Detrital zircon and provenance analysis of Eocene–Oligocene strata in the South Sistan suture zone, southeast Iran: Implications for the tectonic setting

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ABSTRACT

The north-south–trending Sistan suture zone in east Iran results from the Paleogene collision of the Central Iran block to the west with the Afghan block to the east. We aim to document the tectonic context of the Sistan sedimentary basin and provide critical constraints on the closure time of this part of the Tethys Ocean. We determine the provenance of Eocene–Oligocene deep-marine turbiditic sandstones, describe the sandstone framework, and report on a geochemical and provenance study including laser ablation–inductively coupled plasma–mass spectrometry U-Pb zircon ages and Hf isotopic analyses of 3015 in situ detrital zircons. Sandstone framework compositions reveal a magmatic arc provenance as the main source of detritus. Heavy mineral assemblages and Cr-spinel indicate ultramafic rocks, likely ophiolites, as a subsidiary source. The two main detrital zircon U-Pb age groups are dominated by (1) Late Cretaceous grains with Hf isotopic compositions typical of oceanic crust and depleted mantle, suggesting an intraoceanic island arc provenance, and (2) Eocene grains with Hf isotopic compositions typical of continental crust and nondepleted mantle, suggesting a transitional continental magmatic arc provenance. This change in provenance is attributed to the Paleocene (65–55 Ma) collision between the Afghan plate and an intraoceanic island arc not considered in previous tectonic reconstructions of the Sistan segment of the Alpine-Himalayan orogenic system.

INTRODUCTION

The Sistan suture zone (SSZ) is a critical link between the Himalaya and Zagros orogenic belts and is a significant yet poorly studied region in our understanding of the tectonics of the Middle East and Central Asia. This study presents new heavy mineral, sandstone petrography, and zircon U-Pb and Lu/Hf data that provide important information on the paleogeographic and paleotectonic configuration of the region in the Eocene–Oligocene. This work aims to reconstruct the Mesozoic and Cenozoic geological history of the South Sistan Basin, located north of the Makran accretionary complex; we argue for a revised collision age between the Lut and Afghan blocks, which are of regional tectonic significance (Figs. 1–3). We challenge a current hypothesis that detritus from the Sistan Basin was derived from the Himalaya-Tibet region.

It has been suggested that Paleogene sediments of Makran and adjacent basins were supplied from the Himalaya by the paleo–Indus River and deposited in a delta–submarine fan complex, whereas Miocene to recent sedimentary rocks were reworked from the growing accretionary wedge related to convergence between Arabia and Eurasia (e.g., Critelli et al., 1990; Kassi et al., 2013; Qayyum et al., 2001). Carter et al. (2010) suggested that Eocene–Oligocene sandstones of the South Sistan Basin were supplied from the Himalaya by the paleo–Indus delta–submarine fan complex.

Sandstone framework analysis and heavy minerals studies are the main and classic tools of provenance analysis (e.g., Weltje and von Eynatten, 2004), which provides valuable information on the composition of source rocks and, consequently, the past tectonic setting (e.g., Dickinson, 1985; Dickinson and Suczek, 1979; Zuffa, 1985). Among heavy minerals, zircon plays an important role because it is resistant to physical and chemical processes (DeCelles et al., 2007; Gehrels et al., 2011); in addition, zircon U-Pb geochronology reliably determines crystallization ages of individual detrital grains (e.g., Kössler et al., 2002; Veiga-Pires et al., 2009). Measurement of the Hf isotope in dated zircon grains further enables characterization of the isotopic composition of the magma in which the zircons crystallized (e.g., Sáma et al., 2008).

We combine results from field work, sandstone framework compositions, and heavy mineral analysis to characterize the lithologies eroded in the source areas and to constrain the tectonic setting and evolution of this part of the Sistan area. More than 3000 U-Pb ages of detrital zircon obtained by laser ablation–inductively coupled plasma–mass spectrometry are used to evaluate crystallization ages of the source rocks. Hf isotope ratios of ~400 dated zircon grains are used to infer the origin of magmas in the source region. Only a few studies have addressed both detrital zircon geochronology and Hf isotope data of Iranian sedimentary successions and plutonic rocks (e.g., Mohammadi, 2015; Mohammadi et al., 2016a, 2016b; Nutman et al., 2014). Therefore, the large new data set of this study will help in our understanding of the Cenozoic tectono-sedimentary evolution of southeast Iran in the larger regional context. Our results suggest that the detrital material in the South Sistan Basin is mostly derived from Late Cretaceous oceanic island arc and Eocene–Oligocene transitional continental arc sources, with minor contributions from ophiolitic rocks. These sources can be tentatively related to equivalents of the
Chagai–Raskoh Hills arcs and ophiolites to the northeast, in neighboring western Pakistan (Figs. 1–3).

