The Ordovician System in the Levant region (Middle East) and southern Turkey: review of depositional facies, fauna and stratigraphy

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Olaf Elicki[1*], Tim Meischner[1], Semih Gürsu[2], Jean-François Ghienne[3], Ahmad Masri[4], Khaled Ali Moumani[4], Huriye Demircan[5]

[1] TU Bergakademie Freiberg, Geological Institute, Freiberg 09599, Germany

[2] Muğla Sıtkı Koçman University, Department of Geological Engineering, Kötekli-Muğla 48000, Turkey

[3] Institut Terre et Environnement de Strasbourg (ITES, UMR 7063), CNRS-Université de Strasbourg, 5 rue R. Descartes, 67000 Strasbourg, France

[4] Ministry of Energy and Mineral Resources, Geological Mapping Division, Amman 11814, Jordan

[5] General Directorate of Mineral Research and Exploration, Department of Geological Research, Ankara 06520, Turkey

ORCID ID: Olaf Elicki, 0000-0001-6624-5025; Jean-François Ghienne, 0000-0002-9448-5285; Semih Gürsu, 0000-0001-5303-7948, Huriye Demircan, 0000-0001-9883-8650

Present address: Olaf Elicki, TU Bergakademie Freiberg, Geological Institute, Bernhard-von-Cotta Street 2, Freiberg 09599, Germany

*Corresponding author (e-mail: Olaf.Elicki@geo.tu-freiberg.de)

Abstract

This contribution addresses the current state of knowledge of the mainly siliciclastic Ordovician rocks in Jordan, Syria and southern Turkey including advances in palaeontology, stratigraphy, depositional facies analysis and supra-regional correlation.

The extensive and excellent exposures of the sedimentary succession in southern Jordan represent the regional reference for the Ordovician System in the southern Levant. We discuss the sedimentological and faunal characteristics as well as the stratigraphy and correlation of the succession. For the northern Levant (especially southeastern Turkey) and the western and eastern Taurides, the Ordovician succession and an updated sedimentary architecture is explained and a comprehensive correlation for the region is presented. Increased knowledge on the fossil content from these regions enables correlation across the southern parts of the Arabian Plate to southern Turkey, and with the greater Gondwanan regions, far-field as southwestern Europe and northern Africa. The depositional environments in the southern and northern Levant and southern Turkey encompass non-marine to shallow-marine areas in the lower part of the Ordovician that are followed upsection by shelf deposits of variable proximity up to the glacial episode in the Late Ordovician that is tracable in each of the areas. Characteristic signals in the Ordovician succession are represented by the trans-regional early Darriwilian unconformity and by the base of the Hirnantian glacial-related deposits followed by lower Silurian strata, visible across the entire region. New data from zircon-based provenance analysis clearly implicate the Arabian Shield as the main source of the huge

amount of the clastic detritus within the the Ordovician succession. In the course of the entire Cambrian-Ordovician interval, progressive deeper erosion of the Arabian Shield occurred. Sediment sources from regions farther away indicate long time of exposure and resedimentation, and some long-distant transportation, but their sedimentary influence was only of minor extent. The excellent outcrops mainly in southern Jordan, in southeastern Turkey and in the Taurides represent potential regions for further research.

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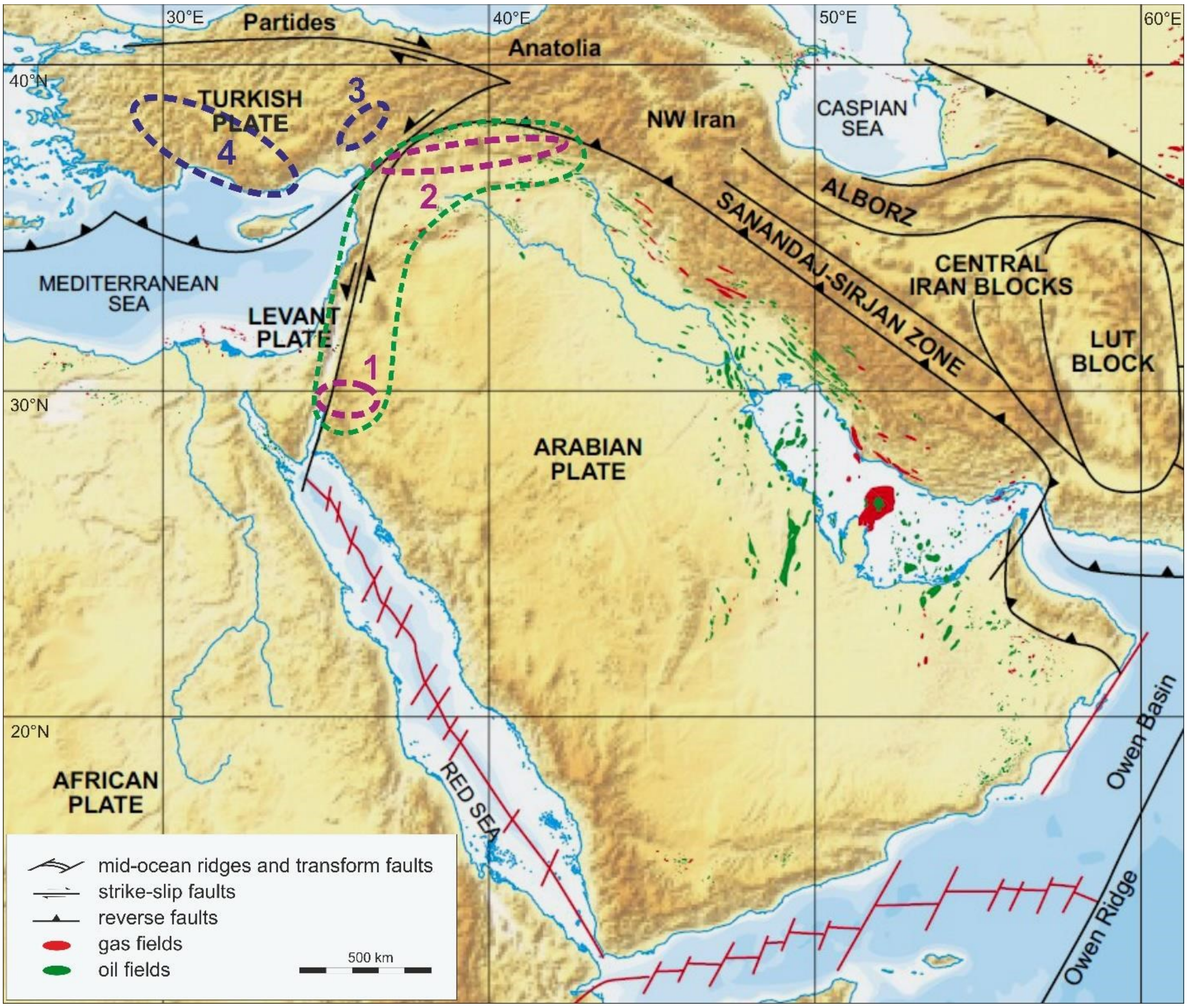
The geographic territory of the Middle East that roughly includes the historic areas of Jordan, Palestine, Lebanon and Syria (respective parts of them) is often referred to as the "Levant". The area extends from the eastern Mediterranean coast up to western Mesopotamia, and from southern Anatolia north of the Syrian border, to the Red Sea in the South, what is more-or-less synonymous with the western arc of the so-called *Fertile Crescent*. Geologically, the region is represented by parts of the Arabian Plate, the Levant Plate and by the marginal parts of the Anatolian Plate (Turkish Plate) (Fig. 1). Major regional structural elements include the SSW–NNE trending Dead Sea Transform Fault, the Palmyra Fold Belt which extends approximately WSW–ESE throughout central Syria, and the East Anatolian Fault Zone which represents the WSW–ESE oriented northern margin of the Arabian Plate.

In the southernmost part of the Levant region the prominent basement outcrops of the Arabian Shield (which is the eastern belt of the combined Arabian-Nubian Shield) are exposed in southern Jordan and Israel. Surface outcrops of Lower Palaeozoic successions are mostly restricted to the margins of these basement areas and to the shoulders of the Dead Sea Rift depression (Wadi Araba and Dead Sea valley until the northeastern margin of the Dead Sea near Wadi Zeraq Main in Jordan). Strata of this age are also reported, however, from subsurface farther north (see below). Generally, they are excised westwards due to several phases of uplift and denudation during the late Palaeozoic and Mesozoic (Powell, 1989; Weissbrod, 2004). At the surface, Palaeozoic rocks are not again exposed until the northern Levant, an area representing the most northern extension of the Arabian Plate close to the modern Syrian–Turkish border.

Information on the nature of the Ordovician sedimentary pile in the Levant is mainly based on the thick and well-preserved successions at the northern margin of the Arabian Shield in Jordan (related exposures on the Sinai Peninsula are considered by Vecoli and Molyneux in chapter 6 of this volume). Here, the Lower Palaeozoic was reported from the early-mid 20th century onward (e.g., Blanckenhorn, 1910; King, 1923; Richter and Richter, 1941; Picard, 1942; Quennel, 1951; Bender, 1968; Shinaq and Bandel, 1992; Amireh et al., 1994, 2008; Powell et al., 1994; Rushton and Powell, 1998; Elicki et al., 2002; Makhlouf, 2003; Schneider et al., 2007; Shinaq and Elicki, 2007; Elicki, 2011; Hofmann et al., 2012; Bandel and Salameh, 2013; Elicki and Geyer, 2013; Mángano et al., 2013; for further references see Elicki et al., 2020). More recent research and reports on the Ordovician from the area are in, e.g, Powell (1989), Makhlouf (1992), Amireh et al. (2001), Turner et al. (2005, 2012), Douillet et al. (2012), Masri et al. (2014), Makhlouf et al. (2017), Masri (2017), Meischner et al. (2019, 2020), Elicki et al. (2020), and from a number of reports of mapping campaigns led by the Jordanian Natural Resources Authority (NRA) and the Ministry of Energy and Mineral Resources (MEMR) of Jordan.

The Ediacaran to Ordovician sedimentary succession in general is unconformable on the predominantly granitoid Proterozoic basement and consists of a suite of marine, marginal-marine, and continental sediments (Sharland et al., 2001; Nehling et al., 2002; Makhlouf, 2003; Khalifa, 2015). Stratigraphic gaps due to denudation are common (Masri et al., 2014; Elicki et al., 2020). Intense silicate weathering during the late Cambrian and Ordovician produced enormous amounts of siliciclastic sediments (Avigad et al., 2005, 2017) assumed to be predominantly supplied by the eroding Arabian Shield (Powell, 1989). More locally, younger Palaeozoic strata are present. Among them, Silurian sediments follow unconformably deposits of the global Late Ordovician (Hirnantian) glacial episode, whereas younger Palaeozoic rocks, of Permian age, are only sporadically preserved (e.g., Keegan et al., 1990; Makhlouf, 1991; Mustafa, 2003; Armstrong et al., 2005; Lüning et al., 2005; Uhl et al., 2007; Loydell et al., 2009; Bandel and Salameh, 2013;

Fig. 1. Regional Map and tectonic setting in the Middle East. Levant region is framed by green broken line. The discussed areas in the southern and in the northern Levant are indicated by purplecoloured ellipses (1 – southern Levant / southern Jordan, 2 – northern Levant and South Anatolian Autochthon Belt / Border Folds); Taurid regions are indicated by blue-coloured ellipses (3 – eastern Taurides, 4 – western Taurides). Reproduced from Sharland et al. (2001) with permission of Gulf Petrolink.



