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The Nowdan anticline of the Zagros orogen as a geoheritage 'window' into the late Mesozoic–Cenozoic evolution of the African–Arabian continental margin

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Abstract

Geological heritage can contribute to our understanding of the long-term evolution of important sectors of our planet. Cretaceous–Neogene rocks (chiefly carbonates) crop out in the Nowdan anticline of the Zagros orogen. Field investigations have permitted the establishment of 10 key localities (stratigraphical reference sections) that represent these rocks within this anticline, which is a single large geosite. The formations are related to the main phases in the evolution of the northeastern sector of the African–Arabian continental margin. For instance, carbonate rocks of the Asmari Formation mark changes in the affinity of the study area, from the African–Arabian plate to only the Arabian plate, separated in conjunction with Red Sea rifting during the Oligocene. Information on the palaeogeographical changes is really precious to geoscientists and geotourists alike, and contributes to the great value of the Nowdan anticline geosite. Evidence from the latter, as well as from a few other places (i.e., the Mountainous Adygeya geodiversity hotspot in Russia, the North Coast of São Paulo in Brazil and the possible Gondwanan geopark in Namibia) illustrates the necessity of distinguishing a palaeomapping subtype in palaeogeographical characterisation of geological heritage.

Key words: geological heritage, palaeogeographical geosite, orogen, tourism resources, Iran

1. Introduction

Geological heritage sites (geosites) are very important in earth science research, education and tourism focused on nature (Henriques et al., 2011; Prosser, 2013; Brilha, 2016; Reynard & Brilha, 2018; Ibáñez et al., 2019; Arrad et al., 2020). Their uniqueness makes them ideal objects for various investigations, explanations of basic geological ideas and appeal to visitors. Equally important is their relevance to the provision of basic ecosystem services (Gray, 2013; Brilha et al., 2018) and aesthetic properties (Mikhailenko et al., 2017).

Geosites inform not only about presently available static objects such as peculiar rocks, tectonic structures and fossils, but also about geological history, including dynamics of depositional environments, ancient ecosystems and palaeogeographical configurations of continents and oceans. Although the great majority of theoreticians and practitioners of geoconservation and geotourism recognise the value of localities that illustrate past changes, the special selection and evaluation of such sites remain poorly discussed in the professional literature. Probably, this bias is linked to the restricted visibility of palaeogeographical features that can be only interpreted on the basis of observable rocks and fossils (Mikhailenko & Ruban, 2019). General inferences have been summarised in papers by Bruno et al. (2014), Plyusnina et al. (2015), Grujicic-Tešic et al. (2016) and Sallam & Ruban (2017), to which reference is made. However, the conceptual basis needs both expansion and illustration by means of additional examples from different parts of the world.

The Zagros Mountains of Iran provide a world-class example of an orogenic domain (Alavi, 2007; Aldega et al., 2018; Bigi et al., 2018; Sarkarinejad & Goftari, 2019). Studies of its geological heritage have permitted to identify a relatively small area, the Nowdan anticline, the geological registers of which illustrate many complex features of the whole late Mesozoic–Cenozoic history of this domain (Habibi & Ruban, 2017; Habibi et al., 2017; Molchanova & Ruban, 2019). Moreover, this history was strongly linked to the evolution of the northeastern sector of the African–Arabian continental margin.

The objective of the present work is to demonstrate the importance of the geological heritage of the Nowdan anticline for our understanding of major events in regional geological history. In the other words, it is intended to shed some light on a very specific kind of geological heritage that depicts major palaeogeographical changes.

2. Geological setting

The Zagros is a large Cenozoic orogen (fold-and-thrust belt) stretching in a northwesterly–southeasterly direction along the Persian Gulf (Sepehr & Cosgrove, 2004; Alavi, 2007; Bigi et al., 2018; Sarkarinejad & Goftari, 2019). The Zagros formed as a result of the collision between the Arabian Plate in the southwest and Iranian terranes in the northwest.

