Dear Jonas Kley & others,

I am pleased to submit the revised version of our original research article entitled 'Birth and closure of the Kallipetra Basin: Late Cretaceous reworking of the Jurassic Pelagonian – Axios-Vardar contact (Northern Greece)' on behalf of all the authors.

We are very grateful for the positive responses and the constructive comments provided by both anonymous referees. Their suggestions have significantly improved our manuscript, and their confusion over some of the main points allowed us to re-write some major sections, edit appropriate figures, and create a new figure in order to more adequately explain our complex geologic interpretations. We believe that our revised manuscript fully addresses the concerns of both referees and hope you will consider it for publication in Solid Earth and the special issue 'Inversion tectonics – 30 years later'.

In this document are point-by-point responses to all referee comments from both referees, a list of relevant (major) changes to the manuscript and figures, and a marked-up version of the revised manuscript.

Response to Interactive Comment by Anonymous Referee #1

We are grateful for the positive response and constructive comments provided by the anonymous referee. They raise 3 main points: (1) the focus of the study needs to be addressed more clearly in the introduction and in the discussion/conclusions; (2) our discussion and reasoning on the tilted thrust fault should be developed further; (3) the extensive discussion on the origin of fluids in the fault zone is not the topic of this study. These are addressed below, and specific comments to individual points of the manuscript are provided. In the following, the referee comments are in italics, and we respond in regular font.

Anonymous Referee #1
Dear Editor, I have read with great interest the work of Bailey and coauthors regarding the Kallipetra Basin in N. Greece. The manuscript is well written, and it presents new data and interpretations in connection to the geodynamics and the problems of ophiolite obduction in the Hellenides. The writing is clear and easy to follow. The authors have put a great effort to document the data and the field evidence related to this study and I have to admit that it is rare to see papers with such a level of detail when it comes to the primary data. However, I have a few comments related to the overall presentation and some of the conclusions of the study. The most important points that I can mention here are:
1) The focus of the study with respect to the general problematics of tectonic scenarios in the Hellenides must be addressed more clearly. This is because the study may look a bit "too regional" from the perspective of a researcher who is not familiar with Eastern Mediterranean geology.

We have altered the introduction of our manuscript to more clearly address the focus of our study with respect to the 'controversies' of the Hellenides. Additionally, we have edited Fig.2 accordingly to address the problematics of the Hellenides tectonic scenarios. Please see our more detailed response on this issue below, in the response to a comment on l.41 by the referee.

2) The authors present their view of the main contact being a tilted thrust towards the NNE. This is a very important point given the current discussion in the literature related to the ophiolite

obduction problem (Pindos vs Vardar etc). I would thus suggest that the authors develop the discussion and explain their reasoning a bit in more detail.
We thank the reviewer for this suggestion. We have added a new figure that provides a clear presentation of our tilted thrust zone, and provided a more detailed reasoning in the manuscript in Section 5.6.

3) The authors get into an extensive discussion about the importance of fluids vs viscous heating while at the same time they also admit that the evidence is not so clear. Since the discrimination of the additional source of heat which is required is not the topic of this study (and there has been no effort inquantify the arguments), I would suggest that the authors mention the possibilities andnot go in a specific discussion on the importance of a particular mechanism.

Our data document an inverted metamorphism below a shear zone. The heating that produced this metamorphism occurred during deformation and reset the FT ages, permitting us to date deformation. We acknowledge that physical models are needed to reproduce and quantify length and timing of the observed metamorphism. Therefore, as asked by the reviewer, we have significantly reduced the extensive discussion in Section 5.5 so the reader can simply recognize the presence of heat along the thrust zone without getting deterred from the main conclusions of our study.

The Specific comments follow below:
l. 27: Please add "e.g." in the reference list. There are numerous works to be cited here.
Done.

l. 28: Please define what is meant by "Internal" Hellenides, either by definition or by citation to the map.
We have referred to the map and have edited Fig. 1 by labelling the Internal Hellenides and External Hellenides more clearly.

l*. 34: Please be more specific about the "Cretaceous Basin". Does it have a name? Is there in a particular location that you refer to?*
Here we refer to the Kallipetra Basin.
The Cretaceous basins that formed at the eastern Pelagonian margin and over the Axios/Vardar zone were first mapped at the large scale by Kossmat 1924. Many workers have found sparse Cretaceous sediments since then (e.g. Mercier and Vergely 1994, Sharp and Robertson 2006). Schenker et al (2015) brought clear evidence that the gneissic detritus in one of these basins (named in this contribution Kallipetra basin) is of Pelagonian and not of Rhodopian origin (e.g. Ricou and Godfriaux 1995).
We have rephrased this part of the text to: "...by the deposition of metamorphic Pelagonian detritus in a Late Cretaceous basin (Schenker et al. 2015) subsequently referred to as the Kallipetra Basin in this study."

l. 37: I would suggest that "pulse" is not the right word here. It is known that the extension and basin formation in the Hellenides is diachronous and migrating southwards (see also Papanikolaou & Royden, 2007) for more details and the relevant literature.
We have rephrased to: "Finally, from the Oligocene-Miocene the western Pelagonia was dissected by diachronous normal faults (Schermer et al., 1990; Lacassin et al., 2007; Coutand et al., 2014; Schenker et al., 2014) within a southward extensional deformation front that affected most of the Hellenides (e.g. Papanikolaou & Royden, 2007)."

