Depositional history of the Devonian Ilanqareh and Padeha Formations in Azarbaijan Province and Eastern Alborz (Iran): constraints from heavy-mineral microtextures

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Abstract: We analysed the surface microtextures well-preserved on stable to ultra-stable heavy minerals such as zircon, tourmaline and rutile from the Devonian siliciclastic rocks which are cropping in northeastern and northwestern Iran by a Scanning Electron Microscope (SEM) techniques to provide useful provenance information on various sedimentary stages, and to reconstruct their sedimentary history. Different surface mechanical and chemical corrosive features point to more detritus sources, and above all on few evolution stages in different environments. The microtexture similarity between the studied Ilanqareh and Padeha deposits indicates that they could have experienced the resembled environmental conditions – from aeolian to subaqueous (fluvial and/or marine) processes. Nature of heavy minerals points to a multi-cyclic character of the sediments, and in addition to previously published ideas about the Arabian-Nubian Shield source, the presence of local source(s) partly supplied the Ilanqareh basin may be assumed.

Key words: Iran, Ilanqareh and Padeha Formations, heavy minerals, surface microtextures, SEM analysis, sedimentary environment

1. INTRODUCTION

Zircon, tourmaline and rutile are traditionally considered to the most stable (ultra-stable) heavy minerals which are resistant to intensive weathering and/or dissolution processes (Hubert, 1962; Morton & Hallsworth, 1999, 2007; Balan et al., 2001; Finzel, 2017). This resistance is crucial for monitoring and reconstructing of many geological processes which the detritus has undergone. Many "developmental features" are imprinted in heavy-mineral surfaces and their detailed study can help to identify specific sedimentary environment and depositional processes. Although quartz grains are usually used for this purpose (Krinsley & Doornkamp, 1973; Whalley & Krinsley, 1974; Mahaney et al., 1988, 2001; Mahaney, 2002; Křížová et al., 2013; Kalińska-Nartiša & Gałka, 2018; Kemnitz & Lucke, 2019; Hossain et al., 2020; Ramos-Vázquez & Armstrong-Altrin, 2020), many benefits result from using heavy minerals (Tejan-Kella et al., 1991; Mange & Maurer, 1992; Mahaney & Milner, 1998; Dill, 1998, 2007; Moral Cardona et al., 1996, 2005; Turner & Morton, 2007; Velbel, 2007; Achab et al., 2017; Bónová et al., 2020; Armstrong-Altrin, 2020; Armstrong-Altrin et al., 2020), because heavy minerals trace the difference in source rocks better than quartz. Albeit subaqueous (mechanical) microtexture features may be difficult to find when too small grains are examined (Krinsley, 1980), as in the case of heavy-mineral study. Even though rutile and zircon generally show no corrosion during deep burial (up to 5000 m) and diagenesis, several mechanical features incurred during the transport can be observed (Morton, 1979).

Previous studies related to the provenance of the Padeha and Ilanqareh formations (fms) which are developed in NE and NW Iran, respectively, were predominantly focused on the petrographic and/or geochemical study of the sandstones (Najafzadeh et al., 2010; Hosseini et al., 2019; Anjerdi et al., 2020; Poursoltani & Pe-Piper, 2020). Upcoming study related to heavy mineral assemblages of the Padeha Fm. signal pronounced tourmaline predominance over zircon and rutile with their relatively stable content in all sandstone types (Jafarzadeh et al., submit.). The Ilanqareh Fm. heavy-mineral spectra composition indicates the highest tourmaline abundance (59-70%) followed by rutile (11-25%) and zircon (10-17%; Anjerdi et al., 2020). Short briefing of the Ilanqareh Fm. heavy mineral assemblage relates to detrital well-rounded zircon and apatite, as well as apatite and rutile needle inclusions in monocrystalline detrital quartz from the quartz arenite (Najafzadeh et al., 2010). This contribution focuses on (1) identification of various evolution stages through which the selected ultra-stable heavy minerals underwent during the transport, and (2) to describe their possible sedimentary history based on their surface features.

2. GEOLOGICAL SETTING

The Upper Devonian Ilanqareh Fm. is cropping out in Azarbaijan Province in north-western Iran (Fig. 1A-C). For the first

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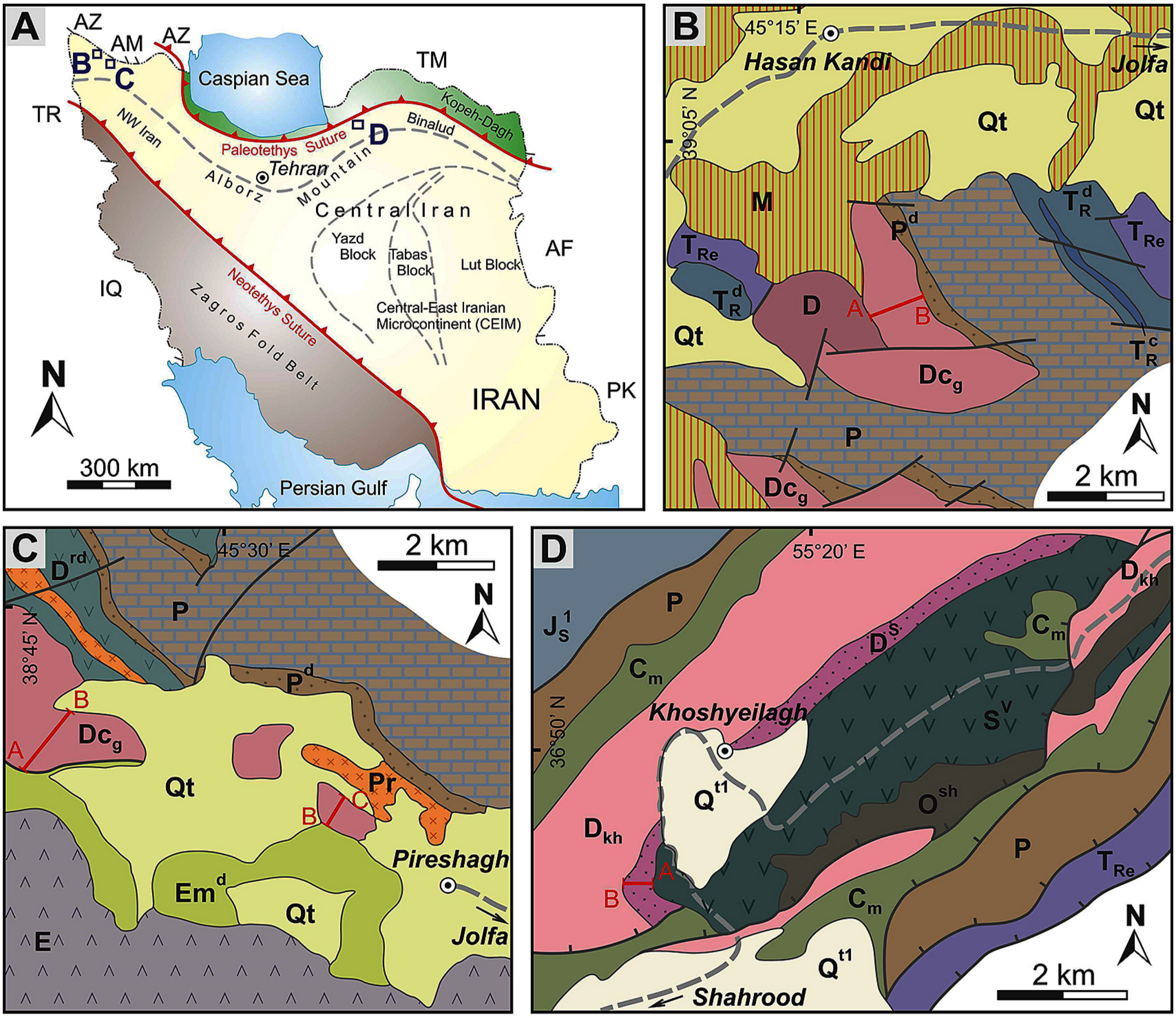

Legend to the geological maps of Ilanlu (B) and Pireshagh (C) sections:

- Qt – Proluvial (fan) deposits (Quaternary)
- M – Red Marl, sandstone (Upper Miocene)
- Em^{d} – Marl (Miocene)
- E – Pyroclastic and lava (Eocene)
- T_{Re} – Dark gray dolomite, limestone (Triassic)
- T_{R}^{c} – Limestone and shale (Triassic)
- T_{R}^{d} – Fossiliferous limestone, marl (Triassic)
- P – ***equivalent of Ruteh Fm.*** Limestone and shale (Permian)
- P^{d} – Sandstone, marl (Permian)
- Pr – Acidic volcanics (Permian)
- D^{rd} – Basalt and sandstone (Devonian)
- Dc_{g} – ***Ilanqareh Fm.*** Shale, sandstone and limestone (Devonian)
- D – Dolomite (Devonian)

Legend to the geological map of Khoshyeilagh (D) section:

- Q^{t1} – Deluvial deposits (Quaternary)
- J_{S}^{1} – ***Shemshak Fm.*** Sandstone, shale (Lower Jurassic)
- T_{Re} – ***Elika Fm.*** Dolomitic limestone (Triassic)
- P – ***Dorud Fm.*** Sandstone and shale, limestone (Permian)
- C_{m} – ***Mobarak Fm.*** Limestone, shaly limestone (Carboniferous)
- D_{kh} – ***Khoshyeilagh Fm.*** Limestone and shale, sandstone (Devonian)
- D^{S} – ***Padeha Fm.*** Conglomerate, sandstone (Devonian)
- S^{V} – ***Soltan Meydan Fm.*** Basalt, andesite (Silurian)
- O^{sh} – ***Qelli Fm.*** Shale, sandstone (Ordovician)

