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Review of the Geology of Afghanistan and its Water Resources

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Review of the Geology of Afghanistan and its Water Resources

Abstract

Afghanistan comprises a collage of many lithotectonic domains sutured together as block terranes on the southern Eurasian Plate by collisional tectonics throughout the Proterozoic and Phanerozoic. Kabul basement rocks are fragments of an Archean block stabilized in early Precambrian with two later metamorphic events correlating well with global-scale orogenies related to assembly of the Paleoproterozoic Columbia and Neoproterozoic Rodinia supercontinents. These collisional tectonics were followed by igneous episodes and production of multiple ophiolite suites divided into three orogenic episodes of the later Paleozoic (Devonian – Permian) Variscan (Hercynian) Orogeny, the Mesozoic (Triassic – Early Cretaceous) Cimmerian Orogeny, and the dominantly Cenozoic (Late Cretaceous – Quaternary) Himalayan (Alpine) Orogeny. Variscan, Cimmerian, and Himalayan accreted blocks are separated by prominent suture and fault zones, several of which are active and a source of considerable seismic hazard, especially in eastern Afghanistan. This resulting mélange of small exotic blocks was brought about by a rifting series of narrow ribbon terranes from the Gondwana coast of the Paleotethys and Neotethys seaways. Recent revival of Afghan-led geological lithologic and geochemical assessments has led to new interpretations of tectonic history, as well as of vital surface and groundwater, and other natural resources. Recurrent droughts have decreased water supplies, which have undergone extensive contamination, along with uncontrolled over-pumping of aquifers. Increasing attention to the rich mineral resource base in the country offers solutions to chronic budgetary shortfalls.

Keywords: exotic terranes; block terranes; ribbon terranes; collisional tectonics; ophiolite suites; Variscan realm; Cimmerian realm; Himalayan realm: Phanerozoic orogenies

Introduction

Understanding the basic bedrock geology of Afghanistan requires interpreting more than half a century of geologic research, mapping, and tectonic modelling in >5 major languages (English, French, German, Italian, Russian) foreign to Afghanistan. The earliest significant work by Russian geologists in the mid-20th century is rooted in the stabilist notions of geosynclines, peneplains, and in the absence of many radiometric age dates, too much timing of geologic history by metamorphic degree (Abdullah and Chmyriov 1980; republished by the British Geological Survey in English in 2008). These early understandings ultimately had to be reinterpreted within a conceptually more mobile, or plate-tectonic paradigm to be considered in modern terms (Siehl 2015).

Although the isotopic dating of rocks from Afghanistan has been accomplished to a certain extent for over half a century (Abdullah and Chmyriov 1980), the total number of dates was not many more than 300 thereafter. Siehl (2015) noted some 289 dates (Wittekindt 1973; Wolfart and Wittekindt 1980; Debon *et al*. 1986; 1987; Suzuki *et al*. 2002; Abdullah and Chmyriov 2008) for all the Phanerozoic rocks (Figure 1). Motuza and Šliaupa (2017b; 2020) have produced 42 new dates of mostly Paleogene (Eocene) age using K-Ar, Ar-Ar, and Rb-Sr that document magmatism possibly related to far-field tectonics caused by the India-Eurasian collision. An additional ~56 Ar-Ar and Th-U-Pb dates on 17 samples (Faryad *et al*. 2016), and a few by Bohannon (2010), all in the Kabul block, have helped redefine some of the Precambrian in the country that is discussed below.

Only limited field work has been possible in most places in the country because of concerted human violence and warfare. This resulted in only minor field sampling by a few foreign geologists and some Afghan geologists, which has produced several recent reinterpretations. Rare visits by different national groups of geologists embedded in the military missions (USA, UK, Germany, Lithuania, Japan, and others) for deployments by the International Security Assistance Forces (ISAF) have enabled short duration field work in Afghanistan in recent years. Several new papers have reassessed old field samples or previously mapped areas to refine newer thinking. This paper is an attempt to review the state of knowledge to date and suggest a few possible new interpretations, mainly for a variety of Afghan students, faculty, and government officials in need of general overviews for educational, policy, and management considerations, and not as much for foreign experts.

General Structure and Plate Tectonics

The continental collage of Afghanistan is made up of a host of separate lithotectonic domains sutured together as block terranes through collisional tectonics (Siehl 2015). Each block represents a distinct terrane that has a geologic genesis distinct from those of surrounding areas, and which formed as a crustal block or fragment mainly through production of ribbon terranes by slab rollback and backarc spreading. These blocks were of various sizes; indeed, several of the larger such blocks were sutured together from several smaller continental fragments. All the blocks are typically bounded by faults and ophiolite suites that reflect sea-floor environments caught up and sutured together during the long-term orogenesis.

Because Afghanistan is such a collage of structural blocks that were detached from continental masses elsewhere and then sutured into place on the growing Eurasian plate, discussion of their complexity is warranted (Benham *et al*. 2009; Faryad *et al*. 2013; 2016; Motuza and Šliaupa 2017a; 2017b; Wheeler *et al*. 2005; Wittekindt *et al*. 1997; Table 1). Nonetheless, although various models of tectonic and structural variations have been presented, we have tended to avoid too much lengthy and confusing discussion and have omitted some competing hypotheses because of our perceived need for greater concision until future scientists can better unravel the complexity.

First, it should be realized that many more separate block movements have occurred than has been recognized and distinguished by mapping, description, and discussion. Some blocks are considered together for the convenience of treating them as a unit whole because of certain structural, lithologic, or timing commonalities. Several authors have divided or named various blocks according to their own preferences, which adds to difficulties of comprehension (Treloar and Izatt 1993; Siehl 2015; and several others). Nevertheless, despite the obvious or even cryptic variations in usage, the overall understandings of prior mobility of the blocks are reasonably clear. For example, the suture zone or block of Middle Afghanistan has been treated as a unit whole by some authors, or further subdivided into the Band-e Bayan, Kohi Baba, and

Hajigak blocks by others. Here we limit further detailed discussion of this region because too much of it is too little studied up to this time.

The landmass of Afghanistan projects south from the Eurasian plate as the most stable part of a 600 – 900 km-wide promontory (Wheeler *et al*. 2005) (Figures 2 and 3). To the east and northeast the Indian plate of the present day subducts northward beneath Eurasia to force up the Western Himalaya, and to the west the Arabian plate has a similar motion that forces up the Zagros and other mountains in Iran. Deformation zones that form the rim of the Eurasian promontory upon which Afghanistan is situated are all seismically active and include strike-slip fault belts (Chaman fault on the east; Sistani suture zone on the west) and thrust complexes. In contrast to the lateral deformation zones on either side, the interior of western and central Afghanistan is much less active. In contrast, the region of northeastern Afghanistan in Badakhshan Province has had in the past 150 years, more >7-8 magnitude earthquakes than anywhere else in the world (Wheeler and Rukstales 2007), with significant resulting surficial effects (Shroder *et al*. 2011b, Shroder 2014). This region beneath the high Hindu Kush and extending on beneath the Pamir Mountains to the northeast in Tajikistan has a seismically defined, tabular zone ~30 km thick and 700 km long. This descending zone dips 50º - 90º northwest beneath the Hindu Kush of Badakhshan, but beneath the Pamirs the zone has been warped by mantle flow forced laterally by the moving Indian plate to dip 50º - 60º southeast, which defines a contorted subduction zone beneath the region (Pegler and Das 1998).

Afghanistan is now known to have some of the most complex and varied bedrock geology and structure in the world in that it is a mélange of small exotic terranes, each assembled with varied lithologies, biostratigraphies, and plutons from diverse locations (Bohannon 2010). A nearly full complement of Archean and Proterozoic rocks is thought to occur throughout Afghanistan, interleaved by faulting with all of the Phanerozoic bedrock systems and the whole overlain with a variety of Quaternary sediments and structures that add to the complexity. The orogenic collage is fairly well understood for most of the Phanerozoic but less so for the Precambrian.

The details of the Precambrian rocks of Afghanistan are not yet well known but recent work (Faryad *et al*. 2013; 2016) has elucidated some of the Precambrian rocks near or within the Neoarchean Kabul Block in Afghanistan and suggested possible associations to the Rodinian

(~1.3 – 0.9 Ga and Columbian or Nunaian (~1.8 – 1.5 Ga) supercontinents. The older interpretations of the Precambrian rocks of Afghanistan included assignment of the different units mainly on the basis of degree of metamorphism (Shareq 1981; Abdullah and Chmyriov 1977; republished 2008), whereas, of course, that method has long been superseded by the more accurate use of radiometric age dating. Dating of Phanerozoic rocks in Afghanistan in the mid-20th century was mainly by guide fossils and biostratigraphic markers, with correlations extended in from neighboring countries where distinctive faults and lithologies enabled that process.

The plate-tectonic evolution of Afghanistan in the Phanerozoic has resulted in the three main plate-tectonic provinces (Figure 2), with the: (1) North Afghan platform; (2) Accreted terranes composed of crustal fragments and volcanic arcs; and (3) Transpressional plate boundary between the Eurasian and Indian plates. The three main phases of tectonic activity that produced these provinces were the Late Paleozoic Variscan realm, the mid-Mesozoic Cimmerian realm, and the Cenozoic Himalayan realm (Siehl 2015) (Figure 1).

Early on in the modern recasting of the geologic history of the country, the amalgamation of the Afghanistan tectonics map (Wheeler *et al*. 2005) was done by the U.S. Geological Survey, apparently to facilitate enhanced comprehension in the face of the apparent plate-tectonic collisional complexity. For example, the entire area of Afghanistan east of the Chaman – Panshir – Central Badakhshan fault system was considered somewhat misleadingly to be the transpressional plate boundary of the northwest edge of the Indian Plate (Figure 2). Although this is not incorrect *per se*, in fact a reevaluation of the region shows the need for a more thorough assessment of this complexity so that the overall transpression can be better understood. In fact, multiple other exotic terranes exist in that region, such as the Kabul block, Nuristan block, Pamir block, and Wakhan block, each with quite different lithologies and geologic histories that in their separate collisions, produced a multidimensional transpression (Figures 2 and 3). In addition, the Katawaz basin in that group of other blocks is one that was deposited more-or-less in place close to where it exists today, although it was subsequently extensively deformed (Treloar and Izatt 1993).

The basement of the North Afghan platform is made up of metamorphic and igneous rocks developed during the Variscan (Hercynian) Orogeny during the Carboniferous-Permian periods and has been comparatively stable since that time (Tapponier *et al*. 1981). The Variscan term has been suggested as conditional only, as an episode of integrated collisional and orogenic events in the assembly of the Pangea supercontinent. The proper Variscan orogeny *sensu stricto* took place in Western Europe and may have no relation to coeval plate-tectonic events in South Eurasia. Nonetheless, we use it here because of its common usage by many other authors in the literature cited here. The result is that the North Afghan platform seems to have been a part of the Eurasian plate for about 350-250 Ma. The North Afghanistan (Tajik) tectonic domain also is considered by some authors (Motuza and Šliaupa 2017a; 2017b) as a Proterozoic continental block split off Gondwana and joined with Eurasia in the Carboniferous-Permian periods so that the whole domain, or at least the southern part could also be included as a part of the Accretionary Terranes. Thus, also the Band-e-Bayan belt is considered by some as part of the North Afghanistan block. In any case, a cover sequence of Mesozoic- and Tertiary-age strata (Triassic basalts, Jurassic evaporites, Cretaceous/Paleocene shallow-water marine limestones, Tertiary continental deposits) overlies the basement with as much as a 6 km thickness of sedimentary rock at the northern border of Afghanistan, and up to 10 km in some platform basins.

Since about 250 Ma several of the continental fragments, oceanic crust, and magmatic arcs have collided with, and been sutured onto the southerly edges of the platform during the Mesozoic Cimmerian orogeny to become part of the Eurasian plate (Wheeler *et al*. 2005; Wheeler and Rukstales 2007). At the present time, the east-west-striking Hari Rud fault zone demarcates the boundary between the North Afghan platform and the accreted crustal fragments and magmatic arcs of the Afghan block to the south. This fault-zone suture between the Eurasian plate and the docking crustal fragments was at its most active during the mid-Mesozoic when the largest of the crustal fragments docked and were accreted. Today the 20- to 60- km-wide fault region of the Middle Afghanistan suture zone (Table 1) has numerous fault-bounded, lenticular masses of rock with a fabric strongly suggesting strike-slip motion. Some offset Paleozoic rocks indicate as much as 600 km of right-lateral displacement (Brookfield and Hashmat 2001; Wheeler *et al*. 2005).

The east-west-trending Hari Rud fault has a right-lateral sense of motion but only a sparse history of activity. This is compared to the left-lateral motion of both the roughly north-south

Darvaz fault north of the main central Hindu Kush aligned with that of the similarly oriented Chaman fault south of the main range. Both of these left-lateral faults are far more seismically active than the Hari Rud. These fault orientations, senses of motion, and stratigraphically constrained timings of motion indicate northwestward convergence of the Indian plate from 35-20 Ma (late Eocene – early Miocene) against the North Afghan platform to produce the right lateral slip on the Hari Rud fault. This was apparently followed since 20 Ma by a change to a more northward convergence of the Indian plate to produce the presently continuing, left-lateral slip on the Chaman and Darvaz faults, as well as a component of reverse slip on part of the northeast Darvaz fault (Brookfield and Hashmat 2001).

