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PROVENANCE OF KARAKUM DESERT SAND (TURKMENISTAN): LITHIC-RICH OROGENIC SIGNATURE OF CENTRAL ASIAN DUNE FIELDS

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Abstract. Major deserts do not necessarily consist of eolian dunes as quartz-rich as those of the Great Nafud, Rub' al Khali, Sahara, and Mega-Kalahari sand seas accumulated in anorogenic settings of Arabia and Africa. The Karakum dune field of Turkmenistan is one of the several examples of central Asian deserts bound by recent or recently reactivated orogenic belts where eolian sand includes abundant sedimentary and subordinately metamorphic and volcanic lithic fragments. Feldspatho-litho-quartzose detrital modes and epidote-amphibole-garnet heavy-mineral suites of southern Karakum dune sand compare well with those in mountain branches of the Amu Darya, indicating provenance from the western Pamir mountains of Tajikistan in the east. Dunes closer to the Caspian Sea in the west contain additional carbonate or felsic volcanic grains which, together with decreasing heavy-mineral concentration and increasing ZTR indices, reveals local recycling of cover strata exposed in the Kopeh-Dagh and Balkhan zone. Our data suggest that the huge Amu Darya River, which in Plio-Pleistocene to historical times has repeatedly changed its course across Turkmenistan from westward toward the Caspian Sea to northward toward the Aral Sea, represents the major sediment source for the Karakum Desert. Together with the Taklamakan sand sea of the Tarim basin, the Ordos and adjacent deserts of northern China, and the Thal and Thar deserts of the western Himalayan foreland basin, the Karakum would thus represent another example of large dune field principally fed by one major fluvial feeder system.

"Either thou shalt renounce thy vaunt and yield,
Or else thy bones shall strew this sand, till winds
Bleach them, or Oxus with his summer-floods,
Oxus in summer wash them all away."
Sohrab and Rustum by Matthew Arnold

Introduction

Turkmenistan occupies the southern part of the Turan depression and over 70% of the territory is covered by the Karakum Desert, part of one of the largest expanses of sand on the planet. Because of extensive Neogene to Quaternary covers, including the recent Caspian Sea deposits and alluvial fans and floodplains, bedrock exposures represent less than 25% of the country (Fig. 1). Bedrock crops out in three regions, including mainly the Kopeh-Dagh range in the south, the Balkhan (Karabogaz) to Kharazm regions in the north (Turan Province), and the Koytendag in the east (Pamir Province). The highest elevations are reached in the Koytendag along the southeastern border with Uzbekistan, where mountain peaks reach as high as 3138 m a.s.l., and in the central Kopeh-Dagh along the southern border with Iran, with altitudes up to 2872 m a.s.l.. Only 435 m a.s.l. are reached in the Balkhan zone, facing the Caspian Sea lying at ~ 27 m below sea level, whereas the lowest point in the country lies at 92 m b.s.l. in the Akhchakaya depression found in the northwestern Trans-Unguz Karakum southeast of Lake Sarygamysh (Babaev 1994).

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This article presents original petrographic and mineralogical data on modern river and eolian-dune sediments, used as tracers to investigate and unravel local versus long-distance provenance of Karakum desert sand. Sand provenance in other major and largely fluvially-fed dune fields of central Asia - including the Taklamakan sand sea (Yarkhand-Tarim River catchment, China), the Ordos and adjacent Tengger, Ulan Buh and Kubuq Deserts (Yellow River catchment, China), and the Thal and Thar Deserts (Indus River catchment, Pakistan and India) - and the contrast in petrographic composition between these lithic-rich orogenic sands and quartzose sands of dune fields in anorogenic settings of Arabia and southern Africa are also discussed.

Geological framework

Turkmenistan is located in the transition zone between the Cimmerian terranes in the south and the stable Eurasian plate in the north. Most studies were carried out by the former Soviet Union geologists (e.g., Kalugin 1957; Rastsvetaev 1966; Volvovsky et al. 1966; Krymus & Lykov 1969; Amursky 1971). Many of these articles, however, are in Russian language and therefore remain scarcely accessible to the international audience. More recent geological studies dedicated specifically to the region include those by Lyberis et al. (1998), Lyberis and Manby (1999), and Garzanti and Gaetani (2002), whereas others have considered Turkmenistan in the wider framework of the regional geology of the Turan platform and of Central Asia in general (e.g., Brunet et al. 2017). Thomas et al. (1999) provided structure-contour and isopach maps for five main stratigraphic intervals, Late Permian to Cenozoic in age, to reconstruct the paleogeographic and paleotectonic evolution of the southern margin of Eurasia. Natal'in and Sengör (2005) analyzed borehole and geophysical data and distinguished different geological units within the Turan domain, including the Bukhara, Chardzou, Karakum–Mangyshlak, Tuarkyr, and Karabogaz units. They suggested that the basement of these terranes, extending from northern Afghanistan and Turkmenistan to the Caucasus and the northern Black Sea, consists of a number of southwest-facing arc fragments formed during subduction of the Paleotethys Ocean and stacked at the close of the Triassic when they were arranged in an en échelon array by large-scale, right-lateral strike-slip motion.

Sedimentologic and petrographic analysis of the upper Paleozoic to Triassic Kizilkaya sedimentary succession in western Turkmenistan led Garzanti and Gaetani (2002) to conclude that the Turan plate consists of an amalgamation of upper Paleozoic to Triassic continental microblocks separated by oceanic sutures. In their reconstruction of the southern margin of Eurasia, Zanchetta et al. (2013) showed that this tectonically active region recorded several episodes of continental accretion and opening of arc-related basins associated with magmatic activity.

Detailed studies by Lyberis et al. (1998) and Lyberis and Manby (1999) investigated the stratigraphic and structural evolution of the Turan continental block, suggesting that post-Triassic sediments were folded and uplifted in the Kopeh-Dagh mountains during convergence between the Iranian and Turan plates. They inferred ~ 75 km of north-south shortening in the western part of the Kopeh-Dagh - Greater-Balkhan area, accommodated by oblique motion along the major Ashk-Abad fault and east-west structures south of it. Lyberis and Manby (1999) suggested that the post-Triassic succession may reach up to 17 km in Turkmenistan. Rapid subsidence in the Middle Jurassic was related to extensional tectonics in the back-arc region of the northward Neotethys subduction zone. Sedimentation continued without magmatic activity (Afshar-Harb 1979) and ~ 7 km of carbonate and siliciclastic deposits accumulated by the late Eocene, when marine deposition ceased and compressional inversion of the basin began (Robert et al. 2014). A recent overview of the geology and geomorphology of the area is provided by Ghassemi and Garzanti (2019).

