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Abstract: An important, 2.4 km-thick Triassic succession is exposed at Nakhlak (central Iran). This succession was deformed during the Cimmerian orogeny and truncated by an angular unconformity with undeformed Upper Cretaceous sediments. This integrated stratigraphic study of the Triassic included bed-by-bed sampling for ammonoids, conodonts and bivalves, as well as limestone and sandstone petrographic analyses. The Nakhlak Group succession consists of three formations: Alam (Olenekian–Anisian), Bāqoroq (?Upper Anisian–Ladinian) and Ashin (Upper Ladinian). The Alam Formation records several shifts from carbonate to siliciclastic deposition, the Bāqoroq Formation consists of continental conglomerates and the Ashin Formation documents the transition to deep-sea turbiditic sedimentation.

Petrographic composition has been studied for sandstones and conglomerates. Provenance analysis for Alam and most of the Ashin samples suggests a volcanic arc setting, whereas the samples from the Bāqoroq Formation are related to exhumation of a metamorphic basement. The provenance data, together with the great thickness, the sudden change of facies, the abundance of volcaniclastic supply, the relatively common occurrence of tuffitic layers and the orogenic calc-alkaline affinity of the volcanism, point to sedimentation along an active margin in a forearc setting.

A comparison between the Triassic of Nakhlak and the Triassic succession exposed in the erosional window of Aghdarband (Koppeh Dag, NE Iran) indicates that both were deposited along active margins. However, they do not show the same type of evolution. Nakhlak and Aghdarband have quite different ammonoid faunal affinities during the Early Triassic, but similar faunal composition from the Bithynian to Late Ladinian. These results argue against the location of Nakhlak close to Aghdarband.

Central Iran is geologically a very complex area, characterized by a tremendous variety of rock types ranging from Precambrian to Miocene sedimentary rocks, Palaeozoic–Cenozoic ultramafic–acid igneous rocks and Palaeozoic–Mesozoic metamorphic rocks. Such an astonishing geological diversity is related to a very long history that started with the assembly of Gondwana in early Palaeozoic times and continued to the present-day collision of the Arabian Plate with Eurasia.

The unravelling of this long and complex history is challenging. The understanding of the Cimmerian system (Sengör 1984) is especially difficult as the Carboniferous–Jurassic rocks were often deformed, eroded, covered and/or metamorphosed during more recent collisional events, and their boundaries were sometimes reactivated by more recent faults and thrusts. Despite many published contributions to the geology of Central Iran, no shared interpretation has emerged at the microplate and local scales.

For instance, there is no consensus on the proposal by Davoudzadeh *et al.* (1981) and Soffel *et al.* (1996) that the present-day Central Iran microplate has rotated by 135° counterclockwise since the Triassic. This model has usually been accepted (Davoudzadeh & Weber-Diefenbach 1987; Ruttner 1993; Alavi *et al.* 1997; Seyed-Emami 2003), but a

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test carried out by Wendt *et al.* (2005) on the basis of the palaeogeographical distribution of Palaeozoic facies actually failed to confirm the model.

At the local scale there are often different interpretations of the stratigraphic *v.* tectonic relationships of several sedimentary and metasedimentary units. For instance, in the key areas of Nakhlak and Anarak, very different pictures were provided not only for the complexly metamorphic Anarak Range (e.g. Sharkovski *et al.* 1984; Bagheri 2007; Bagheri & Stampfli 2008), but also for the nearby unmetamorphosed Nakhlak Range (e.g. Sharkovski *et al.* 1984; Alavi *et al.* 1997).

In order to clarify the general setting of Central Iran and its related Cimmerian history we selected the Nakhlak–Anarak area, which has been known since the 1970s (Davoudzadeh & Seyed-Emami 1972) for the contrast of its peculiar 2.4 km-thick mixed siliciclastic, volcaniclastic and carbonatic succession with the surrounding Triassic successions (i.e. Shotori Range, Tabas: Stöcklin *et al.* 1965; see Seyed-Emami 2003 for a comprehensive summary). Based on lithological similarity, several authors suggested a correlation between the Nakhlak Triassic and an almost coeval succession exposed at Aghdarband (Koppeh Dag, NE Iran). Moreover, this correlation was used to support the 135° counterclockwise rotation of Central Iran since the Triassic (Davoudzadeh *et al.* 1981). Despite its great significance it is worth noting that the geology and stratigraphy of the Nakhlak–Anarak area are not known in detail, as demonstrated by the rather different descriptions available in the literature (Davoudzadeh & Seyed Emami 1972; Sharkovski *et al.* 1984; Alavi *et al.* 1997; Vaziri 2001).

The area was visited by a team of stratigraphers, structural geologists, palaeontologists and palaeomagnetists in 2003 and 2004. Most of the stratigraphic data are presented here, while the geological, structural and the palaeomagnetic analyses are described in separate contributions (Muttoni *et al.* 2009; Zanchi *et al.* 2009).

The geology of the Nakhlak area: open questions

The small village of Nakhlak lies near an old, but still active, lead mine located in a small NW–SE-oriented range, the Kuh-e-Qal'eh Bozorg, about 60 km NNE of the town of Anarak (Yazd block) in central Iran (Fig. 1a, b). The range is about 13 km in length, and the maximum elevation is 1439 m a.s.l. (above sea level) (Fig. 2). From this site, Davoudzadeh & Seyed Emami (1969, 1972) described a very thick Triassic succession consisting of the Alam, Bāqoroq and Ashin formations (Nakhlak Group), which were referred to Early Triassic–Late Ladinian by Tozer (1972) on the basis of ammonoids and daonellids. The Triassic succession exposed in the southwestern and central sectors of the Kuh-e-Qal'eh Bozorg (in the following text simplified as the Nakhlak range) was thrusted southwards onto ophiolites (Holzer & Ghasemipour 1973) and truncated with an angular unconformity by shallow-water limestones of Late Cretaceous age.

Since its first description, the Nakhlak Group turned out to be totally different from the coeval successions of Central Iran (e.g. Shotori Range: Stöcklin *et al.* 1965) because of its great thickness, on the one hand, and its siliciclastic and volcaniclastic content, on the other. For these reasons the Triassic of Nakhlak was always taken into consideration by authors dealing with the Cimmerian history of Iran (Davoudzadeh *et al.* 1981; Ruttner 1993;

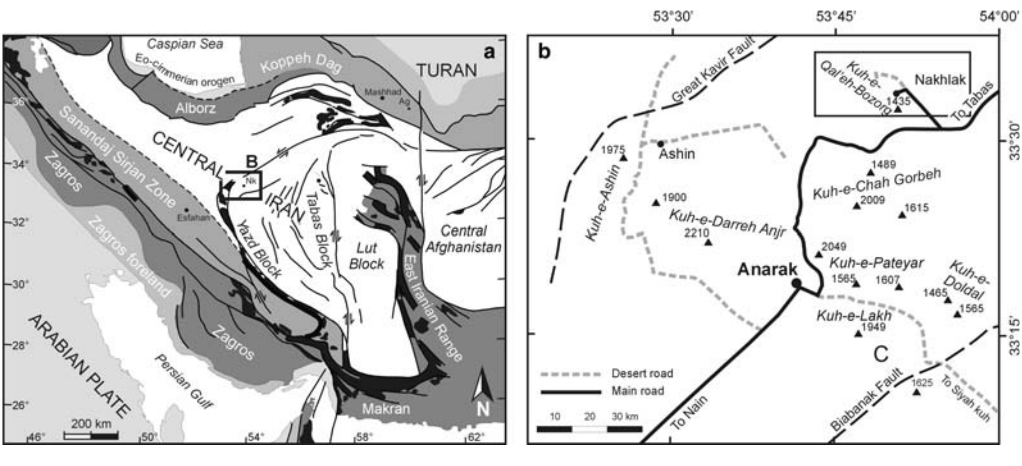

Fig. 1. Location maps of Nakhlak (central Iran). (**a**) Structural model of Iran, from Angiolini *et al.* (2007). (**b**) Road connections of the studied locality (co-ordinates system from GSI 1:250 000 geological map Anarak).

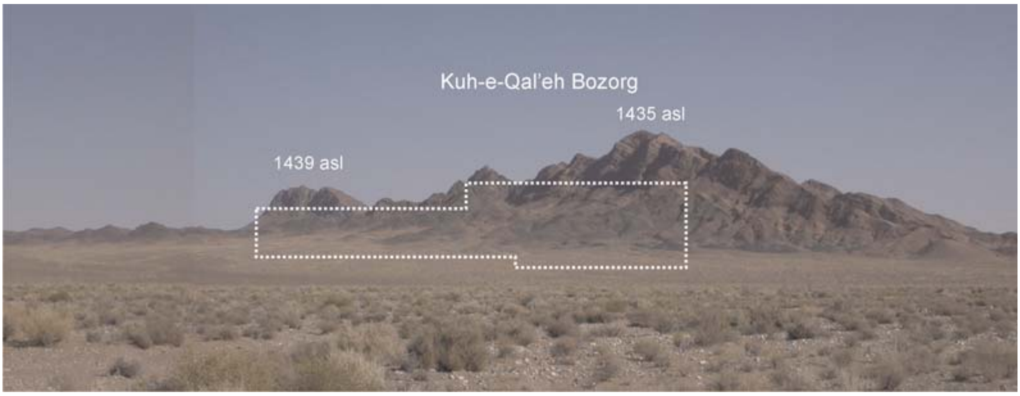

Fig. 2. Panoramic view of the Kuh-e-Qal'eh Bozorg from the SW. The range is divided into two steep cliffs consisting of sandstones and limestones of Late Cretaceous age. The maximum elevation of the northern and southern cliffs is respectively 1439 and 1435 m a.s.l. The Triassic succession is exposed on the very gentle hills in the foreground on the left and central part of the picture. Dotted line shows the studied areas.

Soffel *et al.* 1996; Alavi *et al.* 1997; Saidi *et al.* 1997; Seyed-Emami 2003). However, despite its great importance, the knowledge of the geology and stratigraphy of Nakhlak area has been based on relatively few data, probably because the area was visited very few times after 1972 (Sharkovski *et al.* 1984; Vaziri 1996, 2001; Alavi *et al.* 1997). The few authors who studied the geology and stratigraphy of Nakhlak reported only general information on the stratigraphic succession such as lithology, few elements of lithofacies and qualitative descriptions of conglomerates. No information on sandstone petrography was provided, and dating was based on macrofossils that were not collected bed-by-bed. Most surprisingly, the picture of the Nakhlak area to emerge from our work is notably different. Two main points differ from the literature. The first is the geological setting of the Nakhlak range and the second is the lithostratigraphy of the lower part of the Nakhlak Group, in particular of its oldest unit, the Alam Formation.

The geological setting of the Nakhlak range has been interpreted in three different ways (Fig. 3a–c). In their pioneering works, Davoudzadeh & Seyed-Emami (1969, 1972) interpreted the Nakhlak Group as a NE-dipping monocline truncated with angular unconformity by Cretaceous shallow-water limestones. Holzer & Ghasemipour (1973) and Sharkovski *et al.* (1984) recognized that the Triassic succession is thrusted onto ophiolites, and confirmed the angular unconformity between the Triassic succession and the Upper Cretaceous sediments. However, they illustrated a more complex setting of the Triassic succession (Fig. 3b), forming a NW–SE-oriented syncline. This reconstruction implies folding of the Triassic succession before the uplift and erosion of the Nakhlak Group between the Late Triassic and the Late Cretaceous (Sharkovski *et al.* 1984, p. 122), i.e. in Cimmerian times. This tectonic setting and the related history were not confirmed by Alavi *et al.* (1997). They detected thrust faults within the Triassic succession and between the Nakhlak Group, the Cretaceous and the Palaeocene units (Fig. 3c), documenting that the tectonic setting of the area is at least partially post-Cimmerian.

The second point of disagreement in the literature is the lithology of the lower part of the Nakhlak Group, i.e. of the Alam Formation. According to Davoudzadeh & Seyed-Emami (1972, fig. 4, pp. 10–14), the 873 m-thick Alam Formation consists of a wide variety of lithologies also containing some intervals dominated by limestones. In contrast, Alavi *et al.* (1997, fig. 3, p. 1568) described the 1350 m-thick Alam Formation as mostly consisting of volcanic sandstone lithologies with rare occurrence of detrital/shallow-water limestones.

Geological setting of the area

The structural setting of the Nakhlak Range is much more complex than reported in the literature. The description is provided by Zanchi *et al.* (2009), and here only the main features are summarized.

The entire Triassic succession is stacked on hornblende metagabbros and silicified ultramafics south of Nakhlak along a low-angle trending fault. These rocks were interpreted as ophiolites by Holzer & Ghasemipour (1973), Alavi *et al.* (1997) and Bagheri & Stampfli (2008).

The Triassic succession is strongly folded and faulted. Tectonic repetitions occur especially in the northern part of the area (see also Zanchi *et al.* 2009; Fig. 4), but all the structures are

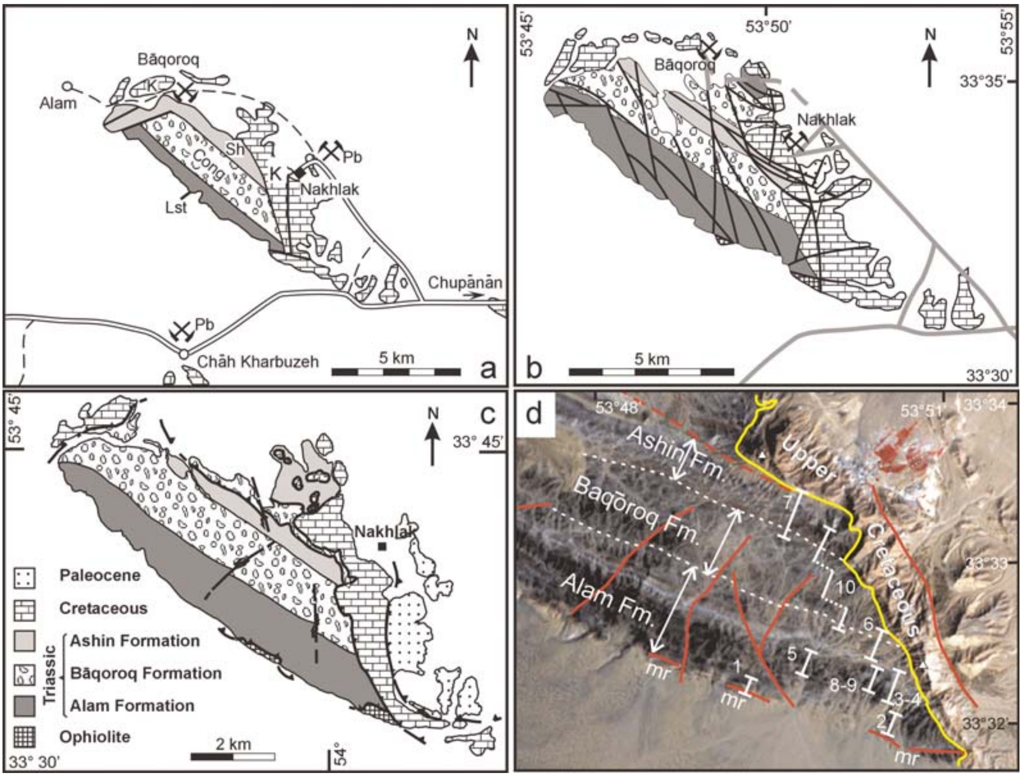

Fig. 3. The different interpretations of the geology of Nakhlak area. (**a**) Monocline truncated by the Cretaceous with angular unconformity (from Davoudzadeh & Seyed-Emami 1972). (**b**) Syncline of Triassic sediments covered with angular unconformity by the Upper Cretaceous (from Sharkovski *et al.* 1984). (**c**) Monocline overthrusted by three structural units (Alavi *et al.* 1997, fig. 1B; the co-ordinate system is probably different in to that (b)). (**d**) Satellite image (ASTER) of the Nakhlak area, with lithostratigraphic boundaries of Triassic units (white dashed line), angular unconformity (yellow line), major faults (red lines) and position of the studied stratigraphic sections (white line). See the text for an explanation on the lithostratigraphy of the Cretaceous succession.

unconformably covered by the Upper Cretaceous limestones that seal this complex deformation with a sharp erosional surface. The Upper Cretaceous and Palaeocene beds are also deformed, showing an asymmetric anticline developed along an important north–south strike-slip dextral fault. This fault is possibly related to the Neogene evolution of central Iran (Walker & Jackson 2004), but it is also of great interest for mining because lead mineralization (cerussite and galena) of the active Nakhlak mine are concentrated in veins along the fault zone (Holzer & Ghasemipour 1973). Minor strike-slip faults orthogonal to the pre-Cretaceous deformational structures also deform the Triassic succession.

The 'Upper Cretaceous' unit (Cenomanian–Turonian) was studied only by Holzer & Ghasemipour (1973) and, more recently, by Vaziri *et al.* (2005). This unit has never been formalized according to the rules of lithostratigraphic nomenclature, but it is mapped as a formation in the Geological Survey of Iran (GSI) 1:100 000 Nakhlak sheet and 1:250 000 Anarak sheet. The lower part of the Upper Cretaceous is transgressive and consists of some tens of metres of sandstones and hybrid arenites followed by shallow-water rudist-rich limestones. It was deposited with a spectacular angular unconformity on the deformed Triassic succession (Fig. 4). The lower boundary of the Upper Cretaceous is erosional and not tectonic, as reported by Alavi *et al.* (1997). The sedimentary nature of this boundary is also indicated by the occurrence of polimictic conglomerates in pockets (Fig. 4d, e). Some reverse faults can be locally detected in the lower part of the Upper Cretaceous unit, but often they reactivate the lithological boundary of the conglomerate in pockets and the overlying sandstones rather than the unconformity, i.e. the base of the conglomerates. In both examples the displacement is only of a few metres (see also Zanchi *et al.* 2009, fig. 6A, B).

