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Seismotectonic Map of Afghanistan, with Annotated Bibliography

By Russell L. Wheeler, Charles G. Bufe, Margo L. Johnson, and Richard L. Dart

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This report has not been reviewed for stratigraphic nomenclature

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1. Abstract

A seismotectonic map shows geologic, seismological, and other information that is pertinent to seismic hazards but previously was scattered among many sources. Afghanistan is part of the Eurasian plate. Afghan seismicity is driven by the relative northward movements of the Arabian plate past western Afghanistan at 33 mm/yr and of the Indian plate past eastern Afghanistan at 39 mm/yr or faster as both plates subduct under Eurasia (fig. 1). Afghanistan is laced with faults (fig. 2). Known faults large enough to have been mapped at a scale of 1:500,000 are least abundant in the stable North Afghan platform, more abundant in the accreted terranes of southern Afghanistan, and most likely to slip rapidly and generate earthquakes in eastern and southeastern Afghanistan in the broad transpressional plate boundary with the Indian plate (fig. 3). Crustal earthquakes are most abundant in and around northeastern Afghanistan as a result of the northward subduction of the Indian plate (fig. 4). Crustal earthquakes are somewhat less abundant in much of the transpressional plate boundary with India. Central and western Afghanistan are least seismically active. Beneath the Hindu Kush of northeastern Afghanistan and the Pamirs of adjacent Tajikistan, numerous mantle earthquakes occur within a steeply dipping, northeast-trending, tabular zone that is 700 km long and extends nearly to 300 km depth (fig. 5). Except for the Chaman fault that forms part of the western edge of the transpressional plate boundary in Pakistan and Afghanistan, published evidence for or against the activity of individual Afghan faults is sparse.

2. Introduction

2.1. Seismotectonic Maps

The purpose of a seismotectonic map is to show geological, seismological, and other geophysical information together that was previously scattered and is likely to be useful to seismologists who will compute seismic-hazard maps, geologists studying possible geologic controls on earthquake occurrence, and anyone who requires an overview of the present-day tectonics (Hadley and Devine, 1974; Kaila and others, 1974; Kazmi, 1979; Haghipour and others, 1984a; Gower and others, 1985; Haghipour, 1992; Rhea and others, 1994, 1996; Wheeler and Rhea, 1994; Wheeler and others, 1994, 1997a, b; Rhea and Wheeler, 1994a, b, 1995, 1996). The present map consists of this text and the five page-sized figures that accompany it.

A seismotectonic map is not a tectonic map, largely because a typical seismotectonic map deals with information that covers much shorter time spans. There are two reasons for the shorter time spans. First, most seismotectonic maps focus on earthquake threats that might be realized within the next few decades. A standard assumption in probabilistic hazard analysis is that seismicity of the near future is likely to resemble seismicity of the recent past. The farther back into the geologic past one looks, the less likely it is that the past seismicity represents the likely seismicity of the near future. Hazard analysts look only as far back as they think the assumption of representativeness is valid. At present, the main way to test the assumption is with paleoseismological studies. Most of these studies can characterize the prehistoric record of individual large earthquakes or groups of them back to several thousands to several tens of thousands of years before the present (McCalpin and Nelson, 1996). Second, faults that have slipped earlier than the Quaternary, or perhaps even earlier than the Late Quaternary, but which have not slipped again since then, probably produce earthquakes that have an annual probability of occurrence that is too small to impact probabilistic seismic-hazard maps (Wheeler, 2002). Accordingly, a modern seismotectonic map is likely to show only those faults, geologic units, and other features that bear on the past few thousand to hundreds of thousand years.

2.2. This Map

The three different audiences for this map might find different parts of the report useful. Readers who need only a brief overview could restrict themselves to the abstract and figures. To assist this audience, the abstract cites the figures. Readers who will compute seismic-hazard maps of Afghanistan may find the main text, the figures, and perhaps Appendix 1 useful. Readers who wish to investigate geologic controls on seismicity are likely to need the entire report.

Simultaneously with production of this map, other groups of U.S. Geological Survey (USGS) scientists worked to produce an Afghan earthquake catalog, fault slip rates estimated from satellite imagery and aerial photographs, and geologic maps. Normally, all of this work would be completed before the production of a seismotectonic map and would be used in it. However, scheduling incompatibilities meant that few of these results were available in time to be incorporated into the seismotectonic map. Thus, the sets of faults and earthquakes shown on the figures here are similar to but not identical to those that will be used in the hazard computations.

A note is appropriate on the names of the main mountain ranges in the study area: the Hindu Kush, the Pamirs, and the Himalaya. According to the National Geospatial-Intelligence Agency (http://gnswww.nga.mil/geonames/GNS/, accessed May 26, 2005), the proper names are not followed by "Mountains" or "Range". The proper names stand alone. Occasionally, the adjective "Himalayan" is formed, as in "the Himalayan deformation".

3. Tectonic Setting of Afghanistan

3.1. Plate Tectonics

Afghanistan forms the most stable part of a promontory that projects south from the Eurasian plate (fig. 1; Ambraseys and Bilham, 2003; DeMets and others, 1990). West of Afghanistan, the Arabian plate subducts northward under Eurasia, and east of Afghanistan the Indian plate does the same. South of Afghanistan, the Arabian and Indian plates adjoin and both subduct northward under the Eurasian promontory. The plate boundaries west, south, and east of Afghanistan are hundreds of kilometers wide. They involve the contractional deformation of large parts of the Eurasian promontory.

More specifically, south of Afghanistan at the Makran subduction zone, the plate contact between the overriding Eurasian plate and the subducting Arabian and Indian plates crops out along a line beneath the Gulf of Oman and the Arabian Sea (fig. 1). Within the plate boundary and north of the plate contact, southwestern Pakistan and southeastern Iran, together with southernmost Afghanistan, make up a broad deformation zone of north-dipping thrust faults and associated folds that trend east (Kazmi, 1979; Shareq, 1981; Haghipour and others, 1984a, b; Hessami and others, 2003). The north-trending direction of plate convergence is nearly perpendicular to the east-trending plate contact (fig. 1). Thus, the deformation zone north of the contact includes dominantly reverse faults and associated folds, with negligible strike-slip faulting (Kazmi, 1979; Hessami and others, 2003).

In contrast, east and west of Afghanistan, the plate boundaries trend north-northeast and north-northwest, respectively. Subduction is oblique, and plate convergence is transpressional. The western plate boundary between Arabia and Eurasia is roughly a mirror image of the eastern boundary between India and Eurasia. The western boundary is entirely within Iran and largely outside the area shown on figure 1; we will not consider the western boundary further. Within the eastern boundary, upper crustal strain of the deformation zone is partitioned into a broad complex of thrust faults at and near the plate contact and a wide, north-northeast-trending belt of left-lateral, strike-slip faults farther inside the Eurasian plate (Kazmi, 1979; Sarwar and De Jong, 1979; Kazmi and Rana, 1982; Haghipour and others, 1984a). The plate contact follows the curved traces of the outermost thrust faults in Pakistan (fig. 1), and the strike-slip belt extends west as far as the left-lateral Chaman fault of Afghanistan (figs. 2, 3). The strike-slip belt contains many large, left-lateral faults that strike north and northeast, and fewer, smaller reverse faults that strike east and northeast and dip northerly (figs. 1, 2; Kazmi, 1979; Sarwar and De Jong, 1979; Kazmi and Rana, 1982).

The thrust complexes and strike-slip belts of the deformation zones that form the rim of the Eurasian promontory are all seismically active (Kazmi, 1979; Haghipour and others, 1984a; Hessami and others, 2003). In contrast, the interior of the promontory in western and central Afghanistan is much less active (fig. 4).

Figure 1 shows an estimate of the crustal stress field that results from these plate interactions. An earthquake focal mechanism contains three-dimensional estimates of the directions of greatest extension and greatest contraction at the earthquake focus. The direction of greatest contraction is a measure of deformation. In addition, it generally is taken as an approximation of the direction of greatest compressional stress (Zoback and Zoback, 1991). In the horizontal plane, the azimuth of the direction of greatest compressional stress is the greatest horizontal compressional stress $S_{H(max)}$ (Zoback, 1992). Plotting many $S_{H(max)}$ orientations on a map can reveal regions of simple or complex stress fields at earthquake depths and can identify regions of similar or different stress orientations (Zoback and others, 1989, 1991). Figure 1 shows that the crustal stress field in the vicinity of Afghanistan is fairly simple at depths of 40 km and less. The moderate to large earthquakes that yield focal mechanisms are most abundant in and near the plate boundaries in Iran, eastern Afghanistan and adjacent Pakistan, and in northeastern Afghanistan and surroundings above the northwestern corner of the subducting Indian plate.

We calculated relative plate-motion vectors from the Euler vectors of the global plate model NUVEL-1 (DeMets and others, 1990), as corrected to NUVEL-1A by DeMets and others (1994). Arabia moves northward with respect to a fixed Eurasia at 33 mm/yr, and India does the same at 39 mm/yr. DeMets and others (1990) used a site within the broad, transpressional deformation zone in southern Pakistan to characterize the relative motion of the Indian plate. If significant transform slip occurs east of the site, then the velocity of 39 mm/yr would underestimate the relative motion of India with respect to Eurasia.

3.2. Present-day Differences in Crustal Ages and in Faulting

Afghanistan, north of the Hari Rod fault and west of the Central Badakhsan fault, comprises the North Afghan platform (figs. 2, 3; Turan platform of Shareq [1981] and Tapponnier

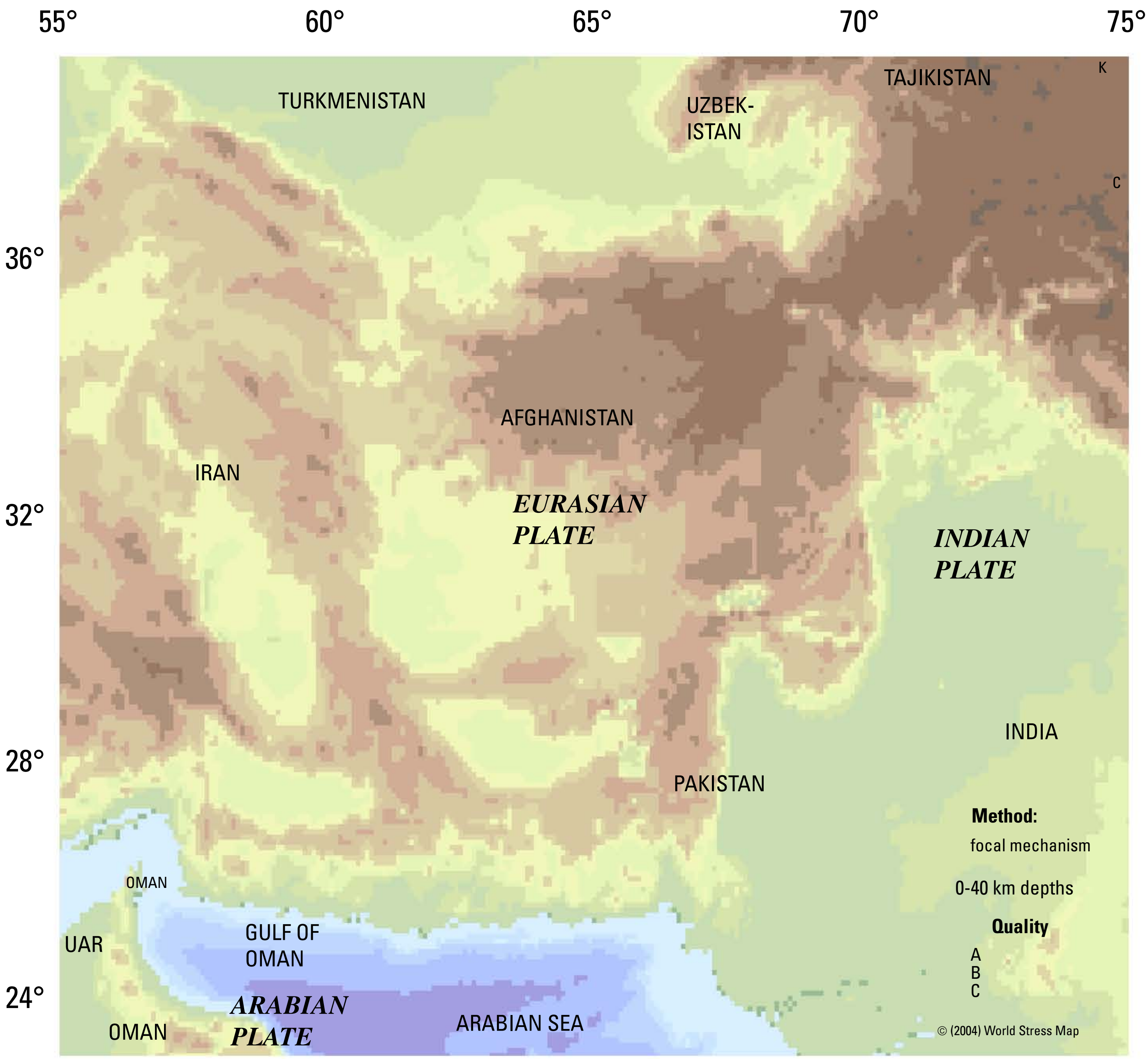

Figure 1. Plate tectonics of Afghanistan. Short blue and green lines with dots show local orientations of greatest horizontal compressive stress. Stress orientations were calculated from focal mechanisms of shallow earthquakes (depths 40 km or less); the focal mechanisms are not shown here. Faulting is overwhelmingly strike slip (green with half-open dots) or reverse (purple with solid dots) in this contractional environment. Eleven scattered stress orientations for normal faulting were deleted as local anomalies. Line length indicates quality of the orientation, decreasing from A to C according to the criteria of Zoback (1992). Thick gray lines show outcrops of plate contacts (see text section 3.1). Thinner black lines represent international boundaries. Abbreviated country names in the northeast and southwest corners of the map: C, China; K, Kyrgyzstan; UAR, United Arab Emirates. Elevation increases from yellow-gray near sea level through yellow to dark brown. Darkest brown areas exceed approximately 3 km in elevation and are as high as 6,504 m in northeasternmost Afghanistan. The Arabian plate moves northward with respect to a fixed Eurasia at 33 mm/yr, and India does the same at 39 mm/yr or faster (see text section 3.1). The figure was modified slightly from a map made and downloaded during February, 2005 from the web site of the World Stress Map Project of the Heidelberg Academy of Sciences and the Geophysical Institute of the University of Karlsruhe (http://www-wsm.physik.uni-karlsruhe.de/). Mercator projection.

and others [1981]; Tadjhik platform of Treloar and Izatt [1993]). The platform basement of metamorphic and igneous rocks was developed during the Carboniferous-Permian Hercynian orogeny and the basement has been comparatively stable since then (Shareq, 1981; Tapponnier and others, 1981). A cover sequence of Mesozoic and Tertiary strata overlies the basement, is as thick as 6 km at the Afghan border, and thickens northward to as much as 16 km (Brookfield and Hashmat, 2001). The cover sequence hosts the mature Amu-Dar'ya gas-oil province of Turkmenistan and Uzbekistan (Kingston and Clarke, 1995). Most faults within the platform strike west or west-northwest and lack significant offset (Brookfield and Hashmat, 2001). Petroleum traps are in folds that are thought to overlie reactivated basement faults.

Mapped faults on the platform are more numerous near its southern and eastern edges than within its interior (figs. 2, 3). However, geologic and tectonic maps show that the Precambrian and Paleozoic basement rocks of the platform are exposed throughout this belt of numerous faults, from northernmost Afghanistan southwest to approximately longitude 67° E (Shareq and Chmyriov, 1977; United Nations Economic and Social Commission for Asia and the Pacific, 1995). Apparently, the belt of more numerous faults is an artifact of exposure, not an indication of greater deformation.

In contrast to the platform, the evolution of Afghanistan south and east of the platform was dominated by collisions of Gondwanan fragments with Laurasia that began during the Mesozoic Era and which continue today in the form of Indian subduction (Exxon Production Research Company, 1985; Haghipour and others, 1984b; Wittekindt and others, 1997). Shareq (1981) showed igneous rocks immediately south of the Hari Rod fault and Exxon Production Research Corporation (1985) interpreted them as ophiolites. The presence of ophiolites implies subduction of oceanic or marginal basin crust beneath the continental crust of the North Afghan platform. Sengor (1984, p. 29, 51) interpreted these relations and many others to conclude that the subducted oceanic crust underlay an early part of the Tethyan Ocean and was subducted during late Early Carboniferous to Triassic time. The rifting that initiated this part of the Tethyan Ocean must have predated subduction of the oceanic crust. Presumably, the rifting postdated the Carboniferous-Permian orogeny that formed the North Afghan platform.