General explanations

- a - geological (lithological) boundaries; b - major faults; c - thrust faults
- a - asphalted road, road; b - village; c - studied lithostratigraphic section

Figure 1: A - Schematic tectonic map of Iran with the studied areas (sections) locations (according to Zand-Moghadam et al., 2014, modified), B – geological map of the Ilanlu section (Bolourchi & Saidi, 1989, modified), C - geological map of the Pireshagh section (Abdolahi & Hosseini, 1996, modified), D - geological map of the Khoshyeilagh section (according to Najafzadeh et al., 2010, modified).

time, Grewingk (1853) recognized that sandstones, conglomerates and fossiliferous limestones of Devonian Ilanqareh Formation transgress over a crystalline basement. The formation is divided into four members: Member A consists of dolomite with interbeds of limestone and shale. Member B is composed of fossiliferous thin-bedded limestone and shale, member C is built mainly by shale and sandstone and based on paleontological evidence member D consists of early Carboniferous sandy limestone (Husseini, 1991; Najafzadeh et al., 2010; Ghorbani, 2019). Based on petrographic and geochemical approach, Najafzadeh et al. (2010) noted the Ilanqareh Fm. sandstones were deposited on a passive margin, and the basin has been filled by mature detritus probably from the Arabian Shield. Here, the sandstones from the member C, which are represented by quartz arenite (Najafzadeh et al. 2010; Anjerdi et al., 2020) from the Ilanlu and Pireshagh sections near Jolfa City in the northwest Iran, Azarbaijan Province were studied (Fig. 1B, C). The sandstones in both investigated sections are medium- to fine-grained, moderately to well-sorted. Monocrystalline quartz prevails markedly over polycrystalline one. Rare feldspars are altered. Muscovite, biotite, tourmaline, zircon and apatite represent accessory minerals (for detailed modal analysis see Najafzadeh et al. 2010; Anjerdi et al., 2020).

The Lower to Middle Devonian Padeha Fm. was introduced in the Ozbak-kuh Mountains (Ruttner et al., 1968), and today is exposed in Central and Eastern Iran, in Binalud, eastern Alborz and also in Kerman area (Wendt et al., 2002; Zand-Moghadam et al., 2013; Poursoltani, 2017; Moghadam et al., 2017; Ghorbani, 2019; Poursoltani & Pe-Piper, 2020; Fig. 1A). The studied samples come from the Alborz Range having an east-west trend in northern Iran (Fig. 1D). Here, the Padeha Fm. represents synrift succession which was formed in the terrestrial environment (the initial phase of rifting), and generally consists of siliciclastic rocks and non-marine carbonates associated with volcanoclastic rocks (Aharipour et al., 2010). The Padeha succession is built by three members: Member 1 predominantly consists of red conglomerates with volcanic, siltstone and mudstone lithic clasts. Member 2 is formed by quartz arenite, arkose and greywacke sandstones with red shales, and Member 3 contains carbonate interlayers in addition to siliciclastic rocks (Aharipour et al., 2010). According to previously published data, the Padeha Fm. sandstones were derived from felsic and mature recycled (polycyclic) rocks of cratonic origin (Arabian Shield, Zand-Moghadam et al., 2013; Hosseini et al., 2019). Interestingly, based on the bulk-rock geochemistry Poursoltani & Pe-Piper (2020) suggest that the Padeha Fm. sandstones exposed today in the most eastern part of the Alborz area were sourced mainly in granitic (I-type granites)/gneissic rocks. For the purpose of our study, the samples from all types of siliciclastic rocks (quartz arenite, arkose and greywacke (Hosseini et al., 2019)) of the Member 2 were analysed. The sandstones are medium- to fine-grained, usually well-sorted. Sub- to well-rounded monocrystalline quartz is a framework component in all sandstone types; amount of feldspars (K-feldspar > plagioclase) and lithic fragments increases in graywacke sandstone (for detailed modal analysis see Hosseini et al., 2019). Schematic Devonian lithostratigraphic units in Azarbaijan and Eastern Alborz, in which studied Ilanqareh and Padeha fms appear, respectively, are shown in the Figure 2. For their detailed characteristics see Wendt et al. (2002).

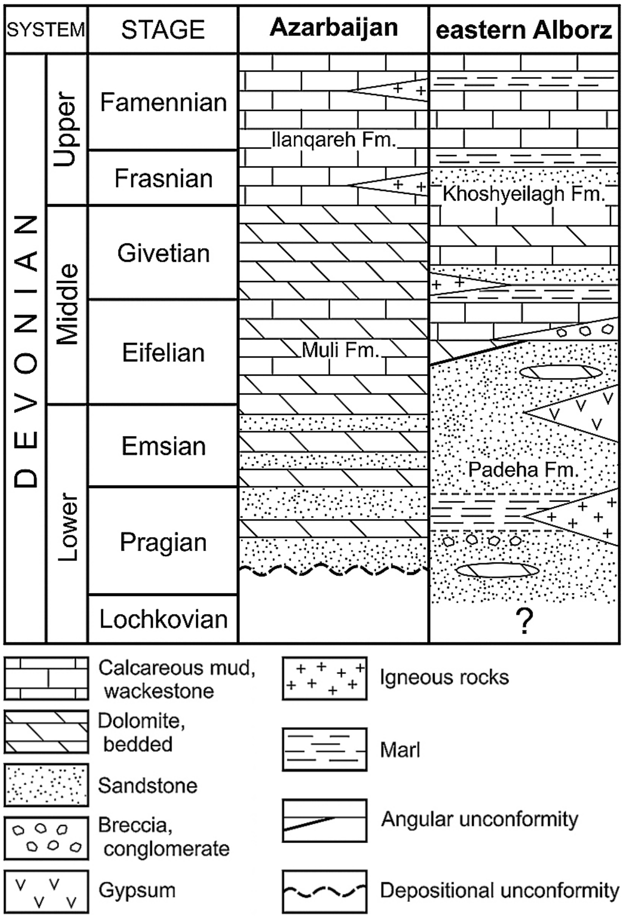

Figure 2: Schematic view of Devonian lithostratigraphic units in Azarbaijan and Eastern Alborz areas (according to Wendt et al. 2002, modified).

In general, the bulk of the studies consider Paleozoic deposits of Iran to represent shallow-marine passive-margin sedimentation with non-significant magmatic activity (Berberian & Berberian, 1981; Alsharhan & Kendall, 1986; Zand-Moghadam et al., 2013). U-Pb detrital zircon geochronology from the Alborz Range deposits showed existence pre-600 Ma and Neoproterozoic-Cambrian grains which indicate the Arabian-Nubian Shield and other parts of the East African orogeny (Horton et al., 2008) as source areas. Pre-Cadomian and Cadomian U-Pb ages and Hf-isotope composition of detrital zircons from the Padeha Fm. indicate transport of detritus from the Arabian-Nubian Shield before Iranian domain rifted away from Gondwana in Early Paleozoic time (Moghadam et al., 2017). These authors (Moghadam et al., 2017) also stated that Ordovician-early Devonian detrital zircons come mostly from the local sources.

3. METHODS

Sandstone samples have been collected from the natural outcrops of (1) the Ilanqareh Fm. in the Ilanlu section located at south of the Aras Dam, NW Iran (39°03′08″N and 45°17′05″E; Figs. 3, 4A) and the Pireshagh section located at south of Jolfa city, NW Iran (38°44′01″N and 45°27′47″E, 38°43′38″N and 45°31′19″E; Figs. 3, 4B) and (2) the Padeha Fm. in Khoshyeilagh in Eastern Alborz (36°49′54″N and 55°20′09″E; Figs. 3, 4C, D). Detailed description of the Padeha and Ilanqareh sedimentary profiles are provided in Aharipour et al. (2010) and Najafzadeh et al. (2010), respectively. The samples weighing about 1 kg were processed in a standard method to obtain heavy-mineral concentrates at the heavy mineral separation laboratory of Shahrood University of Technology in Iran. The selected sandstone samples were crushed, sieved and then heavy minerals from the 63–200 μm size fractions were separated using bromoform.

The mineral composition of these fractions was optically evaluated using stereomicroscope Leica M80 in Institute of Geography (UPJŠ in Košice). An identification of ambiguous rounded to well-rounded (anhedral) grains, as well as the surface microtexture observations were carried out on Scanning Electron Microscope (SEM-EDX) TESCAN VEGA-3 XMU operating at 20 (30) kV, 1 nA at Institute of Physics (UPJŠ in Košice). Heavy minerals from 10 studied samples were picked up and then fixed on a double-stick carbon sticker. Approximately 30 – 40 grains from each sample were analysed in back scattered electron (BSE) mode. The recognition of surface microtextures has been done according to identification methods outlined by Whalley & Krinsley (1974), Krinsley & Doornkamp (1973), Mahaney (2002), Moral Cardona et al. (2005), Vos et al. (2014), Nallusamy (2015), Finzel (2017), Linnemann et al. (2018) and Szerakowska et al. (2018).

4. RESULTS

4.1 Heavy-mineral assemblages

Heavy-mineral associations from the Ilanqareh Fm. sandstones which were studied by visual inspection, show markedly depleted composition. Ultra-stable minerals such as tourmaline and rutile are absolutely dominant, zircon and apatite are more sporadic. While tourmaline is manifold and its colour ranges from blue over dark green to orange-brown, rutile is rather orange-brown. Heavy-mineral suites from the Padeha Fm. sandstones are similar. Besides ultra-stable tourmaline, zircon and rutile, there were observed chromian spinel, garnet and authigenic barite in negligible amounts (Jafarzadeh et al., in submit.; this study). Interestingly, rutile colour varies from orange-brown to dark blue shade in the Padeha Fm. samples. Opaque minerals are common in both studied formations but magnetite is usually missing.