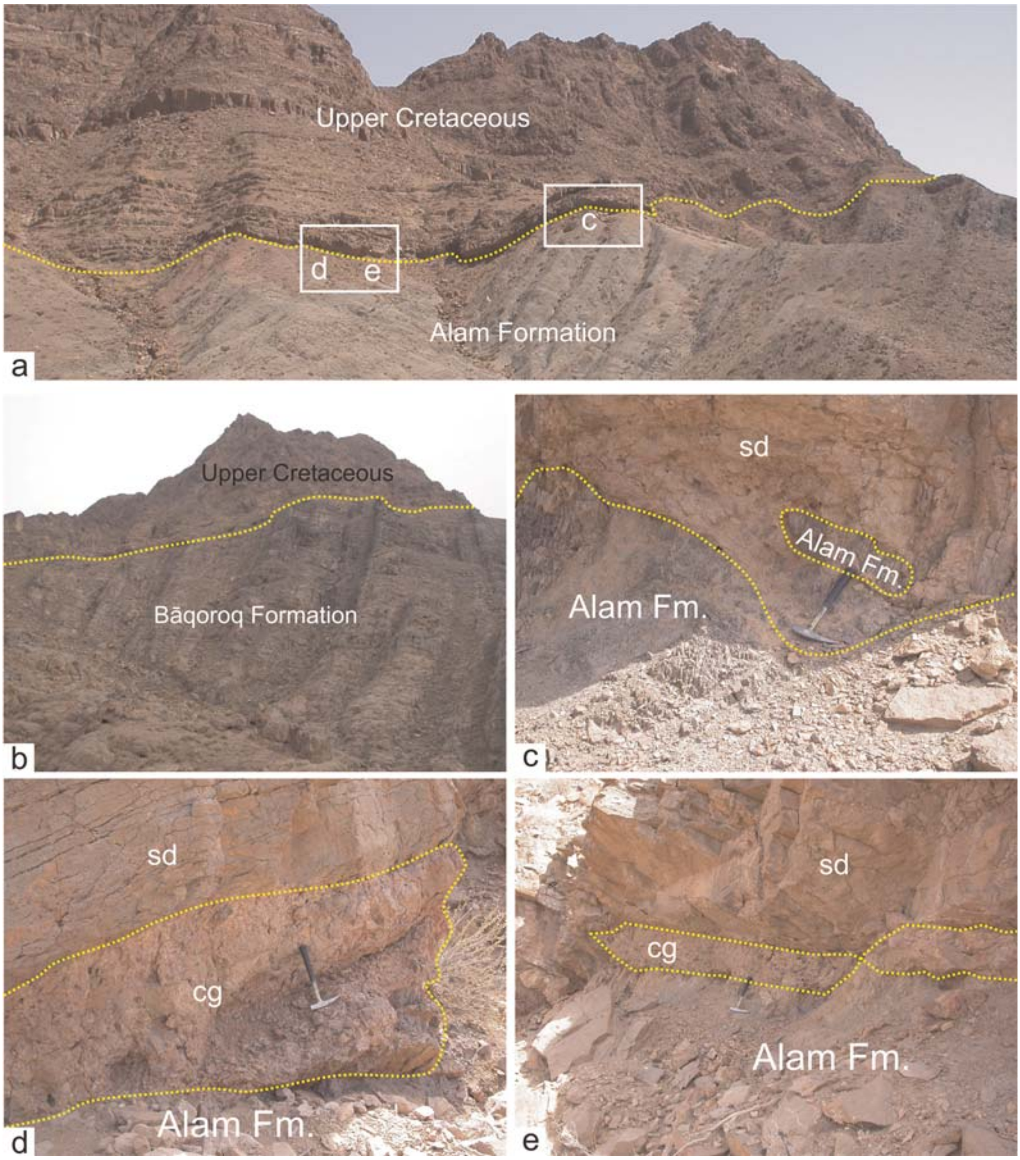

Fig. 4. General and detailed views of the angular unconformity between the Triassic succession and the Upper Cretaceous in the southern cliff of the Kuh-e-Qal'eh Bozorg. (**a**) General view of the angular unconformity between the Alam Formation and the Upper Cretaceous. (**b**) Angular unconformity between the Bāqoroq Formation and the overlying Upper Cretaceous. (**c**) Small boulder of shales from the Alam Formation included in a pocket at the base of the Upper Cretaceous sandstones. (**d**) Detail of the contact between the Alam Formation and the Upper Cretaceous. (**e**) Pockets of conglomerates at the base of the Upper Cretaceous sandstones. Acronyms: cg, conglomerate; sd, sandstone.

Stratigraphic sections and sampling

Owing to the gentle topography, the great stratigraphic thickness and the deformation, there is no single complete exposure of the Nakhlak Group. The composite section across the group (Figs 3d and 5) is based on nine stratigraphic sections that are correlated on the basis of distinct lithological markers.

In the studied part of the Nakhlak range, the total thickness of the Nakhlak Group is about 2400 m, and it is subdivided as follows (from bottom to top): Alam Formation (1150 m); Bāqoroq Formation

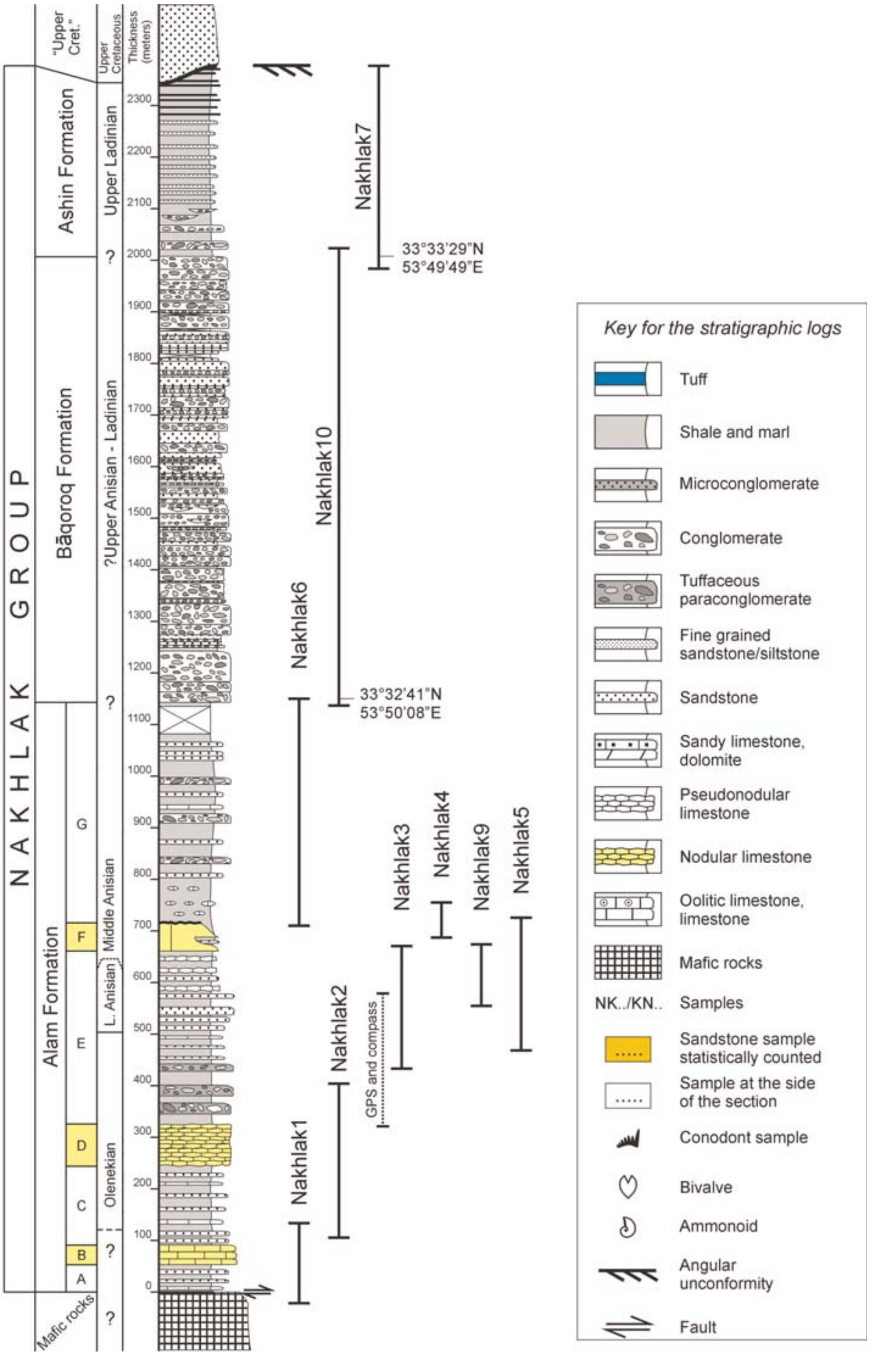

Fig. 5. Composite stratigraphic section of the Nakhlak Group, with the stratigraphic position of the studied sections. The GPS co-ordinates (WGS84 system) of sections Nakhlak 10 and 7 are shown. For the sections within the Alam Formation the co-ordinates are shown in the detailed logs. The stratigraphic position of the Nakhlak 3 section with respect to the base of member E is measured with GPS and compass. The members of the Alam Formation are labelled following the stratigraphic succession (A–G); the limestone members are emphasized in yellow. The approach to the lithostratigraphy of the Alam Formation is explained in the text. The legend is for all the stratigraphic sections.

(870 m); and Ashin Formation (>370 m). The stratigraphic sections were measured with great detail and sampled bed-by-bed for ammonoids, conodonts, bivalves, limestone and sandstone petrographic analyses, as well as for palaeomagnetic analyses. About 680 ammonoids were collected, but most of them are of too small a size or too fragmentary for a complete identification.

Conodonts were never previously reported from the Nakhlak Group; 49 samples were processed in this study and 12 samples (24%) yielded conodonts. The petrographic composition of conglomerate pebbles was recognized in the field and verified using thin sections. Sandstone petrography has been determined for the first time.

Stratigraphy of the Nakhlak Group

Alam Formation (Olenekian–Anisian)

This 1150 m-thick unit shows a very wide lithological composition comprising sandstones, tuffaceous sandstones, conglomerates, tuffaceous conglomerates, tuffs, siltstones, green, red and grey shales–marls, as well as a wide variety of limestones. However, the very wide variety of rocks is organized into lithologically distinct intervals. Davoudzadeh & Seyed-Emami (1972) proposed the subdivision of the Alam Formation into six members that were further subdivided into 13 intervals. This detailed subdivision does not fit very well with the stratigraphic succession observed in our study area, thus we amend Davoudzadeh & Seyed-Emami's lithostratigraphy and propose the subdivision of the formation into seven members (members A–G). The lack of toponyms in the study area prevents a complete formal definition of these members according to the rules of the International Stratigraphic Guide (Salvador 1994). However, we emphasize that the subdivision of the formation in members is justified because of the following reasons:

- the Alam Formation is very thick and covers an interval of at least 6 Ma between the Olenekian

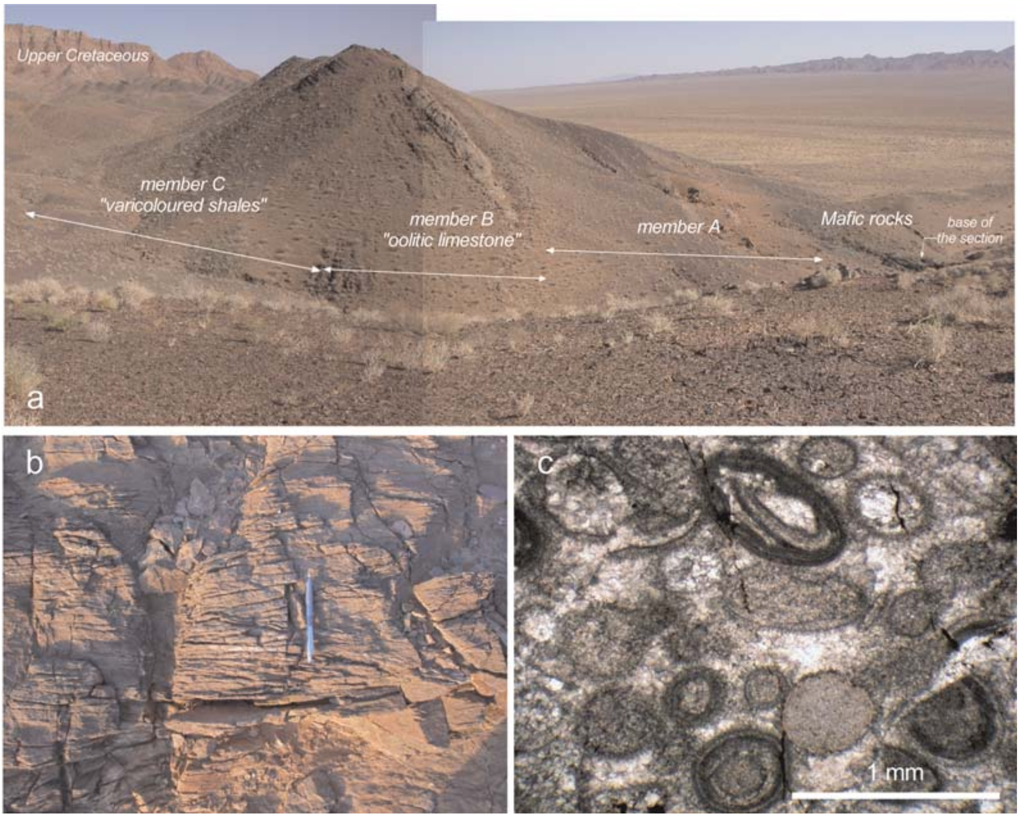

Fig. 6. (**a**) General view of the lower part of the Alam Formation at Nakhlak 1 section. (**b**) and (**c**) Details of member B 'oolitic limestone'. (**b**) Oolitic grainstones with cross-bedding (south of section Nakhlak 2); the scale is 14 cm. (**c**). Oolitic grainstone with bioclasts of echinoderms, also as ooids' core, gastropods and brachiopods; some ooids have slightly micritized rim (sample KN121, south of section Nakhlak 2).

and the Anisian (radioisotopic data from ammonoid-controlled section from south China: Ovtcharova *et al.* 2006; Galfetti *et al.* 2007). The subdivision in members is worthwhile from the point of view of the description of the succession;

- several palaeoenvironments are documented in the Alam Formation, thus the subdivision into members is useful;
- the members have a distinct stratigraphic position within the Alam Formation;
- five members show such a typical lithology that they can be recognized in the field even in small outcrops. The remaining three members can be recognized on the basis of the combination of lithology and stratigraphic position with respect to the other members.

Member A (?lower Olenekian). The lower boundary of the Alam Formation is tectonic, as already described by Sharkovski *et al.* (1984) and Alavi *et al.* (1997). The lowest part of the Alam Formation is usually not very well exposed. The best outcrop in the studied part of the Nakhlak Range is shown in Figure 6a, and the log in Figure 7.

Member A consists of 18 m of brownish siltstones and dolomites, overlain by 35 m of dark brown siltstones, volcanic sandstones and shales. The unit is probably equivalent to intervals 1 and 2 of member 1 of Davoudzadeh & Seyed-Emami (1972).

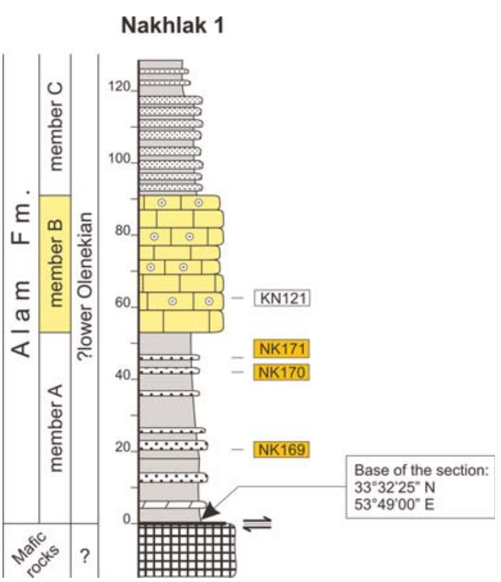

Fig. 7. The lower part of the Alam Formation at Nakhlak 1 section, where the succession of members A to C is exposed. Sample KN121 is from an outcrop some tens of metres south of the base of the Nakhlak 2 section.

The unit does not yield any fossils and the early Olenekian age is suggested on the basis of its stratigraphic position.

Member B 'oolitic limestone' (?lower Olenekian). This member is a very distinct lithological marker that can be recognized within the lower part of Alam Formation, and is probably equivalent to interval 3 of member 1 of Davoudzadeh & Seyed-Emami (1972).

Member B is up to 38 m thick and is a little better exposed than is member A. In the study area it crops out at the Nakhlak 1 section (Figs 6a and 7) and south of the Nakhlak 2 section. The lithology consists of oolitic bioclastic grainstones forming 80 cm–2 m-thick beds with planar bedding, planar lamination and cross-bedding (Fig. 6b, c). The boundaries are sharp, and can be traced on the first and on the last occurrences of oolitic grainstones.

The member does not yield any well-preserved fossils; the possibly early Olenekian age is supposed on the basis of its stratigraphic position.

Member C 'varicoloured shales' (middle–upper Olenekian). Member B is conformably overlain by another lithological marker, member C, consisting of an approximately 30 m-thick sandstone-dominated lower part and an up to 127 m-thick green–red/purple shale-dominated upper part with relatively common ammonoids. This lithological marker can be easily followed for at least 2 km along strike, i.e. through all of the studied part of the Nakhlak range. This unit had already been recognized by Davoudzadeh & Seyed-Emami (1972, p. 14: interval 4 of the member 2), and is exposed along the Nakhlak 1 and Nakhlak 2 sections (Fig. 8).

Boundaries. The lower boundary is rather sharp and is drawn at the top of the uppermost limestone of member B at the Nakhlak 1 section. The upper boundary is drawn at the base of the first red nodular limestone bed of member D at the Nakhlak 2 section.

Lithofacies. Member C is divided into a lower part dominated by sandstones and an upper part dominated by shales.

The lower part is documented at both the Nakhlak 1 and the Nakhlak 2 sections (Figs 7, 8 and 9a). At the Nakhlak 1 section it is 27 m thick, whereas at the Nakhlak 2 section it is at least 30 m thick. The lithology consists of alternations of green volcaniclastic sandstones and hybrid arenites with green shales. Thickness of the sandstone–hybrid arenite beds is from 15 cm to about 1 m. Shales usually occur in thinner interbeds and the sandstone–shale ratio is from 2:1 to 4:1 (Fig. 9a). The sedimentary structures are normal grading, planar and more rarely cross-laminations.