Rivers and canals

Information not only on the geology of potential source areas but also on the river network and its changes in the recent past is of great help in assessing provenance of modern sand. The most important rivers draining into southeastern Turkmenistan and sourced in the Pamir mountains of Tajikistan or in the Hindukush mountains in Afghanistan, are the Amu Darya (Oxus in Latin), the Murghab, and the Hari Rud or Tejen (Arius in Latin). The Amu Darya, the largest river in Central Asia formed by the junction of the Panj, Vakhsh, and Kunduz Rivers (length

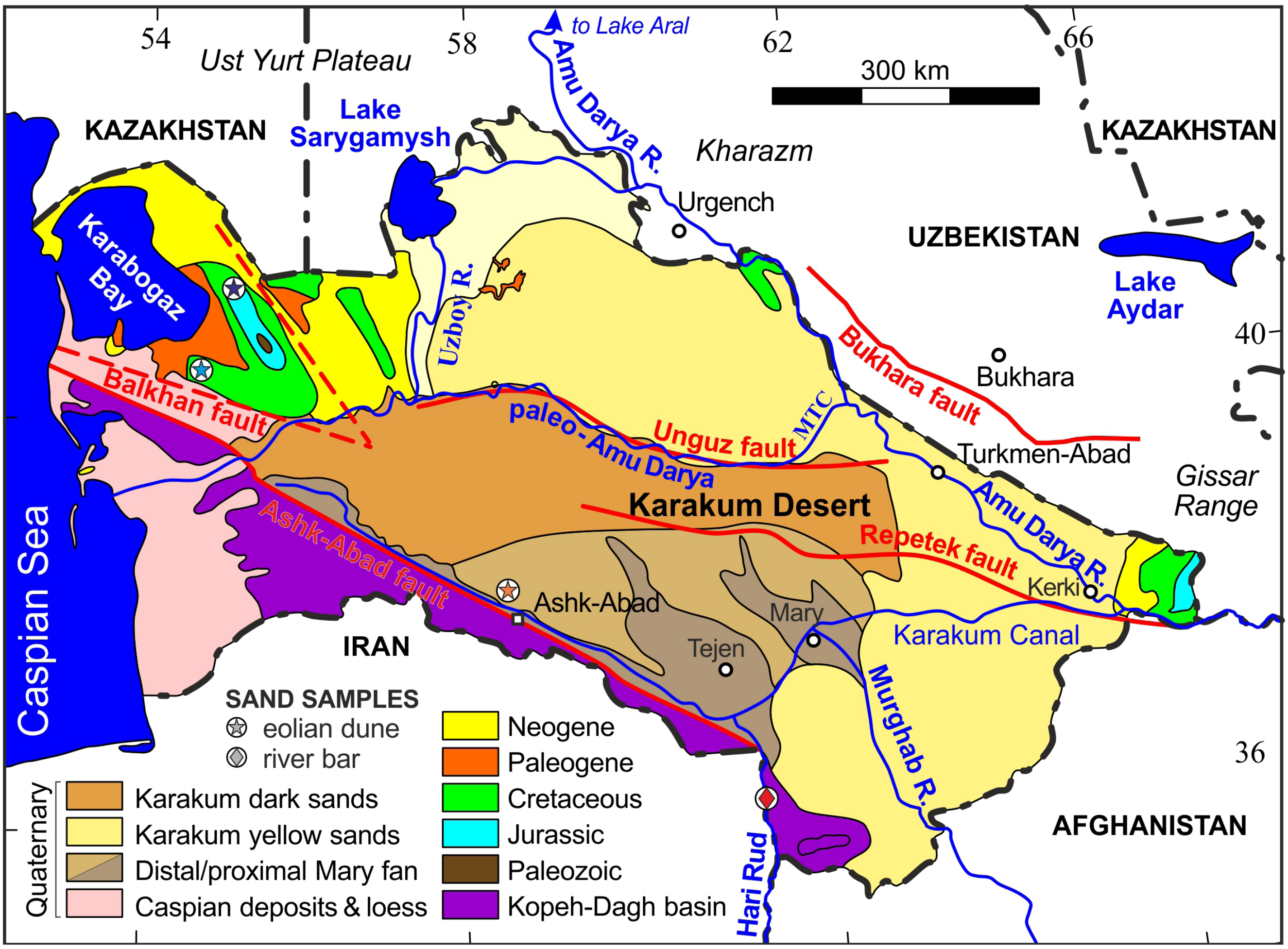

Fig. 1 - General map of Turkmenistan. At different times in the past, the Amu Darya River flowed through the Uzboy River, along the Unguz depression followed by the present Main Turkmen Canal (MCT), or along the present Karakum Canal. Location of modern sand samples collected in Turkmenistan and northernmost Iran is indicated (sampling sites in Tajikistan and Uzbekistan are displayed in Fig. 3 and in the Google Earth TM file *Karakum.kmz*).

~ 2600 km, basin area ~ 530,000 km^2, maximum discharge ~ 6,000 m^3/s) flows from the Pamir mountains across easternmost Turkmenistan to reach the presently dried Aral Sea. Its course across the Karakum Desert has changed repeatedly in the past. Until late Pleistocene to early Holocene times, Amu Darya waters used to flow even largely into the Caspian Sea south of the Karabogaz Bay via the Uzboy River (Fig. 1; Zavialov 2005; Létolle et al. 2007). The Unguz depression may represent another relict course of the Amu Darya towards the Caspian Sea (Fig. 1; Boomer et al. 2000). According to Ptolemy (2nd century A.D.) and Al-Biruni (11th century A.D.), in historical times the river ran westward across southern Turkmenistan from Kerki in the southeastern corner of the country to Mary, and evaporated in the Karakum Desert. Flow into the Caspian Sea resumed at the time of the Mongol conquest of Gorganj (later Urgench) in 1221 A.D., whereas the river was diverted northwestward again towards the Aral Sea around 1575 A.D. (Encyclopedia Iranica).