**GEOLOGICAL SETTING**

The north-northwest–south-southeast–trending SSZ in east Iran separates the continental Lut subblock of central Iran to the west from the Afghan block to the east (e.g., Şengör, 1990; Figs. 1 and 3). The Sistan Ocean was a branch of the Tethys Ocean that closed in the late Eocene and was overprinted by subsequent dextral strike-slip faulting between the Central Iran and Afghan blocks (Tirrul et al., 1983). Zircon U-Pb ages (113 and 107 Ma) of leucogabbros of the Birjand ophiolites in northwest Sistan indicate that this oceanic basin already existed in Aptian time (Bröcker et al., 2013; Zarrinkoub et al., 2012). An eastward dip direction of the related subduction is inferred from palaeogeographic, structural, and petrographic considerations (e.g., Camp and Griffis, 1982; Mohammadi et al., 2016a; Tirrul et al., 1983). The SSZ includes a deformed accretionary wedge and a flanking forearc basin. It consists of three tectonostratigraphic complexes separated by thrust faults (Camp and Griffis, 1982; Tirrul et al., 1983; Fig. 1). The Ratuk complex to the east is an older accretionary wedge that formed prior to Maastrichtian time. It is a narrow, dense tectonic imbrication zone and comprises Cretaceous ophiolitic mélanges, metamorphic rocks including eclogites, blueschists, and epidote amphibolites (Bröcker et al., 2013; Zarrinkoub et al., 2012), and sedimentary rocks including lower Cretaceous limestone, upper Cretaceous turbiditic sandstones, Eocene nummulitic limestones, and Neogene conglomerates (e.g., Bröcker et al., 2013; Fotoohi Rad et al., 2005; Tirrul et al., 1983). Multimethod dating (Rb-Sr, 40Ar/39Ar, and U-Pb) of metamorphic rocks yielded an age of metamorphism between 87 and 81 Ma, which indicates tectonothermal activity during the Late Cretaceous (Bröcker et al., 2013). The Neh complex to the west is a fold-thrust belt consisting of upper Cretaceous allochthonous ophiolites, low-grade metamorphic rocks, shallow-water limestone, Eocene–Oligocene deep-marine turbiditic sandstones, and Eocene–Oligocene intrusions attributed to final suturing in the northern SSZ (Camp and Griffis, 1982; Mohammadi et al., 2016a; Pang et al., 2012; Tirrul et al., 1983; Zarrinkoub et al., 2012). The Sefidabeh forearc complex unconformably covers both the Neh and Ratuk complexes. It comprises an 8-km-thick, essentially clastic and volcanoclastic sequence of Cenomanian–Eocene sedimentary rocks including both deep- and shallow-marine limestones and calc-alkaline volcanic intercalations on the eastern side (Tirrul et al., 1983). This association represents the piggy-back forearc basin that formed on the wedge during pre-Oligocene deformation (Tirrul et al., 1983). Strike-slip faulting and thrusting has generally overprinted the stratigraphic, basal onlap onto the underlying wedge turbidites (Mohammadi, 2015; Tirrul et al., 1983).