Sengor (1984) noted that continued subduction and final closure of the Tethyan Ocean produced the widespread Mesozoic Cimmerian orogeny. South and east of the platform, Afghanistan is laced with hundreds of faults that are large enough to be mapped geologically at a scale of 1:500,000, except where the faults are covered by young Quaternary and some Pliocene strata, as in southwestern Afghanistan (figs. 2, 3) and adjacent Iran and Pakistan (Chmyriov and Mirzad, 1972; Kazmi and Rana, 1982; Exxon Production Research Company, 1985; Shareq and Chmyriov, 1977). Crustal fragments south of the Hari Rod fault and east of the Central Badakhsan fault, but northwest of the Chaman and Konar faults (fig. 2), rifted away from Gondwana before India did, crossed the Tethyan Ocean, and accreted to Eurasia before India did, during the Cimmerian orogeny (Treloar and Izatt, 1993). Fragments accreted successively southward and most or all subduction zones dipped north (Tapponnier and others, 1981). Additional fragments accreted east of the Chaman and Konar faults until the arrival of India (Wittekindt and others, 1997).

The Hari Rod fault (figs. 2, 3) was reactivated in transtension during Oligocene-Miocene time, and most large faults south of the Hari Rod fault were reactivated during the Tertiary Period in strike slip (Treloar and Izatt, 1993). Today, the 20-to-60 km-wide zone between the Hari Rod fault on the north, and the Qarghanaw, Bande Bayan and Onay faults on the south, contains what Shareq (1981) regarded as the most structurally complex rocks in Afghanistan. He named these rocks the "Middle Afghanistan geosuture zone" (his pl. 1). Fault bounded, lens-shaped rock masses trend roughly east throughout Middle Afghanistan (fig. 3). This fabric strongly indicates considerable strike slip, and Brookfield and Hashmat (2001) reported that Paleozoic rocks are displaced right laterally by about 600 km across the Hari Rod fault.

Despite the original north dip of most or all of the Afghan subduction zones, most large faults within the accreted terranes now dip steeply (Tapponnier and others, 1981). Tapponnier and others attributed the steep dips to dominant strike slip and possible north-south shortening. Wolfart and Wittekindt (1980), Treloar and Izatt (1993), and Brookfield and Hashmat (2001) together showed seven cross sections across the Hari Rod fault. The cross sections show numerous thrust faults, most of which dip south, opposite the original dip direction of the subduction zone. Thus, modern fault dips may not be reliable indicators of the crustal-scale geometries of the Afghan subduction zones. We have found no cross sections of the Afghan crust in which fault dips are constrained by modern analyses of adequate seismic-reflection, refraction, and potential-field data.

4. Earthquakes

Figures 4 and 5 show the map distribution of Afghan and nearby earthquakes within two depth ranges that correspond roughly to crustal (fig. 4) and mantle seismicity (fig. 5). The Afghan earthquake catalog used for the figures is an early version of the catalog that USGS and USGS-funded seismologists are compiling (E. Bergman, oral and written communs., February 25, 2005). The preliminary catalog includes magnitudes of various types. We clipped the catalog to the boundaries of figures 2–5 and excluded all earthquakes smaller than magnitude 4.0. The preliminary catalog should not be used to compute hazard or identify active faults.

Figures 4 and 5 show several well-known aspects of Afghan and nearby seismicity (for example, Haghipour and others, 1984b; Quittmeyer and Jacob, 1979; Ambraseys and Bilham, 2003). At crustal depths, seismicity is concentrated in

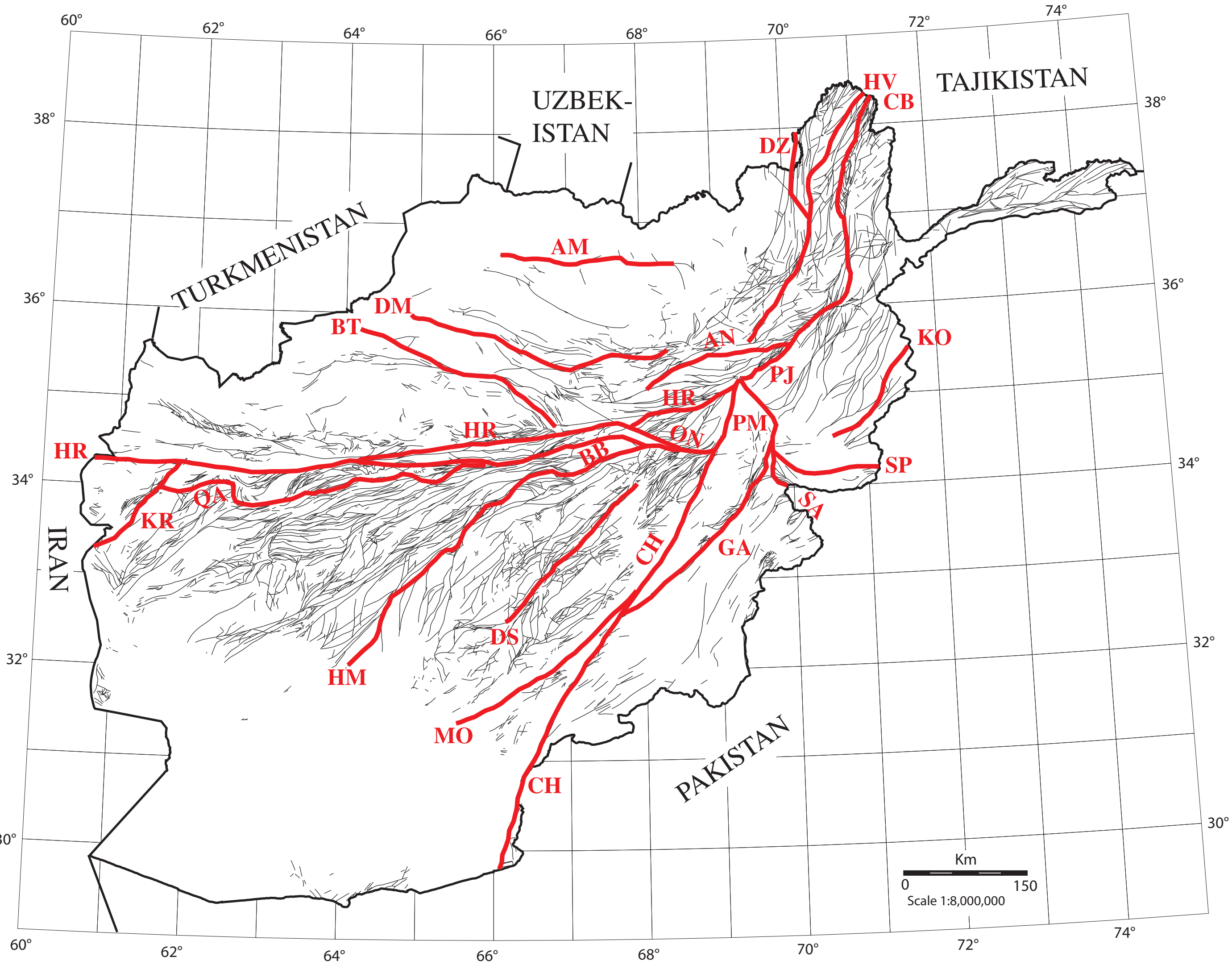

Figure 2. Locations of faults that are named in the text and Appendix 1 (red). Fault traces from USGS-funded digitization of the geologic map of Shareq and Chmyriov (1977) (black). Abbreviations of fault names: AM, Alburz Marmul; AN, Andarab; BB, Bande Bayan; BT, Bande Turkestan; CH, Chaman; CB, Central Badakhsan; DS, Darafshan; DZ, Darvaz; DM, Dosi Mirzavalan; GA, Gardez; HR, Hari Rod; HM, Helmand; HV, Henjvan; KR, Kaj Rod; KO, Konar; MO, Mokur; ON, Onay; PM, Paghman; PJ, Panjshir; QA, Qarghanaw; SA, Sarobi; SP, Spinghar (see text section 3.2). Transverse Mercator projection with scale factor 0.999600 at central meridian 66° E., projection origin is 34° N., false easting and northing are zero.

the plate boundaries that are west and east of Afghanistan and in and near eastern Afghanistan (fig. 4). The greatest concentration of large and small crustal earthquakes is in and around northeastern Afghanistan beneath the Hindu Kush and Pamirs (figs. 3, 4). At mantle depths, seismicity is almost exclusively beneath the Hindu Kush and Pamirs (figs. 3, 5).

Several authors have asserted that individual crustal earthquakes, or groups of them, occurred on individual named faults whose traces are known from geologic mapping (for example, Prevot and others, 1980; Shareq, 1981, 1992, 1993). However, except for historical surface ruptures on the Chaman fault (Quittmeyer and Jacob, 1979), the evidence supporting such assertions is sparse. For example, Prevot and others (1980) conducted several microearthquake surveys near Kabul. They were unable to clearly associate earthquakes with individual known faults by using epicenters, composite focal mechanisms, or both. Prevot and others concluded that most of the seismicity was distributed diffusely throughout a large crustal volume where five large faults intersect in map view.

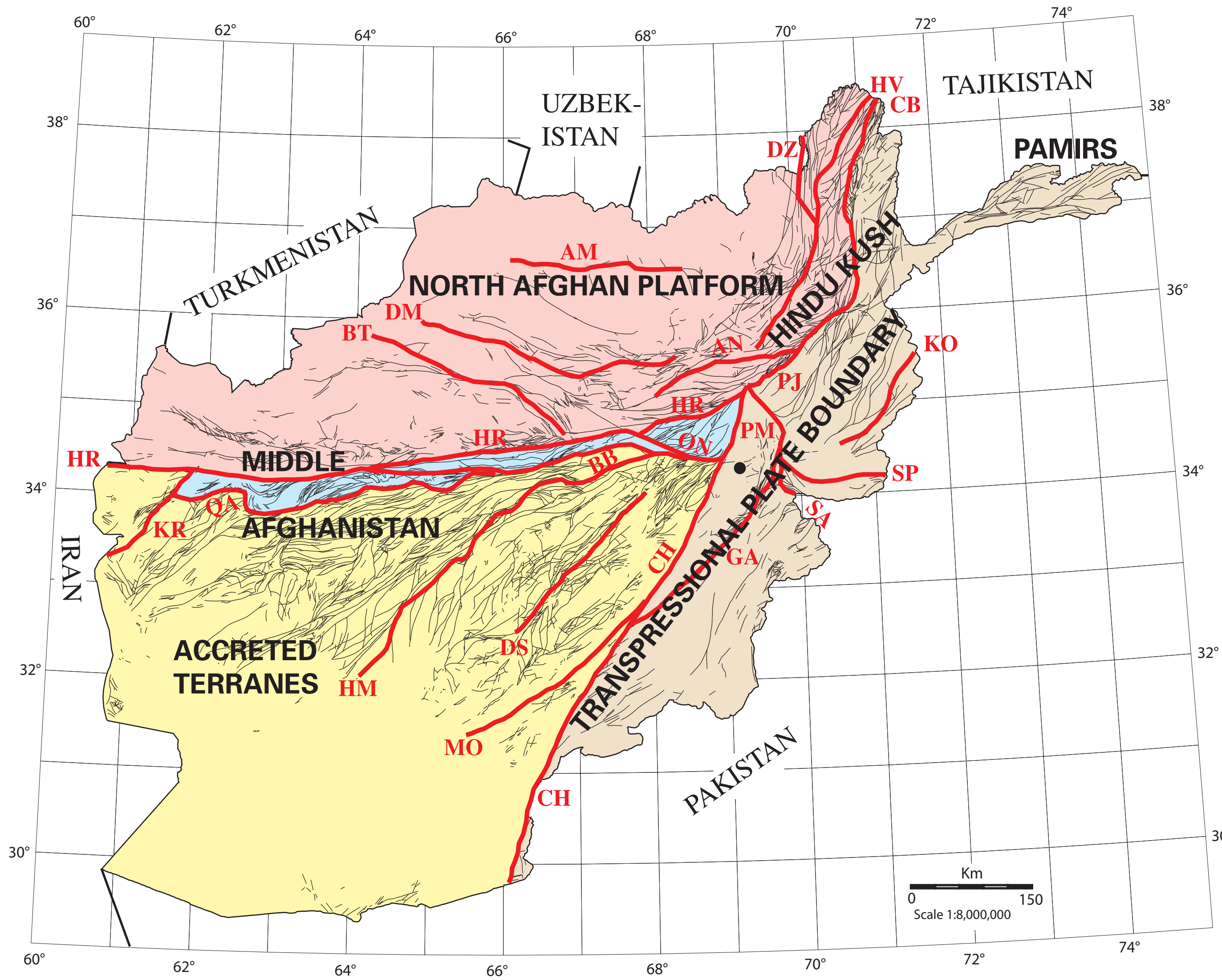

Figure 3. Tectonic regions of Afghanistan. Pink, North Afghan platform; blue, Middle Afghanistan; yellow, terranes that were accreted to the platform; tan, left-lateral transpressional plate boundary between the Indian and Eurasian plates (see text section 3.2). Black dot south of "PM" shows location of Kabul. Black and red fault traces from figure 2. Hindu Kush and Pamirs are high mountain ranges. Projection as in caption of figure 2.

Pegler and Das (1998) computed joint hypocenter locations for nearly 6,000 mantle earthquakes beneath the Hindu Kush and Pamirs. Their improved relative locations, as well as the large number of earthquakes, showed that the seismicity occurs within a steeply dipping tabular zone approximately 30 km thick and 700 km long. In its southwestern part, beneath the Hindu Kush, the tabular zone of seismicity dips 50°–90° northwest and is at depths of 100–300 km. In contrast, in the northeast, beneath the Pamirs, the zone dips 50°–60° southeast and mostly is at shallower depths of 80–200 km. Pegler and Das showed the complex geometry of the tabular zone in a series of 12 maps and 20 cross sections, which cannot be reproduced here. Instead, figure 5 shows a map view of the unrelocated seismicity deeper than 100 km. The zone appears wider than its true width of 30 km because its dip is not vertical. The two oppositely dipping parts of the seismicity zone are continuous and the zone steepens from its southwestern end toward the northeast and overturns farther northeast. Pegler and Das concluded that the entire seismicity zone is an effect of northwestward subduction of the Indian plate beneath the Eurasian plate. They also concluded that the northeastern part of the zone, which dips steeply southeast beneath the Pamirs, was overturned from its original northwest dip by northward flow in the mantle that is driven by continuing northward motion of India.

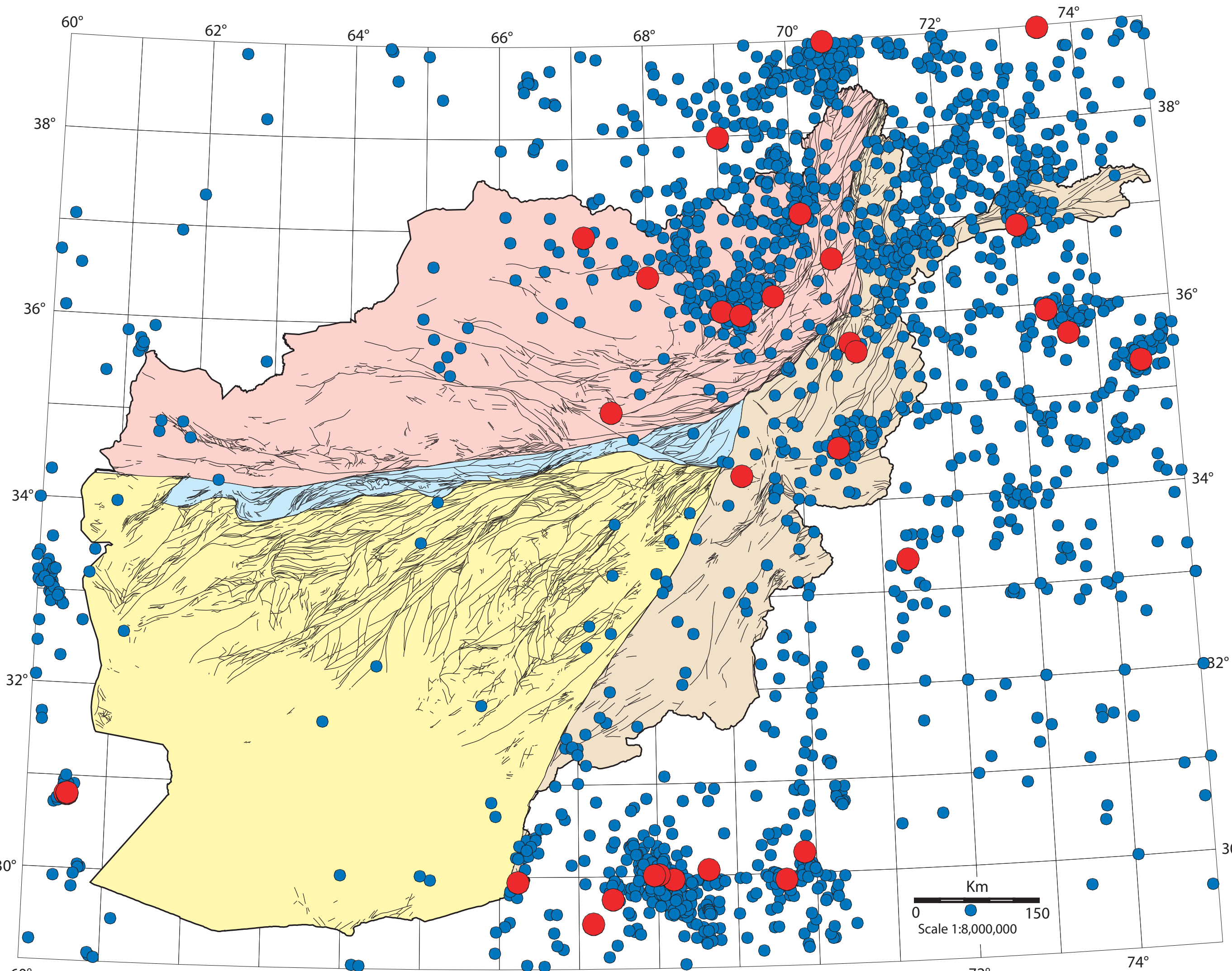

Figure 4. Crustal seismicity at depths of 40 km or less. Small blue dots, magnitudes 4.0–5.9; larger red dots, magnitudes 6.0–7.9. Preliminary earthquake catalog from E. Bergman (oral and written communs., February 25, 2005) (see text section 4). Colored polygons are from figure 3. Projection as in caption of figure 2.