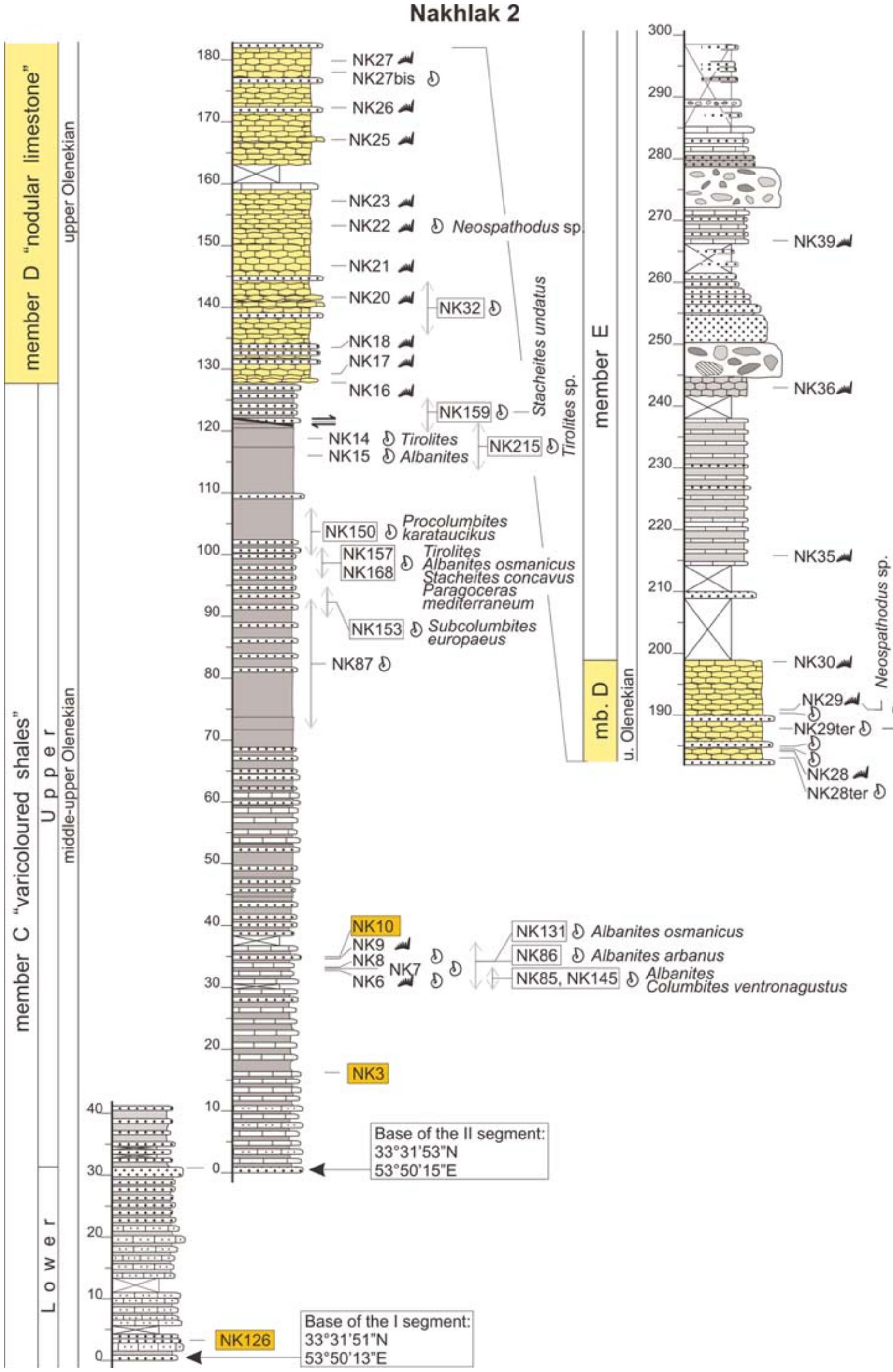

Fig. 8. Nakhlak 2 section. The section consists of two segments that are correlated by the boundary between the lower and upper part of member C. This boundary is sharp, thus it is easy to detect in the field (see also Fig. 9a). The first segment is exposed on the right-hand side of a small valley. At the top of the segment the valley is divided into two branches. The second segment of the section is measured on the right-hand side of the east branch.

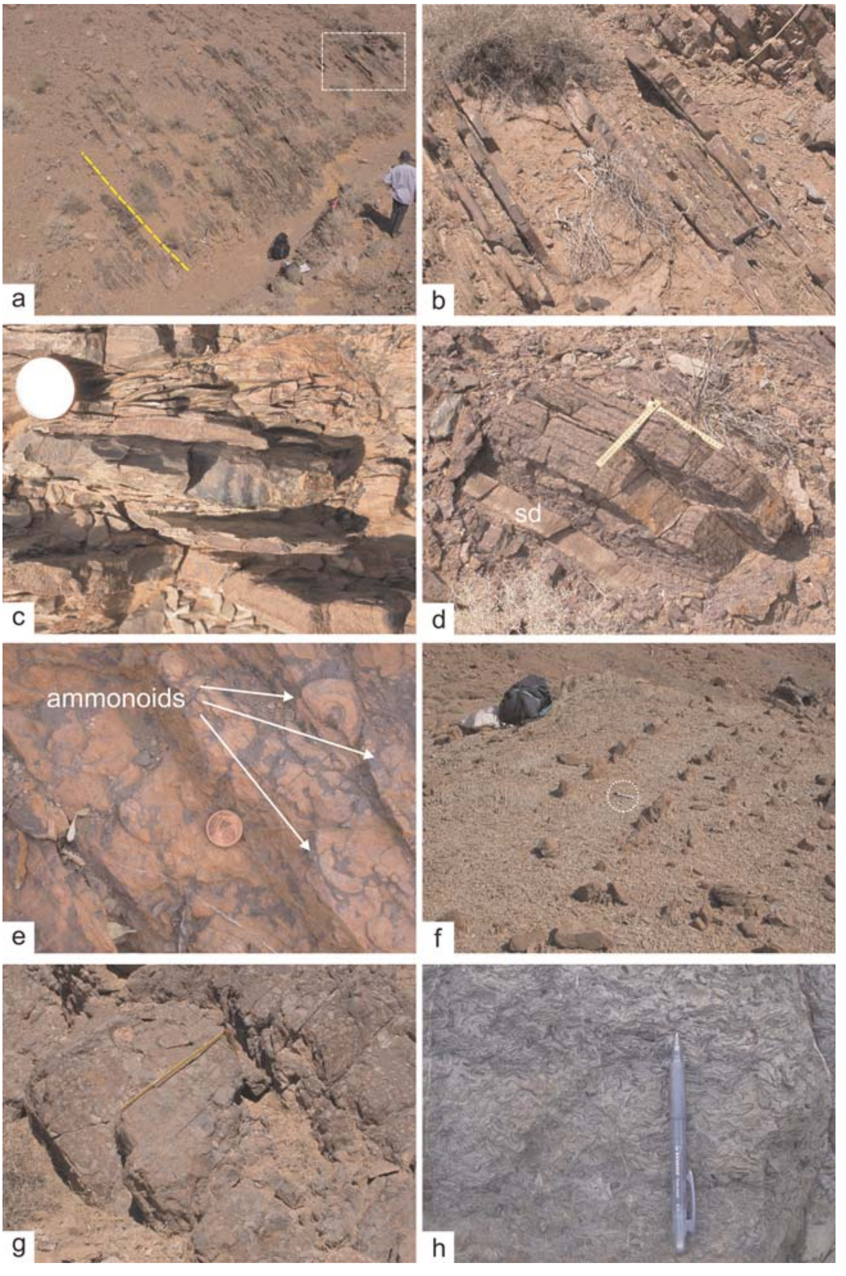

Fig. 9. Lithofacies of the Alam Formation. (**a**) The boundary between the lower and upper part of member C (Nakhlak 2 section, I segment). (**b**) Shales with thin-bedded limestones and sandstones of the upper part of member C (Nakhlak 2 section, position shown in (a)); the scale is 100 cm. (**c**) Ammonoid *Albanites osmanicus* from member C (Nakhlak 2 section, sample NK136); the scale is 20 mm. (**d**) Outcrop view of member D (Nakhlak 2 section, interval between samples NK26 and NK27) showing the typical thin layering of nodular limestone, here with a thin sandstone bed (sd); the scale is 20 cm. (**e**) nodular ammonoid-bearing limestones of member D 'nodular limestone' (Nakhlak 2 section, sample NK32); the scale is 15 mm. (**f**) basal part of member G (Nakhlak 4 section); the scale (felt-tip) is 14 cm. (**g**) member G 'grey shales': detail of the conglomerates (Nakhlak 6 section, sample AL1); the scale is 60 cm. (**h**) member G: close-up view of a bivalve-bearing marly limestone (Nakhlak 6 section, sample NK190); the scale is 14 cm.

The upper part is documented at the Nakhlak 2 section. The lithology consists of an alternation of green or red/purple shales–very-fine-grained siltstones and of very-thin-bedded limestones and sandstones (sandstone–limestone/shale ratio 1:2–1:5) (Fig. 9a, b). The average thickness of the shale intervals is from 40 to 60 cm, whereas the sandstones are 3–14 cm thick (maximum 30 cm). The shales–siltstones are organized into reddish/purplish or green intervals from 40 cm to several meters thick. The upper 22–24 m of the member show a uniform green colour.

Fossils and age. The upper part of this member is well known from the literature (Davoudzadeh & Seyed-Emami 1972; Tozer 1972) as ammonoid bearing, but actually the ammonoids are quite rare. Most of them were collected following the beds along strike or from lateral outcrops correlated to the Nakhlak 2 section. A selection of the most significant ammonoid samples is shown in Figure 8. Two conodont samples were taken from the lower part of the member, but they were barren.

The ammonoids can be found directly interbedded within the shales (Fig. 9c) or on the surface of the beds. The first type of preservation mostly leads to incomplete specimens, consisting of a body chamber with only part of the phragmocone, while the specimens preserved on the bed surface are more complete, but difficult to extract from the matrix.

The taxonomic analysis of the new collection confirms the faunal list provided by Tozer (1972), with the only exception of *Procolumbites karataucikus* Astakhova (Fig. 10b). This species is identified for the first time at Nakhalk, but a specimen conspecific with this taxon had already been collected by Tozer, even if it was attributed to *Paragoceras mediterraneum* (Arthaber) (Tozer 1972, plate 1, fig. 2a, b). The bed-by-bed collection allows the first recognition of the distribution of the taxa within member C. Two main points can be emphasized. The first is that the ammonoids were found through all of the upper part of member C (Figs 8 and 10). The second is that there is not a single fauna in this interval, as some of the genera are confined to the lower, middle or upper part of the interval. The ammonoid assemblages (Fig. 10) are dominated by *Albanites* (*A. arbanus* [Arthaber] and *A. osmanicus* [Arthaber]), which represents more than 50% of the collected specimens. In decreasing order of frequency, the second group of ammonoids are the Columbitidae, represented by *Columbites*, *Subcolumbites* and *Procolumbites* in stratigraphic order. *Tirolites* is documented only in the upper part of the member, together with *Procolumbites* and the long-ranging *Stacheites (S. undatus* [Astakhova] and *S. concavus* Shevyrev).

Columbitidae and *Tirolites* allow the chronostratigraphic attribution of member C to the mid-Olenekian (early–mid-Spathian *sensu* Tozer 1981; late early Spathian *sensu* Ovtcharova *et al.* 2006 and Galfetti *et al.* 2007). More accurate attribution is difficult because, at present, there is not one global ammonoid scale for the Olenekian stage, but some regional scales consisting of informal subdivisions (beds) not yet fully described and formalized according to the rules of the International Stratigraphic Guide (Salvador 1994). Following Tozer's (1981) ammonoid scale the fossiliferous interval can be assigned to the *Columbites* and *Subcolumbites* beds, while following the scale recently outlined in south China (Ovtcharova *et al.* 2006; Galfetti *et al.* 2007) it can be correlated with the *Tirolites/Columbites* and the *Procolumbites* beds. It is worthwhile to note that while in member C the range of *Tirolites* overlaps the range of *Procolumbites*, this overlap does not seem to be documented in China.

The fauna of member C is also coeval with the ammonoid fauna of Mangyshlak (Shevyrev 1968; Balini *et al.* 2000). However, the ammonoid assemblages of member C are much more similar to the Tethyan fauna of Kçira in Albania (Arthaber 1908, 1911; Germani 1997) and Chios (Renz & Renz 1948; Mertmann & Jacobshagen 2003) than to the fauna of Mangyshlak.

Member D 'nodular limestone' (upper Olenekian). Member C is conformably overlain by a very typical unit (member D) consisting of very-thin-bedded pink nodular limestones with ammonoids, and rare thin-bedded sandstone intercalations with a thickness of about 80 m. This member can be followed along strike in the studied area of the Nakhlak range, but it is also documented in the northern part (north of elevation 1439 m). This member is equivalent to unit 5 of member 2 described by Davoudzadeh & Seyed-Emami (1972), but it was not recognized by Alavi *et al.* (1997). The member is best exposed at the Nakhlak 2 section (Fig. 8).

Boundaries. The lower boundary is traced at the base of the first red nodular limestone layer. The upper boundary is located on the top of the last red nodular limestone bed.

Lithofacies. The lithology is quite monotonous and consists of thin-bedded nodular limestones in beds from 1 to 3–5 cm thick, sometimes amalgamated into 20–30 cm-thick beds (Fig. 9d, e). Nodules are light pink (yellow weathering) and very small (5–10 mm). They are bounded by red–purple abundant shales/shaly marls. Some 3–10 cm-thick graded sandstone beds also occur (Fig. 9d).

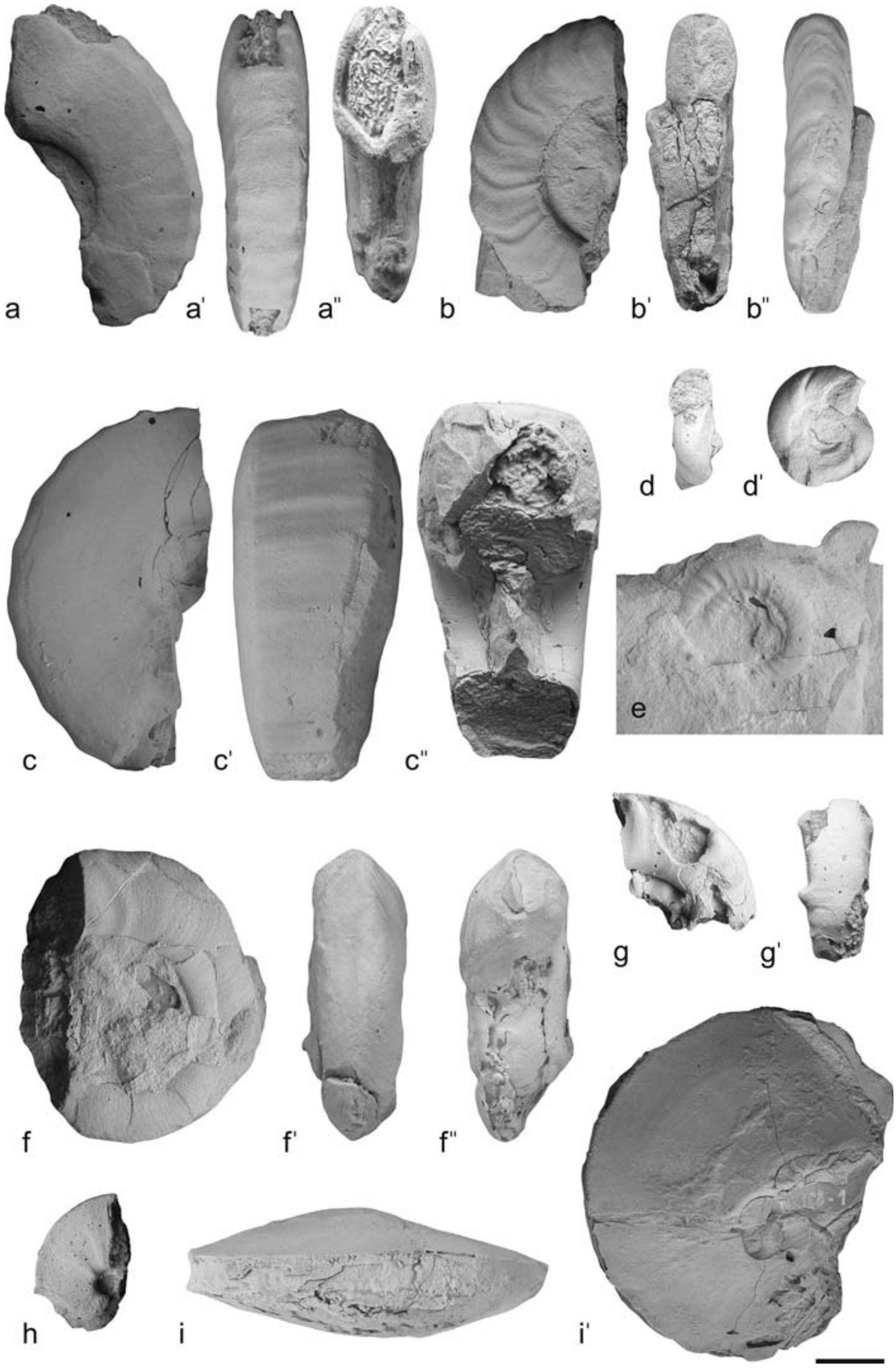

Fig. 10. Olenekian ammonoids from member C 'varicoloured shales'. *Albanites arbanus* (Arthaber), NK86-2 (MPUM 9831) (**a**) lateral view, (**a′**) ventral view and (**a″**) section. *Procolumbites karataucikus* Astakhova, NK150-1 (MPUM 9832) (**b**) lateral view, (**b′**) section and (**b″**) ventral view. *Albanites osmanicus* (Arthaber), NK157-15 (MPUM 9833) (**c**) lateral view, (**c′**) ventral view and (**c″**) section. *Paragoceras mediterraneum* (Arthaber), NK157-12 (MPUM 9834) (**d**) section and (**d′**) lateral view. (**e**) *Columbites ventroangustus* Shevyrev, NK145-1 (MPUM 9835), lateral view.