The Karakum Canal and the Main Turkmen Canal

Turkmenistan has a long history of major human modifications of drainage systems. The Karakum Canal, designed by the Soviet Union government as one of the world's largest water-supply scheme, was built between 1954 and 1988 to transfer 13 km^3 of water annually from the Amu Darya into western Turkmenistan across the Karakum Desert (Fig. 1). Navigable over much of its 1375 km length, the canal supplies water to Ashk-Abad city and opened up new large areas for cultivation and especially for cotton monoculture heavily promoted by the Soviet Union. On the other hand, almost half of the water was lost in the early construction stages of the canal, creating ponds and a groundwater rise

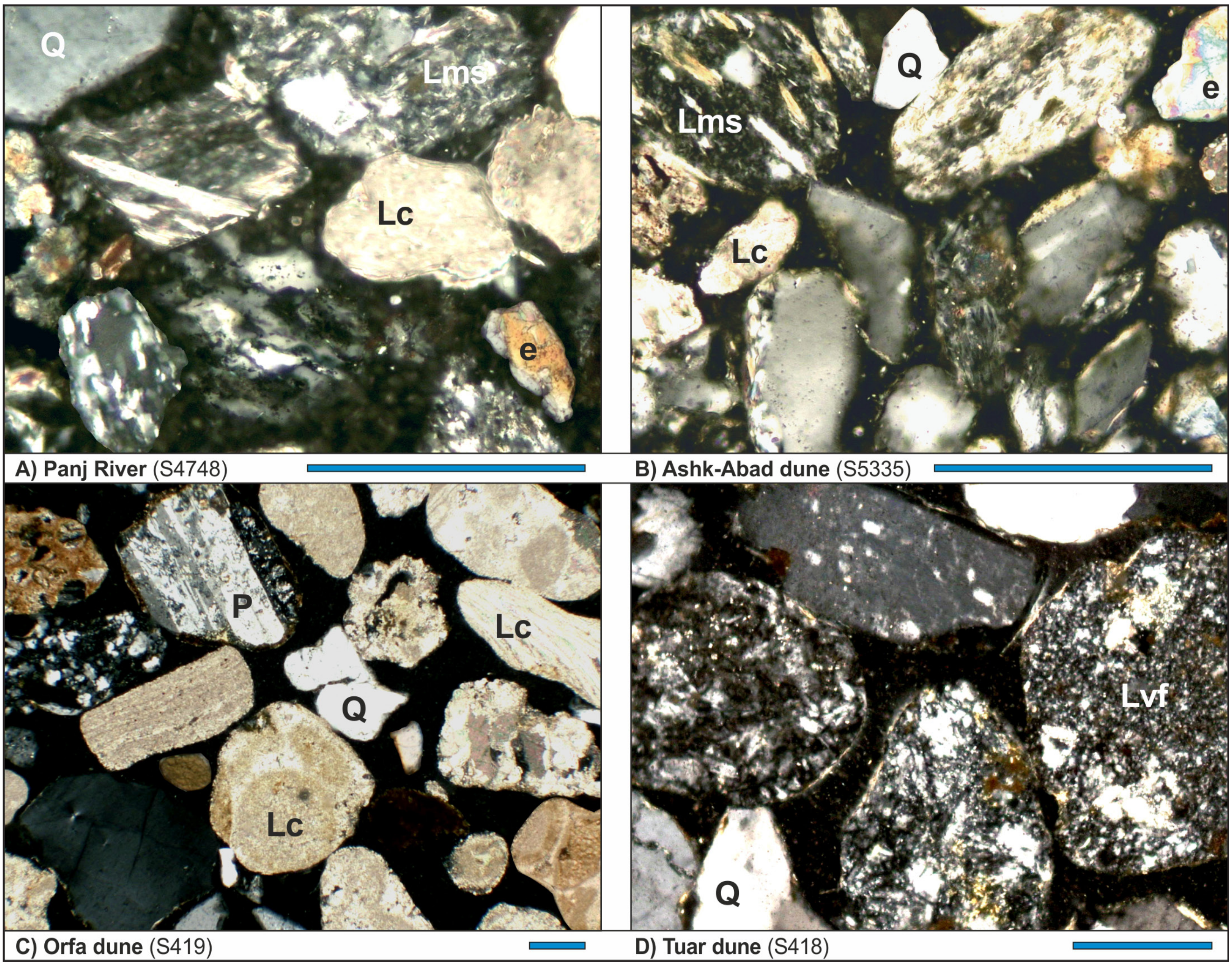

Fig. 2 - Petrography of modern sands. Feldspatho-quartzo-lithic composition characterizes both Panj River A) and Ashk-Abad dune sands B), whereas the coarser-grained Orfa and Tuar dune samples in the westernmost Karakum Desert are notably richer in carbonate C) and mainly felsic volcanic rock fragments D), revealing major local supply from cover strata. Q = quartz; P = plagioclase; e = epidote; Lvf and Lms = felsic volcanic and low-rank metasedimentary lithic grains. All photos with crossed polars; blue bar for scale = 150 µm.

that caused widespread soil salinization problems. The Main Turkmen Canal (Fig. 1; MTC) was planned in the 1970s as a 720 km-long infrastructure to be built following an ancient river bed of the Amu Darya from Turkmen-Abad to the west, along the Unguz salt marshes and across the low-elevation middle part of the Karakum Desert (Zonn & Kostianoy 2014). Huge canals and irrigation systems built to irrigate desert land during the Soviet Union period has led to environmental disaster in the Aral Sea (Kharin 2002; Micklin 2007).

Eolian deposits

Turkmenistan lies in an arid environment sculpted by wind action, and hosts different desert types including sand dunes, loess, rocky areas, and salt deposits (fig. 2 in Babaev 1994). The vast Karakum Desert occupies over 70% of the country and has low elevation, ranging from ~ 220 m a.s.l. in the east to as low as 92 m b.s.l. in the small Akhchakaya depression southeast of Lake Sarygamish (Fig. 1). More than 40 dust storms per year occur in the Karakum Desert and near the Caspian Sea, the highest frequency of all Central Asia. Sources of dust include the Karakum Desert as well as a large dust belt extending from north of the Caspian Sea to south of Lake Balkhash (Indoitu et al. 2012).