5. Active Faults

5.1. Criteria for Identification

In general, active faults are useful in a hazard assessment to the degree that they allow either estimation of the locations, sizes, and dates of large prehistoric earthquakes, or estimation of the rate of fault slip averaged over several earthquake cycles. Chronologies of large prehistoric earthquakes and slip rates are useful because large historical earthquakes can be too few in a given region to allow precise estimation of their frequencies. However, paleoseismologists only can study earthquakes of magnitude approximately 5.0 or larger, and in most settings magnitude 6.0 or larger, because only these larger earthquakes rupture the Earth's surface or produce other geologically recognizable records (McCalpin and Nelson, 1996). Soft-sediment deformation features and faults or folds of outcrop size or smaller can be produced by earthquakes smaller than magnitude 5–6. In general, it is difficult to determine whether such features are of seismic, nonseismic, or even nonfaulting origin (Obermeier, 1996; Wheeler, 2002). The best evidence that a fault is active is a surface rupture that was seen to form during a historical earthquake, or a prehistoric surface rupture that has been studied by paleoseismologists who find evidence that can rule out fluvial, landslide, or other nonseismic origins and which dates the rupture.

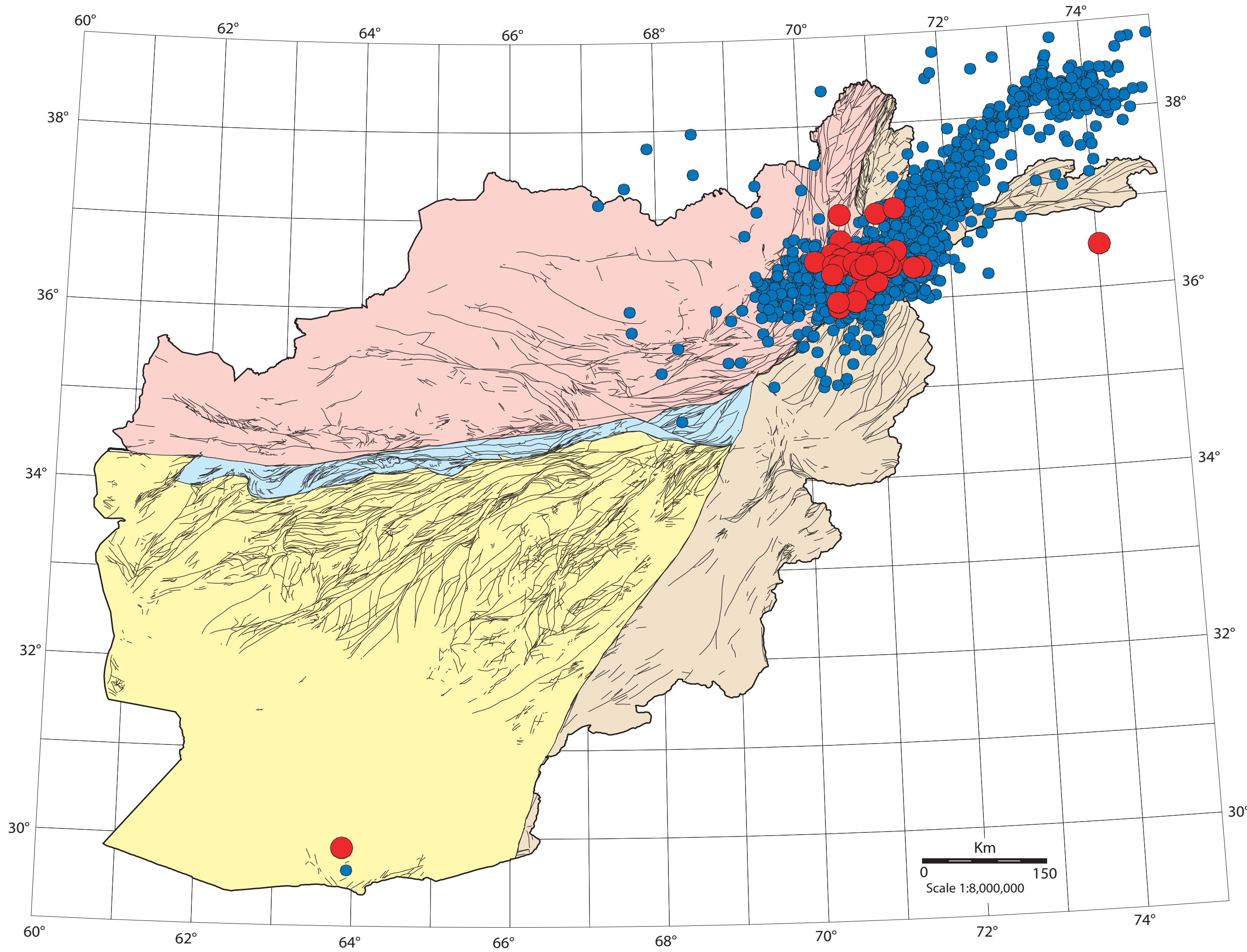

Figure 5. Mantle seismicity at depths greater than 100 km. Small blue dots, magnitudes 4.0–5.9; larger red dots, magnitudes 6.0–7.9. Preliminary earthquake catalog from E. Bergman (oral and written communs., February 25, 2005) (see text section 4). Colored polygons are from figure 3. Projection as in caption of figure 2.

The more frequently a given fault ruptures to produce a large earthquake, the more likely that fault is to significantly impact hazard estimates. An acceptable hazard map could be computed strictly from seismicity, with no contributions from active faults (Frankel, 1995). Therefore, in most cases, in order for an active fault to significantly contribute to a hazard computation, the fault should slip and generate strong ground motion often enough that its hazard rises above that estimated solely from the seismicity of the surrounding region. In general, a pre-Quaternary fault that cannot be shown to have generated a large earthquake during the Late Quaternary probably has an annual probability of producing strong ground shaking that is too small to impact the hazard computations (Wheeler, 2002). In a seismically active region such as Afghanistan and its surroundings, the age cutoff for faulting may be still more recent. Therefore, faults that lack evidence of Quaternary or Holocene faulting, even the faults that were most important during the plate-tectonic assembly of Afghanistan, are unlikely to be pertinent to hazard assessment.

Faults and earthquakes exist in three dimensions. Reverse and normal faults are far from vertical, and even strike-slip faults tend not to be perfectly vertical. At earthquake depths, fault locations are uncertain, typically by kilometers. Earthquake depths are likely to be similarly uncertain in regions where seismometers are as distant from the earthquakes as is the case for Afghan seismicity. These uncertainties invalidate most attempts to attribute one or a few earthquakes to known faults using only the earthquake epicenters and the fault traces.

These considerations yield criteria with which to rank individual large Afghan faults according to the likelihood that they are seismically active. (1) The strongest evidence of activity is the surface rupture of an individual historical or prehistoric earthquake. (2) The second strongest evidence would be identification of likely fault offsets of Quaternary surfaces or landforms, as seen on aerial photographs or satellite images, or offsets of young, dated volcanic rocks. (3) The weakest evidence for attributing seismicity to an individual fault is an alignment or clustering of earthquake epicenters along the mapped trace of a large fault.

5.2. Ranking of Faults by Likelihood of Being Seismically Active

The literature contains evidence and suggestions that 10 large Afghan faults are seismically active. The criteria of section 5.1 allow the faults to be ranked on the strengths of the published evidence for activity. Only the first five or six faults listed below appear to have enough evidence to warrant additional investigation. Eventually, results of the imagery analysis mentioned in section 2.2 are likely to supplant the following estimates.

1. The Chaman fault has the most evidence for seismic activity by far. It is part of the western edge of the transpressional plate boundary between Eurasia and India (fig. 3). Movement of the fault has produced three historical surface ruptures along the fault trace. An earthquake on July 5 or 6, 1505, produced 60 km of surface rupture with several meters of vertical offset (Quittmeyer and Jacob, 1979). The rupture broke the northern end of the Chaman fault, which some authors named separately as the Paghman fault (PM on fig. 2). A second surface rupture that formed on December 20, 1892, at approximately latitude 31° N. (fig. 2) also was 60 km long, produced 60–75 cm of left-lateral slip, and dropped the west wall of the fault down 20–30 cm (Lawrence and others, 1992; Quittmeyer and Jacob, 1979). Quittmeyer and Jacob summarized earlier reports that, in interviews with village elders after the 1892 shock, the elders reported three prior surface ruptures within their lifetimes. Finally, a magnitude 6.4 earthquake occurred in 1978 in the same general area as the 1892 shock. The 1978 earthquake produced 5 km of ground cracking, up to 4 cm of left-lateral offset, and a lesser amount of vertical slip that dropped the east wall of the fault down (Yeats and others, 1979).

Wellman (1965) examined aerial photographs, listed the magnitudes and locations of offsets at seven sites along the Chaman fault, and estimated a slip rate of 2–20 mm/yr. Tapponnier and others (1981) reported that "Studies of Quaternary geomorphology yield a displacement rate of 1–2 cm/yr along the master fault during the last 100,000 years …. Since the beginning of the Quaternary, the average rate across the whole fault zone could have been higher (2.5–3.5 cm/yr) …" (p. 358). Sborshchikov and others (1981) showed left-lateral offsets of several kilometers (their fig. 5) but gave no location. Shareq (1981, 1993) asserted that microseismic studies showed the Chaman fault to be active but provided no evidence. Lawrence and others (1992) cited a report of volcanic rocks in Pakistan that are 2 m.y. old and had been offset sufficiently to indicate a slip rate of 25–35 mm/yr. Lawrence and others described offsets throughout the fault in Pakistan that are young enough that "only the alluvium of the bottom of active dry washes is not displaced" (p. 204). Satellite geodesy (section 3.1) yielded a slip rate of 39 mm/yr for India relative to Eurasia for a site that is approximately 40 km east of the Chaman fault (Kazmi and Rana, 1982; DeMets and others, 1990). Therefore, the site is 40 km inside the west edge of the transpressional plate boundary, and there may be other left-lateral faults between the Chaman fault and the site. Accordingly, 39 mm/yr may be an overestimate of the slip rate of the Chaman fault alone.

2. After the Chaman fault, the Darvaz fault has the most evidence for young slip. The north-striking part of the fault is partly in Tajikistan but mostly in Afghanistan (Trifonov, 1978, 1999). Trifonov (1978) cited field observations from this part of the fault showing up to 20 m of left-lateral slip during the late Holocene, up to 120 m during most or all of the Holocene, and 300 m during the Late Pleistocene. Shareq (1993) asserted without evidence that earthquakes concentrate along the Darvaz fault. If one assumes that the offset landscape features of late Holocene, Holocene, and Late Pleistocene age are 3, 10, and 130 ka, then the offsets reported by Trifonov would imply slip rates of 7, 12, and 2 mm/yr, respectively.

3. The Hari Rod fault has a striking geomorphic expression on satellite images but there is evidence for and against its present-day activity. Wellman (1965) noted aerial photographic evidence of stream offsets at two localities, but Trifonov (1978) reported on p. 1069 a personal communication from Molnar that disputed those observations. Sborshchikov and others (1981) examined satellite images, noted 800 m of right-lateral offsets of streams "in the midstream of the Hari Rud river" (p. 58), and reported that "similar displacements, which can be attributed only to a dextral slip, were observed elsewhere" (p. 58) but provided no locations. Their figure 5 shows stream offsets of several kilometers across the fault. They noted that aerial and satellite photographs show average offset of approximately 5 km (p. 61). They inferred that "the time of the shaping of the river system in this region is most likely the Upper Pliocene, i.e. about 2 m.y. before present … and the velocity amounts thus to 0.2–0.3 cm yr^{-1}" (p. 61). Sborshchikov and others reported that

Neogene conglomerates fill grabens along the fault, from which they inferred strike-slip faulting during or since the Early Miocene. Shareq (1993) asserted that earthquakes concentrate along the Hari Rod fault, but considered it less active than the Chaman and much less active than the Darvaz, Central Badakhsan, and Konar faults of northeastern Afghanistan.

In contrast, Tapponnier and others (1981) observed that "although the fault zone is still sharply expressed in the Quaternary morphology, it may no longer be active since post-Miocene deposits are not clearly offset along it" (p. 359), cited a French paper for the evidence, and also noted "the … fault trace, although clear on Landsat photos, is not as sharp as that of active faults such as the Chaman …." (p. 364). Quittmeyer and Jacob (1979) reported that a damaging earthquake occurred near Herat on or near the western part of the fault in the ninth century, and that another occurred north of Kabul and perhaps on or near the eastern part of the fault in 1874, but concluded that "even for these events the evidence is not strong" (p. 803) for a causal association with the fault. Additionally, note that the fault strikes at a high angle to the regional northerly trend of the greatest horizontal compressive stress (figs. 1, 2). The fault is far from optimally oriented for slip in the ambient regional stress field.

4. The Andarab fault has two sites at which Wellman (1965) interpreted evidence of right-lateral strike-slip offset from aerial photographs. However, Trifonov (1978) noted a personal communication in which Molnar disputed Wellman's interpretations (p. 1069).

5. On the Darafshan fault, Wellman (1965) examined aerial photographs and found one site having evidence of left-lateral strike-slip offset.

6. On and near the Sarobi fault, an array of portable seismographs recorded microearthquakes whose precisely located epicenters clustered or aligned on the fault trace (Prevot and others, 1980). The only composite focal mechanism from clustered earthquakes with epicenters on or near the fault trace had a nodal plane parallel to the fault strike.

7. Quittmeyer and Jacob (1979) reported teleseismic activity on the Konar fault, but gave no locations or specifics. Prevot and others (1980) operated an array of portable instruments that recorded microearthquakes. All three composite focal mechanisms of earthquakes on or very near the fault trace had nodal planes parallel to the trace, but numerous epicenters formed a large, diffuse cluster that straddled the fault trace but appeared otherwise unrelated to it. Shareq (1981, 1993) asserted that earthquake concentrations and microearthquake studies showed the Konar fault to be active, but provided neither evidence nor citations.

8, 9, 10. Shareq (1981, 1993) noted that the Central Badakhsan, Alburz Marmul, and Panjshir faults are active according to results from earthquake concentrations and microearthquake studies. However, no evidence was given.

6. Seismic-Hazard Computations

This section draws on preceding ones to offer suggestions that might be useful in designing the seismic-hazard computations that will produce an Afghan hazard map. Most of this section offers suggestions for the treatment of crustal seismicity in the hazard computations. The mantle seismicity beneath the Hindu Kush and Pamirs (figs. 3, 5; section 4) will need to be treated separately from the crustal seismicity because of their different depths.

6.1 Geologic Source Zones

Wheeler and Frankel (2000) defined three source zones for the central and eastern United States according to the few aspects of geology that they accepted as likely to influence seismicity east of the Rocky Mountains. These aspects include global geologic and tectonic analogs, as well as deductions and observations of the types and ages of faults that are generating seismicity at several representative locales. Application of this same strategy suggests dividing Afghanistan into two or three geologic source zones. The source zones will allow hazard analysts the option of assigning different maximum magnitudes and attenuation relations to different parts of Afghanistan.

The most obvious source zone is the broad transpressional plate boundary outlined on fig. 3. It is the zone along which the Indian plate moves northward past central and western Afghanistan at a relative rate of at least 39 mm/yr (section 3.1). The boundary generates more crustal seismicity than does the rest of Afghanistan, with the notable but local exception of the eastern part of the North Afghan platform (fig. 4). Five of the ten individual faults that have been suggested to be seismically active are within the plate boundary or at its west edge despite the small fraction of Afghanistan that the boundary occupies (section 5.2, fig. 3). These five faults include the Chaman fault, which has stronger evidence of activity than any other Afghan fault.

The fault with the second strongest evidence for activity is the Darvaz fault (section 5.2). It is within the North Afghan platform, near its eastern border with the plate boundary (fig. 3). Depending on the eventual findings of the USGS group that is examining aerial photographs and satellite images for evidence of fault activity, one might decide to follow Trifonov (1999) and extend a plate-boundary source zone west to the Darvaz and Henjvan faults (fig. 3). There would be two geologic justifications for such a westward extension of a plate boundary source zone. First, if the Darvaz and perhaps Henjvan faults are found to have geomorphic evidence of recent left-lateral strike slip, such slip might indicate that the blocks of the platform between the Darvaz and Henjvan faults, on the west, and the Central Badakhsan fault, on the east, are being sheared off the North Afghan platform. Such shearing would straighten the plate boundary by removing the restraining bend of the western Hindu Kush at the northeast end of the Chaman fault (fig. 3). Second, the eastern part of the North Afghan platform is more seismically active than the rest (fig. 4). This additional activity might be evidence that the platform east of the Darvaz fault is being incorporated into the plate boundary.