Fossils and age. Ammonoids occur frequently (Figs 8 and 9e), especially in the upper half of the member. However, the very small size (diameter about 15 mm, rarely up to 25 mm), together with the preservation of their tests, often prevents complete classification. The ammonoid assemblages are dominated by leiostraca, long-ranging ammonoids typical of the red nodular 'Ammonitico Rosso'-like limestones. In this case *Procarnites* and *Isculitoides* are the most common genera. *Dagnoceras* sp. indet. has also been identified in sample NK29ter. *Isculitoides* and *Dagnoceras* are typical of the Spathian, but their range is not yet well calibrated. Taking into account also the age of the underlying member C, a late Olenekian age can be suggested for member D. The assignment to the Olenekian is also confirmed by the occurrence of the Olenekian conodont *Neospathodus homeri* (Bender) in sample NK22.

Member E (upper Olenekian–lower Bithynian). Member E is about 330 m thick and shows a rather wide lithofacies variability both along and across strike. The interval is equivalent to member 3 of Davoudzadeh & Seyed-Emami (1972). In all the studied sections the lower part of the member is not well exposed. The thickness of the member has been estimated by GPS and compass measurements of the stratigraphic position of the Nakhlak 3 section with respect to the base of the member (Figs 5 and 11).

Boundaries. The lower boundary of member E is drawn at the top of the last red nodular limestone bed of member D. In the central part of the study area member E is conformably covered by member F. In the eastern part of the study area, member F interfingers with the upper part of member E. The latter is covered by member G and the boundary is traced at the top of the last planar limestone bed.

Lithofacies and fossils. Member E is dominated by siliciclastic and volcaniclastic sediments with rare limestones in the lower part (the Nakhlak 2 section: Fig. 8). Limestones become gradually more frequent in the upper part (the Nakhlak 3 section: Fig. 11). From east to west, i.e. from the Nakhlak 2 and 3 sections to the Nakhlak 5 section (Fig. 12), the succession becomes more siliciclastic, with a strong reduction in the carbonates. The following description of the succession is mostly based on the Nakhlak 2 and 3 sections. The distribution of fossils is described together with the lithofacies because it is strictly connected with the distribution of the limestone intervals.

In the lower part of the member there are paraconglomerate beds with erosional bases ranging from 3 to 5 m thick. They yield blocks with low roundness and sphericity, and with an average maximum size of between 10 and 30 cm (cobbles), but sometimes up to 1 m (boulders), within a tuffaceous sandy matrix. The cobbles and boulders consist of grey–green sandstones, limestones and pink nodular limestones, which can be referred to members E, D 'nodular limestone' and, possibly, the basal part of member C of the Alam Formation.

The middle part of the member (lower part of the Nakhlak 3 section: Fig. 11) consists of dark grey–green, black weathered volcaniclastic sandstones, often organized in thickening- and coarsening-upwards cycles (Fig. 13). The limestones are rare in this part (NK45–NK47; NK48; NK50; NK53bis-53) and consist of thin-bedded light-brown–light-green bioclastic mudstones with rare ammonoid cross-sections. Samples NK402 and NK48 (Fig. 14a–e) provided conodonts *Neospathodus homeri* (Bender) and *N. gondolelloides* (Bender), which are Olenekian in age. *Chiosella timorensis* (Nogami), marker of the Olenekian–Anisian boundary has been identified in sample NK53 together with *Neogondolella regale* (Mosher), *Ng.* sp. A (Fig. 14f-g), occurring also in sample NK53bis and the ammonoid *Leiophyllites* sp.

The upper part of the member (Nakhlak 3 and Nakhlak 9 sections: Fig. 11) is characterized by an increase in wavy- (pseudonodular) to planar-bedded bioclastic packstones with crinoids, brachiopods, gastropods and rare volcanic quartz (samples NK55–NK68) (KN61–KN74 at Nakhlak 9). Sometimes the bivalves *Plagiostoma* cf. *striatum* and *Neoschizodus* sp. (sample NK431 and NK433, Fig. 15) also occur. The uppermost part of the member consists of wackestones with filaments, some crinoids and brachiopods (from sample NK72bis to NK75 at Nakhlak 3; sample KN82 at Nakhlak 9). Two Anisian conodont assemblages have been identified (Fig. 11). Sample NK63 yielded *Neogondolella* cf. *regale* and transitional *Ng. regale-Paragondolella bulgarica*. The second fauna is documented in

Fig. 10. (*Continued*) *Subcolumbites europaeus* (Arthaber), NK153-10 (MPUM 9836) (**f**) lateral view, (**f′**) ventral view and (**f″**) section. *Tirolites* sp., NK215-12 (MPUM 9837) (**g**) lateral view and (**g′**) ventral view. (**h**) *Stacheites undatus* (Astakhova), NK159-21 (MPUM 9838), lateral view. *Stacheites concavus* Shevyrev, NK168-1 (MPUM 9839) (**i**) ventral view and (**i′**) lateral view. All the specimens are housed at the Museo di Paleontologia, Dipartimento di Scienze della Terra, Milano University; the inventory number is shown in brackets. All the specimens are whitened with ammonium chloride. The scale bar for all specimens is 1 cm.

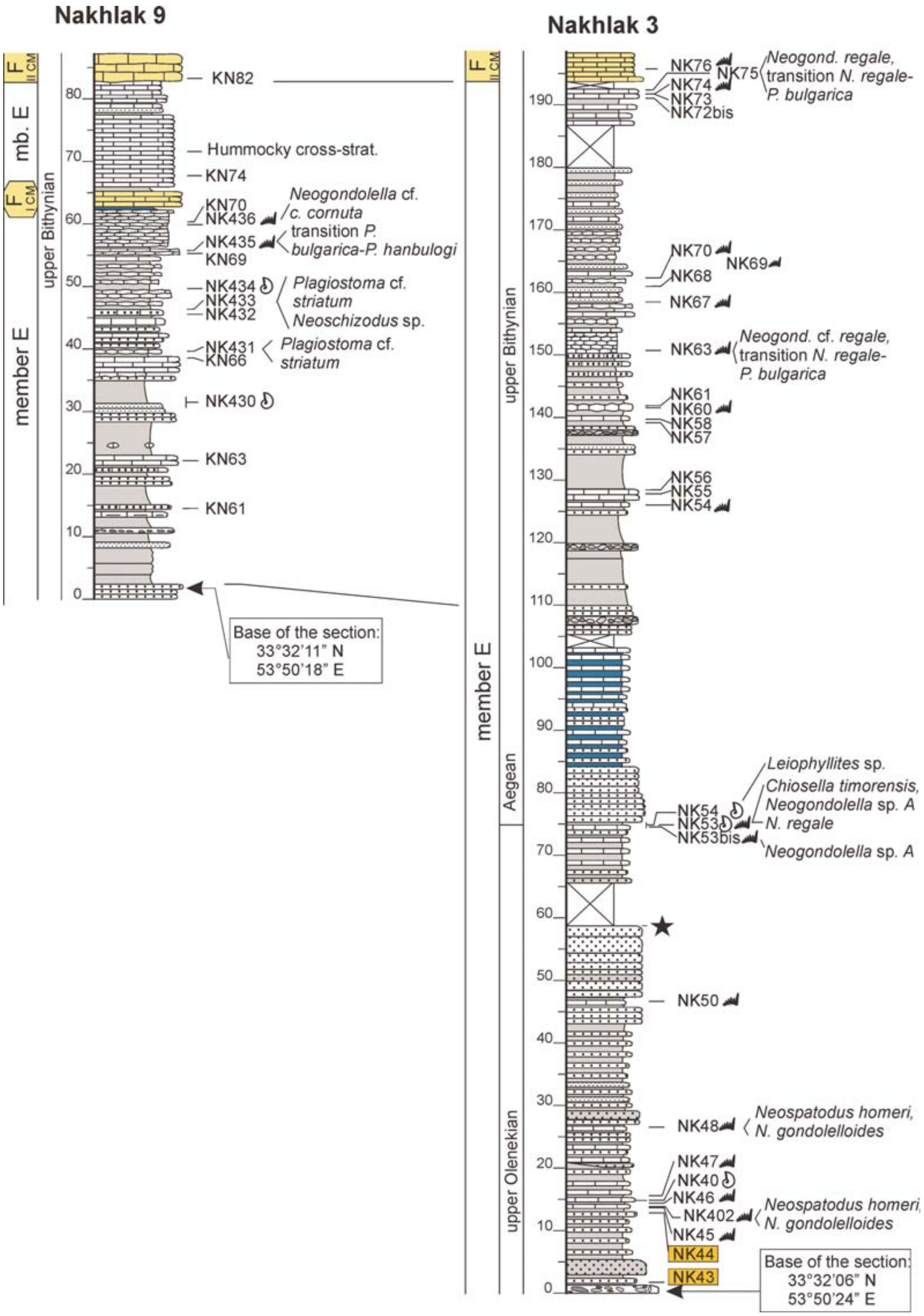

Fig. 11. Stratigraphic logs of sections Nakhlak 3 and 9 showing the upper part of member E and the basal part of member F. The position of the two sections is shown in Figures 13b, 16a and 17. The black star shows the marker level that has been used to calibrate with GPS and compass the Nakhlak 3 section with respect to the top of member D.

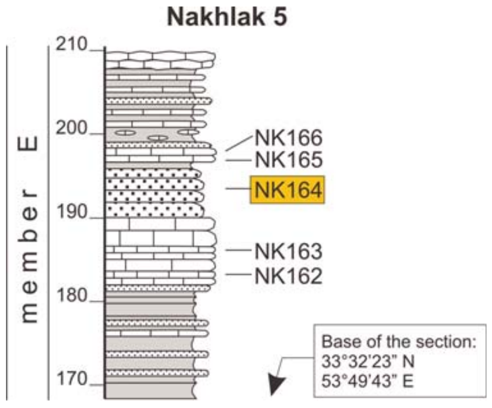

Fig. 12. Upper part of the Nakhlak 5 section. The section is 250 m thick and consists of a monotonous succession of sandstones that are exposed on the right-hand side of a wide valley located in the western part of the study area (see Figs 2 and 3d). Here only the upper part is shown. The three limestone intervals are coeval with member F. The age of this part of the section is Bithynian on the basis of lithological correlations with the Nakhlak 3, 4 and 9 sections.

sample NK435 and consists of transitional forms *P. bulgarica–P. hanbulogi* while NK436 consists of *Ng.* cf. *constricta cornuta*. Both faunas can be attributed to the late Bithynian.

The uppermost part of member E includes the basinal facies coeval with member F 'carbonate mounds' (Nakhlak 9 and 3 sections: Fig. 16a; Nakhlak 4 section: Fig. 17). Lithology is dominated by an alternation of grey–light green shales–marls with ammonoid-bearing bioclastic mudstones. Sample NK77 yielded the Bithynian ammonoids *Aghdarbandites ismidicus* (Arthaber) (Fig. 18a) and *Nicomedites*, together with the conodonts *Neogondolella regale* (Mosher), *P. bulgarica* (Budurov & Stefanov) and transitional *N. regale–N. constricta cornuta. Acrochordiceras* was found in sample NK106 and *Kocaelia toulai* (Arthaber) occurs in sample NK452 (Fig. 18b). The brachiopod *Tetractinella* is also rather common.

Age. The late Olenekian–late Bithynian age of member E is well defined by the integration of ammonoid and conodont data. The lowest fossiliferous interval (NK402 and NK48) is late Olenekian in age. The occurrence of *Chiosella timorensis* (Nogami) in sample NK53 marks the base of the Aegean, while the *Aghdarbandites ismidicus* Zone (late Bithynian) is documented by its index fossil, as well as by *Kocaelia toulai* (Arthaber), which is an additional marker of this zone (Fantini Sestini 1988, 1990).

Member F 'carbonate mounds' (Bithynian). Member F consists of at least two coalescent carbonate bodies (Fig. 16) that reach a maximum thickness of about 50 m and have a present-day lateral length of about 500 m. This rock body had already been mapped as a distinct unit by Holzer & Ghasemipour (1973). It is equivalent to part of Davoudzadeh & Seyed-Emami's (1972) member 4, and it was also recognized by Alavi *et al.* (1997).

Boundaries. The upper part of the underlying member E shows an increasing amount of carbonate debris (mainly skeletal), but makes a sharp boundary with the bottom of member F. Member F interfingers with member E and is capped by the member G. The upper boundary is sharp, and the flat top of the mound is characterized by abundant ammonoids and crinoids.

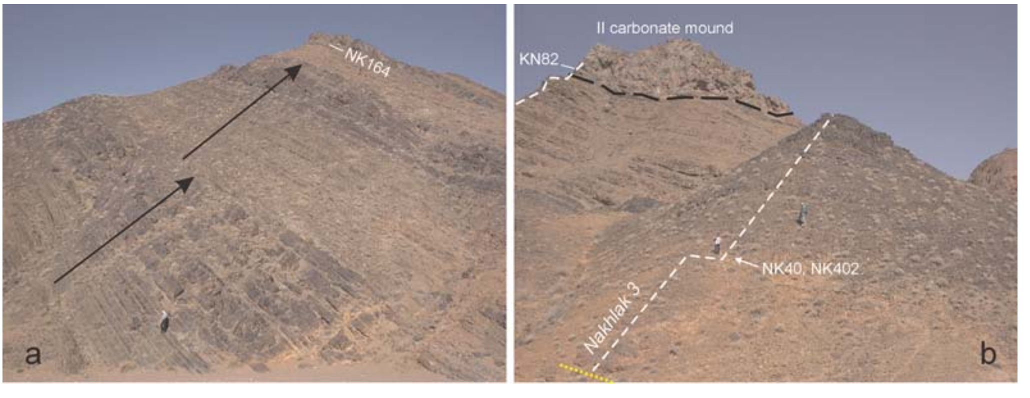

Fig. 13. Outcrop views of the upper part of member E. (**a**) Coarsening- and thickening-upwards cycles in the upper part of the Nakhlak 5 section. The beds on top of the slope are the limestone interval with samples NK162 and NK163 (see Fig. 12). (**b**) Lower part of the Nakhlak 3 section: the dashed line shows the trace of the section, the dotted line marks the base of the conglomerates at the base of the section; in the background is the II carbonate mound of member F 'carbonate mounds' and the upper part of the Nakhlak 9 section.

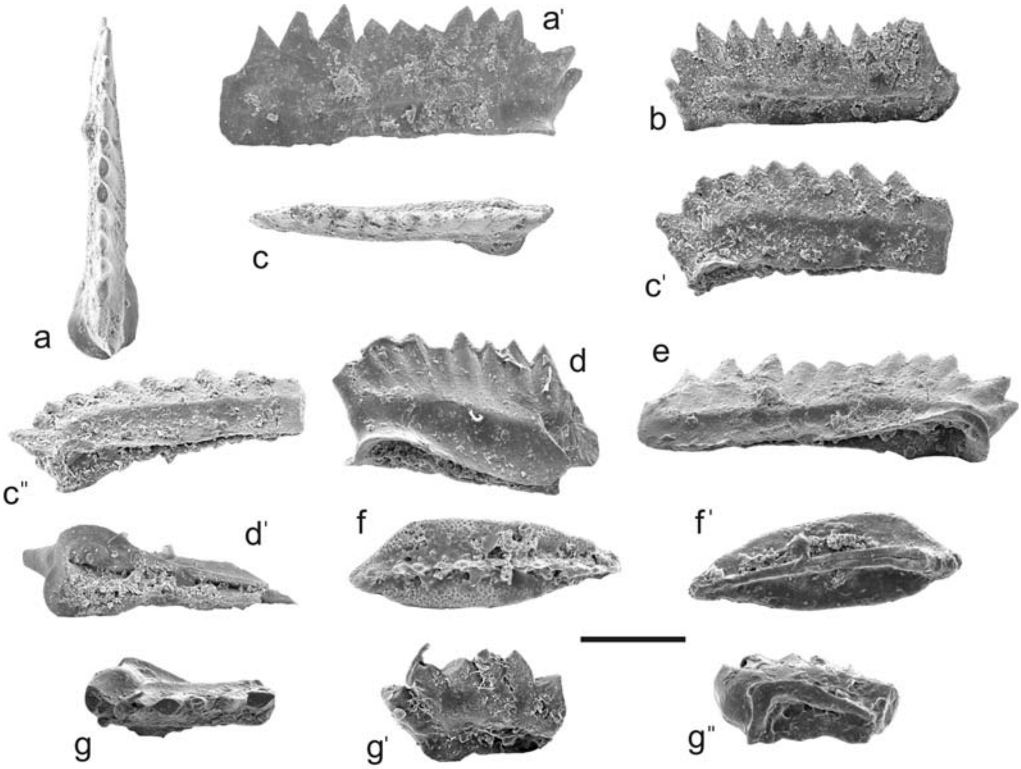

Fig. 14. Conodonts from the Alam Formation. *Neospathodus gondolelloides* (Bender), NK48 (**a**) upper view and (**a′**) lateral view. (**b**) *Neospathodus gondolelloides* (Bender), NK402, lateral view. *Neospathodus gondolelloides* (Bender), NK402 (**c**) upper view, (**c′**) lateral view and (**c″**) oblique/lower view. *Neospathodus homeri* (Bender), NK402 (**d**) lateral view and (**d′**) lower view. (**e**) *Neospathodus gondolelloides* (Bender), NK48 oblique/lower view. *Neogondolella* sp. *A*, NK53 (**f**) upper view and (**f′**) lower view. *Chiosella timorensis* (Nogami), broken specimen, NK53 (**g**) upper view, (**g′**) lateral view and (**g″**) lower view. The scale bar for all specimens is 200 μm.

Lithofacies. The mounds are characterized by a massive portion that passes laterally to clinostratified (angles evaluated in about 10°–15°), bedded bioclastic limestones that cover the underlying siliciclastics and carbonates. Two mounds can be distinguished and separated by intercalation of fine-grained sandstones in the marginal part. They seem to be amalgamated in the innermost part, where the massive portions are coalescent. The carbonate mounds pinch out laterally, and represent isolated carbonate bodies that interfinger with the prevailing volcanoclastic succession of member E. Whereas the lateral transition between the mounds and the siliciclastics is gradual, the sharp topmost boundary of the mounds is indicative of a rapid change in the depositional environment.

