foredeep and the Dezful Embayment (Fig. 9) with thickening of the post-Asmari deposits (Neogene Gachsaran Evaporites and the Aghajari–Bakhtiari synorogenic molasse) provides evidence of relative motion along the MFF and the Dezful Embayment fault since Early Miocene times. The geological evidence, based on the present position of the top of the Eocene–Oligocene Asmari Formation, from stratigraphic, seismic and borehole data (Falcon, 1974; Huber, 1977; M. Berberian, 1986, 1989), demonstrates the vertical displacement along this thrust is more than 6 km (Fig. 3).

Due to vertical motion along the MFF, the southwestern edge of the Zagros Simple Fold Belt is being uplifted mainly along the underlying MFF and the frontal asymmetric surface folds over it. The evidence is provided by terraces related to the incised river system. Terraces of the Karun River rise to a considerable height above the present flowing level of the river. Active reverse motion and uplift along the MFF is the main cause of the remarkable incisions and changes in stream sinuosity and slope made by the Karun and other major rivers, which cut across many bedrock structures.

The MFF is composed of discontinuous, complex thrust segments of 15–115 km long, with a total length of more than 1350 km in Iran (Fig. 1). The fault segments at depth, together with their contiguous asymmetric folds at the surface, are separated by gaps and steps in the observed topographic and morphotectonic features. They form two broad arcs in Fars (the southeastern Zagros) and Lorestan (the northwestern Zagros), and are arranged in “left- and right-stepping en échelon pattern” in the eastern and the western sides of these two arcuate patterns, respectively (Fig. 1). Because the maximum observed frontal asymmetric surface folds, which conceal contiguous segments of the MFF, are less than 115 km long, they are not likely capable of generating “great” earthquakes ($M \sim 8$).

The MFF is a master topographic front. It is marked at the surface by the 500 m contour east of the Kazerun–Borazjan transverse fault in Fars province (to the southeast, Figs. 5–7) and west of the Kabir Kuh in Lorestan province (to the northwest, Fig. 10). It follows the 1000 m contour south of the Bakhtiari culmination (north of the Dezful Embayment) between the Kazerun–Borazjan active fault to the east and the Kabir Kuh anticline in the west (Figs. 8–10). The MFF usually forms a large topographic step and follows the inverted and sheared southwestern limbs of asymmetric anticlines at the southwestern edge of the Simple Fold Belt that are cored by the active MFF.

The longitudinal MFF is displaced at least for 140 km right-laterally by the Kazerun–Borazjan active transverse fault (Fig. 7). This displacement is accompanied by about 500 m in elevation change of the surface expression of the MFF (500 m to the east vs. 1000 m to the west of the Kazerun–Borazjan strike-slip active fault). To the east of the Kazerun–Borazjan active fault (Figs. 6 and 7), the MFF with two right-stepping segments makes a great curve around the Fars arc [the western segment of this arc was introduced by M. Berberian (1981) as the “Assaluyeh basement fault”, see also Fig. 6]. In the Bandar Abbas region (Figs. 5 and 11) it is truncated by the southeastern segment of the HZF in the Khurgu area where the 1977.03.21 earthquake ($M_s = 7.0$) and its aftershock sequence took place (M. Berberian and Papastamatiou, 1978).

Apparently, the Khurgu sequence with E–W-oriented nodal planes (Jackson and Fitch, 1981; Jackson and McKenzie, 1984), which took place along the southeastern segment of the MFF, triggered the aftershock of 1977.03.24 ($M_b = 5.3$) with a NW–SE-oriented nodal plane, parallel to the HZF (Fig. 11).

Study of the meizoseismal areas of the moderate- to large-magnitude earthquakes along different segments of the MFF (Figs. 5–11) shows that the studied earthquakes concentrate at breaks in the fold trains at the surface, i.e., earth-
Quakes appear to nucleate near the gaps in basement faulting along different segments of the MFF bordering these fold trains. Examples are 1052 (Ms ~ 6.8, Fig. 8), 1883.10.05.- (Ms ~ 5.8, Fig. 8), 1929.07.15 (Mb = 6.5, Fig. 9), 1950.01.19 (Ms = 5.5, Fig. 6), 1954.08.20 (Io = VII, Fig. 6), 1978.12.14 (Ms = 6.2, Fig. 9; M. Berberian, 1986, 1989), 1988.03.30 (Ms = 5.7, Fig. 8) and 1991.11.04 (Mb = 5.4, Fig. 8) earthquakes. Apparently ruptures nucleate near the gaps and propagate away from them (see, for example, M. Berberian et al., 1984).