l. 41 (MAIN POINT): It is not clear what are the main features that you would like to address in all these contrasting interpretations. In terms of the sketches that are presented in Fig. 2 the focus of this work can be i) the position of Pelagonia, ii) the number of subduction zones etc. Therefore, I suggest you develop on the specific features that you want to address in more detail. In other words, please identify the problem/hypothesis and then explain why you chose to focus on this area to solve it/test it.
The many and contrasting geodynamics models present in the literature source from the difficulties of connecting the Rhodope and the Pelagonian zone. This is a longstanding debate on the number and dimension of oceans in the Mesozoic Pindos-Vardar realm between researchers proposing a single unifying Early Jurassic Vardaric ocean that has been partly subducted, partly obducted and dismembered during successive tectonic events and researchers that embraced a multi-ocean early Jurassic scenario that led to several subduction zones. In these scenarios, the Cretaceous sediments were deposited on the eastern Pelagonian zone either within a Jurassic-Cretaceous passive margin or during a subsequent Cretaceous tectonic event (compressional or extensional depending on the authors). These geodynamic interpretations are presented in Fig.2 and display the different positions of the Pelagonia-Vardar margin relative to the Alpine orogenic wedge after the Jurassic convergence. We have subsequently edited Fig.2 to show the position of the Kallipetra Basin in the different geodynamic scenarios.

By studying the small Upper Cretaceous Kallipetra Basin that lies on the Pelagonia-Vardar 'suture zone', we can begin to address questions on if and how the Pelagonian-Vardar margin was deforming. Our study will ultimately provide constraints on the position of the eastern Pelagonian margin relative to the Alpine orogenic wedge, hence ruling out some of the geodynamic models so far proposed.

Thanks to the comments of both reviewers, we have adjusted the manuscript so as to better identify the problem we want to address, and to show the importance of the birth and the closure of the Kallipetra basin in the context of the Hellenides. This can be seen in our revised Introduction, discussion, and conclusion.

l. 68: Please add e.g. in the citation list since the development of these basins were known already from the time of Brunn and Aubouin (1950-60s)
Done.

l. 77: "metamorphic ages of migmatites" should change to "zircon ages from the leucosomes from the migmatites".
OK, we agree: the term proposed is more descriptive.

l. 80: "of the wedge" Please rephrase so that you can be more specific on the kind of the wedge (e.g. accretionary, orogenic etc).
We mean orogenic wedge and have rephrased accordingly.

l. 93: Please add Brun & Sokoutis as well as Dinter & Royden for the Rhodope corecomplexes.
This has been done.

l. 95: leucogneiss -> leucogneisses
Changed.

l. 105: Please avoid terms that refer to processes which you cannot show (i.e. "hydraulically").
The unit "hydraulically brecciated serpentinite" has been re-named to "Dark massive fractured to brecciated serpentinites" throughout the text and figures.

l. 117: Please add reference to show who did this interpretation (after “basin”).
OK, it is the interpretation of Schenker et al 2015.

l. 118: As above, please add reference at the end.
Schenker et al 2015

l. 127: “package” -> “pile”?
We have replaced “sedimentary package” with “sedimentary sequence”.

l. 131: Please be specific because there are also other kinds of grade (i.e. ore grade). I suggest rewording as: “to determine grade...” -> to determine the metamorphic grade in low-grade metapelitic
We agree with this suggestion, and the phrase “to determine grade” has been replaced with “to determine diagenetic grade”.

l. 141: What exactly do you mean by the “determination of metapelitic zones”. I think you refer to the “metamorphic” zones. Right?
Yes, we refer to low-grade metamorphic zones, so we have replaced ‘metapelitic zones’ with ‘low grade metamorphic zones’ in the manuscript.

l. 168: As before, please remote the word “hydraulically”.
We have removed the term ‘hydraulically’ and changed it to ‘“Dark massive fractured to brecciated serpentinites”, as mentioned in an above comment.

l. 449: "dramatic" has been struck through. Please check the sentence.
Thank you for alerting us to this, the word dramatic has been removed.

l. 457: “and on viscosity”. I would remove the specific mention to “and on viscosity”since any irreversible deformation mechanism would also contribute to shear heating (e.g. rate-independent plasticity)
We agree with the reviewer and deleted “and on viscosity”.

l. 460: “With a <2cm/a the heat is...” This statement assumes that the movement is steady. Since this hypothesis cannot be supported by the present data, I would suggest removing this sentence.
See comment below the following point.

l. 465-467 (MAIN POINT): As before, the discussion around viscosity only, neglects the frictional part of the heat. Therefore, since this is not the main topic of this paper and there is no detailed analysis in this direction, I would remove specific conclusions related to the most-likely source and the magnitude of shear heating.