The Nowdan anticline is located to the west of the city of Shiraz, in the Fars Province of Iran. Cretaceous (Kazhdumi, Sarvak, Ilam and Gurpi formations), Paleogene (Pabdeh and Asmari formations) and Neogene (Asmari and Gachsaran formations)

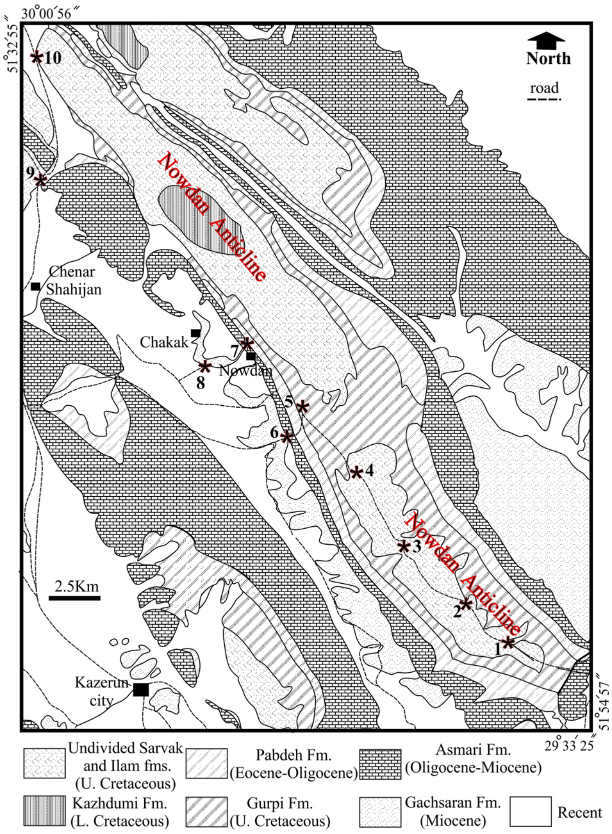

Fig. 1. Localities in the Nowdan anticline (geological map modified from MacLeod & Majedi, 1972)

rocks occur here (Fig. 1). The upper Mesozoic–Cenozoic sedimentary succession of the Nowdan anticline is dominated by limestones (Fig. 2) that was deposited on large carbonate platforms on the transition between Arabia in the southwest and Iranian terranes in the northeast (Alavi, 2004; Golonka, 2004). The growth of these platforms initially took place in the Neo-Tethys Ocean and later in its remnant, i.e., a seaway between the Mediterranean Sea and the Indian Ocean (Golonka, 2004). Shallow-marine conditions dominated during the Cenozoic and resulted from closure of the Neo-Tethys (Leturmy & Robin, 2010). Specific features of the regional geological history were the mid-Cretaceous uplift and the related regression and unconformity (Turonian event), which can be recognised across the entire Arabian plate (Sharland et al., 2001) and ophiolite obduction along the plate margin during the Late Cretaceous (Beydoun et al., 1992).Mesozoic and Cenozoic rocks that crop out in the study area show extensive folding structures trending along the main orogen axis.

Molchanova & Ruban (2019) have recently demonstrated that the entire Nowdan anticline should be considered as a large and complex geosite of national relevance. It exhibits various unique