A single case of migration of activity is documented along the MFF. The Genu earthquake of 1977.01.05 (Mb = 5.5, Io = VII, Fig. 11) took place along the eastern extremity of the Genu segment of the MFF. Seventy-six days after this event, the Khurgu earthquake of 1977.03.21 (Ms = 7.0) took place along the Khurgu segment of the MFF which is located to the northeast of a small gap with a left-stepping offset between Genu and Khurgu (Fig. 11).

Fault-plane solutions of earthquakes along the MFF yield nearly pure thrust faulting with nodal planes striking parallel to the trend of the regional geological structures and the MFF. The northern and northeastern planes of the mechanisms are consistent with the dip of the MFF deduced from structural and morphotectonic data (Figs. 5–11).

2.7. The Zagros Foredeep and the Dezful Embayment

The Zagros Foredeep is bounded to the northeast by the MFF and to the southwest by the Zagros Foredeep fault (ZFF), which marks the northeastern edge of the alluvial covered Coastal Plain of the Persian Gulf. The formation of the Zagros Foredeep was associated with motion along the MFF and uplift of the Simple Fold Belt (Figs. 1–3).

The Zagros Foredeep, which consists of elongate, symmetrical folds, is characterized by badlands of the Miocene Fars Group sediments (Gachsaran, Mishan and Aghajari formations), sheared off from the subsurface Eocene–Oligocene Asmari Limestone base along “décollement thrusts” in the Gachsaran Evaporites. Salt tectonics (disharmonic folding, flowage and diapirism) is an important phenomenon in the Zagros, especially in the Foredeep. Due to cover of the Eocene–Oligocene Asmari Limestone by the Miocene Gachsaran Evaporites, which forms the “upper décollement”, the major Iranian and Iraqi oilfields are located in this unit.

There is a thick sequence of the Lower Miocene to Pleistocene synorogenic molasse cover (Aghajari–Bakhtiari formations) in the belt. The growth of the Zagros Foredeep structures was coeval with deposition of the Upper Pliocene–Pleistocene Bakhtiari conglomerate (Fig. 3).

The anticlines associated with the Zagros Foredeep are still growing, and the evidence from continuous unconformities in the Pliocene freshwater sediments and folded recent gravels shows they have been active since just before the beginning of the Pliocene (Lees and Falcon, 1952; Falcon, 1961).

There are two regional saddles in the Zagros Foredeep, namely the “Dezful” (in Iran) and the “Karkuk” (in Iraq) embayments (Figs. 1, 9 and 10). The Dezful Embayment (Figs. 1, 2, 8 and 9) appears to be a discrete structural unit, with boundaries defined by the Dezful Embayment fault (DEF) to the north (Figs. 8 and 9), the Kazerun–Borazjan transverse fault to the east and southeast (Fig. 8), segments of the MFF to the northwest (Figs. 9 and 10) and the Zagros Foredeep fault (ZFF) to the southwest (Fig. 1). It was a sedimentary basin with pronounced subsidence and thickening of the post-Eocene–Oligocene Asmari deposits in the Zagros Foredeep at the foot of the uplifting Simple Fold Belt. The vertical drop of the basin of the Lower Miocene–Pliocene Aghajari Formation (Huber, 1977) is more than 3 km in the Dezful Embayment.

The rocks within the Dezful Embayment are considerably less folded than those north of it, and the embayment appears to have acted as a “semiresistant buttress” while the Simple Fold Belt ‘flowed’ around, and to some extent over it. The magnetic basement in the Dezful Embayment is very deep; it lies a depth probably between 8 and 15 km (Morris, 1977).
The Dezful Embayment fault (DEF)

The DEF, which forms the northern boundary of the Dezful Embayment (foreland basin of the Neogene molasse of the Aghajari–Bakhtiari formations), is located in the area between the MFF and the Zagros Foredeep fault (ZFF). It roughly follows the 500 m contour (Figs. 1, 2, 8 and 9). Based on geological evidence of the top of the Miocene Gachsaran Formation (Huber, 1977), the vertical displacement along the DEF is more than 3000 m.

Two earthquakes of 1977.06.05 ($M_s = 5.8$; $h = 12$ km) and 1985.09.18 ($M_s = 5.2$) with thrust mechanism (Fig. 9) seem to be associated with reactivation of the DEF at depth.

