Comments on the geology of the Crimean Peninsula and a reply to a recent publication on the Theodosia area by Arkadiev et al. (2019): "The calcareous nannofossils and magnetostratigraphic results from the Upper Tithonian-Berriasian of Feodosiya region (Eastern Crimea)"

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Abstract: Here we assess the evidence for the placing of magnetic and fossil biozonal boundaries in Upper Tithonian to Lower Berriasian (Jurassic–Cretaceous boundary) sedimentary rocks on the Black Sea coast south of Theodosia (Ukraine): that is, in magnetozones M19n to M17r. We consider our earlier-published results from these sections in relation to the correlative pattern that has become well established further west in Tethys. Additionally, this is compared and contrasted with other, alternative, results from Crimea that have been published in recent times.

Keywords: Tithonian, Berriasian, calcareous nannofossils, ammonites, magnetostratigraphy, Ukraine.

Introduction

The authors want to express their appreciation of this opportunity to discuss the methodologies and results of Arkadiev et al. (2019), especially as this gives us a chance to answer criticisms made by those authors of an earlier published work on southern Ukraine (Bakhmutov et al. 2018). It is our suggestion that the criteria they use (*op. cit*.) to correlate the upper Tithonian–Berriasian of Theodosia with the rest of Tethys are not in accord with those used by other researchers, who have consistently applied a body of integrated data (palaeomagnetism, calpionellids, calcareous nannofossils and ammonites).

In order to analyse the comments of Arkadiev et al., the authors here discuss the tangible evidence provided by the sections, including our own data on the Crimean coast – litho-, bio- and magnetostratigraphic – drawing on field and laboratory study over the last twenty years. On these bases, it will be very simple to evaluate the discrepancies that are apparent between the facts of the Theodosia sequence (Bakhmutov et al. 2018) – and the standard Tethyan correlative scheme that we apply – versus the proposed correlations of Arkadiev et al. (2019).

A reply to the comments in the paper of Arkadiev et al. (2019) will allow us to lay to rest a number of 'red herrings' about correlations in the J/K boundary interval. Several of these have been recycled with variations (*e.g.* Arkadiev et al. 2012, 2017; Guzhikov et al. 2012; Platonov et al. 2014; Arkadiev et al. 2018, fig. 3), even though they have been conclusively and repeatedly seen as unreliable (see discussion and literature cited below). Another particular issue is the selective citing of older publications (*e.g*. Casellato 2010; Wimbledon et al. 2011), and the discussion of old ideas and outdated correlations in preference to considering the facts that have been presented in well-researched accounts in recent years. When such works are considered, it can be seen that the stratigraphic conclusions in Arkadiev et al. (2019) are somewhat imperfect.

In their introduction and conclusion chapters Arkadiev et al. (2019) promote ammonites as defining the J/K boundary, and then contradict themselves with the statement that "According

to widely accepted concepts *Nannoconus steinmannii* Kamptner is a species determining the Jurassic–Cretaceous boundary... the latter bioevent correlates with the Calpionella elliptica Subzone and…M17r". Such statements are not in accord with the bulk of research results published in recent years. If the subspecies *N. steinmannii kamptneri* was meant, then its FO does not correlate with the Elliptica Subzone. If it was intended to mention *N. steinmannii*, then that species does not have its first appearance coincident with either the base of the Elliptica Subzone or the base of the ammonite Jacobi Zone, or the base of a Grandis Subzone (if one uses older biozonal definitions from southeastern France). Moreover, the species *N. steinmannii*, or any species, in the Elliptica Subzone cannot determine the J/K boundary: by international consensus, that boundary lies two calpionellid subzones lower – at the base of the Alpina Subzone (*e.g.* Wimbledon et al. 2017b). And, except in the older records in the nannofossil literature (*e.g.* Bralower et al. 1989), the Elliptica Subzone is not correlated with the FO of *N. steinmannii steinmannii*: that nannofossil is often found in M18r (*fide* Casellato 2010), but is found in M19n in the Alpina Subzone – for example, it has been recorded that low in recent accounts of Tré Maroua, Saint Bertrand, Le Chouet, Theodosia and Rio Argos (full references in Wimbledon et al. 2020b).

Lithostratigraphy

In Ukraine, notable outcrops in marine Tithonian to Berriasian sedimentary rocks are seen in two regions: in the southwest, in Transcarpathia (Reháková et al. 2011), and more extensively in the hills of Crimea (Fig. 1).

In 2018, our team published an account of the uppermost Jurassic to lowest Cretaceous rocks of eastern Crimea – that crop out in the cliffs at the eastern extremity of the hill mass of Tepe Oba, around the headland of Ili Burnu. That publication was then commented upon by Arkadiev et al. (2019). We are at something of disadvantage in discussing local lithostratigraphy in reply, because whereas we have tried to present carefully measured representations of the accessible stratigraphic sections at Theodosia (Bakhmutov et al. 2018, figs. 2 and 3), Arkadiev et al. (*e.g.* 2019, fig. 2; and earlier papers by the same authors, cited herein) promote synthetic and composite diagrams. It is not possible to compare measured logs of tangible rock sequences, an accurate lithostratigraphy, with stylised diagrams and estimated thicknesses. Earlier, Bakhmutov et al. (2018) referred to problems encountered when trying to make comparisons with published Russian accounts, where it was apparent that the thicknesses given were less than accurate.