Dune fields in the Karakum are mostly stabilized by vegetation supported by sufficient rainfall (> 100 mm/a) in a low wind-power environment (Maman et al. 2011). As a consequence, dunes may have formed under wind regimes different from those of today. Some dune ridges contain intercalated clay, suggesting fluvial and not only eolian activity (Shahgedanova 2002). A sand sample from the northern margin of the Karakum Desert in the Kharazm region yielded an Optically Stimulated Luminescence (OSL) age of 7.3 ± 0.8 ka (Maman et al. 2011).

Longitudinal north/south-trending sand dunes with a maximum relief of ~ 30 m and average spacing of ~ 2.5 km characterize the southern Karakum Desert. Mobile dunes rest over the Murghab alluvial fan hosting the Mary (Merv) oasis and made in the distal part of fluvial silt and organic-rich clay sculpted as yardangs (Stoppato et al. 2003). Salt pans, some seasonally filled by water leaking from the Karakum Canal or from fields irrigated with canal waters are common in the southern Karakum Desert close to the Kopeh-Dagh mountains.

Loess

Turkmenistan lies within the mid-latitude Eurasian loess belt. Deposition of loess and paleosol sequences began around 22 Ma (Guo et al. 2002), but most of the loess was deposited in the Pleistocene. The traditional view about the Chinese loess is that dust was largely derived from the stony Gobi Desert in the north (e.g. Sun 2002), although deflation of Yellow River sediments has been favored in recent studies (Stevens et al. 2013). Loess deposits in Turkmenistan could thus be derived either from stony deserts mostly located in the northwestern part of the country or from deflation of alluvial fans fed from the south. Loess deposits south of the Iranian border consist of silt (> 80%) with minor clay, sand and intercalated paleosols. Loess deposits in northernmost Iran range in age from 145 to 9.5 ka (Frechen et al. 2009), and record cool and dry phases of increased dust accumulation alternating with moist and warm phases with soil formation (Kehl et al. 2006).

Petrography and mineralogy of Karakum Desert sand

The dark sands that give the name to the Karakum Desert (in Turkish kara = black, kum = sand) characterize only the central belt extending from Turkmen-Abad in the east to Serdar in the west, whereas other parts are covered with light-colour-

River	Site	Q	KF	P	Lv	Lc	&Ls	Lms	Lmv	Lmf	Lmb	Lu	mica	HM		MI*	MI	tHMC	ZTR	Ttn	Ap	Ep	Grt	SKA	Amp	Px	&tHM	
Panj	Kishti Poyen	40	5	12	1	15	3	7	1	4	0.5	0.3	3	8	100.0	224	165	5.9	2	0.5	3	43	6	5	36	5	---	100.0
Yakhsu	Dara-Khurdak	11	0.3	2	---	62	1	14	1	6	0.3	0.3	2	1	100.0	214	205	1.2	9	---	5	44	21	1	20	---	0.5	100.0
Khingou	Obikhinghob	28	1	10	1	23	5	14	1	2	4	1	3	9	100.0	215	171	6.2	2	---	1	69	6	4	16	1	---	100.0
Vakhsh	Chumdon	32	2	9	1	14	6	12	5	3	5	---	1	8	100.0	216	168	9.1	0.5	---	0.5	71	8	---	20	---	---	100.0
Hari Rud	Gush Sargousi	38	9	13	9	8	1	9	5	4	---	1	2	1	100.0	199	131	2.3	10	1	4	28	9	2	26	18	2	100.0
eolian dune	Ashk-Abad	49	3	17	1	13	1	5	3	1	2	---	0.3	6	100.0	200	175	4.6	4	0.5	2	54	10	1	25	3	0.5	100.0
eolian dune	Orfa	29	9	6	3	37	9	3	3	1	0.2	---	---	---	100.0	187	62	1.9	6	0.5	1	43	11	1	31	5	---	100.0
eolian dune	Tuar	48	12	9	7	4	6	3	9	2	---	---	---	---	100.0	149	75	0.5	15	---	3	44	18	0.5	14	5	---	100.0

Tab. 1 - Petrography and heavy minerals in eolian dunes of Turkmenistan and potential fluvial sources of Karakum desert sand. Q = quartz; KF = K-feldspar; P = plagioclase; L = lithic grains (Lv = volcanic; Lc = carbonate; &Ls = other sedimentary; Lms = low-rank metasedimentary; Lmv = low-rank metavolcanic; Lmf = high-rank metapelite/metapsammite/metafelsite; Lmb = high-rank metabasite; Lu = ultramafic). MI* and MI = metamorphic indices (Garzanti & Vezzoli 2003). HM = heavy minerals; tHMC = transparent-heavy-mineral concentration; ZTR = zircon + tourmaline + rutile; Ttn = titanite; Ap = apatite; Ep = epidote; Grt = garnet; SKA = staurolite + andalusite + kyanite + sillimanite; Amp = amphibole; Px = pyroxene; &tHM = other transparent heavy minerals including barite, chloritoid, Cr-spinel, and axinite.