2.8. The Zagros Foredeep fault (ZFF)

The ZFF separates the Zagros Foredeep (to the north and northeast) from the Zagros Coastal Plain (in the south and southwest). It forms the northeastern edge of the alluvial covered Coastal Plain of the Persian Gulf (Figs. 1–3) and is principally a reverse-slip system.

As with the MFF, the ZFF is a discontinuous line and is roughly parallel to the MFF at an altitude of a few hundred metres above sea level to sea level (Figs. 5–10). It is displaced for about 150 km right-laterally by the Kazerun–Borazjan active fault (Fig. 7). As with the MFF, the displacement was accompanied by increasing elevation of the surface expression of the ZFF in the area west of the Kazerun–Borazjan active fault (Fig. 7). In this area the ZFF constitutes the southwestern limit of the Dezful Embayment (Figs. 8 and 9) and is expressed at the surface by segments of thrust faults cutting the southwestern inverted limbs of anticlines, such as the Ahwaz. Earthquakes associated with reactivation of this covered fault are indicated in Figs. 5 through 11.

2.9. The Zagros Coastal Plain

The Zagros Coastal Plain (Figs. 1 and 3) is a narrow feature bounded to the north by the Zagros Foredeep fault (ZFF) and to the south by the Persian Gulf and the Zagros–Arabia boundary, which is the southern edge of the intensely thrusted Zagros folds. The Coastal Plain slopes very gently to the south at a rate of 1 m per 5 km between Ahwaz (Fig. 9) and Khoramshahr near the Iraqi border.

2.10. The Persian Gulf–Mesopotamian lowland

This morphotectonic unit lies south and southwest of the Zagros Coastal Plain and is partly covered by the Persian Gulf. The Persian Gulf (Figs. 1 and 3), with an area of about 226,000 km$^2$, 800 km long and from 185 to 115 km wide, is a shallow epicontinental sea with a tectonic origin (a foreland depression), which covers the Arabian shelf platform with water depths of less than 100 m (average depth = 35 m, maximum depth = 110 m). Some small off-shore islands in the Persian Gulf are Hormoz salt plugs, partly fringed by the Neogene clastic and marine deposits and by recent coral reefs. The larger islands near the Iranian coast are gentle anticlines (Seibold and Vollbrecht, 1969; Kassler, 1973; Ross et al., 1986).

3. Transverse active strike-slip faults

The NW–SE- to E–W-trending longitudinal Zagros folds are distorted and disrupted locally by N–S- to NNW–SSE-trending right-lateral fault zones. There are at least three major right-lateral strike-slip faults clearly cutting the Zagros folds (Figs. 1–3). These are the Kazerun–Borazjan, the Kareh Bas and the Sarvestan faults (M. Berberian and Tchalenko, 1976a). The fault zones at the surface are marked by an alignment of the Hormoz Salt plugs which have been faulted right-laterally since emplacement. The courses of transverse streams are partly controlled by these transverse strike-slip faults. As implied by Falcon (1969, 1974), the transverse strike-slip faults seem to be older inherited basement structures within the Arabian shield cutting the sedimentary cover folds in the Zagros.

3.1. The Kazerun–Borazjan active strike-slip fault

The Kazerun–Borazjan active fault (M. Berberian and Tchalenko, 1976a; M. Berberian, 1981) is located along a line marking the projected continuation of the Qatar Peninsula into Iran.
Fig. 13. Regional neotectonic features of the Kazerun (left)–Borazjan (right) transverse right-lateral active fault in western Fars of the Zagros Mountains. The map on the right is the southern continuation of the one on the left. Black patches are outcrops of the Lower Cambrian Hormoz Salt complex. $R$ and $R'$, on the minor faults in the Kazerun–Borazjan fault zone, denote right-lateral Riedel shear ($R$) and left-lateral conjugate Riedel shear ($R'$), possibly associated with the Kazerun–Borazjan active fault motion. Note right-lateral changes along the Khersan (top left) and the Fahlian (centre left) river courses crossing the Kazerun transverse right-lateral active fault. Anticlinal axes are either displaced or dragged right-laterally by the Kazerun–Borazjan fault motion. The NW–SE strike of anticlinal axes of Sarbisheh, Giskan and Chah–Rig becomes north–south, approaching the fault. Also note meizoseismal areas of the 1824 and 1986 earthquake ruptures initiated/terminated on both sides of a sharp bend along the Kazerun active transverse fault. See also captions for Figs. 1 and 4.
(Figs. 1–3, 7 and 13). It is a N–S-trending fault crossing the Zagros trend with bending, dragging and offsetting the fold axes in a right-lateral sense (Fig. 13). Cumulative right-lateral displacement of 140 and 150 km of the Zagros Mountain Front (MFF) and the Zagros Foredeep faults (ZFF) can be measured, respectively, along the Kazerun–Borazjan active strike-slip fault (Fig. 7). If slip began after deposition of the Lower Miocene Gachsaran Formation (around 10 Ma), it yields an average slip rate of 14.5 mm/yr.