Stephenson and Powell, 2013; Blomenkemper et al., 2018, 2021). Bender (1968) speculated that Palaeozoic strata younger than the Silurian may have originally been present throughout Jordan, too, because they are partly known from adjacent areas in Syria, Saudi Arabia and from the Sinai Peninsula, but they may have been eroded during the later Palaeozoic and the Mesozoic. Powell (1989) mentioned post-Llandovery

Lower Palaeozoic strata from boreholes in Jordan's north-east region. Together with Bandel and Salameh (2013) they further noted the occurrence of Lower Devonian sediments in deep exploration wells in the SE near to the Saudi Arabian border (northernmost extension of the Tabuk basin), but neither provided any more detailed information or references. So, from surface exposures, Ordovician strata –the focus of this contribution – within the Levant region are nearly exlusively known from southern Jordan. Minor outcrops occur on northernmost Arabian Plate of central-north Syria (see below). Albeit limited, subsurface data, in contrast, indicate a distinctly wide distribution of Ordovician strata, however, also in the area in between, but concealed by Cenozoic to Mesozoic sedimentary cover of up to several thousand meters in thickness.

According to Sharland et al. (2001) deposition of Ordovician siliciclastic sediments at the northern rim of the Arabian-Nubian Shield occurred on the Gondwanan passive margin and represents a second tectonostratigraphic megasequence within the Arabian Plate, that lasted from the later early Cambrian until the Late Ordovician. It is generally agreed that during the Ordovician the Levant region was palaeogeographically situated in high southern latitudes. According to Scotese (2001, 2014), Golonka (2002), Ruban et al. (2007), Torsvik and Cocks (2013, 2017), Cocks and Torsvik (2021) and others a position of about 55° to 65° South or even more is reasonable (Fig. 2). Within this latitudinal zone the region migrated only moderately to the north. Significant sea-level fluctuations and a general cooling trend is recognisable thoughout the Ordovician (e.g., Cocks and Torsvik 2021) from relatively warm and humid at the beginning of the period to periglacial conditions culminating in the Late Ordovician glaciation episode (Saharan glaciation; Hirnantian glaciation), indicated by the development of typical glacigenic lithofacies in southern Turkey and in the Levant (see below). From the southern region of the latter, Turner et al. (2012) suggested glacial episodes also during the Middle Ordovician (Darriwilian).

The aim of this contribution is to give an updated introduction and an overview on the Ordovician deposits of the Levant region and in southern Turkey by considering results from recent research. For more details, sedimentary columns, figured fossils and sedimentary structures, the reader is referred to the cited literature.

Ordovician of the southern Levant

In the southern Levant (as currently understood; see above) Ordovician strata are exclusively known from southern Jordan (figs 1 and 3). In Israel, the Cambrian succession is unconformably overlain by Cretaceous sediments (Segev, 1984). But, in close vicinity to its southern border, the Ordovician sandstones of the Upper Araba Formation and Naqus Formation (pars) are known from the Sinai Peninsula (Khalifa, 2015; see Vecoli and Molyneux, this volume).

The siliciclastic Ordovician succession in southern Jordan is up to 1000 m thick and commences with fluvial strata at the beginning of the period (Tremadocian) with marine-influenced deposition in the

Fig. 2. Palaeogeography of the main landmasses in the Late Ordovician and location of the Hirnantian glaciation center. Position of the Levant-Taurid region is indicated. Modified after Sharland et al. (2001) and Cocks and Torsvik (2021).

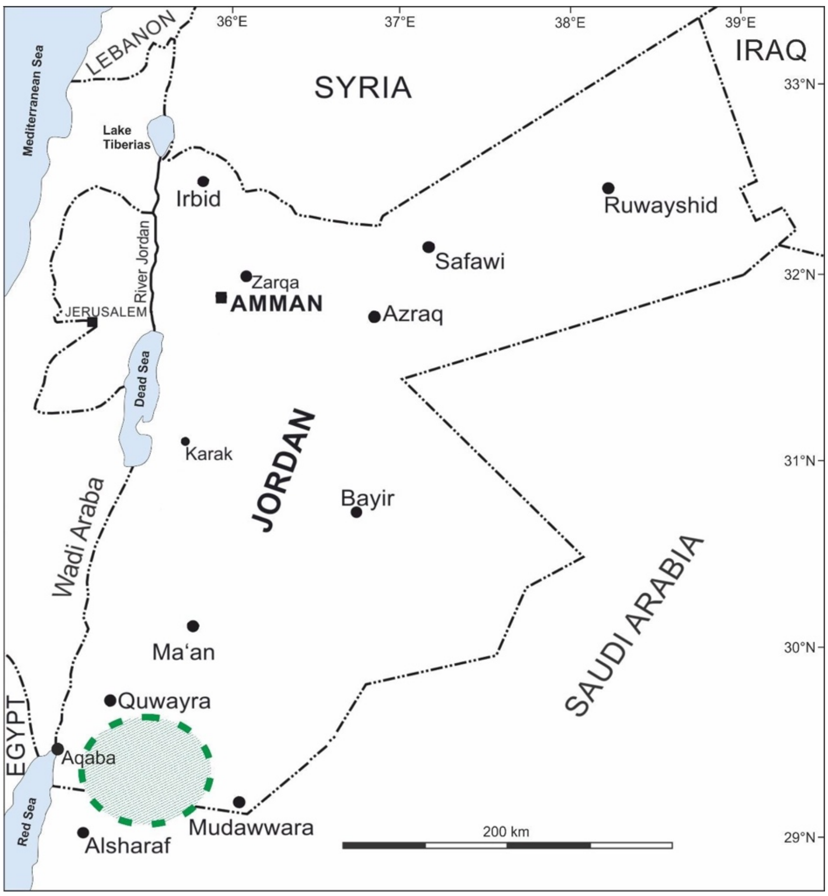


Fig. 3. Geographic map showing the distribution of Ordovician surface successions in southern Jordan, east of Aqaba. Due to quality and completeness of the sedimentary record, southern Jordan represents the reference region of the Ordovician in the southern Levant. In the subsurface, sediments of that age are widely distributed over significantly larger areas (for details see text).

Floian. The marine transgression from the east to north-east occurred during the late Early to Middle Ordovician. Up until the end-Ordovician the depositional area represented an epeiric and slowly subsiding shelf-sea with only few phases of instability or prominent sea-level fluctuations, that prompted unconformities or changes in sediment type. Most relevant research on the subject was published by Bender (1968), Selley (1970), Powell (1989), Makhlouf (1992, 1998), Abed et al. (1993), Amireh et al. (2001), Turner et al. (2005, 2012), Schneider et al. (2007), Masri et al. (2014), Douillet et al. (2012), Makhlouf et al. (2017), Meischner et al. (2019, 2020) and Elicki et al. (2020), (see for further research and references) and by a large number of bulletins and map explanations from mapping projects carried out by the Geological Survey of Jordan (NRA, MEMR).

The Ordovician in southern Jordan can be subdivided in six formations belonging to two lithostratigraphic groups (compare Fig. 10 below): (1) the Ordovician part of the Ram Group with the higher Disi Formation and the Umm Sahm Formation, and (2) the Ordovician part of the Khrayim Group with the Hiswah Formation, the Dubaydib Formation, the Tubayliyat Formation, and the Ammar Formation (Masri, 1988, 2007; Abu Lihie, 1988; Masri et al., 2014; Elicki et al., 2020). Ram Group and Khrayim Group are separated by an unconformity. Whereas the lower boundary of the Ordovician is transitional within the Ram Group, the Ordovician upper boundary (within the Khrayim Group), in contrast, is represented by another unconformity, in fact a disconformity linked to end-Ordovician glaciation.

The **Disi Formation** is characterised by up to 380 m of light (“white”) sandstones and minor siltstones (Khalil, 1994). In the subsurface the formation was drilled by a number of petroleum wells in central and northern Jordan – Teimeh et al. (1990) reported a thickness of up to more than 1100 m. The lowest part of the unit consists dominantly of massive, trough cross-bedded and planar bedded fluvial braidplain sandstones (large-scale subaqueous dunes and channels; palaeocurrent direction to the north / north-north-west), it is partly conglomeratic and periodically interrupted upsection by marginal to fully marine incursions (Moumani, 2003). Various authors have reported the occurrence of trace fossils from the upper part of the Disi Formation: *Cruziana furcifera*, *C. goldfussi*, *C. rugosa*, *Gyrochorte zigzag*, as well as *Diplichnites*, *Ichnyspica*, *Incisifex*, *Tasmanadia*, *Merostomichnites*, and rusophycids (Powell, 1989; Amireh et al., 2001; Moumani, 2003; for full list see Meischner et al., 2020). A Tremadocian (Early Ordovician) age is indicated for the upper part of the Disi Formation. Because the Disi Formation evolves continuously (change in colour from brown to white) from the Miaolingian to Furongian (middle to upper Cambrian) Umm Ishrin Fromation, a Furongian (late Cambrian) age of the fluvial, non-fossiliferous 130 m of the lower Disi Formation is largely accepted.

The overlying **Umm Sahm Formation** reaches a thickness of up to 300 m in southern Jordan. As for the underlying Disi Formation, the thickness of the Umm Sahm Formation increases towards the east, i.e., toward the Tabuk basin of Saudi Arabia (Masri et al., 2014). In the subsurface, the formation has a wider regional distribution, but is absent from southwest and central Jordan as well as from the northern Highlands (Teimeh et al., 1990). The Umm Sahm Formation consists of thick trough cross-bedded and tabular cross-bedded quartz-arenite with thin beds of micaceous siltstone. The lower boundary of the Umm Sahm Formation is gradational and marked by its characteristic colour change from white to brown (“brown-weathering sandstone” of Bender, 1968). The lower part of the formation represents a fluvial-dominated, deltaic braidplain environment with meandering streams. No fossils are known from this section. The upper part of the Umm Sahm Formation shows a decrease in deltaic influence, temporarily returning to marine facies with a tidally influenced lower to upper shoreface including subaqueous dunes and sand waves. The rare occurrence of channels is reported by Powell (1989) from the upper part of the Umm Sahm Formation. In heterolithic lithologies, marine deposition is clearly indicated by abundant typical marine trace fossils such as cruzianids (e.g., *Cruziana furcifera*, *C. goldfussi*, and *C. rugosa*) and *Skolithos*, *Planolites*, *Diplichnites* and *Merostomichnites.* Masri et al. (2014) mentioned the graptolite *Didymograptus* cf. *bifidus* from the uppermost part of the Umm Sahm Formation. Due to its fossil content and to the assigned Tremadocian age of the strata below (Disi Formation, see above), and due to the appearance of the Darriwilian graptolite *Didymograptus murchisoni* within the overlying Hiswah Formation (see below), a Floian to Dapingian (late Early to early Middle Ordovician) stratigraphic position of the Umm Sahm Formation is confirmed.

According to Powell (1989) the Umm Sahm Formation represents a somewhat transitional depositional unit between the predominantly fluvial conditions of the upper Ram Group below and the marine conditions of the Khrayim Group above. Above the Umm Sahm Formation there is an unconformity marking the onset of a distinct transgressive phase and therefore the beginning of the Khrayim Group that contains all the higher Ordovician (and Silurian) strata.

The oldest unit of the Khrayim Group is represented by the **Hiswah Formation**. This unit consists of a 50 m to 70 m thick succession of fine to coarse clastics that can be divided into a lower, mainly finegrained portion, and an upper, coarser-grained portion. As for the underlying Umm Sahm Formation, the Hiswah Formation has a large regional distribution, subsurface and has an increasing thickness (up to about 150 m) towards the north-east, but is absent from southwest and central Jordan and from the northern Highlands (Teimeh et al., 1990). The base of the Hiswah Formation is characterized by a graptolite-bearing sandstone horizon (on top of trough-cross-bedded, brown weathering Umm Sahm sandstones) with rippled surfaces, overlain by red-green fossiliferous shales. The Hiswah Formation has a predominantly "shaly" habit with a sandstone cap and thus it forms a characteristic morphological element in the landscape and an identifiable feature in aerial photographs and in geophysical logs. The lower part of the Hiswah Formation (HS1) consists of red, mauve and greenish, laminated, distal mudstones with only occasional thin beds of rippled siltstone. The upper part (HS2), however, is more proximal and contains sandstone-siltstone alternations with some hummocky cross-stratification (in its lower part) and trough cross-bedding, ripple crosslamination and planar cross-lamination indicating shallower-water conditions.