Different facies assemblages have been recognized, on the basis of the sedimentological structures and of the microfacies association (Fig. 16b–g). The inner part of the mounds is characterized by calcimicrobial limestones. They consist of massive clotted framestones, characterized by open-space structures filled with fine-grained internal sediments or spar calcite. Bioclasts are generally rare and consist of large isolated sponges (up to 5 cm in diameter), ostracods, serpulids and bryozoans. Bryozoans and serpulids grow on calcimicrobial limestones, thus indicating hard substrate. Close to the margins of the mounds, bioclastic limestones (rich in crinoids, echinoids, bivalves, gastropods, brachiopod, bryozoans and green algae) or intraclastic packstones prevail. Intraclasts are locally present, together with extrabasinal volcanic fragments. Reworking of the bioclasts is generally high, as documented by mechanical erosion and by rounded shape. Basinwards, the dominant facies is represented by hybrid limestones. They consist of wackestones with a calcareous matrix and abundant fine-grained quartz-rich volcanic material, with sparse bioclasts. Bioclasts are represented by thin-shelled bivalves, brachiopods, crinoid ossicles, ostracods and bryozoans. Hybrid limestones with lithic fragments are common.

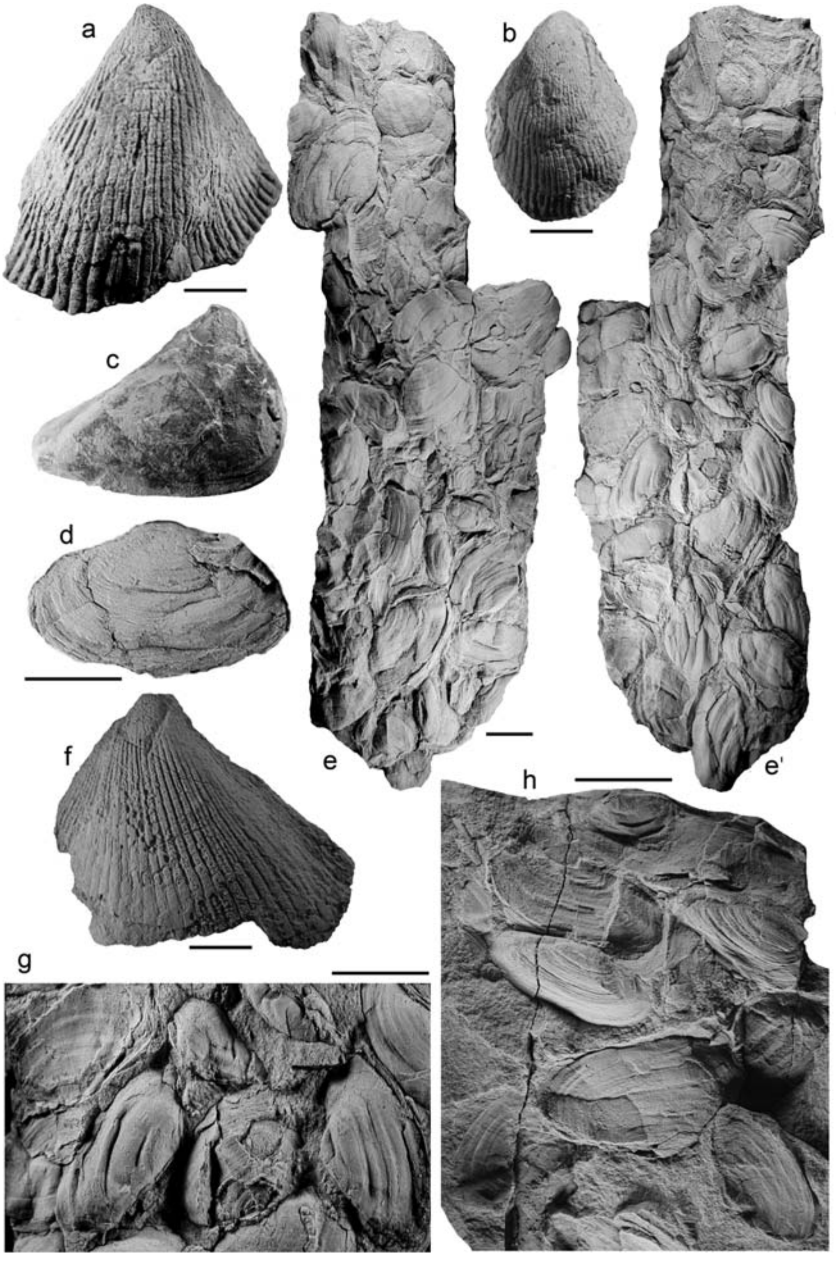

Fig. 15. Bivalves from the Alam Formation, members E and G 'grey shales'. (**a**) *Plagiostoma* cf. *P*. s*triatum*, left valve, NK431 (MPUM 9842-1). (**b**) *Plagiostoma* cf. *P*. s*triatum*, right valve, NK433 (MPUM 9843). (**c**) *Neoschizodus* sp., right valve, NK433 (MPUM 9844). (**d**) *Unionites* sp., left valve, NK454, specimen from (e). Marly limestone showing monotypic assemblage consisting of *Unionites* sp., NK454 (MPUM 9840) (**e**) lower surface and (**e′**) upper surface. (**f**) *Plagiostoma* cf. *P*. s*triatum*, right valve, NK431 (MPUM 9842-2). (**g**) *Unionites* sp., NK454, specimens from (e). (**h**) *Unionites* sp., NK454 (MPUM 9841). All the specimens are housed at the Museo di Paleontologia, Dipartimento di Scienze della Terra, Milano University; the inventory number is shown in brackets. All the specimens are whitened with ammonoium chloride. The scale bar for all specimens is 10 mm.

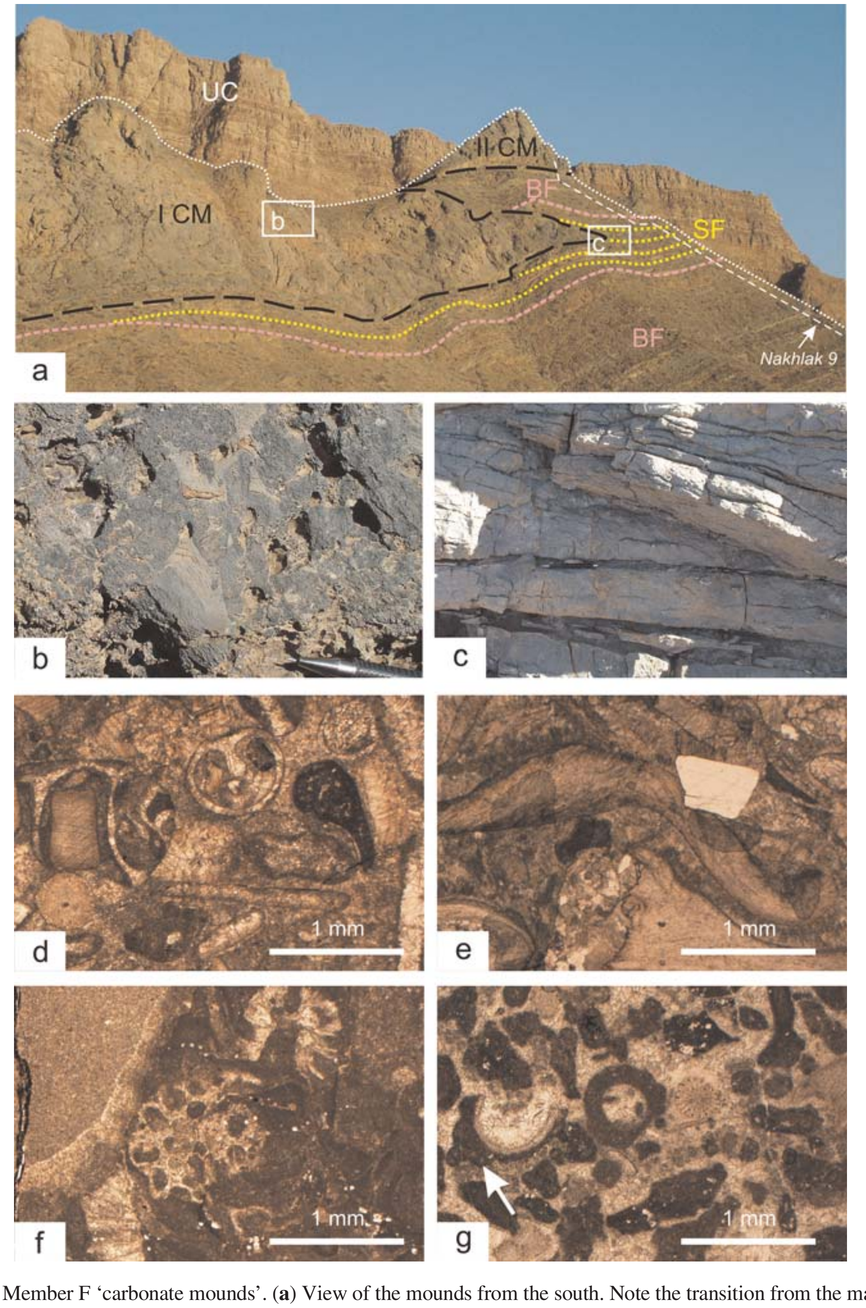

Fig. 16. Member F 'carbonate mounds'. (**a**) View of the mounds from the south. Note the transition from the massive carbonates (CM; inner part of the mounds) to the basinal facies (BF; member E) across clinostratified low-angle slope facies (SF). In the background is the Upper Cretaceous succession that unconformably covers the Alam Formation. The Nakhlak 9 section (Fig. 11) was measured along the right slope. (**b**) Detail of the massive limestones of the inner part of the mound. Note the presence of light-grey cavities filled by internal sediments. (**c**) Clinostratified bioclastic (crinoidal) limestones of the slope facies. (**d**) Bioclastic packstone from the slope facies of the mound. Skeletal grains are mainly represented by gastropods and crinoids. Note that several skeletal grains are rounded, suggesting an intense reworking of the bioclasts on the sea bottom. Sample NK55. (**e**) Bioclastic packstone with extrabasinal grains (quartz). Transition from slope to basinal facies. Sample NK61. (**f**) Massive wackestone with bryozoans in life position. In the top left-hand corner note the cavity filled with light-coloured internal sediments. Sample KN109. (**g**) Intra-bioclastic packstone at the transition between the massive mound and the slope facies. Some clasts are encrusted by organisms (arrow). Most of the intraclast consists of clotted micrite, probably derived by the inner part of the mound. Sample NK109.

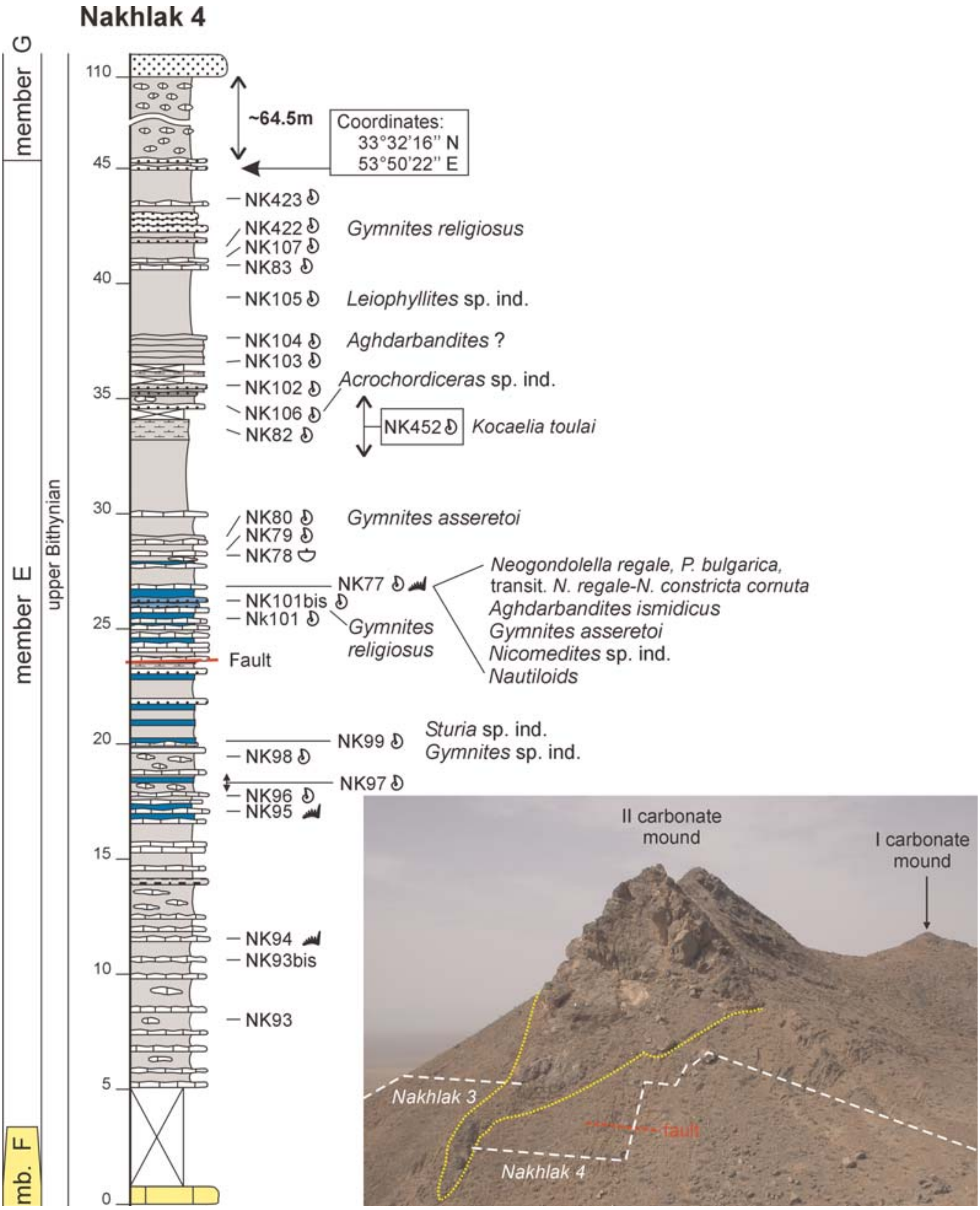

Fig. 17. The Nakhlak 4 section showing the upper part of member E and the lower part of member G 'grey shales'. The field photography shows the position of the section with respect to the II carbonate mound and the upper part of the Nakhlak 3 section.

The geometry of the mound and the presence of shallow-water structures (i.e. hummocky cross-stratification; Fig. 11) indicate that the carbonate production occurred above storm-weather wave base. The top of the mound was likely within the lower photic zone, suggesting that the microbial carbonate was probably produced by a light-sensitive community.

The Anisian carbonate mounds of Nakhlak represent a particular carbonate factory that closely resembles the Early Triassic mounds of Southern China (Lehrmann 1999). They were, however,

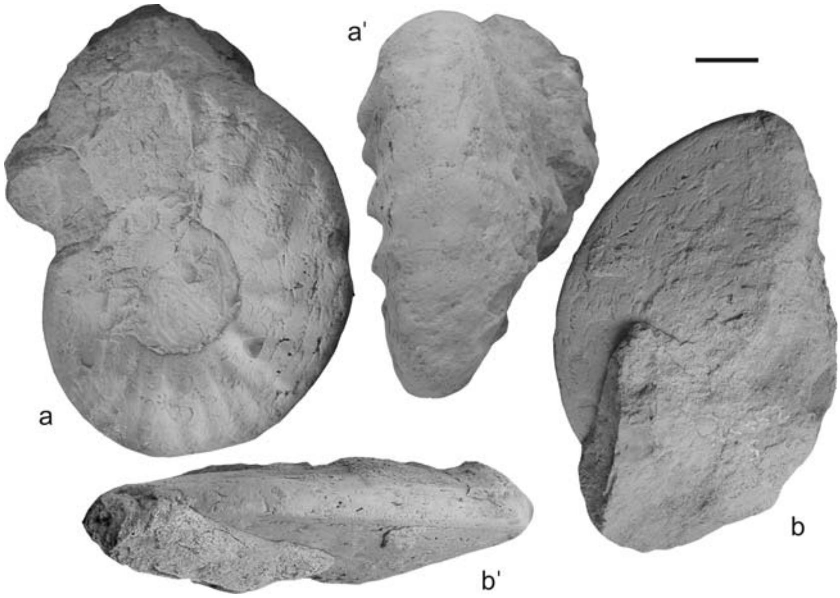

Fig. 18. Bithynian ammonoids from member E of the Alam Formation. *Aghdarbandites ismidicus* (Arthaber), NK77-37 (MPUM 9850) (**a**) lateral view and (**a′**) ventral view. *Kocaelia toulai* (Arthaber), NK452-5 (MPUM 9851) (**b**) lateral view and (**b′**) ventral view. All the specimens are housed at the Museo di Paleontologia, Dipartimento di Scienze della Terra, Milano University; the inventory number is shown in brackets. All the specimens are whitened with ammonoium chloride. The scale bar for all specimens is 1 cm.

developed in different bathymetric conditions; subtidal for Nakhlak and peritidal for southern China.

Fossils and age. Member F is quite fossiliferous, but most of the fossils can be recognized only in thin sections. Nevertheless, some age-diagnostic ammonoids and conodonts occur below and above the member, as well as in coeval basinal facies, firmly fixing the chronostratigraphic position of the member. The base of the member is Bithynian, probably close to the boundary between the *Nicomedites osmani* and *Aghdarbandites ismidicus* zones. The top is late Bithynian (*Aghdarbandites ismidicus* Zone) on the basis of the ammonoids found at the very base of the member G.

Brachiopods were found in the limestone-dominated lithofacies of the top of the underlying member E, within the clinostratified facies of the slope of the mounds and in the neritic limestones coeval with the mounds. The genus *Tetractinella* is rather common.

Member G 'grey shales' (upper Bithynian–Pelsonian or Illiryan). The upper part of the Alam Formation (Nakhlak 6 section, Fig. 19) is about 420 m thick and is dominated by light-grey to rare light-green shales and marls. The abundance of shales and marls makes this interval very easily recognizable. The member includes a thick interval attributed by Davoudzadeh & Seyed-Emami (1972, figs 3 and 4) to the upper part of member 4, members 5 and 6 of the Alam Formation, and the lower part of member 1 of the Bāqoroq Formation.

Boundaries. The lower boundary with member F is traced immediately above the hardground at the top of the carbonate mounds. Where member G overlies member E, its boundary is traced at the base of the 65–78 m-thick subunit consisting of grey shales with marly limestone lenses. The upper boundary with the Bāqoroq Formation is located at the base of the first massive red conglomerate bed.