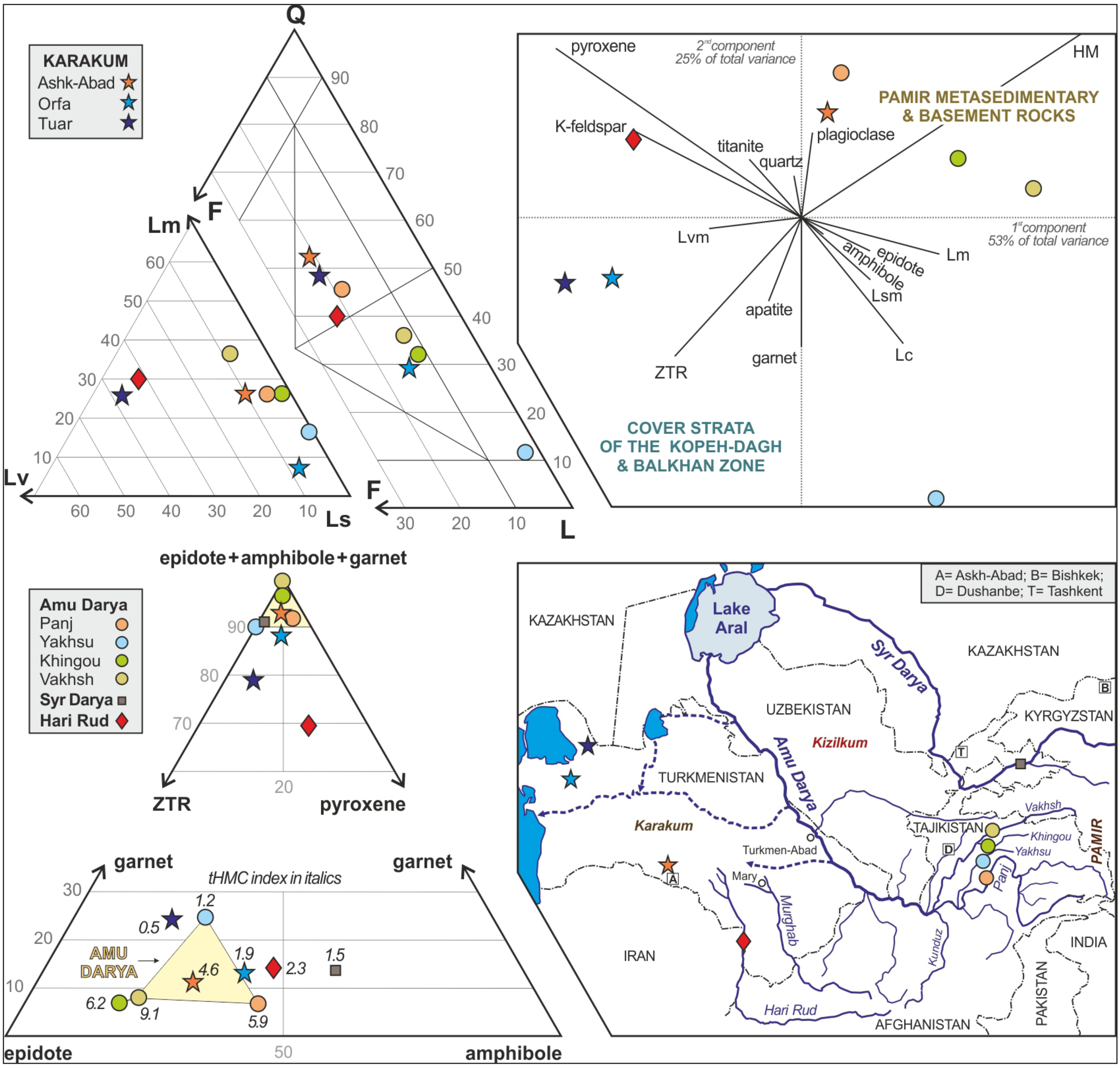

Fig. 3 - Provenance of Karakum desert sands. Detrital modes of the Ashk-Abad dune in the southern central Karakum are close to those of Panj (Amu Darya) river sand, whereas the Orfa and Tuar dunes at the western edge of the desert are enriched in carbonate and volcanic lithic fragments, respectively. Heavy-mineral signatures of the Ashk-Abad dune are intermediate among those of main Amu Darya mountain branches in Tajikistan, whereas Hari Rud and Syr Darya sediments are richer in clinopyroxene and amphibole, respectively. Data indicate the Amu Darya River as the dominant source of eolian sand in the central Karakum Desert. Transparent-heavy-mineral concentration decreases and the ZTR index increases in dune fields to the west, revealing additional local contribution from the Kopeh-Dagh and Balkhan zone. Q = quartz; F = feldspars; L = lithic grains (Lm = metamorphic; Lv = volcanic; Ls = sedimentary). HM = heavy minerals. ZTR = zircon + tourmaline + rutile (Hubert 1962). In the compositional biplot (Gabriel 1971), both multivariate observations (points) and variables (rays) are displayed. The length of each ray is proportional to the variance of the corresponding element in the data set. If the angle between two rays is close to 0°, 90°, or 180°, then the corresponding elements are directly correlated, uncorrelated, or inversely correlated, respectively. Lc, Lsm and Lvm = carbonate, other sedimentary + metasedimentary, and volcanic + low-rank metavolcanic lithic grains.

ed sand. The Kizilkum Desert (in Turkish kizil = red) extends northeast of the Amu Darya River into Uzbekistan and southern Kazakhstan. Provenance of these sands has never been investigated in any detail. They were thought of as derived from neighboring mountains including the Kopeh-Dagh, the Hindu-Kush, and the Pamir, or from the northern steppe in Kazakhstan and beyond as suggested by prevailing wind systems.