A second possible geologic source zone could be the North Afghan platform, with or without the area east of the Darvaz and Henjvan faults. The argument for making the platform a source zone rests on a global tectonic analog. The platform is not a stable continental region (SCR) in the sense of Johnston (1989; 1994) and Kanter (1994). Nonetheless, the platform has a geologic history similar to that of the Appalachian Mountains of eastern North America; North America east of the Rocky Mountains is the type SCR. The Appalachian Mountains are part of the Phanerozoic rim of North America, a large source zone made of contractional and extensional terranes (Wheeler and Frankel, 2000). The Appalachian Mountains underwent their culminating orogeny during the Carboniferous and Permian Periods and so did the North Afghan platform (section 3.2). The Appalachian orogenic crust was rifted beginning in the Triassic Period to form the Atlantic Ocean, whereas the North Afghan platform was rifted to form part of the early Tethyan Ocean at the same time or earlier (section 3.2). The Appalachian Mountains and central and eastern Afghanistan are both under compressional deviatoric stress, with extensional earthquakes being rare (Zoback and others, 1991; fig. 1). Thus, the two regions have had similar lengths of time for their crusts to cool and for their fault rocks to strengthen by recrystallization.

The main difference between the Appalachian Mountains and the North Afghan platform is that the North Afghan platform borders an active plate boundary, whereas the Appalachian Mountains do not. However, other SCRs border active subduction boundaries in Australia, South America, Arabia, India, and China, and the South American SCR is bounded on the north and south by active transform plate boundaries within continental crust (Broadbent and Allan Cartography, 1994). Thus, the presence of an active plate boundary next to the North Afghan platform does not necessarily undercut the tectonic analogy between the platform and the Appalachian Mountains.

There does not appear to be any obvious geologic explanation for the more abundant crustal seismicity of the eastern North Afghan platform compared to the central and western platform (fig. 4). The same is true for parts of the central and eastern United States, for which the smoothed seismicity method of Frankel (1995) accommodates the unexplained differences in seismicity. The same method could be used for the North Afghan platform.

If the platform and plate boundary are both made geologic source zones, then we suggest that Middle Afghanistan and the rest of the accreted terranes should form a third zone by exclusion (fig. 3). The accreted terranes docked against the platform throughout the Mesozoic Era (section 3.2). Older accreted terranes were deformed as younger ones docked against them. Most of the large faults within and between the terranes were reactivated in strike slip during the Tertiary Period. Thus, the crust of the accreted terranes might still be warmer and weaker than that of the platform, and fault rock within and between the terranes might not have had time to recrystallize to the strengths of platform faults. Either factor could favor more seismic slip within the accreted terranes than within the platform. For these reasons, if the platform is made a second source zone, we suggest that the accreted terranes not be included.

6.2. Maximum Magnitudes (M[max])

The magnitudes (M) of the earthquakes mentioned in this section may change as the USGS catalog of Afghan earthquakes is completed (Section 4). Also, the catalog magnitudes may be of more than one type, and some may have to be converted to moment magnitudes. Thus, the following suggestions should be checked against the final M values of the Afghan catalog.

The preliminary earthquake catalog shown in figures 4 and 5 contains six crustal earthquakes of M 7.0 or larger. The smallest three are the largest earthquakes that figure 4 shows in the plate boundary. One earthquake of M 7.0 and two of M 7.1 occurred within the cluster of plate-boundary seismicity that is centered in Pakistan at latitude 30° N., longitude 68° E. In contrast, the three largest crustal earthquakes occurred in the North Afghan platform. One shock of M 7.2 and another of M 7.6 occurred in the Tajikistan part of the platform. Their epicenters were at the western two of the three large red dots north of Afghanistan in fig. 4. Another M 7.6 earthquake occurred in the Afghan part of the platform. Its epicenter is the southwesternmost large red dot that figure 4 shows in the platform. Thus, when the Afghan catalog and its magnitudes are completed, the historical record is likely to require that the platform have M(max) at least as large as moment magnitude Mw 7.6. The geologic similarities of the North Afghan platform and the Appalachian Mountains (section 6.1) would be consistent with such an assignment, because the similarities may indicate that the platform should have M(max) at least as large as the Mw 7.5 that Wheeler and Frankel (2000) assigned to the Appalachian Mountains and Atlantic Coastal Plain.

The younger tectonic age and more recent orogenic activity of the accreted terranes south of the platform could be seen as indicating an M(max) at least as large as that assumed for the platform. However, the accreted terranes are no more seismically active than the central and western parts of the platform (fig. 4). Similar low levels of crustal seismicity could be grounds for assigning the same M(max) to all of Afghanistan except the transpressional plate boundary.

The plate boundary is a continental transform system. Other continental transform systems that also are of great length, have large total displacement, and have slip measured in cm/yr include the San Andreas, North Anatolian, Alpine, and Denali faults. These analogs would support an M(max) for the transpressional boundary that is larger than whatever values are chosen for the North Afghan platform and the region of accreted terranes.

The mantle earthquakes of northeastern Afghanistan included 19 of M 7.0 or larger. Of these, five had M 7.4, two had M 7.5, and three had M 7.6. These values and the greater number of the large mantle earthquakes compared to the large crustal earthquakes argue for M(max) at least as high as M 7.6 for the mantle seismicity.

6.3. Attenuation Relations

The transpressional plate boundary of eastern Afghanistan is dominated by numerous active strike-slip faults of many sizes, and it has ubiquitous and abundant seismicity (fig. 3, section 3.2). Tectonic maps show many reverse and oblique strike-slip faults that are appropriately oriented to accommodate some of the transpression (Chmyriov and Mirzad, 1971; Shareq, 1981). The history of large, rapid, transpressional movement may have fractured intensely the rocks throughout the plate boundary. The best North American analog could be the San Andreas fault system. If so, then one or more California attenuation relations may be the most appropriate for crustal earthquakes in the plate boundary.

As argued in section 6.1, the best North American geologic and tectonic analogue to the North Afghan platform appears to be the Appalachian Mountains. The analogy suggests that attenuation relations developed for the central and eastern United States could be appropriate for the North Afghan platform.

The accreted terranes of Middle Afghanistan and southern Afghanistan lack a clear North American geologic or tectonic analogue. It is presently unclear whether the accreted terranes are undergoing strike-slip reactivation of their faults. Thus, an analogy to western California and its strike-slip faulting may or may not be appropriate. Although the Hari Rod fault incorporates Neogene grabens (section 5.2), it is presently unclear whether the young grabens represent extensive extensional faulting throughout the accreted terranes, such as that of the Basin and Range province. It is possible that ongoing geologic mapping and estimation of fault slip-rates by other USGS personnel (section 2.2) may resolve some of these uncertainties. However, present geologic information appears insufficient to provide a clear guide for the choice of attenuation relations for the Afghan accreted terranes. If attenuation relations for strike-slip and extensional environments do not predict greatly different hazard, perhaps a combination of both attenuation treatments could represent the uncertainty arising from lack of a clear North American tectonic or geologic analogue.

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Appendix 1. Variable names and spellings of Afghan faults

Locations, names, and spellings of the names of Afghan faults vary between authors, between papers by the same author, and occasionally within a single paper. This may be because spelling of translated Persian and Arabic words commonly is phonetically based (R.G. Bohannon, oral commun., February 10, 2005), and varies with accent, region, and personal preference.

No attempt is made here to rationalize locations, names, or spellings. Instead, we took as authoritative the names and spellings on an inset map of the tectonic map of Chmyriov and Mirzad (1971). Table 1 lists them and the variants of other authors; the list may be incomplete. Four additional faults were not shown by Chmyriov and Mirzad: the Darafshan, Darvaz, Gardez, and Panjsher faults. For each of the four, table 1 cites the source of the preferred spelling as well as the sources of any variant spellings. Most of the variants will not confuse readers and footnotes explain those that might. However, anyone searching GeoRef or elsewhere on the Internet for new information will need to search on all variants of a fault's name. The publications cited in table 1 are listed and annotated in Appendix 2.

Table 1. Variable names and spellings of main Afghan faults.

Preferred name	Variants
Alburz Marmul	Alburs-Mormul (Wolfart and Wittekindt, 1980); Alburz-Marmul (Shareq, 1981, 1993); Alburz-Mormul (Kingston and Clarke, 1995); Alburz-Momul (Brookfield and Hashmat, 2001)
Andarab	Part of Andarab-Mirza Wolang (Shareq, 1981, 1993) and Anderab-Mirzawolang (Brookfield and Hashmat, 2001); part of Talemazar (Wellman, 1965; Trifonov, 1978)
Bande Bayan	Most authors included this fault as part of Qarghanaw, no variants found
Bande Turkestan	Bande Turkestan-Bande Amir (Wolfart and Wittekindt, 1980); Bandi Turkestan (Shareq, 1993); Banrie Turkestan (UNESCAP, 1995); Band-e-Turkestan (Shareq, 1981; Wittekindt and others, 1997)
[1, 2]Chaman	Caman (Chmyriov and Mirzad, 1971; Wolfart and Wittekindt, 1980; UNESCAP, 1995)
Central Badakhsan	Central Badakhshan (Lawrence and others, 1992; Shareq, 1981, 1993; UNESCAP, 1995); Zentral Badakhshan (Wolfart and Wittekindt, 1980); Central Badakshan (Wittekindt and others, 1997); Central Badakhstan (Treloar and Izatt, 1993; Wittekindt and others, 1997); Gunt-Alichur (Everett and others, 1986)
Darafshan (Wellman, 1965)	Tirin (Wolfart and Wittekindt, 1980; Wittekindt and others, 1997)
Darvaz (Trifonov, 1978)	Darwaz Karakul (Prevot and others, 1980); Khokan (Shareq, 1981); Khohan-Ishkamish (Shareq, 1993); Khoakan (Wittekindt and others, 1997); Darvaz-Alai (Trifonov, 1999); Ishkamish-Khohon (Brookfield and Hashmat, 2001)
Dosi Mirzavalan	Mirzavalan Dosi (Wolfart and Wittekindt, 1980); Mirzavalang (Kingston and Clarke, 1995); Anderab-Mirzawolang (Brookfield and Hashmat, 2001); Andarab-Mirza Wolang (Shareq, 1981, 1993); part of Talemazar (Trifonov, 1978)
Gardez (Lawrence and others, 1992)	No variants found
[3]Hari Rod	Hari-Rod (Shareq, 1981); Harirod (Herat) (Shareq, 1993); Hari Rud (Sborshchikov and others, 1981); Harirud (Sengor, 1984; Brookfield and Hashmat, 2001); Hari-rud (Kingston and Clarke, 1995); Herat (Wellman, 1965; Trifonov, 1978; Quittmeyer and Jacob, 1979; Wolfart and Wittekindt, 1980; Everett and others, 1986; Lawrence and others, 1992; Ambraseys and Bilham, 2003)

Table 1. Variable names and spellings of main Afghan faults.—Continued.

Preferred name	Variants
Helmand	Hilmand (Shareq, 1993); Helmund (Everett and others, 1986; Lawrence and others, 1992; Ambraseys and Bilham, 2003); Waser (Schreiber and others, 1972; Wolfart and Wittekindt, 1980)
Henjvan	Henjran (UNESCAP, 1995); Khejwand, Khajwand (Shareq, 1981); most authors did not name this fault
Kaj Rod	Of the papers and maps examined, only Chmyriov and Mirzad (1971), Wolfart and Wittekindt (1980) and UNESCAP (1995) named this short fault that crosses into Iran
Konar	Kodar (UNESCAP, 1995); Kunar (Quittmeyer and Jacob, 1979; Wolfart and Wittekindt, 1980; Everett and others, 1986; Lawrence and others, 1992; Shareq, 1981, 1993; Ambraseys and Bilham, 2003)
[2]Mokur	Moqor (Wittekindt and others, 1997); Moqur (Wolfart and Wittekindt, 1980; Shareq, 1981); Mukur-Chaman (Sborshchikov and others, 1981); Mukur-Tarnak (Shareq, 1993); Muqur (Shareq, 1981, 1993)
Onay	Ona (UNESCAP, 1995); most authors did not name this short fault that strikes northwest between the Hari Rod and Helmand faults west of Kabul
Paghman	Pagman (Shareq, 1981; UNESCAP, 1995). Other authors did not give this short fault west of Kabul a separate name but included it as the northernmost part of the Chaman fault
Panjshir (Shareq, 1993)	Panjser (Wolfart and Wittekindt, 1980); Pansher, Pansjer (Shareq, 1981). Many authors did not name this fault but included it as the southern part of the Central Badakhsan fault or the eastern part of the Hari Rod fault
Qarghanaw	Garghanaw (Wittekindt and others, 1997); Karganaw (Shareq, 1981)
Sarobi	Sarubi (Prevot and others, 1980; Lawrence and others, 1992); Safed Koh (Schreiber and others, 1972)
Spinghar	Spin Gawh (Wittekindt and others, 1997); of the other maps examined, only that of UNESCAP (1995) named this fault

1 This is the only departure from the spellings of Chmyriov and Mirzad (1971). They used “Caman”, as did UNESCAP (1995) in its reproduction of the 1971 map. However, all other authors use “Chaman”, including Shareq (1981, 1993) of the Afghanistan Geological Survey and the Afghanistan Academy of Sciences. Schreiber and others (1972) used “Chaman” and stated that their fault names and spellings were in accord with the Royal Afghan Cartographic Institute. Other users of the “h” have spent much time in Afghanistan (Wellman, 1965; Wittekindt and others, 1997).

2 Older maps show the Chaman and Mokur faults striking northeast across southeastern Afghanistan, to pass east and west of Kabul, respectively, and to terminate against the Hari Rod fault (Chmyriov and Mirzad [1971, 1972] and maps based on them, such as the maps of Shareq [1981, 1993] and the tectonic map of UNESCAP [1995]). These maps show the Mokur fault on the west as concave west, and the Chaman fault on the east as mainly concave east. At their closest approach, near their midpoints at latitude 32°-33°N., the two faults are shown as only 6-15 km apart. In contrast, maps based on aerial photographs, Landsat images, and more recent mapping tend to join the south half of the Chaman fault to the north half of the Mokur fault, with the join at the point of closest approach, and to call the result the Chaman fault (Wellman, 1965; Schreiber and others, 1972; Trifonov, 1978, 2000; Lawrence and others, 1992; Kingston and Clarke, 1995; the geologic map of UNESCAP, 1995; Brookfield and Hashmat, 2001). A large, seamless, full-color, Landsat mosaic that is in production by the USGS clearly shows that the latter interpretation of the Chaman fault is correct. Some authors now use the name Gardez fault for the remaining, northern half of the former Chaman fault (Prevot and others, 1980; Everett and others, 1986; Lawrence and others, 1992).

3 Afghan authors follow the Russian usage of Chmyriov and Mirzad (197l). English-speakers tend to follow the New Zealander Wellman, who named the fault “Herat” (Wellman, 1965, p. 724). West Germans who had mapped in Afghanistan are split, with Schreiber and others (1972) using Hari Rod and Wittekindt and others (1997) using Herat. We use the Afghan name for the fault because it lies entirely within Afghanistan.

Appendix 2. Annotated bibliography for seismotectonic map of Afghanistan

The annotations emphasize information that is pertinent to the seismotectonic map. They point out strengths or weaknesses of the annotated publications, make observations or draw inferences from them, and give cross references to other publications in this bibliography. Limited resources restricted the literature search to English-language publications and Afghanistan, and required a preference for review or summary papers. We made no attempt to trace ideas back to their first published appearances. For the same reason, some papers and maps on eastern Iran and western Pakistan are cited here for the reader's information, but we did not read those that lack annotations. Fault names and their spellings vary because each is that of its annotated publication (see also Appendix 1).

Ambraseys, Nicholas, and Bilham, Roger, 2003, Earthquakes in Afghanistan: Seismological Research Letters, v. 74, no. 2, p. 107–123.

Most of the paper presents and describes an earthquake catalog of Afghanistan and surroundings that begins in A.D. 734. The "Tectonic Setting" section and figs. 1–2 summarize plate-tectonic context, blocks or subplates, main fault zones, seismicity clusters, and the sparse constraints on slip rates between plates. The figures show the Afghan border. GPS measurements of regional deformation rates and directions are too few to compare to relative plate velocities that have been computed from seafloor magnetic anomalies and similar data.

Berberian, Manuel, 1981, Active faulting and tectonics of Iran, *in* Gupta, H.K., and Delany, F.M., eds., Zagros, Hindu Kush, Himalaya—Geodynamic evolution: American Geophysical Union Geodynamics Series 3, p. 33–69.

Berberian, Manuel, Jackson, J.A., Qorashi, M., Khatib, M.M., Priestley, K., Talebian, M., and Ghafuri-Ashtiani, M., 1999, The 1997 May 10 Zirkuh (Qa'enat) earthquake (M_w 7.2)—Faulting along the Sistan suture zone of eastern Iran: Geophysical Journal International, v. 136, no. 3, p. 671–694.