The fault consists of two right-stepping segments of the Kazerun (to the north) and Borazjan (to the south) faults with a gap in between (M. Berberian, 1981). Apparently, the Kazerun–Borazjan active fault forms the effective western limit of the Hormoz Salt-intruded Zagros and is associated with two Hormoz Salt plugs (Fig. 13). This may indicate that the main Hormoz Salt basin was located east of the Kazerun–Borazjan active fault in the Fars arc of the Simple Fold Belt. The fault is clearly visible on the aeromagnetic map of the region as a sharp magnetic lineament (M. Berberian, 1985).

The Kazerun segment (M. Berberian, 1976) is a nearly N–S-trending fault situated 15 km west of Kazerun, with a surface length of about 125 km (Figs. 7 and 13). The 1986.07.12 earthquake ($M_h = 5.7$, $M_s = 5.5$ and $I_o = VII$) with a right-lateral CMT solution (HRVD) took place along the Kazerun active fault (Fig. 13; see also Baker et al., 1993). Historical earthquakes of 1824.06.02 of $I_o = VIII$ and 1891.12.14 of $I_o = VII$ (Ambraseys and Melville, 1982) took place near the Kazerun active fault (Figs. 7 and 13). The meizoseismal region of the latter shock with that of 1986.7.12 ($I_o = 5.5$, this study) lie on the Kazerun fault and have N–S orientation in line with the fault (Fig. 13). It is important to note that the 1824.6.2 ($I = VIII$) earthquake took place south of a sharp bend along the Kazerun fault, while the 1986.7.12 event took place north of this bend (Fig. 13). This may indicate that the 1824 and the 1986 ruptures presumably initiated from this fault bend and propagated southward (1824 earthquake) and northward (1986 earthquake) along the Kazerun active fault. Similar cases of changes of fault strike and rupture initiation/termination have been documented elsewhere (King and Nab-eleck, 1985; Bilham and Williams, 1985).

The Borazjan segment, with a length of about 180 km, is located south of the Kazerun segment with a right-stepping gap (Figs. 7 and 13). Due to right-lateral motion along the Borazjan segment, the NW–SE-striking anticlinal axes of Khormuj and Gisakan in the west are dragged and folded to a N–S trend and the Qaleh Dokhtar anticline between them have N–S-striking axes. The segment NW–SE-trending reverse faults are also dragged; the CMT solution of the 1990.12.16 earthquake (HRVD) in the Kalameh area (near the Siah anticline, Fig. 13) yielded NNW–SSE-oriented nodal planes indicating rotation of the basement (blind) active thrust due to the dragging effect of the Borazjan right-lateral fault. The Borazjan fault scarp is clearly visible from the area north of Borazjan to Ahram and Khormuj. Several thermal and sulphur springs are aligned at the foot of the fault scarp (Fig. 13).

3.2. The Kareh Bas strike-slip fault

The Kareh Bas fault (M. Berberian and Tchalenko, 1976a) with a total length of 160 km is situated about 65 km east of the Kazerun active fault and 35 km west of Shiraz (Figs. 1, 6 and 7). It is a nearly N–S-trending right-lateral strike-slip fault, and, like the Kazerun fault, has dragged and displaced anticlinal axes for at least 10 km. The fault is made up of at least six segments. The Kareh Bas Plain is a pull-apart depression formed along the Kareh Bas fault. Five large Hormoz salt domes were intruded along the fault. The southern segment of the Kareh Bas fault turns toward the east and forms the Surmeh thrust fault with the only exposed lower Paleozoic anticlinal core in the Simple Fold Belt (see section 2.5). No large earthquake has yet been found to be directly associated with the motion along the Kareh Bas transverse fault. The Dadenjan earthquake of 1992.09.08 ($M_b = 5.2$, $I_o = VII$) seems to be associated with the motion along this fault (Fig. 7).