The western part of the Hari Rud (Herat) fault apparently was largely inactive following the main collision and docking events of the mid-Mesozoic but seems to have been reactivated in Oligocene – Miocene time (Treloar and Izatt 1993) when pull-apart basins developed, along with Oligocene volcanic rocks in them (Figure 3). The lack of clear fault offsets of deposits in the Hari Rud valley younger than Miocene indicates its post-Miocene inactivity. This apparent locking of the fault in post-Miocene, yet continued stress from the on-going collision of India with Asia seems to have led to ongoing right-lateral movement of the Band-e Turkestan fault that is ~70 – 130 km north of the Hari Rud and oriented roughly parallel to it. These faults are connected by an approximate 55° bend in the trend that has opened the ~5-10-km-wide, 90-km-long Yakawlang pull-apart graben. This graben formed a northwest-oriented trench into which first flowed mid-Cenozoic andesitic lavas, followed by other late Cenozoic sediments. Ultimately, in the Quaternary, drainage from the famous travertine-dammed, Bandi-Amir lakes near Bamiyan flowed out through the graben as the Balkh Ab (river) and onto the northern plains.

Farther west along the Band-e Turkestan fault (Wheeler *et al*. 2005), it is crossed by the north-flowing Maimaneh River, where recent right-lateral activity on the fault has progressively moved the south headwaters of the river to the west and on the north side has offset several old channels progressively to the east. The Sari Hawz lake and reservoir there on the south side was partially dammed by motion on the fault, although the most recent reservoir was established with an anthropogenic dam (Figure 4).

In Badakhshan Province the modern Hindu Kush and Pamir mountains reveal complex, highly faulted terrain where the dominantly north–south- or northeast–southwest-oriented faults in the bedrock are an earlier generation of movement formed during the plate-tectonic construction of Afghanistan (Wheeler and Rukstales 2007). These faults are cut across now by a younger generation of northwest-oriented, shorter and less continuous faults that may delineate a system of new or recently reactivated faults (Figure 5). The straight lines of these younger faults across the tall mountains and deep valleys of the region suggest that the northwest-striking faults dip steeply. Wheeler and Rukstales (2007) noted that the steep dips and northwest strikes would be consistent with a new strike-slip motion developed in the ambient stress field.

The Chaman fault system in southeast Afghanistan (Figure 3) that extends across southern Pakistan is a major left-lateral strike-slip fault zone that accommodates most of the recent differential movement between the Indian and Eurasian plates (Ruleman *et al*. 2007). Several different estimates of relative plate motions and velocities have been proposed for the overall region of about 2.9 cm/yr to 3-4 cm/yr for the India plate moving north, and ~1.3 cm/yr of the Eurasian plate moving south (Sella *et al*. 2002; Jade 2004; Bird 2003; Vernant *et al*. 2004; Ruleman *et al.* 2007). The Chaman fault system itself has reported slip rates of 1.9 – 2.4 cm/yr (Lawrence *et al*. 1992). This rate of movement categorizes the Chaman fault as a major structure that is prominently expressed in the landscape and one that is likely to continue to play an important role in determining the modern tectonics and seismic hazards.

In Afghanistan, the main Chaman fault is about 650 km long and extends another 500 km south across Pakistan. To the north the fault seems to bifurcate around the Kabul block and pass on into the Paghman fault on the west side, and the Gardez, Sarobi, and other faults on the east side of the block (Ruleman *et al*. 2007). Shroder (2014) postulated that some thrust-fault loading by the steeply dipping Paghman fault on the west edge of the Kabul block might have pushed down the Kabul block on the west and raised it on the east, which caused the Panjshir River to cut a prominent canyon in the bedrock (Shroder 2014) to become tributary to the Kabul River lower down.

The source of the Kabul block is controversial (Faryad *et al*. 2016; Li *et al*. 2008; Stampfli *et al*. 2002), so exactly where in the Gondwana margins it was located originally is not agreed upon. The block might have been part of the south Asian Cimmeride collage that was displaced during an early stage of the Himalaya collision, or it may have been part of the Indian plate that was displaced by strike-slip faulting, or it could have been a quite separate, exotic fragment from somewhere else entirely (Figure 6). The Kabul Block occurs in the triple junction of three terranes; (1) North Afghanistan block; (2) Afghanistan Central blocks (Farah and Helmand blocks); and (3) Frontal fold and thrust belt (Katawaz Basin) of the Indian plate. The Kabul block itself is formed by Paleo- and Neoproterozoic basement with Carboniferous through Triassic cover marbles, shales, phyllites, and meta-conglomerates that are locally tectonically overlain by ultramafic sheets interpreted by some as obducted ophiolites and others as fragments of subducted mantle lithosphere (Faryad *et al*. 2013; Bohannon 2010). Based upon metamorphic characteristics and ages, the Kabul basement rocks show affinity to the Neoarchean rocks of the Tarim and/or South China cratons (Faryad *et al*. 2016).

The nummulitic limestone of Eocene age (Figure 8), which in Afghanistan and Pakistan heralds the last of the marine incursions in southwest Asia, indicates that the continental microplate of the Kabul block had to have been emplaced into the Afghanistan landmass somewhat before that. At some point in the late Mesozoic, the Kabul block is thought to have existed as an island mass completely surround by ocean-basin rocks (Treloar and Izatt 1993), with two magmatic island arcs between it and the Asian landmass. The main magmatic arc was the Ladakh - Kohistan - East Nuristan-Kunar mafic region and the other was the Kandarhar arc. These magmatic arcs were sutured onto the Asian landmass from about 100 Ma to 55 Ma. The Kabul block seems to have docked in about Late Cretaceous to Paleocene time (Siehl 2015), just prior to the arrival of the Indian plate and deposition of the Katawaz Basin sediments to the south of the Kabul Block. The best idea for emplacement of the Kabul block into the main Asian landmass and between the magmatic arcs on either side is likely to have been sometime in the Paleocene (66 – 56 Ma). The rocks of the ocean basin that originally surrounded the Kabul block ultimately seem to have produced the Logar and Khost ophiolite-like ultramafics. These appear to have been obducted onto the Kabul block when the ocean closed and the main Kabul-block mass collided into the triple junction at the head of the Kabul block where the Chaman-Paghman fault meets the Hari Rud fault, which together join the Panjshir-Central Badakhan fault system.

Rocks of the Helmand-block terrane were derived from the margins of Gondwana in the southern hemisphere when the ribbon rifting of the time brought the landmass fragments north. The basement beneath this block is Proterozoic metavolcanics and metasediments intruded in the north by S-type granitoids of Cambrian age (Siehl 2015). This is overlain by Ordovician quartzites, siltstones, and shales, followed by Silurian limestones and calcareous sandstones. Devonian-age platform carbonates, reefs, and siliciclastic rocks follow. Carboniferous and Early Permian cold-water faunas and probable tillites show their proximity to characteristic Gondwana glaciation (Termier *et al*. 1973). Marine platform carbonates followed in Late Permian and Triassic, which because the southern part of the adjacent Kabul block also has similar sedimentary rocks has suggested to some that the two were attached, although Faryad *et al*. (2016) suggested otherwise.

Inception of the Chaman fault in left-lateral strike-slip motion appears to have occurred during the Pliocene Epoch (Treloar and Izatt 1993). This fact coupled with the apparent lack of significant post-Miocene movement on the Hari Rud (Herat) fault indicated to Treloar and Izatt (1993) that the two faults were never active at the same time. If true, then the two faults could not have acted to extrude the whole of central Afghanistan south in response to the Indian plate indentor into the Eurasian plate, as had been postulated by many. In fact, however, the postulated extrusion could be accommodated still if dextral motion on the Band-e Turkestan and Andarab faults to the north and east of the Hari Rud fault were recognized as providing the necessary fault linkages with the same sense of motion since the Miocene (Figure 3).

Magmatism and Metamorphism Linked to Block Accretion

The accretion of the Indian continent onto the southern margin of Eurasia was a stepwise process that involved separation of many small blocks from the greater Indian terrane of Gondwanaland and the formation of magmatic arcs prior to the main continental collision of India with Eurasia (Faryad et al. 2013). The accretionary events began in Paleozoic and continued into recent times. Much of the tectonic evolution of Afghanistan is related to the closure of the Paleozoic and Mesozoic Tethys. Three major magmatic stages of Triassic, Cretaceous, and Eocene-Oligocene age were formed by subduction of oceanic crust beneath the region, as well as far-field rifting and magmatics caused by the terminal collision of India with Eurasia (Motuza and Šliaupa, 2017a; 2017b) (Figure 6). The Cretaceous granitoids of Afghanistan are a direct continuation of the main

Himalayan-age batholith stretching laterally across the Kohistan – Ladakh – Transhimalaya region. Similarly, three different metamorphic events have been distinguished in the southern part of the Western Hindu Kush as well; with the first two amphibolite and greenschist facies metamorphic events being Proterozoic and pre-Carboniferous, and the third being of Eocene age within Triassic and Cretaceous granitic rocks close to the Kabul Block.

Stratigraphy and Tectonic Context

Precambrian

Precambrian crystalline rocks form large areas in many of the structurally higher regions of Afghanistan (Wittekindt *et al*. 1997), as well as much of the basement beneath sedimentary rock and sediment covers throughout the country. Unfortunately, because of the limited number of isotopic dates in the earlier geologic mapping in the country (Shareq 1981; Abdullah and Chmyriov 1977; 2008), far too many non-Precambrian rocks were judged on the basis of degree of metamorphism to be of that age, when in fact, they were actually much younger. Only in the Kabul block from new dates are some of the rocks known definitively to be Archean and Proterozoic (Bohannon 2010; Faryad *et al*. 2016). Thus, the Kabul-block basement is now recognized to be a fragment of an Archean craton that was stabilized during the early Precambrian and then subjected to a magmatic crystallization event in the Neoarchean of 2.5 – 2.8 Ga. This was followed by a Paleoproterozoic event of 1.85-1.80 Ga and then another in the Neoproterozoic at 0.9 - 0.85 Ga. These basement rocks in the Kabul block show a possible affinity to the Neoarchean rocks of the Tarim or South China cratons.

The Ediacaran Period was recognized in Afghanistan by the Soviet-era geologists and was purportedly recognized based on its organic remains. The period, however, was considered to be a part of the earliest Paleozoic rather than the latest Precambrian. Stromatolites were a featured part of the description (Abdullah and Chmyriov 1980), but because much of the Ediacaran in Afghanistan is composed of fine-grained clastics, it is therefore likely that once security improves in the country, careful field work will allow discovery of impressions of the Ediacaran soft-bodied organisms that are typical of such sediment of the latest Precambrian world-wide. Below we elected to mention general taxa of chief guide fossils occurring in all systems throughout the country in the belief that leaving them out would be too misleading, but including the associated lithofacies and tectonic settings would also be misleading because so few of these relations have yet been studied sufficiently.

Paleozoic

In general, the rocks of the Paleozoic in Afghanistan are fairly well represented for all the different periods, but in the absence of many of the isometric age dates that are so common in much of the rest of the world, systematic collections of the era's typical guide fossils became the main dating control. Most of the major phyla are well represented, with many representatives of such organisms as trilobites, brachiopods, corals, porifera, ectoprocta (bryozoans), graptolites, pelecypods, cephalopods, conodonts, foraminifera, and a few others that occur.

Cambrian

Cambrian rocks appear to be of limited extent in Afghanistan, although a few small outcrops that were dated with trilobites are known in the Panwai region between the Farah and Helmand blocks (Abdullah and Chmyriov 1980). Similarly, Cambrian outcrops occur southwest of Kabul, west of Moqor, and in the north of the country, but most are too small to be plotted on the Doebrich and Wahl's (2006) 1:850,000-scale geology map of Afghanistan.

Ordovician

Outcrops of Ordovician rocks are far more common in Afghanistan than the Cambrian. Extensive outcrops occur in the Helmand block in Wardak Province where they are described by Doebrich and Wahl (2006) after Abdullah and Chmyriov (1980) as sandstone and silt more than shale. In the Ghorband and Panshir river valleys areas in middle Afghanistan, the description is limestone, sandstone and shale. In several places (Baghlan, Taliqan) in northern Afghanistan the primary lithologies are shale, sandstone, and chert. Ordovician-age trilobites, brachiopods, graptolites, sponges, pelecypods, conodonts, and a few other types are the chief guide fossils (Abdullah and Chmyriov 1980).

Silurian

The Silurian Period is represented in Afghanistan dominantly by carbonates that are dated by brachiopods, tabulate corals, crinoids, orthocerid cephalopods, and a few crinoids (Abdullah and

Chmyriov 1980). Outcrops of these rocks are known in the Helmand block (Arghandab and Logar areas) and have been suggested by poorly preserved fossils in a few other areas.

Devonian and Carboniferous

Wittekindt *et al*. (1997) noted that carbonate and clastic sediments of Devonian age are widely distributed in the country and contain rich faunal assemblages. The fossil groups include various genera of tetra- and tabulate corals, brachiopods with spiriferoid types, bryozoans, crinoids, and conodonts (Abdullah and Chmyriov 1980).