Fig. 1. Locality map of sites mentioned in the text.

The clearest and most accessible Mayak Formation section on the south-facing Ili Burnu cliff up to 2013 was the one nearest to the lighthouse, our section A, around 45°00'44.3"N, 35°25'16.4"E. We anticipated this was the outcrop to which Guzhikov et al. (2012) gave the number 2456. But Arkadiev et al. (2019) have its position as 45°00'41.7"N, 35°25'17.0"E – low on the slope, on the edge of a gully, where there is no outcrop. Bagaeva (2014) has it in another position, at 45°01'16.3"N, 34°24'53.8"E (near to Bilohirsk, 74 km to the west).

In recent years, in presentations at several Jurassic/Cretaceous workshops (twice at Smolenice, at Warsaw, and at the Cretaceous Symposium in Vienna, Wimbledon et al. 2017a) our team presented evidence on the Theodosia sections, showing the results of fieldwork that commenced on the coast in 2004 – evidence summarised in Bakhmutov et al. (2018). In presentations and publications, the name "Mayak Formation" was used consistently to describe the uppermost *circa* 100 m of what used to be called the Dvuyakornaya Formation (Permyakov et al. 1984). This 100 m-thick interval consists predominantly of alternating white micrites/biomicrites and marls that top the coastal sequence south of Theodosia: patently, these are very different to the sediments below: dark mudstones with numerous grainstone (to fine rudstone) turbidites, and occasional massive breccias, the characteristic lithologies of the main mass of the Dvuyakornaya Formation. Arkadiev et al. (2019, p. 367) have objected to this rationalisation of the lithostratigraphy and the logical separation of these two mappable formations. We should note that the 'new' formation name was earlier referred by us to the National Stratigraphic Commission of Ukraine in Kyiv for official consideration, as we considered this was an issue for the national authority.

Arkadiev et al. (2019, fig. 7) also opine that Bakhmutov et al. (2018) have some intervals "mistakenly included in the composite section". Their figure 7 (again diagrammatic) suggests a different equivalence. They suggest that our shore sections 2 and 3 at Ili Burnu duplicate our sections 5 and 6, high above. Such a juxtaposition could only result from the effects of a major tectonic dislocation somewhere in the cliff below the lighthouse, but no such faulting has ever been described, and no-one has suggested that beds exposed high in the cliff pediment are repeated on the shore.

Arkadiev et al. show composite sections (*e.g.* 2019, fig. 2), whereas Bakhmutov et al. (2018, fig. 2) present actual lithological logs, in which the continuity between the nine separate profiles (Dvuyakornaya Formation sections 1–6, and Mayak Formation A–C) is clearly shown. The succession is made up of overlapping parts: it is cumulative, not simply composite. Apart from one concealed interval, a gap, between the basal (breccia) section (1) and the next (section 2), we were satisfied that we could detect an overlap between every one of the figured profiles, traced from the shore up and across the cliff pediment (see Fig. 2 herein).

We traced the constituent beds of sections 2–3 and the lower part of 4 along the sea shore, over a distance of about 100 metres. The bedding dip angles and directions of dip are given in Fig. 2. The strike of the beds here averages 305–125 degrees, and is normal to the shoreline.

We can only say that every discernible and measurable section at Ili Burnu was carefully logged by us. No logs, *per se*, are presented in Arkadiev et al. (2019) or in their earlier works. Moreover, beds shown in our sections 2 and 3 are not lithologically comparable to higher beds: the distinctive nature of the limestones on the shore, their scale and spacing, is nothing like the succession in sections 5 and 6, or 4 with which section these two overlap. It is not possible to confuse the distinctive micrites and massive grainstones of the shore sections (profiles 2 and 3) – the latter often being rough, irregular and heavily burrowed – with the square bedded, regular, grainstones, often thin-bedded and sometimes with graded bedding, that occur above (in sections 4, 5 and 6). It is worth mentioning that Arkadiev et al. (*op cit.*) overlook the fact that we record a substantial reversed magnetic interval in the latter (sections 4–6) and that sections 2 and 3 exhibit entirely normal polarity (Bakhmutov et al. 2018, fig. 23). Further, Arkadiev et al. (2019, abstract) indicate that Bakhmutov et al. made mistakes in interpreting the cliff sections north of Ili Burnu: stating that the Mayak Formation section at the Ili Burnu lighthouse (our section A) (="Cape Saint Ilia", Arkadiev et al.) is a duplicate of the Mayak section in the Theodosia boathouse cliff (our section C). It is difficult to test this statement, as Arkadiev et al. (*op cit*.) present no evidence, having never provided an accurate log for the Ili Burnu cliff, and never described the boathouse section. Figure 7 in Arkadiev et al. (*op cit*.) provides measurements that do not match those in their earlier publications.