As the reviewer has helpfully pointed out, the discussion around the specific magnitudes of heating related either to shear heating or advected hot fluids is highly hypothetical, and we therefore do not have adequate evidence to support one of the two sources of heat. Rather, the goal of this particular paragraph was to draw attention to the unusual inverse geothermal gradient and explore possibilities of how/why this formed.
Therefore, we have re-written, simplified, and shortened Section 5.5 ‘The inverted geothermal gradient in the Kallipetra Basin’ to address the concerns of Referee #1.

l. 470-471: As before, there is no evidence to suggest what is considered "normal" by the authors since: (i) the rheology does not have to be purely viscous, (ii) the motion does not need to be steady. Therefore, the suggestion of a particular heating mechanism is beyond the scope and the data presented in this study.
We acknowledge that we have no evidence or data that addresses the convergence rates, viscosities, or plate velocities and therefore agree that the suggestion of particular heating mechanisms goes beyond the scope and data presented in this study. Therefore, we have re-written and shortened this section so that we only relate the observed inverse geothermal gradient to the closure (and timing of closure) of the Kallipetra Basin so that it remains in the scope of our study.

l. 475: Why the direction of tectonic transport is related to the fluid flow. Assuming a fault zone as a region of high permeability is well established. However, I cannot see how the transport is related for this conclusion.

We agree that transport is not necessarily related to this conclusion, therefore we have replaced "The overriding unit over the Kallipetra basin would have allowed fluid focusing and differential loading that caused any fluids to flow in the direction of tectonic transport" with "Differential loading from the overriding unit over the Kallipetra Basin could have focused fluids along the fault zone".

l. 488-490: How did you conclude that this must be thrusting (MAIN POINT). Why not normal fault with top NE kinematics. Please explain your reasoning in more detail.

The conclusion for thrusting to the NE came from the stratigraphic evidence, predominantly from the character of the rudist mounds (e.g. mound asymmetry, younging direction, and ophiolitic detritus) along with kinematic indicators. We see stacking of serpentinitic breccias on south-western flanks of rudist mounds, sourced from ophiolitic debris up slope. The absence of ophiolitic detritus on the northeastern mound flanks document a 'shadow' effect of the mounds with respect to a south-southwestern provenance of serpentinite clasts. The highest, and therefore youngest, mound is located at Asomata Quarry which is the most northeastern mound suggesting movement of the ophiolite from SSW to NNE. Part of the reason the rudist mounds are so interesting is that they tell us something about the tectonic activity the basin is experiencing without needing to observe the fault itself.

We understand that this is complicated and was difficult to grasp in the way we originally wrote the manuscript. In order to provide some clarification and to expand our reasoning in more detail, we have added a new figure that documents the opening and closure of the Kallipetra Basin, and the figure also compares features we would expect to see for both normal faulting and thrust faulting scenarios (New Fig. 12). We have also expanded our reasoning in Section 5.6.

l.494: As before, since the authors already state in line 478 that the sources of heat are not clearly established. I would leave the interpretations out of this.
See comments above pertaining to this issue. We have removed the interpretations of heat sources from this sentence.

l. 494-496: These places are quite far from each other.
Indeed they are. We have removed this sentence.

l. *496-498: From Turonian to Campanian is more than 10 Myr. For a crust ~10km thick and standard thermal parameters, the conductive thermal relaxation timescale is ca1Myr. Therefore,*

I do not think that the advective heat was maintained long enough to cause the heating. Therefore, I would suggest that the authors revise this sentence to defend or reject this conclusion.
We have deleted this sentence as it directly follows from the previous sentence which was deleted in response to the reviewer comment above.

Legend Fig. 3: "Dark blue circles", the samples are very small. Please use larger and more discrete symbols.
We agree, very small - we have adjusted the figure so the sample location circles are much larger and a brighter color.

Response to Interactive Comment by Anonymous Referee #2

We thank the reviewer for their detailed and thorough review of the manuscript, which will allow us to significantly improve our manuscript. The referee's main point was addressing the lack of large-scale implications and comparison with neighboring areas with Upper Cretaceous sediments. We have addressed their main concerns and respond to their individual comments below. We believe that our revised manuscript and newly created or edited figures have now included further comparison to nearby regions and a clearer statement of our study goals and the controversies we wish to elucidate. In the following, the referee comments are in italics, and we respond in regular font.

Anonymous Referee #2
This work deals with the paleogeographic and tectonic evolution during the Upper Cretaceous of an area of Continental Greece that belongs to the so-called Internal Hellenides. Little is known about the Cretaceous evolution of this sector of the Hellenides and many questions await answers. Apart from the number of oceanic basins, the polarity of the subduction zone, etc, there are questions about the origin, age, deposition paleoenvironment and the geodynamic significance of the Cretaceous sediments deposited unconformably on top of the obducted Vardar ophiolite complexes and the Pelagonian passive margin. Thus, this manuscript fills a significant gap in our knowledge of these issues.
It is a well-written and well-structured manuscript with a wealth of data clearly presented, but in the end, it leaves the reader partially dissatisfied. And this has to do mainly with the large-scale implications of the results and their comparison with other neighboring areas of the Internal Hellenides where Upper Cretaceous sediments are also observed. As the authors report, in order to elucidate part of the controversies, they studied this small Upper Cretaceous basin, but the part of their manuscript that refers to those is poorly developed. I believe that a better analysis of this would strengthen their work even more.

Based on that I have noted the following:

a) The work that first described the Cretaceous sediments east of the Pelagonian (Almopias Zone) is not included in the reference list, although this work is about an area just north of the Kallipetra basin and gives detailed lithostratigraphic columns presenting their paleogeographic and tectonic evolution. This work is: Mercier, J., 1968. Etude geologique des zones Hellenides en Macedoine centrale(Grece). Ann. Geol. Pays Hell. 20 (792 pp.).