Bernard, M., Shen-Tu, B., Holt, W.E., and Davis, D.M., 2000, Kinematics of active deformation in the Sulaiman Lobe and Range, Pakistan: Journal of Geophysical Research, v. 105, no. B6, p. 13,253–13,279.

Brookfield, M.E., and Hashmat, Ajruddin, 2001, The geology and petroleum potential of the North Afghan Platform and adjacent areas (northern Afghanistan, with parts of southern Turkmenistan, Uzbekistan and Tajikistan): Earth-Science Reviews, v. 55, no. 1-2, p. 41–71.

The North Afghan platform is bounded on the south and southeast by the east-striking, right-lateral Harirud fault zone. The Harirud and related faults continue eastward, then bend northeastward around the edge of the platform and eventually are continued northward as the Darvaz fault zone. The Harirud fault zone offsets Paleozoic rocks more than 600 km. The southern part of the Darvaz fault zone strikes north and undergoes left-lateral slip, but farther north the fault zone bends to the northeast and adds a northwest-verging reverse component. The change in strike-slip sense between the Harirud and Darvaz fault zones occurs approximately north of Kabul. In contrast, most faults within the North Afghan platform strike east-west and lack significant offsets, although the known offsets are right lateral. The structural grain represented by the right-lateral Harirud and platform faults terminates farther west, near the Iran border, against the north-striking Seistan fault and related faults.

Nearly all of the deformation, uplift, and formation of petroleum traps within the North Afghan platform is of Miocene or younger age and most is younger than 5 Ma (contrast the conclusions of Kingston and Clarke [1995]). The Harirud fault zone is only sparsely seismically active; in contrast, the Darvaz fault zone and the aligned, north-striking, left-lateral Chaman fault farther south are much more seismically active. Brookfield and Hashmat interpret these orientations, slip senses, and timings as indicating northwestward convergence of the Indian plate against the North Afghan platform from 35 Ma to 20 Ma, to produce the right-lateral slip on the Harirud and platform faults, followed by a change to northward convergence of India since 20 Ma, to produce the continuing left-lateral slip on the Chaman and Darvaz faults and the reverse slip on the northeastern part of the Darvaz fault.

Chandra, Umesh, 1981, Focal mechanism solutions and their tectonic implications for the eastern Alpine-Himalayan region, *in* Gupta, H.K., and Delany, F.M., eds., Zagros, Hindu Kush, Himalaya—Geodynamic evolution: American Geophysical Union Geodynamics Series 3, p. 243–271.

The author compiled and computed hundreds of single-earthquake focal mechanisms for shocks that occurred from westernmost Iran to western Burma. Eight moderate earthquakes (M 5.6–6.7) in eastern Afghanistan and western Pakistan yielded mechanisms. Three of the mechanisms are from the eastern part of the strongly arcuate, south-directed thrust sheets of the Sulaiman Range in Pakistan. All three indicate thrust faulting toward the east-southeast, consistently with the direction of vergence in the active thrust complex. Three other mechanisms from the central and western part of the Sulaiman Range thrust sheets, and a fourth from farther west in Afghanistan, indicate strike slip under north-northwest shortening, consistently with possible tear faults in the active thrust complex and with active left-lateral strike slip on and near the north-striking Chaman fault in Afghanistan. Most of the 14 mechanisms from the Hindu Kush and surroundings were subcrustal (see also Chatelain and others, 1980; Pegler and Das, 1998), but one crustal earthquake indicates thrust faulting under northwest-southeast shortening.

Chatelain, J.L., Roecker, S.W., Hatzfeld, D., and Molnar, P., 1980, Microearthquake seismicity and fault plane solutions in the Hindu Kush region and their tectonic implications: Journal of Geophysical Research, v. 85, no. B3, p. 1365–1387.

Two microearthquake surveys located about 600 hypocenters and determined 28 focal mechanisms (Roecker and others, 1980), with another 17 mechanisms coming from teleseismic data. Very few earthquakes occurred shallower than 70 km. The data define deep zones of varying strikes and dips. The zones may be results of subduction of two small pieces of oceanic lithosphere in opposite directions (but see Pegler and Das, 1998).

Chmyriov, V.M., and Mirzad, S.H., eds., 1971, Tectonic map of Afghanistan: Kabul, Afghanistan, Ministry of Mines and Industries of Royal Afghanistan, Department of Geology and Mines, 4 sheets, scale 1:1,000,000.

USGS scanned, rectified, digitized, and attributed a paper copy of this map that was found in Kabul. Lack of stable base materials and an unknown original projection degraded accuracy slightly from the nominal scale.

Chmyriov, V.M., and Mirzad, S.H., eds., 1972, Geologic map of Afghanistan: Kabul, Afghanistan, Ministry of Mines and Industries of Royal Afghanistan, Department of Geology and Mines, 4 sheets, scale 1:1,000,000.

USGS scanned, rectified, digitized, and attributed a paper copy of this map that was found in Kabul. Lack of stable base materials and an unknown original projection degraded accuracy slightly from the nominal scale.

DeMets, C., Gordon, R.G., Argus, D.F., and Stein, S., 1990, Current plate motions: Geophysical Journal International, v. 101, p. 425–478.

The paper describes the NUVEL-1 model of relative motions between 12 plates. Table 2(a) of the paper gives the Euler vectors for the relative motions between the Arabian, Eurasian, Indian, and other plates. Figure 48 shows a map of the India-Eurasia and Arabia-Eurasia relative velocities. The tabulated Euler vectors allow a reader to compute the relative motions of Arabia and India with respect to a fixed Eurasia: Arabia moves northerly along N. 4°E. at 35 mm/yr, and India moves along N. 6°E. at 40 mm/yr. Table 2 indicates that the 2° difference in the relative-movement directions of Arabia and India is not significant. An Euler pole is provided for the relative motions of Arabia and India, but it has too large an uncertainty to be meaningful. The angular velocities of the Euler vectors were later revised by DeMets and others (1994).

DeMets, C., Gordon, R.G., Argus, D.F., and Stein, S., 1994, Effect of recent revisions to the geomagnetic reversal time scale on estimates of current plate motions: Geophysical Research Letters, v. 21, no. 20, p. 2191–2194.

The relative motions of NUVEL-1 (DeMets and others, 1990) are too fast. The optimal correction is to multiply them by 0.9562. The results are tabulated as NUVEL-1A. Space geodetic rates had been slower on average than those of NUVEL-1 by 6 percent; the discrepancy is reduced to less than 2 percent when space geodetic rates are compared to NUVEL-1A. Table 2 of the paper gives the new relative angular velocities between the Arabian, Indian, Eurasian, and other plates. From these, a reader can calculate that Arabia moves northward with respect to a fixed Eurasia at 33 mm/yr, and India does the same at 39 mm/yr.

The 39 mm/yr result is for a site in the east wall of the left-lateral Ornach-Nal fault, which strikes north in southwestern Pakistan. The Ornach-Nal fault is southeast of the Chaman fault and within the transpressional zone that accommodates most motion between Afghanistan and India at that latitude (Lawrence and others, 1992). Sella and others (2002, p. 27) calculated a NUVEL-1A rate of 48 mm/yr for a site in southern India. The southern India site is farther from the Euler pole in northern Africa than is the site in southwestern Pakistan. The greater distance would produce a larger northward velocity for southern India, but probably not large enough to account for 9 mm/yr of difference between the two sites. Part of the difference may be taken up by minor motion on north-striking faults east of the Ornach-Nal fault; the seismotectonic map of Kazmi (1979b) shows several faults there and labels them "probable Recent". Therefore, the relative motion between India and Eurasia across southeastern Afghanistan and adjacent Pakistan might be represented best as 39–48 mm/yr.

Everett, J.R., Morisawa, M., and Short, N.M., Sr., 1986, Tectonic landforms, *in* Short, N.M., Sr., and Blair, R.W., Jr., eds., Geomorphology from space: National Aeronautics and Space Administration, ch. 2, 6 p., 61 plates (http://daac.gsfc.nasa. gov/DAAC_DOCS/geomorphology/GEO_HOME_PAGE.html, accessed Nov. 22, 2004).

This book is out of print but available digitally. Plate T-43 features a Landsat mosaic showing Afghanistan and surroundings, with a page-sized index map showing the traces and names of the main faults from the western Himalaya of India to central Iran. The preparer of the map is anonymous, the sources are unstated, and no international borders are shown.

Exxon Production Research Company, 1985, Tectonic map of the World: 21 sheets, scale 1:10,000,000 at the equator (copyrighted and publicly distributed by American Association of Petroleum Geologists Foundation, Tulsa, Oklahoma, 1994).

The map shows the Seistan basin in southwestern Afghanistan and the North Afghanistan basin in the north as platforms with 0–2 km of sedimentary cover. The cover of the North Afghanistan basin thickens northward to 5–6 km at the Afghan border.

Between the two basins is a broad, east-trending belt of exposed orogenic rocks that were deformed at various times.

The northern part of this belt of orogenic rocks is what the folded plate of Shareq (1981) refers to as the Middle Afghanistan geosuture zone. Middle Afghanistan lies between the Hari Rod fault, on the north, and the Qarghanaw, Bande Bayan, and Onay faults, on the south. The most abundant rocks within the geosuture zone were deformed during Pennsylvanian to Early Triassic time (Hercynian orogeny). Less abundant within the zone are rocks that were deformed during Late Precambrian to Middle Cambrian time (Baikalian orogeny), extrusive and intrusive rocks of Late Cretaceous to Oligocene age, and ophiolites of unspecified age. From the eastern end of the Middle Afghanistan geosuture zone in the vicinity of Kabul, the rocks that were deformed during Pennsylvanian to Early Triassic time form a belt roughly 100 km wide that sweeps northeastward and then northward through northernmost Afghanistan into Tajikistan. This belt that extends from Kabul into Tajikistan is bounded on the west by the Darvaz fault and on the east by the Central Badakhsan fault.

South of the Middle Afghanistan geosuture zone lie rocks that were deformed during the Late Precambrian to Middle Cambrian Baikalian orogeny, rocks deformed during Late Cretaceous to Oligocene time and coeval extrusive rocks, a few Miocene to Recent extrusive rocks and active volcanoes, and ophiolites of Late Jurassic to Late Cretaceous age. This complex of rocks extends east to the Chaman fault. East of the Chaman fault are rocks deformed during Late Cretaceous to Oligocene age, which extend into Pakistan. These rocks east of the Chaman fault also extend northeast, east of the Central Badakhsan fault within Afghanistan and adjacent Pakistan.

Haghipour, A., 1992, Seismotectonic map of the Middle East: Geological Survey of Iran and Commission for the Geological Map of the World, Teheran, Iran, 1 sheet, scale 1:5,000,000.

This large-format map shows the region from westernmost China and India in the east to central Sudan and southeasternmost Bulgaria in the west. The tectonic elements shown include plate boundaries and motion vectors, deformed zones that are color-coded by age of the most recent major deformation, large faults with senses of movement and some slip rates, free-air gravity isogals, Moho depth contours, and centers of young basins. Earthquake epicenters are coded by year of occurrence, magnitude, and focal depth. A footnote cites compilation sources and attributes the Afghan portion of the map to Haghipour and others (1984a). Two strategic omissions hinder study of the map by readers unfamiliar with the region. First, the main basins, tectonic blocks, and geographic features are named but faults are not. Second, international borders are absent from the map.

Haghipour, A., Ghorashi, M., and Kadjar, M.H. (compilers), 1984a, Seismotectonic map of Iran, Afghanistan and Pakistan: Teheran, Iran, Commission for the Geological Map of the World, 1 sheet, scale 1:5,000,000, 24 p. pamphlet.

The map covers approximately the northeastern half of the map of Haghipour (1992). One inset map shows contours of "possible potential peak horizontal ground acceleration". A second shows earthquake focal mechanisms, schematic plate boundaries, relative-motion vectors, and slip senses of main faults. A sequence of 11 tectonically-oriented stratigraphic columns labels each column with the names of the parts of the map area to which it applies. However, the names do not appear on the map itself, which causes difficulty in linking the columns to the map. An atlas with a good index will help the reader. The pamphlet that accompanies the map (Haghipour and others, 1984b) is cited separately here because the USGS library files them separately.

Haghipour, A., Ghorashi, M., and Kadjar, M.H., 1984b, Explanatory text of the seismotectonic map of Iran, Afghanistan and Pakistan: Tehran, Iran, Commission for the Geological Map of the World, United Nations Educational, Scientific and Cultural Organization, and Geological Survey of Iran, 24 p.

This is the pamphlet that accompanies the map of Haghipour and others (1984a). They are cited separately because the USGS library files them separately. The pamphlet summarizes some of the decisions that led to design of the map, and provides short descriptions of the tectonic histories of the regions to which each stratigraphic column of the map applies. One chapter on neotectonics and another on seismotectonics and seismicity occupy nearly one-half of the pamphlet. Central and western Afghanistan form a south-projecting promontory of Eurasia, against which the Indian plate subducts from the south and the Arabian plate subducts from the south-southwest. Contractional strike-slip faulting predominates in and near Afghanistan. The main reverse-faulting regimes in the map area are driven by subduction in the Makran ranges south of Afghanistan, in the thin-skinned fold-and-thrust ranges of northwestern Pakistan, and in the deeply penetrating continental subduction zones in and around northeastern Afghanistan. Extensional faulting and focal mechanisms are rare. Seismicity in and near Afghanistan is concentrated in and near the north-trending continental transform zones to the east and west, in the Makran subduction zone south of Afghanistan, and especially in the Hindu Kush and Pamirs. The Hindu Kush-Pamirs area is part of the Himalayan continental subduction zone in and around northeastern Afghanistan. Subcrustal seismicity in or near Afghanistan is largely limited to the Hindu Kush-Pamirs area. North-central Afghanistan is sparsely seismically active and western and central Afghanistan are still less active.

Hessami, Khaled, Jamali, Farshad, and Tabassi, Hadi, 2003, Major active faults of Iran: International Institute of Earthquake Engineering and Seismology, Tehran, Iran, 1 sheet, scale 1:2,500,000 (http://www.iiees.ac.ir/seismology/ActiveFault.pdf, accessed Nov. 30, 2004).

The large-format map shows many tens of faults, some as short as approximately 10 km. Ornamentation and subtle shades of red distinguish reverse faults, strike-slip faults, and faults of unknown slip sense; known and inferred faults; and faults with coseismic surface ruptures, faults with attributed seismicity but no surface ruptures, and faults with Quaternary offset. Notable earthquakes are represented by their epicenters, dated focal mechanisms, horizontal components of slip vectors, and horizontal components of the maximum principal stress computed from the individual focal mechanisms (actually, greatest shortening), but magnitudes are not given. An explanatory text includes some conclusions drawn from examination of the map. The text cites the ten main sources but does not give their references.

Heuckroth, L.E., and Karim, R.A., 1973, Afghan seismotectonics: Philosophical Transactions of the Royal Society of London, Series A, Mathematical and Physical Sciences, v. 274, p. 389–395.

The authors examined Wellman's (1965) map of active faults in Iran, Afghanistan, and Pakistan that he developed from study of air photo mosaics. Largely from Wellman's map and superposed locations of Afghan earthquakes, the authors developed a speculative tectonic model for central Iran and most of Afghanistan. Unfortunately, the model is undercut by a scarcity of citations or summaries of evidence to support their assertions, by failure to consider the large active faults of western Pakistan, and by a lack of historical seismicity along the Herat fault that the model predicts to be presently active.

Ioffe, A.I., Govorova, N., Volchkova, G., Irifonov, R., 1993, Data base of active faults for the USSR area: Geoinformatics, v. 4, p. 289–290.

The paper is an early version of Ioffe and Kozhurin (1996). Listings of three Turkish faults show the ASCII format used for database entries. Data are not given for any other faults. Data were compiled from maps at scales ranging from 1:500,000 to 1:2,500,000. See also Trifonov (2000, 2004).

Ioffe, A.I., Kozhurin, A.I., 1996, Database of active faults of Eurasia: Journal of Earthquake Prediction Research, v. 5, p. 431–435.

The described database is that compiled for the eastern-hemisphere half of a World Map of Active Faults (Trifonov, 2004). Data are in the form of ASCII (text) files for ease of dissemination and incorporation into GIS. At the time of writing, the database contained information on over 6,000 faults from nearly all of Eurasia except northern Europe. The paper contains data only for one example on northern Sakhalin Island in eastern Russia. An appendix describes the 16 fields in a typical database record. The fields include the time of most recent movement, slip rate in mm/yr, dip, slip sense, various kinds of field observations, a reliability estimate, and cited sources.

Kaila, K.L., Rao, N.M., and Narain, H., 1974, Seismotectonic maps of southwest Asia region comprising eastern Turkey, Caucasus, Persian Plateau, Afghanistan and Hindukush: Bulletin of the Seismological Society of America, v. 64, no. 3, p. 657–669.

Maps of a-values, b-values, and return periods of earthquakes of magnitude 6 and larger are compared with regional tectonics. The paper suggests that specific individual faults within broad areas of high seismicity are active, but the small scale of the maps renders the suggestions untestable.

Kazmi, A.H., 1979a, Active fault systems in Pakistan, *in* Farah, Abul, and De Jong, K.A., eds., Geodynamics of Pakistan: Quetta, Pakistan, Geological Survey of Pakistan, p. 286–294.