The study area is located in the southern part of the SSZ, in the Neh complex, and covers parts of the area described in the Narreh-Now, Saravan, Pishin, Khash, Iranshahr, and Nikshahr 1:250,000-scale geological maps (Figs. 1 and 4; Eftekhar Nezhad and McCall, 1993; Eftekhar Nezhad et al., 1995; Morgen et al., 1979; Sahandi et al., 1996; Samimi Namin et al., 1994, 1986). Some interpret the southern Neh complex as a transitional zone between the Sistan and Makran Basins (e.g., Carter et al., 2010; McCall, 2002). This area is principally composed of Eocene and Oligocene deep-marine turbidites, as indicated by presence of, e.g., Paleodictyon and Spirorhaphe involute ichnofossils (Fig. 5; Crimes and McCall, 1995; Shabani Goraji, 2015), and their...
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Figure 2. (A) Simplified tectonic map of the potential source terranes. Abbreviations: CHF—Chaman fault; Ch-Ra—Chagai-Raskoh arc; JD—Jaz Murian depression; KB—Katawaz Basin; MAW—Makran accretionary wedge; MF—Minab fault; OOB—Oman Ophiolite Belt; SFTB—Sulaiman fold-thrust belt; Sa-Si-Z—Sanandaj-Sirjan zone; SSZ—Sistan suture zone. Hachured area in SSZ indicates study area. (B) Simplified tectonic map of the south Tibet–Himalayan regions with potential sources discussed in the text. Figure and caption modified from Mohammadi et al. (2016b).

Figure 3. Paleogeographic map of the Sistan Ocean including microcontinental blocks and subduction zones during the Eocene (modified from McCall et al., 1985).
Figure 4. Simplified geologic map of the South Sistan Basin. Stratigraphic ages according to the 1:250,000-scale geological maps of Pishin, Narre-Now, Saravan, Khash, Iranshahr, and Makran (Dolati, 2010; Eftekhar Nezhad and McCall, 1993; Eftekhar Nezhad et al., 1995; Morgen et al., 1979; Sahandi et al., 1996; Samimi Namin et al., 1994, 1986). Location of stratigraphic sections in Figure 6: A-A′—East Iran flysch; B-B′—Kaskin unit; C-C′—Saravan unit; D-D′—Badamu-Siahan unit; E-E′—Shirinzad unit.
Figure 5. Trace fossils of Eocene deep-marine turbidites of the Neh complex. (A) *Spirorhaphae involute*. (B) *Nereiles jacksoni*. (C) *Taphrhelmintopsis auricularis* Sacco. (D) *Paleodictyon carpathicum*. (E) *Helminthoida crassa*. (F) *Helminthoida ichnosp.*
Figure 6. Composite stratigraphic section of the South Sistan Basin with paleocurrent directions and sampling locations. Badamu-Siahan unit is equivalent to the Zaboli unit in the 1:250,000-scale geological map of Saravan and to the Kuh-e Badamo unit in the 1:250,000-scale geological map of Narreh-Now. The Saravan unit is equivalent to the East Iran flysch unit in the 1:250,000-scale geological map of Khash. The Shirinzad unit is equivalent to the Mashkid unit in the 1:250,000-scale geological map of Saravan, and the Kaskin unit is equivalent to the Rask unit in the 1:250,000-scale geological map of Pishin. All cited maps published by the Geological Survey of Iran.
very low-grade metamorphic equivalents such as slate and phyllite. These turbiditic sequences were subdivided into nine lithostratigraphic units (typically as thick as several hundred meters) that are dominated by Bouma-type turbiditic sandstones and shales (Eftekhar Nezhad and McCall, 1993; Eftekhar Nezhad et al., 1995; Morgen et al., 1979; Sahandi et al., 1996; Samimi Namin et al., 1994, 1986; Fig. 6). Most sandstones are feldspathic litharenites and lithic arkoses, and contain assemblages of planktonic and benthic foraminifera and nannofossils (Table S1 in the Data Repository; McCall et al., 1985).

METHODS AND SAMPLES

We investigated 20 medium-grained turbiditic sandstones (with prefix 12 a.m. and 13 a.m. in the ETH Zurich collection) from 5 lithostratigraphic units of the Neh complex (Figs. 4 and 6; Table S2). For nannofossil determinations, samples were taken from hemiplegic sediments of turbiditic sequences to avoid reworked nannofossils. Pelagic nannofossils confirmed the mapped stratigraphy, suggesting sedimentation ages ranging from Eocene to Oligocene (Table S1). Analytical methods, including mineral separation and identification techniques, are described in Appendix 1.

RESULTS

Paleocurrents

Paleocurrent directions were measured from 53 flute casts and 3 asymmetric ripple marks of 53 outcrops from different parts of the South Sistan Basin Neh complex. Readings were rotated to horizontal around the local strike direction of bedding. Measurements indicate a regional northeast to southwest paleoslope with a source area to the northeast of the basin (Fig. 7).