We have entered in more detail the comparison of the Lower Cretaceous basin to the work of Mercier, Robertson, Ricou and others. We hope that by adding some detailed comparisons with other Upper Cretaceous basins in nearby regions has strengthened the part of our manuscript that aims to elucidate the controversies.

b) *There is no comparison or correlation with other areas where the Cretaceous sediments are also observed. There could be a comparison apart from Mercier's work with the results of other papers, e.g. the paper of Sharp and Robertson (2006), who give anevolution model of a similar Upper Cretaceous basin north of the study area. Mercier(1968) places the beginning of the deposition of the Upper Cretaceous sediments in Aptian-Albian, while other researchers such as Sharp and Robertson and Galeos etal. (1994) describe even older aged sediments (Upper Jurassic). It could also be compared to other areas of the non-metamorphic Pelagonian, e.g. in Othrys Mt (Ferriere,1982) and Argolida (Baumgartner, 1985). It is important to comment on the age of onset of the deposition of the Upper Cretaceous sediments, as well as the age of the emplacement of ophiolitic complexes on them, highlighting the possible differences that may exist from region to region.*

   Ferriere J (1982) Paleogeographies et tectoniques superposees dans les HellenidesInternes au niveau de l'Othrys et du Pelion (Grèce). Soc Geol Nord Publ 8:1–970.

   Galeos, A., Pomoni-Papaioannou, F., Tsaila-Monopolis, S., Turnsek, D. & Ioacim, C.1994. Upper Jurassic–Lower Cretaceous 'molassic-type' sedimentation in the westernpart of the Almopia subzone, Aridhea Loutra Unit (northern Greece). 7th Congress of the Geological Society of Greece, Thessaloniki, May 1994.

We agree with this point (see reply above) and we have compared our units with others, specifically with ages of deposition and/or emplacement, located not too far North of our study area.

c) *The phrase "Upper Cretaceous basin" is used in two ways: either to describe the wider paleogeographic area where the Upper Cretaceous sediments were deposited or the small basin of Kallipetra. This dual use of the term confuses the reader. It must be made clear that the Kallipetra basin is part of a wider paleogeographic domain which, during the Upper Cretaceous, was the site of deposition of large thickness sediments.*

Thank you for bringing this to our attention - we have gone through the manuscript to make sure this is cleared up to eliminate any confusion. In line 34, for example, we refer to the Kallipetra Basin and have rephrased this part of the text: "...by the deposition of metamorphic Pelagonian detritus in a Late Cretaceous basin (Schenker et al. 2015) subsequently referred to as the Kallipetra Basin in this study", and have clarified other uses of 'Upper Cretaceous Basin' in our manuscript.

d) *An important key in the evolution of the basin is the origin of the fault that places the Vardar Oceanic Complexes (VOC) on the Upper Cretaceous sediments in the easternpart of the basin. According to the authors, the direction of tectonic transport of the VOC sealing Kallipetra Basin was from SSW to the NNE. It seems difficult that this transport can place the VOC on the sediments of the basin in a distance at least 4km into the basin and* *westwards, as shown by the geological map in Figure 3 and the geological sections in Figure 8. This could happen if the VOC nappe crossed the entire basin from southwest to northeast. Also, in the map of figure 3 the fault is characterized as a reactivated thrust fault. This is not clearly described in the text except perhaps from the sentence in line 490. A much better analysis and documentation of the interpretation given is needed.*

We do not fully understand the argument in this comment, however this, along with a similar comment from Reviewer 1, alerted us to confusion over the reactivated thrust fault and direction of transport in our manuscript. We have made sure there is a better description and documentation of the reactivated thrust fault in section 5.6 'Sealing of the Kallipetra Basin and large-scale implications. We have also created a new figure with 2D sketches that show (1) the north eastward migration of the mounds is related to thrusting and not to normal faulting, (2) normal vs. inverted thrust, and (3) subsequent rotation of the fault into a 'normal' position.

e) *What is the origin of the basin and how is it associated with the growth of the Hellenides? Is it a fore-arc basin formed on top of an evolving accretionary wedge, is it a basin formed at the back of an orogenic wedge that collapsed due to underplating at its base, or is it a back-arc basin?*

Towards the end of the Kallipetra Basin timeline, the basin could be described as sediments accumulating in a foredeep generated ahead of an emplacing ophiolite. However, the basin formed under an extensional exhumation phase where there was a lot of erosion of both the Pelagonian continent and the Jurassic ophiolite, forming a depression. The upward deepening of the successions (before we shallow again due to the incoming ophiolite), suggests a phase of extension. In our area of focus, we see no evidence of the presence of a volcano so therefore the Kallipetra Basin was not a fore-arc or back-arc basin, and coeval volcanism is not known elsewhere. The basin formed on to of a suture zone. We have made sure our descriptions and discussion on both the opening and closure of the basin have been more clearly addressed in our revised manuscript, along with a new figure to alleviate some of the confusion. Furthermore, in section 5.6 of the revised manuscript, we discuss the location/position of the Kallipetra Basin with respect to the regional tectonics.

f) *The evolution of the basin could be captured by a series of sketches, which can be either NE-SW striking cross-sections or 3D sketches, beyond the snapshot of Figure12.*

We agree that this is a great idea and we have created a new figure, Fig. 12 in the revised manuscript, to help solidify some of our explanations and interpretations, especially with regards to your point (d). We have added a new figure that includes a snapshot of various times: (1) exhumation/erosion and opening of the basin; (2) deepening; (3) shallowing, mound growth, fault reactivation, and closure; (4) and tilting of the faulting contact and basin. Also in this figure is a comparison of top-to-the-NE **normal** faulting versus top-to-the-NE **thrusting** to show that we require top-to-the-NE thrusting to agree with our data and observations.