4.2 Grain morphology and surface features

Heavy-mineral samples from both investigated formations show rather uniform spectrum of grain morphology with apparent dominance of rounded to well-rounded detrital grains. The euhedral grains (showing sharp edges) are scarce but they were more often found in the Ilanqareh Fm. sediments. Surface microtexture features identified on tourmaline, rutile and zircon grains are displayed in Figures 5 – 8. Their types associated with characteristic environment in which they could be found are listed in Table 1.

Table 1: Mechanical and chemical microtextures identified on the detrital tourmaline, rutile and zircon surfaces in the Ilanqareh and Padeha Fm. sediments.

*Microtexture	tourmaline		rutile		zircon		*Depositional environment/transport
	Ilanqareh	Padeha	Ilanqareh	Padeha	Ilanqareh	Padeha	
Mechanical							
abraded (rounded) edges	•••	•••	••	•••	•••	•••	aeolian, fluvial, recycled
bulbous edges	•••	•••	••	••	••	•••	aeolian, fluvial
conchoidal fractures	••	••	••		•	••	fluvial, coastal, aeolian
straight/arc-shaped steps		•	•			•	fluvial, coastal, aeolian
V-shaped depressions	•	•	•	•	••	•	subaqueous, fluvial, marine, tsunami
crescentic percussion marks	•••	•••	•••	••	•••	•••	aeolian
scratch marks	•		•	•			litoral, aeolian
breakage patterns	••	••	•			•	non-specific
Chemical							
solution pits	••	•	•	•			diagenetic, marine (seawater percolation)
dull surfaces	•	•	••		•	•	subaqueous – fluvial, marine
crevasses	•		•				diagenetic
Mechanical/Chemical							
arcuate/polygonal cracks	•	•••	•	•	•	••	non-specific
cavities after inclusions			•	•		•	non-specific
adhering particles		•	•	•			aeolian, diagenetic

Legend: ••• – abundant, •• – common, • – present. *The table was compiled from data of Krinsley & Doornkamp (1973), Tejan-Kella et al. (1991), Mahaney (2002), Moral Cardona et al. (2005), Vos et al. (2014), Achab et al. (2017), Finzel (2017), Linnemann et al. (2018), Szerakowska et al. (2018), Mohammad et al. (2020), Armstrong-Altrin (2020), Armstrong-Altrin et al. (2020).

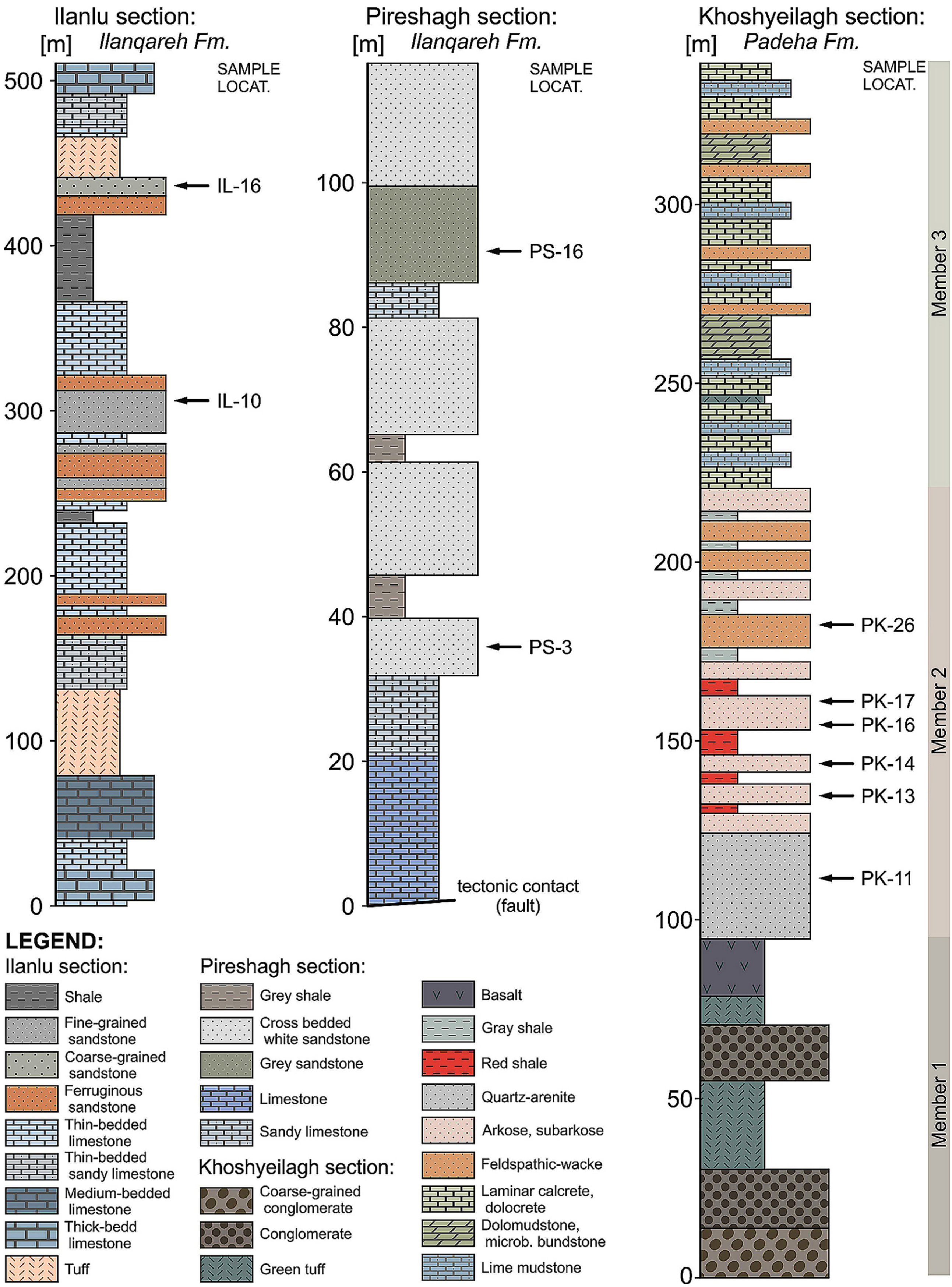

Figure 3: Schematic litostratigraphic sections of the Ilanqareh Fm.: Ilanlu section (according to Najafzadeh et al. 2010, modified), Pireshagh section (according to Anjerdi et al. 2020, modified) and the Padeha Fm. (according to Hosseini et al. 2019, modified) with sampling points.

4.2.1 Ilanqareh Formation

Tourmaline. While euhedral (Fig. 5A) to subhedral (Fig. 5B-D) tourmaline grains are very rare, poorly shaped anhedral grains prevail among the all heavy-mineral concentrates in the studied samples. Grains show mechanical features, such as irregular breakage patterns that are developed mostly on the grain edges (Fig. 5B-D), and sometimes the fractures perpendicular to crystallographic c axis were observed (Fig 5D). Some rounded to well-rounded grains were affected by chemical solution processes which caused formation an almost parallel solution etching and pitting to crevasses (Fig. 5E). This texture signals the progress of chemical dissolution. However, the bulk of well-rounded grains with bulbous edges and fairly regular, fine microtexture and low grain relief show crescentic percussion marks (Fig. 5F, G), mechanically-upturned plates almost on their entire surface and occasionally impact depressions (Fig. 5F). There are also the tourmalines with rounded edges, whereas areas of indentations are protected from abrasion (dull surfaces, Fig. 5H).

Rutile. For detrital rutile, the different morphological types were observed. The first group consists of subhedral grains showing predominantly mechanical marks on their surfaces with an obvious predominance of the conchoidal fractures (Fig. 5I). These cracked surfaces are occasionally covered by adhering particles. The second group is represented by rounded to well-rounded grains with bulbous edges (Fig. 5J-L). Their surfaces show abundant crescent-shaped cracks, impact depressions and breakage block features. On the other hand, regular outlines of some pits can be observed. The surface of some grains is etched more significantly. This indicates intensive chemical dissolution that penetrates to the inside of the grain (Fig. 6A-C). The deep arcuate cracks developed on some grains were observed (Fig. 6D), too.

Zircon. Euhedral prismatic and dipyramidal zircon grains with very slightly eroded edges show scarce small conchoidal fractures predominantly developed on the grain edges (Fig. 6E-G), at which the grain corners had been almost undamaged. These grains exhibited primarily features and their classification *sensu* Pupin (1980) is possible. The flat nature of the edge abrasion is observed on some subhedral grains and these edges are slightly outlined (Fig. 6H, I). Generally, above mentioned categories of zircon show traces only of mechanical abrasion. These grains are rather rare. Most of the grains are semi-rounded to rounded due to the abrasion (Fig. 6J-L). While the zircon edges are rounded, some crystallographic planes were protected from abrasion (Fig. 6K). Mechanical features represented by irregular V-shaped depressions, conchoidal fractures and crescentic percussion marks prevail among delaminated surfaces, which indicate scaling (Fig. 6L).