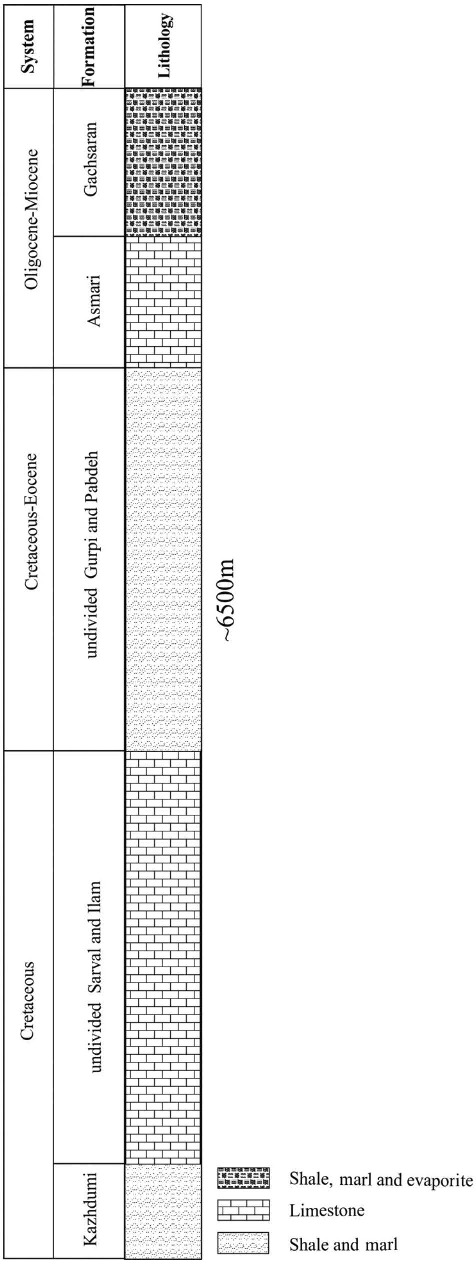

Fig. 2. Composite stratigraphical section of the Nowdan anticline

features that can be attributed to stratigraphical, sedimentary, structural, palaeogeographical and other types of geological phenomena. These features occur and even intersect in a restricted space, which determines the high integrity of the geosite. Palaeogeographical features, which are the subject of the present note, are represented by rocks archiving depositional environments relevant to particular palaeotectonic settings. In other words, these features are represented indirectly but their essence can be deduced from interpretations of sedimentary rock archives.

3. Methodology

The entire Nowdan anticline is a single geosite with significant integrity of geological heritage (Molchanova & Ruban, 2019). Its large size means that particular manifestations of this heritage should be considered. The localities that exhibit unique features are not geosites (and should not be described as such), but just small elements of one large geosite. The possibility of such geosite definition has been considered earlier by Fuertes-Gutiérrez & Fernández-Martínez (2010).

The territory of the Nowdan anticline was surveyed in order to find representative sections of the sedimentary succession. These sections were described and correlated (Fig. 3) and relevant localities were mapped (Fig. 1). Some of these (Table 1) were described in recent papers (Habibi & Ruban, 2017; Habibi et al., 2017; Molchanova & Ruban, 2019); there is no need to repeat these here. However, others are defined for the first time here, and their formal characteristics are given in Table 1 (see also lithology; Fig. 3).

Bruno et al. (2014) stressed the importance of distinguishing a palaeogeographical type of geological heritage. This type includes different and unique features that constitute evidence of past geological events locked in rock units. For each geosite, the relevance (global, national, regional (provincial) and local) of a particular type can be established by examination of the spatial dimension of the uniqueness of such relevant features (Ruban, 2010). For instance, a given geosite will have national relevance if specific palaeogeographical information is available only from this site and not from any other place in the country.

For the purposes of the present study, a synopsis of events in the late Mesozoic–Cenozoic evolution of the northeastern African–Arabian continental margin has been constructed. The basic geological descriptions of the Zagros and its development (Alavi, 2004, 2007; McQuarrie, 2004; Sepehr & Cosgrove, 2004; Mouthereau et al., 2012; Aldega et al., 2018; Bigi et al., 2018; Kordi, 2019; Sarkarinejad & Goftari, 2019) and some other works (see citations below) have facilitated this task. The main phases in the regional geological history have been established. Each lithostratigraphical unit that crops out within the Nowdan anticline has then been associated to a particular phase. This approach allows to understand how the evolution of the entire margin is reflected by the sedimentary archives of the anticline. Such judgements are essential for further assessment of the palaeogeographical heritage value of the geosite analysed.