Modal Framework Composition

The studied sandstones classify mainly as lithic arkose and feldspathic litharenite (Fig. 8A). Quartz grains are mostly monocrystalline (82%), and feldspar is dominantly plagioclase (>91%) with minor amounts of K-feldspar (Fig. 8B). Lithic fragments are represented by sedimentary (Ls), volcanic (Lv), and metamorphic clasts (Fig. 8C). Volcanic rock fragments are mostly andesite and volcanic glass. Sedimentary lithic fragments include mainly siltstone and limestone. Metamorphic lithic grains generally consist of low-grade to medium-grade phyllites and schists.

Figure 7. Rose diagram of paleocurrent measurements from 53 flute cast and 3 asymmetric ripple marks from 53 outcrops restored to horizontal around the local strike of bedding. Arrow indicates average direction.

Similar Ls:Lv ratios indicate magmatic arc provenance rather than recycled orogen suites (Fig. 6D). The sources plot mostly in the recycled orogenic field (Fig. 8E), more precisely in the field of dissected arcs (Fig. 8F).

Heavy Minerals

Heavy mineral suites show very variable compositions and can be subdivided into four groups: (1) most stable minerals (zircon, tourmaline, rutile [ZTR], monazite, brookite, and anatase; ZTR = 75%-65%) and apatite derived from continental crust sources; (2) variably abundant (4%-70% of 200 counted grains) less stable minerals (epidotes, garnet, staurolite, chloritoid, kyanite, andalusite) suggesting different detrital sources of medium-grade metamorphic rocks; (3) Cr-spinel (to 20% of total grain count) and very small amounts of serpentine indicating contributions from exhumed ultramafic rocks; (4) pyroxenes (diopside, enstatite, ferrosilite, and hedenbergite) from basic to intermediate magmatic rocks (Fig. 9). Lower-middle Eocene sandstones (samples 123, 157, 186, and 237) generally show large amounts (to 80% of total grain count) of epidotes and pyroxenes. Oligocene sandstones (samples 97 and 105) yielded large amounts (to 87% of total grain count) of garnets, epidotes, and pyroxenes (Fig. 9).

Detrital Zircon Dating and HF Isotope Geochemistry

Most detrital zircon crystals (85%) are euhedral to anhedral, suggesting short transport distances from source to sink. U-Pb dating of detrital zircons was done on 17 Eocene–Oligocene sandstone samples (Figs. 10–13). Ages with discordance >5% are not included. Zircon ages older than 1100 Ma were not plotted due to their rarity. Cretaceous and Eocene ages prevail with Cretaceous peaks at 106, 89, and 68 Ma and an Eocene peak at 49.5 Ma (Figs. 10–13). Zircon ages were measured on dated zircons (Woodhead et al., 2004). The evolved epsilon hafnium (εHf(t)) time-correlated data from zircons older than 600 Ma are not shown in Figure 10. Late Cretaceous zircon grains show a large variation in εHf(t) from −17 to +20.4. Most range between εHf(t) = 0 and +20.1, a few range between 0 and −17 (Fig. 15). Zircons with Eocene ages have εHf(t) values between +16 and −24, a large majority between 0 and +15, and a few with negative values (Fig. 15). Compared to the upper Cretaceous zircons, Eocene zircons show less positive εHf(t) between the (CHUR) and depleted mantle lines (Fig. 15). Negative εHf(t) indicate magmatic zircons with a continental crust signature whereas positive εHf(t) values indicate depleted mantle signatures (e.g., Naing et al., 2014; Patchett, 1983).

DISCUSSION

Taken together the new sandstone framework composition, heavy mineral, U-Pb geochronology, and HF isotope data for Eocene–Oligocene sandstones of the South SSZ allows for refining evolutionary models of the southern part of the Sistan segment of the Asian Tethyan sutures.