Rocks of the Carboniferous have been mapped extensively throughout Afghanistan, with more than 15 different symbols for the varying lithologies on the Doebrich and Wahl (2006) map. Several different limestones have been mapped, along with sandstones and undifferentiated sedimentary rocks; all with a great diversity of fossils. A wide variety of foraminifera have been located in these rocks, along with different tabulate and tetracorals, brachiopods, spirifers, crinoids, and goniatite cephalopods. Perhaps the most interesting lithologies in the Carboniferous may be the diversity of extrusive igneous rocks, the tuffs, and the different lava compositions (Abdullah and Chmyriov 1980). Siehl (2015) discussed these early manifestations of the Variscan Orogeny, a period of considerable tectonism worldwide that is generally understood as the Late Paleozoic continental collision between Euramerica (Laurussia) and Gondwana to form the supercontinent of Pangaea. The Variscan realm of Afghanistan is dominantly confined to the southern parts of the Turan block that extends north of the middle Afghanistan fault and suture zone of the Hari Rud and Panshir valleys. The basement of the Turan block is an accreted-terrane aggregation of Variscan age that is composed of deformed and partly metamorphosed Paleozoic rocks. These outcrop in Afghanistan particularly along the south part of the Feroz Koh near Herat and into the western Hindu Kush. Siehl (2015) also noted that little data exist to indicate igneous intrusions younger than 400 Ma during the early Variscan. He thought that this might indicate that the Afghanistan portion of the Turan block probably consisted mainly of sedimentary accretionary wedges with no Variscan magmatic arc that would compare to the later early Cimmerian igneous activity in the same region.

Permian

Rocks of Permian age are known to be widespread in Afghanistan and are represented mainly by marine carbonates and terrigenous types, and particularly, for example, by redbeds in the northwest of the country (Abdullah and Chmyriov 1980). The contacts with the underlying Carboniferous are conformable in some places and disconformable or angularly unconformable in others. The upper contacts with the Triassic are marked by erosion in places and are also angularly unconformable in others. Guide fossils include extensive fusulind foraminifera, and many brachiopod genera, including spiriferoid and productid types. Tetracorals are common, along with some goniatite cephalopods, and a number of terrestrial plant remains.

Mesozoic

Rocks from this era are quite widely dispersed in Afghanistan and all are fossiliferous (Abdullah and Chmyriov 1980). Marine carbonates and terrigenous deposits prevail in all periods and the volcanics are noticeably subordinate, although in Early Cimmerian (Triassic) time, a magmatic arc was emplaced across Afghanistan from west to northeast at the edges of what later became the Turan block (Figures 7 and 9).

Triassic

The Early Cimmerian orogenesis across Afghanistan at the time seems to have had a forearc accretionary wedge at the edge of the Turan block (Figures 7 and 9). This was invaded by a frontal igneous arc in the Paleotethys Seaway. A North Hindu Kush back-arc rift zone seems to have developed behind the frontal island arc in which the Doab Series sediments were deposited (Siehl 2015). This would seemingly result from a subduction zone dipping beneath the Turan plate to the north, although a south dip had been postulated earlier by Debon *et al.* (1987).

The characteristic guide fossils of the Triassic in Afghanistan are an abundance of diagnostic ammonoids and pelecypods, along with some brachiopods, gastropods, corals, and other forms (Abdullah and Chmyriov 1980). Some of the coals in the latest Triassic also have abundant plant fossils.

Jurassic

In this period in the north of Afghanistan the igneous intrusion and extrusion of the Variscan orogeny decreased, while the extensive coals of the Saighan Series developed in shallow swamps near the Pamir sea. Also, in the north in the latest Jurassic, extensive salt deposits accumulated and continued on into the earliest Cretaceous. South of the Feroz Koh at this time, collision with the Band-e Bayan block produced the Paleotethys Suture. After this, the Waras-Panjao (Panjaw) ocean developed in the Farah Basin to allow accumulation of the Panjao and Waras Series. The Farah Basin was established as a large and deep marine depression into the northern parts of which was poured a several km-thick succession of the Panjao flysch series of clastic and calcareous turbidites, some or all derived from material to the north (Siehl 2015). Ammonites, radiolaria, and microplanktonic calpionellids are characteristic fossils, some in limestone reefs (Abdullah and Chmyriov 1980). In the southern part of the basin the Waras ophiolites consisted of ultramafic rocks and submarine basalts that also hosted large-scale olistolithic submarine landslide deposits that probably were derived from the adjacent rocks of the Helmand block (Siehl 2015). The whole was subjected to intermediate-grade metamorphism from greenschist facies in the north to amphibolite facies in the south.

Cretaceous

Both Lower and Upper Cretaceous rocks are widespread all over Afghanistan, and most are quite fossiliferous with a great many of the typical guide fossils of the period. Ammonites, orbitolinid foraminifera and many other such types, pelecypods, rudistids and oysters, gastropods, brachiopods, echinoids, corals, and many other species occur as well (Abdullah and Chmyriov 1980). In the northern Afghanistan of the Variscan realm, following the marine invasion of the Late Jurassic and the regressive deposition of evaporates, the ‘Red Grit series’ of continental clastics with evaporites was deposited unconformably overtop (Figure 8). A renewed marine transgression there in the later Early Cretaceous that lasted into the Paleogene produced the ‘Green Beds’ of marls and limestones. In the Farah Basin to the south the lower parts of the Lower Cretaceous rocks are mainly red terrigenous deposits of reworked shallow metamorphic material from the Panjao turbidites (Siehl 2015). The western portions have shallow marine sediments with orbitolinid and rudistid fossils intercalated with tuffs and lavas from possible back-arc divergence and volcanism. At this time, the possible northwest-directed subduction of the Neotethys beneath the southeast Helmand block is thought to have produced intrusion of granite batholiths as well. Early Cretaceous red beds and calcareous sandstones there were next capped with orbitolinid and rudistid limestones. Finally, the Kandahar fore-arc basin began in the Late Jurassic along the margins of the Helmand block and continued with emplacement of volcanics in the Early Cretaceous and granitoid batholiths on into the Late Cretaceous. Some of the Cretaceous intrusions occurring from the Kandahar area through the Wakhan Corridor (Figure 7) are thought by many to be a direct continuation of the large Kohistan-Ladakh-TransHimalaya batholith (Faryad 2013).

Cenozoic

Sediments and sedimentary rocks from this era are the product of marine, lagoonal-terrestrial, and continental-terrestrial environments of deposition and are abundant throughout Afghanistan (Abdullah and Chmyriov 1980). The most significant event to occur was the arrival and initial docking of the Indian subcontinent that began the rise of the Himalaya and Hindu Kush.

The Neogene Period in Afghanistan, encompassing the 23 Ma of geologic history there as it does, is the four-epoch (Miocene, Pliocene, Pleistocene, Holocene) time during which the geomorphologic face of the country emerged most strongly. The landform-controlling processes in the region were first and foremost the fundamental underlying rock structural control of so many landforms, followed by erosion and deposition by rivers, glaciers, mass movement, and the wind.

The Katawaz Basin just south of the Kabul block, and extending across the border south into Pakistan, is a Cenozoic depocentre of long-term shallow-water subsidence. Up to an 8 km thickness of dominantly siliciclastic sediments was poured into a large flexural, originally marine basin at the edge of a thinned transitional ocean-continental crust of the formerly passive-margin of the western Indian plate. The nummulitic limestones of Eocene age at the base of the pile indicate the final stage of the shallow marine basin that closed progressively as a high-discharge river delta prograded south (Treloar and Izatt 1993; Siehl 2015). This basin is bounded on the west by the Late Cimmerian Kandahar arc and the active sinistral, strike-slip Chaman and

Gardez faults, and on the east by the north-south axial belt of ophiolites obducted upwards at the edge of the Indian plate in Pakistan and adjacent Afghanistan. Most of the uppermost rocks of the Katawaz basin are comprised of Pliocene sediments from an apparent paleo-Indus River system bringing sediments dominantly from the rising Himalaya to the northeast. These units were subjected to an intense syn-sedimentary folding that culminated in a final period of late Pliocene deformation, prior to deposition of disconformably overlying and undeformed Pleistocene terrigenous materials.

Because of the remoteness and inaccessibility of the high Hindu Kush and Pamir mountains of northeast Afghanistan, they were only ever mapped geologically in a rather superficial or reconnaissance fashion (Abdullah and Chmyriov 1980). Accordingly, and because of the high stratigraphic, metamorphic, intrusive, and structural complexity of much of the region, only a generalized overview can be presented. In general, therefore, the region is characterized by steeply dipping, commonly sinistral strike-slip faulting, particularly in more recent Neogene time, which broke the region into a series of fault blocks wedged into each other (Siehl 2015). Many of the larger such strike-slip faults roll over into both north- and south-plunging thrust faults in the central Pamir ranges northeast of Afghanistan (Figure 9). Each small block may have a variety of Precambrian, Paleozoic, and Mesozoic strata cut by Variscan and Cimmerian intrusions that are all overprinted with the great deformation and uplift associated with the Himalayan-orogenic realm of the Cenozoic. The whole assembly is eroded into the complex and labyrinthine valleys cut into the high mountains. Interestingly also, caught in the abundant fault slivers in a few places in northeastern Afghanistan are sediments and sedimentary rocks of probable Mio-Pliocene age that were mapped first by Desio (1975) as Tertiary conglomerate.

Quaternary

The Pleistocene and Holocene of Afghanistan, of course, at only a 2.6 Ma of total duration, encompass a minimal amount of geologic history but during that time the Earth-surface processes have exerted maximal control on the existing natural environment within which humanity seeks to maintain a future. The fundamental diastrophic processes that built the complex rock structures of Afghanistan set up the minor and major faults of the country that generate the dangerous seismicity of the present day. The long history of igneous activity in the region seems to have finally ended up with only two recent volcanos in the Pleistocene: (1) the eruptive centre of the Dashti Nawar caldera near Ghazni, which last erupted about 2.2 Mya to send a huge volcanic lahar mudflow all the way to the Indus River (Khan *et al*. 1985; Shroder 2014); as well as, (2) the Kohi Khanneshin carbonatite eruptive centre in the lower Helmand that was emplaced in the Pleistocene ~ 0.61 Ma (Whitney 2006; Tucker *et al*. 2011). These volcanos represent the waning stages of magmatic eruption from the subduction that once existed beneath Afghanistan as the Indian plate moved northward beneath the Eurasian plate.

The main Earth-surface processes that sculpted most of the geomorphology of Afghanistan are the glaciers, rivers, mass movement, and wind. In the mountains of the country the increased precipitation, high seismicity, and weak lithologies in some places contribute to the pervasive mass movement. Some of these lithologies lack significant shear strength so that they are quite prone to failure, with the result that they can liquefy in some cases and flow down into lower valleys, as they once did near Zebak (Shroder *et al*. 2011a). In addition, and also in part because of pervasive fault-shattered and frost-riven bedrock in the mountains, a sizable number of complex large rock slides have occurred (Shroder 1989; Shroder and Weihs 2010; Shroder *et al*. 2011a), many of which have undergone secondary mobilization as rock glaciers when interstitial ice or ice cores formed in them (Bishop *et al*. 2014). A further example of a common slope failure in Afghanistan occurs where wind-blown loesses have accumulated as the dust was blown up onto the less permeable crystalline rocks of the Hindu Kush and Pamir in the northeast of Afghanistan (Shroder *et al*. 2011b), and the unstable dust can easily fail when wet or disturbed by seismicity. On 2 May 2014, a landslide of loess occurred in the Aab Barik, Argo District in Badakhshan Province, which killed over 2100 people and left hundreds of others missing. Around 300 houses were buried and overall, over 14,000 people were affected (Tanha 2014).

Despite the fact that Afghanistan is an arid country, the erosive action of rivers has been paramount in eroding the bedrock into the strong, structurally controlled landforms throughout (Shroder 2014). These fluvial processes, including some catastrophic breakout floods from probable unstable ice dams during the Pleistocene, have caught up masses of prior colluvium and swept it as the repeated rapid wet debris flows and flash floods onto the large alluvial-colluvial fans that have been repeatedly observed in action throughout the arid country (Shroder 2014; Shroder and Ahmadzai 2016).

Snow and ice in Afghanistan are critical sources of meltwater that feeds agricultural irrigation systems almost everywhere in the country. Porter (2004) mapped the minimum extent of late Pleistocene glacial ice in the Hindu Kush to discover that some descended as low as 2600 m, with the longest being about 70 km, especially in north-trending valleys. Several authors (Shroder and Bishop 2010; Haritashya *et al*. 2009) mapped ~3000 small glaciers that remain in the present day but noted especially the strong downwasting and backwasting in recent years that threaten water supplies. Such ice masses, and certainly even larger ones in the earlier Pleistocene, once provided much greater meltwater sources that even filled some deep sedimentary basins with deep ground-water sources and overflowing lakes (Sistan Basin). Ever decreasing precipitation through long-term natural climate change, coupled with recent human-caused, environmental despoliation (Shroder 2012) and climate change have combined to threaten greatly the future of Afghanistan's water resources (Shroder and Ahmadzai 2016).