Kazmi, A.H., 1979b, Preliminary seismotectonic map of Pakistan: Quetta, Pakistan, Geological Survey of Pakistan, scale 1:2,000,000.

The map shows earthquake epicenters, faults, and ages of exposed deposits and rocks. Epicenters are coded by depth and magnitude of the corresponding earthquakes. Patterns distinguish Quaternary deposits from pre-Quaternary rocks. Red solid and dashed lines distinguish active faults from probable Recent faults. Black dotted lines show lineaments, and solid black lines are ornamented to distinguish inactive reverse, thrust, strike-slip, and undifferentiated faults. One inset map shows locations and affected areas of damaging earthquakes. A second inset map divides Pakistan into 15 provinces of different seismicity levels and abundances of active faults. The map does not explain criteria or describe evidence for distinguishing active from inactive faults. However, Kazmi (1979a) does.

Kazmi, A.H., and Rana, R.A., compilers, 1982, Tectonic map of Pakistan: Geological Survey of Pakistan, 1 sheet, scale 1:2,000,000.

Kingston, John, and Clarke, J.W., 1995, Petroleum geology and resources of Afghanistan: International Geology Review, v. 37, no. 2, p. 111–127.

The southern portion of the Eurasian continental platform in northern Afghanistan is bounded on the south and east by a series of northeast-trending accreted continental terranes. Sutures containing ophiolites separate the terranes and are interpreted as remnants of subducted oceanic crust. The North Afghanistan basin is on the platform north of the accreted terranes. The basin represents the southeastern part of the mature Amu Dar'ya gas-oil province of Turkmenistan and Uzbekistan. Kingston and Clarke conclude that the basin contains the only appreciable Afghan petroleum prospects. Traps are in folds inferred to overlie reactivated basement faults. The largest of these faults strike east-west; the authors mention the Alburz-Mormul and Mirzavalang faults in Afghanistan, and figure 2 locates both faults. Older traps grew during the Mesozoic; whereas younger ones began to develop during the early Neogene with growth peaking in the Pliocene and continuing today (contrast Brookfield and Hashmat [2001]). Figure 1 of the paper applies the name Hari-rud to a poorly defined fault zone that strikes northerly through easternmost Iran, contrary to all other usage of variants of this name (see table 1 above).

Lawrence, R.D., Hasan Khan, S., Nakata, T., 1992, Chaman Fault, Pakistan-Afghanistan, *in* Bucknam, R.C., and Hancock, P.L., eds., Major active faults of the world—Results of IGCP Project 206: Annales Tectonicae, Special Issue Supplement to v. 6, p. 196–223.

This is the authoritative description and analysis of the Chaman fault. It is based on aerial photographs and fieldwork on nearly all of the southern (Pakistan) half of the fault, and on interpretations of satellite imagery for the entire fault in Pakistan and Afghanistan. There is no mention of trenching or attempts to identify or characterize individual prehistoric earthquakes. The Chaman fault forms the western edge of the north-trending, left-lateral, transpressional plate boundary between the relatively northward-moving Indian plate on the east and the Eurasian plate on the west. Within its latitude range, the Chaman fault is the most active strand in the transpressional boundary. At its northern end, the fault terminates against the east-striking Herat fault north of Kabul.

Relatively sparse seismicity in the northern section of the Chaman fault and relatively more earthquakes on the Gardez fault, which forks northeast from the Chaman, have led to suggestions that modern slip bypasses the northern section of the Chaman fault in favor of the Gardez fault. Lawrence and others suggested that left-lateral strike slip may continue north along the aligned Chaman, Panjshir, and Central Badakhshan faults on the west, and along the aligned Gardez and Kunar faults on the east. At the south end of the Chaman fault, strike slip is transferred west to a complex of south-facing thrust faults in the Makran Coast Range of Pakistan.

Lawrence and others measured offsets and estimated ages of four large geologic features across the Chaman fault, obtaining a minimum slip rate of 19–24 mm/yr since 20–25 Ma. They cited another estimate from offset volcanic rocks of 25–35 mm/yr since 2 Ma. In Pakistan, the Chaman fault is a zone of crushed bedrock with an average width of 500 m and a maximum width of 1 km. Individual fault strands can be mapped within the zone. Lawrence and others documented recent strike slip throughout the Pakistan half of the fault and showed photographs of abundant field and aerial photographic evidence of the recent slip: “only the alluvium of the bottom of active dry washes is not displaced” (p. 204). In the Afghanistan half of the fault, they had no field or aerial photographic data and poorer quality satellite images than were available for Pakistan.

North of the junction of the Chaman and Gardez faults, Lawrence and others did not find clear evidence of surface rupture on either fault except in the vicinity of the large 1505 Kabul earthquake. South of the junction, field observations allowed the authors to conclude that an earthquake in 1892 produced a surface rupture at least 60 km long, thereby doubling the literature-based length estimate of Quittmeyer and Jacob (1979). Lawrence and others also cited an 1893 report that the 1892 earthquake produced 60–75 cm of left-lateral slip and dropped the western wall of the Chaman fault down 20–30 cm. Near the southern end of the Chaman fault, they described continuous pressure ridges parallel to the fault. They interpreted the ridges as indicating transpression caused by slight convergence of the Indian plate against the Chaman fault during the mainly northward relative motion of the Indian plate. Lawrence and others summarized reports of historical earthquake damage that were also summarized by Quittmeyer and Jacob (1979). Additionally, Lawrence and others cited a published report of five kilometers of ground cracking, as much as 4 cm of left-lateral strike slip, and smaller amounts of east-side-down slip, from a magnitude 6.4 earthquake that occurred on October 3, 1975, in the same general area as the 1892 Chaman earthquake.

Lawrence, R.D., and Yeats, R.S., 1979, Geological reconnaissance of the Chaman fault in Pakistan, *in* Farah, Abul, and De Jong, K.A., eds., Geodynamics of Pakistan: Quetta, Pakistan, Geological Survey of Pakistan, p. 351–357.

Maggi, A., Jackson, J., McKenzie, D., and Priestly, K., 2000, Earthquake focal depths, effective elastic thickness and the strength of the continental lithosphere: Geology, v. 28, p. 495–498.

The authors inferred that the results of Maggi, Jackson, Priestly, and Baker (2000) imply that continental elastic thickness is similar to, although slightly smaller than, seismogenic thickness and that the continental lower crust generally is stronger than the upper mantle. Note that this result reinforces the suggestion of Pegler and Das (1998) and previous workers that the intermediate-depth seismicity beneath the Hindu Kush and Pamirs originates in a subducted slab. The suggestion implies that the intermediate-depth seismicity would be in subducted continental crust that is stronger than the surrounding mantle into which the subducted slab is penetrating.

Maggi, A., Jackson, J., Priestly, K., and Baker, C., 2000, A reassessment of focal depth distribution in southern Iran, the Tien Shan and northern India—Do earthquakes really occur in the continental mantle?: Geophysical Journal International, v. 143, p. 629–661.

The authors performed waveform modeling of teleseismic records of earthquakes in the Zagros and Makran subduction zones of southern Iran, the Tien Shan region of western China and Kyrgyzstan, and northern India and adjacent areas. Their primary purpose was to “see whether our rheological views of the continental lithosphere based on earthquake focal depths need modification in the light of the large amount of extra data now available since the original studies of 15–20 years ago” (p. 630). Within the study areas, the authors found that centroid depths were entirely within the continental crust, and they questioned whether the continental mantle is significantly seismically active anywhere. Note that this finding is consistent with the suggestion of Pegler and Das (1998) and previous workers that the intermediate-depth seismicity beneath the Hindu Kush and Pamirs originates in a subducted slab.

Nakata, Takashi, Tsutsumi, Hiroyuki, Khan, Shahid Hasan, and Lawrence, Robert D., 1991, Active faults of Pakistan—Map sheets and inventories: Hiroshima, Japan, Hiroshima University Research Center for Regional Geography Special Publication No. 21, 141 p.

The authors compiled Late Quaternary surface faults from recently displaced landforms as interpreted on 1:40,000-scale aerial photographs, the literature, and their own fieldwork. Faults are shown on 1:500,000-scale topographic maps of 55 1° × 1° quadrangles that cover most of the northwestern two-thirds of Pakistan and small adjacent parts of Afghanistan and Iran. The authors found no active faults in the Indus Plain, which covers the southeastern third of Pakistan. Each fault is characterized by a short text and by a table containing text or numerical entries in 11 fields.

Pegler, G., and Das, S., 1998, An enhanced image of the Pamir-Hindu Kush seismic zone from relocated earthquake hypocenters: Geophysical Journal International, v. 134, p. 573–595.

The Hindu Kush are in northeastern Afghanistan and the Pamirs lie farther northeast, in eastern Tajikistan. The study analyzed many more earthquakes (about 6,000) from a larger area than had been studied previously. The authors' goal was to determine whether the intermediate-depth earthquakes under the Pamirs and Hindu Kush represent a single, steeply dipping, contorted seismicity zone or two separate steep zones. Hypocenters were relocated with joint hypocenter determinations.

In map view, the combined intermediate-depth seismicity beneath both mountain ranges extends northeast in an open S that is 700 km long. In section view, the seismicity zone is tabular, generally no thicker than 30 km. Within the S-shaped, tabular zone, earthquakes cluster with gaps between some clusters. Beneath the Hindu Kush the zone dips steeply (50°–90°) north and is mostly at depths of 100–300 km, but beneath the Pamirs it dips steeply (50°–60°) south and is concentrated at depths from 80 km to 150–200 km. The seismicity zone beneath the Hindu Kush steepens eastward until, at its eastern end, it overturns and dips 70°–80° south. Pegler and Das illustrated the complex three-dimensional geometry of the seismicity with a series of 12 maps and 20 cross sections. It is unclear what geologic feature the seismicity represents. Chatelain and others (1980) suggested subduction of two small ocean basins, but Pegler and Das found no reported geologic evidence of subducted oceanic rocks. Pegler and Das concluded that the seismicity zone is continuous along its 700 km length; previous, shorter-term studies had reported a gap between the Hindu Kush and the Pamirs but Pegler and Das's longer-term catalog filled the gap. They cited several papers to demonstrate wide acceptance that the Hindu Kush intermediate-depth seismicity reflects northward subduction of part of the Indian plate. They noted that some of the Hindu Kush seismicity extends to depths as shallow as 60 km and might reach the surface near the Main Mantle Thrust or the Main Karakorum Thrust of the western Himalaya.

They considered, but found wanting, analogous suggestions by other authors that the Pamirs seismicity reflects southward subduction of Asian continental crust. Instead, Pegler and Das suggested that the entire 700-km-long seismicity zone represents northward-subducted crust of the Indian plate, with the eastern part under the Pamirs having been rotated, the top to the north, about a horizontal axis. At depths shallower than 90 km, the eastern part was torn away northward from the adjacent western part beneath the Hindu Kush. Pegler and Das suggested that the greater northward movement of the shallower levels in the east could have been accommodated by right-lateral strike slip on the Karakorum fault, which strikes northwest across the eastern end of the Pamirs. They concluded that the intermediate-depth seismicity beneath the Pamirs reflects a single subducted slab that has been deformed by northward flow within the upper mantle under the Pamirs.

Pennington, W.D., 1979, A summary of field and seismic observations of the Pattan earthquake—28 December 1974, *in* Farah, Abul, and De Jong, K.A., eds., Geodynamics of Pakistan: Quetta, Pakistan, Geological Survey of Pakistan, p. 143–147.

Prevot, R., Hatzfeld, D., Roecker, S.W., and Molnar, P., 1980, Shallow earthquakes and active tectonics in eastern Afghanistan: Journal of Geophysical Research, v. 85, no. B3, p. 1347–1357.

Several microearthquake studies near Kabul, Afghanistan, showed clusters of earthquake epicenters near or along the traces of the Chaman and Sarubi faults. However, overall the epicenters are scattered and do not appear to concentrate near traces of known faults. Composite focal mechanisms from clusters of earthquakes near the faults had nodal planes parallel to the faults. Other composite mechanisms were constructed from earthquake clusters far from mapped faults. The mechanisms have a wide range of nodal plane orientations, but P-axes generally cluster near the north trend of the plate vector along which India converges with Eurasia. With the exception of the Chaman and Sarubi faults, most of the data appear to indicate diffuse deformation throughout a large crustal volume where several large faults intersect in map view. This suggestion is consistent with a later one of Lawrence and others (1992, p. 202).

Quittmeyer, R.C., Farah, Abul, and Jacob, K.H., 1979, The seismicity of Pakistan and its relation to surface faults, *in* Farah, Abul, and De Jong, K.A., eds., Geodynamics of Pakistan: Quetta, Pakistan, Geological Survey of Pakistan, p. 271–284.

Quittmeyer, R.C., and Jacob, K.H., 1979, Historical and modern seismicity of Pakistan, Afghanistan, northwestern India, and southeastern Iran: Bulletin of the Seismological Society of America, v. 69, no. 3, p. 773–823.

This authoritative summary covers seismicity through 1965. It cites papers interpreting the Herat and Chaman faults in Afghanistan as active surfaces along which crustal blocks are being extruded as India indents Eurasia. Particularly useful here are Appendixes 1 and 2, which contain summaries of reports of historical surface ruptures and other evidence indicating activity of individual Afghan faults.

Seismicity is low to moderate along and near the Chaman fault, but two large historical earthquakes have ruptured it. On July 5 or 6, 1505, slip associated with the Paghman earthquake ruptured approximately 60 km of the northern Chaman fault, with vertical displacements of several meters. Such large vertical movement on a mainly strike-slip fault led Quittmeyer and Jacob to suggest that a strike-slip component may have gone unreported. On December 20, 1892, slip that caused the Chaman earthquake offset railroad tracks by least 75 cm left-laterally; surface rupture extended at least 30 km along the central Chaman fault. (Note that field observations of Lawrence and others [1992] doubled this length estimate to 60 km.) Additionally, Quittmeyer and Jacob reported that interviews with local village elders indicated three surface ruptures before 1892 during the lifetimes of the interviewees, with similar reports from the oral history that had been handed down to the interviewed elders from their ancestors. Quittmeyer and Jacob suggested that these repeated large ruptures and the long, continuous nature of the Chaman fault indicate that the fault accommodates “a significant portion of the motion between the Indian and Eurasian plates” (p. 802).

On February 19, 1842, the Alingar Valley earthquake occurred northeast of Kabul. The shock lacked a reported surface rupture, but “contemporary narratives indicate that rupture proceeded from the north-northeast to the south-southwest along a portion of the Gardez fault” (p. 791). (Note that Quittmeyer and Jacob used the name Gardez for a fault that extends from approximately 50 km east of Kabul to about 200 km northeast of Kabul. In contrast, Everett and others (1986) and Lawrence and others (1992) applied the name to a longer, west-concave fault that lies farther southwest, east of and roughly parallel to the northern part of the Chaman fault. The fault named Gardez by Lawrence and others and Everett and others passes near Gardez, Afghanistan, whereas the southern end of the fault named Gardez by Quittmeyer and Jacob is 100 km north-northeast of Gardez. Apparently Quittmeyer and Jacob misused the name Gardez.) Quittmeyer and Jacob also reported that teleseismic data indicate that the central part of the fault they labeled Gardez, including the part thought to have ruptured in 1842, is seismically active. They reported the same for the southern part of the Kunar fault, as well as unpublished microseismicity along this fault.

The authors considered the morphologically prominent Herat fault to be seismically inactive historically. They mentioned an earthquake near Herat in the ninth century and one in 1874 north of Kabul, both near the Herat fault and possibly associated with it. However, they concluded that “even for these events the evidence is not strong” (p. 803) for an association with the Herat fault.

Roecker, S.W., Soboleva, O.V., Nersesov, I.L., Lukk, A.A., Hatzfeld, D., Chatelain, J.L., and Molnar, P., 1980, Seismicity and fault plane solutions of intermediate depth earthquakes in the Pamir-Hindu Kush region: Journal of Geophysical Research, v. 85, no. B3, p. 1358–1364.

This paper gives details of the focal mechanisms of Chatelain and others (1980).

Sarwar, Ghulam, and De Jong, K.A., 1979, Arcs, oroclines, syntaxes—The curvatures of mountain belts in Pakistan, *in* Farah, Abul, and De Jong, K.A., eds., Geodynamics of Pakistan: Quetta, Pakistan, Geological Survey of Pakistan, p. 341–349.

The authors described the strongly curved mountain ranges of northwestern Pakistan and adjacent parts of Afghanistan. They followed previous authors in concluding that the curved ranges are thin-skinned, south-verging, fold and thrust belts. This conclusion implies that the thin-skinned belts may be too thin to be involved in seismogenic basement faulting in their southern parts. However, if the thin-skinned belts thicken northward, then their faults might penetrate basement in their northern parts, in or near Afghanistan.

Sborshchikov, I.M., Savostin, L.A., and Zonenshayn, L.P., 1981, Present plate tectonics between Turkey and Tibet: Tectonophysics, v. 79, no. 1-2, p. 45–73.