Comments on the text of the manuscript:
Line 28: There are dozens of references that could be placed here. It is better to include "e.g." at the beginning of the reference list.

Done.

Line 28: You should give the definition for the Internal Hellenides as the term is not only geographical or spatial but also has a geodynamic meaning by dividing the Hellenides into two areas with different evolution during the alpine orogenesis. Also, the first letter must be uppercase (Internal).

Corrected 'internal' to Internal - we also noticed this same mistake on line 35, which has also been corrected in the manuscript. Reviewer 1 also suggested we refer to the map or provide a definition of the Internal Hellenides, therefore we have made the positions of the Internal and External Hellenides more apparent in Fig.1 to address the concerns of both reviewers.

Line 34: What is the origin of this "Upper Cretaceous basin"? How was it created? Is it a single basin or more?

We have rephrased this part also considering the comment of reviewer 1.

Line 36: I think that the migration is towards the SW-SSW.

The migration direction depends on whether one is talking about present-day coordinates or not, therefore we will eliminate any confusion and simplify this sentence by replacing SSE with 'southward' in the text.

Line 41: What are these controversies? I believe it needs further analysis beyond a simple reference to "controversies" and the presentation of a figure (Figure 2). You need to clarify the problem that you want to solve with this work.

This is very similar to a point raised by reviewer 1 – we need clarify the controversies and the problem we wish to solve. The many and contrasting geodynamics models present in the literature source from the difficulties of connecting the Rhodope and the Pelagonian zone. This is a longstanding debate on the number and dimension of oceans in the Mesozoic Pindos-Vardar realm between researchers proposing a single unifying Early Jurassic Vardaric ocean that has been partly subducted, partly obducted and dismembered during successive tectonic events and researchers that embraced a multi-ocean early Jurassic scenario that led to several subduction zones. In these scenarios, the Cretaceous sediments were deposited on the eastern Pelagonian zone either within a Jurassic-Cretaceous passive margin or during a subsequent Cretaceous tectonic event (compressional or extensional depending on the authors). These geodynamic interpretations are presented in Fig.2 and display the different positions of the Pelagonia-Vardar margin relative to the Alpine orogenic wedge after the Jurassic convergence. By studying the small Upper Cretaceous Kallipetra Basin that lies on the Pelagonia-Vardar 'suture zone', we can begin to address questions on if and how the Pelagonian-Vardar margin was deforming. Our study will ultimately provide constraints on the position of the eastern Pelagonian margin relative to the Alpine orogenic wedge, hence ruling out some of the geodynamic models so far proposed.

We have edited Fig. 2 by outlining the position of the Kallipetra Basin with respect to the different geodynamic scenarios. We have changed our introduction to further elaborate on the controversies and our study goals, and referred back to the geodynamic interpretations in the Discussion. We expanded our discussion to include where our Basin is located compared to the regional tectonics.

Line 68: Add "e.g." at the beginning of the reference list as there are numerous works that could be cited here.

We have added ‘e.g.’.

Lines 78-81: The area in which this stratigraphic gap has been described (Aptian-Albian) is very far from the study area and paleogeographically belongs to the wester nmargin of Pelagonian and not to the eastern. Furthermore, other researchers (e.g. Sharp and Robertson 2006) argue that the onset of sedimentation occurs during the Aptian-Albian north of the study area.

We agree that the area to which we refer to is far from the study area. Therefore, we have investigated descriptions of the Aptian-Albian hiatus and/or deposition from other studies such as Sharp and Robertson (2006) that are closer to our study area and edited the text accordingly.

Line 82: There are papers that describe older in age transgressive sediments which unconformably overlay the Pelagonian and Vardar units (e.g. Mercier 1968; Brown and Robertson 2004; Sharp and Robertson 2006; etc). See also my comment b.

We agree, but here we are referring to transgressive sediments to the south and not to the north. We will also rephase this part.

Line 83: You need to add more references here. There are numerous works to be cited here, with primary data except from the synthetic work of Papanikolaou (2009).

Ok, we have added more works: Mercier, 1968 and Mercier & Vergely, 2002.

Line 92: Add “e.g.” at the beginning of the reference list as there are numerous works that could be cited here.

We have added e.g. at the beginning of the reference list.

Line 95: Leucogneisses?

We have corrected ‘leucogneiss’ to ‘leucogneisses’.

Lines 95-96: Are you referring exclusively to the area west of the Kallipetra Basin or to the Pelagonian in general? If the latter is true you should add more references, as it is not only Schenker (2013) who describes the above lithologies. You could add “Schenker 2013 and references therein”.

In this case, we are referring to and describing only the lithologies in the study area - hence just the area west of the Kallipetra Basin studied in Schenker (2013).