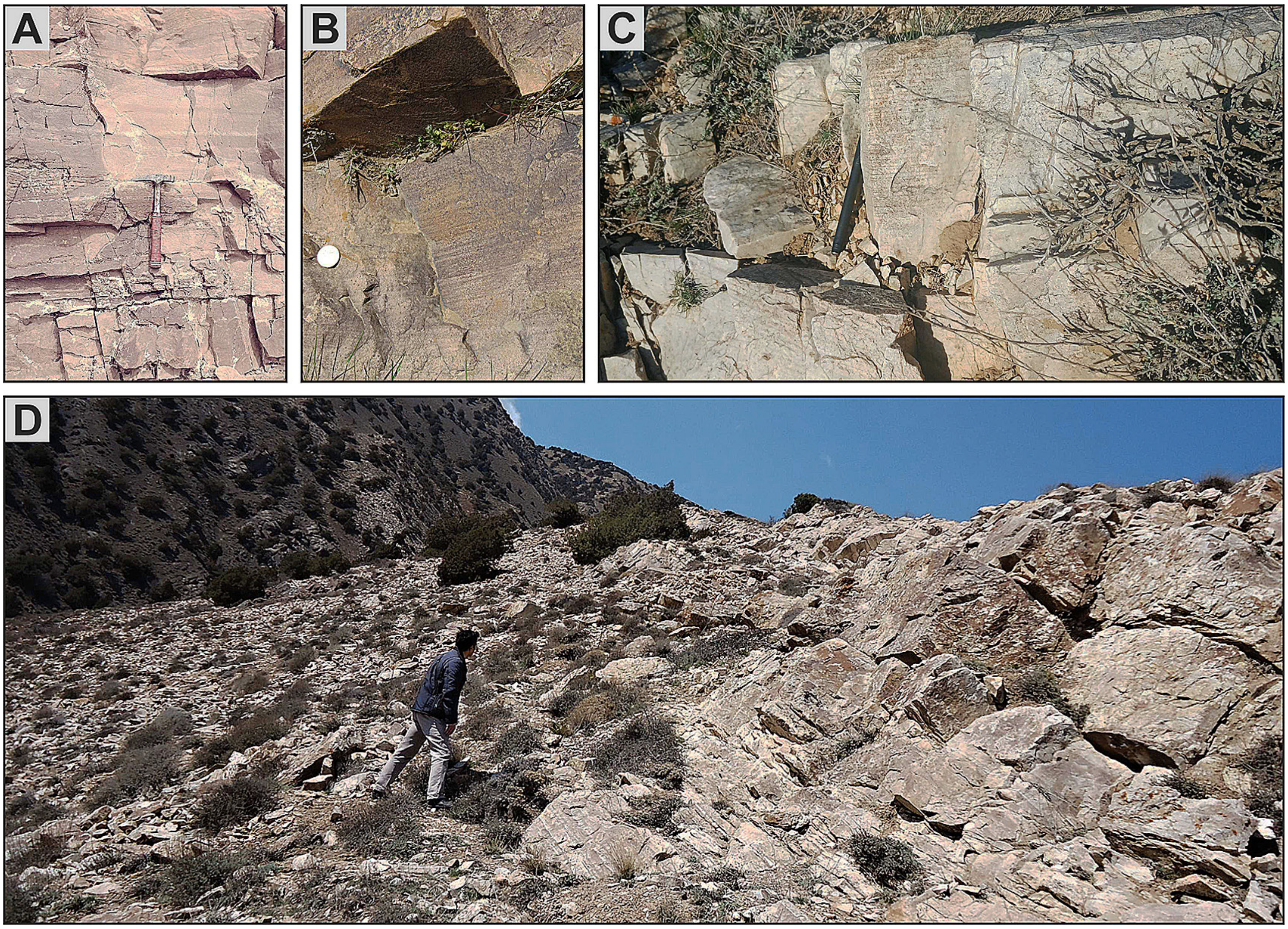

Figure 4: Quartz arenites from which the samples were obtained: A – Ilanqareh Fm., Ilanlu section; B – Ilanqareh Fm., Pireshagh section; C, D – Padeha Fm. (base of the Member 2; the succession is in normal position), Khoshyeilagh section.

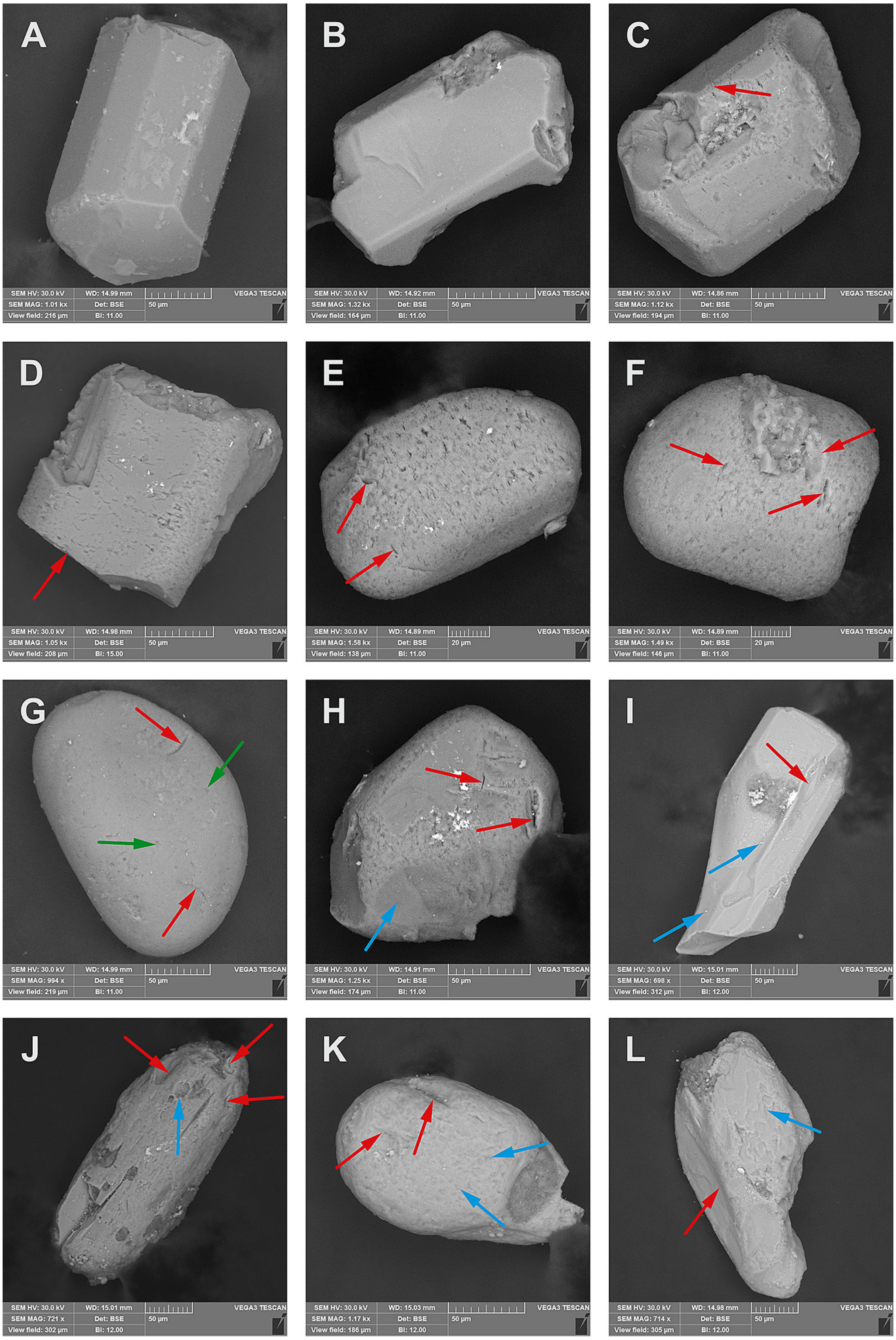

Figure 5: Scanning electron microscope (SEM) images of representative detrital tourmaline (A-H) and rutile (I-L) from the Ilanqareh Fm. sandstones: A – euhedral unweathered grain, B-D – subhedral grains with irregular breakage patterns on the edges, and the fracture perpendicular to crystallographic c axis (red arrow); E – rounded grain affected by chemical dissolution with crescentic marks (red arrow); F-H – rounded to well-rounded, wind-abraded grains with crescentic marks (red arrow), local V-shaped pits (green arrow) and dulled surface (blue arrow); I – subhedral grain with conchoidal features (red arrow) and adhering particles (blue arrows); J – rounded grain with crescent-shaped cracks (red arrows) and depression after inclusion extraction (blue arrow); K – rounded grain with conchoidal features (red arrows) and small V-shaped depressions (blue arrows); L – dulled surface (red arrow) and flutes and grooves (blue arrow) on subhedral grain surface.