3.3. The Sarvestan strike-slip fault

The Sarvestan fault (M. Berberian and Tchalenko, 1976a) with a length of about 90 km,
has a NNW–SSE strike and is roughly parallel to the Kazerun–Borazjan and the Kareh Bas transverse faults (Figs. 1, 6, 7 and 12). It is located in the eastern part of the Maharlu–Sarvestan Depression and has dragged and displaced an anticline about 20 km right-laterally. Three Hormoz salt domes were intruded along the fault.

No direct seismic evidence associated with motion along the Sarvestan fault has been found. The 1890.03.25 earthquake (M_s ~ 6.4), which was felt in Fasa (Ambraseys and Melville, 1982), may be associated with motion along the Sarvestan fault (Fig. 12).

3.4. The Sabz Pushan strike-slip fault zone

A transverse deformation zone of local NNW–SSE-trending right-lateral strike-slip (minor) faulting exists east of the Kareh Bas and west of the Sarvestan faults (Figs. 7 and 12), extending from Shiraz to east of Qir (M. Berberian and Tchalenko, 1976a). Right-lateral flexural distortion and drag of NW–SE-striking fold axes along the Sabz Pushan fault zone can be readily observed. For example, east of Qir, the Chaghal, Alhar and Bandobast anticlinal axes have been dragged right-laterally by the Sabz Pushan zone (Fig. 12). The course of the Mand River (Qara Aghaj), which is a large transverse stream that separates the Qir from the Tang-e-Ruin Valleys, seems to be partly controlled by the Sabz Pushan fault zone. The zone also locally marks the limit between the Eocene Asmari Formation facies (to the west) and the Asmari–Jahrom Formation facies (to the east).

No seismic activity associated with the Sabz Pushan fault has yet been documented, although, the mezoseismal region of the northwestern Shiraz earthquake of 1824.06.25 (M_s ~ 6.4, I_o = VIII) (Ambraseys and Melville, 1982) is elongated parallel to the northwestern extension of the Sabz Pushan transverse fault (Fig. 7).

4. Concluding remarks and discussion

In the Zagros fold-thrust belt of southwestern Iran, northern Iraq, southern Turkey and northern Syria, seismogenic basement thrust faults are concealed and hence are not easily recognizable. Seismic activity is dispersed and poor correlation exists between seismicity at depth and the geological structures on the surface. For example, the blind source zones of the two largest hidden earthquakes in the seismic history of the Zagros (the 1972.04.10 Qir and the 1977.03.21 Khurgu events of M_s = 6.9 and M_s = 7.0, respectively) were unknown before this study began (Figs. 5–7, 11 and 12).

The apparent lack of correlation between seismicity and surface geologic structure, due to the presence of ductile layers, made several attempts to assess earthquake-fault hazard study and seismic-risk evaluation in the Zagros very difficult (M. Berberian and Mohajer-Ashjai, 1977; Mohajer-Ashjai and Nowroozi, 1978; M. Berberian, 1981; Y. Bozorgnia and Mohajer-Ashjai, 1982; Mohajer-Ashjai and Bozorgnia, 1984; Burton et al., 1984; Mohajer-Ashjai, 1985; Moinfar et al., 1987). Despite lack of detailed deep-crustal knowledge, geodetic survey, precise epicentre/hypocentre locations and seismic reflection studies in the Zagros, topographic–morphotectonic features and patterns of surface folds and faults, coupled with the mezoseismal regions of moderate- to large-magnitude earthquakes, and displaced marker beds at depth are used herein to define the approximate location and geometry of the major basement (blind) seismogenic faults (Fig. 14). These faults are marked by the Phanerozoic folded sedimentary cover, but have a distinct effect at the surface morphotectonics and topography, and major displacement at depth. Despite evaporite layers at the Lower Cambrian Hormoz and the Miocene Gachsaran horizons (the lower and the upper detachments), a tentative correlation can now be made between the surface structures, topography, macroseismic pattern and some major basement active faults in the Zagros (Fig. 14). Seismic slip along the basement (blind) faults has produced coseismic uplift and folding of Quaternary deposits and surfaces in the belt.