Examining formation thicknesses, at the Ili Burnu lighthouse the Mayak Formation has generally been indicated as being in the range of 12–13 metres (Arkadiev 2003, member 8; Arkadiev et al. 2006, member 23; Arkadiev et al. 2012, member 12; Guzhikov et al. 2012, member 12 – outcrop 2456). However, these measurements do not accord with the facts: the Mayak Formation, the marl and micritic top part of the section in the lighthouse cliff, measures 21 metres – with *circa* another three metres concealed in overgrown banks above the cliff top. Arkadiev et al. (2012) and Guzhikov et al. (2012, fig. 5, outcrop 2921) did not identify the Mayak Formation in the Middle Cliff, only the same members as they had already shown for Ili Burnu. It actually has a thickness there in excess of 26 m. In the Boathouse section there is more than 32 m of the same formation.

It is perhaps useful to consider some basic facts concerning the local field geology. On the small headland of Ili Burnu, the Mayak Formation is exposed high in the south-facing cliff and in the top of the slope around and west of the lighthouse. North of the headland, the formation is next seen in a small cliff a little above sea level (at 45°00'55"N, 35°25'10"E) and in gullies just inland to the west, down-faulted on the north side of the major fault that emerges in 'Smugglers Bay'. It is brought down by the fault almost to the level of the 2m-plus breccia from the Ili Burnu shore, seen a few metres south of

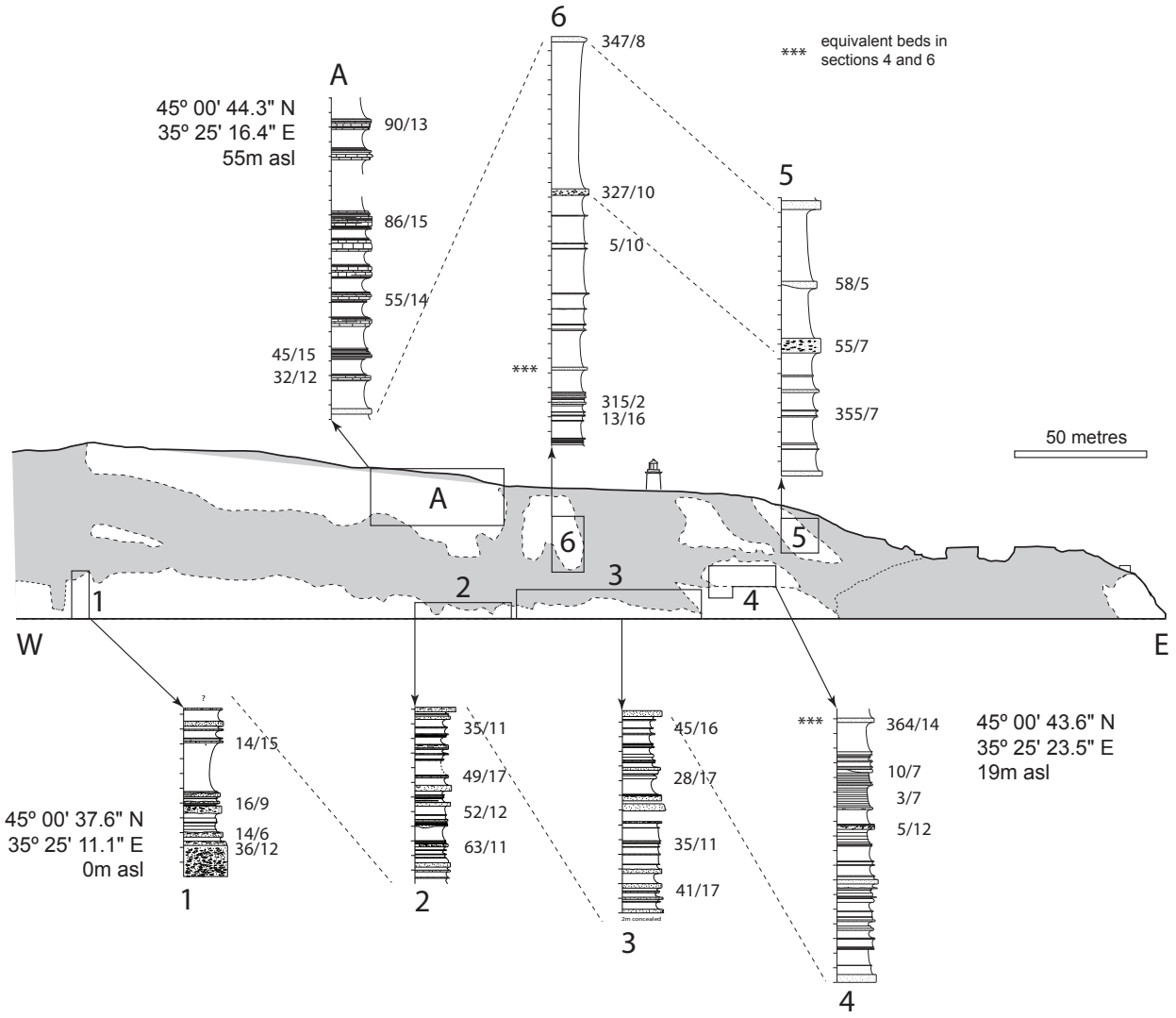

Fig. 2. Outcrops at Ili Burnu, as recorded by Bakhmutov et al. 2018, with dip and strike orientations related to logged sections.