Lithofacies. The member can be subdivided into three parts. The lowest interval is about 65 m thick at the Nakhlak 4 section and consists of light-grey to light-green shales with marly limestone lenses (Fig. 9f), sometimes with tuffitic layers. This facies yielded ammonoids and is also documented at the Nakhlak 6 section (about 78 m thick).

The intermediate interval is about 200 m thick and is characterized by three main intercalations of 1–4 m-thick lenticular–planar-bedded conglomerates, as well as by quite common sandstones and microconglomerates. The conglomerates are clast-supported (Fig. 9g), and the clasts, consisting of sedimentary rocks, are well rounded with good

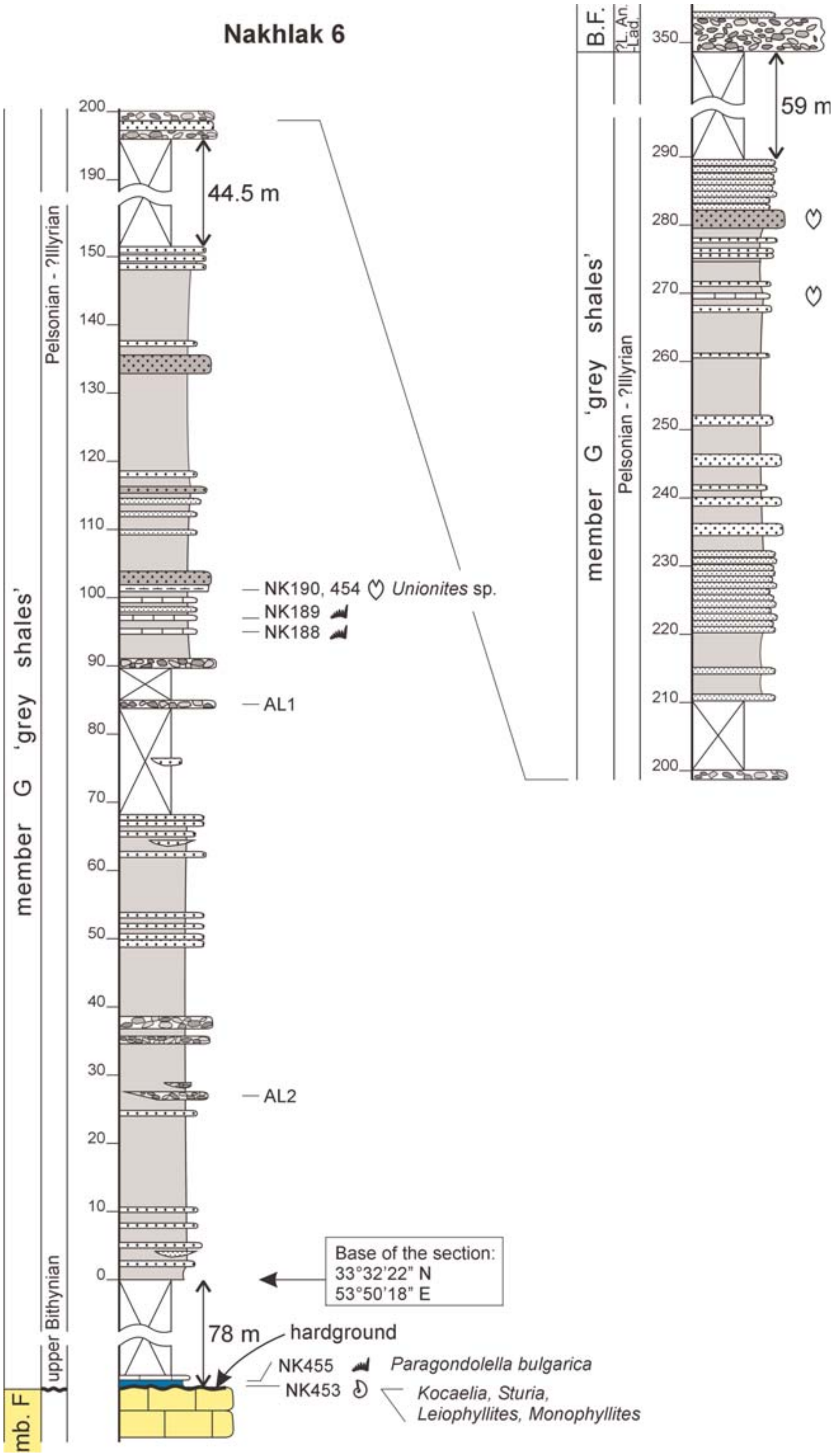

Fig. 19. The Nakhlak 6 section, showing the top of member F, member G and the base of the Bāqoroq Formation (B.F.).

sphericity. In this intermediate part of the member, some bivalve-bearing marls and limestones also occur (Fig. 9h).

The upper part of the member shows an increasing amount of fine-grained sandstones, as well as sandstones and microconglomerates.

Fossils and age. Ammonoids have been found in the lower part of this member, while bivalves are relatively common in the intermediate and upper part.

The lower part of the member at the Nakhlak 4 section (Fig. 19) yielded mostly long-ranging leiostraca ammonoids of the family Gymnitidae, particularly *G. religiosus* Diener and *G. asseretoi* Tozer, which are not age-diagnostic. A pelagic leiostraca-dominated ammonoid fauna is also documented at the Nakhlak 6 section, immediately above the hardground on top of member F. A rich fauna consisting of *Kocaelia*, *Sturia*, *Leiophyllites* and *Monophyllites* was identified in sample NK453, and the conodont *Paragondolella bulgarica* (Budurov & Stefanov) was found in the first limestone level (sample NK455). *Kocaelia* is typical of the *Aghdarbandites ismidicus* Zone (late Bithynian: Fantini Sestini 1988, 1990; cf. Krystyn & Tatzreiter 1991), thus fixing the late Bithynian age of the base of the member, which is also consistent with the presence of *P. bulgarica*.

The marls and limestones of the intermediate interval of the member yielded an extremely abundant bivalve fauna consisting only of *Unionites* (Fig. 15e, g, h), but are barren of conodonts (samples NK188 and NK189). They are, therefore, referred to a brackish–freshwater lagoonal environment. The bivalves occur in 5–20 cm-thick layers dominated by specimens with closed valves (autochthonous assemblages), and in comparably thick levels as open-articulate–butterfly specimens mostly concentrated in nests (parautochthonous assemblages: Fig. 9 g). Autochthonous and allochthonous oligotypic *Unionites* fauna are common in the upper part of the member.

Age-diagnostic fossils are lacking in the intermediate and upper part of the member. Thus, the age of the top of the member and top of the Alam Formation is not biochronostratigraphically calibrated.

Bāqoroq Formation (?Late Anisian–Ladinian)

This weathering-resistant unit is normally very well exposed. The unit was sampled along a single section (Nakhlak 10) located in the eastern part of the working area (Fig. 3d). At this site the overall thickness of the Bāqoroq Formation is about 870 m.

Lithology. The Bāqoroq Formation (Nakhlak 10 section; Figs 5 and 20) is dominated by red conglomerates and microconglomerates, within which red–yellow sandstones can also be found, especially in the upper part of the unit. The general trend of the unit is slightly fining-upwards. Conglomerates are normally organized in 1–20 m-thick intervals (in the lower part, exceptionally, up to 60 m thick) separated by microconglomerates or sandstones intercalations up to 5 m thick. In the uppermost part of the unit these intercalations are made of light-grey–light-green siltstones. The conglomeratic intervals are chaotic (lowermost part of the unit), but more commonly they show lenticular- to cross-bedding. Clasts are rounded to well rounded, and discoidal–subspherical. Grain size of the conglomerates covers the range between pebbles and cobbles, but in the chaotic intervals in the lowermost part of the unit small boulders are rather common.

Fossil content. The unit is reported as non-fossiliferous in the literature. A conodont sample from a bioclastic limestone layer located in the lowermost part of the formation (12–15 m from the base) was barren. In the absence of biostratigraphic data, the ?Late Anisian–Ladinian age of the unit is defined on the basis of its stratigraphic position between the Alam and the Ashin formations.

Ashin Formation (Late Ladinian)

This unit crops out in the tectonically disturbed part of the Nakhlak range, and only one section (Nakhlak 7) was measured. In this section about 370 m of the formation are exposed. However, the stratigraphic boundary with the Upper Cretaceous is not preserved as the Ashin Formation is locally in tectonic contact with the Bāqoroq Formation so that the true thickness of the Ashin Formation is unknown.

Lithology. The formation can be subdivided into three parts (Fig. 5). In the lower part the lithology consists of shales and very-fine-grained siltstones, with intercalation of up to 4–5 m-thick white–grey quartz-rich conglomeratic layers. The general trend of this part of the formation is fining- and thinning-upwards, and the conglomeratic layers are gradually replaced by sandstones that become thinner bedded. In the middle part of this interval there are tuff levels, testifying to syn-sedimentary volcanic activity.

The middle part of the formation, starting approximately from sample NK176 (about 75 m above the base of the Nakhlak 7 section), consists of an alternation of fine-grained sandstones in 5–10 cm-thick beds and shales in 10–100 cm-thick beds. The sandstones show the typical sedimentological features of

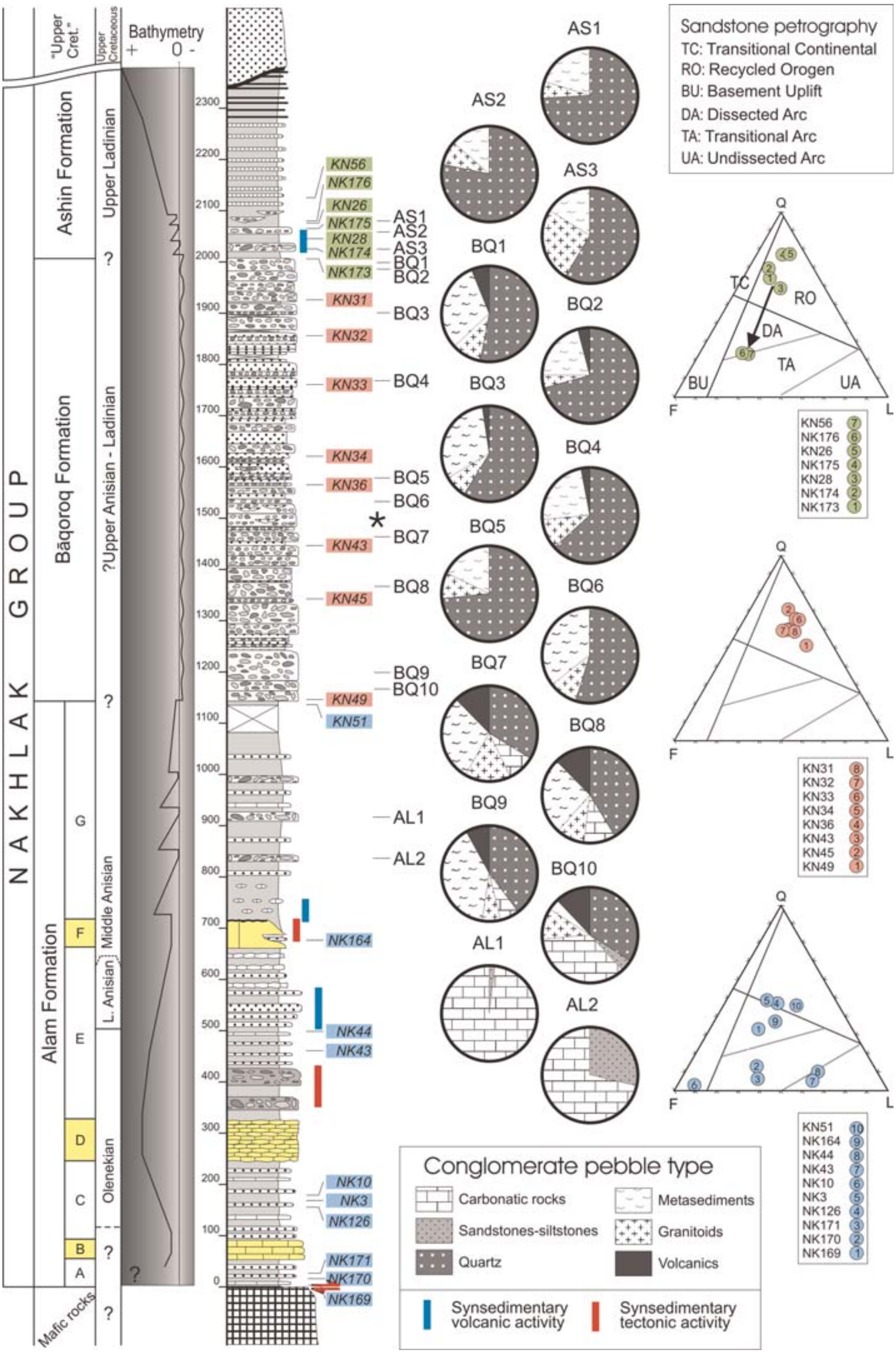

Fig. 20. Composite section of the Nakhlak Group showing the palaeobathymetry, the position of sandstone and conglomerate samples, the petrographic composition of the conglomerates of the upper Alam (sites AL2–AL1), Bāqoroq (sites BQ10–BQ1) and lower Ashin (sites AS3–AS1) formations, and the composition of sandstones plotted in a Q–F–L diagram (quartz–feldspar–aphanitic lithic grains). The asterisk marks the last occurrence of pebbles of oolitic limestone. GPS co-ordinates of the 15 sampling sites for conglomerates are listed in the Appendix.

turbidites, such as scour and tool marks, parallel-, cross- and convolute-lamination.

The upper part of the Ashin Formation, starting about 270 m above the base, continues the fining- and thinning-upwards trend, as the lithology consists of an alternation of 0.5–1 cm-thick very-fine-grained sandstones or siltstones with 1–5 cm-thick shales. Occasionally, there are limestones up to 5 cm in thickness.

Fossil content. The Ashin Formation is known for a rather poor body fossil fauna and more diverse ichnofossil assemblages. Tozer (1972) described the ammonoids *Megaphyllites* sp. indet., *Proarcestes* sp. indet. and *Arpadites* cf. *A. szaboi*, as well as the bivalve *Daonella lommeli* from the middle part of the unit. More recently, Vaziri (1996) reported *Romanites simionescui* from the lower part of the formation. During the fieldwork neither ammonoids nor bivalves were found. The soft-bottom deep-water trace fossils Agrichnia, Pascichnia and Repichnia (*Nereites* ichnofacies), as well as iso-oriented crinoid stems, are quite common, especially in the middle part of the Ashin Formation (see also Vaziri & Fürsich 2007).

The fine-grained and often siliciclastic lithology is not the best for conodont analysis. Only one conodont sample was taken from a limestone level in the upper part of the section (sample NK178, about 310 m from the base), but it was barren.

In the absence of new data, the chronological assignment of the Ashin Formation relies on data from the literature. Not one of the ammonoids reported from the Ashin Formation is a short-ranging form: *Arpadites* is a Ladinian genus, and *Romanites simionescui* in uncondensed successions is found only in the Upper Ladinian (see Krystyn & Tatzreiter 1991). The bivalve *Daonella lommeli* is very common in the Upper Ladinian, but it can also be found in the lowermost Carnian. We assign the Ashin Formation to the Late Ladinian, while the age of the top of the formation remains an open problem.

Sandstone and conglomerate petrography

Sandstone petrography was studied in thin sections. In each section, 400 points were counted by the Gazzi–Dickinson method (Ingersoll *et al.* 1984). Traditional ternary parameters and plots (Dickinson 1985) were supplemented, specifically as lithic grains are concerned, by an extended spectrum of key indices. Metamorphic rock fragments were classified according to both composition and metamorphic rank, mainly inferred from degree of recrystallization of mica flakes. Average rank for each sample was expressed by the 'metamorphic index' (MI), which varies from 0 in detritus from sedimentary and volcanic cover rocks to 500 in detritus from high-grade basement rocks (Garzanti & Vezzoli 2003) (see Table 1).

Alam Formation

Mostly upper medium to coarse-grained sandstones of the Alam Formation (10 samples) are volcanic arenites, dominated by microlitic–felsitic lithic fragments and plagioclase (Fig. 21); common quartz, granophyric–granitoid rock fragments, chessboard albite, micas and minor metasedimentary rock fragments occur locally (Q = quartz 25 ± 19, F = feldspar (KF = K-feldspar; P = plagioclase) 42 ± 20, Lv = volcanic grains 31 ± 18, Lm = metamorphic grains 2 ± 3; P/F = plagioclase/feldspar 88 ± 16). Such composition documents provenance from a magmatic arc dissected to various degrees, with sporadic contribution from metamorphic wallrocks ('Magmatic Arc Provenance' of Dickinson 1985; Marsaglia & Ingersoll 1992; Garzanti *et al.* 2007).

The coarse-grained basal layers of the unit (NK169, member A, Nakhlak 1 section) include abundant quartz, chessboard albite and granophyric–granitoid rock fragments, indicating relatively deep erosional levels within the arc massif ('Dissected Arc' subprovenance). Slightly higher in the succession (NK170 and NK171, member A, Nakhlak 1 section), overwhelming plagioclase and microlitic–felsitic volcanic grains suggest a major phase of intermediate (latite–andesite?) active volcanism ('Undissected Arc' subprovenance). The very-fine-grained sandstones of member C (NK126 and NK3, Nakhlak 2 section) point to an incision phase with subordinate supply from metamorphic wallrocks (quartz, micas, and quartz + mica lithic fragments). A second volcanic cycle is suggested by the overlying sandstone layers, principally derived from plagioclase-rich tuffs (NK10, member C, Nakhlak 2 section), followed by sandstones (NK43 and NK44: member E, Nakhlak 3 section) dominated by microlitic volcanic rock fragments and plagioclase, derived from relatively mafic products (basaltic andesite?). The unit is capped by sandstones (NK164: top of member E; KN51: member G, Nakhlak 10 section) relatively rich in quartz, chessboard albite, K-feldspar and granophyric–granitoid rock fragments, suggesting a phase of ceased volcanism and renewed erosion.