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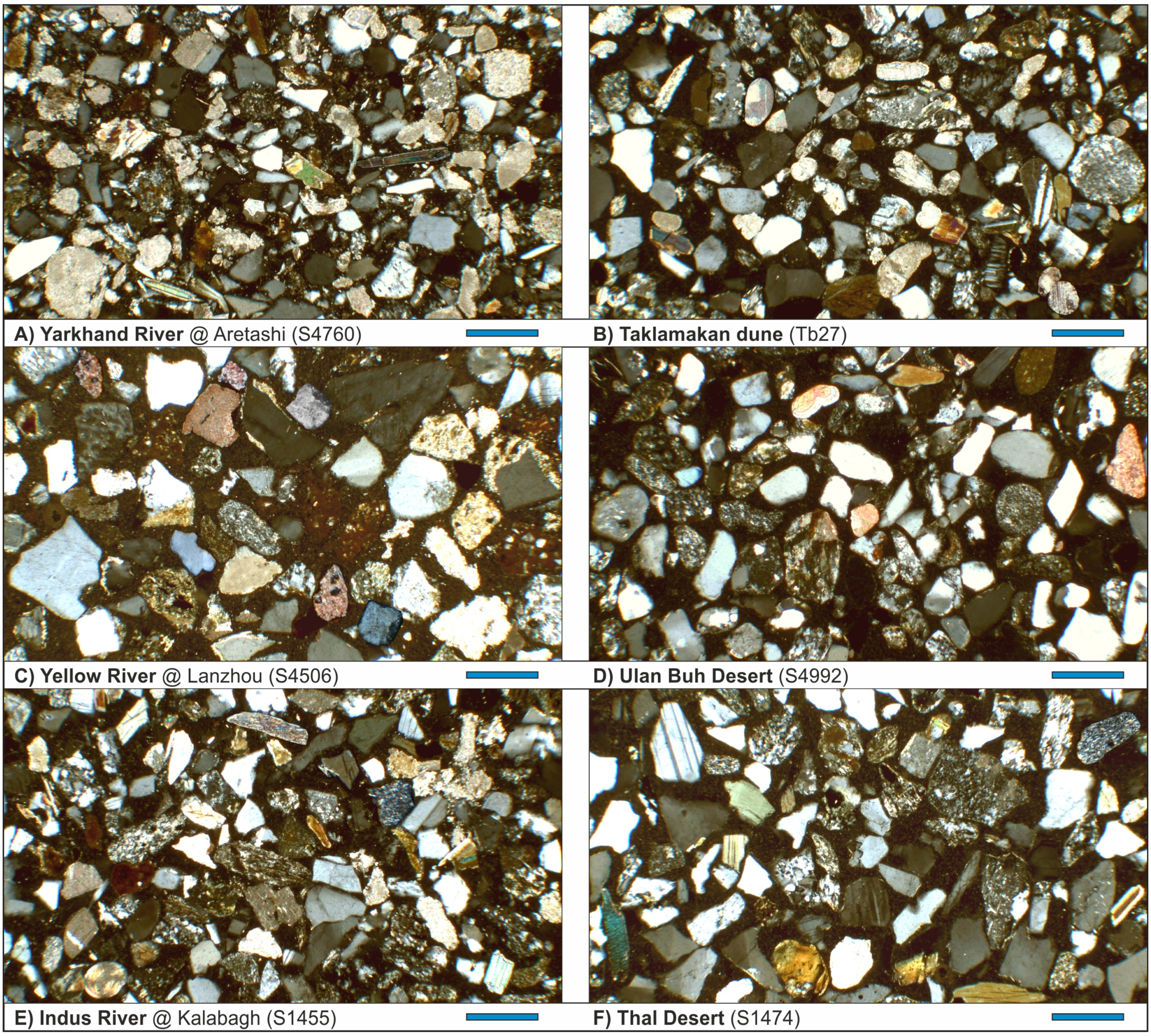

Fig. 4 - Lithic-rich orogenic sands of Central Asia deserts compared with their fluvial feeder systems. Sand of the Yarkhand River 50 km upstream of the entry point into the Tarim basin A) compares with Taklamakan dune sand 460 km to the NE B). Yellow River sand upstream of the Big Bend C) compares with Ulan Buh dune sand 500 km to the NE D). Sand of the Indus River entering the foreland basin at the Salt Range front E) compares with Thal dune sand 265 km to the south F). All photos with crossed polars; blue bar for scale = 150 μm.

below we compare original petrographic and heavy-mineral data on three dune sands collected in the Karakum desert north of Ashk-Abad and in the Balkhan region as far as the Karabogaz Bay, with fluvial sediments collected in the Hari Rud in Iran just south of the border, in four main mountain branches of the Amu Darya in Tajikistan, and in the Syr Darya River in Uzbekistan (Table 1).

Methods

Sand samples were point-counted in thin section according to the Gazzi-Dickinson method (Ingersoll et al., 1984), and classified by their main components exceeding 10%QFL (e.g., in a feldspatho-quartzo-lithic sand L > Q > F > 10%QFL; Garzanti 2016). Full quantitative information was collected on different types of volcanic, sedimentary, and metamorphic rock fragments, which were classified according to protolith composition and metamorphic rank. Average rank of rock fragments in each sample is expressed by the metamorphic indices MI and MI*. MI varies from 0 (detritus shed by sedimentary and volcanic cover rocks) to 500 (very high-rank detritus shed by high-grade base-