Finally, the strong katabatic and monsoon-driven winds in the west of Afghanistan have driven deep deflation throughout the lowlands that has mobilized hundreds of km^2 of sand dunes and loess blankets. Such aeolian deposits occur as thick deposits throughout the country, but are especially pronounced in the north where strong winds from central Asia and profuse sediment is supplied from the Karakum desert in Turkmenistan and the floodplain of the Amu Darya, as well as in the southwest by the wind of 120 days in the Sistan.

Mineral Resources

The issues of the rich mineral-resource base in Afghanistan in recent years has become a point of vigorous discussion and debate in geologic and political circles (Ali and Shroder 2011; Shroder 2014). Known or suspected for over a century and a half (Shroder 2015), major discoveries were confirmed in the major mapping programme conducted by the many Soviet geologists in the 1960s and 1970s. Following the Soviet invasion of 1979, their departure in defeat in 1988-89, and several decades of civil war and reinvasion by the USA and ISAF since then, the resource story has been paramount (Shroder 2014; 2015). World-class ore deposits of copper, iron, and rare earths, lithium, a sufficiency of oil, gas, coal, precious stones, and several other industrial minerals have drawn the world's attention. The U.S. Geological Survey and U.S. Department of Defense's Task Force on Business Stability Operations (TFBSO) produced new reports, interpretations, and extensive digital data for 24 Areas of Interest in Afghanistan. Many of these AOI are world class in size and tenor. The data packages constitute Information Packages that will help reduce risk to investors and developers and are designed to be used by the Afghanistan Ministry of Mines in the bidding process and the commercial development of these areas. The extraction of these abundant mineral resources (Table 2; Figure 10) is considered critical for creating economic growth, employment, and security (Peters 2011; Peters *et al*. 2011).

In the media excitement about the several trillion dollars of unmined mineral resources in the country (Risen 2010; Tucker et al. 2011; Katawazai 2020) the rare earths and lithium were especially touted, with the US military noting a 'Saudi Arabia of lithium' (Shroder 2014, p. 365). Although successful in some cases (marble quarrying and some stone finishing, oil and gas production, coal, and gold mining), other cases have been partly or largely corrupted (lapis lazuli, podiform chromite, etc.) by the so-called mineral mafias that have greatly marred the extraction processes and diverted royalties from the government and people of Afghanistan. Recent attempts are infusing transparency in the extractive industries in Afghanistan and have been underway for about a decade with considerable external support from EITI, the extractive industries transparency initiative that is based in Norway but working worldwide (Shroder 2014; 2015).

Plans have been developed for greatly improved extraction and transportation for the well-phased resource-corridors project (Shroder 2015) that may fit well into the Chinese plans for a One Belt – One Road trading network linking East Asia with the Western world, and with Afghanistan serving as a neo-Silk-Road hub. Such long-term plans are not at all characteristic for many countries in the West or for Afghanistan, but certainly would be a game changer for this portion of the world.

Water Resources

Generally, the people of Afghanistan are indifferent too their mineral resources because these are mostly seen as a rich man's game, or under control by warlords or Taliban, but water supplies are exceptionally vital to them. Everyone must have water for living and especially for agriculture. As has been noted recently (Favre and Kamal 2004; Shroder and Ahmadzai 2016) the total amount of water that is delivered annually in Afghanistan is rather substantial (55 – 84 km^3/yr) but is unevenly distributed throughout the country. Furthermore, Afghanistan has long had major deficits in dams, well-developed irrigation structures, wells, sewers, hydroelectric power, and all the other water infrastructure that is desirable for human welfare, agriculture, industry, and environmental protection. These pervasive deficits have allowed long-term water surpluses to be exported across international borders where neighboring countries expect as a matter of course, regular delivery of water from Afghanistan. When these supplies are threatened because of planned upstream development and use inside Afghanistan, belligerence has resulted. Water-supply diminution because of climate change also adds to uncertainty, with emergence of water-war threats. Problems with inadequate water inside Afghanistan because of recurrent drought, over-pumping of groundwater (GW), especially around Kabul, and other water-wasteful practices have further threatened the war-torn nation. New ideas about hydro-cognizance, hydro-hegemony, and hydro-diplomacy (Shroder and Ahmadzai 2016; 2017) may offer some longer-term solutions.

Current Status in Afghanistan

Afghanistan is semiarid with high variability and irregularity in precipitation. Use of surface and GW for different purposes has always been important. Because of increasing population, demographic changes, and growing economy, as well as climate changes in precipitation types from less snow to more rain, both surface and GW have gained attention. Massive increases in surface and GW uses are expected, being driven by higher irrigation, domestic, and industrial needs.

Recently, due to low annual precipitation nationwide and disappearance of much local surface water, ever more people use GW resources for multiple purposes. This causes GW depletion and contamination, especially in central parts of the most densely populated and cultivated provinces.

During recent drought years, use of deeper GW via better pumps is rapidly decreasing water tables and depleting aquifers. Both state and non-state organizations drill many of these new wells and extract without restraint as much water as possible.

A main challenge for sustainable GW management is lack of realistic data, or exact information on aquifer potential and water quality. No systematic planning exists for management and development of GW, and lack of capacity or technical knowledge prevails. Development and management of the GW sector needs a renewed technical and institutional framework. Urgent needs occur for: (1) establishing continuous-monitoring networks of GW quantity and quality; (2) conducting survey inventories of main characteristics of GW resources; (3) evaluation of climate-change effects; (4) identification of vulnerability zones, and (5) establishing a national GW database. Development of new reservoirs for surface water storage are essential to decrease GW use, along with surface storm-water basins to enhance GW recharge. Surface water is a priority for drinking use in many places in Afghanistan and must be considered most carefully, along with regulation of GW use by the private sector for any purpose. Bottling GW for export must be stopped, especially in GW-vulnerable areas of Afghanistan such as city centres and populated areas.

Aquifer Regions of Afghanistan

Based on scattered hydrogeological data in Afghanistan, three generalized major aquifer regions have been recognized but not mapped in any detail (Malyarov and Chmyriov 1976; United Nations, 1986; Uhl and Tahiri 2003) (Figure 11):

(1) **The north Afghanistan artesian (confined) aquifer:** Generally, the northern artesian aquifers are medium to highly porous, consisting of consolidated and unconsolidated sediments and sedimentary rocks with low to medium permeability and transmissivity, limitations of GW storage, and no suitable GW quality observed or proved in most areas. Shallow unconfined aquifers here are commonly salty. Fresh-water aquifers occur closer to the mountain sources in the younger alluvium. (2) **Central Afghanistan hydrogeological region**: The central aquifer is mostly hard metamorphic and igneous rocks in which GW is only in fractures or weathered zones with medium values of permeability and transmissivity. Thermal springs occur with good quality GW in a few localities (Abdullah and Chmyriov 1977b). Unfortunately, no detailed

investigation has been done on occurrence of GW resources in fractured aquifers of metamorphic and igneous rocks or the karst aquifers of carbonate rocks in Afghanistan**.** Fresh-water GW storage occurs in the river basins in the alluvium. (3) **The south (and west) Afghanistan artesian (confined) aquifer**: The southern and western artesian aquifer that extends north along the Iranian border contains consolidated sedimentary rocks and unconsolidated sediments with low to medium permeability values. Fresh-water GW storage occurs in river basins and plains areas with medium to high capacity of storage.

Most Quaternary sediments located in river basins and flat plain areas in Afghanistan consist primarily of loess, river-channel sands, gravels, and alluvial-colluvial fans with good porosity and permeability. The principal fresh-water aquifer systems in Afghanistan are in Quaternary deposits in major river valleys, particularly in the Kabul River Basin, the southwestern river basins of Helmand, Ghazni, Tarnak, Arghistan, Arghandab, and Hari Rud, as well as certain river systems within the northern and Amu Darya river basins (Figure 11). Most deep production wells for irrigation are drilled in productive aquifer zones of the Hari Rud, Farahrud and Kabul rivers basins. Geophysical investigations indicate that the depth to the base of these Quaternary and Neogene sediments may be as much as 600 to 1000m toward the centre of some sub-basins in the Kabul region (JICA 2007a). More than 95% of the GW abstracted from the aquifers is mostly returned through infiltration discharge to the Quaternary sediments in Afghanistan.

The lack of surface water and use of GW for multi-purposes (irrigation, drinking, other) changes the water’s natural distribution and impacts the ecosystems that depend on it. Demand for GW for irrigating crops usually occurs when insufficient precipitation occurs during the growing season, potentially causing river and GW levels to be reduced in the southwestern parts of Afghanistan. Afghanistan possesses only limited reserves of GW storage to keep as a strategic source for use during drought periods. The concept of use of GW for multi-purposes must be rethought because of its potential main priority for use for drinking purposes in places where no surface water occurs. Creation of qualitative and quantitative monitoring networks are needed for the aquifers of Afghanistan. More intensive data-collection programmes must be followed for alluvial wells, including continuous water-level measurements to define interactions between GW and surface water over the seasonal hydrograph. Creation of management tools (GIS, data bases of documents, thematic maps, town-planning documents) are required to support decision makers in future (Sinfield and Shroder 2016).

Overexploitation of GW

Currently GW is abstracted irregularly via diesel engines, electrical submersibles, and solar pumps throughout Afghanistan, especially for irrigation uses with unlimited extraction through NGOs, farmers, opium cultivators, warlords, and in the private sector. Most people use GW for different purposes all over the country without any scientific consideration. They have abstracted GW in huge amounts throughout the country, with the result that a negative balance exists between surface-water recharge and GW discharge. Large numbers of deep wells drilled in sectors (governmental/nongovernmental) and the overexploitation of GW is causing aquifer water levels to fall locally (Alley *et al*. 1999). Heavy drawdown, with deep cones of depression and interference between closely spaced wells is causing unacceptable reduction in flow of springs and karez or drying up of all water features such as shallow wells. In most parts of the populated and irrigated areas of Afghanistan, GW abstraction rates are already overexploited and exceeding recharge. In the Bagrami project area of Kabul City, most of the surrounding shallow wells are expected to dry up soon (Mills 2018). In south-southwestern parts of Afghanistan this deficit is bringing internal conflict between opium cultivators and other residents.

Based on the JICA (2007a; 2007b) report about shallow Quaternary aquifers in Kabul Basin already in negative GW balance, they clearly have no more development potential. To avoid depletion of shallow GW, pumping up from shallow aquifers should be controlled carefully. Also, the deep Neogene aquifer in the Kabul Basin is fossil water, outside of the natural water cycle without any recharge so it cannot be developed sustainably and is not even an emergency water source. The Afshar Aquifer in Kabul city is an example of this case in that currently out of 9 deep wells only 3 are still functioning for 12 hr/day and 6 wells have dried up. The Afshar water supply project was functional from 1976 up 2017 and was only for drinking purposes (interview with Eng. Muzafarkhil, technical advisor of AUWSSc, 20 March 2018). The Afshar Aquifer consists largely of the Quaternary sediments and is unconfined (Mills 2018).

Increasing use of pumped wells for various uses in different parts of Afghanistan is likely to be unstoppable and in the absence of any actively functioning responsible authority for regulating or studying the GW status, it fairly clear that the future of sustainable GW use will be poor. The challenge of GW shortage is a catastrophic phenomenon and together with GW contamination constitute a dour future for Afghanistan.

For good GW management in Afghanistan, GW governance must be established (Banks 2001; 2014). This is a process by which the GW resources are managed through the application of responsibility, participation, information availability, transparency, custom, and rule of law. It is the art of coordinating administrative actions and decision-making between and among the different jurisdictional levels. Development of new capacious storage facilities for surface-water supply (instead of GW use**)** is required for all of Afghanistan. Some short-term solutions will be recycling of waste water, strongly focused upon using surface water for any purposes other than first priority drinking, regulating GW use by the private sector, especially in GW-vulnerable areas Afghanistan (centres of cities, populated areas), as in Kabul. GW should be considered as a national strategic resource and should be used only based on sustainable good management plans.

GW contamination

Water contamination is from natural and anthropogenic sources in Afghanistan. The natural effect is very low to negligible but the sources of anthropogenic or human-made sources (agricultural, human, and industrial wastes) are the main challenge, due to rapid population increase, unplanned urbanization, poor sanitation infrastructure, open defecation, lack of public awareness, and too much use of fertilizers and pesticides in agriculture areas. Concerns over GW pollution from agricultural chemicals were raised as a major issue in the rural areas of Afghanistan, and microbiological contamination within the populated centres of provinces in Afghanistan (Uhl and Tahiri, 2003).

Sewage is largely disposed of in countless domestic drainage pits and open sewage channels (traditional latrines) mostly in rural areas. Therefore, it is likely that the important shallow GW aquifers are contaminated by effluents. The contaminant and the process by which the contaminant is generated and transported to the water body need to be identified. Once identified, an appropriate control method needs to be designed and implemented to interfere with the availability, detachment, or transport of the contaminant. Encouragement of public participation in household sanitation and hygiene practices are needed as a practical response to degradation of GW quality and quantity. Establishment of sewer systems (centralized and decentralized) are required, as well as waste-water treatment plants and regulation of urban planning and restricted controlling of illegal settlement. Protection zones are required around well-field areas for existing and new well fields, especially upstream of these water-supply projects.