Whereas the predominantly shale and fine-grained silt to sandstone of the lower Hiswah Formation represents deposition in a pelagic outer, open-marine, siliciclastic upper offshore to outer shelf environment (within or beneath the storm wave base; maximum of the marine transgression) under low-energy conditions (Meischner et al., 2019), in the coarser grained upper Hiswah Formation the environment returns to higher energy foreshore to shallow upper shoreface conditions (Fig. 4). For the shaly subunit (HS1) water depths of 200 m at least are concluded by Meischner et al. (2019), the greatest water depth within the entire Ordovician succession in this region. This general depositional model for the Hiswah Formation is also supported by the fossil content of the two subunits. HS1 yields the planktonic graptolite *Didymograptus murchisoni* (formerly, erroneously determined as *Didymograptus bifidus*, see Meischner et al., 2019) and the small benthic obolid brachiopod *Palaeoglossa* cf. *attenuata* as the most common element. Further remarkable fossils are of the problematic arthropod *Hanadirella* cf. *bramkampi* (and a second, indeterminate species) and the very rare cephalopod ?*Dideroceras* sp. – most were typical pelagic organisms. The shallow-water facies HS2, in contrast, contains the noted (and transported) graptolite only rarely, but *Skolithos* burrows and rusophycid and cruzianid traces occur. This fauna gives good indication of a (middle to) late Darriwilian age (late Middle Ordovician) for the Hiswah Formation. Palaeogeographically, the taxa are related to northern and northeastern Saudi-Arabia and to the high to mid-latitude region of the Gondwanan margin in general (Meischner et al., 2019).

The **Dubaydib Formation** (165 m thick) overlies the upper Hiswah Formation. The unit is recognised from the subsurface too, but it is absent from the Northern Highlands and from central and southwest Jordan (Teimeh et al., 1990). Also here the largest thickness (up to 1300 m subsurface) is in the most North-east part of Jordan. The lower boundary of the Dubaydib Formation is very clearly marked by the onset of thin bedded sandstone, that is intensely bioturbated by *Skolithos* (= densily spaced burrows of *Sabellarifex*, see Meischner et al., 2020). This about 35 m thick "*Sabellarifex* sandstone" succession, where some flat channels may be present, represents the entire lower part of the formation and is overlain by massive sandstone bodies. Whereas the lower part of the succession represents a lower intertidal marine and shallow subtidal environment, higher up the sandstones and siltstones with some shales in the upper and somewhat heterolithic portion of the Dubaydib Formation was deposited on the lower foreshore to upper shoreface and mid-shelf. Typical and confirmatory sedimentological structures are, e.g., hummocky cross-stratification, trough cross-bedding, channels, planar cross-bedding, parallel lamination and ripple crosslamination (Turner et al., 2012; Masri et al., 2014).

Marine trace fossils occur at several levels within the Dubaydib Formation. *Skolithos* (= *Sabellarifex*) is common in the lower part ("pipe-rocks", "Spaghetti-rocks"), but may also occur upsection, too, but by not in the enormous frequency as previously. Additionally, arthropod and other traces (e.g., the ichnogenera *Cruziana, Diplichnites, Merostomichnites, Rouaultia, Rusophycus, Arthrophycus*) and some brachiopods, are present. The fossils suggest a latest Darriwilian to Sandbian age for the Dubaydib Formation (latest Middle to early Late Ordovician).

The Dubaydib Formation is succeeded by the **Tubayliyat Formation** with a total thickness of about 200 m (subsurface, in northeastern Jordan a thickness up to 1300 m is suggested by Teimeh et al., 1990). The base is defined by the occurrence of an up to 15 m thick varicoloured siltstone to finegrained sandstone bed, distinctly different from the lithology of the Dubaydib Formation below (Powell, 1989). In older publications and reports this formation was described as part of the socalled "Tubayliyat Member" (TB1 and TB2), part of the former "Mudawwara Formation" a term which is abandoned in more recent literature. The unit (and the whole higher Ordovician lithostratigraphy) has been re-defined and re-named by Elicki et al. (2020). The Tubayliyat Formation consists of sheet like beds of thin-bedded silty sandstones and siltstones with extensive ripple crosslamination and hummocky cross-stratification. Shallow marine upper and lower shoreface deposits are characteristic of the Tubayliyat Formation. The fossil content includes a few *Cruziana flammosa*, *C. perucca*, *C. lineata* and *C. petraea*, and *Arthrophycus, Skolithos*, as well as brachiopods (e.g., *Orbiculothyris*, *Trematis*), and a reported assemblage of acritarchs and chitinozoans (pers. comm. of Molyneux, 1986, mentioned in Powell, 1989). They indicate a Katian age (Late Ordovician).

The highest Ordovician lithostratigraphic unit is the **Ammar Formation** (Abed et al., 1993; Amireh et al., 2001). This formation includes what in older literature was called the upper part of the former "Tubayliyat Member" (= TB3 and TB4 of Masri et al., 2014; compare Powell et al., 1994; Armstrong et al., 2005; Elicki et al., 2020). The same interval is referred to as the Risha Fm. in the subsurface of NE Jordan (Hirst and Khatatneh, 2019). The Ammar Formation includes all the upper Hirnantian (Ashgill) glacial related

Fig. 4. Reconstruction model of the depositional environment of the Hiswah Formation and habitats of the biota preserved by fossil assemblages according to Meischner et al. (2019, slightly modified). Reprinted from Meischner et al. (2019: p. 60, slightly modified), with permission of Elsevier.

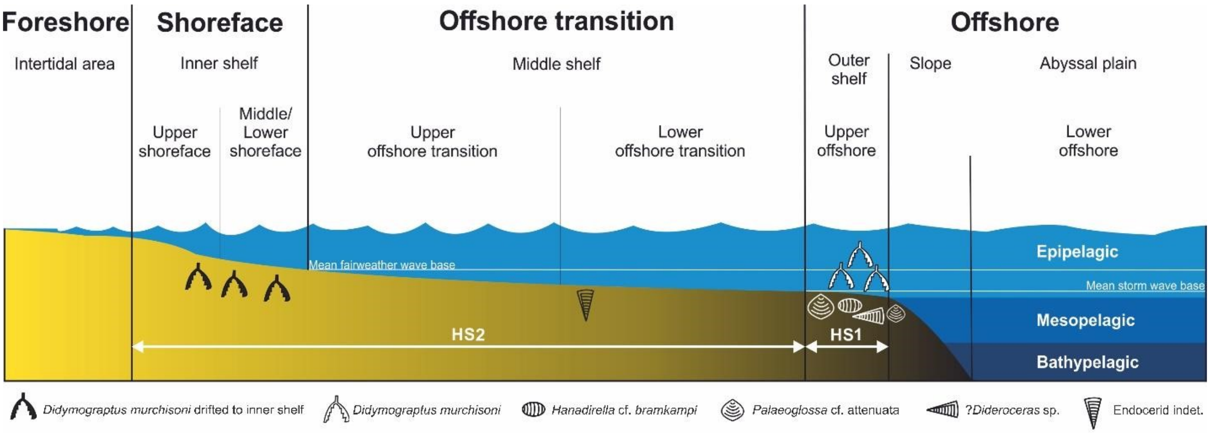
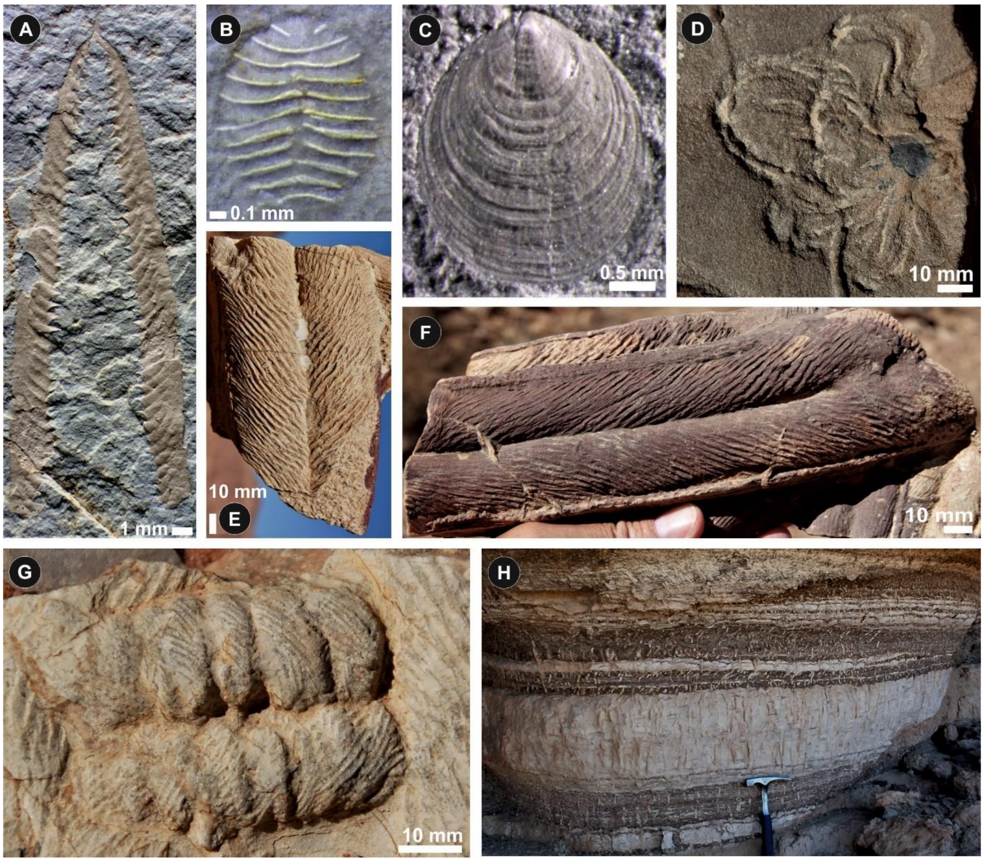


Fig. 5. Characteristic fossil content of the Ordovician suite in southern Jordan (Meischner et al. 2019, 2020). (A) planktonic graptolite *Didymograptus murchisoni* (Beck in Murchison, 1839), lower Hiswah Formation; (B) arthropod *Hanadirella* cf. *bramkampi* El-Khayal, 1985, lower Hiswah Formation; (C) obolid brachiopod *Palaeoglossa* cf. *attenuata* (Sowerby, 1839), lower Hiswah Formation; (D) trace fossil *Zoohycus* sp., upper Hiswah Formation; (E-G) trilobite trails *Cruziana furcifera* d'Orbigny, 1842 (E), *Cruziana goldfussi* Rouault, 1850 (F), and *Cruziana rugosa* d'Orbigny, 1842 (G), all from upper Disi Formation; (H) piperock of lower Dubaydib Formation showing mass occurrence of *Skolithos linearis* Haldeman, 1840 (in older literature synonymously reported as *Sabellarifex*; for discussion see Meischner et al. 2020).



sediments (glacio-fluvial facies, post-glacial shoreface, shales) and can reach a thickness of up to about 150 m in the axis of the palaoevalleys, with restricted thickness outside (Abed et al., 1993; Powell et al., 1994; Turner et al., 2005; Douillet et al., 2012; Masri, 2017). The lower part of the Ammar Formation is represented by shoreface sandstones, glacial channel fills and palaeo-valleys known from scattered, isolated outcrops. The lithology mostly consists of fine-grained to coarse-grained sandstone, sometimes with a diamictite texture due to large subangular exotic clasts. Interestingly, sparse brachiopods and *Skolithos* are also reported (Masri et al., 2014). This part is overlain by alternating thin beds of shale and sandy siltstone of the upper Ammar Formation, locally with trace fossils and ripple marks as indication of shallow marine conditions. According to Armstrong et al. (2005) the glaciation in Jordan ended in the late Hirnantian *persculptus* Biozone.