The main hypothesis previously put forward for the provenance of the South Sistan Basin sandstones is that these deposits were derived from the Himalayas in the paleo–Indus delta–submarine fan (Katawaz Delta) and transported further westward into the Khojak submarine fan and Makran–South Sistan Basins accretionary wedges (e.g., Carter et al., 2010; Ellouz-Zimmmann et al., 2007; Kassi et al., 2003). Comparison of U-Pb ages and HF isotopic compositions of the studied detrital zircons with those in Himalaya Eocene–Oligocene sandstones (the Indus suture molasses, Kailas Basin, Sulaiman fold-thrust belt, and Katawaz Basin) and magmatic zircons of the Karakoram, Kohistan-Ladakh arc and Zahedan-Shah Kuh plutonic belt.

1GSA Data Repository Item 2016316, Tables S1–S6, is available at www.geosociety.org/pubs/ft2016.htm, or on request from editing@geosociety.org.
Figure 8. Detrital composition and classification of the South Sistan sandstones in provenance ternary diagrams. (A) Sandstone classification diagram (Folk, 1980). (B) Qm-P-K diagram (after Dickinson and Suczek, 1979). (C) Lvh-Ls-Lm diagram (after Dickinson, 1985). (D) Qp-Lvh-Ls diagram (after Dickinson and Suczek, 1979). (E) QF (Dickinson, 1985). (F) QmLt (Dickinson, 1985). Literature data from the middle Eocene–early Miocene Khojak Formation in the Katawaz Basin are from Qayyum et al. (2001).
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Figure 9. Heavy mineral assemblages of the South Sistan Basin sandstones arranged in stratigraphic order and showing the relative abundance of heavy mineral groups.

Figure 10. Zircon U-Pb age distribution pattern of all sandstone samples from the South Sistan Basin. Time scale is after Gradstein et al. (2012).
Figure 11. Probability density diagrams for detrital zircon $^{206}\text{Pb}/^{238}\text{U}$ age populations with corresponding Concordia plots of concordant detrital zircons of samples 186, 206, 157, 166, 123, and 218 from South Sistan Basin sandstones. Ages with discordance >5% are not included. Time scale is after Gradstein et al. (2012).
Figure 12. Probability density diagrams for detrital zircon $^{206}$Pb/$^{238}$U age populations with corresponding concordia plots of concordant detrital zircons of samples 237, 224, 293, 246, 135, and 124 from South Sistan Basin sandstones. Ages with discordance >5% are not included. Time scale is after Gradstein et al. (2012).
Figure 13. Probability density diagrams for detrital zircon $^{206}\text{Pb} / ^{238}\text{U}$ age populations with corresponding concordia plots of concordant detrital zircons of samples 263, 260, 252, 280, and 134 from South Sistan Basin sandstones. Ages with discordance >5% are not included. Time scale is after Gradstein et al. (2012).
Figure 14. Zircon mean U-Pb age populations versus stratigraphic age of sandstone samples. Time scale is after Gradstein et al. (2012). Paleo.—Paleocene; Olig.—Oligocene.

Figure 15. Time-corrected $\varepsilon_{Hf(t)}$ values versus $^{206}$Pb/$^{238}$U zircon ages (Ma) of the South Sistan Basin sandstones and published $\varepsilon_{Hf(t)}$ data of northern-central Lhasa belt, Karakoram batholith, Kohistan-Ladakh arc, Gangdese-Trans Himalaya, and Indus Molasse (Bouilhol et al., 2013; Heuberger et al., 2007; Ji et al., 2009; Ravikant et al., 2009; Wu et al., 2007; Zhuang et al., 2015). Age correction based on chondritic values (CHUR—chondritic uniform reservoir) from Blichert-Toft and Albarède (1997). Depleted mantle evolution trend (dashed line) is from Griffin et al. (2000). Time scale is after Gradstein et al. (2012).
challenges the paleo–Indus delta–submarine fan hypothesis (Figs. 15 and 16; Table 1).