Conclusion

The bedrock geology of Afghanistan is seen to be an unusual mixture of many exotic small tectonic terranes rafted into place throughout much of geologic history and then sutured together in multiple plate-fragment collisions. The Variscan, Cimmerian, and Himalayan orogenic episodes in the late Paleozoic, early to mid-Mesozoic, and the Cenozic to the present day have produced the lithologic and structural aspects of the country. Diverse lithologies with rich natural resources were brought in from elsewhere or were formed largely in place in the active tectonic milieu. Deciphering the geologic complexity has been the work of many foreign geologists being led or accompanied by a host of Afghan geologists who have carried on as much geologic research as they could even through the most difficult and violent times of the past four decades.

The diverse geology of Afghanistan could become part of the salvation of the sorely beset country through wise resource extraction, and protection of its vital water supplies, or could be merely another complexity in that seemingly forever fraught milieu (Shroder 2015). The transparency initiatives to reduce individual, corporate, and government corruption can certainly help, as well the development of new resource corridors, with the increased training and education about water in the hydro-cognizance approaches that are underway (Shroder and Ahmadzai 2017), or the increased attention to water security for the widest possible variety of people (Ahmadzai and Shroder 2017). If the present government of Afghanistan is able to maintain some minimum control over the fragile security of the country, the understanding and use of the geology in development and rebuilding of the nation will continue.

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Figures and Captions

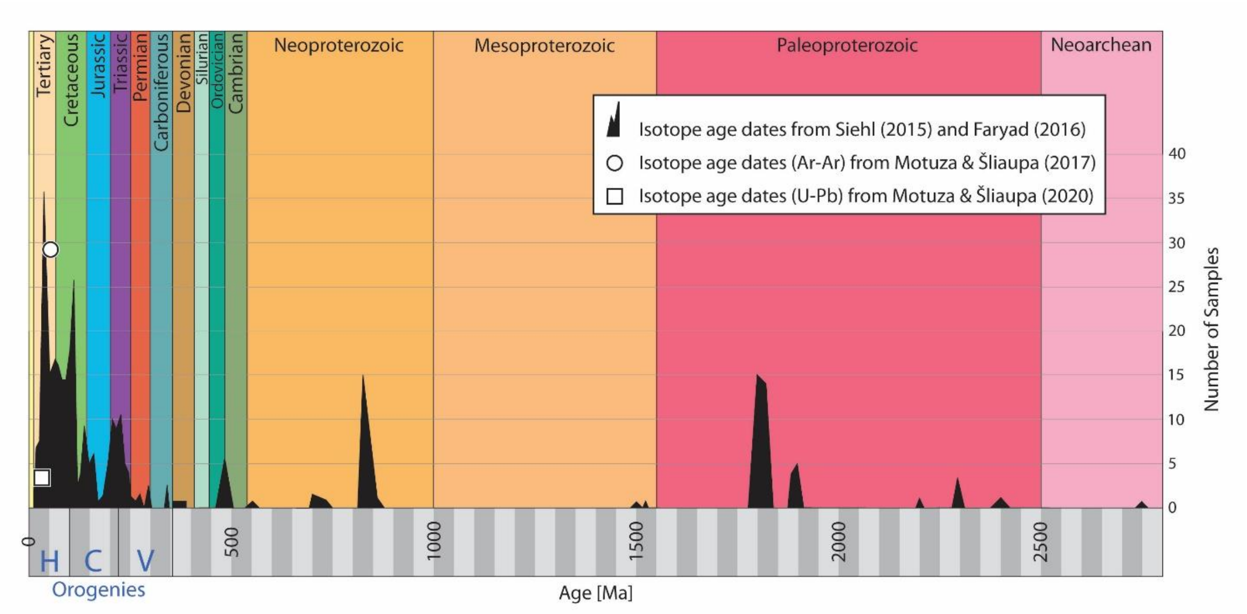


Figure 1. Phanerozoic isotopic age dates (n=289) published in mid to late 20th century and Precambrian and early Paleozoic isotopic age dates (n=108) obtained in recent decades for the Kabul block in Afghanistan (authors listed in text). U-Pb dates from zircons indicate a Neoarchean age of 2500-2800 for their magmatic crystallization in the original block (craton). U-Pb dates from zircons and U-Th dates from monazite show a Paleoproterozoic age of metamorphism, followed by a Neoproterozoic metamorphic event that was defined largely by the Ar-Ar dates from micas (Faryad *et al*. 2016). The three great orogenic episodes (blue letters V, C, H) of the Phanerozoic in Afghanistan are the Variscan (Hercynian), Cimmerian, and the Himalayan (Alpine). Modified from Siehl (2015), and Motuza and Šliaupa (2017a; 2020).

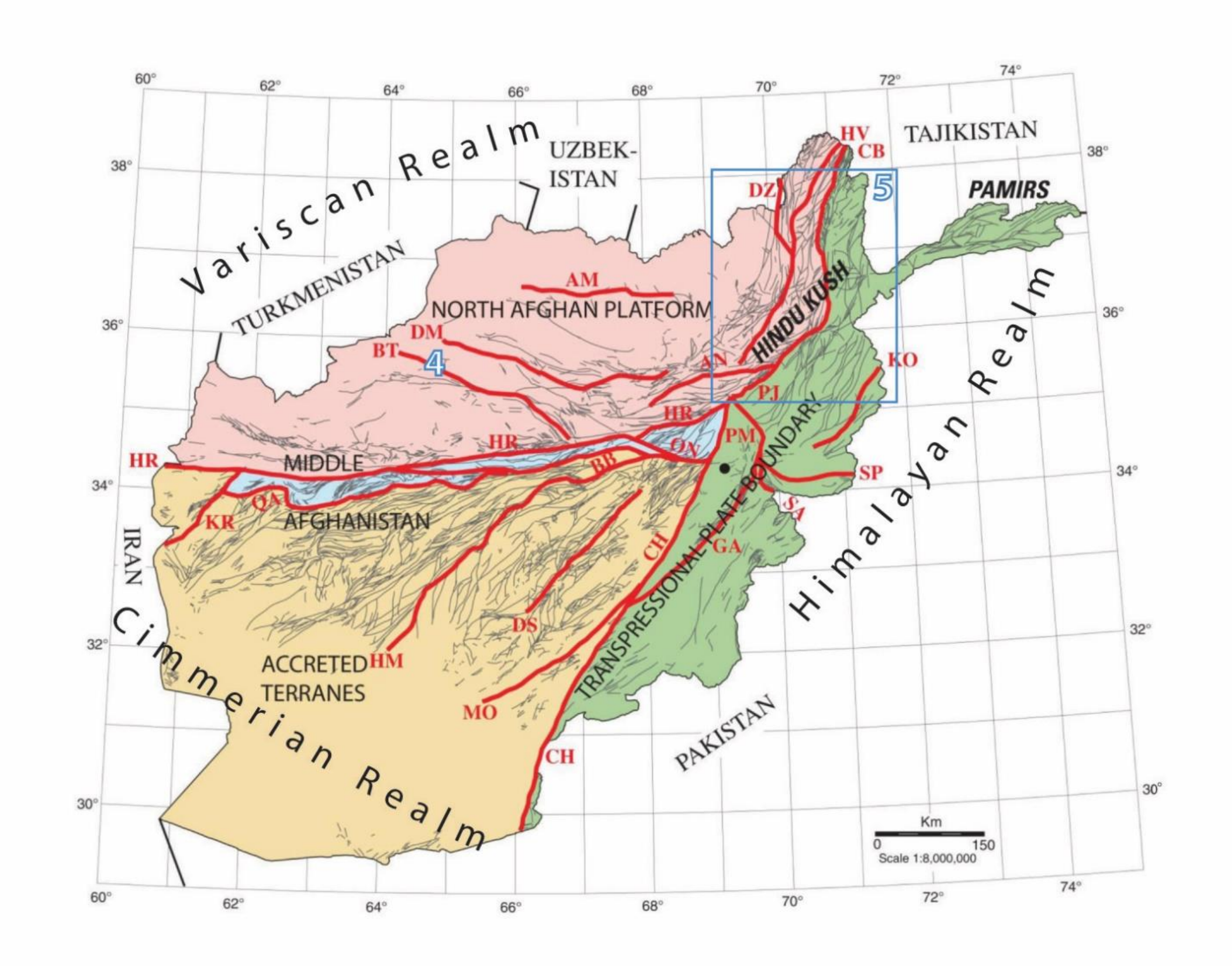


Figure 2. Map modified from Wheeler *et al.* (2005) showing the four main structural – plate-tectonic subdivisions of Afghanistan according to the U.S. Geological Survey, along with the main faults: AM – Alburz – Marmul; AN – Andarab; BB – Band-e Bayan; BT –Band-e Turkistan; CB – Central Badakhshan; CH – Chaman; DM – Dosi Mirzavalan; DS – Darfashan; DZ – Darvaz; GA – Gardez; HM – Helmand; HR – Hari Rud (Herat); HV – Hanjan; KO – Kunar (Konar); KR – Kaj Rud; MO – Mokur; ON – Onay; PJ –Panjshir; PM – Paghman; QA – Qarghanaw; SA – Sarobi (Altimoor); SP – Spin Ghar (Safed Koh). Most of these faults are actually zones of faulting rather than single strands, and several have alternate names. The location of figure 4 is shown by the blue and white “4”. The location extent of figure 5 is demarcated by a fine blue line and a blue and white “5”.

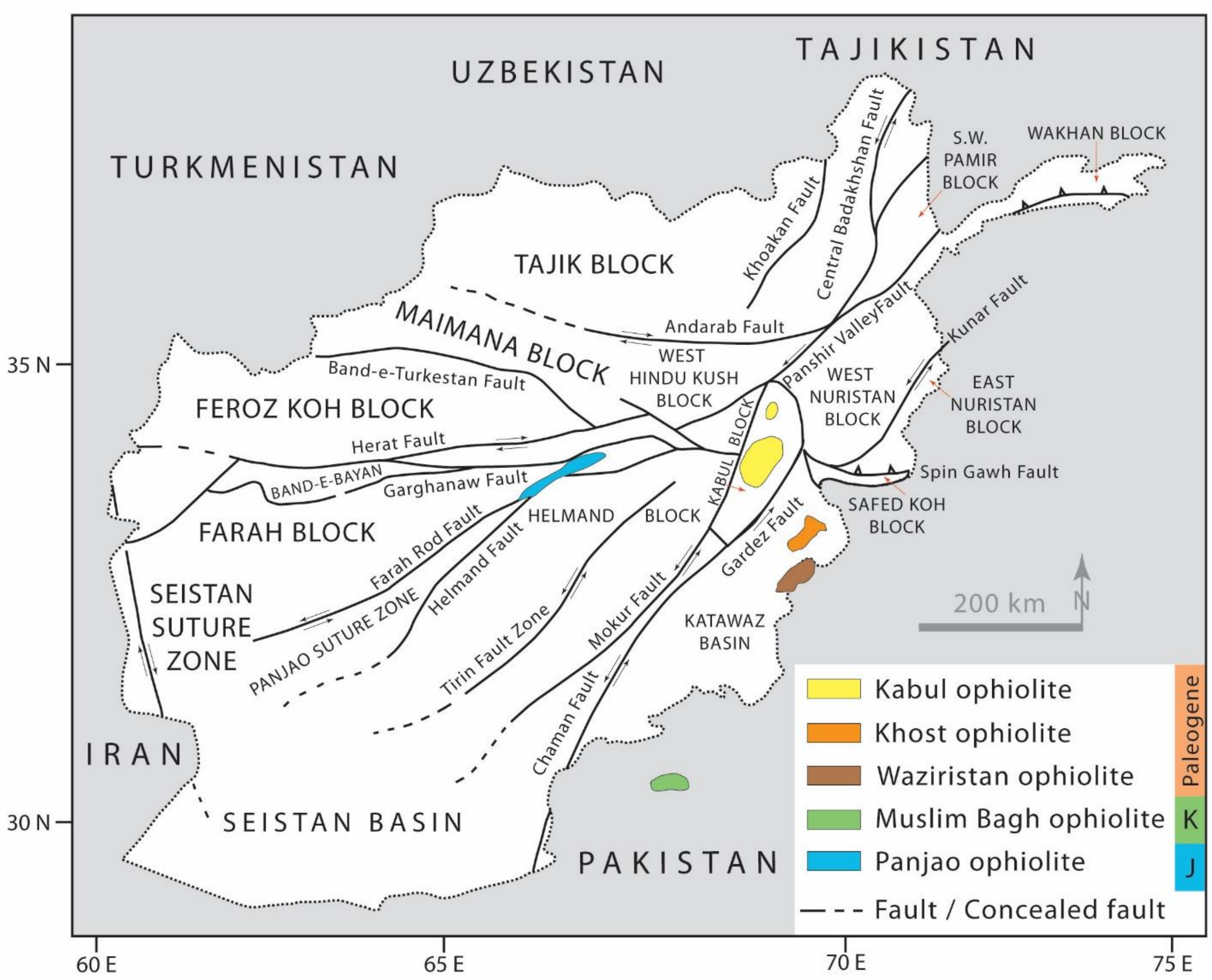


Figure 3. Map of the faults and the main lithological-structural blocks of Afghanistan (modified from Wittekindt *et al.* 1997). Many of the most prominent ophiolite zones are included but a number have been left out at this scale. The Herat fault is also known as the Hari Rud Fault. The fault directly west of the Kabul Block that seems to be an extension of the Moqur Fault is also known as the Paghman Fault. The fault directly east of the Kabul Block is also known as the Sarobi or Altimoor fault. The Spin Gawh Fault is also known as the Spin Ghar Fault.