Above the Ammar Formation there is a distinct unconformity on which Silurian deposits sit. The finegrained offshore clastics (shales and siltstones) of this sedimentary cover represents the Batra Formation which is equivalent to the upper part of the abandoned Mudawwara Formation in older literature (Elicki et al., 2020). The boundary between the Silurian and the underlying Ordovician glacial deposits of the upper Ammar Formation is lithologically sharply defined and supported by the appearance of typical early Silurian graptolites within the unconformably overlying Batra Formation (= marine flooding after the Ordovician glacial event; e.g., Powell, 1989; Loydell, 2007; Masri et al., 2014).

It should be noted that relatively rich assemblages of acritarchs and chitinozoans have been reported from a number of wells from a northern area of the southern Levant by Keegan et al. (1990). The authors described four palynozones from eastern Central Jordan (three wells in the Wadi Sirhan area) and from northeastern Jordan (six wells in the Risha area) representing an “Ashgillian assemblage” (Hirnantian, latest Ordovician) with the index fossils *Veryhachium subglobosum, Villosacapsula setosapellicula, Armoricochitina nigerica, Desmochitina minor* and *Orthosphaeridium* cf. *inflatum*; and a “Caradocian to early Ashgillian assemblage” (Sandbian to early Hirnantian, Late Ordovician) with *Actinotodissus crassus, Baltisphaerosum bystrentos, Peteinosphaeridium nudum* and *Orthosphaeridium bispinosum*. A “Llanvirnian assemblage” (Darriwilian, Middle Ordovician) consists of the index taxa *Stelliferidium striatulum, Baltisphaeridium klabavense* and *Frankea Iongiuscula/sartbernardensis* whereas index taxa of a “Tremadocian assemblage” (lower Early Ordovician) comprise *Cymatiogalea cuvillieri, C. membranispina, Dasydiacrodiurn* cf. *palmatilobum* and *Vulcanisphaera* cf. *africana*. The association of the assemblages with lithostratigraphic units (formations) was not attempted by those authors.

Zircon-based provenance studies in the southern Levant

Geochronological provenance data for Ordovician sediments from Jordan are relatively rare. The only research on zircon-based provenance was published by Kolodner et al. (2006, from the Umm Sahm and Dubaydib formations), and by Elicki et al. (2020, from the lower Hiswah, the middle Dubaydib and the Tubayliyat formations). Thus, with the exception of lowermost and the uppermost Ordovician strata, related zircon data for each of the Ordovician formations of southern Jordan are available. The typical fine-grained mature sandstones of the Disi Formation have not provided suitable zircons, and from the Ammar Formation no material has been investigated so far (but, see the outline paragraphs below on the provenance of glacial material in the northern Levant and southern Turkey, and Fig. 9). In southern Jordan 85 % of all recognised ages from zircons from the Ordovician siliciclastics are Proterozoic, with a very clear predominance of Neoproterozoic and late Mesoproterozoic ages. Zircons from the Umm Sahm Formation generally show a very similar age spectrum as those for the Cambrian strata below, that is characterised by clearly dominant Neoproterozoic zircons (575–986 Ma). From the lower to higher Hiswah Formation, the age spectrum is shifted slightly to somewhat older ages from 534–631 Ma to 597–991 Ma (discussion in Elicki et al., 2020), that is a similar trend compared to the Cambrian strata below. The zircon ages of the overlying Dubaydib Formation are quite similar to those of the Hiswah Formation (582–969 Ma), but, the number of Palaeoproterozoic and Archean ages, however, increases. This is a tendency that continues into the Tubayliyat Formation above, where only 40 % of all zircons are still of

Neoproterozoic age. Here, in contrast, a majority of about 60 % is Meso- to Palaeoproterozoic. This phenomenon is interpreted by the mentioned authors by a deepening of the erosional level in the hinterland throughout the Cambrian-Ordovician evolution due to increased exposure of older basement and continued intense denudation.

Elicki et al. (2020) indicated in the closely located Arabian-Nubian Shield the main source of Neoproterozoic to Mesoproterozoic detrital zircons present in the entire Cambrian-Ordovician sandstone suite of southern Jordan. Nevertheless, for the Cadomian Gondwanan regions today farther north, Avigad et al. (2017), Ben Dor et al. (2018) and Stephan et al. (2019) have speculated additional potential sources in present-day North Africa (Saharan Metacraton) or in the southern regions of the East African Orogen. The occurrence of the minor proportion of Palaeoproterozoic and Archean zircons may support the assumption of the existence of more distant additional source areas.

Ordovician of the northern Levant and southeastern Turkey

Gondwanan related upper Neoproterozoic to Lower Palaeozoic basement successions are located in Syria and in southeastern Turkey in different tectonic units of the South Anatolian Autochthon (SAAB, details in Göncüoğlu, 1997, 2010; Ghienne et al., 2010). The Late Ordovician palaeogeographic position of the region is shown in Fig. 2. Whereas Lower Palaeozoic outcrops in Syria are exclusively subsurface (see below), they are continuous with outcrops in southeastern Turkey mainly in the Hakkari (Samurdağ), Mardin (Derik), Mardin (Bedinan), Adıyaman (TutPenpegli), Kahramanmaraş (İnderesi), Kahramanmaraş (Uludaz), and Hatay (Hassa) areas within the SAAB (Fig. 6).

Syria

The Lower to Upper Ordovician succession of Syria is exclusively known from the subsurface and consists of marine sandstones and shales (Sawaf, 1993) as indicated by a number of wells in the vicinity of the Aleppo Plateau (NW Syria), of the Palmyrides (central Syria), of the Jebel Abd el Aziz and the western extension of the Sinjar Uplift of NE Syria approximately 50 to 70 km south of the Turkish border (Husseini, 1990; Barrier et al., 2014). Regional unconformities are reported as common. Seismic logs indicate a shallow layering of the strata that are somewhat faulted by younger tectonics. The thickness of the Ordovician strata is reported as possibly more than 2.3 km. The Lower Ordovician comprises the sandstone dominated Khanasser Formation, whereas the Middle Ordovician Swab Formation is of shale lithology, and the Upper Ordovician Afendi Formation is of sandstones again (Brew et al., 1999). The general lithological succession is roughly similar to that known from the southern Levant region (see above). The large-scale depositional environment during the Ordovician is interpreted as relatively shallow shelf. Former authors (Sudbury, 1957; Flügel, 1963; Weber, 1964; Bogdanova et al., 1969) described a fauna from the Jezireh region (the area between the Euphrates and Tigris rivers) containing graptolites, but their taxonomic

Fig. 6. Geographic distribution of Lower Palaeozoic sediments in southern Turkey. Border Folds area is at the northern rim of the Arabian Plate and so, it is partly belonging to the northern Levant region in the context in this paper. Reproduced from Ghienne et al. (2010: p. 103, slightly modified), with permission of Elsevier.

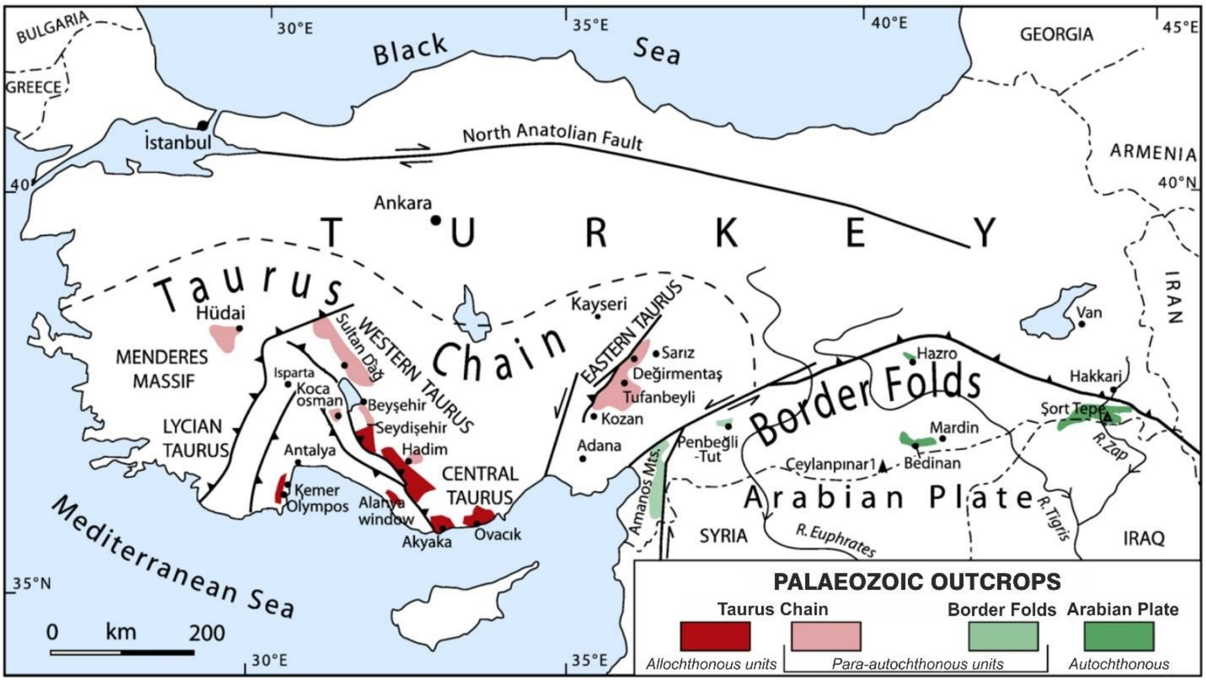
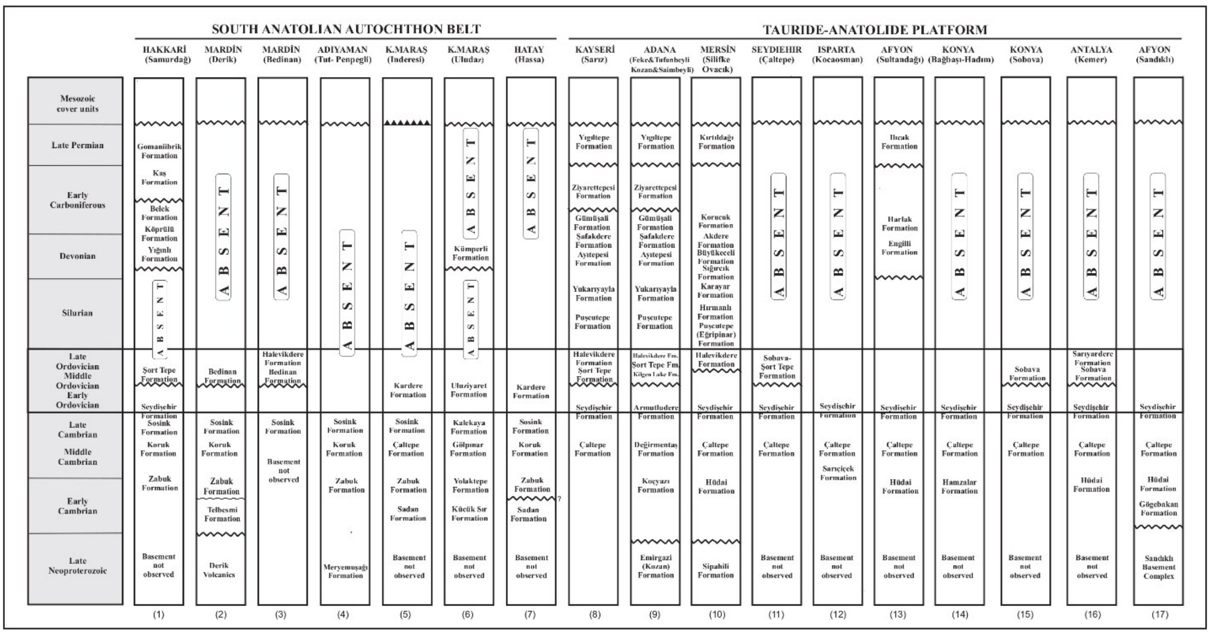