Bāqoroq Formation

Fine- to medium-grained sandstones of the Bāqoroq Formation (seven samples + basal sample: Fig. 21) have remarkably homogeneous quartzolithic metamorphiclastic composition (Q 63 ± 4, F 14 ± 4,

Table 1. *Detrital modes of Nakhlak sandstones. In each of 25 very-fine- to coarse-grained sandstone samples, 400–450 points were counted by Irene Bollati at the Milano-Bicocca University according to the Gazzi–Dickinson method (Ingersoll* et al. *1984). A detailed classification scheme allowed us to collect quantitative information on metamorphic rank of rock fragments (MI; Garzanti & Vezzoli 2003). Mean grain size of studied samples was determined in thin section by comparison with standards. Compositional parameters are defined in Garzanti* et al. *(2007)*

	N	GSZ (μm)	GSZ (ϕ)	Q	KF	Pl	Lvf	Lvm	Ls	Lmlr	Lmf	Lmb	Lu	mica	HM	Total	MI
Ashin Formation (volcanic arenites)	2	504	1.0	23	0	55	5	17	0	0	0	0	0	0	0	100.0	1
			0.5	0	0	1	3	1	0	0	0	0	0	0	0		2
Ashin Formation (metamorphiclastic sandstones)	5	203	2.3	67	7	9	1	1	0	0	10	0	0	4	0	100.0	328
			0.8	6	4	3	1	1	0	1	3	0	0	3	0		41
Bāqoroq Formation (main body)	7	288	1.8	61	7	7	1	2	0	1	17	0	0	4	0	100.0	338
			0.5	4	5	5	1	1	0	1	3	0	0	1	0		15
Bāqoroq Formation (base)	1	388	1.4	51	3	9	13	22	1	0	0	0	0	0	0	100.0	13
Alam Formation	10	367	1.4	24	4	38	6	24	0	1	1	0	0	3	0	100.0	26
			1.2	17	4	22	4	21	0	1	1	0	0	3	0		35

N, number of counted samples; GSZ, grain size; Q, quartz; KF, K-feldspar; PI, plagioclase; L, aphanitic lithic grains (Lvf, felsic volcanic; Lvm, microlithic volcanic; Ls, sedimentary; Lmlr, low-rank metamorphic; Lmf, felsic metamorphic; Lmb, metabasite; Lu, ultramafic); HM, heavy minerals; MI, metamorphic index. Mean and standard deviation are given for each stratigraphic interval.

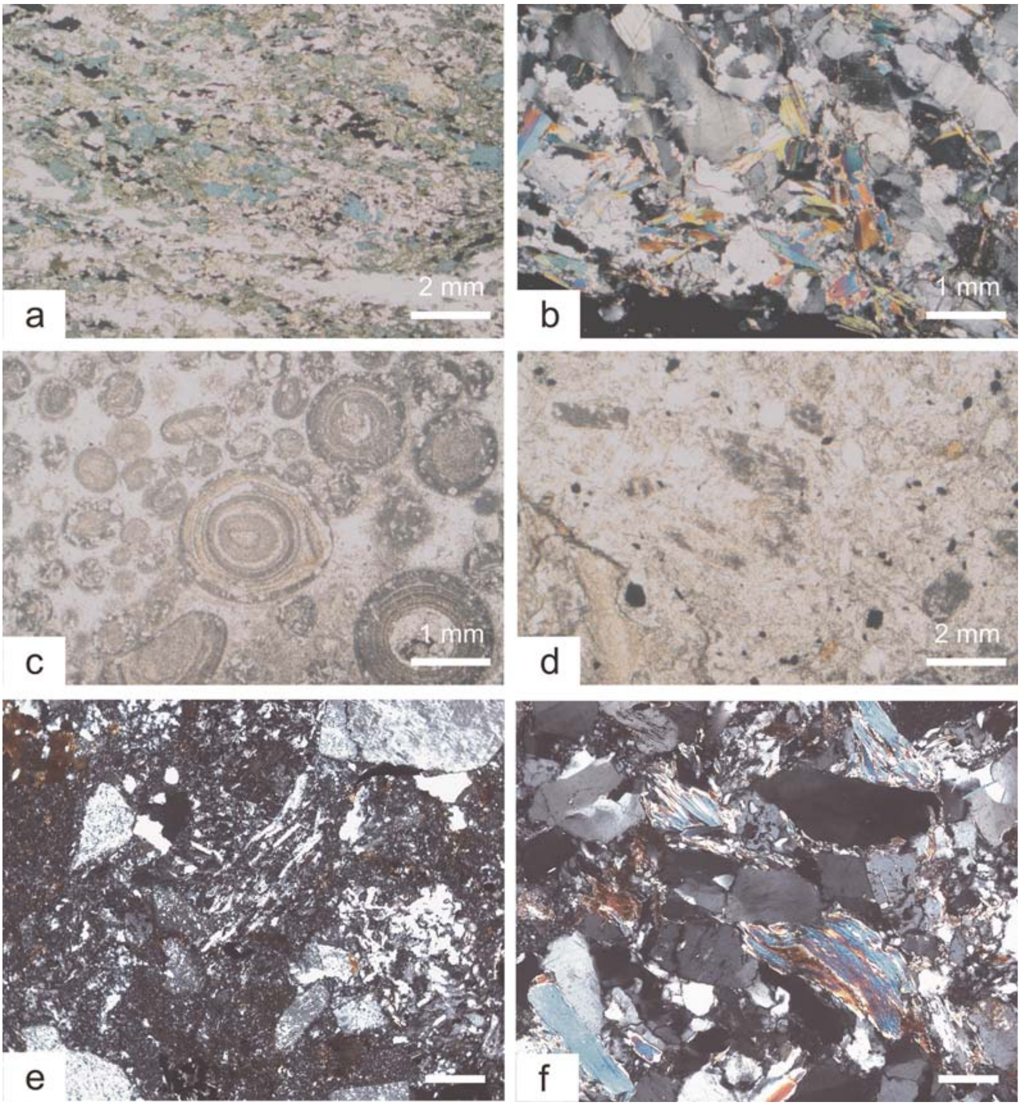

Fig. 21. Conglomerate and sandstone petrography of the Bāqoroq Formation. (**a**) Epidote amphibolite pebble of the Bāqoroq Formation (KN35). The light-green–bluish-green fine-grained amphiboles individuate a pervasive foliation. Rutile/ilmenite and plagioclase are also visible. (**b**) Slightly deformed granite pebble. White mica flakes and quartz display undulose extinction (KN39). (**c**) Oolitic limestone pebble from the lower part of the formation. (**d**) Deeply altered pebble made of acidic volcanic with a porphyritic texture. Quartz and plagioclase phenocrysts, almost completely saussuritized, are visible. Sandstone petrography. (**e**) Feldspatholithic sandstone of the Alam Formation (NK171) derived from an undissected volcanic arc. (**f**) Quartzolithic micaceous sandstone of the Bāqoroq Formation (KN32) derived from an axial metamorphic belt. Both photographs were taken with crossed polars. The bar scale for (e) and (f) is 100 μm.

Lv 4 ± 1, Lm 19 ± 4; P/F 51 ± 29), contrasting sharply with that of underlying Alam sandstones. Provenance from a metamorphic complex is indicated ('Recycled Orogen Provenance' of Dickinson 1985; 'Axial Belt Provenance' of Garzanti *et al.* 2007). Only the basal layer (KN49) contains common volcanic rock fragments, suggesting either terminal volcanic activity or erosion of older volcanic and volcaniclastic rocks. Sandstones in the main body of the unit (KN45, KN43, KN36, KN34, KN33, KN32 and KN31) monotonously consist of quartz, metamorphic rock fragments, feldspars, granitoid rock fragments and micas, in that order of abundance. A few volcanic–subvolcanic rock fragments are invariably present. Dominant medium- to high-rank schistose–gneissic rock fragments (MI 338 ± 15; Garzanti & Vezzoli 2003) indicate provenance from low-grade metasedimentary rocks.

Ashin Formation

Sandstones of the Ashin Formation have bimodal compositions (Fig. 21), mainly including very-fine to medium-grained quartzolithic metamorphiclastic sandstones such as those of the Bāqoroq Formation (KN173, KN174, KN28, KN175 and KN26; Q 70 ± 8, F 17 ± 7, Lv 2 ± 2, Lm 11 ± 3; P/F 62 ± 16; MI 328 ± 41), intercalated with upper medium- to coarse-grained volcanic arenites such as those of the Alam Formation (KN176, KN56; Q 23 ± 0, F 55 ± 1, Lv 22 ± 2, Lm 0 ± 0; P/F 100 ± 0). Volcanic arenites consist of virtually pure volcanic detritus, including monocrystalline quartz with straight extinction and embayed or bipyramidal outlines, and microlitic–vitric and pyroclastic grains, testifying to a phase of renewed intermediate–felsic (dacite–rhyodacite?) explosive volcanism. Absence of sediments with mixed volcanic–metamorphic signatures (volcanic arenites invariably contain trivial amounts of metamorphic grains, and quartzolithic sandstones invariably include trivial amounts of volcanic detritus) indicate two sharply separate sources at the two opposite sides of the sedimentary basin.

Conglomerate analysis

Ten sites for conglomerate analysis were selected in the field within the Bāqoroq Formation, and some additional sites were selected within the uppermost Alam Formation (two sites) and lower Ashin Formation (three sites). The composition of at least 100 pebbles was identified at each site, according to a classification of the pebbles in 10 classes, simplified later to six classes (Fig. 21). Furthermore, in order to verify the pebble description, in these sites we sampled pebbles of all the lithologies for thin section analysis (Fig. 20).

The following remarks can be pointed out, summarizing the data (Fig. 21):

- the conglomerates of the uppermost Alam Formation are composed only of clasts of sedimentary rocks;
- sedimentary rocks are also an important component of the conglomerates of the lower part of the Bāqoroq Formation (sites BQ10–BQ7), but, from the base of the formation, the quartz pebbles become increasingly very common;
- the most frequent type of sedimentary rocks in the sites BQ10–BQ7 are oolitic grainstones (Fig. 20c). Note that oolitic limestones are documented only within the member B 'oolitic limestone' of the Alam Formation (38 m thick at the Nakhlak 1 section). No oolitic limestones are reported from the nearby outcrops of Ordovician–Permian successions of sedimentary rocks east of Anarak (Sharkovski *et al.* 1984; Mattei *et al.* 2004);
- within the Bāqoroq Formation, quartz is accompanied by metamorphic rocks and by granitoids;
- ophiolitic fragments, quoted by Alavi *et al.* (1997), have not actually been recognized;
- volcanoclastic–volcanic rocks are not documented within the conglomerates of the Ashin Formation.

Sedimentary evolution

The stratigraphic evolution of the Nakhlak Group was previously described by Davoudzadeh & Seyed-Emami (1972), and more recently by Alavi *et al.* (1997) and Seyed-Emami (2003). These authors subdivided the evolution of the entire succession into three different stages, corresponding to the three lithostratigraphic units: Alam, Bāqoroq and Ashin formations. Alavi *et al.* (1997) described a first shallowing- and coarsening-upwards evolution in the Alam Formation, a major unconformity at the base of the fining-upwards Bāqoroq Formation, and another unconformity at the base of the Ashin Formation that was referred to as a turbiditic unit. Alavi *et al.* (1997) interpreted the Nakhlak succession as arc-related, and deposited between the trench and the trench–slope break.

The subdivision of the Nakhlak Group into three major depositional cycles (lower marine, intermediate continental and upper marine) is confirmed by our data. The first cycle is documented by the Alam Formation (Olenekian–Anisian), while the third cycle, preserved only in the transgressive part, is represented by the Ashin Formation (Upper Ladinian). The intermediate continental episode is recorded by the Bāqoroq Formation (Lower Ladinian). We provide a more detailed and constrained reconstruction of the evolution of the succession that documents a more complex interaction between clastic–volcanoclastic supply and carbonate sedimentation, between regional subsidence and uplift, and between relative sea-level changes and syn-sedimentary tectonic and volcanic activity. In particular the evolution of the Olenekian–Anisian part of the succession (Alam Formation) notably differs from the interpretation available in the literature.

The Alam Formation represents a general transgressive–regressive cycle containing short cycles of variation of siliciclastic and volcaniclastic supply. The base of the succession is not preserved, as it tectonically lies on metagabbros. The transgressive part of the lower cycle is documented by the interval from member A to member D ('nodular limestone'), while the general regression is represented from member E to member G ('grey shales').

The older unit (member A, ?lower Olenekian) was deposited in a coastal marine–transitional environment with input of fine-grained volcaniclastics with dissected–transitional arc provenance, probably under arid conditions (presence of dolostones). Member B ('oolitic limestone'; about 38 m; ?lower Olenekian), deposited in an high-energy shallow-marine environment, documents a rapid transgressive trend with a reduction of volcaniclastic supply. The transition from member A to member B is sharp, as is the boundary between members B and C. The transgressive trend continues after the deposition of member B, and shows an increase in volcaniclastic supply that consists of green volcaniclastic sandstones, hybrid arenites and green shales of the basal part of member C (27 m; Olenekian). This unit was deposited under the influence of currents (cross-laminations) and was probably above the storm wave base. The abundance of shales and siltstones in the upper part of member C ('varicoloured shales', up to 127 m; middle–upper Olenekian) represents the deposition in slightly deeper water, probably below the storm wave base. Provenance analysis of sandstones from member C documents an increase of metamorphic content that reflects uplift and erosion of the nearby volcanic arc coeval with the deepening of the basin. The end of the uplift of the arc is marked by the decreased clastic input that preceeded the deposition of the overlying member D ('nodular limestone', about 80 m thick, upper Olenekian). This member was deposited in a deep-water environment under relative tectonic quiescence, with sparse input of volcaniclastic sandstones. The low-energy environment, the abundance of ammonoids and the typical nodular facies prove the maximum deepening of the basin.

The transition from member D to the overlying thick member E (about 330 m; upper Olenekian-lower Bithynian) records a renewed, abundant volcaniclastic input and syn-depositional tectonic activity leading to the deposition of the thick paraconglomeratic beds. The abundance of extrabasinal input and the thick paraconglomerates suggest an increase of sedimentation rate with a strong dilution of carbonate input by volcaniclastic sediments. The general trend of member E is regressive, with gradual reduction of the accommodation space due to the infilling of the basin. Sea bottom was surely above the storm wave base and the reduction of bathymetry, coupled with the decreased volcaniclastic supply, favoured the onset of the carbonate mounds of member F (up to 50 m; Bithynian). The carbonate production of the mounds influenced sedimentation in the surrounding basinal areas, with deposition of an alternation of resedimented bioclastic limestones and fine-grained sandstones. The carbonate production suddenly ended in the late Bithynian. The driving mechanism for this crisis of the carbonate factory can be deduced from some observations. The boundary between the bioclastic limestones of member F and the tuffs and marls with pelagic ammonoids of the basal part of member G is very sharp and marked by a hardground at the top of the carbonate mounds. Transitional facies such as nodular–pseudonodular limestones with brachiopods in between members F and G are completely absent, indicating that the carbonate production ceased very rapidly. The occurrence of the hardground on top of the carbonate mounds indicates that the crisis of the carbonate factory cannot be ascribed to the siliciclastic input. Therefore, the most probable cause of the end of the carbonate production can be due to a very rapid sea-level rise (drowning unconformity). Considering the environmental setting, the evidence of volcanic activity after the drowning and the rapidity of the environmental change, we suggest that the drowning of the mound could very probably be tectonically controlled, before the deposition of the basal tuff of member G.

Member G ('grey shales', upper Bithynian–Pelsonian or Illyrian) is characterized by a coarsening-upwards trend, coupled with a general regressive evolution. The maximum depth of the basin is documented by the leiostraca ammonoid-bearing marls immediately overlying the top of the carbonate mounds (member F). The sandstones and conglomerate intervals of the middle and upper part of the members reflect the progradation of coastal to alluvial facies intercalated with freshwater–brackish water lagoonal facies with oligotypic *Unionites* fauna.

The Bāqoroq Formation (up to 870 m thick; ?Upper Anisian–Ladinian), mostly consisting of red conglomerates and sandstones, is referred to a fluvial environment in a semi-arid climate. The unit continues the continental evolution of member G of the Alam Formation and shows a general fining-upwards trend with a reduction in coarse-grained massive conglomerates and an increase in sandstones. The fining-upwards trend and the clastic input of the Bāqoroq Formation are indicative of a tectonic uplift in the surroundings of the Nakhlak Basin. The uplift started during the deposition of member G, as indicated by the petrographic composition of sandstones and conglomerates, which suggest erosion of the volcanic arc during an interval of scarce or absent volcanic activity. Sedimentary rock pebbles are abundant in the conglomerates of member G of the Alam Formation, while their frequency considerably decreases in conglomerates of the lower part of the Bāqoroq Formation (Fig. 21: samples BQ10–BQ7). The sedimentary pebbles disappear between sample BQ6 and BQ5, reflecting the end of the erosion of the sedimentary cover. The erosion of the volcanic rocks was, in part, coeval with the erosion of the sedimentary rocks. The frequency of volcanic pebbles is relatively high in samples from BQ10 to BQ7, then they disappear in the middle part of the formation, but slowly become more frequent in the upper part of the unit. The exhumation of the metamorphic basement, documented by quartz, granitoids and metamorphic rocks, started at the base of the Bāqoroq Formation (Upper Anisian or Lower Ladinian) and continued in the lower part of the Ashin Formation (Lower Ladinian).

In the Late Ladinian a new tectonic event led to the very fast transgression of the Ashin Formation. The quartz-rich conglomeratic beds at the base of the unit were deposited in a fluvial–transitional environment, which became open marine in a few tens of metres, as documented by the occurrence of the ammonoid *Romanites simionescui* reported by Vaziri (1996). This fast environmental change is accompanied by a reprisal of volcanic activity documented by tuff layers up to a few metres thick, and continues with the deposition of the fine-grained turbiditic sandstones of the middle and upper part of the Ashin Formation. This part of the formation is interpreted to be deposited at a water depth of several hundreds of metres not only because of its sedimentological features, but also because of the rich deep-water ichnofacies (Vaziri & Fürsich 2007).

The petrographic analyses of sandstones fully support this picture. A Bāqoroq-like clastic supply from the metamorphic and intrusive rocks (quartzolithic metamorphiclastic sandstones), and a new source from volcanic centres (volcanic arenites), are emphasized. The latter type of arenite especially documents the presence of volcanoes close to the study area.