4.2.2 Padeha Formation

Tourmaline. The observed settings are comparable to the results obtained from the Ilanqareh Fm. The bulk of detrital tourmaline grains are sub-rounded to well-rounded (Fig. 7). Latter have usually low relief and well-abraded bulbous edges (Fig. 7A-C). Many grains are affected by fractures and scratches under the influence of which the grain delamination often occurs (Fig. 7A). There are many crescentic percussion marks on their surfaces (Fig. 7C). Some tourmalines show abundance of large conchoidal fractures which often induced a disintegration of the grain (Fig. 7D-F). Interestingly, the adhering particles are common mainly on these flat fractured surfaces. For the other group of rounded tourmaline grains, the deep irregular depressions are characteristic (Fig. 7C). Rounded to well-rounded grains with arcuate and polygonal fractures, as well as traces of chemical

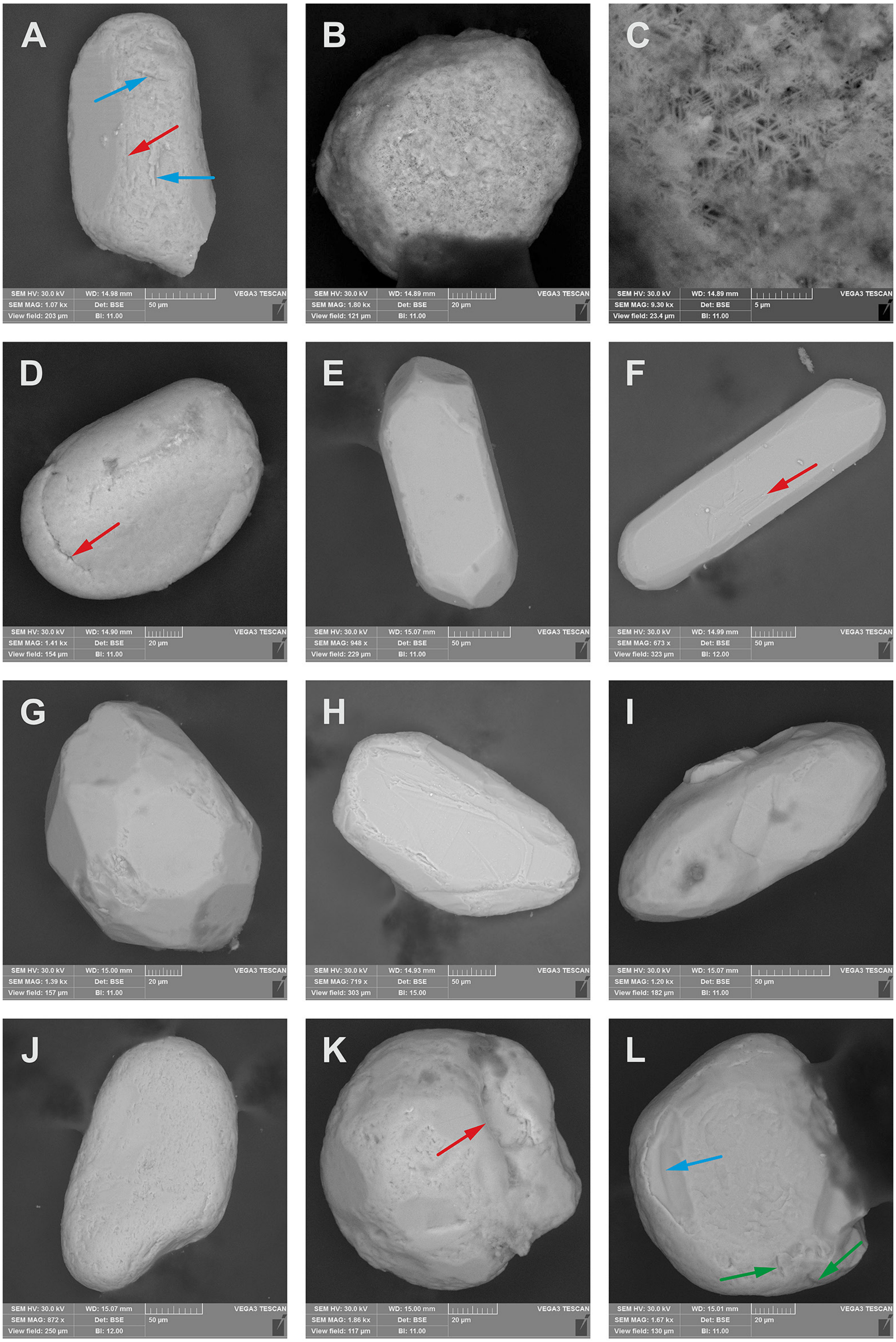

Figure 6: SEM images of detrital rutile (A-D) and zircon (E-L) from the Ilanqareh Fm. sandstones: A – subhedral grain with solution crevasses (red arrow) and scratch marks (blue arrow); B – subhedral grain with deeply etched surface; C – B in detail; D – rounded grain with smooth dull surface and arcuate cracks (red arrow); E-G – almost euhedral grains with smooth surface and minor mechanical traces (red arrow); H, I - subhedral grains with flat edge abrasion; J-L – sub-rounded to rounded grains with elongated smooth depression (red arrow), conchoidal fracture (blue arrow) and crescent-shaped cracks (green arrows).

corrosion on the edges are characteristic for arkosic samples (Fig. 7G-I). The grains obtained from the top of the Padeha Fm. Member 2, which is formed by greywacke, show occasionally traces after their original morphology (Fig. 7J); somewhere with scarce solution pits. Many rounded grains with mechanically-formed craters and crescentic marks are broken (Fig. 7K, L).

Rutile. Heavily abraded well-rounded rutile with usually low relief and bulbous edges is typical for all Padeha Fm. samples (Fig. 8A-D). Besides oriented solution and etch pits, there are many collision impact points and/or percussion cracks on the rutile surfaces.

Zircon. Surface of rounded to well-rounded zircons observed in SEM is characterised by crescentic gouges and small conchoidal cracks (Fig. 8E), some of them show many impacted microforms and “hairline” arcuate fractures. Fracture occurrence is often dependent on inclusion presence (Fig.

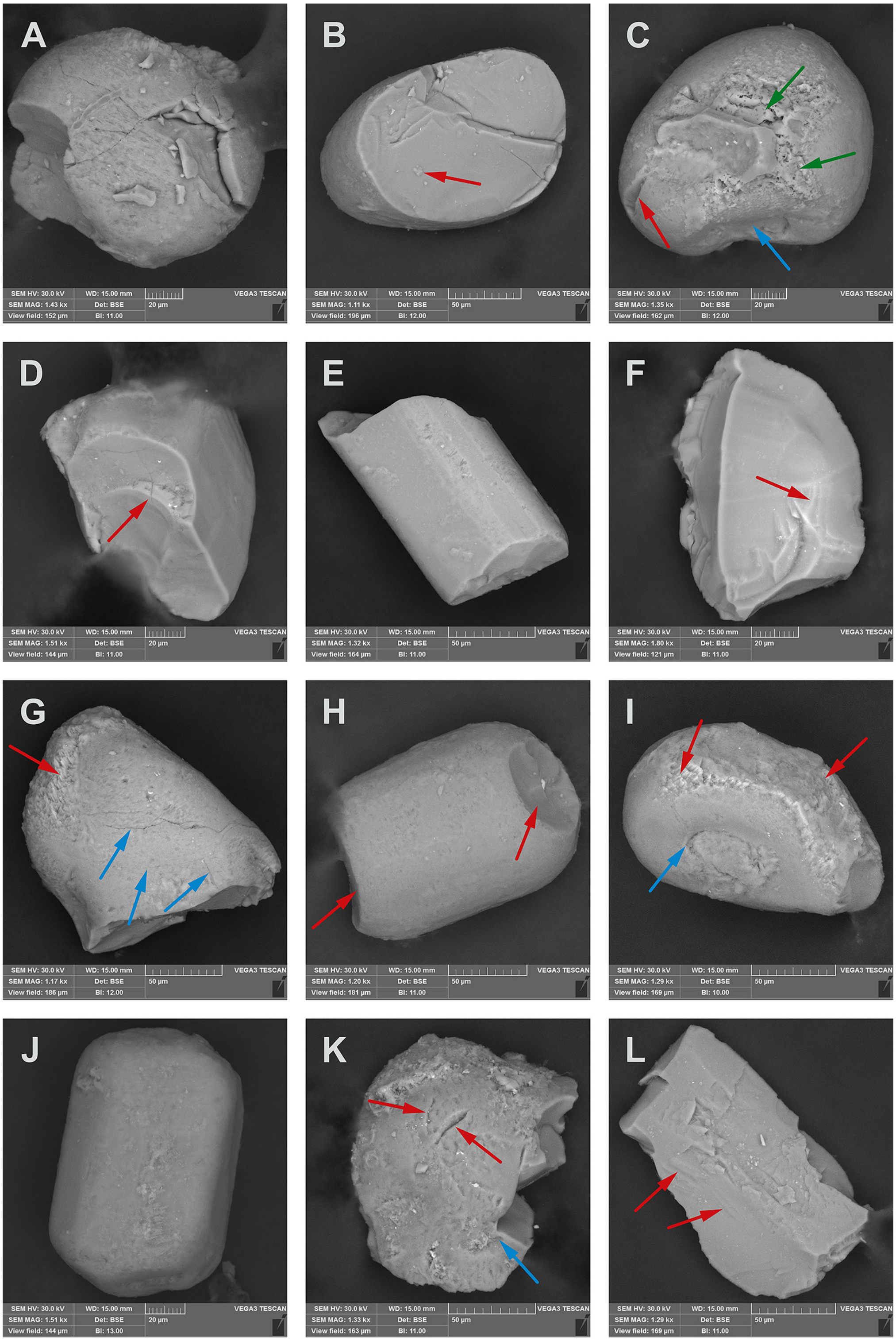

Figure 7: SEM images of detrital tourmaline from the Padeha Fm. sandstones (A-F: quartz arenite, G-I: arkose; J-L: greywacke): A – rounded grain with smooth surface and many polygonal fractures along which the grain disintegrates; B – fractured initially well-rounded grain with small adhering particles on fractured surface; C – well-rounded grain with dish-shaped impact depression (blue arrow), crescent-shaped cracks (red arrow) and dissolution pits (green arrows); D-F – grain fragments with fresh conchoidal features and arcuate steps (red arrow); G – sub-rounded grain with arcuate and polygonal fractures (blue arrows) and traces of chemical corrosion on the edge (red arrow); H – well-rounded grain with fairly regular, fine microtexture and fresh fractured edges (red arrows); I – grain with smooth surfaces with circular crack (blue arrow) and traces of dissolution on the edges (red arrows); J – subhedral grain with smooth surface; K – fragment of rounded grain with craters (blue arrow) and crescentic marks (red arrows); L – broken grain with linear steps on fresh fractured plane (red arrows).