the fault. Just north of the gulley a prominent 1m-plus breccia within the Mayak Formation first crops out. This bed is then seen again (apparently up-faulted) at the very cliff top (at 45°01'03"N, 35°24'56"E), and thereafter it is next clearly observable in the Middle Cliff (45°01'16"N, 35°24'55"E), whence it dips below sea level. No such thick, coarse breccia was detected in the Theodosia boathouse profile.

In the three Mayak Formation sections we describe, the base of the formation is only exposed at Ili Burnu (Bakhmutov et al. 2018, section A). In the bay of Theodosia, at the boathouses (section C) the base is below sea level, and in our Middle Cliff (section B), the lower part of the Mayak Formation outcrop is obscured by debris, but it is clear that the lower part of the formation there exposed is profoundly affected by a major, low-angle dislocation. The few metres of beds beneath this fault cannot safely be assigned or connected to the main cliff profile.

From the description above, it is thus still our interpretation that the three Mayak Formation sections come in sequence, with the lowest being at Ili Burnu (A), the Middle Cliff section (B) being intermediate and the boathouse cliff (C) showing the highest beds. This is reinforced by the different ammonite occurrences in the three cliffs. At Ili Burnu the formation yields an assemblage dominated by *Delphinella*, the Middle cliff has only yielded a handful of specimens: including one *D. tresannensis* at its base (Guzhikov et al. 2012) and *Retowskiceras* to us. The boathouse cliff is notable in yielding fairly frequent larger specimens of *Pseudosubplanites*, including *P. grandis*. In passing, it is worth mentioning that *D. tresannensis* was transferred to *Pseudoneocomites retowskyi* by Frau et al. (2016).

Arkadiev et al. now accept our often-repeated interpretation, by stating (2019, p. 357) that they mistook the large breccia low in the Middle Cliff (unmistakably in the Mayak Formation micrite/marl interval) for the massive 2m-plus breccia (stratigraphically 100 metres lower) on the shore and around the headland at Ili Burnu. However, though they mention "gaps of undetermined thicknesses" in their account, they do not

explain how they (Guzhikov et al. 2012, fig. 5) showed the highest beds in the sequence (the Mayak Formation) as equivalent to higher members of their Dvuyakornaya Formation, as developed at Ili Burnu, members 9–12 (Arkadiev et al. 2012, fig. 4, fig. 38). Though the implication of this acceptance is that it invalidates their earlier published lithostratigraphies, this matter is not explored: but the five stratigraphic intervals shown in the composite figure as "not observed" (fig. 2, Arkadiev et al. 2019) perhaps hold the answers.

Correlative precision in the J/K interval using ammonites

In the last twenty years, great progress has been made with Tithonian–Berriasian correlation using, in particular, calpionellids, calcareous nannofossils, ammonites and magnetostratigraphy, and in the last ten years, under the auspices of ICS, numerous specialist meetings and two Cretaceous Symposia have examined the exact positioning of the Tithonian/Berriasian boundary. Amongst other fossil groups, the ammonite assemblages of the upper Tithonian and lower Berriasian have been examined in some detail. A consensus has been reached on both the best markers and the optimum level for a Berriasian stage boundary (Wimbledon et al. 2017b). All that notwithstanding, Arkadiev et al. (2019) in their paper about nannofossils, state that "…the boundary between the Jurassic and Cretaceous has been assumed by the authors to be the base of the Berriasella jacobi ammonite zone". Further, they promote supposed biozonal indicators with no critical assessment of their vertical ranges.

In recent times, in fact, since the J/K colloquium in 1973, ammonites have not been most favoured in defining the base of the Berriasian. Moreover, this has been the viewpoint even amongst ammonite specialists (Tavera et al. 1994; Wimbledon et al. 2013; Bulot et al. 2014; Frau et al. 2015, 2016a,b,c; Wimbledon et al. 2020a). Enigmatically, Arkadiev et al. do not refer to recent results from the French type Berriasian where the relevant ammonite biozonation (between the Microcanthum Zone and "Grandis Subzone") has been studied and documented. Two relevant facts coming out of recent research on key French localities (key because they are the type localities for the ammonite zonal indices in the literature) are overlooked by Arkadiev et al. (*op cit*.), as in earlier papers. The first is that *Strambergella jacobi* cannot be used as an index species to define the base of the Jacobi Subzone, and the second is that (even if the evidence existed in Ukraine) any past definition of a base for a Grandis Subzone is of doubtful use (the taxonomy and ranges of micro- and macroconch *Pseudosubplanites* in France are still being revised). Both these facts have profound implications for the traditional interpretations often put forward by Russian authors, not to mention that they make no reference to how the subzones have been and are defined in France.