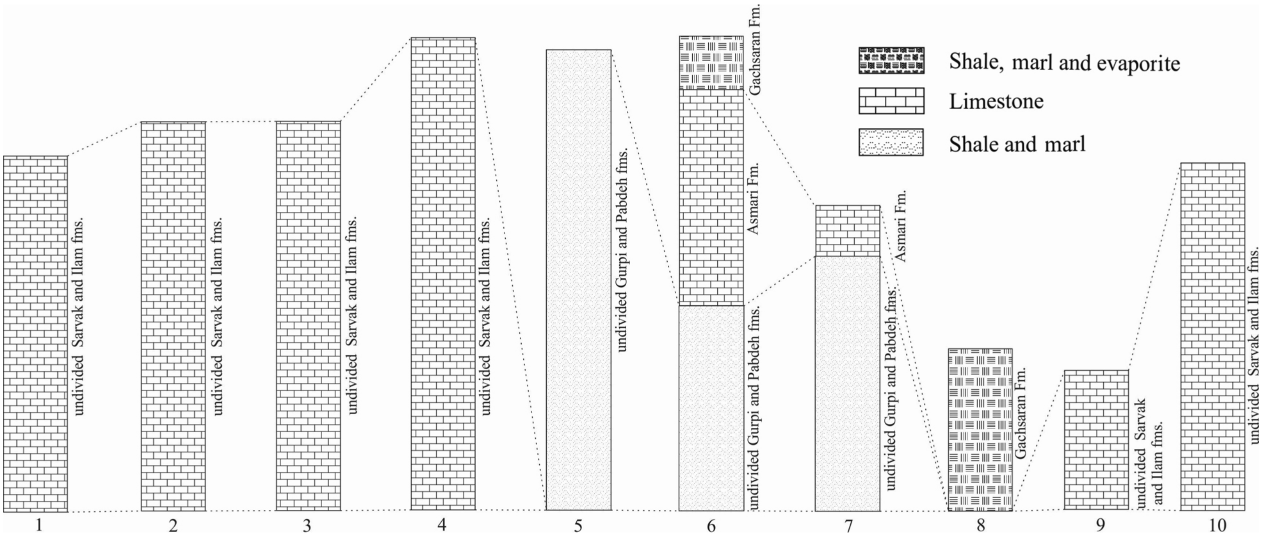

Fig. 3. Correlation of the upper Mesozoic–Cenozoic sections of the Nowdan anticline (see Figure 1 for numbers of localities and Figure 2 for a lithological key)

Table 1. Key localities in the Nowdan anticline geosite (see also Fig. 1).

Locality*	1–4	5	6	7	8	9, 10
Main unit	Sarvak and Ilam fms.	Pabdeh and Gurpi fms.	Pabdeh, Asmari and Gachsaran fms.	Pabdeh, Gurpi and Asmari fms.	Gachsaran Fm.	Sarvak and Ilam fms.
Source	Molchanova & Ruban (2019)	Habibi et al. (2017)	Habibi & Ruban (2017); Habibi et al. (2017)	Habibi & Ruban (2017)	This work (see descriptions below)	
New locality	Description			Unique features		
8	Mixed carbonate and evaporite sediments of Miocene age. The Gachsaran Fm. contains remains of fossil bivalves (rudists), bryozoans, echinoids, corals and benthic foraminifera.			One of the most representative (reference) lithostratigraphical sections of the Gachsaran Fm.; also evaporite rocks and fossils.		
9** 10**	Late Cretaceous carbonates are represented by medium- to thick-bedded limestones bearing cephalopods, bivalves, echinoids, coralline red algae, bryozoans, and planktonic and benthic foraminifera.			Reference section of the Sarvak and Ilam fms.; also fossils.		

*These localities are not geosites, but just elements of a big geosite corresponding to the entire anticline. If so, these localities do not require in-depth descriptions like geosites; the characteristics of the Nowdan anticline geosite is given by Molchanova & Ruban (2019).

**Although these localities may look identical, they display different portions of the Late Cretaceous sedimentary succession.

4. Results

A total of 10 localities, representing all the formations that crop out in the Nowdan anticline, were identified (Fig. 3l; Table 1). These occur either in the axial part of the anticline (localities 1–4) or on its western flank (localities 5–10) forming a kind of chain that crosscuts laterally almost the entire anticline (Fig. 1). Many localities show not only a single, but two or more formations with visible contacts between them (Figs 4, 5). The Sarvak, Ilam, Gurpi and Pabdeh formations are the best represented in the study area (Figs 6, 7). The description given below relates the main phases of regional geological history to formations of the Nowdan anticline, with Figure 3 demonstrating at which localities these formations are represented. As many sections display overlapping stratigraphical intervals (Fig. 3; Table 1), it is unreasonable to justify this description against the localities. Moreover, the entire anticline is one large geosite, and, thus, it is sensible to avoid attaching different stages to different localities.