Line 111-112: The sentence ‘the sediments belong.............as the Kallipetra bas-inÂ ̇z causes confusion (see also previous comment c). What is called as Kallipetra basin? Is it the paleogeographic domain where the large thick Upper Cretaceous sediments were deposited or only the small basin under study?

The Kallipetra Basin is the small basin under study but could be correlated with other Late Cretaceous sediments found in nearby areas along the suture zone.

Lines 115-118: Please enter references as you seem to be referring to older works.

The work referenced here is Schenker et al 2015, we have added this to the manuscript

Line 141: What do you mean by the term "metapelitic zones"?

We mean 'diagenetic zones' or very low- to low-grade metamorphic zones. The term 'metapelitic zones' has been replaced by 'diagenetic zones'.

Lines 235-236: You argue that the fossils are deformed and reworked and are supplied by the VOC based only on the work of Schenker (2013). Apart from this study, I do not remember any other study that reports Lower Cretaceous sediments in the VOC. On the contrary, there are papers that support the start of deposition in Aptian-Albian(see also previous comment b). Even in your own work it is described that sediments of Kallipetra Formation with VOC form duplexes, so how are you convinced that the fossils belong to VOC and not to the Kallipetra formation? Îd'here are also studies that describe Upper Jurassic-Lower Cretaceous sediments unconformably on the VOC, which seal the tectonic emplacement of the VOC onto the passive margin of the Pelagonian. If you include those Upper Jurassic-Lower Cretaceous sediments in what you have named as Vardar Oceanic Complexes then you need to clarify that.

Thank you for your comment. We have added the following paragraph to Section 4.2 to address the origin of these fossils:
"However, the fossils are deformed and not perfectly preserved, suggesting that they have been reworked and are supplied from elsewhere (Fig. S1). Indeed, Schenker (2013) discovered Lower Cretaceous Orbitolina in the VOC, located very close to the tectonic contact with the Kallipetra Basin. Late-Jurassic to Lower-Cretaceous limestones directly overlying the Pelagonian basement and the dismembered, eroded ophiolites are the probable source of these fossils (e.g. Brown & Robertson, 2004; Sharp & Robertson, 2006). Therefore, this sample is excluded from discussions about the depositional age of the Kallipetra Basin."

Lines 311 and 312: Please correct the references. There is no Schenker (2014) in your reference list.

Schenker (2014) has been corrected to Schenker et al., (2014).

Line 415: Please enter reference as you seem to be referring to older work.

This work should be Schenker et al., (2015).

Line 449: The word "dramatic" has been struck through. I believe you need to delete that word.

Yes, dramatic has now been deleted.

Lines 488-489: See my comment d. As in the following lines (490-492) you suggest a localized inversion that predated the start of the general convergence, you have to enforce your interpretation.

We have reinforced our interpretation with a series of sketches, as mentioned in our response to commend (d), and expanded on Section 5.6 that refers to the localized inversion.

Lines 494-498: I suggest to delete this interpretation as you have already weakened it in the second sentence.

See reply on the heat source to reviewer 1. The discussion around the specific magnitudes of heating related either to shear heating or advected hot fluids is highly hypothetical, and we therefore do not have adequate evidence to support one of the two sources of heat. Therefore we have deleted a significant portion of the Section 5.5 that used to address the heating mechanisms and sources of heat.

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Comments on the Figures

1. *Figure 2 shows various models of evolution of the Hellenides in the Cretaceous, which are not analyzed in the manuscript and in the end there isn't any suggestion about them. Therefore, it does not offer anything substantial to this work and could be removed.*

We have kept figure 2 but made sure we explained our study goals more clearly in the revised manuscript, and we now refer back to the figure once we interpret our data in the discussion sction. We made sure to be more specific on the controversies we would like to address (see reply on the scientific question to review 1). We also added the hypothetical locations of the Kallipetra Basins on the various models of evolution of the Hellenides during the Cretaceous.

2. In the geological map of figure 3 some things are not visible and difficult to distinguish, e.g. difficult to distinguish black dots from dark blue ones. Therefore, some symbols need to be magnified.

We, and Reviewer 1, agree that the dots were very small. We have made the dots much larger and also changed their colors to make them more visible.

3. In the geological sections of Figure 8, there is a large number of faults. According to the manuscript and the map of figure 3, these are normal, thrust and strike- slip faults. In order for the reader to find out which is which, he must constantly resort to the map. Therefore, I suggest the relative slip of the fault-blocks should be plotted along the faults.

We appreciate having this brought to our attention. The relative slip of the fault blocks was plotted along the faults, however the reduction in size of the figure was not taken into account so the labels were no longer visible. We have made the relative slip symbols much larger and visible to the reader. We also changed the colors of the cross sections so they correspond correctly to the geologic map symbology.

4. In figure 12 there is no legend explaining the symbols used to describe the different geological formations of the sketch. The sketch also gives a false impression that the basin has developed mainly east and northeast of the VOC. Perhaps the sketch should also include the western margin of the basin in order for the reader to have a complete picture. See also previous comment for 3D sketches.

We have added a new figure that includes a series of sketches that show the evolution of the basin that includes the western margin of the basin. We also added colors to the 3D sketch (previous Figure 12, now Figure 13) that correspond to the colors used in the geologic map.