Fig. 7. Correlation of the Neoproterozoic–Palaeozoic outcrops in the SAAB and TAP. (1) Dean (2006); (2) Kellog (1960), Dean et al. (1981); (3) Monod et al. (2003); (4) Dean et al. (1997); (5) and (6) Usta et al. (2015); (7) Dean et al. (1986); (8) Özgül et al. (1972), Monod et al. (2003); (9) Özgül and Kozlu (2002); (10) Demirtaşlı (1984), Kozlu et al. (2002); (11) Dean and Monod (1979); (12) Gürsu et al. (2003); (13) Özgül et al. (1992); (14) Dean and Özgül (1981); (15) Sarmiento et al. (2002); (16) Göncüoğlu and Kozur (1999), Ghienne et al. (2010); (17) Dean and Özgül (1994).



determination must be largely doubted today and needs revision. According to Jörg Maletz (pers. comm. 2022) the taxonomic diversity of the graptolite fauna is low, but may represent a Sandbian to Katian stratigraphic age. Further fossils reported by Sudbury (1957) and Flügel (1963) include brachiopods (*Lingula* cf. *rugosa*, *Lingula* sp., *Sowerbyella*? sp.), trilobites (*Colpocoryphe arago*, *Pseudobasilicus* cf. *nobilis*), and the machaerid annelid worm *Plumulites* cf. *fraternus*. A SandbianKatian age is supported by the occurrence of *C. arago* and *P. fraternus.*

In the Amanos Mountains (next to NE shore of the Mediterranean Sea, compare Fig. 6) the nonfossiliferous shales are petrographically compared to Ordovician fossiliferous (?)equivalents in the Bahçe region (Turkey, see below); cruzianids from this area support such a stratigraphic correlation.

A few further fossil occurrences are briefly listed in Bogdanova (1969) and Ejel and Abdul Rahim (1974), but, these are rather problematic and are probably not stratigraphically significant.

South Anatolian Autochthon Belt (SAAB)

Rock types, biostratigraphy and palaeontology

In the Hakkari area, Middle Cambrian trilobite-bearing carbonate rocks of the Koruk Formation are conformably overlain by silty shale dominated, siliciclastic rocks with nodular limestone lenses at the base (compare Fig. 7). They continue with shale-sandstone alternations in the upper Cambrian to Lower Ordovician Seydişehir Formation displaying silty shale dominated siliciclastic rocks at the base and afterwards with shale/sandstone alternations. The Ordovician is disconformably overlain by Upper Devonian Yığınlı Formation (Dean, 1975, 2006; Dean et al., 1981; Dean and Monod, 1997).

Lower to Upper Ordovician successions in the Mardin (Bedinan) area are unconformably underlain by the middle to late Cambrian siliciclastic rocks of the Sosink Formation and disconformably overlain by Cretaceous platform-type carbonates (Ghienne et al., 2010). The lower part of the Upper Ordovician Bedinan Formation starts with storm-dominated fine-grained siliciclastic rocks and continues with cross-bedded sandstones. Sandbian to Katian ages were proposed for the Bedinan Formation in the Mardin (Bedinan) area based on graptolites, brachiopods and trilobite faunas (*Calymenella boisseli*, *Dreyfussina* sp.) by Kellogg (1960), Dean (1967, 1983), Dean and Monod (1990), and on chitonozoans by Paris et al. (2007). The succession is unconformably overlain by the Hirnantian glacial unit, the Halevikdere Formation (Monod et al., 2003). Additionally, Oktay and Wellman (2019) have recently reported a new chitinozoan and acritarch fauna from the lower to upper parts of the Bedinan Formation by evaluation of rock fragments from a well near Diyarbakır area. They assigned the *moussegoudaensis/oulebsiri* biozone for the upper parts of the formation, expanding northward the spatial distribution of the glaciation-related Halevidere Formation.

Ordovician outcrops have been reported from the Derik (Mardin), from Tut-Pen Pegli (Adıyaman) and Bahçe areas and from the Uludaz Nappe (Kahramanmaraş) area in the SAAB. In the Uludaz Nappe, the basement rocks start with lower Cambrian meta-siliciclastic rocks of Küçük Sır and Yolakdere formations and continue with middle Cambrian trilobite bearing recrystallised carbonates (Usta et al., 2015). The succession is conformably overlain by trace fossil bearing the metasiliciclastic rocks of the Kalekaya Formation (e.g., *Cruziana goldfussi, C. rugosa, C. furcifera;* Fig. 8), (Demircan and Usta, 2012, Demircan et al., 2012), and meta-siliciclastic rocks of the Middle to Late Ordovician Uluziyaret Formation with unidentified trace fossils and trilobite remains (Usta et al., 2015). The Lower Palaeozoic units are unconformably overlain by Upper Devonian siliciclastic rocks of the Küperli Formation and Cretaceous cover units (Usta et al., 2015). In the Bahçe Nappe, lower Cambrian (meta-siliciclastic rocks of Dedeler and Zabuk formations) and middle Cambrian (mainly calcareous Çaltepe Formation) is overlain by the upper Cambrian to Lower Ordovician Seydişehir Formation with *Cruziana* ichnofacies trace fossils from a tide-dominated shallow marine environment (*Arthrophycus*, ?*Circulichnis*, *Cruziana*, *C. furcifera, C. imbricata, C. rugosa, C. goldfussi, Deadulus*, *Didymaulichnus*, *Diplocraterion*, *Monocraterion*, *Monomorphichnus*, *Teichichnus*, *Skolithos*, *Palaeophycus*, *Planolites*, *Rusophycus*, *Protovirgularia*, *Trichophycus*)(Demircan and Usta, 2012) (Fig. 8). The succession is conformably overlain by the meta-siliciclastic rocks of the Kardere Formation with a well-preserved and nearly identical Early Ordovician arthropod and vermiformtype trace fossils (but, with *Bergaueria* instead of *Arthrophycus* and ?*Circulichnis*) (Demircan et al., 2016a, b). The Lower Palaeozoic sequences are unconformably overlain by the meta-siliciclastic rocks of the Upper Devonian Hamzabeyli Formation (Usta et al., 2015).

Lower to Upper Ordovician successions have been reported in the SAAB from the Mardin (Derik) region and from trace fossil bearing strata in the Adıyaman (Tut-Penpegli), Hakkari (Samurdağ), Kahramanmaraş (İnderesi and Uludaz Nappes), Hatay (Hassa) and Mardin (Bedinan) areas.

Sedimentological Features

Based on long-term major transgressive and regressive events and subsequent shelf progradation, Ghienne et al. (2010) classified the Cambrian-Ordovician sequences as depositional sequences. The Cambrian Depositional Sequence 2 is conformably overlain by Depositional Sequence 3, commencing in the Cambrian essentially includes Tremadocian, Floian and Dapingian strata, but, a stratigraphic hiatus is reported at the boundary between the Depositional Sequences 3 and 4 (see also Fig. 11, below). Depositional Sequence 4 relates to rocks of Darriwilian, Sandbian, Katian and early Hirnantian ages in the SAAB and TAP.

In the SAAB, Depositional Sequence 3 starts with shallow-marine strata (storm and offshore dominated siliciclastic rocks) of the highest Cambrian to Lower Ordovician Seydişehir Formation in the Zap valley near Hakkari area (Martin, 1996; Dean, 2006; Ghienne et al., 2010) and is disconformably overlain by fine-grained siliciclastic rock of the Upper Ordovician Şort Tepe Formation (Bedinan Formation). Lower to Middle Ordovician successions represent Depositional Sequence 4 and are known from the Kahramanmaraş and Hatay area (Kardere Formation and Uluziyaret Formation). They conformably overlie the upper Cambrian Sosink Formation and are composed of meta-siliciclastic rocks deposited in a high-energy shallow marine environment (best preserved in the Kahramanmaraş area, İnderesi Nappe and Uludaz Nappe, and in the Hatay/Hassa area; Usta et al., 2015). The Sandbian to Hirnantian Ordovician succession (Depositional Sequence 4), is exclusively cropping out near Mardin (Bedinan) with an angular unconformity at the regional scale above the underlying upper Cambrian Sosink Formation due to regional tectonic uplift of the

Mardin High between late Cambrian and Sandbian (Bozdoğan and Erten, 1990; Ghienne et al., 2010).

A recent study (Ghienne et al., 2010) shows that here the Sandbian to lower Katian Bedinan Formation starts with storm-dominated fine-grained siliciclastic rocks at the base and continues with high-frequency, storm-dominated, offshore to shoreface cycles and cross-bedded sandstones. The suite is later truncated by the upper Katian to Hirnantian glaciation-related deposits (Paris et al., 2007; Monod et al., 2003) of the Halevikdere Formation.

Ordovician of Central southern Turkey

Tauride-Anatolide Platform (TAP)

Outside the South Anatolian Autochthon additional Gondwanan related upper Neoproterozoic to Lower Palaeozoic successions occur in the area of the Tauride-Anatolide Platform (TAP; Göncüoğlu, 1997; Ghienne et al., 2010). Here, the Lower Palaeozoic outcrops are mainly located in the eastern Taurides (ET) within the Kayseri (Sariz) and Adana (Feke, Saimbeyli, Tufanbeyli) areas, and in the Central and Western Taurides (CT, WT) within the Mersin (Silifke-Ovacık), Seydişehir (Çaltepe), Isparta (Kocaosman), Afyon (Sultandağı, Sandıklı), and Konya (Bağbaşı-Hadim) regions. Outside the Taurides sensu stricto Ordovician rocks are recognised close to Antalya (Kemer area) (Fig. 6, Fig. 7).