8F). Dissolution or removal of mineral inclusions during the transport produced small regular cavities on some surfaces (Fig. 8G). Well-rounded zircons usually have fairly regular, fine microtexture with low relief (Fig. 8H, I) although the roundness is sometimes freshly disrupted (Fig. 8H). In addition to the above-mentioned microtextures, for the greywacke samples are typical fresh conchoidal features, local curved grooves and arcuate steps developed on sub-rounded grains with abraded edges. Straight and arc-shaped steps are also observed (Fig. 8J-L). Sporadic elongated or oval-shaped depressions may signify the removal of mineral inclusions by weathering or during the transport (Fig. 8L).

Interestingly, many grains obtained from the whole sequence of the Padeha Fm. sedimentary rocks (from the quartz arenite to greywacke) show almost identical morphological (anhedral) habitus and similar microtextural features. In general, various

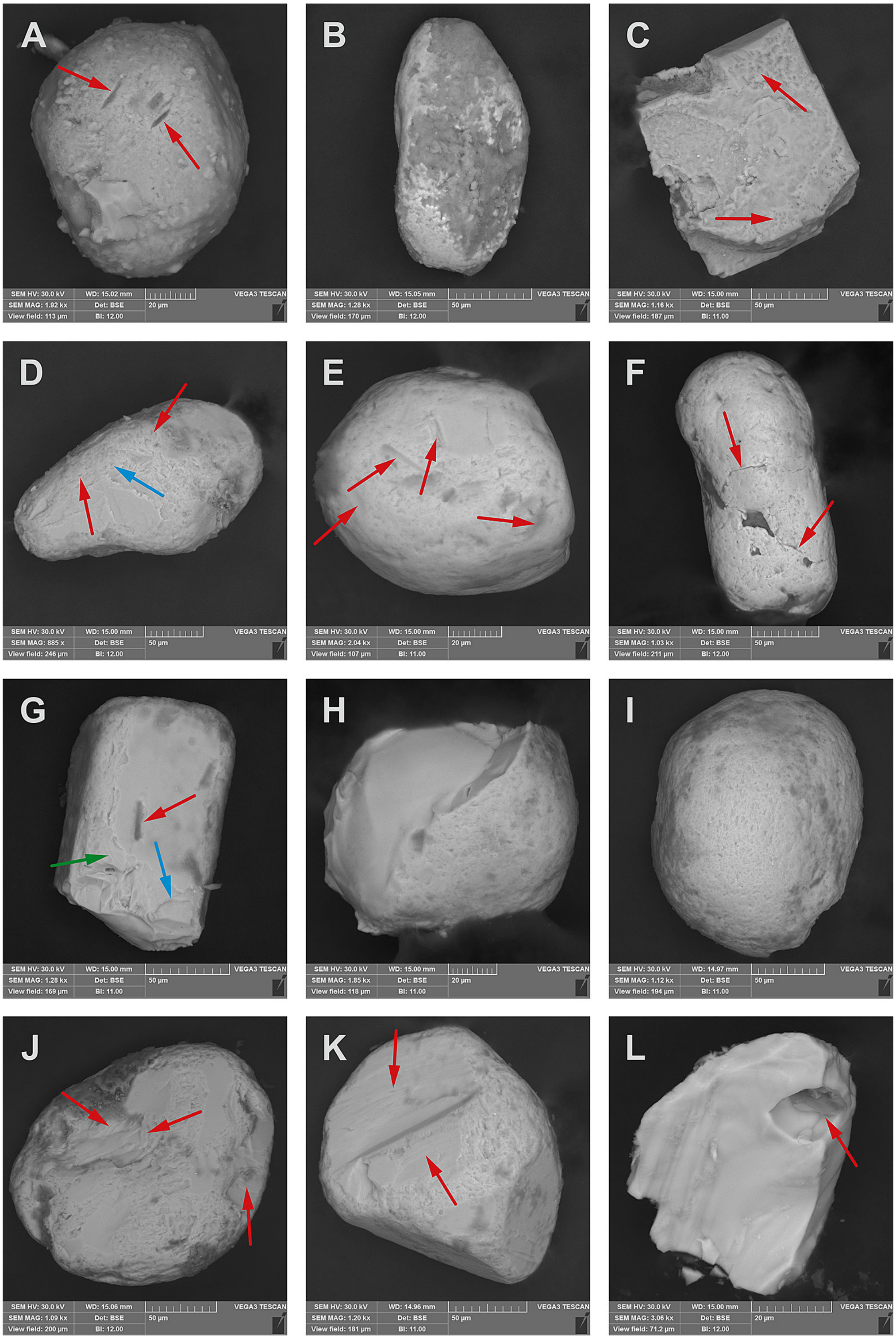

Figure 8: SEM images of detrital rutile (A-D) and zircon (E-L) from the Padeha Fm. sandstones (A-C, G-I: arkose; D, J-L: greywacke; E, F: quartz arenite): A, B – well-rounded grains with eroded surface and crescent-shaped cracks (red arrows); C – subhedral grain with dissolution etching; D – rounded grain with crescentic marks (red arrow) and small V-shaped pits (blue arrow); E – rounded grain with crescentic marks; F – well-rounded grain with smooth surface and fractures due to inclusions (red arrows); G – sub-rounded grain with partly abraded/bulbous edges and small cavities produced by dissolution or removal of inclusions (red arrow), breakage patterns (blue arrow) and conchoidal features with arc-shaped steps (green arrow); H – fractured initially well-rounded grain with fairly regular, fine microtexture in a high energy environment; I – well-rounded grain with tiny impact marks on the surface; J, K – sub-rounded grains with abraded edges, conchoidal features and arcuate steps (red arrows); L – fresh grain fragment with oval cavity after inclusion removal (red arrow).

mechanical features significantly predominate over chemical ones in both formations studied.

5. DISCUSSION

Grain morphology is predominantly controlled by (1) the specific conditions existing during the crystallisation/recrystallization stages in their parent rocks, (2) by the mechanical and chemical processes including the weathering and alteration that operate either during the transport or in the depositional environment (Malusà & Garzanti, 2019).

Character of microtextures developed on the detrital grain surface depends on four crucial factors: (1) the sedimentary environment in which the grain was shaped, (2) the energy of the environment (low- to high-energy conditions), (3) the duration of the mechanical and/or chemical weathering processes, and on (4) grain's previous weathering, transport and diagenetic history (e.g., Pye, 1983; Mahaney, 2002; Vos et al., 2014; Szerakowska et al., 2018). Shape and surface microtextures often reflect storage and subsequent reworking of the heavy minerals (Malusà & Garzanti, 2019). Many microtexture features may represent several environments, but combination of them is usually very peculiar (Krinsley, 1980).

Intensive chemical weathering in long-term storage, reworking and/or diagenesis can cause broad dissolution of some heavy minerals and their disappearance from the sedimentary record (Andò et al., 2012; Fielding et al., 2017; Garzanti et al., 2018; Malusà & Garzanti, 2019). This alternative is apparent, given the significantly depleted heavy-mineral spectra of both formations, the Ilanqareh and Padeha fms. Chemical weathering is evident from the study of the odd grain surfaces; for others, it may be obscured by loaded mechanical processes. Diagenetic dissolution of stable heavy minerals within the Devonian basin(s) is unlikely due to predominance of mechanical features well-preserved on their surfaces after their definitive deposition. Consequently, extensive surface pitting and etching with deep holes probably result of pre-Devonian dissolution processes or diagenesis. On the other hand, solution pits may indicate a sea water percolation (Mohammad et al., 2020) which has affected heavy minerals during later evolutionary stage. The adhered particles are sometimes preserved on cracked flat surfaces. These particles may be compatible with cementing-decementing episodes and are associated with low-energy environment (Krinsley & Doornkamp, 1973; Moral Cadrona et al., 2005). They are also characteristic for aeolian environment (Mahaney, 2002) or may be remnants of the parent rocks.

Based on detailed SEM study of the detrital ultra-stable heavy minerals from the studied formations we can conclude a multicyclic character of the sediments. While the bulbous edges of the grains and crescentic percussion marks are typical for aeolian environment, the V-shaped percussion cracks or V-shaped pits were more frequently observed on grain surfaces from subaqueous fluvial or marine environments (Krinsley & Doornkamp, 1973; Mahaney et al., 2012; Vos et al., 2014). The cracks indicate high-energy collision between transported grains. In general, aeolian effects should be stronger than fluvial effects. "The momentum of the grains is higher, the transporting medium is less viscous, and there exists hardly any laminar sublayer around the grains to protect them against collision" (Lindé, 1983). For instance, the roundness of quartz grains increases during aeolian transport and the surfaces are often covered by upturned plates (Lindé, 1983; Pye, 1983; Krinsley & Trusty, 1985). The presence of smooth surfaces on some studied grains, which were not affected by abrasion, is often identified on smaller grains (90 – 300 μm diameter; Krinsley & Trusty, 1985). This is related to their sizes, when small grains are more commonly carried in suspension (non-settling grains) rather than by creep or saltation, and therefore the collisions between the grains decrease. Smooth surfaces and circular or arcuate cracks on grains were identified mainly on desert sand (Krinsley & Trusty, 1985; Pye & Tsoar, 2009). In other words, rounded edges of grain with protected areas of indentation from abrasion indicate aeolian process (Krinsley & Doornkamp, 1973).

The bulk of studied rounded and well-rounded tourmaline, rutile and zircon grains with bulbous edges and fairly regular, fine microtexture and low grain relief show crescentic percussion marks, local impact depressions and V-shaped pits. The combination of these microtextures signifies wind action followed by grain evolution most likely in a subaqueous environment. It means, for the succession point of view, the well-rounded grains with above mentioned specific mechanical features suggest an aeolian transport (Pye & Tsoar, 2009; Zoleikhaei et al., 2016) or aeolian abrasive history, which is characteristic mainly for lower Paleozoic (and Pre-Cambrian) craton surfaces. This is associated with generally accepted fact about the absence of macroscopic land vegetation (e.g., Dott, 2013). Loaded mechanical microtextures, such as sporadic irregularly curved grooves, conchoidal fractures, V-shaped pits and percussion cracks signal high-energy collision subaqueous environment (Moral Cardona et al., 2005; Vos et al., 2014; Hossain et al., 2020).