Grabens along the Hari Rud fault of central Afghanistan are filled with Neogene conglomerates, from which the authors inferred that strike slip on the fault began at least in the Early Miocene. Satellite photographs show 800 m of right-lateral offsets of streams “in the midstream of the Hari Rud river” (p. 58) at a location that is otherwise not identified. The authors mentioned in passing that “similar displacements, which can be attributed only to a dextral shift, were observed elsewhere” (p. 58); again, no location was specified. Their figure 5 shows much larger stream offsets across the Hari Rud fault, and p. 61 states that aerial and satellite photographs show the average offset to be approximately 5 km. The authors inferred that “the time of the shaping of the river system in this region is most likely the Upper Pliocene, i.e. about 2 m.y. before present … and the velocity amounts thus to 0.2–0.3 cm yr^{-1}” (p. 61). Accordingly, they regarded the Hari Rud fault as active despite its lack of significant seismicity. Similarly, their figure 5 also shows left-lateral stream offsets of several kilometers along the Mukur-Chaman fault at an unstated location. From the modern strike slip on the Hari Rud and Mukur-Chaman faults, the authors concluded that Afghanistan south of the Hari Rud fault is being extruded westward in response to collision farther east between the Indian and Eurasian plates.

Schindler, J.S., 2002, Afghanistan—Geology in a troubled land: Geotimes, v. 47, no. 2, p. 14–18.

The article contains brief summaries of Afghanistan’s geologic evolution, the level of knowledge of its geology and

mineral resources, and geographic and human factors that impact efforts to build a nation. An inset map shows main faults, including the Chaman and Hari-Rod (also called Hari Rud and Herat) faults.

Schreiber, Alfred, Weippert, Dietrich, Wittekindt, H.-P., and Wolfart, Reinhard, 1972, Geology and Petroleum Potentials of Central and South Afghanistan: The American Association of Petroleum Geologists Bulletin, v. 56, no. 8, p. 1494–1519.

Numerous stratigraphic columns, detailed stratigraphic descriptions, and a page-sized summary of a 1970 geologic map of Afghanistan comprise a useful summary of Afghan geology. Fieldwork and analysis were performed by the Afghan Geological Survey and the West German Geological Survey from 1959 through 1971. Fault names and spellings accord with the Royal Afghan Cartographic Institute. However, the authors' use of geosynclinal theory, which predates plate tectonics, makes the tectonic interpretations of Wittekindt and others (1997) more useful. Descriptions of Quaternary geology are too sparse to suggest which faults might be active today.

Seeber, Leonardo, and Armbruster, John, 1979, Seismicity of the Hazara arc in northern Pakistan —decollement vs. basement faulting, *in* Farah, Abul, and De Jong, K.A., eds., Geodynamics of Pakistan: Quetta, Pakistan, Geological Survey of Pakistan, p. 131–142.

Sella, G.F., Dixon, T.H., and Mao, Ailin, 2002, REVEL – A model for Recent plate velocities from space geodesy: Journal of Geophysical Research, v. 107, no. B4, p. 11-1–11-32.

The paper uses only seven years of space geodetic data to compute relative velocities between 19 plates and parts of continents. As an aside, p. 11–27 gives 48 mm/yr as the rate of the relative motion between India and Eurasia for a site that their figure 5 shows to be in southern India, as calculated from the NUVEL-1A model of DeMets and others (1994). The annotation for DeMets and others (1994) assesses the 48 mm/yr result.

Sengor, A.M.C., 1984, The Cimmeride orogenic system and the tectonics of Eurasia: Geological Society of America Special Paper 195, 82 p.

This massive summary of the Cimmeride orogeny integrates field observations and literature on geology and its development from Gibraltar to Malaysia and the Pacific coast of Russia. An ocean named Tethys lay between Laurasia and Gondwana during and before the early and middle Mesozoic Era. Beginning in the Triassic Period, and in some places earlier, continental fragments rifted from Gondwana and drifted north toward Laurasia. North of the drifting fragments lay the original Tethys, or Paleo-Tethys. South of the fragments lay Neo-Tethys. The effect of the north-drifting continental fragments was to subduct Paleo-Tethys as Neo-Tethys grew. As Paleo-Tethys finally closed at the south edge of what is now northern Afghanistan, some of the continental fragments accreted to form what is now central and southern Afghanistan.

Shareq, Abdullah, 1981, Geological and geophysical investigations carried out in Afghanistan over the period 1972–1979, *in* Gupta, H.K., and Delany, F.M., eds., Zagros, Hindu Kush, Himalaya—Geodynamic evolution: American Geophysical Union Geodynamics Series 3, p. 75–86, 1 folded plate, scale 1:2,500,000.

The paper summarized Russian and Afghan geologic and tectonic maps of Afghanistan, and stratigraphy, magmatism, tectonics, geophysical surveys of parts of the country, and seismicity. Shareq reported that results of fieldwork up to 1972 were compiled into 1:1,000,000-scale geologic, tectonic, and magmatic maps of Afghanistan for the 24th International Geological Congress in Montreal (presumably these are the maps of Chmyriov and Mirzad [1971, 1972]). Subsequent data yielded a 1977 1:500,000-scale geologic map of Afghanistan (presumably this is the map of Shareq and Chmyriov [1977]). The sections of the paper on stratigraphy, igneous rocks, and tectonics are largely descriptive, with tectonic interpretations that use geosynclinal concepts from before the advent of plate tectonics. Radiometric dates from igneous rocks are generalized and of unspecified type.

The descriptions can be read in terms of successive southeastward accretions of exotic terranes to the Turan (North Afghan) platform. Basement of the platform comprises Hercynian (Variscan: Carboniferous and Permian) metamorphic, volcanic, and sedimentary rocks that are exposed only in deep valleys, cores of anticlines, and in northeastern Afghanistan. The platform is bounded on the south and east by the most structurally complex rocks in the country. These complex rocks form a belt that trends east across most of Afghanistan to the vicinity of Kabul, and is bounded by the Hari Rod fault on the north and the Karganaw fault on the south. Near Kabul, the belt bends northeastward and northward, and is bounded on the southeast and east by the Central Badakhshan fault. The author asserted that microseismic studies showed the Alburz-Marmul, Central Badakhshan, Pansjer, Pagman, Kunar, and Chaman faults to be seismically active, and that hypocenters northwest of the trace of the Pansher fault show it to dip northwest. However, no evidence or figures were provided to support these assertions. A folded plate bears a 1:2,500,000-scale tectonic map of Afghanistan that is dated 1975. One smaller-scale index map on the plate shows tectonic provinces and a second shows names of major faults and the tectonic blocks between them. The plate refers to the east-trending belt of structurally complex rocks as the Middle Afghanistan geosuture zone.

Note that distances labeled on the rake scale of the tectonic map are too small by a factor of 10. Note also that the reference list showed the author's name as "Abdullah, Sh.", indicating that his family name is Abdullah. Some Georef citations list him as Abdullah Shareq but other citations list Shareq Abdullah. Inquiries at the University of Nebraska's

Center for Afghanistan Studies verified that the author's given name is Abdullah and his family name is Shareq.

Shareq, Abdullah, 1992, Major active faults in Afghanistan, *in* Section I-2-09, Evaluation of active faults and seismic hazards: International Geological Congress, 29th, Kyoto, 1992 [Abstracts], p. 77.

Most of this summary is in Shareq (1993), but this abstract also named the geologic features that are separated by each of the Alburz-Marmul, Khohan-Ishkamish, Kunar, and Chaman-Muqur faults. Additionally, the use of seismicity to identify each of the faults as active was described more clearly and specifically than in Shareq (1993), although still so briefly that it is difficult to assess the statements that individual faults are seismically active.

Shareq, Abdullah, 1993, Seismic hazard in the Islamic State of Afghanistan, *in* McGuire, R.K., ed., The practice of earthquake hazard assessment: International Association of Seismology and Physics of the Earth's Interior, p. 1–6.

The short paper concentrated on seismicity and construction of a hazard map. Figures showed page-sized maps of seismicity, major faults with their names, and "seismic danger zones". Faults were distinguished by whether they are "certain" or "supposed" and by the geological Periods of their origins and of their main movements. The danger zones were characterized by high, medium, or weak frequencies of earthquakes of specified magnitudes, maximum intensities, and focal depths. The text listed as active or briefly described the activity of 13 named faults. The fault map showed 11 of them as well as 3 others, for a total of 16 named active faults. Clusters of epicenters were assigned to individual known faults without explanation.

Maximum magnitudes were estimated for individual faults from historical seismicity and unspecified geological information. In seismically active northeastern Afghanistan, "the Khohan-Ishkamish fault is one of the most important seismogenic structures in Afghanistan" (p. 2). This is the Darvaz fault of Trifonov (1978) (Appendix 1). Shareq estimated that earthquakes as large as surface-wave magnitude Ms 7.5–8 occur along this fault approximately once per 1,000 years. The Central Badakshan fault has the same estimated maximum magnitude, occurring at much longer estimated intervals of about 50,000 years. The Kunar fault "is also notable for its high seismic activity" (p. 2), up to an estimated maximum body-wave magnitude of mb 7.5. Felt crustal earthquakes were estimated to occur most frequently along the Alburz-Marmul fault. In less active central and western Afghanistan, the Harirod (Herat) fault has an estimated maximum magnitude of mb 6. In southeastern Afghanistan, the Chaman Muqur fault has associated seismicity higher than that of the Harirod fault, but lower than the northeastern faults, and an estimated maximum magnitude of mb 7. See also Shareq (1992).

Note that the reference list showed the author's name as "Abdullah, Sh.", indicating that his family name is Abdullah. Some Georef citations list him as Abdullah Shareq but other citations list Shareq Abdullah. Inquiries at the University of Nebraska's Center for Afghanistan Studies verified that the author's given name is Abdullah and his family name is Shareq.

Shareq, Abdullah, and Chmyriov, V.M., editors-in-chief, 1977, Map of mineral resources of Afghanistan: Ministry of Mines and Industries of the Democratic Republic of Afghanistan, Department of Geological and Mineral Survey, scale 1:500,000.

The map consists of a geologic map with superimposed symbols showing locations of mineral deposits and resources. It is uncertain whether the map was published as a single large sheet, in a few smaller sheets, or as a folio of many separate quadrangles. The map was digitized and scanned by the Russians in 2004 with USGS funding. USGS received only the digital files, not the paper map. The citation above was extracted from a scanned image of the title page or title block of the map. Details in the files suggested to R.R. Wahl (oral commun., February 10, 2005) that the digitized materials may have been compilation maps at a scale smaller than 1:500,000. Note that the list of editors in chief, the list of compilers, and the list of contributors all show the senior editor's name as "Sh. Abdullah", indicating that his family name is Abdullah. Some Georef citations list him as Shareq Abdullah but other citations list Abdullah Shareq. Inquiries at the University of Nebraska's Center for Afghanistan Studies verified that the author's given name is Abdullah and his family name is Shareq.

Tapponnier, P., Mattauer, M., Proust, F., and Cassaigneau, C., 1981, Mesozoic ophiolites, sutures, and large-scale tectonic movements in Afghanistan: Earth and Planetary Science Letters, v. 52, p. 355–371.

Afghanistan is largely the result of successive suturing of Gondwanan fragments to the active southern margin of Laurasia since the Paleozoic, ending with the arrival of India. Fragments accreted successively southward along as many as four sutures from the Early Jurassic through the Late Paleocene. Most, perhaps all, of the sutures originally dipped north. Subsequent strike-slip and perhaps north-south shortening produced steep to vertical dips and obscured the original dips and dip directions of at least the northern sutures. Ophiolites were obducted southward, at least in the southern sutures, as north-dipping subduction zones were choked with continental crust. Today, east of the Chaman fault, several units are being thrust southward onto the subducting Indian plate as it chokes the final suture.

The Chaman fault itself has undergone several hundred kilometers of Tertiary left-lateral strike slip. "Studies of Quaternary morphology yield a displacement rate of 1–2 cm/yr along the master fault during the last 100,000 years …. Since the beginning of the Quaternary, the average rate across the whole fault zone could have been higher (2.5–3.5 cm/yr) …" (p. 358); the only citation given for these two statements is a 5-page paper in French.

Between the Chaman and Herat faults, numerous other faults dip steeply and strike northeasterly. The Herat fault marks the northernmost suture and, farther south, the Panjao suture divides central Afghanistan into the Farah block on the north and the Helmand block on the south. Tertiary tectonics within and between these blocks were largely strike-slip faulting. The linearity of the Herat fault over hundreds of kilometers, horizontal slickensides in Cretaceous and Eocene strata, and narrow basins containing continental sediments of Oligocene and Miocene age demonstrate right-lateral strike slip. However, "although the fault zone is still sharply expressed in the Quaternary morphology, it may no longer be active since post-Miocene deposits are not clearly offset along it" (p. 359); the main support for this conclusion is a citation of a French paper. Additionally, on p. 364 the authors observed that "the Herat fault trace, although clear on Landsat photos, is not as sharp as that of active faults such as the Chaman …."

North of the Herat fault, the Asian or Turan platform was deformed only mildly during the Tertiary. The platform basement was formed during the Hercynian (Carboniferous-Permian) orogeny; whereas, there is no evidence of this orogeny south of the Herat fault. The platform cover consists of possible Triassic basalts, Jurassic evaporates, Cretaceous/Paleocene shallow-marine limestones, and Tertiary continental deposits that, together, reach thicknesses of 10 km in some platform basins.

The authors inferred that the northwest corner of the Indian plate indented Eurasia, raising the Pamirs and thrusting them northward, and extruding central Afghanistan southwestward since the Eocene by strike slip along the Herat, Panjao, and Chaman-Panjshir faults. They suggested that the main extrusion culminated during the Oligocene and ended during the Miocene. However, they allowed that some minor extrusion might continue today on the west-striking Andarab fault that parallels the Herat fault farther north within the Turan platform (see also Treloar and Izatt, 1993).

Tirrul, R., Bell, I.R., Griffis, R.J., and Camp, V.E., 1983, The Sistan suture zone of eastern Iran: Geological Society of America Bulletin, v. 94, no. 1, p. 134–150.

Treloar, P.J., and Izatt, C.N., 1993, Tectonics of the Himalayan collision between the Indian Plate and the Afghan Block—A synthesis, *in* Treloar, P.J., and Searle, M.P., eds., Himalayan tectonics: Geological Society Special Publications, v. 74, p. 69–87.

The paper is an excellent summary of its topic and suggests answers to questions that remain open. Crust north and west of the Herat and Central Badakhstan faults has been part of the Eurasian plate (Tadzhik platform) since Late Paleozoic time. Crustal fragments south and east of the two faults and north and west of the Chaman and Konar faults rifted away from Gondwanaland before India did, and accreted to the Tadzhik platform during the Cimmerian orogeny (Triassic-Jurassic) before India did. The accreting terranes were added successively southward. "Permo-Triassic subduction related granitoids" (p. 71) in the southernmost part of the Tadzhik platform may indicate that at least the first subduction zone dipped northerly. Today the Herat fault forms the northern edge of the outcrop of this northernmost subduction zone.

After Cimmeride accretion, a Mesozoic shelf sequence was deposited atop the accreted terranes. The authors referred to this basement of Cimmeride accreted terranes and its sedimentary cover as the Afghan block, which is therefore bounded on the southeast by the Chaman and Konar faults. Both basement and cover were later deformed and intruded as results of the Indian collision and related subduction of Tethyan oceanic crust; thus, these subduction zones also dipped north. By Oligocene and Miocene time, the widespread Mesozoic platform sedimentation had given way to localized basins that received red molasses on both the Tadzhik platform and the Afghan block. The authors attributed this change in sedimentary regime to regional uplift caused by the start of the Himalayan collision of India with Asia.

During Oligocene-Miocene time the Herat fault was reactivated. Pull-apart basins with Oligocene-Miocene fills, Oligocene alkaline volcanic rocks, and left-lateral offsets demonstrate a transtensional setting for this reactivation. "Most of the internal block boundaries, including Cimmeride suture zones, within the Afghan Block have been reactivated during the Tertiary as fault zones with strike-slip displacement senses …" (p. 73). The authors repeated the conclusion of Tapponnier and others (1981) that a lack of clear offsets of deposits younger than Miocene along the Herat fault indicates post-Miocene inactivity. In contrast, they noted surface ruptures and geomorphic evidence that demonstrate present-day activity of the Chaman fault and suggest the same for the Andarab, Tirin, and Central Badakhstan faults (see also Wellman [1965], Trifonov [1978], Quittmeyer and Jacob [1979], Yeats and others [1979], and Lawrence and others [1992]).

The Afghan block was subsequently further deformed during the Himalayan collision, as evidenced by folded and reverse-faulted Paleogene and Neogene(?) rocks. The authors and Brookfield and Hashmat (2001) presented four cross sections across the eastern Herat fault. The sections show reverse faults, most of which dip south. Additionally, figure 69 of Wolfart and Wittekindt (1980) shows three additional cross sections across the Herat fault and all three show solely south-dipping reverse faults. In contrast, recall that most or all subduction zones are inferred to have dipped north originally. An unstated implication of this difference is that, depending on the intensity of the Himalayan deformation, modern dip of faults at the outcrop may not reflect either modern or original dip of a crustal-scale suture.