The Cretaceous formations of the Nowdan anticline formed on the margin of the African–Arabian

Fig. 4. Panoramic view showing the contact between the undivided Sarvak and Ilam formations (1) and the undivided Gurpi and Pabdeh formations (2) at locality 5

plate (Table 2). The carbonate and fine siliciclastic lithologies of the Kazhdumi, Sarvak, Ilam and Gurpi formations are sedimentary registers of the stage when the elongated Sanandaj-Sirjan terrane detached from Arabia at the beginning of the Mesozoic (Mehdipour & Moazzen, 2015), becoming later attached to Arabia by subduction (Golonka, 2004). The Kazhdumi Formation formed in a mixed carbonate-siliciclastic environment that has been interpreted as a carbonate ramp with coastal-deltaic facies (Aghanabati, 2004). The Sarvak Formation formed in a shallow-marine ramp setting during the Cenomanian to early Turonian (Setudehnia, 1978; Taghavi et al., 2006). The depositional environment of the Ilam Formation is interpreted as a carbonate ramp with a very gentle slope (Adabi & Mehmandosti, 2008). The Upper Cretaceous–Paleocene Gurpi Formation consists of shales, marls and argillaceous mudstones that accumulated in changing depositional settings (James & Wynd, 1965; Motiei, 2003).

Paleogene formations register significant changes in the affinity of the Nowdan anticline (Table 2). Shales and marls of the Pabdeh Formation reflect a time span of remarkable reorganisation of tectonic blocks. On the one hand, the former Sanandaj-Sirjan terrane was unified with Arabia in the southwest, and, on the other hand, this terrane joined with the other Iranian and Caucasian terranes in the north (Golonka, 2004). Thus, the Eocene sequences of the Nowdan anticline are indicative of the 'growth' of the African–Arabian margin after terrane stacking. The Pabdeh Formation formed on a carbonate ramp; Alsharhan & Nairn (1997) also believed that some parts of thus unit were laid down in intrashelf basins.

The carbonate-dominated Asmari Formation marks a key episode in regional geological history. The Arabian Plate separated from the African Plate during the Oligocene together with the onset of Red Sea rifting (Bosworth et al., 2005; Blanchette et al., 2018; Habibi, 2018). After this, the previously solid African–Arabian continental margin did not exist as a unique domain any longer. At the same time, tectonic activity increased along the Sanandaj-Sirjan

Fig. 5. The contact between the undivided Sarvak and Ilam formations (1) and the Gurpi Formation (2) at locality 3

Fig. 6. Sequenceof shales and marls of the undivided Gurpi and Pabdeh formations at locality 4

structure and the Zagros domain started to evolve (Golonka, 2004; Kordi, 2019). A carbonate platform occupied vast territories on the Arabian Plate periphery (Golonka, 2004; Habibi, 2018), and this depositional environment was locally perturbed by intensified tectonic activity of the future Zagros. The Asmari Formation formed generally in a ramp setting (Habibi, 2016a, b; Habibi & Bover-Arnal, 2018). Various lithologies of the Gachsaran Formation reflect the Neogene history of this fold-and-thrust belt during active growth. The Gachsaran Formation is interpreted to have been deposited in coast-