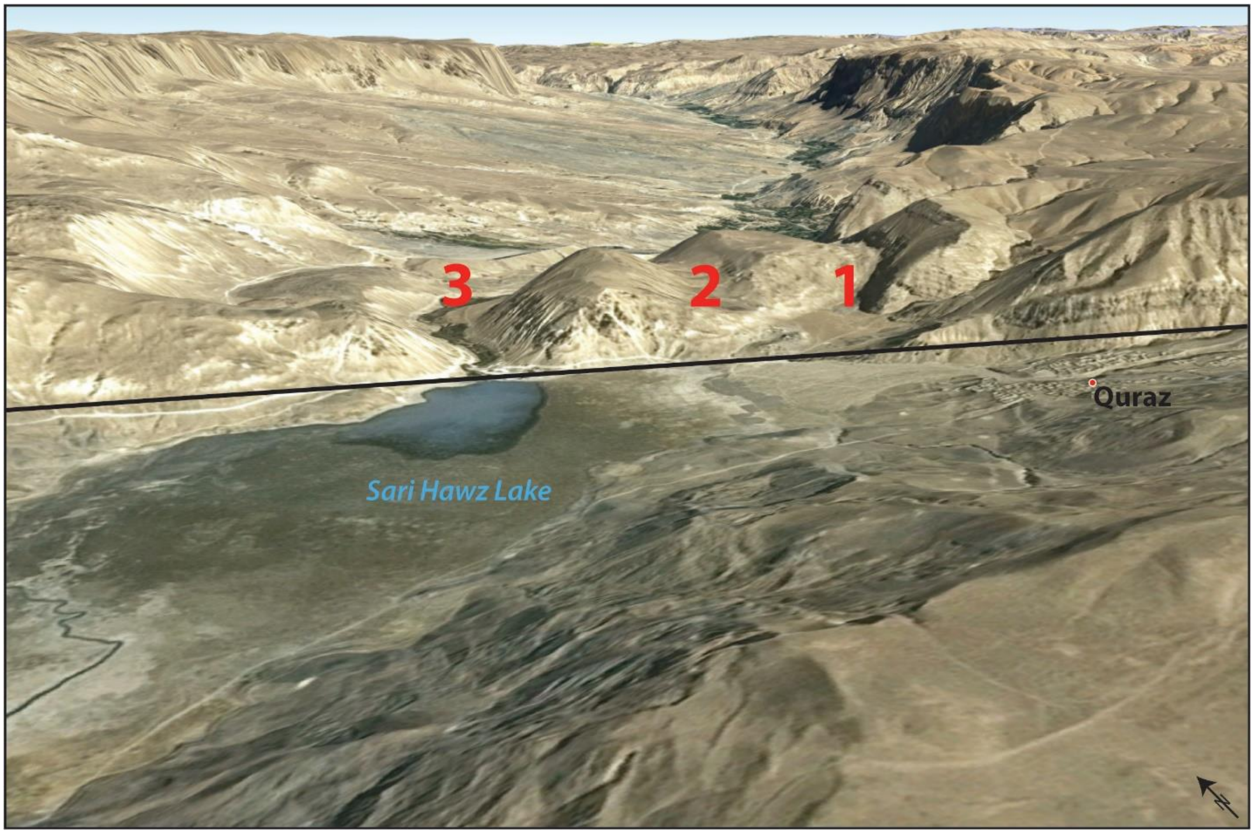


Figure 4. View to the northeast downstream along the Maimana River where it is cut across by the dextral Band-e Turkestan fault showing progressively truncated and abandoned river outlet channels: (1) oldest; (2) middle-most; and (3) modern river channel. Figure location on Figure 9 as red “4” and in figure 2 as blue and white “4”. The natural impoundment of the Sare Howz by the fault has been artificially enhanced by construction of a low dam on the fault, which cannot be a favorable site for a dam foundation. (modified Google Earth version of figure 5.20 in Shroder 2014).

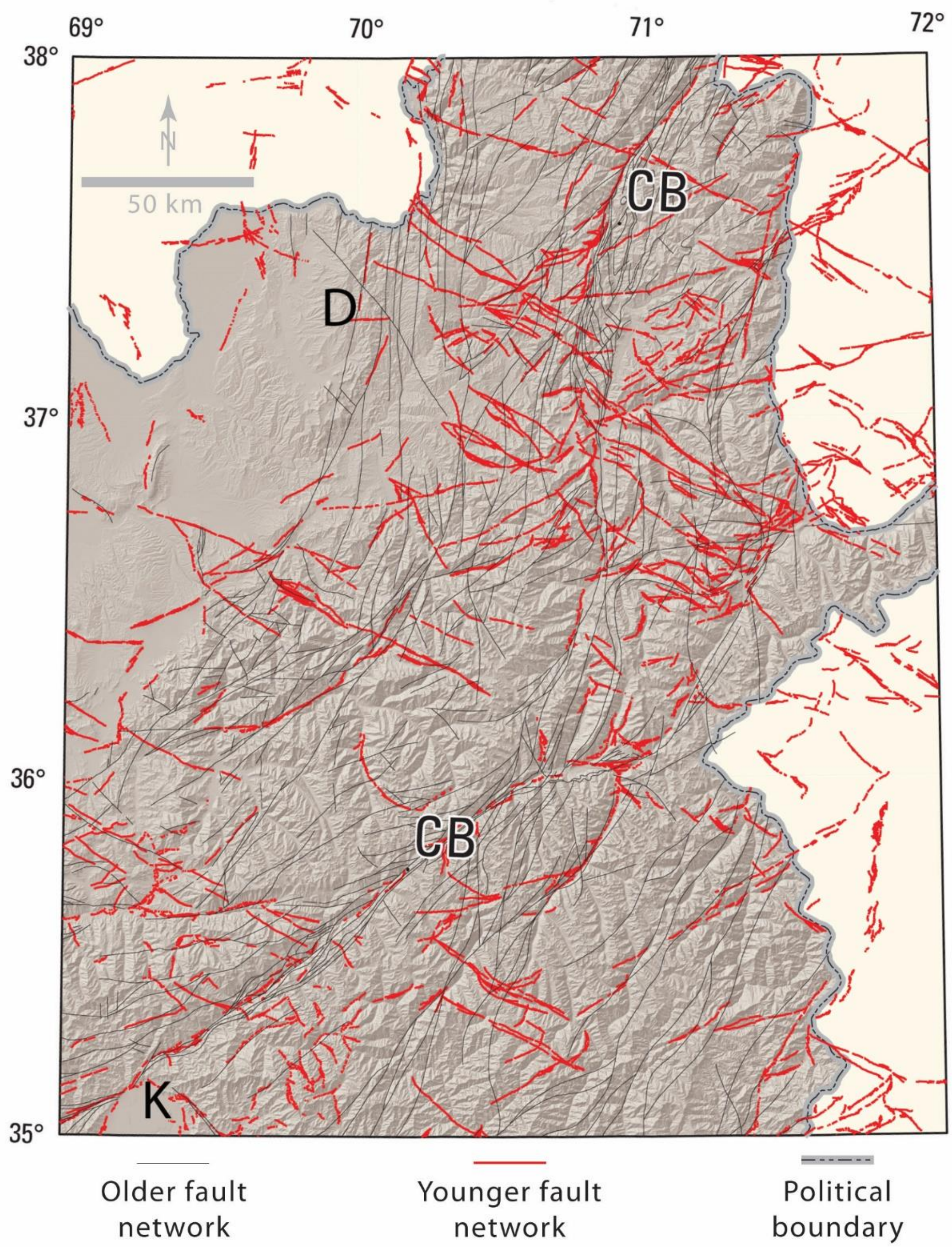


Figure 5. Map adapted from Wheeler and Rukstales (2007) showing the complex network of faults in northeastern Afghanistan, with the older faults in black and younger faults in red. CB – Central Badakhshan fault zone; D – Parvaz fault zone; K – north end of the Kabul block where the Sarobi (Altimoor) fault on the east meets the Paghman fault on the west. The southern part of the CB fault zone is also known as the Panjshir fault.

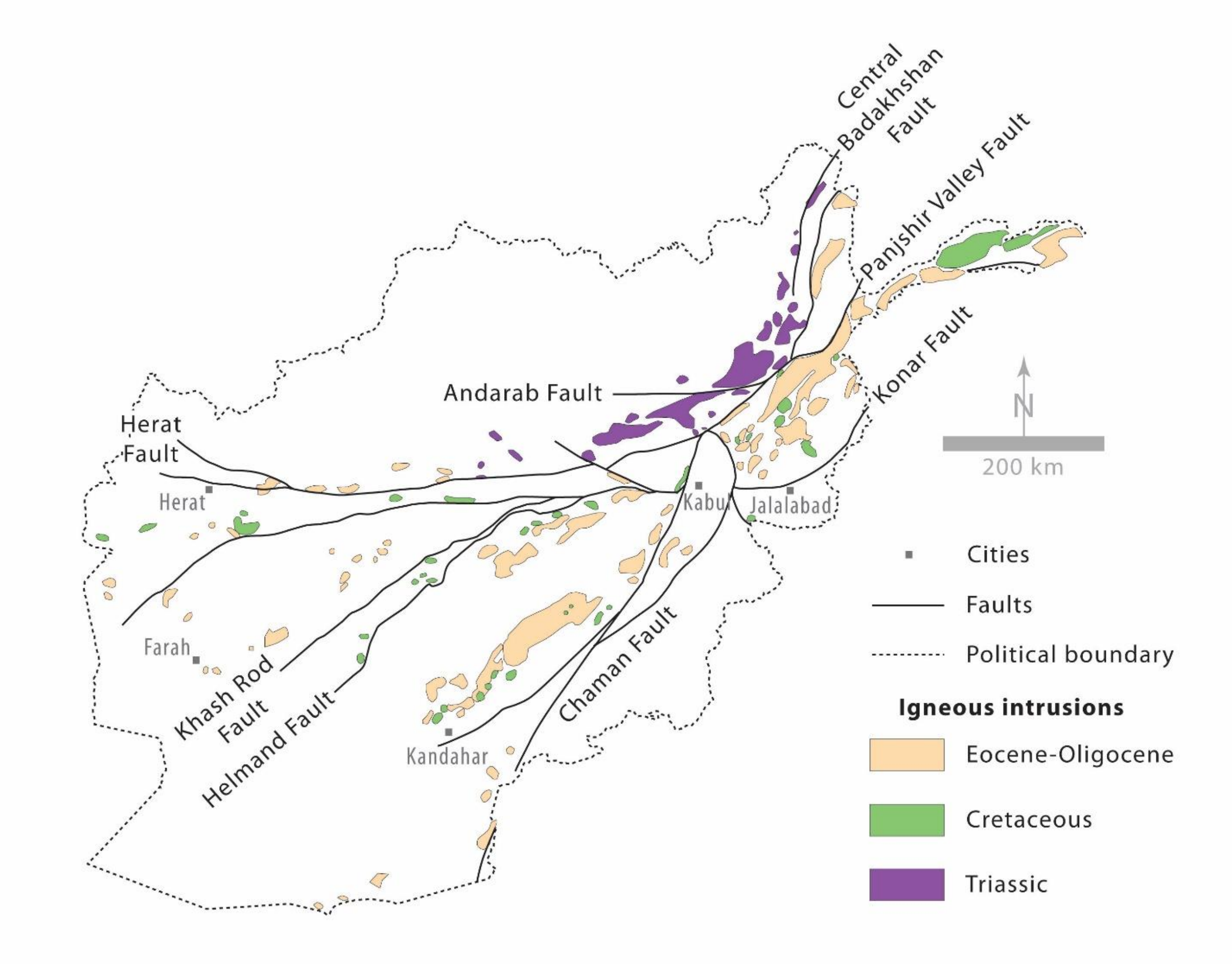


Figure 6. Map of magmatic belts in Afghanistan adapted from Faryad *et al.* (2013), and Motuza and Šliaupa (2017b, 2020) showing the main igneous intrusions by time period. Note in particular the linear chain of Triassic-age plutons (purple) in the north of the country. These define a Variscan orogenic episode of igneous intrusion and extrusion in the region.