After detailed descriptions of field relations in eastern Afghanistan and southwestern Pakistan, Treloar and Izatt concluded that India's collision with the Afghan block, closure of the Katawaz basin that formed either on oceanic crust or on the western edge of the Indian plate, and inception of the Chaman fault in left-lateral strike slip all occurred during the Pliocene Epoch. From this, and from the apparent lack of significant post-Miocene slip on the Herat fault, the authors concluded that the Chaman and Herat faults were never active at the same time and cannot have combined to extrude the Afghan block southwestward in response to the Indian indentation into Asia. They noted that minor extrusion might have occurred on the presently active Andarab and Talemazar faults north of the Herat fault within the Tadzhik platform (see also Tapponnier and others, 1981).

Trifonov, V.G., 1978, Late Quaternary tectonic movements of western and central Asia: Geological Society of America Bulletin, v. 89, p. 1059–1072.

Interpretations of satellite imagery, aerial photographs, and field observations identify and characterize late Pleistocene and Holocene surface ruptures throughout a vast region from Turkey to east of Lake Baikal. The faulting is driven by northerly subduction of the Arabian and Indian plates beneath the Eurasian plate. Between converging plates, shortening produces reverse and conjugate strike-slip faulting. Between the Arabian and Indian plates, north-striking continental transform faults accommodate differential northward movement. Additionally, convergence of both subducting plates against Eurasia extrudes slices of continental crust along wrench faults.

The author reported young offsets for many individual faults. Where offsets have been measured and ages of offset surfaces or landforms have been estimated, slip rates could be calculated for hazard computation. However, such rates would be highly uncertain because surfaces are poorly dated. For example, the paper neither gives nor cites numerical definitions of the time terms used in the following paragraph. Nearly two decades later, Ioffe and Kozhurin (1996) stated that the Middle Pleistocene extended from 0.7 Ma to 0.1 Ma, but is unclear whether Trifonov (1978) used these dates.

Trifonov summarized offsets and ages for several Afghan faults. The northeast-striking part of the Darvaz fault underwent 60–95 m of strike slip with minor reverse slip during the late Holocene, 150–160 m during the Holocene, 300–350 m during the end of the late Pleistocene and the Holocene, 800 m during the entire late Pleistocene and Holocene, and 1200 m since the end of the middle Pleistocene. The north-striking part of the Darvaz fault underwent up to 20 m of strike slip during the late Holocene, up to 120 m during most or all of the Holocene with rare displacements as large as 140–150 m, and 300 m during the entire late Pleistocene and Holocene. Offset surfaces on the Chaman and Darafshan faults are undated. Holocene offsets on the east-striking Herat fault, and on the parallel Talemazar fault to the north, were reported by Wellman (1965) but disputed by Molnar in a personal communication that Trifonov cited on p. 1069.

Trifonov, V.G., 1999, Neotectonics of Eurasia: Moscow, Russia, Nauchnyi Mir (Scientific World) Press, 252 p. (in Russian with 17 p. English summary, and abstract, table of contents and figure captions in both English and Russian).

The book deals largely with neotectonics, regional deformation, and tectonic and plate-tectonic models instead of Holocene or Quaternary slip rates of individual faults. There are no tables. Several well-studied faults are used to illustrate classes and subclasses of fault behaviors, but none are in Afghanistan. Trifonov noted that the transform boundary between eastern Afghanistan and the Indian plate is the Chaman fault in southeastern Afghanistan and the Darvaz-Alai fault farther north in Tajikistan (p. 211 and fig. 9).

Several sentences scattered through section 1.2 on the Pamir-Himalayan Region contain statements about offsets of features of known age, or actual slip rates. G. Ulmishek of the USGS was kind enough to translate these sentences verbally. The following page numbers and paragraph counts refer to the Russian original. A paragraph that overlaps from the previous page onto the page in question is counted as the first paragraph. Quotations in the following paragraphs distinguish translated material from the longer annotations. Some short annotations are within the quotes but identified by parentheses and question marks.

Page 33, para. 4: “In the northeastern part of the Darvaz fault, slip is 10–15 mm/yr.” A similar statement appears in Trifonov (1978, p. 1066). Note that the Darvaz fault is mainly in Tajikistan, but it extends south into northeastern Afghanistan. In Afghanistan the fault strikes north and is right-lateral strike slip, but in Tajikistan it curves toward eastern strikes and a reverse component dominates. According to Trifonov (1978), this slip rate was measured on the reverse-fault section of the fault. However, it also may indicate rapid slip on the strike-slip section that extends into Afghanistan.

Page 40, para. 6 – p. 41, para. 3: “The east part of the Surkhob-Ilyak zone between the villages of Tajikabad and Garm is right-lateral strike slip with reverse faults and thrusts. One of them, tilted to the south at a dip of 40°–45° near the mouth of the Runou river, offsets an early Holocene terrace by 15 m. Multi-year geodetic observations show systematic, although amplitude-varying, uplift of the south limb (hanging wall?) at 15 mm/yr, and also the limbs (hanging and footwalls?) become closer (move together?) at 20 mm/yr.” Tajikabad and Garm are along the Surkhob River in Tajikistan and approximately 80 km north of the Afghan border.

“Repeated observations-with-light (laser ranging?) measurements on a large base (large distance, large number of measurements?) found shifting of an observed point in the northeastern part of Vakhsh ridge to the southwest at 20 mm/yr, which means longitudinal lengthening and squeezing to the southwest of the External Zone relative to both the North Pamir and Darvaz, on the one hand, and the South Tien Shan, on the other hand. …” Vakhsh is in Tajikistan approximately 50 km north of the Afghan border.

“In the southwest part of the Surkhob-Ilyak zone near the mouth of the Obigarm River the velocity of geodetically measured thrusting is 10 mm/yr. In the same area, deformation of relief and young sediments indicate late Quaternary thrusting, and in one of the branches of the zone, right-lateral strike slip up to 10 m. South of the town of Fayzabad the fault is not exposed, but correlation of wells indicates vertical offset of the base of upper Pleistocene sediments by 200 m. Farther southwest at Zaredolyu Pass and near the town of

Yavan, a right-lateral component of faulting much larger than the vertical component is clearly indicated by deformation of topography. The velocity of late Quaternary strike slip is 1.5–3 mm/yr." The town of Obigarm is in Tajikistan approximately 150 km north of the Afghan border. Fayzabad is in northeastern Afghanistan at approximately 36.1°N., 70.6°E.

Page 42, para. 3, last sentence: "GPS data indicate that the present-day shortening of the Tien Shan, both West and East (parts?), is 20 mm/yr." The Tien Shan range is in Kyrgyzstan and western China, far north of Afghanistan.

Trifonov, V.G., 2000, Using active faults for estimating seismic hazard: Journal of Earthquake Prediction Research, v. 8, p. 157–174.

The author summarized the organization of the eastern-hemisphere part of the database for the World Map of Active Faults. A page-sized version of the map is too generalized to tell much about Afghanistan. He described methods for using the data to assess seismic hazard and difficulties encountered, for example different slip rates obtained from GPS, ground geodesy, and geology. He used the North Anatolian fault zone to illustrate application of the results.

Trifonov, V.G., 2004, Active faults in Eurasia – General remarks: Tectonophysics, v. 380, p. 123–130.

This short paper described the project and contributors that produced the eastern-hemisphere half of a World Map of Active Faults. The paper contains a page-sized, enormously simplified map of active faults of Eurasia and most of Africa, and suggests a few generalizations about active faults. One passing statement about paleoseismology was shown to be wrong many years ago. No information is given about individual faults, and the map is too generalized for use in such Fa small region as Afghanistan. See also Ioffe and Kozhurin (1996).

United Nations Economic and Social Commission for Asia and the Pacific, 1995, Geology and mineral resources of Afghanistan, Atlas of Mineral Resources of the ESCAP Region, v. 11: New York, United Nations, 85 p., 4 maps, scales 1:2,000,000, 1:2,500,000.

About one sixth of the volume summarizes the geology of Afghanistan, and the rest is devoted to mineral resources. The volume is based on information from the Department of Geology and Mineral Exploration of the Ministry of Mines and Industry of Afghanistan. Most data were compiled from findings made by Soviet and Afghan geoscientists during the 1960s–1980s. The tectonic map (scale 1:2,000,000) is a reproduction of a 1:2,500,000 map prepared in 1972 by Afghan and Soviet geologists. The tectonic map contains a small inset map that identifies and names areas of Paleozoic and Mesozoic deformation, as well as eight Neogene-Quaternary downwarps and basins and 18 major faults. All the named faults and Neogene-Quaternary downwarps and basins are shown on the large map, together with numerous smaller faults and young downwarps and basins. Faults are coded as large ("largest failures by rupture"), small, inferred ("supposed"), reverse, strike-slip, normal ("downthrust"), and buried beneath young deposits, but not according to whether or not they are considered to be active. However, inactivity can be hypothesized for faults that are buried by Neogene-Quaternary deposits (western part of Hari Rod fault; southwestern Kodar fault) or inferred beneath them (Spinghar fault; short section of Caman fault; Kaj Rod fault). Activity can be hypothesized where Neogene-Quaternary deposits fill faulted or unfaulted troughs that parallel a large fault on one side (Mokur fault and its northeast continuation, the Pagman fault; Hari Rod fault).

Walker, Richard, and Jackson, James, 2002, Offset and evolution of the Gowk Fault, S.E. Iran—A major intra-continental strike-slip system: Journal of Structural Geology, v. 24, no. 11, p. 1677–1698.

Wellman, H.W., 1965, Active wrench faults of Iran, Afghanistan and Pakistan: Geologische Rundschau, v. 55, no. 3, p. 716–735.

Wellman used a sabbatical leave from his New Zealand university to visit the Geological Surveys of Afghanistan, Pakistan, and Iran, and Bonn University. He examined air-photo mosaics for displaced topography as indications of active faulting and compiled the results on a 1:1,000,000-scale base. The scales of the mosaics were 1:100,000 to 1:500,000. His paper contains only a page-sized map of the interpreted faults, of which he named nine faults along which he found interpreted indicators of strike slip at 26 localities. Eight small sketch maps that Wellman traced from air photos of individual localities and text descriptions provide details. A table lists the localities, with latitudes and longitudes to the nearest minute; fault strike at each locality, slip sense, and fault name; and type of geomorphic indicator of offset, with a qualitative estimate of the reliability of the indicator and estimated offsets that range from 25 to 1,100 m. Two offsets of 1 m and 10 cm during earthquakes came from cited reports of direct observations.

Wellman suggested that, in moderately steep terrain, probably evidence of offsets older than roughly 20,000 years will have been obliterated by erosion. He noted that the main active faults cut all materials except alluvium in modern rivers. Of the nine named faults, Wellman stated (p. 724) that only the Kuhbanan fault in Iran had previously been named although some others appeared on published maps. He named the other eight faults after nearby villages or towns, including the Herat fault. Four of the nine faults are in Afghanistan, and 10 of the 26 faulted localities are along them. Wellman traced the Herat fault for 1100 km almost entirely across northern Afghanistan. Two groups of displaced and trailing streams indicated right-lateral strike-slip on the fault, 200 km northeast of Kabul and 500 km west of Kabul. Wellman estimated that the streams may be no more than 10,000 years old. The east-striking Talemazar fault parallels the Herat fault but is approximately 80 km farther north. Wellman traced the Talemazar fault for 200 km and suggested that it extends another 100 km farther east. Trailing streams at one locality and offsets in seven small ridges at a second locality indicate right-lateral strike-slip. Wellman interpreted the ridges as post-glacial features.

Wellman traced the Chaman fault south for 800 km from its north end near the Herat fault. Trailing and offset streams at seven localities and a 1 m offset of a railway line during an 1892 earthquake demonstrate left-lateral slip. From geologic maps Wellman estimated total offset on the Chaman fault of "about 500 km" (p. 726). From topographic disturbances similar to those along the San Andreas and Alpine faults, he estimated a slip rate of 2–20 mm/yr. Both estimates are strikingly similar to the modern values of Lawrence and others (1992). West of the Chaman fault, six offset streams at a single locality suggest left-lateral slip on the northeast-striking Darafshan fault. Wellman traced the Darafshan fault for 300 km. (Several authors cited this paper as published in 1966. It is bound in the 1965 volume and listed in its table of contents, and the volume's title page and table of contents state the volume number as 55 and the year as 1965.)

Wittekindt, H.-P., Wolfart, Reinhard, and Moores, E.M., 1997, Afghanistan, *in* Moores, E.M., and Fairbridge, R.W., eds., Encyclopedia of European and Asian regional geology: London, Chapman and Hall, p. 1–7.

The first two authors were part of a West German Geological Survey team that collaborated with the Afghan Geological Survey from 1959 through 1971 to produce a geologic map of Afghanistan (Schreiber and others, 1972). This short paper provides a modern summary of the geography, geomorphology, stratigraphy, plate-tectonic evolution, and mineral resources of the country. One map names places, regions, mountain ranges, and rivers; a second map names crustal blocks, suture zones, and main faults. Afghan tectonic evolution was dominated by the collision of Laurasia (Eurasia) with Gondwana (Arabia and India). The early Mesozoic continental margin of Laurasia and the adjacent suture are now represented by the Herat and Central Badakshan faults and associated rocks. Between these two faults on the north and the Chaman and Konar faults on the east lie diverse blocks of Gondwanan continental crust and parts of island arcs. These terranes were amalgamated before their collision with Eurasia by mid-Cretaceous time. Additional blocks were added east of the Chaman and Konar faults, and by Pliocene or Pleistocene time no ocean remained between India and what is now Afghanistan. Today, Afghan faulting is dominated by strike slip (for example, the Chaman fault). Some presently active faults were originally sutures, and some faults were active in the Tertiary but lack clear evidence of modern activity (for example, the Herat fault).

Wolfart, Reinhard, and Wittekindt, Hanspeter, 1980, Geologie von Afghanistan: Berlin and Stuttgart, Federal Republic of Germany, Gebrueder Borntraeger Verlagsbuchhandlung, 500 p., 3 folded maps, scale 1:4,000,000 (in German with 14 p. English Summary).

The English summary consists of stratigraphic and structural descriptions and tectonic interpretations that were expressed in geosynclinal theory with few mentions of plate tectonics. Accordingly, the summary emphasizes disconnected vertical motions that, while important in determining sedimentary lithologies, were dwarfed by the horizontal plate motions that drove the system and whose recognition is necessary to make sense of the vertical motions. The first two sections of the summary deal with general geology and stratigraphic descriptions that, together, comprise the largest part of the summary. Both sections consist of sentences and paragraphs whose topics seem disjointed and isolated from each other. The lack of linkage to horizontal plate movements makes the inferred paleogeographies and paleoclimates suspect. A few descriptions can be read in terms of subduction zones. The following section on structural styles and deformation ages in the various parts of Afghanistan is more descriptive and clearer. A page and a half on plate tectonics makes more sense to the present-day reader, but is still obscured somewhat by an awkward integration with geosynclinal terminology. This section may be easier to understand after one has read Treloar and Izatt (1993) and Tapponnier and others (1981). Two short concluding sections deal with mineral resources and hydrology. According to the table of contents (in German), the main German text has the same organization as the English summary, with most of the main text (303 pages) being devoted to rock descriptions that are organized by geologic age. Because of the length of the main text, translations of its stratigraphic and lithologic descriptions could be valuable to geologic mappers.

Yeats, R.S., Lawrence, R.D., Jamil-Ud-Din, Syed, and Khan, S.H., 1979, Surface effects of the 16 March 1978 earthquake, Pakistan-Afghanistan border, *in* Farah, Abul, and De Jong, K.A., eds., Geodynamics of Pakistan: Quetta, Pakistan, Geological Survey of Pakistan, p. 359–361.

There was no surface rupture from the body-wave magnitude mb 5.2 earthquake; the authors attributed a linear crack on a shallowly-sloping hillside to slope failure. The epicenter was approximately 25 km east of the trace of the Chaman fault. The paper describes moderate damage in the town of Nushki, roughly 70 km south-southeast of the epicenter. The paper describes the trace of the Chaman fault at and near Nushki as four en echelon, left-stepping sections whose lengths total at least 7 km. The sections cut deformed older fanglomerate that is folded to dip as steeply as 70°, as well as a younger fanglomerate that overlays the older one unconformably. The fault trace does not cut the modern alluvial gravels in the bed of the Kaiser Rud and its tributaries. The authors did not know the ages of the fanglomerates but presumed that they are at least partly Quaternary in age. If their presumption is correct, then this part of the Chaman fault has produced at least 7 km of surface rupture during the Quaternary.

Yeats, R.S., and Madden, Christopher, 2003, Damage from the Nahrin, Afghanistan, earthquake of 25 March 2002: Seismological Research Letters, v. 74, no. 3, p. 305–311.

The earthquake had a moment magnitude of 6.1, occurred at shallow depth in northeastern Afghanistan, and produced no surface rupture, liquefaction, or other geologic effects that would be recognizable in the future or in the young geological record. The authors recognized no neotectonic landforms. They concluded that the long-term slip rate on the nearby, linear, range-front fault is low. Nonetheless, maximum Modified Mercalli intensity was VII and an estimated 1,200 people died. The main cause of building collapse and life loss was widespread construction with mud bricks that had been mortared with mud. These materials are heavy, and such construction lacks reinforcement or other features that might withstand strong ground motion. These effects and observations demonstrate that moderate earthquakes can strike in Afghan areas that lack recognized geomorphic evidence of hazard. Such earthquakes can have far more severe consequences than they might in developed nations because of the nature of local construction practices.