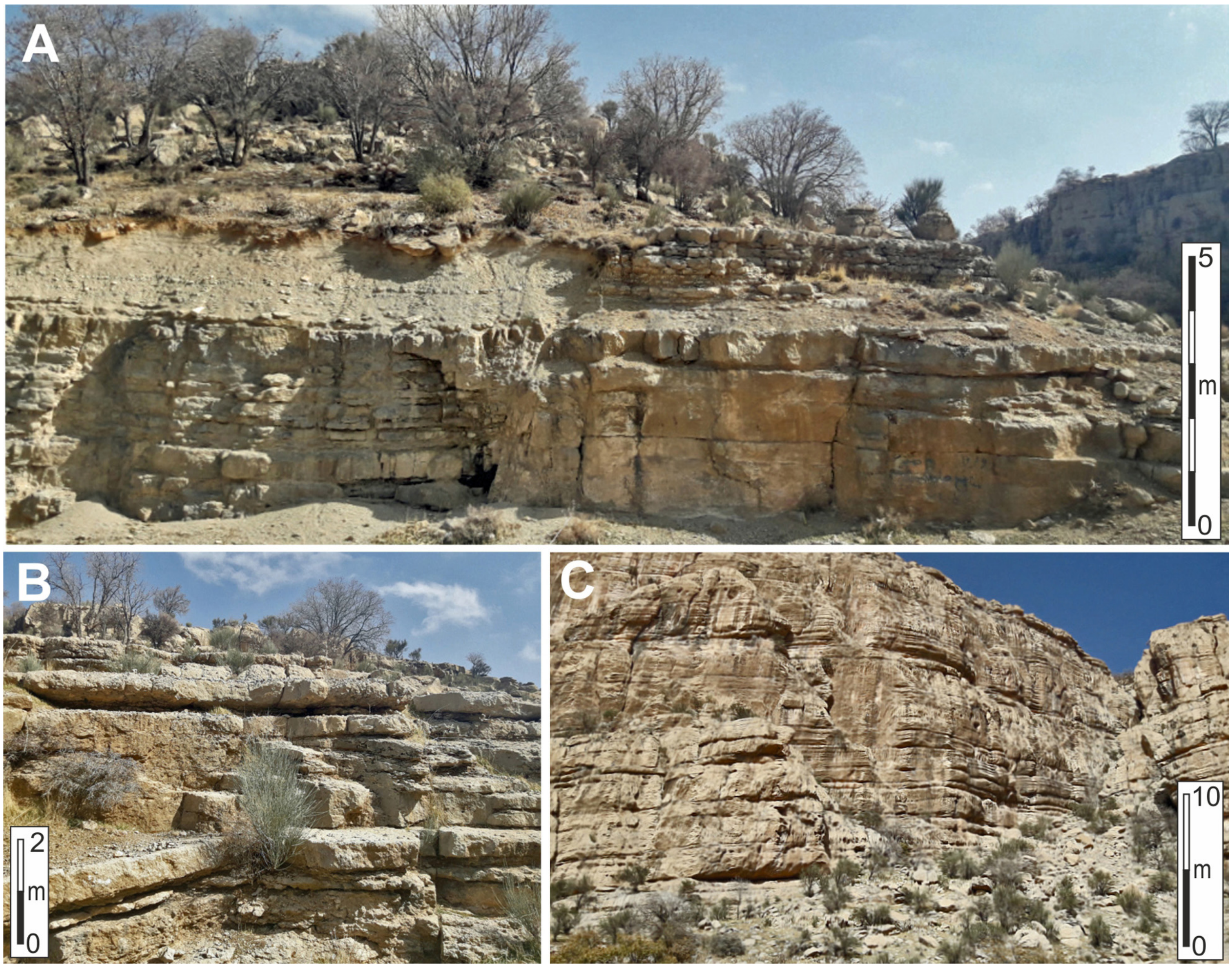

Fig. 7. Limestone sequences of the undivided Sarvak and Ilam formations
A, B – locality 1; **C –** locality 2.

Table 2. Affinity of the Nowdan anticline to the main phases in the late Mesozoic–Cenozoic evolution of the northeast African–Arabian continental marginv

Geological time slice	Affinity	Unit(s)	Dominant lithologies and thickness
Late Cretaceous	African (+Arabian) plate: Sanandaj-Sirjan terrane suturing along Arabia; subduction	Kazhdumi, Sarvak, Ilam and Gurpi fms.	shales and marls in the lower and upper parts, limestones in the middle part (~300 m)
Paleocene Eocene	African (+Arabian) plate: Sanandaj-Sirjan terrane joins Arabia	hiatus Pabdeh Fm.	shales and marls (~150 m)
Oligocene	Arabian plate separates from African plate; start of the Red Sea rifting	Asmari Fm. (lower part)	limestones (~50 m)
Miocene	Arabian plate: activization in the modern Zagros domain	Asmari (upper part) and Gachsaran fms.	limestones in the lower part and shales, marls and evaporites in the upper part (~150 m)

al sabkha, lagoonal and terrestrial environments (Bahroudi & Koyi, 2004). The Oligocene–Miocene rock units of the Nowdan anticline (Asmari and Gachsaran formations) illustrate the shift from the African–Arabian margin to only the Arabian margin, as well as the shift from a more or less stable margin to the orogen (Table 2).