Rock types, biostratigraphy and palaeontology

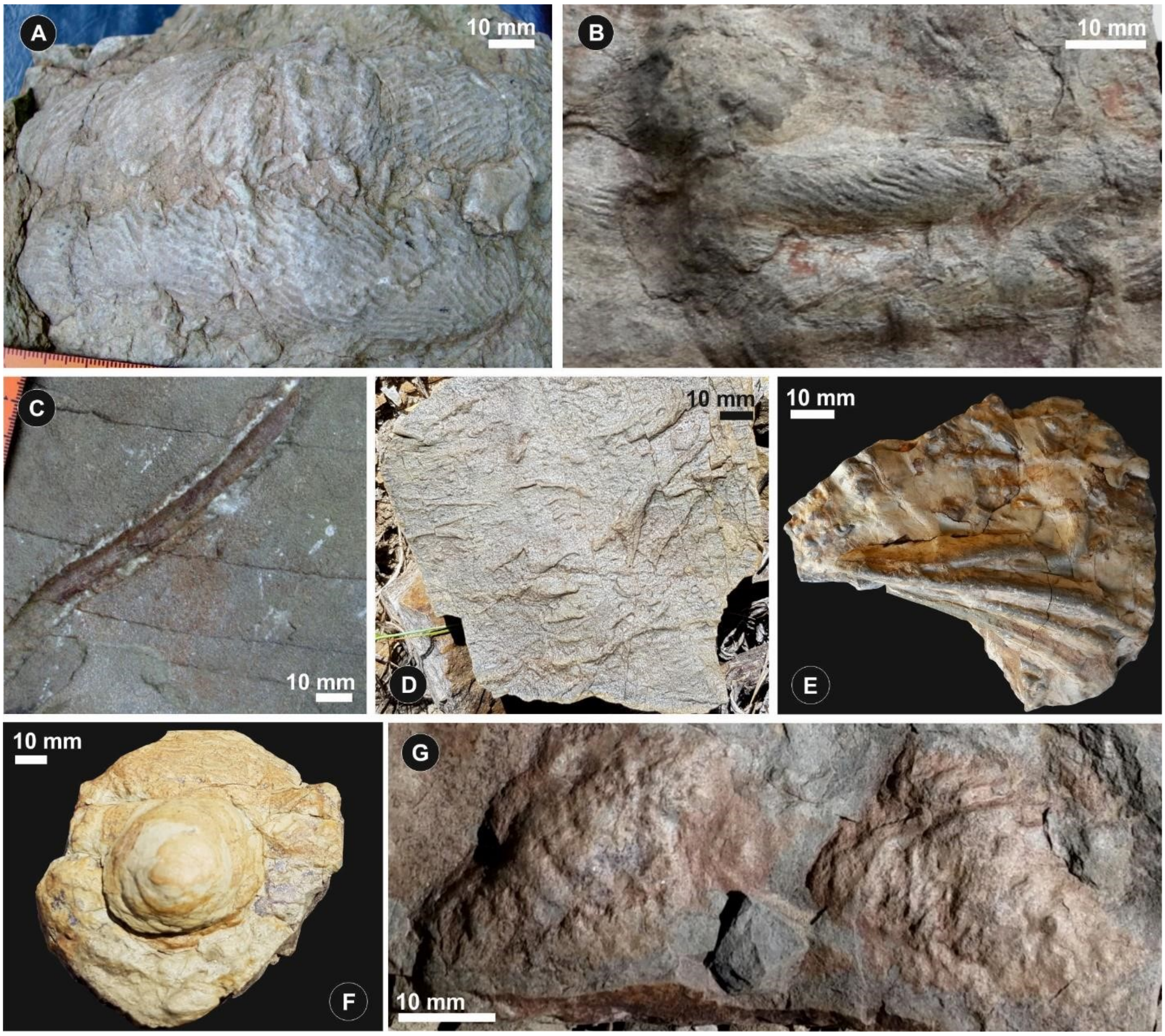
In the Feke-Tufanbeyli-Saimbeyli-Kozan (Adana, ET) region, the basement unit consists of the upper Neoproterozoic Emirgazi (Kozan) Formation, that is disconformably overlain by lower Cambrian meta-siliciclastic rocks of the Koçyazı Formation, and by middle Cambrian trilobite bearing (*Paradoxides* sp.) meta-carbonates of the Çaltepe Formation (Özgül et al., 1973; Kozlu and Göncüoğlu, 1997; Özgül and Kozlu, 2002). The succession has a transitional contact with metasiliciclastic rocks (with trilobites, graptolites, brachiopods and trace fossils) of the upper Cambrian to Lower Ordovician Armutludere Formation and continues upwards into the fossiliferous Upper

Ordovician meta-siliciclastic rocks of Şort Tepe Formation (Özgül et al., 1973; Özgül and Kozlu, 2002; Monod et al., 2003). The conodonts *Acodus*? sp., *Ansella jemtlandica*, *Baltoniodus navis*, *B.* cf. *navis*, *B. norrlandicus*, *Baltoniodus*? sp., *Cornuodus longibasis*, *Drepanodus* sp., *D. arcuatus*, *D.* cf. *planus*, *Drepanoistodus basiovalis*, *D.* cf. *basiovalis*, *D. bellburnensis*?, *D. forceps*, *Lenodus* sp., *Microzarkodina* sp., *Protopanderodus rectus*, *Protopanderodus* sp., *Scolopodus rex*, *Trapezognathus* sp., *Triangulodus brevibasis* and *Tropodus*? sp., as well as a chitinozoan fauna were reported from the Şort Tepe Formation in the Kozan-Adana area and were attributed to the *Baltoniodus norrlandicus* biozone representing an early Darriwilian age (Sarmiento et al., 2003). In the same area, Paris et al. (2007) identified a chitinozoan fauna with *Cyathochitina campanulaeformis*, *Desmochitina minor*, *D. cocca*, *L. clavata, Linochitina pissotensis*, various *Conochitina* and *Belonechitina* species and *Tanuchitina* aff. *ontariensis, Belonechitina*, *Conochitina*, *Euconochitina, Calpichitina* sp., *Cyathochitina* ssp., suggesting a Darriwilian to Sandbian age. The succession is disconformaby overlain by the glacial succession of the Hirnantian Halevikdere Formation (Monod et al., 2003). Near the base, an acritarch assemblage of *Baltisphaeridium* cf. *hirsutoides*, *Baltisphaeridium* spp., *Multiplicisphaeridium bifurcatum*, *Ordovicidium heteromorphicum*, *Peteinosphaeridium* cf. *bergstroemi*, *P. trifurcatum intermedium*, *Polyancistrodorus intricatus*, *Solisphaeridium nanum*, *Veryhachium trispinosum* and *Villosacapsula irroratumre* from the highest Ordovician (Hirnantian) were identified by Paris et al. (2007). The Palaeozoic units continue upwards with lower Silurian to Upper Permian units in the ET.

One of the best regions with continuous Lower Palaeozoic successions is located near the Değirmentaş village in the Sariz-Kayseri (ET) area. The basement rocks include the middle Cambrian Çaltepe Formation with disarticulated shelly fossils and echinoderms, followed by the upper Cambrian (Furongian) to Lower Ordovician (Tremadocian) conodont bearing offshore siliciclastics of the Seydişehir Formation (Özgül et al., 1972; Monod et al., 2003; Göncüoğlu et al., 2004, 2012). The succession is disconformably overlain by Upper Ordovician (Katian) outer shelf siliciclastics of the Şort Tepe Formation and the glaciomarine outwash fan to distal glaciomarine to offshore siliciclastic sediments of the Hirnantian Halevikdere Formation (Özgül et al., 1972; Monod et al., 2003; Ghienne et al., 2012; Ghienne and Kozlu, 2012). The stratigraphic age of the Şort Tepe Formation is indicated by chitinozoans (*Cyathochitina, C. latipatagium*, *Desmochitina minor*, *Euconochitin*a aff. *communis*, *Lagenochitina)* and acritarchs (*Actinotodissus crassus*, *Baltisphaeridium* spp., *Multiplicisphaeridium* cf. *irregulare*, *Orthosphaeridium*, *Villosacapsula irrorata*, *Veryhachium,* cryptospores, leiospheres, triapsidate veryhachiids, *Baltisphaeridium, Dactylofusa platynetrella*), as well as by trilobite assemblages (Dean and Monod, 1990; Paris et al., 2007). Lower Silurian to Upper Permian sediments follow conformably on the Lower Palaeozoic succession in the Sarız-Kayseri area (Özgül et al., 1972). In Silifke-Ovacık (CT), the succession begins with upper Neoproterozoic meta-siliciclastic rocks and meta-volcanic rocks-dominated Sipahili Formation and is disconformably overlain by metasiliciclastic rocks of the lower Cambrian Hüdai Formation. Meta-carbonates of the middle Cambrian Çaltepe Formation and of the upper Cambrian to Middle Ordovician (upper Darriwilian) metasiliciclastic rocks of the Seydişehir Formation follow upwards (Demirtaşlı, 1984; Gül, 1990; Koç et al., 2005). The latter formation contains abundant conodonts (*Complexodus originalis*, *Sagittodontina kielcensis*, *Baltoniodus* sp., *Drepanoistodus* sp., *Panderodus* sp., *Semiacontiodus* n. sp. A, *Cornuodus longibasis*, *Scalpellodus gracilis*?, *Scalpellodus* sp., *Lenodus* sp*.*, *Ansella*? n. sp., *Microzakodina* cf. *hagetiana*) and chitinozoans (*Conochitina* sp. and Conochitinidae), (details in Kozlu et al., 2002; Paris et al., 2007). The Hirnantian Halevikdere Formation rests disconformably on the basement rocks and in the Mersin-Silifke-Ovacık area it is followed by fossiliferous lower Silurian to Upper Permian successions (Demirtaşlı, 1984; Kozlu et al., 2002; Koç et al., 2005; Gürsu et al., 2017, 2018). In the Seydişehir (Çaltepe, CT), Isparta (Kocaosman, CT), Afyon (Sultandağı, CT), Konya (BağbaşıHadım, CT), Konya (Sobova, CT) and Afyon (Sandıklı, WT) areas, upper Cambrian to lower Middle Ordovician (lower Darriwilian) meta-siliciclastic rocks of the Seydişehir Formation rests conformably on the middle Cambrian Çaltepe Formation and are unconformably overlain by the Darriwilian Sobova Formation (Dean and Monod, 1970; Dean and Özgül, 1981; Özgül et al., 1992). A fauna of conodonts (*Baltoniodus norrlandicus*, *Drepanodus arcuatus*, *D.* cf. *arcuatus*, *D.* cf. *planus*, *Drepanodus* sp., *Drepanoistodus forceps*, *Drepanoistodus* sp., *Cornuodus* cf. *longibasis*, *Lenodus*? sp., *Microzarkodina* sp., *Protopanderodus calceatus*, *Protopanderodus* sp., *Scolopodusrex, Triangulodus*? sp.), acritarchs (*Coryphidium bohemicum*, *Ericanthea pollicipes*, *Polygonium acuminosum*, *Striatotheca rarirugulata*) and sphaeronitid blastozoans (*Diploporita, Aristocystitida*, *Asteroblastida*, *Protocrinitida, Sphaeronites*, *Diplosphaeronis*) support a Middle Ordovician (latest Dapingian to earliest Darriwilian) depositional age for the Sobova (Bedinan) Formation in the Sobova-Konya area (Sarmiento et al., 1999; Paris et al., 2007, Nardin et al., 2014). Similarly, chitinozoans (*Conochitina, Euconochitina, Belonechitina* sp., *Cyathochitina campanulaeformis*, *Yathochitina* sp.) and acritarchs (*Peteinosphaeridium*, *Aremoricanium rigaudae)* indicate a middle late Darriwilian age (Middle Ordovician) of the Sobova Formation in the Seydişehir-Çaltepe area (Paris et al., 2007). Middle to Upper Ordovician successions are missing in the Isparta (Kocaosman, CT), Afyon (Sultandağı, CT), Konya (Bağbaşı-Hadım) and Afyon (Sandıklı) areas.

In the Kemer area (Antalya Nappes), the basement succession starts with the middle Cambrian Çaltepe Formation and continues with the upper Cambrian to Lower Ordovician Seydişehir ormation. Göncüoğlu

Fig. 8. Cambrian-Ordovician trace fossils from southeastern Turkey (Demircan et al., 2016a, b; Demircan and Usta, 2012). (A) *Cruziana rugosa* d'Orbigny, 1842, lower part of the Kardere Fm., Lower Ordovician; (B) *Cruziana goldfussi* Rouault, 1850, lower part of the Kardere Fm., Lower Ordovician; (C) *Trichophycus* isp., lower part of the Kardere Fm., Lower Ordovician; (D) ?*Monomorphichnus* isp., lower part of the Seydişehir Fm., upper Cambrian to Lower Ordovician; (E) *Phycodes circinatum* Richter, 1853, lower part of the Seydişehir Fm., upper Cambrian to Lower Ordovician; (F) *Bergaueria* isp., lower part of the Seydişehir Fm., upper Cambrian to Lower Ordovician; (G) *Rusophycus* isp., lower part of the Seydişehir Fm., upper Cambrian to Lower Ordovician.



and Kozur (1999) identified the conodonts *Phakelodus tenuis*, *P. terashimai*, *Furnishina furnishi*, *Furnishina* sp., *Cordylodus lindstromi*, *Eoconodotus* sp., *Paltodus varanguensis*, *Drepanodus?* sp., and *Paltodus* sp., indicating a late Cambrian to early Tremadocian depositional age for the nodular lower parts of the Seydişehir Formation. From a similar red nodular limestone near Kemer, Gedik (1977) reported a conodont fauna consisting of *Drepanoistodus forceps*, *Microzarcodina flabellum*, *Baltoniodus triangularis*, *Acontiodus arcuatus*, *Oistodus inaequalis*, *Trapezognathus triangularis* and *Oepikodus evae*, and suggested an early Tremadoc to middle Arenig (Early Ordovician) depositional age for the Seydişehir Formation (refined to Floian according to L. Popov, pers. comm.). Katian lower offshore fossiliferous siliciclastic rocks of the Sarıyardere Formation (the chitinozoans *Euconochitina* sp., *Cyathochitina* sp. according to Paris et al., 2007) continue upwards. This is overlain by the glaciomarine shelf-deposited Hirnantian Halevikdere Formation (Dean et al., 1999; Ghienne et al., 2010).