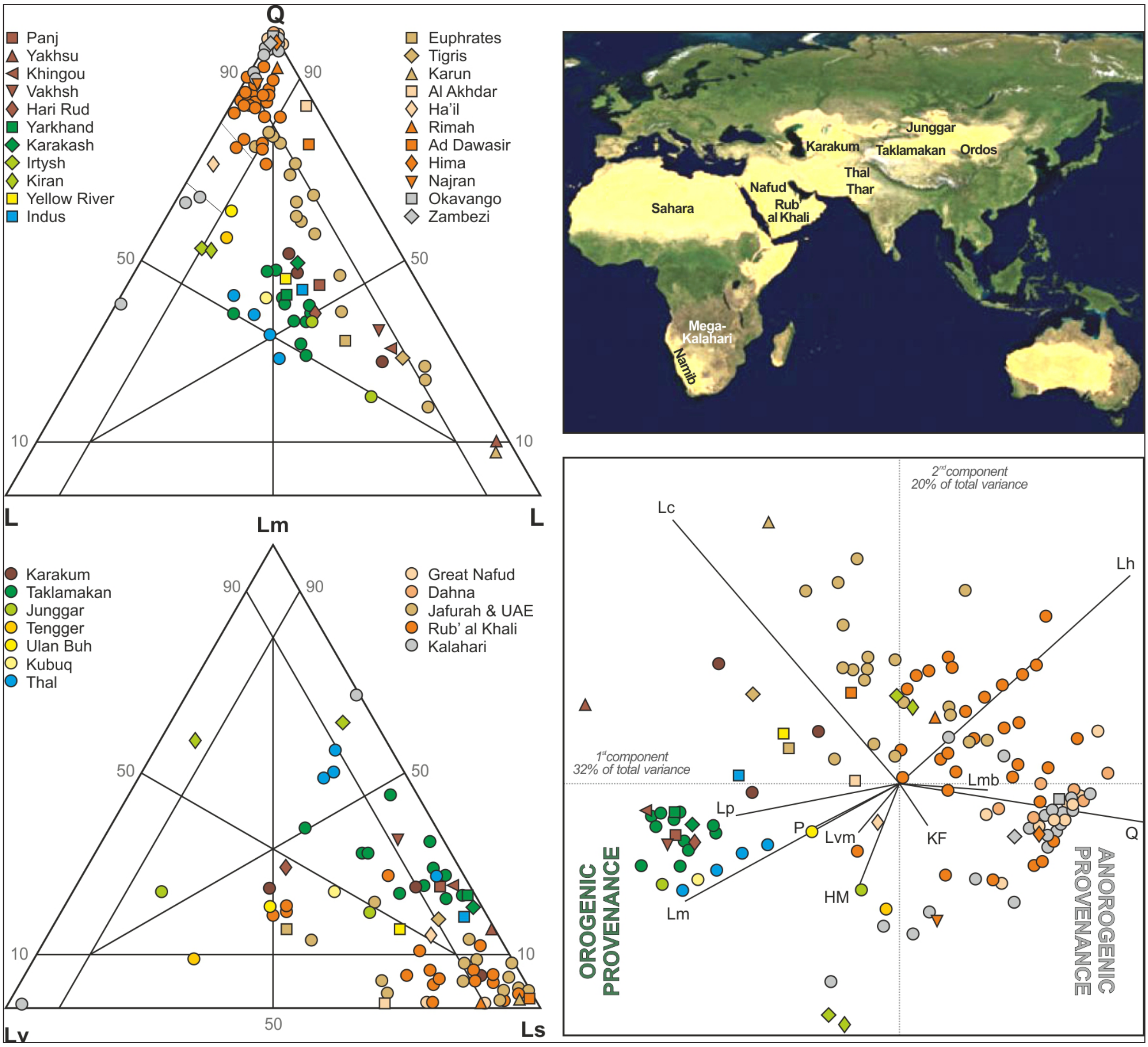

Fig. 5 - Sand composition in deserts of Asia and interior southern Africa compared with their fluvial feeder systems. Note general consistency of detrital modes in eolian (circles) and river sands (squares, rhombs, and triangles of corresponding colour). Mineralogical variability within each dune field reflects sediment supply from additional local sources. Dominant monocrystalline quartz occasionally associated with mainly sedimentary rock fragments characterize anorogenic settings of Arabia and interior southern Africa, whereas dune fields fed from major rivers draining orogenic belts throughout the Asian landmass, from the Arabian/Persian Gulf and the Caspian Sea to northern India and northern China are relatively quartz-poor, and rich instead in sedimentary and subordinately metamorphic lithics. Data sources: Taklamakan and Junggar (Rittner et al. 2016); Tengger, Ulan Buh and Kubuq (Pan et al. 2016; Pang et al. 2018); Thal (Garzanti et al. 2005); Arabia (Garzanti et al. 2003, 2013, 2017); Kalahari (Garzanti et al. 2014). Q = quartz; F = feldspar (KF = K-feldspar; P = plagioclase); L = lithics (Lm = metamorphic; Lv = volcanic; Ls = sedimentary; Lc = carbonate; Lh = chert; Lp = siltstone/shale; Lvm = volcanic + metavolcanic; Lmb = metabasite); HM = heavy minerals.

ment rocks). MI* considers only metamorphic rock fragments and thus varies from 100 (very-low-rank detritus shed by very low-grade metamorphic rocks) to 500 (Garzanti & Vezzoli 2003).

Heavy minerals were separated from a split of the bulk sample or of the sieved 15-500 µm or 32-500 µm fraction by centrifuging in Na-polytungstate (2.90 g/cm^3) and point-counted on grain mounts (Galehouse 1971). Transparent-heavy-mineral concentration, calculated as the percentage of transparent heavy minerals in the sample (Garzanti & Andò 2007a), ranges from poor (tHMC < 1) to rich (tHMC > 5). The ZTR index, the sum of zircon, tourmaline and rutile over total transparent heavy minerals (Hubert 1962), is classically used to estimate the mineralogical durability of the assemblage (i.e., the extent of recycling and/or the intensity of selective diagenetic dissolution in ancient sandstones; Garzanti 2017).

River sands

Silty levee sediments of the Syr Darya River in Uzbekistan yielded a moderately poor heavy-mineral suite with common hornblende associated with epidote, garnet, and subordinate apatite, zircon, and titanite (ZTR 7). The Panj River carries feldspatho-litho-quartzose sand with metasedimentary, limestone, dolostone, shale/siltstone, and minor volcanic and metavolcanic grains (Fig. 2A). The Vakhsh and Khingou Rivers carry feldspatho-quartzo-lithic sands with a similar lithic spectrum including common metabasite grains. The Yakhsu River carries instead quartzo-lithic carbonaticlastic sand. All four mountain branches of the Amu Darya in Tajikistan are characterized by plagioclase >> K-feldspar (P/F 0.84 ± 0.10), biotite >> muscovite, and low metamorphic indices (MI* 184 ± 24, MI 111 ± 52). Transparent-heavy-mineral suites range from moderately poor to rich and from epidote-dominated to epidote-rich with amphibole and garnet, and may include minor apatite, tourmaline, clinopyroxene, staurolite, and zircon (ZTR 4 ± 4). Sillimanite is most common in Panj river sand. The Hari Rud carries feldspatho-litho-quartzose sand with plagioclase > K-feldspar, mafic to felsic volcanic to metavolcanic, limestone, other sedimentary to metasedimentary, and rare ultramafic lithic fragments. The moderately rich suite includes epidote, amphibole, clinopyroxene (mainly green augite), and subordinate garnet, zircon, apatite, and tourmaline (ZTR 10).

Eolian dunes

The Ashk-Abad dune is feldspatho-litho-quartzose sedimentaclastic with plagioclase >> K-feldspar, limestone, and subordinate metasedimentary, metavolcanic, and metabasite grains (Fig. 2B). Volcanic lithics are minor. The moderately rich, epidote-dominated suite includes amphibole, garnet, and minor clinopyroxene and zircon (ZTR 4). The Orfa dune is feldspatho-quartzo-lithic sedimentaclastic with K-feldspar > plagioclase, abundant limestone to impure limestone grains, and subordinate volcanic and other sedimentary to metasedimentary lithic fragments (Fig. 2C). The moderately poor suite includes epidote and amphibole with garnet, and minor zircon and pyroxene (ZTR 6). The Tuar dune is feldspatho-litho-quartzose with K-feldspar > plagioclase, felsic to mafic volcanic to metavolcanic, sedimentary (limestone, siltstone, shale, chert), and metasedimentary lithic fragments (Fig. 2D). The poor transparent-heavy-mineral suite includes epidote with garnet, amphibole, zircon, and minor clinopyroxene and apatite (ZTR 15).