Biozonations are matters of interpretation, but with regard to primary evidence, it is necessary to say that even if there was continuity and a complete succession of ammonite faunas could be established in southern Ukraine, as indicated above, they could still only be used to approximate the base of the Berriasian. As it is, substantive ammonite evidence in the J/K interval in eastern Crimea is imperfect, and no zonal resolution is possible there: no clear boundary can be defined between any of the ammonite biozones in the late Tithonian to middle Berriasian, no typical later Andreaei Zone ammonites have been recorded in the Ili Burnu–Theodosia cliffs, and the ammonite assemblage that which would be expected next, that which typifies the immediately pre-Berriasian interval in France, with the genera *Elenaella* and *Praedalmasiceras*, is absent (references above). Therefore, no boundary between an Andreaei and Jacobi zones can be proved. Large intervals with no ammonites below the Mayak Formation and another within that formation mean there is no possibility to meaningfully position any kind of a base for a Grandis Subzone. Accuracy required for biozonal definition is lacking in accounts of Crimean ammonites: concrete species ranges that could allow definition of boundaries have not been published, and (as previously noted by Bakhmutov et al. *op cit*.) locality data is conflated. An example: *Pseudosubplanites grandis* was first found at the Theodosia boathouse section by Glushkov (Glushkov 1997), but the specimen has been repeatedly recorded at Ili Burnu headland ("Cape St Ilia" – Arkadiev et al. 2012, 2019 or "St Elias Cape" – Arkadiev et al. 2018) – a different locality and outcrop. Thus this ammonite record is conflated with the *Delphinella* fauna that really does typify the lowest Mayak Formation at Ili Burnu (but not the Glushkov section).

One other example of stratigraphic fluidity: the finding of *Delphinella* cf. *tresannensis* was announced at or about the base of the Berriasian (Guzhikov et al. 2012), said to come from a level that would be *circa* 100 metres lower in the sequence (member 9) than it really did, for it actually came from the Mayak Formation (described by Bakhmutov et al. (2018) as section B). For Arkadiev et al. (2006) this level had been Tithonian, and the new find was placed in a "Durangites Zone" (Arkadiev et al. 2012). Our team (at the Warsaw and Smolenice workshops) showed this level and this cliff section to be within the Mayak Formation. There followed an abrupt alteration: *D.* cf. *tresannensis* was next placed in the middle of a Grandis Subzone (Baraboshkin et al. 2016, fig. 1.5), but it was still (seemingly impossibly) shown in member 9 – the members remaining unchanged. Next the species was shown (composite section – Arkadiev et al. 2019, fig. 2, outcrop 2921) above all other listed Grandis Subzone species, even though it had been found at the bottom of the Middle Cliff section (Guzhikov et al. 2012, outcrop 2921). This is not explained, but it suggests a certain flexibility when it comes to the biostratigraphic application of supposedly definitive species. Further, the statement was made (Arkadiev et al. 2019) that the nannofossil species "*Hexalithus strictus*… correlates directly with the *Berriasella chomeracensis*, the latter being characteristic of the Lower Berriasian". Further west in Tethys, *Hexalithus strictus* has its first occurrence around

the base of the Berriasian (Alpina Subzone) and it has a presumed limited, but uncertain, range after this (Casellato 2010; Wimbledon 2017). In France, *B. chomeracensis* has been described in both the Jacobi and Grandis subzones of authors (*e.g*. Le Hégarat 1973), that is, in the ?Colomi to Elliptica interval, so it spans the late Tithonian and the lower Berriasian. As the type specimen of *B. chomeracensis* came from the Chomérac breccia, its exact stratigraphic horizon can only be guessed.

Nannofossils

Over the last thirty years or so, numerous studies have shown the greater usefulness of microfossils in fixing a base for the Berriasian (see references in Wimbledon et al. 2020a,b). However, unlike other regions, in the Theodosian sections no calibration is possible between ammonites and calpionellids (as explained in Bakhmutov et al. 2018, p. 220): unfortunately, pervasive reworking in the Theodosia sequence makes it unsafe to try to construct a calpionellid biozonation there. We consider nannofossils to be very useful secondary indicators of the J/K boundary interval, if there is sufficiently dense collecting from precisely recorded profiles.