Evidence from Heavy Mineral Assemblage

The heavy mineral spectrum indicates that the Eocene–Oligocene lithic-rich arkoses and feldspathic litharenites of the South Sistan Basin region represent detritus from magmatic arcs (residual mantle signature), ophiolites (Cr-spinel and serpentinite), and metamorphic suites. (1) Cr-spinels have TiO$_2$ contents <0.2%, suggesting an ultramafic rather than a volcanic origin (Hu et al., 2014; Kamenetsky et al., 2001). (2) Epidote and pyroxene may derive from exhumed ophiolite suites, metamorphic rocks or mafic to intermediate intrusive rocks. (3) Abundant metamorphic lithic grains and metastable heavy minerals such as garnet, staurolite, and chloritoid represent metamorphic rocks and metamorphosed sedimentary rocks as subsidiary sources (Deer et al., 1992). The amount of metamorphic heavy minerals such as garnet, pyroxene, amphibole, and epidote significantly increases while the amount of Cr-spinel decreases in the Oligocene sandstones. This implies that metamorphic rocks were more eroded than the ophiolite sources in late Eocene–Oligocene time.

Provenance of the Detrital Zircons

The 3015 detrital zircon grains analyzed from the Eocene–Oligocene turbiditic sandstones yielded apparent ages ranging from ca. 3.3 Ga to ca. 31 Ma (Figs. 10–13). Three U-Pb age ranges broadly characterize the South Sistan Basin detrital zircon grains.

The oldest age range, represented by ≤5% of studied grains, dates from Archean (3.3 Ga) to Jurassic (200 Ma). This age range does not make a single homogeneous spectrum, and Cambrian zircons (540–480 Ma) are slightly more abundant. The rounded and anhedral shape of zircon grains without internal growth zoning suggests that they are either fragments or old zircons reworked from continental crystalline rocks or inherited magmatic zircons. The origin of these old grains is uncertain. Possible igneous and/or metamorphic source areas could be anywhere after repeated reworking through several tectonic cycles since the Archean. Restricting conjecture to the closest continental blocks, in agreement with other euhedral grains indicating proximal source regions, points to the Central Iran and the Afghan blocks in the western and eastern margins of the South Sistan Basin, respectively. Zircon U-Pb age of magmatic, metamorphic, and siliciclastic rocks of central Iran range from 1870 to 462 Ma with few Archean zircon cores; the major population peak is between 547 and 525 Ma (Ramezani and Tucker, 2003). The southwestward paleocurrent directions favor derivation from the Afghan block.

D detrital zircon ages from the Himalayas and regions farther north range from 2.8 Ga to 95 Ma, while Eocene detrital zircons are absent in sandstones of the Lesser Himalaya, Tethyan Himalaya, and Greater Himalaya (e.g., Alizai et al., 2011; DeCelles et al., 2000; Gehrels et al., 2011; Fig. 16). South Sistan Basin sandstones have few Archean (to 3.3 Ga) detrital zircons older than those of the Himalayan regions, and the main age populations are Late Cretaceous and

Figure 16. Normalized probability plots of South Sistan Basin strata, Kailas Basin (DeCelles et al., 2011), Indus suture molasse deposits (Henderson et al., 2010), Sulaiman fold-thrust belt (Zhuang et al., 2015), Gangdese batholith (Chu et al., 2006; Ji et al., 2009; Wen et al., 2008), Katawaz Basin (Carter et al., 2010), Makran accretionary wedge (Mohammadi, 2016b), Karakoram batholith and Kohistan-Ladakh arc (e.g., Fraser et al., 2001; Honegger et al., 1982; Jain and Singh, 2008; Krol et al., 1996; Parrish and Tirrul, 1989; Phillips et al., 2004; Ravikant et al., 2009; Schaltegger et al., 2002; Schärer et al., 1984; Singh et al., 2007; Upadhyay et al., 2008; Weinberg et al., 2000), Tethyan Himalayan strata, Lesser Himalayan strata, and Higher Himalayan strata (e.g., Gehrels et al., 2011). Figure and caption are adapted from Gehrels et al. (2011).
Eocene, younger than Himalayan populations. Indus suture molasse deposits contain detrital zircons with main peaks at 58 Ma and 98 Ma and Hf isotopic compositions that are noncompliant with Sistan detrital zircon ages. Furthermore, Cr-spinel as a key heavy mineral is absent in the Indus suture molasse deposits, but represents as a high region preventing a connection between the Gangdese and regions to the southwest. A connection through the Indus and Yarlung probably did not start before the late Oligocene–Miocene (e.g., Carrapa et al., 2014; Dai et al., 2013).