The transition from continental conglomerates of the Bāqoroq Formation to the deep-water turbiditic facies of the Ashin Formation occurs in about 100 m of stratigraphic thickness. The bathymetric change documented in such a relatively thin thickness shows a relative sea-level rise of several hundreds of metres that cannot be explained by eustasy alone. Eustasy might have provided an additional contribution to the facies change, as the Ladinian was characterized by an eustatic sea-level rise (Haq *et al.* 1988), but most of the relative change must be ascribed to a rapid increase in subsidence. The reprisal of volcanic activity, documented by tuffs and by sandstone petrography, is also consistent with a sudden increase in subsidence of the area during the Late Ladinian.

The significance of the Nakhlak Group

The new stratigraphically well-constrained data have a good potential for improving the knowledge of the geological and geodynamic setting of the Nakhlak area during the Triassic, although a new geodynamic model for Central Iran cannot rely only on these data. The relationship of the Triassic of Nakhlak with the Anarak metamorphic range, and the discussion of Bagheri & Stampfli's (2008) model for the evolution of Central Iran, are treated in a separate contribution (Zanchi *et al.* 2009). The discussion of the 135° counterclockwise rotation of Central Iran from a palaeogmagnetic viewpoint is treated by Muttoni *et al.* (2009).

Geodynamic setting

The available stratigraphic, geological and petrographic data from the Triassic succession of Nakhlak support the following considerations:

- a 2.4 km-thick succession was deposited in an irregularly subsiding sedimentary basin during Early–Middle Triassic times;
- volcaniclastic and siliciclastic supply in the basin was high from Olenekian to Late Ladinian, with a few carbonate-dominated episodes restricted to short periods of reduced clastic supply;
- sedimentation in the basin was strongly influenced by active syn-sedimentary tectonics documented by fast changes of the subsidence (i.e. the 'drowning' of the Bāqoroq Formation), as well as by sudden changes in facies (i.e. the drowning of member F of the Alam Formation) and by the debris flow at the base of member E of the Alam Formation;
- the basin was close to an active volcanic area, as documented by tuffaceous intervals in the succession from the Olenekian to the Late Ladinian;
- provenance analyses on Alam sandstones and some Ashin sandstones indicate supply from a magmatic arc;
- magmatism occurred in several distinct pulses, and was characterized by orogenic calc-alkaline affinity including latite–andesite (lower Alam Formation), basaltic andesite (upper Alam Formation) and rhyodacite (Ashin Formation);
- two different sources for volcanic and metamorphic detritus co-existed at Late Ladinian times (Ashin Formation);

- the occurrence of ophiolitic rock fragments (serpentinites) in the Bāqoroq Formation mentioned by Alavi *et al.* (1997) is not confirmed. No fragments of serpentinites were recognized during the statistic counting of 400 grains per seven thin sections of sandstones and more than 100 grains of conglomerates per 10 sites;
- the Triassic succession was deformed during the Cimmerian orogeny before the Late Cretaceous. The study area was not affected by post-Cretaceous thrusts; thus, there is no evidence for post-Cimmerian tectonics as reported by Alavi *et al.* (1997).

These data suggest the location of the Nakhlak area along an active margin during the Triassic. The absence of proximal volcanic deposits excludes the possibility that deposition occurred in an intra-arc basin and strongly supports the inference that the Nakhlak succession represents a portion of a forearc basin related to a subduction zone that was active during the Early–Middle Triassic. The geology of the Anarak area, south of Nakhlak, is consistent with this reconstruction, and the Anarak Metamorphic Complex might represent the remnant of an accretionary wedge (Bagheri & Stampfli 2008; see Zanchi *et al.* 2009 for discussion).

Comparison of Nakhlak and Aghdarband

Since its first description (Davouzadeh & Seyed-Emami 1972) the Triassic Nakhlak Group has been compared and correlated with the Triassic succession exposed in the erosional window of Aghdarband (Ruttner 1984, 1991, 1993; Alavi *et al.* 1997), in the Koppeh Dag. These comparisons attempted to explain the striking difference in the Triassic of Nakhlak compared with the Triassic of the surrounding areas of Alborz, Central Iran and Sanandaj–Sirjan (see Seyed-Emami 2003 for a summary). The stratigraphic similarities between the two areas provided support to the model of 135° counterclockwise rotation of Central Iran since the Triassic (Davoudzadeh *et al.* 1981; Davoudzadeh & Weber-Diefenbach 1987; Soffel *et al.* 1996). However, the lithological correlations emphasized the similarities and ignored the differences between Nakhlak and Aghdarband.

Recent investigations on the distribution of Devonian–Lower Carboniferous facies in central and northern Iran question the 135° counterclockwise rotation. Wendt *et al.* (2005, pp. 77–78) stressed a facies distribution that is almost consistent with the present-day position of Central Iran with respect to the Koppeh Dag. Muttoni *et al.* (2009) also advise caution in considering the counterclockwise model because the very few samples from the Triassic of Nakhlak with possible primary magnetization show no rotation (site IR02) or only moderate counterclockwise rotation (site IR04) since the Olenekian.

In the light of these new data a more careful comparison of the Nakhlak and Aghdarband successions is warranted. Here we briefly review not only the similarities, but also the differences, between the two successions. For Aghdarband we used data from the literature and new data collected during two field seasons in the area (2005 and 2007).

General setting

Even if the geodynamic position of Nakhlak is uncertain, the location of Aghdarband on the southern margin of the Laurasia is well accepted. This palaeoposition relies on the identification of an ophiolitic belt (Eftekharnezhad & Behroozi 1991) and an accretionary wedge (Alavi 1991; Ruttner 1993; Alavi *et al.* 1997) to the south, both related to the subduction of the Palaeotethys, as well as on the basis of faunal affinity of the Devonian–Carboniferous fauna recorded in units underlying the Triassic succession (Wendt *et al.* 2005).

Stratigraphic succession and correlation

The Triassic of Aghdarband is known from several contributions (Ruttner 1984, 1991, 1993; Baud & Stampfli 1989; Baud *et al.* 1991*a*, *b*; Krystyn & Tatzreiter 1991; Alavi *et al.* 1997). The succession is illustrated in Figure 22, which is mostly based on Ruttner (1991, fig. 4). The succession shows some similarities with Nakhlak, as well as some differences. Only the lower–middle part of the succession, below the Cimmerian unconformity (Qara Geithan–Sina formations), has time equivalents in the Nakhlak section. Within this interval there is an important unconformity at the base of the Sina Formation that was not well detected by all the authors. This unconformity was first recognized by Ruttner (1984, 1991, 1993) and is confirmed by our investigations, while Baud *et al.* (1991*b*, fig. 6) identified an unconformity in a lower stratigraphic position, between the Sefid Kuh Limestone and the overlying 'fossil horizon 1', i.e. the Nazarkardeh Formation.

The lower parts of the Aghdarband and Nakhlak successions are different in six major ways:

- The 500 m-thick Qara Geithan Formation (Lower Triassic: Ruttner 1991 and Baud *et al.* 1991*b*; Upper Permian: Alavi *et al.* 1997), consisting of alluvial sandstones and conglomerates rich in granitoids, has no counterpart in the Nakhlak Group.

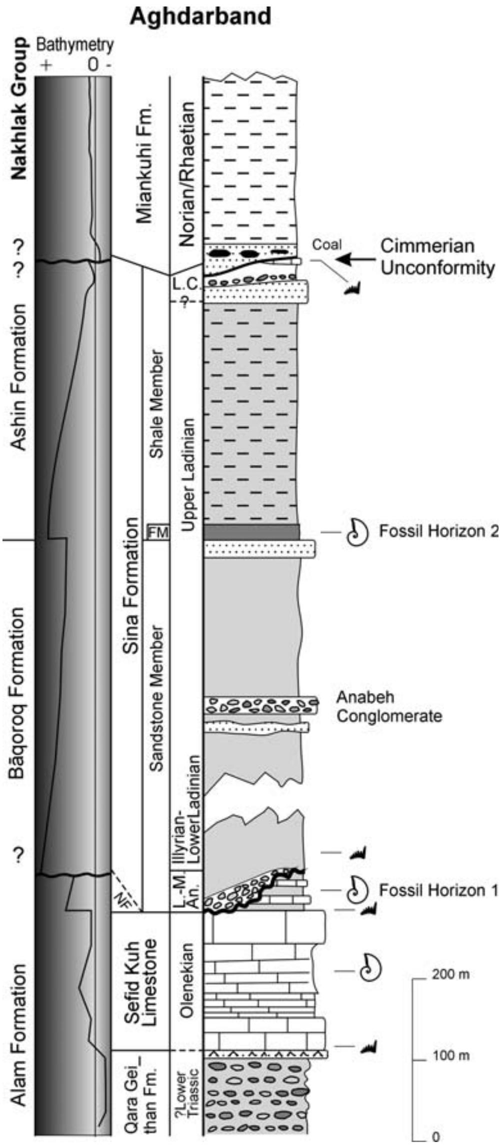

Fig. 22. Comparison of the Nakhlak Group (left) with the the Triassic succession exposed in the erosional window of Aghdarband (Koppeh Dag, NE Iran). The Aghdarband log is composite and based on Ruttner's (1991) tectonic slice I and II, with projection of the Anabeh Conglomerate from tectonic slice III. The calibration of the succession is based on ammonoid and conodont data from Baud *et al.* (1991*a*, *b*), Krystyn & Tatzreiter (1991) and a new Olenekian ammonoid fauna. Dating of the Miankuhi Formation is based on plant megafossils (Boersma & van Konijnenburg-van Cittert 1991). Abbreviations: NF, Nazarkardeh Formation; FM, Faqir Marl Bed.

- The overlying Sefid Kuh Limestone, a 200 m-thick Olenekian (Spathian: Baud *et al.* 1991*a*) carbonate ramp, shows a different evolution to that of the Alam Formation. The Sefid Kuh Limestone is dated with conodonts as middle–upper Olenekian (Spathian), and it is coeval with members C, D and with the lower part of member E of the Alam Formation. During this interval the general trend of the Nakhlak Basin was first deepening (members C and D), after which the basin was affected by tectonic instability and started a shallowing trend (lower part of member E: Fig. 21). The sudden drowning of the Sefid Kuh Limestone is Aegean in age (Baud *et al.* 1991*a*), coeval with a relatively monotonous and shallowing part of member E of the Alam Formation (middle part of the Nakhlak 3 section).
- The development of the carbonate mounds of member F of the Alam Formation (Bithynian) at Nakhlak is coeval with the deposition of the basinal Nazarkardeh Formation. The latter is very similar to the upper part of member E of the Alam Formation, but the late Bithynian–Late Anisian evolution of the two areas is very different. The tectonically controlled drowning of member F of the Alam Formation is late Bithynian in age and is followed by a rather regular shallowing trend from marine–transitional–continental fluvial facies (member G 'grey shales') up to the base of the Bāqoroq Formation.
- The Bāqoroq Formation, which documents the uplift and erosion of a metamorphic basement, is dated only by its stratigraphic position as ?Late Anisian–Ladinian in age at Nakhlak. However, some Late Anisian–Early Ladinian conodonts were reported from the basal part of the Sina Formation at Aghdarband (Ruttner 1991, p. 32), which demonstrates that between the Bithynian and the Late Anisian–Early Ladinian the Aghdarband succession was first uplifted and eroded, and then the basin suddenly subsided in the Late Anisian–Early Ladinian to accumulate marine sediments. This trend is reversed with respect to the sedimentary evolution of the Nakhlak Basin.
- That rapid subsidence at Aghdarband leads to the deposition of the turbiditic volcanoclastic sandstones of the Sandstone Member of the Sina Formation. This member is almost coeval with the Bāqoroq Formation but the depositional setting is very different, the Bāqoroq Formation being deposited in a continental setting.
- From a petrographic point of view, the two units are slightly different. The Sina Formation mostly consists of volcanoclastic sandstones with a minor amount of metamorphic fragments,

while the metamorphic fragments are much more abundant in the Bāqoroq Formation.

In contrast to differences in their early history, during the Late Ladinian both the Aghdarband and the Nakhlak successions show a similar deepening trend. At Nakhlak the deepening trend is documented by the transition of the Bāqoroq and Ashin formations, which was mainly controlled by tectonics with a possible additional eustatic component. At Aghdarband an almost coeval deepening is represented by the transition from the Sandstone to Shale members of the Sina Formation. The first member is referred to a sandstone-dominated deep-marine environment, while the Shale Member represents a shale-dominated turbiditic system (Baud *et al.* 1991*b*).

Faunal similarity

Three ammonoid-bearing intervals can be recognized in the Aghdarband succession (Fig. 22). The oldest interval has recently been found in the Sefid Kuh Limestone and is Olenekian in age (Balini *et al.* in prep.). The second is Bithynian in age, while the third is Late Ladinian in age (Fossil horizon 1 and 2 of Krystyn & Tatzreiter 1991 and Ruttner 1991). Two Bithynian ammonoid zones are recorded in the Nazarkardeh Formation: the early Bithynian *Nicomedites osmani* Zone and the late Bithynian *Aghdarbandites ismidicus* Zone. The Late Ladinian ammonoids are concentrated in the Faqir Marl Bed, i.e. at the base of the Shale Member of the Sina Formation.

The occurrence in both the Nakhlak and the Aghdarband successions of three coeval ammonoid faunas is unusual, but faunal composition is even more interesting. The Olenekian ammonoid fauna of member C of the Alam Formation is dominated by *Albanites* and Columbitidae, showing typical Tethyan affinity with Kçira (Albania: Arthaber 1908, 1911; Germani 1997) and Chios (Greece: Renz & Renz 1948; Mertmann & Jacobshagen 2003). The few Olenekian ammonoids of the middle Sefid Kuh Formation consist of tirolitids of the group of *T. rossicus* Kiparisova (Balini *et al.* in prep.). This group of tirolitids is known only from Mangyshlak (Shevyrev 1968; Balini *et al.* 2000) and suggests a pericaspian affinity for the Olenekian of Aghdarband. This notably different faunal composition of the two sites does not persist in the Bithynian and the Late Ladinian, which are characterized by almost identical ammonoid fauna at Nakhlak and Aghdarband.

The understanding of the palaeogeographic and palaeogeodynamic significance of the Triassic faunal affinities requires further investigation. The change in faunal affinity took place between the Olenekian and Bithynian. In the Aghdarband succession no major unconformity seems recorded in this interval, but the basal unconformity of the Sina Formation is slightly younger. The easiest solution could be to locate Nakhlak on an active margin of a microplate approaching Aghdarband (i.e. the Turan Plate) during the Early Triassic. However, this model cannot be supported by only ammonoid data and would require a solution to the doubts on the 135° counterclockwise rotation of Central Iran. What can be concluded at the present is that the Alavi *et al.* (1997) location of Nakhlak and Aghdarband on the same arc–trench system is not consistent with Triassic ammonoid palaeobiogeography.

Conclusions

The stratigraphic revision of the Triassic succession of Nakhlak based on the analyses of lithofacies, ammonoids, conodonts, bivalves, petrography of sandstones and conglomerates lead to the following results:

- the stratigraphic evolution of the succession consisting of the Alam (Olenekian–Anisian), Bāqoroq (?Upper Anisian–Ladinian) and Ashin formations (Upper Ladinian) has been documented. The 2.4 km-thick succession is divided into two sedimentary cycles. Dominant magmatic arc provenance for Alam sandstones and some Ashin sandstones indicate deposition in an arc-related setting. Magmatism occurred in several distinct pulses, and was characterized by orogenic calc-alkaline affinity;
- the sandstone and conglomerate petrography of the Nakhlak succession records two intervals (Olenekian and Early–Late Ladinan) of important metamorphic supply. In particular, the Bāqoroq Formation documents the exhumation of a metamorphic basement, as well as the erosion of a volcanic arc. The sedimentary succession around the base of the Bāqoroq Formation does not show any indication of deformation that would be necessary to provide a final demonstration of a collision;
- the succession was deposited along an active margin, most probably in a forearc setting;
- facies comparison demonstrates that the Aghdarband (NE Iran, Koppeh Dag) and Nakhlak successions were both deposited on an active margin, but lithological constrains are not sufficient to demonstrate their possible proximity. The interpretation of similarities and differences between the two localities is not unequivocal, especially with regard to the relative palaeogeodynamic position of the two areas;

- Nakhlak and Aghdarband have different ammonoid faunal affinities during the Early Triassic, and similar affinities from the Bithynian to the Late Ladinian;
- Triassic ammonoid palaeobiogeographical data argue against the location of Nakhlak close to the active margin of Aghdarband, at least during the Early Triassic, and do not support the model suggested by Alavi *et al.* (1997, fig. 10), who placed Nakhlak and Aghdarband, respectively, towards the arc and towards the trench of the same trench–slope break.

Fieldwork (2003: M. Balini, A. Nicora and R. Salamati; 2004: M. Balini, F. Berra, G. Muttoni, M. Levera, M. Mattei, A. Zarchi and F. Mossavvari) was carried out in the structure of two MEBE projects: 'Stratigraphy of Selected Permian and Triassic Sections in Iran' (leader M. Gaetani) and 'Tectonic Evolution of the Yazd, Tabas and Lut Blocks (Central Iran) by Means of Palaeomagnetic, Structural and Stratigraphic Data' (leader M. Mattei). We are deeply indebted to the Geological Survey of Iran and especially with M. Ghassemi, for the logistic and technical support. We would like to thank the GSI drivers, and, in particular Mr Takshin for the extremely efficient help and co-operation. The administration and the miners of the Nakhlak Mining Company and village showed us extreme kindness and hospitality. This manuscript has been improved by stimulating suggestions of the reviewers, A. Robertson and A. Baud. Warm thanks also to the editorial board, and especially to M.-F. Brunet, for support and stimulation. Very special thanks to F. S. Aghib, for her patience throughout the days, nights and weekends required for writing this paper.

Appendix 1

GPS co-ordinates (WGS84 system) of the 13 statistic sites for petrographic analysis of conglomerates within the Bāqoroq and Ashin formations. The two sites in the Alam Formation (AL1 and AL2) are located in the Nakhlak 6 section (Fig. 19).

The sites AS1–AS3 and BQ1 are located at very close distance, in the same stratigraphic section.

AS1–AS3	33°33′26″	53°50′02″
BQ1	same as AS1	
BQ2	33°33′27″	53°49′51″
BQ3	33°33′12″	53°50′06″
BQ4	33°33′08″	53°50′04″
BQ5	33°33′00″	53°50′04″
BQ6	33°32′55″	53°50′08″
BQ7	33°32′52″	53°50′09″
BQ8	33°32′47″	53°50′11″
BQ9	33°32′42″	53°50′09″
BQ10	33°32′40″	53°50′13″

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