Sand provenance

Petrographic composition of the Ashk-Abad dune compares best with sand of the Panj River draining the thin-skinned Tajik fold-thrust belt, whereas the coarser-grained Orfa and Tuar dunes are notably enriched in limestone and volcanic grains, respectively, revealing contributions from cover rocks exposed locally in the Balkhan zone (Fig. 3). Petrographic composition of eolian sand in the Karakum desert thus indicates orogenic provenance, with signatures reflecting a transitional unroofing stage in the center-east but much closer to detritus shed from undissected tectonic domains in the west (Garzanti et al. 2016).

Heavy-mineral suites of dune sands are dominated by epidote, amphibole and garnet, the classic "triad" diagnostic of orogenic provenance (Garzanti & Andò 2007b). The mineralogical spectrum of the Ashk-Abad dune, in the south-central part of the Karakum Desert, corresponds remarkably well with the average of heavy-mineral modes characterizing river sands in major branches of the Amu Darya River (Fig. 3), which confirms provenance from the western Pamir mountains of Tajikistan in the east (Angiolini et al. 2015; Chapman et al. 2017). Transparent heavy-mineral concentration decreases towards the Caspian Sea at the northwestern edge of the dune field, where epidote and amphibole decrease, whereas zircon, tourmaline, rutile, garnet, and clinopyroxene relatively increase slightly, revealing additional local supply by recycling of cover strata exposed in the Kopeh-Dagh and Balkhan zone.

Fluvial feeders of eolian sand seas

A large part of Karakum dune sands was most probably fed by the Amu Darya River. Turkmenistan thus represents one more interesting case of sand sea developed chiefly as the inland delta of a major river reworked by eolian processes, not dissimilarly from the Taklamakan Desert of the Tarim basin on the opposite side of the Pamir, principally fed by the Yarkhand River (Fig. 4A,B; Rittner et al. 2016), or from the Ordos and Ulan Buh Deserts in northern China, mostly fed by the Yellow River (Fig. 4C,D; Stevens et al. 2013; Bird et al. 2015; Nie et al. 2015; Fenn et al. 2017; Pang et al. 2018). At the northwestern edge of the Himalayan foreland basin, the Thal Desert of Pakistan is considered as a wind-reworked inland delta of the Indus River formed shortly downstream of the entry point of the Indus into the Punjab lowlands (Fig. 4E,F; Garzanti et al. 2005; Liang et al. 2018). Further downstream, the much larger Thar Desert straddling the political border between India and Pakistan documents repeated cycling of orogenic sediment carried by the Indus River and its large Punjab tributaries draining the Himalayan belt in a strongly coupled fluvial-eolian system at the scale of hundreds of kilometers (East et al. 2015).

Examples of major eolian sand seas largely fed by major river systems are commonly found also in anorogenic settings, including the Namib, Skeleton Coast, Cunene and Moçamedes Deserts, accumulated along the hyperarid Atlantic coast of southern Africa in Namibia and Angola and all principally supplied by the Orange River (Garzanti et al. 2012, 2014a, 2018). In the huge Mega-Kalahari Desert of southern Africa, much of the sand is inferred to be of fluvial origin (Moore & Dingle 1998). Multiple successive recycling involved deflation of paleo-Kunene, paleo-Okavango, and paleo-Zambezi river sediments by easterly winds during drier periods, followed by fluvial reworking during wetter periods (Thomas et al. 2000; Shaw & Goudie 2002; Garzanti et al. 2014b). Even in the huge Rub' al Khali Desert of southern Arabia, sand was ultimately derived from major fluvial feeder systems in wetter periods of the past, and eventually blocked inland by uphill-blowing Shamal winds carrying additional sand from the Gulf region – in turn derived from the Tigris, Euphrates, Karun and other rivers draining the Zagros fold-thrust belt in Iran – during hyperarid Pleistocene stages (Garzanti et al. 2013, 2017). In arid inland areas, river sediments may be trapped in subsiding troughs in front of active orogens such as the Kopeh-Dagh, Kun Lun, Altyn Tagh, Tian Shan, or western Himalayan thrust belts. In anorogenic settings of tropical arid Arabia and southern Africa, instead, development of endorheic drainage and expansion of landlocked sand seas occurs in continental rim basins behind rift shoulders. Such deserts may be long-lived, because rift-flank uplifts initially triggered by asthenosphere upwelling are maintained throughout the proto-oceanic stage, and commonly rejuvenated even during the long subsequent passive-margin stage (Paton 2012).

Whereas sand mineralogy is typically dominated by commonly rounded monocrystalline quartz in large sand seas hosted in anorogenic rim basins such as the Rub' al Khali and the Mega-Kalahari, river-fed dune fields formed adjacent to fold-thrust belts are typically made of lithic-rich sand including common sedimentary, metamorphic, or volcanic rock fragments (Fig. 5).

Conclusions

The Karakum Desert, where most dune fields are stabilized by vegetation, covers most of Turkmenistan. Mainly upper Pleistocene loess deposits mantle the foothills of the Kopeh-Dagh, where eolian dust may have been blown largely from a wide dust belt in the north. Petrographic composition and epidote-amphibole-garnet heavy-mineral suites of southern Karakum dune sand, instead, compare well with sediment carried by mountain branches of the Amu Darya, indicating provenance from the western Pamir mountains of Tajikistan in the east. Common carbonate and felsic volcanic grains, together with decreasing heavy-mineral concentration and increasing ZTR indices towards the Caspian Sea in the west reveal local recycling of cover strata exposed in the Kopeh-Dagh and Balkhan zone. The course of the huge Amu Darya River, which in the Pliocene represented a major detrital source for the Red Beds reservoir rocks of the eastern South Caspian Basin, has seen repeated major shifts across Turkmenistan since then. Drainage to the Aral Sea, first established in Pleistocene or early Holocene times, was finally restored only after Medieval times when the river still emptied into the Karakum Desert.

The Karakum dune field is one of the several examples of major river-fed Central Asian sand seas bounded by active orogenic belts and characterized by relatively quartz-poor, lithic-rich eolian sand, a composition that contrasts sharply with quartzose and pure quartzose dune sand accumulated in anorogenic settings of Arabia and interior southern Africa.

Supplementary material: Supplementary data associated with this article include information on sampling sites (Table A1) together with the sand petrography (Table A2) and heavy-mineral datasets (Table A3). The Google-EarthTM map of sampling sites Karakum.kmz.is also provided.

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