A compilation of the main provenance indicators from north to south of the Himalayan system, including the Gangdese and Kohistan-Ladakh magmatic arcs, the Karakoram batholith, the Zahedan—Shah Kuh plutonic belt, the Sanandaj-Sirjan metamorphic zone, and the Makran accretionary wedge, is given in Table 1 and Figures 15 and 16. Misfits of sandstone framework, heavy minerals, zircon U-Pb ages, and εHf(t) exclude all of these areas as sources of Eocene–Oligocene detritus of the South Sistan Basin. Therefore, equivalents of the Chagai-Raskoh magmatic arc remain the most plausible source.

### Regional Tectonic Implications

A large quantity of detrital material in the South Sistan Basin is derived from rocks with ages and compositions comparable to rocks of the Chagai Hills—Raskoh arc system. In this arc system, a late-Early Cretaceous–Late Cretaceous (120–65 Ma) intraoceanic island arc collided with the Eurasian margin (Afghan block) in latest Cretaceous–Paleocene time; the collided arc then evolved during the Eocene to Oligocene as

#### TABLE 1. COMPILATION OF PROVENANCE INDICATORS FROM MAGMATIC ARCS AND CONTEMPORANEOUS SEDIMENTARY BASINS IN THE HIMALAYAN SYSTEM AND MAKRAN ACCRETIONARY WEDGE