Arkadiev et al. (*op cit*.) look for support for their ammonite correlations from a handful of nannofossil samples. The very short Conclusion of their paper has only one conclusion: that the identification of a nannofossil zone "NKT" is close to the base of M18r and the base of a Grandis Subzone. Their fig. 2, however, contradicts this: it shows the base of what they label as NKT nowhere near to the base of either M18r, or a Grandis Subzone. Casellato (2010) defined the base of her zone NKT with the FOs of *N. steinmannii minor* and *N. kamptneri minor*, with *C. octofenestratus* as a secondary marker. The FOs of the first two species have been well documented in sections across western Tethys (for references see Wimbledon 2017). In more recent accounts, *N. steinmannii minor* has predominantly been found to make a first appearance in the middle of M19n.2n, *i.e.* straddling the boundary between the Colomi and Alpina zones; *N. kamptneri minor* appearing in late M19n within the Alpina Zone (Fig. 3). At Theodosia, Bakhmutov et al. (2018, figs. 23 and 24) recorded these same stratigraphic relationships, those that are seen in sites from Iberia to Bulgaria,

Turning to actual nannofossil finds from the Theodosia cliffs, it is necessary to make a comment on the scale of evidence, i.e. the number of samples and thus the merits of the data. Our team has studied some two hundred and forty-nine samples from the Berriasian sequence between the headland of Ili Burnu and the town of Theodosia (Bakhmutov et al. 2016, 2018). We have further studied nannofossils in a separate latest Tithonian section 2 km to the west (Svobodová et al. 2019b), and another just west from Ili Burnu (thus far unpublished). Arkadiev et al. discuss and analyse our nannofossil finds (and they erect a nannofossil biozonation), and they do this founded on eleven samples that they have collected in the same stratigraphic interval (2019, fig. 2).

Focussing on specifics, Arkadiev et al.'s (2019) sample 2921/7 was reported as coming from a bed low in our "Middle Cliff" (Bakhmutov et al. 2018, fig. 3, section B): it yielded to them *N. steinmannii steinmannii*, seen by them as its earliest occurrence, "a major event" – an event said to mark the base of zone "NK1", in M17r (Arkadiev et al. 2019, fig. 2 & fig. 7). However, this is, stratigraphically, too high: sample 2921/7 at this level is many metres above beds at Ili Burnu already shown to contain the FO of *N. steinmannii steinmannii* in M19n (Bakhmutov et al. 2018, appendix 1, section 2). And it is many metres below beds that also yield it in the highest Mayak Formation in the boathouse cliff (actually within M17r). Further, their sample level appears to come from beds that we record as being in a normal magnetic interval, M18n (Bakhmutov et al. 2018, fig. 23), so a reversal (M17r) is certainly contraindicated.

In French sections (as in other sites in Tethys), where ammonites and nannofossils can be much more accurately calibrated with calpionellids, *N. kamptneri minor* has been recorded as appearing in M18r, and even in M19n, just as Bakhmutov et al. (*op. cit.)* recorded the subspecies at Theodosia. However, Arkadiev et al.(2019, fig. 2, fig. 8) place it not even in M18r, but high in M18n, in the middle of their Grandis Subzone, but also at the same time in the Alpina Subzone (see Fig. 3). This is not possible.

Further, as the index for the base of a "NKT" biozone, they use the FO of *Nannoconus kamptneri minor*. That subspecies and *N. steinmannii minor* have been recorded at least sixty metres lower in the Ili Burnu section (Bakhmutov et al. 2018). In other Tethyan sections the FO of *Nannoconus kamptneri minor* is recorded high in M19n, and *N. steinmannii minor* a little lower: that is the case in the Vocontian basin, at Fiume Bosso and Rio Argos, as well as at Theodosia. Similarly, the idea that *Nannoconus wintereri* has its first occurrence in M18n in a Grandis Subzone (Arkadiev et al. 2019, fig. 2) simply cannot be countenanced: its first occurrence in sections in France, at Kurovice, Torre de' Busi, Velykyi Kamianets, Bosso, Puerto Escaño etc., lies in M19n.2n, around the Colomi/Alpina zonal boundary, and in the "Jacobi Subzone" of older usage (Fig. 3)

Calcareous nannofossil species that first appear in the late Tithonian and early Berriasian mostly have very long ranges. Recent correlative work has been founded on the excellent results of Casellato (2010). Further development of her scheme has been made possible in the last ten years by multiple high-resolution studies. An examination of fig. 8 of Arkadiev et al. (2019) reveals that the nannofossil marker species "FOs" that they show are even later than those that were recorded in early studies, prior to 2010. It is not clear therefore what this figure demonstrates: the FADs of nannofossils noted by Arkadiev et al. are not FADs, but only random points on the long ranges of the taxa named. The three species they cite have been recorded as having their FADs far earlier, in M19n, not where they indicate them. The concluding remarks of