Considering the fresh fractured surface of few tourmaline, zircon or rutile grains is often free of any mechanical and/or chemical features and its edges are usually very sharp, so it happened at a later time and it may be result of sample preparation in a laboratory. These are grains with predisposition to break along existing fractures.

For the provenance point of view, Moghadam et al. (2017) documented that the stratigraphically lower Padeha Fm. sandstone (quartz arenite) contains mainly Silurian (peak at 435 Ma) detrital zircons, upper sandstone (arkose) has predominantly Cadomian (~0.5 Ga) and Neoproterozoic (~1.01, ~0.9, ~0.76, ~0.6 Ga) ones. Although these authors suggest that "Cadomian basement rocks were locally uplifted during Early Devonian time" in Iran and consider them to be main sources for the detrital zircon in the Padeha sandstones, the re-sedimentation of previously deposited detritus derivable from the Arabian-Nubian Shield and/or reworked Gondwana sources (Morag et al., 2011) cannot be excluded. Local source(s) with respect to the studied heavy-mineral shapes and their surface microtexture features may be considered, however, they relate rather to scarce euhedral/subhedral zircon grains with fresh and smooth surfaces which were probably not subjected to long-distance transport or recycled processes. The temporary storage of some heavy minerals studied in aeolian environment is furthered by existence of the Cambrian Amin Fm. widespread over Oman today, which reflects a period of arid, continental desert conditions (Hughes Clarke, 1988). It consists of quartz-rich sandstone and contains alluvial fan, fluvial and aeolian deposits without fossils (Droste, 1997). Local source(s), which partly supplied the Devonian Ilanqareh basin, may be also assumed.

6. CONCLUSION

Based on detailed SEM analysis of the ultra-stable heavy minerals from the Devonian Ilanqareh and Padeha deposits exposed today in Azarbaijan Province and Eastern Alborz, respectively, we can conclude that they exhibited mostly rounded and well-rounded shape, and sub-rounded grains are rather minor. Various mechanical features such as abraded and bulbous edges, conchoidal features, straight/arc-shaped steps, V-shaped depressions and crescentic percussion marks predominate significantly over chemical solution pits in both formations studied. Arcuate and polygonal cracks as well as adhering particles of combined mechanical or chemical origin were also found.

In summary, the microtexture surface heavy-mineral similarity between the Ilanqareh and Padeha deposits indicates that they could have experienced the resembled environmental conditions during their transportation and sedimentation/re-sedimentation history – from aeolian processes to subaqueous (fluvial and/or marine) ones. Except limited local source(s), many microfeatures imposed on the grain surfaces indicate multi-cyclic character of the studied sediments probably originated from numerous more distant sources. Despite single heavy-mineral populations in sandstones represented by ultra-stable tourmaline, zircon and rutile we can conclude usefulness of investigation their surface microtextures which may reflect the transport style and specific processes of depositional environment for better understanding their sedimentary history.

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References

Abdolahi M. R. & Hosseini M., 1996: Geological map of Iran, Julfa, 1:100000 series, sheet 5167, Geological Survey of Iran.

Achab M., Cardona J. M., Gutiérrez-Mas J. M., Bellón A. S. & González-Caballero J. L., 2017: Sedimentary provenance and depositional history of Cadiz Bay (SW Spain) based on the study of heavy minerals surface textures. *Thalassas: An International Journal of Marine Sciences*, 33 (1), 29–42.

Alsharhan A.S. & Kendall C.G.S.C., 1986: Precambrian to Jurassic rocks of Arabian Gulf and adjacent areas: their facies, depositional setting, and hydrocarbon habitat. *American Association of Petroleum Geologists Bulletin*, 70, 977–1002.

Andò S., Garzanti E., Padoan M. & Limonta M., 2012: Corrosion of heavy minerals during weathering and diagenesis: a catalog for optical analysis. *Sedimentary Geology*, 280, 165–178.

Anjerdi J., Jafarzadeh M., Najafzadeh A. & Mahari R., 2020: Provenance of the siliciclastic deposits of Ilanqareh Formation in the Pireshagh section, south of Jolfa, based on the petrography, geochemistry and heavy mineral assemblage [in Persian with English summary]. *Scientific Quarterly Journal, Geosciences,* 30 (117), 205–216.

Armstrong-Altrin J. S., 2020: Detrital zircon U-Pb geochronology and geochemistry of the Riachuelos and Palma Sola beach sediments, Veracruz State, Gulf of Mexico: a new insight on palaeoenvironment. *Journal of Palaeogeography*, 9 (4), 1–27.

Armstrong-Altrin J. S., Ramos-Vázquez M.A., Hermenegildo-Ruiz N.Y. & Madhavaraju J., 2020: Microtexture and U–Pb geochronology of detrital zircon grains in the Chachalacas beach, Veracruz State, Gulf of Mexico. *Geological Journal,* 56 (5), 2418–2438

Balan E., Trocellier P., Jupille J., Fritsch E., Muller J. P. & Calas G., 2001: Surface chemistry of weathered zircons. *Chemical Geology*, 181 (1–4), 13–22.

Berberian F. & Berberian M., 1981: Tectono-plutonic episodes in Iran. In: Gupta, H.K. & Delany F. M. (Eds.): Zagros-Hindu Kush-Himalaya Geodynamic Evolution. Geodynamics Series, vol. 3. American Geophysical Union, Washington D.C., pp. 5–32.

Bolourchi M. H. & Saidi A., 1989: Geological map of Iran, Poldasht, 1:100000 series, sheet 5068, Geological Survey of Iran.

Bónová K., Bóna J., Panczyk M., †Kováčik M., Mikuš T. & Laurinc D., 2019: Origin of deep-sea clastics of the Magura Basin (Eocene Makovica sandstones in the Outer Western Carpathians) with constraints of framework petrography, heavy mineral analysis and zircon geochronology. *Palaeogeography Palaeoclimatology Palaeoecology*, 514, 768–784.

Dill H. G., 1998: A review of heavy minerals in clastic sediments with case studies from the alluvial-fan through the nearshore-marine environments. *Earth-Science Reviews*, 45 (1–2), 103–132.

Dill H. G., 2007: Grain morphology of heavy minerals from marine and continental placer deposits, with special reference to Fe–Ti oxides. *Sedimentary Geology*, 198 (1-2), 1–27.

Dott R. H., Jr., 2003: The Importance of Eolian Abrasion in Supermature Quartz Sandstones and the Paradox of Weathering on Vegetation-Free Landscapes. *The Journal of Geology*, 111 (4), 387–405.

Droste H. H. J., 1997: Stratigraphy of the Lower Paleozoic Haima Supergroup of Oman. *GeoArabia*, 2, 419–472.

Fielding L., Najman Y., Millar I., Butterworth P., Andò S., Padoan M., Barford D. & Kneller B., 2017: A detrital record of the Nile River and its catchment. *Journal of the Geological Society*, 174 (2), 301–317.

Finzel E. S., 2017: Detrital zircon microtextures and U-Pb geochronology of Upper Jurassic to Paleocene strata in the distal North American Cordillera foreland basin. *Tectonics*, 36, 1295–1316.

Garzanti E., Andò S., Limonta M., Fielding L. & Najman Y., 2018: Diagenetic control on mineralogical suites in sand, silt, and mud (Cenozoic Nile Delta): Implications for provenance reconstructions. *Earth-Science Reviews*, 185, 122–139.

Ghorbani M., 2019: Lithostratigraphy of Iran. Springer, Switzerland, 296 p.

Grewingk C., 1853: Die geognostischen und orographischen Verhaeltniss des noerdlichen Persiens, Verhandlungen derrussisch-kaiserlichen: St. Petersburg, Mineralogischen Gesellschaft zu St. Petersburg, 1852–1853.

Horton B. K., Hassanzadeh J., Stockli D. F., Axen G. J., Gillis R. J., Guest B., Amini A., Fakhari M. D., Zamanzadeh S. M. & Grove M., 2008: Detrital zircon provenance of Neoproterozoic to Cenozoic deposits in Iran: Implications for chronostratigraphy and collisional tectonics. *Tectonophysics*, 451 (1–4), 97–122.

Hossain H. M. Z., Armstrong-Altrin J. S., Jamil A. H. M. N., Rahman M. M., Hernández-Coronado C. J. & Ramos-Vázquez M. A., 2020: Microtextures on quartz grains in the Kuakata beach, Bangladesh: implications for provenance and depositional environment. *Arabian Journal of Geosciences*, 13 (291), 1–12.

Hosseini M., Jafarzadeh M., Taheri A. & Zand-Moghaddam H., 2019: Petrography and geochemistry of siliciclastic sedimentary rocks of the Padeha Formation in Khoshyeilagh section; Eastern Alborz; implication for provenance [in Persian with English summary]. *Journal of Stratigraphy and Sedimentology Researches University of Isfahan* 35 (2), 1–24.

Hubert J. F., 1962: A zircon-tourmaline-rutile maturity index and the interdependence of the composition of heavy mineral assemblages with the gross composition and texture of sandstones. *Journal of Sedimentary Research*, 32 (3), 440–450.

Hughes Clarke M. W., 1988: Stratigraphy and Rock Unit Nomenclature in the Oil-Producing Area of Interior Oman. *Journal of Petroleum Geology*, 11, 5–60.