<u>List of relevant changes in the manuscript</u>

Authors: The author order was changed from:
Lydia R. Bailey, Vincenzo Picotti, Maria Giuditta Fellin, Filippo L. Schenker, Miriam Cobianchi, Thierry Adatte

to:
Lydia R. Bailey, Filippo L. Schenker, Maria Giuditta Fellin, Miriam Cobianchi, Thierry Adatte, Vincenzo Picotti

Abstract

- The abstract was re-written to de-emphasize the sources of heat responsible for the inverse geothermal gradient.

1. Introduction

- The introduction was re-written to better explain our study goals and hypothesis, and to clarify the controversies addressed in Fig. 2 and how they relate to our study.

2.1 Large Scale tectonic setting

- In addition to some minor alterations, we mention the studies of Sharp and Robertson (2006) and Mercier to elaborate on the large scale tectonic setting of our study area (lines 94 to 98).
- We add in more citations on lines 114-115.

2.2 Main geologic features of the eastern Pelagonian margin

- We changed 'hydraulically brecciated serpentinite' to 'dark massive fractured to brecciated serpentinites' in response to Referee 1, here and throughout the text.
- We add Schenker et al., 2015 to the citations when we refer to their work.

3 Methods

- Very minor changes in all sections.
- 'Diagenetic' added before 'grade' on line XX
- Metapelitic zones changed to 'low-grade metamorphic zones' on line XXX

4.1 The Kallipetra Formation: facies and boundaries (in 4 Results)

- Some additions were made to unit descriptions for clarification.

4.2 Biostratigraphic data (in 4 Results)

- A few sentences were added to explore alternative sources of reworked, deformed fossils that have been excluded from discussions about the depositional age of the Kallipetra Basin.

5.1 Onset and evolution of the Kallipetra Basin

- Schenker, 2014 was corrected to Schenker et al., 2014 (here, and throughout the text)
- We added comparisons to the Kallipetra Basin onset to nearby study areas to the north (Mercier, Sharp and Robertson, etc) and speculate further on the regional-scale setting and how that might have affected the onset of the Kallipetra Basin.

5.2 The Rudist mounds: facies and evolution at the slope of the Kallipetra Basin

- We directly compare our rudist bioherms to similar rudist mounds observed nearby, north of the study area, by Sharp and Robertson (2006).

5.5 The inverted geothermal gradient in the Kallipetra Basin

- We removed a significant portion of this section, as we do not have adequate data to speculate on the sources of heat that caused the inverse geothermal gradient, and this was not the main goal of our study.
- We added some clarifying sentences about the timing of the heating event.

5.6 Sealing of the Kallipetra Basin and large-scale implications

- This section saw the most significant changes and additions due to some confusion experienced by both referees. We made sure to clarify the reasoning and evidence behind the top-to-the NE tectonic transport *through thrusting* (to also accompany the new fig. 12) and compare our results and interpretations to nearby study areas, with speculations on why the Kallipetra Basin experienced a different tectonic history.
- We compare the inversion observed by the Kallipetra Basin to the regional-scale tectonics.
- We refer back to Fig.2, our introduction, and the controversies we aimed to clarify at the end of this section.

Figures:

- Any terms 'Vardar Ophiolitic Complex' in the figures were renamed to 'Vardar Oceanic Complex' to be consistent with the text.

- Figure 1 – The 'Vardar/Sava Zone' and 'Ophiolites' were combined into one unit labelled 'Ophiolites & associated sedimentary rocks'. We felt that there was confusion around the additional 'Ophiolite' unit, as the Vardar/Sava Zones are also ophiolitic units, so by combining them into one eliminates any of that confusion. We also added labels 'Internal Hellenides' and 'External Hellenides' to the map.
- Figure 2 – Different colors were given to the Pelagonia and Rhodope terrains to make their positions more clear to the reader. The position of the Kallipetra Basin was inserted on each geodynamic interpretation as a red bar.
- Figure 3 – The sample location circles (previously very small black and dark blue dots) were significantly enlarged and changed to red and yellow circles with black outlines to make them more visible. The SKB unit in the legend was renamed to 'Serp. & Kallipetra Fm. Breccia' in case the reader hadn't noticed yet what SKB stands for in the text. The cataclasites in the legend were renamed to more descriptive terms 'Pelagonian & serp. Cataclasite' and 'Serpentinite cataclasite'. 'Hydraulically brecciated serpentinite (& ophicalcite)' was renamed to 'Fractured to brecciated serpentinite (& ophicalcite)'. We changed the color of the Aliakmon River so it doesn't interfere with the mapped units. We made the colors of the units on the map brighter for clarity.
- Figure 4 – the resolution of the Sfikia Lower Road section (4a) was improved.
- Figure 7 – the resolution of the photographs were improved and we switched the positions of 7b and 7c to correspond to the order they are introduced in the text.
- Figure 8 – Some of the contacts and bed dips on the cross sections were corrected to more geologically realistic configurations that better match our observations. Arrows showing relative slip of fault blocks were enlarged. The mound, mound flank, and SKB facies were colored to correspond to the colors on the geologic map.

- Figure 11 – The figure was mirrored so the thrust was facing the opposite direction and the units were colored to correspond to the colors/legend used in the geologic map. Arrows that indicated movement of fluid along the fault zone were removed.
- Figure 12 (NEW) – We created a new figure that shows the onset and closure of the Kallipetra Basin and compares closure due to normal faulting to closure due to thrusting.
- Figure 13 (former Figure 12) – We colored the units in the figure to correspond to the legend used in the geologic map (Figure 3) and the rest of the figures to remain consistent.