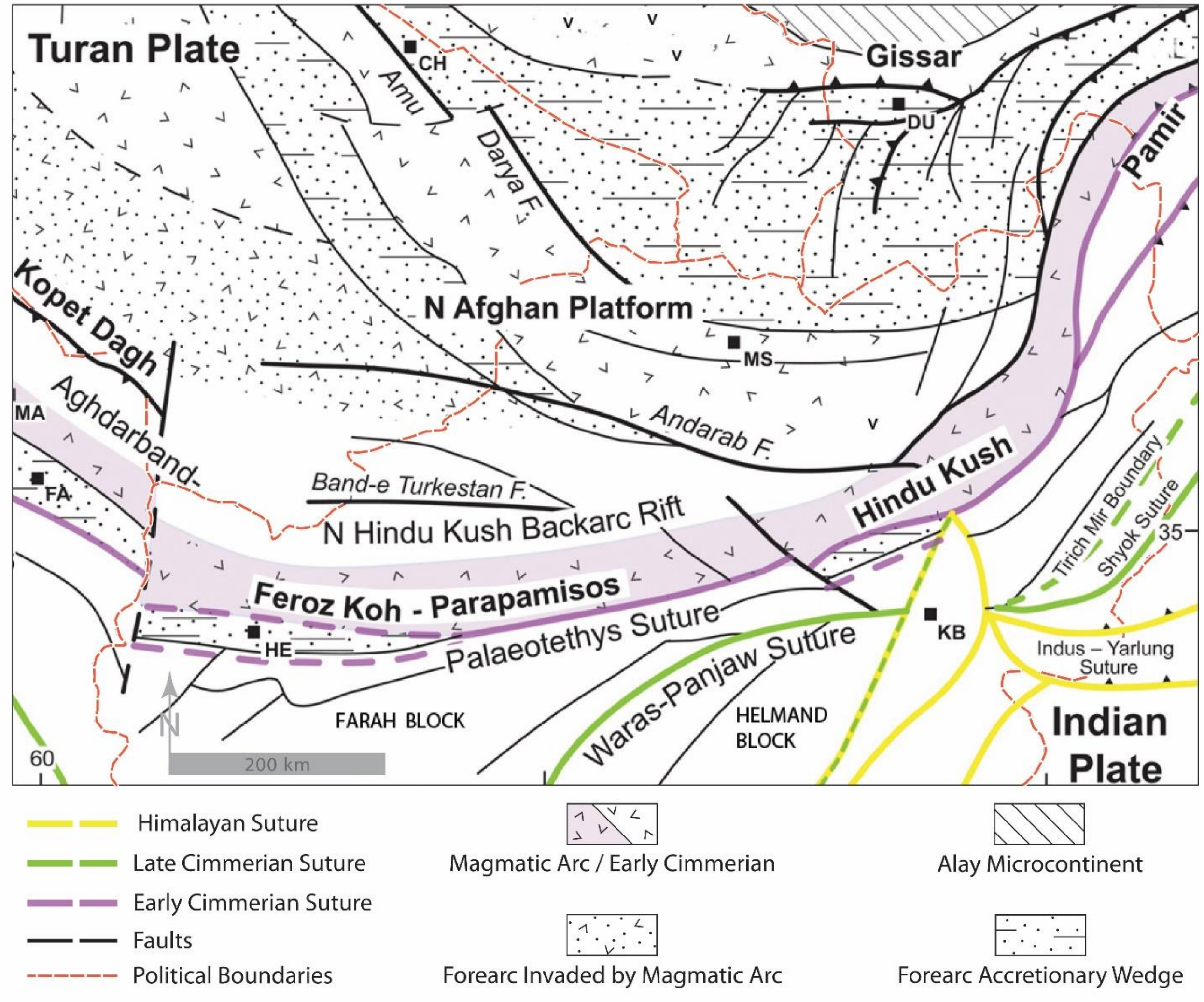


Figure 7. Paleogeographic map adapted from Siehl (2015) showing possible configuration of a magmatic arc (purple and v) across central and northeastern Afghanistan in the Early Cimmerian. The Variscan Realm is Late Paleozoic (LPz); the Cimmerian Realm is Late Triassic to Early Cretaceous (LTr - LK), and the Himalayan Realm is Cenozoic (Cz).

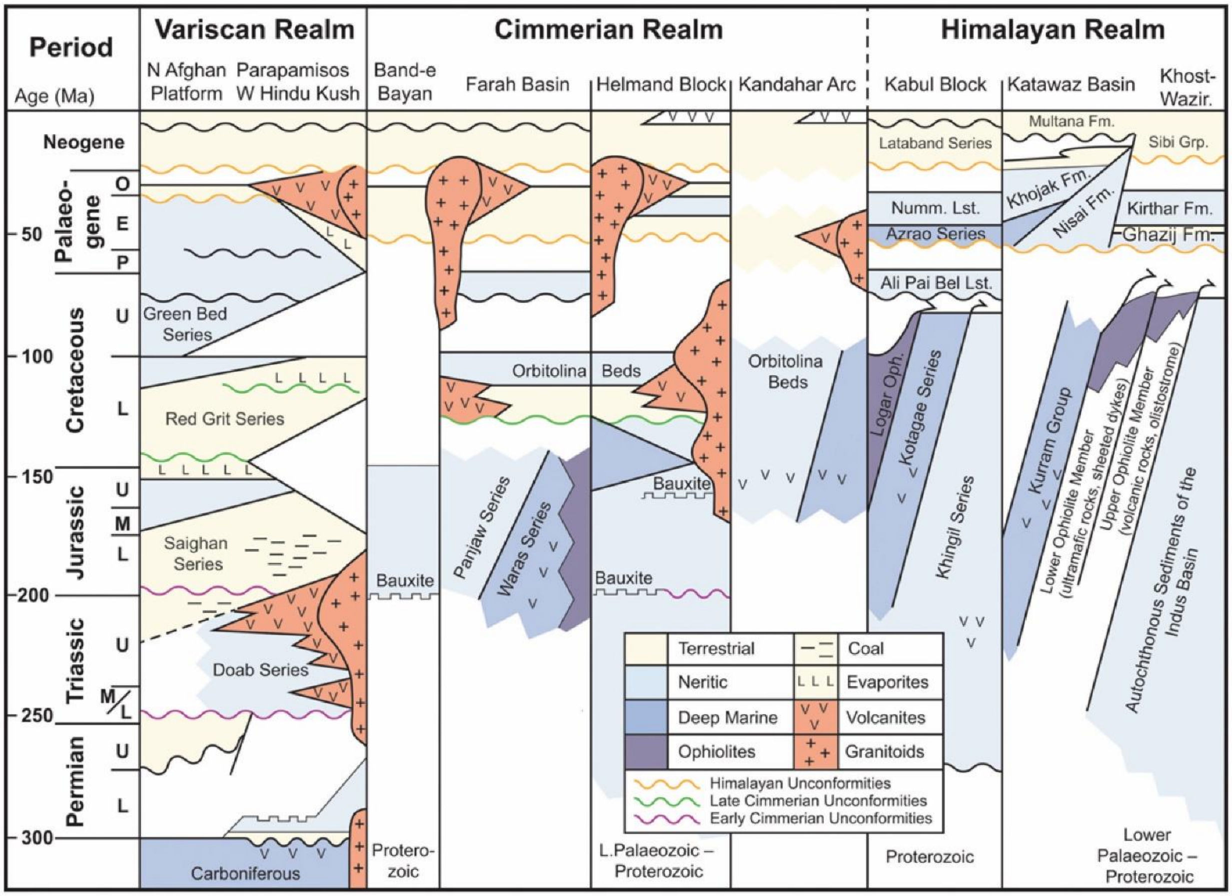


Figure 8. An abbreviated time-event and stratigraphic cartoon of the various geological situations prevailing across Afghanistan that shows the geographical variations arranged in temporal sequence according to the three main orogenic realms from the Late Paleozoic through the Cenozoic (from Seihl 2015). Most of the symbols are either explained in the key and are indication of some feature of note to explain the geological history of erosion, sedimentation, structural movement, or igneous intrusion or extrusion. White background indicates either unknown or absent rock record, or not diagrammed here at that time period.

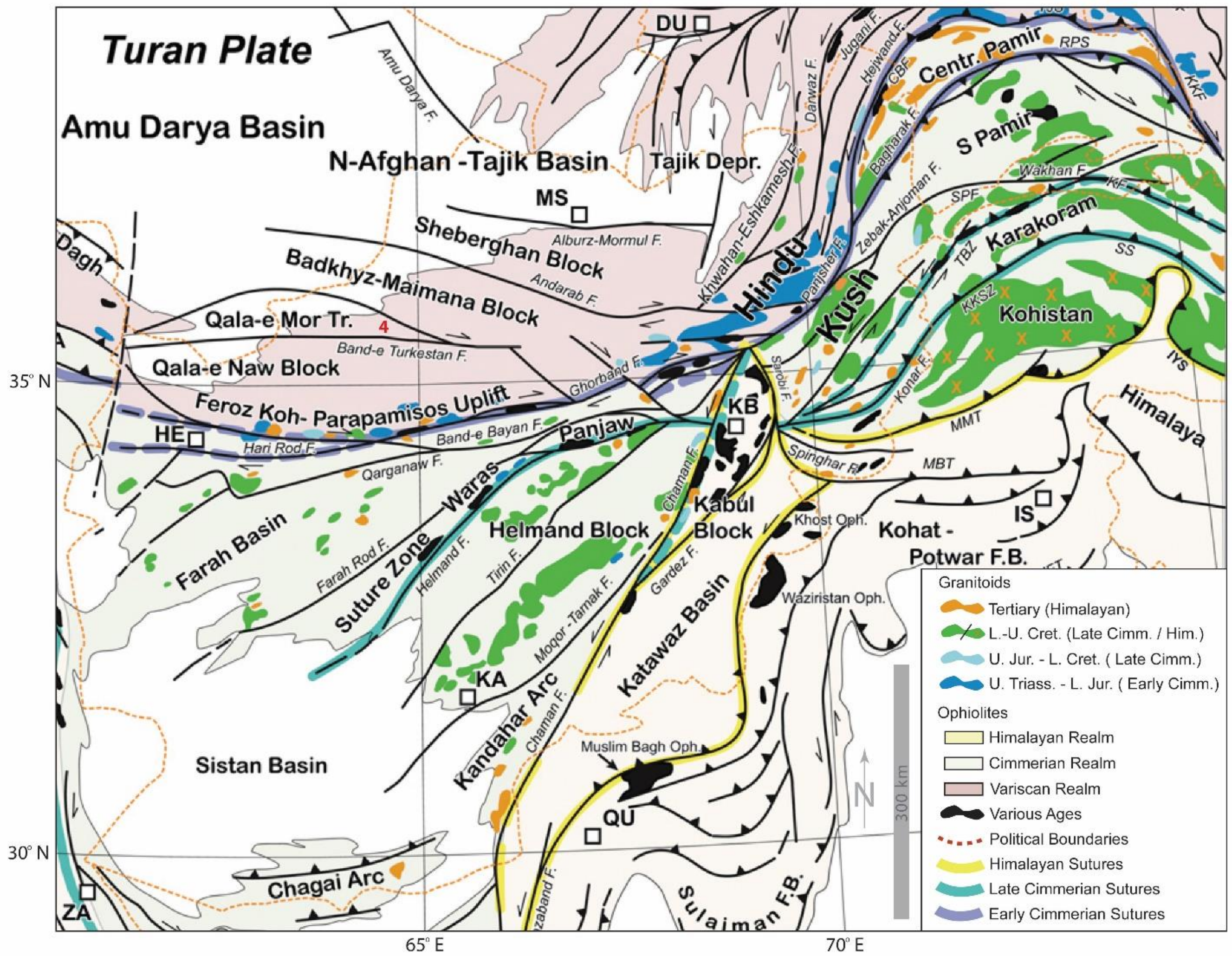


Figure 9. Tectonic sketch map of the Afghanistan orogenic segment, modified from Siehl (2015). □ city; DU – Dushanbe; HE – Herat; IS – Islamabad; KA – Kandahar; KB – Kabul; MS – Mazari Sharif; QU – Quetta; ZA – Zahedan.