Quaternary and coseismic deformation in the continuously deforming orogen of the Zagros is dominated by basement (blind) longitudinal thrust
Fig. 14. Map of the proposed active basement (blind) longitudinal thrusts (with sawteeth), the basement-surface transverse active strike-slip faults and the longitudinal active Main Recent fault, with focal mechanism solutions and macroseismic regions of moderate- to large-magnitude earthquakes in the Zagros active fold-thrust mountain belt of southwestern Iran. Only selected fault plane solutions and seismogenic faults related to the topics of this study are shown. $B$ = Beriz, $L$ = Lar, $Q$ = Qir buried faults. Abbreviations as in Figs. 1 and 4. For sources and more explanations see Figs. 1-13 and the text.
and transverse right-lateral active faulting (with surface rupture). The crustal shortening in the Zagros shows transfer of strain from predominant longitudinal pure thrust slip to occasional transverse pure right-lateral slip. The nodal planes of the fault plane solutions of the Zagros earthquakes (Fig. 14) are parallel to the regional anticlinal axes at the surface and deep-seated (blind) longitudinal thrust faults (except for the transverse strike-slip active faults) with linear Hormoz Salt intrusions along them. This pattern presumably proposes that the asymmetric longitudinal anticlines of the Zagros are cored by longitudinal active basement (blind) thrust faults, and that part of their growth with Quaternary deformation can be explained by repeated motion on these basement faults during hidden earthquakes. Seismic slip on basement thrust faults in the Zagros have produced the asymmetric surface folds and Quaternary deformation, but neither the presence of such covered faults, nor the seismic potential had been demonstrated. Unfortunately, the ages and detailed allostratigraphic units of the youngest folded strata and thus the shortening and uplift rates across the active anticlines of the Zagros are not clear. Therefore, we can not assign the slip rates on the concealed basement thrust faults in the Zagros at the present time. Detailed Quaternary stratigraphy, morpho-neoseismo-tectonic studies, morphometric analyses and construction of retrodeformable cross sections will help identify areas of increased late Quaternary deformation at the surface and assess the patterns and rates of deformation (long-term average slip rate for each blind thrust) in this active and young fold-thrust mountain belt. The asymmetry of the Zagros anticlines (with steeper or inverted southwestern flanks), with the dip of the deep-seated boundary faults, favour interpreting active basement (blind) reverse faults in the Zagros having a dip to the northeast and north (Fig. 14). The anticlinal mountains and hills in the Zagros are therefore propagating into the synclinal depressions and valleys toward the south and southwest.

Regarding the nucleation sites of the earthquakes along the buried thrusts, it has been observed that some earthquakes were controlled by the gaps and/or offsets between the segmented basement (blind) faults corresponding to the surface gaps in the fold trains. Therefore, these gaps and/or offsets will probably be the candidate sites for nucleation of the future events.

The plate motion model NUVEL-1 (De Mets et al., 1990) predicts an oblique component to the convergence between Arabia and Eurasia in the Zagros. Apparently this oblique convergence is partitioned into pure thrusting along the longitudinal blind basement faults and pure right-lateral strike-slip motion along the MRF and eastward motion of central Iran relative to Eurasia (Fig. 15). Moreover, the change in the strike of the active transverse strike-slip faults of the Zagros (Fig. 15) may indicate a probable rotation of these faults about vertical axes. Active deformation in the Zagros (Figs. 3, 14 and 15) is taking place by: (1) seismic thrust and strike-slip faulting in the discontinuous-frictional-seismogenic zone (~8–12 km) below the lower detachment zone/Lower Cambrian Hormoz Salt; (2) coseismic folding and thrusting of the sedimentary cover above the seismogenic zone; and (3) aseismic plastic flow in the continuous-quasi-plastic shear zone below the seismogenic zone.

The morphotectonic unit-boundary fault approach proposed in this study may be used for the estimation of maximum earthquake potential in the Zagros. This important (though not exclusive) new interpretation may show a better correlation with the seismic activity of the belt. In this case each morphotectonic unit can be considered as a separate seismotectonic unit or province within the Zagros. If this interpretation is correct, the largest earthquake that occurred somewhere along the segmented frontal blind thrusts (and the transverse active strike-slip faults), can be assessed as a credible (i.e., characteristic) earthquake that may occur along fault segments in the future. It may also be assumed that major earthquakes in the Zagros will occur along the introduced regional seismogenic faults, because they happened earlier. In this case and at this stage of knowledge, the highest seismic risk in the Zagros is confined to the introduced major segmented blind thrusts. However, much more work is needed in order to define and evaluate the seis-
mic hazard in the Zagros which is undergoing seismically active convergence causing development of a basement involved fold-thrust belt.