Sedimentological Features

Depositional Sequence 3 (see above for explanation of the defined depositional sequences) starts with the meta-siliciclastic rocks of the Seydişehir Formation affected by low-grade metamorphism and imbricated due to the Alpine orogeny. These upper Cambrian (Furongian) siliciclastic rocks represent a transgressive system and condensed sedimentation (Ghienne et al., 2010). The succession is composed of alternations of shoreface fine-grained sandstones, inner to outer shelf offshore shales and silts, and red nodular limestone horizons at the base with a fauna indicating a Tremadocian age (Haude, 1975; Özgül et al., 1972; Göncüoğlu et al., 2004). The upper part of the formation is composed of an alternation of macrofossil bearing siltstones and sandstones indicating a Floian and early Middle Ordovician age (Dean and Monod, 1970; Monod, 1967). Sedimentological features of the upper Cambrian to Lower Ordovician Seydişehir Formation corresponds to the similarly short-term regressive succession in the Hakkari (Zap) area (Dean, 2006; Ghienne et al., 2010). In the CT, the formation is composed of siltstone-sandstone alternations displaying bioturbation, wave ripples, climbing ripples, cogenetic ripples and gutter casts typical of a stormdominated, shallowing-upward facies (Ghienne et al., 2010). The conodont and chitinozoan faunas indicate a depositional age of late Darriwilian (Middle Ordovician) for the upper parts of the formation (Sarmiento et al., 2003; Kozlu et al., 2002; Paris et al., 2007). Ghienne et al. (2010) reported thin tidal-dominated siliciclastic rocks in a proximal depositional environment from upper parts of the Seydişehir Formation what is comparable to equivalent units in the TAP. Depositional Sequence 4 of the TAP rests disconformably on the Depositional Sequence 3.

Stratigraphically, Ghienne et al. (2010) classified the Depositional Sequence 4 as Darriwilian, Sandbian to Katian, and Hirnantian. In the Kayseri (Sariz, ET), Adana (Feke-Tufanbeyli-Saimbeyli-Kozan, ET), Seydişehir (Çaltepe, CT), Konya (Sobova, CT) and Antalya (Kemer, CT) areas the Depositional Sequence 4 starts with the lower Darriwilian Şort Tepe (Sobova) Formation (Dean and Monod, 1970; Dean, 1973; Sarmiento et al., 2003), (Fig. 7). The succession begins with thick limestones deposited in shoreline backsteps reflecting distal conditions. They continue upwards with condensed sedimentation at high sea-levels (Ghienne et al., 2010). Middle to upper Darriwilian parts of the formation represent delta sediments with flute casts and current ripples, especially in the outcrops in the CT. Equivalent outcrops in the ET are composed of meta-siltstones and intraformational conglomerates with overlying meta-sandstones of deltaic or mass-flow deposition during fast and forced regression (Paris et al., 2007; Ghienne et al., 2010). The middle unit of Depositional Sequence 4 in the CT is mainly composed of regionally diachronous thick siltstones to fine-grained sandstones of generally fine-grained storm-dominated successions. Equivalent sequences in the

ET are made up of graptolite-bearing siltstones and fine-grained sandstones of a non-subsiding outer shelf to upper-slope depositional environment with bottom-current sand deposits (Paris et al., 2007; Ghienne et al., 2010).

The Hirnantian Halevikdere Formation begins with sandy diamictites, massive coarse-grained conglomeratic sandstones from the glaciomarine outwash, and clay bearing sandstones. This continues upwards with distal glaciomarine grading upwards to offshore shelf deposits of clayey sandstone-siltstone/mudstone alternations in the Adana (Kozan, Feke, Saimbeyli), Mersin (SilifkeOvacık), and Antalya (Kemer, CT) regions (Monod et al., 2003; Ghienne et al., 2010, Gürsu et al., 2017). Abundant erosion-based coarse-grained sandstone lenses with striated facets, dominant quartz clasts, a few felsic pebbles, and reworked micro- and macrofauna in the glaciomarine sequence have been reported from outcrops of the TAP and SAAB (Monod et al., 2003; Ghienne et al., 2010; Gürsu et al., 2018).

Hirnantian glaciation and related zircon-based provenance studies in southern Turkey

Late Ordovician (Hirnantian) glaciomarine deposits are best exposed in the Mardin-Bedinan (SAAB), Adana-Kozan (ET), Adana-Feke-Saimbeyli (ET), Adana-Tufanbeyli (ET), and Mersin-Silifke-Ovacık (CT) areas (e.g., Cater and Tunbridge, 1992; Bozdoğan et al., 1996; Göncüoğlu, 1997; Göncüoğlu and Kozlu, 2000; Ghienne et al., 2010; Özgul and Kozlu, 2002; Monod et al., 2003; Göncüoğlu et al., 2004; Paris et al., 2007; Gürsu et al., 2017). Previous studies have shown that glaciation-related successions (Halevikdere Formation) have two diamictite units that identify a lower and upper glacial cycle separated by condensed offshore shales in the Kemer area (Monod et al., 2003; Ghienne et al., 2010). In the Degirmentas-Kilgen Lake area, however, the two cycles are amalgamated, separated by a glacial pavement. Granitic and sedimentary lonestones, some of which are deposited as dropstones, are best exposed in the glaciomarine successions within the diamictites of the lower glacial cycle, especially in the outcrops at Adana-Kozan-Feke-Saimbeyli-Tufanbeyli (ET) and MersinSilifke-Ovacık (CT) areas, respectively. The glaciomarine succession in the SAAB rests unconformably on the Katian siliciclastic rocks of the Bedinan Formation and continues upwards with sandy diamictites, massive coarse-grained conglomeratic sandstones, clay bearing sandstones and clayey sandstone-siltstone/mudstone alternations (Ghienne et al., 2010; Gürsu et al., 2017). In the TAB the glaciomarine succession rests disconformably on the Lower Ordovician (Tremadocian to Floian) Seydisehir Formation in the Adana-Feke-Gökmenler area (ET, with a Darriwilian to Sandbian unit in between; see Ghienne et al., 2010; Kozlu and Ghienne, 2012), and in the Mersin-Silifke-Ovacık area. In the Adana-Kozan (ET), Adana-Feke-Gökmenler (ET), Adana-Tufanbeyli (ET) and Antalya-Kemer (CT) areas, however, the glaciomarine successions are disconformable on top of the Katian (Late Ordovician) Şort Tepe Formation and Sarıyardere Formation (Gürsu et al., 2017). In the ET and CT, the glaciomarine succession starts with coarse-grained conglomeratic sandstones and pebbly sandstones with sandy diamictite. Upwards follow bedded sandy diamictites, coarse-grained laminated sandstones, sandstone lenses, pebbly sandstone (dropstones), and distal shallow marine fine-grained sandstone lenses and sandy / muddy diamictites (details in Monod et al., 2003; Ghienne et al., 2010).

Geochronological characteristics of the rock fragments transported during glacial episodes combined with U-Pb dating offer extensive evidence for determining the provenance of the glaciomarine sands and other dropstones. Based on zircon U-Pb geochronology, Gürsu et al. (2017, 2018) evaluated the provenance of granitic and sedimentary pebbles of the diamictites. All studied diamictite samples were from the lower part of the glaciomarine succession of the glacial cycle in the SAAB and TAP. Gürsu (2016) and Gürsu et al.

(2017, 2018) suggested that granitic pebbles in the CT and ET originated from the Neoproterozoic granitic/meta-granitic/meta-granodioritic rocks of the northern Nubian Shield (Egypt) and were transported to the TAP segments of Turkey by Late Ordovician ice sheets. The detrital zircon ages indicate a provenance close to the Cadomian basement of the periGondwanan terranes during the Late Ordovician. Kernel/probability density diagrams of ages from detrital zircons from the glaciomarine successions showed that they were derived from strata comparable to the middle/upper Cambrian siliciclastic rocks in the Israeli part of the Sinai Peninsula (southern Levant). Abundant upper Neoproterozoic detrital zircons with high percentages of Cryogenian ages from the CT indicate that this region was seemingly closer to the juvenile basement of the Arabian-Nubian Shield than its counterparts in the ET and SAAB. The provenance of the material of the glaciomarine successions in the CT and ET is directly correlated with magmatic activity in the Elat-Feinan island arc, the Sa'al island arc, and the post-collisional magmatic suites of the Sinai Peninsula. Coeval glaciomarine succession of the SAAB, however, may have been derived from the Ha'il/Afif terranes of the eastern Arabian Shield during the Late Ordovician glaciation (Fig. 9).

Correlation and conclusions

The Cambrian-Ordovician depositional evolution of the region was interpreted by Sharland et al. (2001) as comprising a distinct tectonic megasequence (extending from the lower Cambrian Salib Formation and Umm Gaddah Formation, to the Upper Ordovician Tubayliyat Formation and its equivalents plus the glacial deposits of the succeeding tectonic megasequence (Ammar Formation and its equivalents). Thus, a comparison of the southern Levant, the northern Levant, southern Turkey and Saudi Arabia is possible due to a common setting (Fig. 10). Characteristic for this region is, generally, that Lower and higher Middle to Upper Ordovician inner shelf clastics are separated by Middle Ordovician outer shelf shales (e.g., Konert et al., 2001; Garfunkel, 2002; Al Husseini, 2008; Ghienne et al., 2010; Masri et al., 2014). Based on recurrent sequence stratigraphic features, Ghienne et al. (2010) noted similar trends in the Lower Palaeozoic successions in the Taurides region over the entire area as far as the Arabian plate (Fig. 11). Additionally, there seems to be a remarkable similarity between the Early to Mid-Ordovician trace fossil assemblages and related depositional systems of the Levant and southwestern Europe and northern Africa (Meischner et al., 2019, 2020; Elicki and Magnus, 2021; Elicki, unpublished). These areas may offer a further potential correlative tool within this palaeogeographic domain.

Biostratigraphic data from the Ordovician successions are limited from the Levant and southern Turkey, because (i) relevant surface outcrops are missing over large areas (e.g., in the wide expanses of central and northern Jordan and in Syria), because (ii) wells (that currently exist) are mostly concentrated only in distinct regions (prospective basins), or because (iii) of erosion due to regional or local uplift and emergence (as for Israel and northwest Syria). Thus, the exact stratigraphic position of formation boundaries, and consequently the stratigraphic correlation of these units over distances are based for the large part on the lithostratigraphic characteristics alone and remain confused. A further problem is the often outdated taxonomic identifications of stratigraphically significant, but rare key fossils. A number of determinations are obviously problematic and need reevaluation. Figure 10 illustrates a synopsis by considering various stratigraphic data and suggestions (by lithostratigraphy, biostratigraphy, sequence stratigraphy, and log-data) from the southern and northern Levant and southern Turkey. Additionally, a stratigraphic scheme for Saudi Arabia is included for comparison.