Husseini M.I., 1991: Tectonic and depositional model of the Arabian and adjoining plates during the Silurian-Devonian. *American Association of Petroleum Geologists Bulletin*, 75, 108–120.

Jafarzadeh M., Bónová, K., Mikuš, T., Bóna, J., Rezaei-Kahkhaei, M., Taheri, A.: Tourmaline and rutile geochemistry in the Early-Middle Devonian sandstones of the Padeha Formation, Alborz Range, Northern Iran. *Geological Journal* (accepted).

Kalińska-Nartiša E. & Gałka M., 2018: Sand in Early Holocene lake sediments – a microscopic study from Lake Jaczno, northeastern Poland. *Estonian Journal of Earth Sciences*, 67 (2), 122–132.

Kemnitz H. & Lucke B., 2019: Quartz grain surfaces – A potential microarchive for sedimentation processes and parent material identification in soils of Jordan. *Catena*, 176, 209–226.

Krinsley D., 1980: Sanning Electron Microscope Examination of Quartz Sandgrain Microtextures. *Kwartalnik Geologiczny*, 24 (2), 217–232.

Krinsley D. H. & Doornkamp J. C., 1973: Atlas of quartz sand surface textures. USA, Cambridge University Press, New York, 91 p.

Krinsley D. & Trusty P., 1985: Environmental interpretation of quartz surface textures. In: Zuffa G. G. (Ed.): Provenance of arenites. Springer Sci. and Business Media Dordrecht, NL, pp. 213–230.

Křížová L, Křížek M. & Lisá L., 2011: Applicability of quartz grains surface analysis to the study of the genesis of unlithified sediments [in Czech with English summary]. *Geografie*, 116, 59–78.

Lindé K., 1983: Some surface textures of experimental and natural sands of Icelandic origin. *Geografiska Annaler: Series A, Physical Geography*, 65 (3–4), 193–200.

Linnemann U., Pidal A. P., Hofmann M., Drost K., Quesada C., Gerdes A., Marko L., Gärtner A., Zieger J., Ulrich J., Krause R., Vickers-Rich P. & Horak J., 2018: A ~565 Ma old glaciation in the Ediacaran of peri-Gondwanan West Africa. *International Journal of Earth Sciences*, 107, 885–911.

Mahaney W. C., 2002: Atlas of sand grain surface textures and applications. Oxford, England, Oxford University Press, 237 p.

Mahaney W. C., Vortisch W. & Julig P. J., 1988: Relative differences between glacially crushed quartz transported by mountain and continental ice; some examples from North America and East Africa. *American Journal of Science*, 288 (8), 810–826.

Mahaney W. C., Stewart A. & Kalm V., 2001: Quantification of SEM microtextures useful in sedimentary environmental discrimination. *Boreas*, 30 (2), 165–171.

Mahaney W. C., Fairén A. G., Dohm J. M. & Krinsley, D. H., 2012: Weathering rinds on clasts: Examples from earth and Mars as short and long term recorders of paleoenvironment. *Planetary and Space Science*, 73, 243–253.

Mahaney W. C. & Milner M. W., 1998: Zircon microstriators in the sand of auriferous Andean tills: fine tools and noble metals. *Boreas*, 27 (2), 140–152.

Mange M. A. & Maurer H. F., 1992: Heavy minerals in colour. Chapman and Hall. London, UK, 147 p.

Malusà M. G. & Garzanti E., 2019: The sedimentology of detrital thermochronology. In: Fission-Track Thermochronology and its Application to Geology. Springer, Cham., pp. 123–143.

Moghadam H. S., Li X-H., Griffin W. L., Sternd R. J., Thomsen T. B., Meinhold G., Aharipour R. & O'Reilly S. Y., 2017: Early Paleozoic tectonic reconstruction of Iran: Tales from detrital zircon geochronology. *Lithos*, 268–271, 87–101.

Mohammad A., Murthy P. B., Rao E. N. D. & Prasad H., 2020: A study on textural characteristics, heavy mineral distribution and grain microtextures of recent sediment in the coastal area between the Sarada and Gosthani rivers, east coast of India. *International Journal of Sediment Research*, 35 (5), 484–503.

Morag N., Avigad D., Gerdes A., Belousova E. & Harlavan Y., 2011: Crustal evolution and recycling in the northern Arabian-Nubian Shield: new perspectives from zircon Lu–Hf and U–Pb systematics. *Precambrian Research*, 186, 101–116.

Morton A. C., 1979: The provenance and distribution of the Palaeocene sands of the central North Sea. *Journal of Petroleum Geology*, 2 (1), 11–21.

Morton A. C. & Hallsworth C. R., 1999: Processes controlling the composition of heavy mineral assemblages in sandstones. *Sedimentary Geology*, 124, 3–29.

Morton A. C. & Hallsworth C., 2007: Stability of detrital heavy minerals during burial diagenesis. *Developments in Sedimentology*, 58, 215–245.

Moral Cardona J. P., Bellón A. S., López-Aguayo F. & Caballero M. A., 1996: The analysis of quartz grain surface features as a complementary method for studying their provenance: the Guadalete River Basin (Cadiz, SW Spain). *Sedimentary Geology*, 106 (1–2), 155–164.

Moral Cardona J. P., Gutiérrez Mas J. M., Sánchez Bellón A., Domínguez-Bella S. & Martínez López J., 2005: Surface textures of heavy mineral grains: A new contribution to provenance studies. *Sedimentary Geology*, 174, 223–235.

Najafzadeh A., Jafarzadeh M. & Moussavi-Harami R., 2010: Provenance and tectonic setting of Upper Devonian sandstones from Ilanqareh Formation (NW Iran). *Revista Mexicana de Ciencias Geológicas*, 27, 545–561.

Nallusamy B., 2015: Morphology, trace and rare earth elements of detrital zircon of Kayamkulam, Thottappally Placers, south West India – Implications for provenance. *Marine Georesources and Geotechnology*, 33, 437–446.

Poursoltani M. R., 2017: Petrography and diagenesis of Padeha Formation sandstones (Lower-Middle Devonian) at Bujhan section, Binalud Basin, NE Iran [in Persian with English summary]. *Journal of Stratigraphy and Sedimentary Research*, 4, 87–112.

Poursoltani M. R. & Pe-Piper G., 2020: Diagenetic history and provenance of Devonian terrestrial sandstones at the margin of Gondwana: Padeha Formation, Eastern Alborz, Iran. *Journal of Asian Earth Sciences*, 204, 104576.

Pupin J. P., 1980: Zircon and granite petrology. *Contributions to Mineralogy and Petrology*, 73 (3), 207–220.

Pye K., 1983: Formation of quartz silt during humid tropical weathering of dune sands. *Sedimentary Geology*, 34, 267–282.

Pye K. & Tsoar H., 2009: Aeolian Sand and Sand Dunes. Springer-Verlag Berlin Heidelberg, 458 p.

Ramos-Vázquez M. A. & Armstrong-Altrin J. S., 2020: Provenance and palaeoenvironmental significance of microtextures in quartz and zircon grains from the Paseo del Mar and Bosque beaches, Gulf of Mexico. *Journal of Earth System Science*, 129 (225), 1–16.

Ruttner A. W., Nabavi M. H. & Hajian J., 1968: Geology of the Shirgesht area (Tabas area, east Iran). *Reports of the Geological Survey of Iran*, 4, 1–133.

Szerakowska S., Woronko B., Sulewska M. & Oczeretko E., 2018: Spectral method as a tool to examine microtextures of quartz sand-sized grains. *Micron*, 110, 36–45.

Tejan-Kella M. S., Fitzpatrick R. W. & Chittleborough D. J., 1991: Scanning electron microscope study of zircons and rutiles from a podzol chronosequence at Cooloola, Queensland, Australia. *Catena*, 18, 11–30.

Turner G. & Morton A. C., 2007: The effects of burial diagenesis on detrital heavy mineral grain surface textures. *Developments in Sedimentology*, 58, 393–412.

Velbel M. A., 2007: Surface textures and dissolution processes of heavy minerals in the sedimentary cycle: Examples from pyroxenes and amphiboles. *Developments in Sedimentology*, 58, 113–150.

Vos K., Vandenberghe N. & Elsen J., 2014: Surface textural analysis of quartz grains by scanning electron microscopy (SEM): From sample preparation to environmental interpretation. *Earth-Science Reviews*, 128, 93–104.

Wendt J., Kaufmann B., Belka Z., Farsan N. & Karimu-Bavandpur A., 2002: Devonian/Lower Carboniferous stratigraphy, facies patterns and palaeogeography of Iran. Part I. Southeastern Iran. *Acta Geologica Polonica*, 52, 129–168.

Whalley W. B. & Krinsley D. H., 1974: A scanning electron microscope study of surface textures of quartz grains from glacial environments. *Sedimentology*, 21 (1), 87–105.

Zand-Moghadam H., Moussavi-Harami R., Mahboubi A. & Rahimi B., 2013: Petrography and Geochemistry of the Early-Middle Devonian sandstones of the Padeha Formation in the North of Kerman, SE Iran. Implications for provenance. *Boletín del Instituto de Fisiografía y Geología*, 83, 1–14.

Zand-Moghadam H., Moussavi-Harami R. & Mahboubi A., 2014: Sequence stratigraphy of the Early–Middle Devonian succession (Padeha Formation) in Tabas Block, East-Central Iran: Implication for mixed tidal flat deposits. *Palaeoworld*, 23 (1), 31–49.

Zoleikhaei Y., Frei D., Morton A. & Zamanzadeh S. M., 2016: Roundness of heavy minerals (zircon and apatite) as a provenance tool for unraveling recycling: A case study from the Sefidrud and Sarbaz rivers in N and SE Iran. *Sedimentary Geology*, 342, 106–117.