The proximity of these major unrecognized blind seismogenic sources to the proposed and selected nuclear power plant sites along the Persian Gulf shoreline, with the selected accelerations by multinational consulting companies during the 1970s, projects a possible regional catastrophe if the nuclear power plants had been built in the past.

The Zagros active fold-thrust mountain belt is probably the largest area on the planet Earth (400,000 km²) where continuous seismicity associated with active blind thrusting at depth is not expressed by coseismic surface rupture in the whole belt. It is therefore, the cheapest natural laboratory and the best test site on the important topic of blind thrusts and coseismic folding. This continuously deforming orogen provides an opportunity to investigate the interaction between regional-scale surficial and crustal processes in a passive margin setting. Continued studies on areas like the Zagros offers perhaps the best hope of characterizing buried faults (and their associated surface features) that might be capable of generating large-magnitude earthquakes. The blind thrust/hidden earthquake hazard is not unique to the Zagros or California; several other large metropolitan areas are situated on sedimentary basins or foreland fold-thrust belts that are bordered by, contain, or are underlain by active buried thrust faults. Unlike the extensive focus on seismogenic strike-slip faults (such as the San Andreas fault system of western California) during the last three decades, buried (blind) thrust faults, hidden earthquakes and coseismic folding are poorly studied. Therefore, little is known about the buried seismogenic faults in different basement-involved fold-thrust belts and sedimentary basins undergoing seismically active convergence. Potentially hazardous and unrecognized

Fig. 15. Summary map of the active tectonic deformation in the Zagros with relatively low and high levels of seismicity along the transverse strike-slip faulting (Kazerun, Kareh Bas, Sarvestan, etc.), and along the longitudinal basement (blind) thrusts (with sawteeth), respectively. The large open arrow shows the direction of motion of Arabia to Eurasia from De Mets et al., 1990). Inset (a) summarizes the active deformation in the Zagros. The changes in the strikes of the parallel transverse strike-slip faults in the Zagros (from K = Kazerun to S = Sarvestan) may indicate that these faults have probably been rotating about vertical axes during their seismogenic slips. Inset (b) simply illustrates the active Zagros deforming zone separating two plates of Arabia in the southwest and central Iran (southern Eurasia) in the northeast. The oblique convergence is partitioned into pure strike-slip faulting (MRF at the zone boundary) and pure blind thrusting in the belt. The active deformation is taking place by: (1) seismic reverse and strike-slip faulting in the metamorphic basement; and (2) coseismic folding and thrusting in the top sedimentary cover. The sawteeth symbols point down the dip of the thrust faults and indicate the relatively upthrown side of the fault. The oppositely directed arrows on either side of the faults denote strike-slip faulting. Abbreviations used: BR = Balarud left-lateral shear zone; EAF = East Anatolian fault; HZF = High Zagros fault; K = Kazerun fault; KB = Kareh Bas strike-slip fault; L = Lar blind thrust; M = Zagros fault at Minab; Makran S.Z. = Makran active subduction zone; MFF = Zagros Mountain Front fault; MRF = Main Recent fault; MZRF = Main Zagros reverse fault; NAF = North Anatolian fault; Q = Qir/Surme blind thrust; S = Sarvestan strike-slip fault; SP = Sabz Pushan strike-slip fault zone.
buried thrusts generating large-magnitude hidden earthquakes pose serious threat to millions of people in many parts of the world. These hidden events can cause unusually widespread damage, local amplified shaking and focusing of elastic energy, and may develop widespread secondary features related to coseismic flexural-slip folding such as widespread flexural-slip faults (bedding-plane slips with thrust or normal mechanism), bending-moment faults, conjugate faults and ground failure, particularly ground spreading and liquefaction. Moreover, portions of the shallow to surface thrusts, which ramp off the lower and/or the upper detachments, or collapse structures, can be reactivated, as was observed during the Mishan earthquake of 1972.07.02 (Fig. 8; see M. Berberian and Tchalenko, 1976a). Unfortunately, after a century of geologic mapping we are still caught by surprise when the Northridge, CA, hidden earthquake of January 17, 1994 occurred on an unrecognized buried fault in metropolitan Los Angeles. This may indicate that our programmes, policies and research with regard to earthquakes, are still on shaky ground!

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