The stratigraphic horizon showing the initiation of the Ordovician sedimentation, that is the exact Cambrian-Ordovician stratigraphic boundary, cannot be clearly fixed within the successions of the region due to facies changes in the depositional systems that are sometimes non-marine with rare fossils. In each of the areas mentioned in Fig. 10 this boundary is located within a transitional lithostratigraphic unit (formation). A distinct supra-regional signal is not developed until the early Middle Ordovician paraconformity at the base of the Hiswah Formation and its regional equivalents. In the Upper Ordovician the glacial-related „within Hirnantian“ unconformity is well articulated in most regions and represents a further supra-regional signal.

To achieve more detailed correlation of the Ordovician formations of the various areas the following research is needed: (i) an intensification of stratigraphic research on surface outcrops, e.g. in southern Jordan and Turkey, (ii) a critical re-evaluation of the hitherto reported palaeontological material from wells, and (iii) a combined stratigraphic evaluation considering all available geophysical data (log data and seismic profiles). Although fundamental changes in the stratigraphical and depositional model of the Ordovician in the Levant and southern Turkey regions is not expected, a refinement, however, of (a) the supra-regional correlation of depositional units and their detailed stratigraphic signature and extent, and (b) the larger scale palaeogeographic relations, especially to the more southerly located Ordovician successions of the Arabian Plate and northern Africa together with the southern to central European “Perigondwanan” regions.

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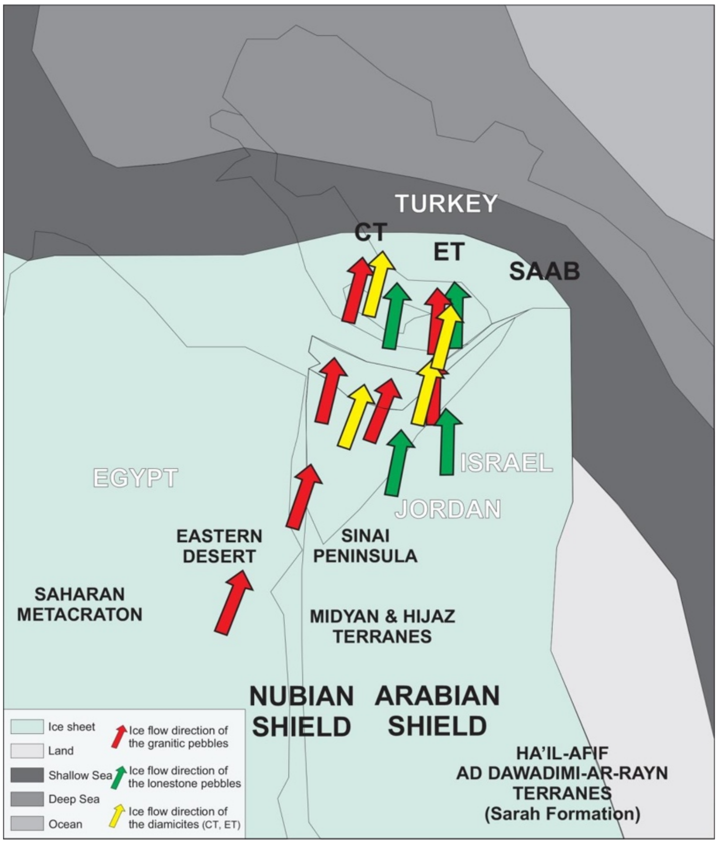


Fig. 9. Schematic reconstruction of the ice flows during the Late Ordovician glaciation in the southern part of Turkey. CT: Central Taurides; ET: Eastern Taurides; SAAB: Southeast Anatolian Autochthon Belt (Gürsu et al. 2017, 2018).

Fig. 10. General stratigraphic correlation of the Ordovician formations of the southern and northern Levant and of southern Turkey. The stratigraphic position of the subsurface formations in Central Syria (mainly Aleppo Plateau region) is not well constrained. Data according to Powell et al. (1994), Sharland et al. (2001), Alsharan and Nairn (2003), Al-Husseini (2008), Ghienne et al. (2010), Barrier et al. (2014), Masri et al. (2014), Meischner et al. (2019, 2020), Aqrawi et al. (2020), Elicki et al. (2020) and others.

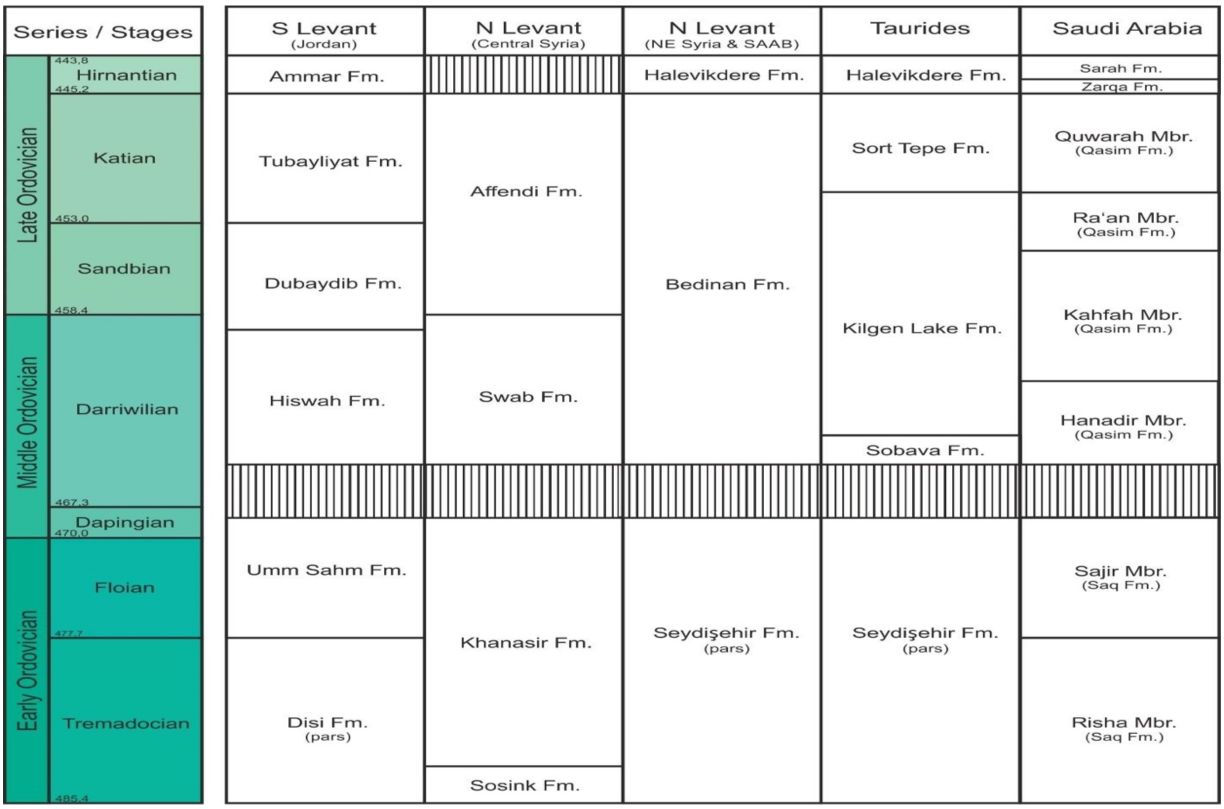
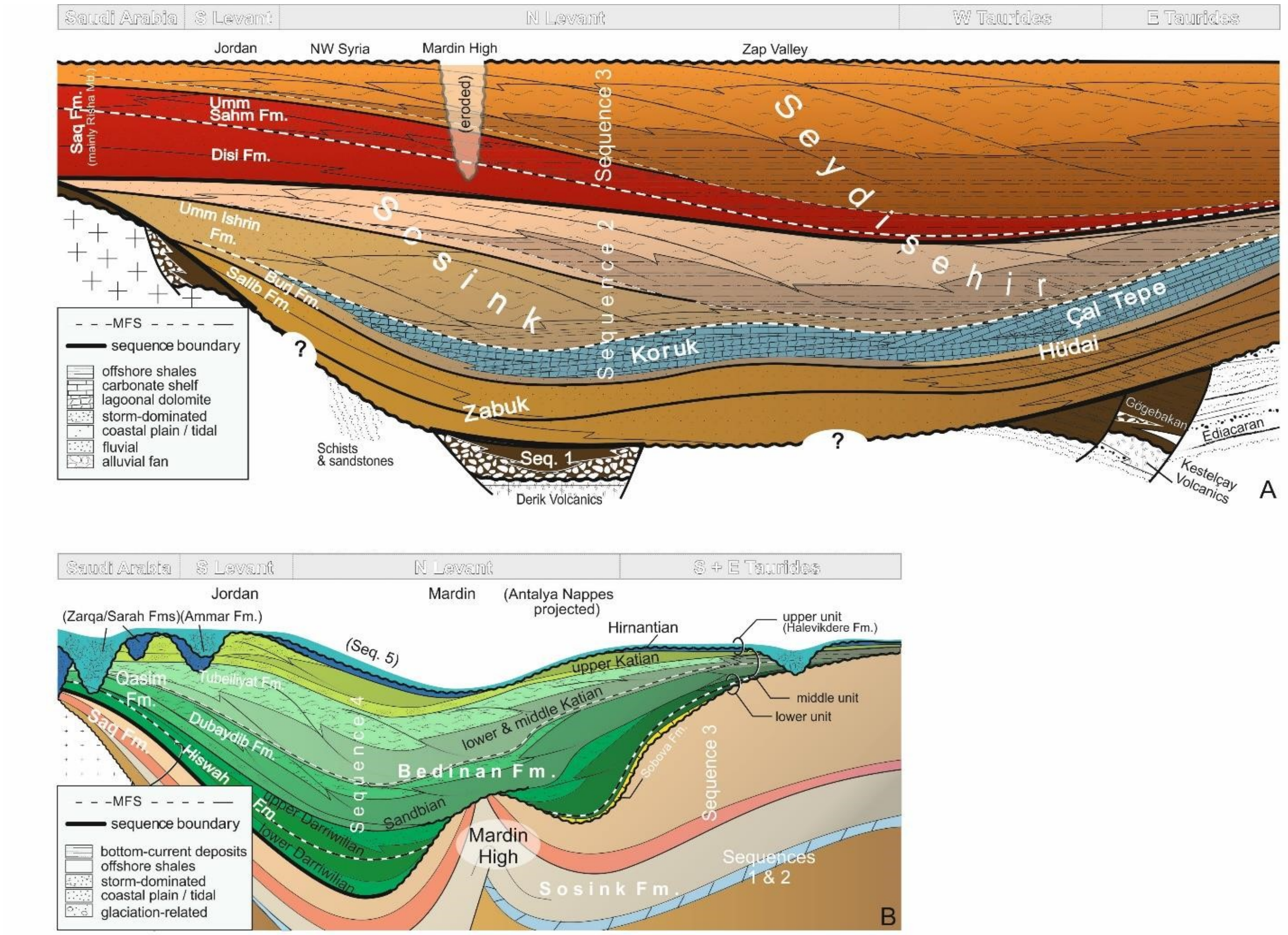


Fig. 11. Transregional architecture of the Cambrian to early Middle Ordovician Depositional Sequences 1 to 3 (A) and late Middle Ordovician and Late Ordovician Depositional Sequence 4 (B). "Mardin High" is a local uplift in the northern Levant due to Middle Ordovician tectonics. Upper Ordovician (Hirnantian) glacial deposits overlay a deeply incised erosion surface regionally reaching the Lower Ordovician (Taurides) and the Cambrian (Saudi Arabia). Reproduced from Ghienne et al. (2020: pp. 103, 109, slightly modified) with permission of Elsevier.



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