5. Discussion

The sedimentary succession of the Nowdan anticline geosite registers all main stages in the evolution of the northeastern sector of the African–Arabian continental margin (Table 2). Thus, this geosite provides an exceptional opportunity (a 'window') to learn about the long-term geological history of an important sector of the planet. This history can be interpreted from the rock archives in a relatively small area with 10 representative sections. This opportunity implies that the palaeogeographical type of geological heritage of the Nowdan anticline is really valuable, with global relevance. Although other types have been documented for the same geosite (Habibi & Ruban, 2017; Habibi et al., 2017; Molchanova & Ruban, 2019), the palaeogeographical type appears to be dominant (*sensu* Ruban, 2010), i.e., the most important.

The established heritage value of the Nowdan geosite provides an insight into the classification of the palaeogeographical type of geological heritage. According to Bruno et al. (2014), palaeogeographical geosites may be subdivided into seven subtypes, namely facies, palaeoecosystem, ichnological, taphonomic, event/catastrophic, geoarchaeological and complex subtypes. However, it would be difficult to assign the Nowdan geosite to any of these types. Information on the late Mesozoic–Cenozoic history of the northeastern sector of the African–Arabian margin sheds light on the palaeogeographical configuration of major blocks and shifts in the affinity of particular domains. This is only partly relevant to the event subtype, which comprises geosites that illustrate particular events, not long-term processes.

Bruno et al. (2014) also provisionally suggested to recognise yet another subtype, which includes geosites that are important for palaeogeographical reconstructions for any given geological time slice. The Nowdan anticline geosite can be attributed to this subtype unequivocally. There are some other examples of geological heritage with unique palaeogeographical features that are similar to the Nowdan anticline, such as the Mountainous Adygeya geodiversity hotspot in the Western Caucasus (southwest Russia). Plyusnina et al. (2015) demonstrated that a series of geosites established in this area reflect the highlycomplex geological evolution of the Greater Caucasus and, particularly, changes in its affinity, namely first to the Gondwanan margin, then to the Galatian superterrane, the European Variscides, the Northern Neo-Tethyan periphery and finally to the modern Alpine belt. The geosites of the North Coast of São Paulo represent the Precambrian–Cenozoic history of western Gondwana, including supercontinent assembly and breakup (Garcia, 2012). Similarly sounding are ideas by Schneider & Schneider (2004) and Yoshida & Upreti (2013) about the creation of geoparks that represent the geological history of Gondwana; one of these potential geoparks has been proposed for Namibia.

Geological heritage that represents long-term, planet-scale palaeogeographical changes can be defined as thematic geological heritage (Plyusnina et al., 2015). However, such a definition appears to be too wide, and it is better to support the tentative idea of Bruno et al. (2014) of a palaeomapping subtype in addition to other subtypes of the palaeogeographical type. For instance, geosites that represent this subtype reflect the history of opening and closure of oceans, amalgamations/assemblies and destruction of continents, terrane motions and changes in their affinity to major blocks, etc. The Nowdan anticline in Iran seems to be a representative example of the palaeomapping subtype, which fact itself contributes to the high rank of this geosite. With regard to the growing interest of geotourism in Iran (Kamyabi, 2014; Shafiei et al., 2017; Pourahmad et al., 2018; Farsani et al., 2019; Khoshraftar & Torabi Farsani, 2019), the Nowdan geosite appears to be an important element of geotourism resources of the entire Zagros domain of the country.

6. Conclusions

The Nowdan anticline geosite of the Zagros orogen provides important data on the late Mesozoic–Cenozoic evolution of the northeastern sector of the African–Arabian continental margin. As many as ten localities of the anticline exhibit rock units that reflect different tectonic affinities of the study area. This information determines the high value of a palaeogeographical type of geological heritage of the Nowdan geosite and confirms the validity of the palaeomapping subtype.

Further studies should be aimed at finding other geosites of the palaeomapping subtype. For instance, these could represent the evolution of Precambrian landmasses (e.g., Kenorland and Rodinia) and Tethyan, Gondwana-derived terranes.

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