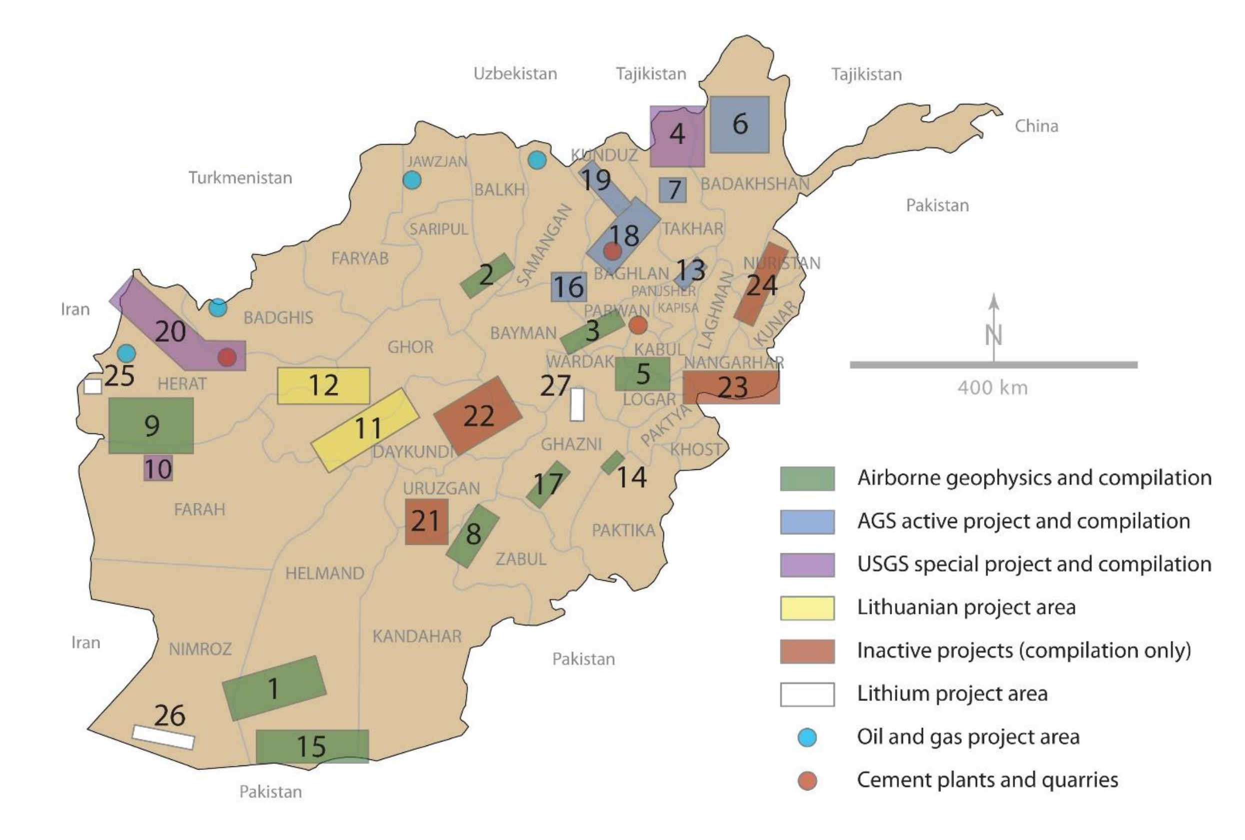


Figure 10. Map of Afghanistan showing the 24 Areas of Interest (AOIs) identified by the USGS and the TFBSO and the locations where the mineral data and their associated information were compiled and activities were planned and implemented with the Afghanistan Geological Survey and the Ministry of Mines (Peters 2011; Peters *et al*. 2011). Compare with Table 2 for complete names of the AOI.

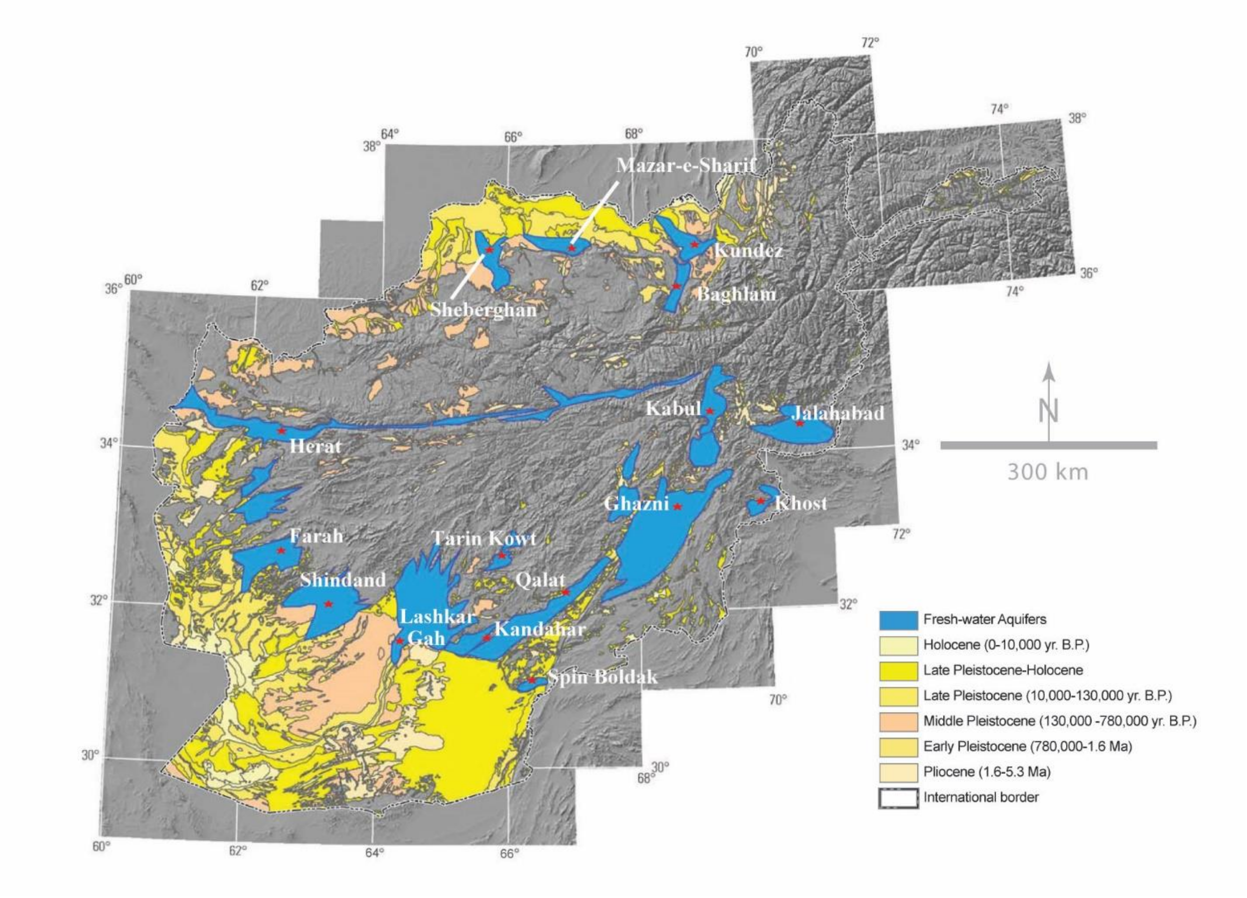
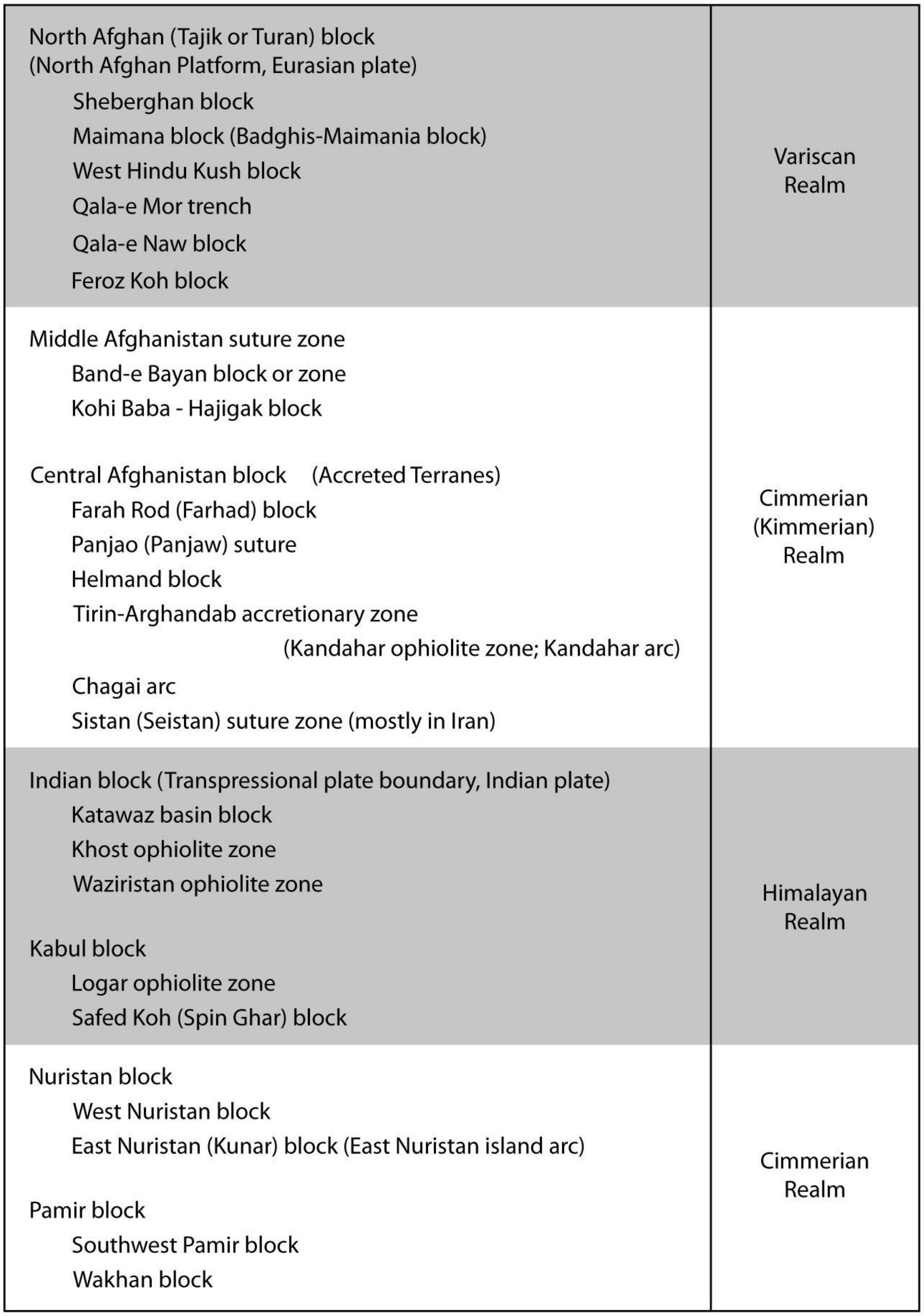


Figure 11. Fresh-water aquifers (blue) plotted on a U.S. Geological Survey map of the surficial deposits of Afghanistan (from Figure 3.13 in Sinfield and Shroder 2016). The blue color of the aquifers obscures the dominantly Holocene and Late Pleistocene deposits of the highest porosity and permeability where the aquifers occur but comparison with Figure 4 in Ruleman *et al*. (2007) should enable useful interpretations if necessary.

Tables and Captions



North Afghan (Tajik or Turan) block (North Afghan Platform, Eurasian plate)	Variscan Realm
Sheberghan block	
Maimana block (Badghis-Maimania block)	
West Hindu Kush block	
Qala-e Mor trench	
Qala-e Naw block	
Feroz Koh block	
Middle Afghanistan suture zone	Cimmerian (Kimmerian) Realm
Band-e Bayan block or zone	
Kohi Baba - Hajigak block	
Central Afghanistan block (Accreted Terranes)	
Farah Rod (Farhad) block	
Panjao (Panjaw) suture	
Helmand block	
Tirin-Arghandab accretionary zone (Kandahar ophiolite zone; Kandahar arc)	
Chagai arc	
Sistan (Seistan) suture zone (mostly in Iran)	
Indian block (Transpressional plate boundary, Indian plate)	Himalayan Realm
Katawaz basin block	
Khost ophiolite zone	
Waziristan ophiolite zone	
Kabul block	
Logar ophiolite zone	
Safed Koh (Spin Ghar) block	
Nuristan block	Cimmerian Realm
West Nuristan block	
East Nuristan (Kunar) block (East Nuristan island arc)	
Pamir block	
Southwest Pamir block	
Wakhan block	

Table 1. Hierarchy of lithotectonic blocks, zones, or terranes of Afghanistan, together

with ophiolite suture zones and volcanic arcs. The hierarchical table organization reflects the somewhat informal aggregations of several smaller blocks into a single greater block to facilitate discussion. Several smaller terrane fragments have not been included. Alternate names are given for some blocks because no definitive list of all features has been prepared, and various terminologies have been proposed by different authors (Shroder 1984; Treloar and Izatt 1993; Wittekindt *et al*. 1997; Wheeler *et al.* 2005; Benham *et al.* 2009; Siehl 2015; Faryad *et al.* 2013; 2016; Motuza and Šliaupa 2017b). Lower case is used to distinguish all blocks, zones, and other features until authoritative and formal designations can be agreed and perhaps used more widely. The realms used by Siehl (2015) are geographically distinguished by dominant timing of their tectonic emplacement in more-or-less their present positions relative to each other.

1. Khanneshin carbonatite
2. Balkhab copper
3. Hajigak iron
4. Takhar placer gold
5. Anyak copper
6. Badakshan load gold
7. Takhar evaporite
8. Kundalyan gold and copper
9. Dusar-Shaida copper and tin
10. Tourmaline tin
11. Karnak-Kanjar mercury
12. Nalbandon lead and zinc
13. Panshir Valley emerald
14. Katawaz gold
15. Chagai Hills travertine, copper, and gold
16. Baghlan clay and gypsum
17. Zarkashan gold and copper
18. Dudkash industrial minerals
19. Kunduz celestite
20. Herat barite and limestone
21. Bakhud fluorite
22. Uruzgan tin and tungsten
23. Ghunday Achin magnesite and talc
24. Nuristan pegmatites
25. Namaksar lithium salts
26. Godzareh (Gaudi Zireh) lithium salts
27. Dashti Nawar lithium salts

Table 2. U.S. Geological Survey and TFBSO Project Areas in Afghanistan – 2010-2011 (after Peters 2011). Numbers are keyed to Figure 10.