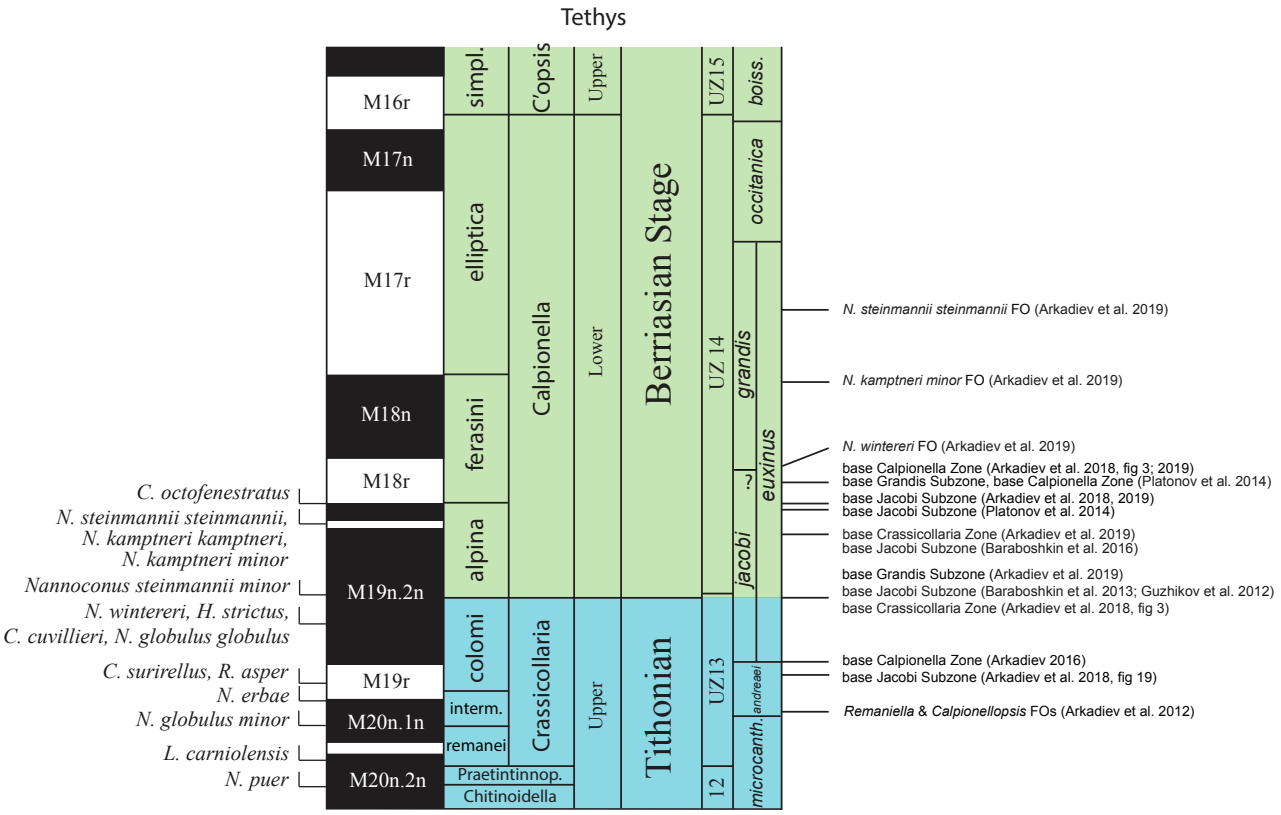

Fig. 3. Bases of zones and FOs as mooted by Arkadiev et al. 2019 etc. (right-hand column) are plotted against the correlative scheme for the Tithonian–Berriasian of Tethys. Events are related to the standard magnetostratigraphic and calpionellid scale, plus ammonite zones and nannofossil FOs.

Arkadiev et al. (p. 367) are that "new data from nannofossils from the Feodosiya [Theodosia] section significantly enlarges its characteristics and highlights this section as one of the best in terms of degree of description of details of the Jurassic–Cretaceous boundary". In fact, the limited data presented from Theodosia, and its interpretation, make no difference to earlier published nannofossil biostratigraphy.

Magnetostratigraphy

Arkadiev et al. (*op. cit.*) do not present new magnetostratigraphic data. In outcrop 2921, Guzhikov et al. (2102, fig. 5) had shown a long reversal and short normal. They matched this reversal and normal (see their fig. 6) with what they stated to be the same reversal and normal at Ili Burnu. Outcrop 2921 is our section B (the "Middle Cliff"), and the whole section is in the Mayak Formation, in which we recorded (Bakhmutov et al. 2018) a short normal below (M18n) and a long reversal above (M17r). The problem is not analysed by Arkadiev et al. (*op. cit.*) and is overlooked in their fig. 7: where, apparently, these magnetozones are no longer seen as being the same. Arkadiev et al. (*op. cit.*) discuss our magnetic susceptibility results relative to the lithostratigraphic succession. However, we do not see that that informs any discussion of our interpretation of the sequence or its parts.

Consistent recording of key stratigraphic markers

In a string of papers on the coastal sections of southern Ukraine, the same Russian colleagues have noted the position of various fossil markers and magnetozones. But there has been a certain variability with regard to the relative positions of these important markers. A few examples are perhaps illustrative (see Fig. 3)

- The base of M18r was placed below the middle of the Jacobi Subzone, and that biozone's base in the middle of M19n.2n. The rest of the magnetozone was in an unsubstantiated "Durangites Zone", and the base of the Grandis Subzone in the middle of M18r (Guzhikov et al. 2012).
- The calpionellid *Tintinopsella carpathica* was recorded in the Microcanthum Zone, and *Remaniella* and *Calpionellopsis* in a "Durangites Zone" (Arkadiev et al. 2012, fig. 4).
- The base of the Jacobi Subzone was indicated in mid M19n.2n and the base of the Alpina Subzone in the upper half of M19n.2n, with the Grandis Subzone in mid M18r (Baraboshkin et al. 2013).