<table>
<thead>
<tr>
<th>Potential sources area</th>
<th>Sandstone modal framework</th>
<th>Heavy minerals</th>
<th>Zircon U-Pb age</th>
<th>Hf isotopic composition εHf(t)</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kailas Basin</td>
<td>dominant volcanic and sedimentary lithics</td>
<td>absence of Cr-Spinel</td>
<td>younger than 100 Ma (19.5% of zircons older than 100 Ma) main peaks ca. 24–26 Ma; 48 Ma; 75–80 Ma</td>
<td>Late Cretaceous: +4.2 to +14 Paleocene–Eocene: +1 to +14 (with few grains with −2 to −8.7)</td>
<td>DeCelles et al. (2011)</td>
</tr>
<tr>
<td>Indus suture molasse deposits</td>
<td>dominant volcanic and felsic plutonic lithics</td>
<td>absence of Cr-Spinel</td>
<td>main peaks at 58 Ma and 98 Ma dominant age at 480–1250 Ma</td>
<td>Late Cretaceous: +4.2 to +14 Paleocene–Eocene: +1 to +14 (with few grains with −2 to −8.7)</td>
<td>Henderson et al. (2010); Wu et al. (2007)</td>
</tr>
<tr>
<td>Sulaiman fold-thrust belt</td>
<td>dominant metamorphic and subordinate volcanic lithic</td>
<td>zircon, tourmaline, rutile + apatite (9%–86%) and Cr-spinel</td>
<td>main peak at 42–47 Ma; 70 Ma; 83 Ma; 98 Ma secondary peak at 490–960 Ma</td>
<td>–</td>
<td>Roodz et al. (2011); Zhuang et al. (2015)</td>
</tr>
<tr>
<td>Katawaz Basin</td>
<td>dominant quartz-rich lithics with low-grade metamorphic and subordinate volcanic lithic</td>
<td>–</td>
<td>main peak at 58 Ma; 80 Ma; 93 Ma secondary peak at 563–836 Ma</td>
<td>–</td>
<td>Carter et al. (2010); Qayyum et al. (2001)</td>
</tr>
<tr>
<td>North Sistan suture zone</td>
<td>–</td>
<td>–</td>
<td>ranging from 24.4 to 31.0 Ma; 38.3 to 46.4 Ma; 86.1 Ma to 88.7 Ma; 11 Ma in North Sistan suture zone and also 107 and 113 Ma</td>
<td>–</td>
<td>Bröcker et al. (2013); Pang et al. (2012); Zarrinkoub et al. (2012)</td>
</tr>
<tr>
<td>Makran accretionary wedge</td>
<td>dominant volcanic and sedimentary lithics</td>
<td>ZTR + apatite ≥ 75%, Cr-spinel and blue amphibole</td>
<td>main peaks at 166.5 Ma; 88.7 Ma; 48.9 Ma minor peak at 563–868 Ma</td>
<td>Middle Jurassic: −13 to +2 Early Cretaceous: −17 to +11 Late Cretaceous–Eocene: −6 to +14 Cretaceous: −4.7 to +1 and +9.2 to +15.3 Eocene: −4.1 to +15 Cretaceous: −6.5 to +5</td>
<td>Mohammadi (2015); Mohammadi et al. (2016b)</td>
</tr>
<tr>
<td>Gangdese arc</td>
<td>–</td>
<td>–</td>
<td>ranging from 40 Ma to 218 Ma main peaks at 46–65 Ma; 80–103 Ma</td>
<td>Cretaceous: −17 to +11 Late Cretaceous–Eocene: −6 to +14</td>
<td>e.g., Ji et al. (2009); Wen et al. (2008); Zhu et al. (2008)</td>
</tr>
<tr>
<td>Karakoram batholith</td>
<td>–</td>
<td>–</td>
<td>ranging 10 Ma to 110 Ma main peaks at 18 Ma; 64 Ma; 108 Ma</td>
<td>Cretaceous: −4.7 to +1 and +9.2 to +15.3 Eocene: −4.1 to +15 Cretaceous: −6.5 to +5</td>
<td>e.g., Honegger et al. (1982); Jain and Singh (2008); Krol et al. (1998); Parrish and Hodges (1996); Phillips et al. (2008); Ravikant et al. (2009); Schaltegger et al. (2002); Schärer et al. (1984); Singh et al. (2007); Weinberg et al. (2000)</td>
</tr>
<tr>
<td>Kohistan-Ladakh arc</td>
<td>–</td>
<td>–</td>
<td>ranging from 29 Ma to 154 Ma main peaks at 58 Ma and 98 Ma</td>
<td>Cretaceous: −6 to +17 Eocene: −7.40 to +14</td>
<td>Mohammadi et al. (2015); Pang et al. (2012); Qayyum et al. (2001)</td>
</tr>
<tr>
<td>Zahedan—Shah Kuh plutonic belt</td>
<td>–</td>
<td>–</td>
<td>40.5–44.3 Ma (Eocene) 28.9–30.9 Ma (Oligocene)</td>
<td>Eocene: −7.13 to +8.54 Oligocene: −3.3 to +11.65 Neoproterozoic: +2.2 to −2.6 and −7.3 to 10.7 Mesoproterozoic: +8 to +9 Acmean: 0.0</td>
<td>Mohammadi et al. (2016a)</td>
</tr>
<tr>
<td>Sanandaj-Sirjan metamorphic zone</td>
<td>–</td>
<td>–</td>
<td>35–60 Ma; 90–110 Ma; 144–157 Ma; 160–185 Ma; 568 and 637 Ma with inherited cores of 800–900, 2000, 2400, 3600</td>
<td>Eocene: −7.13 to +8.54 Oligocene: −3.3 to +11.65 Neoproterozoic: +2.2 to −2.6 and −7.3 to 10.7 Mesoproterozoic: +8 to +9 Acmean: 0.0</td>
<td>Mohammadi et al. (2016a)</td>
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*Note: Dash indicates no data available.*
a mature Andean-type continental margin and continued as such to the present (Nicholson et al., 2010; Perelló et al., 2008; Richards et al., 2012; Siddiqui, 2004). Extending this information to the South Sistan Basin, the first appearance of Cretaceous zircons with positive εHf and detrital Cr-spinel in sandstones records accretion of an intraoceanic subduction system to the Afghan continental margin at 65–55 Ma (Siddiqui et al., 1988). The newly accreted arc became a tran- sitional continental arc during the Eocene, as recorded in the detrital zircon pattern, and a mature Andean-type continental margin in the Oligocene. This places the complete closure of the SSZ in the late Oligocene (25–23 Ma), more recently than previously accepted (Sengör, 1990; Tirull et al., 1983).

CONCLUSIONS

Our work assessed the provenance of detrital material in Eocene to Oligocene turbiditic sandstones of the Neh complex of the South SSZ. Results yield protolith ages from Late Creta-

Heavy Mineral Separation

Results yield protolith ages from Late Creta-

Determination of detrital zircon ages in the the SSZ in the late Oligocene (25–23 Ma), more recently than previously accepted (Şengör, 1990; Burg, 2011).

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APPENDIX 1. ANALYTICAL METHODS

Sandstone Thin-Section

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