- The base of M18r was placed immediately above the base of a Jacobi Zone, in the calpionellid Crassicollaria Zone. The Grandis Subzone's base was in the middle of M18r, exactly coinciding with the base of the Calpionella Zone (Platonov et al. 2014).
- The bases of the Jacobi and Alpina zones were said to coincide (Arkadiev 2016).
- At Ili Burnu, the Mayak Formation alone was shown in the Grandis Subzone, and the rest of the photographed profile was placed in a Jacobi Subzone. Lower beds (equivalent to Berriasian sections 1–3 of Bakhmutov et al. 2018) were relegated to the Tithonian (Baraboshkin et al. 2016, fig. 1.2).
- The base of M18r was placed in the Crassicollaria Zone. The base of the Crassicollaria Zone was shown in M19n.2n, and the Berriasian Stage base in M19n.1n, at the base of a Jacobi Zone (Arkadiev et al. 2018, fig. 3).
- The base of the Jacobi Zone in western Tethys was correlated with the upper part of the Andreaei Zone in Crimea, which was placed within M19n.2n (Arkadiev et al. 2018, fig. 19).
- The base of M18r was shown to coincide with the base of the Jacobi Zone (Arkadiev et al. 2019, fig. 2).
- The Chitinoidella Zone was extended up to just below what was labelled as M19n.1r, and the Alpina Zone had its base in M18r, coinciding with a Grandis Subzone (Arkadiev et al. 2019, fig. 2).

Unfortunately, this approach, with ever-changing and contradictory interpretations, is not congruent with other data on Crimea that has been published (Bakhmutov et al. 2018; Svobodová et al. 2019b), nor is it consistent with data from other regions, where the calibration of markers has been accurately determined at numerous sites (*e.g.* Michalík et al. 2009, 2016; Channell et al. 2010; Lukeneder et al. 2010; Pruner et al. 2010; Wimbledon et al. 2013; Svobodová & Košťák 2016; Hoedemaeker et al. 2016; Grabowski et al. 2017, 2019; Stoykova et al. 2018; Svobodová et al. 2019a; Wimbledon et al. 2020a). The best correlative framework for the late Tithonian to Berriasian is based on a calpionellid biozonation tied to magnetostratigraphy, supported by nannofossils and ammonites. With the international correlative framework well established and the relative positions of markers clearly discernible in the literature, still Arkadiev et al. (2018, 2019) propose a variety of unusual correlations. They would place the base of the Crassicollaria Zone just below a supposed "M19n.1r": it is a position that has never previously been recorded. It would put that biozonal boundary not in M20, where it is normally found, but well into the Berriasian, so high that it would even be above both the established base of the Jacobi Zone (*circa* the base of M19n.2n), and well above the Alpina Subzone base (in mid M19n.2n). These contentions and the placing of M18r in the Crassicollaria Zone are inconsistent with all evidence, as was pointed out previously by Bakhmutov et al. (2018). Nor, self-evidently, can the base of the Alpina Subzone be made to coincide with a Grandis Subzone, somewhere in M18r.

Conclusion

The evolving interpretations in Arkadiev et al. (2019) (following Arkadiev et al. 2012, 2017, 2018; Guzhikov et al. 2012; Platonov et al. 2014 etc.), introduce both conceptual and methodological misunderstandings. The literature cited above fully reveals these misunderstandings and misinterpretations, and a flexible and uncritical approach to interpreting data. The evidence laid out above demonstrates why we have doubts about the data presented and grave misgivings about how these are interpreted. It is evident that literature has been overlooked, that lithological logs were not recorded prior to collecting of fossils, that fossils are inaccurately recorded, or they are associated when they do not occur together in nature, some taxa are applied biostratigraphically when they can only be derived and are not autochthonous, biozones and magnetozones are associated in time when they do not occur together. Examples are: *Chitinoidella* high in M19n; a 'FO' for *Nannoconus steinmannii minor* sixty metres above its published first occurrence; ammonite taxa said to be definitive for the uppermost Tithonian changed to being definitive for a Grandis Subzone; M18r was placed in the Crassicollaria Zone (Fig.3). Given this confusing application of bio- and magnetostratigraphy, it is not possible to accept suggestions made by Arkadiev et al. (*op. cit.*) about the numbering of magnetozones in Bakhmutov et al. (*op. cit*), or that these assignments should be amended.

We are content that our Theodosia results (Bakhmutov et al. 2018) are accurate, and that they are consistent with records from other Tithonian-Berriasian profiles and their magnetostratigraphic and nannofossil frameworks. Our interpretation of stratigraphy is most closely aligned with the data obtained from the Theodosia sections

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