Birth and closure of the Kallipetra Basin: Late Cretaceous reworking of the Jurassic Pelagonian – Axios-Vardar contact (Northern Greece)

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Abstract. Some 20 Ma after the Late Jurassic to Early Cretaceous obduction and collision at the eastern margin of Adria, the eroded Pelagonia (Adria) – Axios-Vardar (Oceanic Complex) contact collapsed, forming the Kallipetra Basin, described around the Aliakmon river near Veroia (Northern Greece). Clastic and carbonate marine sediments deposited from early Cenomanian to end Turonian, with abundant olistoliths and slope failures at the base due to active normal faults. The middle part of the series is characterized by red and green pelagic limestones, with minimal contribution of terrigenous debris. Rudist mounds in the upper part of the basin started forming on the southwestern slope, and their growth was competing with a flux of ophiolitic debris, documenting the new fault scarps affecting the Vardar Oceanic Complex (VOC). Eventually, the basin was closed by overthrusting of the VOC towards the northeast and was buried and heated up to ~ 180 ˚C. A strong reverse geothermal gradient with temperatures increasing up-section to near 300 ˚C is recorded beneath the VOC by illite crystallinity and by the crystallization of chlorite during deformation. ~~and zircon fission tracks, with temperatures increasing up-section to near 300 ˚C at the tectonic contact with the VOC~~. ~~We interpret this anomaly as due to fluid migration from deeper sources and/or shearing affecting the porous and permeable deposits during early burial diagenesis.~~ This syn-tectonic heat partially reset the zircon fission track ages bracketing the timing of closure just after deposition of the ophiolitic debris in the Turonian. This study documents the reworking of the Pelagonian – Axios-Vardar contact, with Cenomanian extension and basin widening followed by Turonian compression and basin inversion. Thrusting occurred earlier than previously reported in the literature for the eastern Adria, and shows a vergence toward the northeast, at odds with the regional southwest vergence of the whole margin, but in accordance to some reports about 50 km north.

1. Introduction

The Hellenides are an integral segment of the main Alpine-Himalayan orogenic belt (Fig. 1). They have recorded polyphase Alpine deformation since the Middle Jurassic, when they were involved in the obduction of imbricate oceanic units over the eastern Apulian margin (e.g. Bernoulli and Laubscher, 1972; Zimmerman and Ross, 1976; Schmid et al., 2020). In the I~~i~~nternal

Hellenides (Fig. 1), continuous convergence led to collision of continental promontories with Eurasia in the Late Jurassic-Early Cretaceous that built a metamorphic crustal-scale orogenic wedge involving the Pelagonian zone and Rhodope (Ricou et al., 1986; Burg et al., 1996; Schenker et al. 2014). In the Late Cretaceous, the metamorphic thrust sheets of the Pelagonian zone were exhumed to shallow depths. This is testified by a cooling below ca. 240 °C from 83 Ma onwards along the northern margin of the Pelagonian zone (Most, 2003; Schenker, 2013), from 54 Ma to the south (Lipps et al., 1998, 1999; Coutand et al., 2014), and by the deposition of metamorphic Pelagonian detritus in a Late Cretaceous basin (Kossmat, 1924; Schenker et al., 2015), subsequently referred to as the Kallipetra Basin in this study. During the Late Cretaceous-Eocene, thrusting resumed in the I~~i~~nternal Hellenides (Godfriaux et al., 1988; Schermer, 1993) and progressively migrated southward~~SSE~~ to the E~~e~~xternal Hellenides (e.g. Aubouin, 1973). Finally, in the Oligocene-Miocene, the Pelagonian zone was dissected by diachronous normal faults~~a pulse of extensional exhumation occurred~~ (Schermer et al., 1990; Lacassin et al., 2007; Coutand et al., 2014; Schenker et al., 2014) within a southward extensional deformation front that affected most of the Hellenides (e.g Papanikalaou and Royden, 2007).

In the Pelagonian zone and adjacent units, the record of this orogenic system in the time interval between collision in the Early Cretaceous and resumed thrusting in the Late Cretaceous-Early Cenozoic remains sparse, and the discontinuous, sometimes contrasting, large-scale interpretations source from the difficulties to establish a coherent tectonic history across the Rhodope and the Pelagonian zone (Fig. 2). ~~leading to many and sometime contrasting large-scale interpretations (Fig. 2).~~ To elucidate part of these controversies, this study investigates the~~a~~ small Upper Cretaceous Kallipetra Basin that formed on both ophiolitic and continental units along the eastern Pelagonian margin (Fig.1) and was overthrusted by serpentines of a Jurassic oceanic floor (the ophiolitic fragments now l~~a~~ying west of the Pelagonia zone named Axios/Vardar/Almopias zone by Schenker et al., 2015). According to the scenarios proposed in Figure 2, the Kallipetra Basin may have formed: (i) within a long-lived Jurassic-Cretaceous passive margin characterized by the income of flysch from the approaching Rhodopian trench to the East (e.g. Papanikolaou, 1989; Ricou et al., 1998; Papanikolaou, 2009); (ii) during an extensional tectonic event in between the Pindos obducting from the northwest and the Axios/Vardar/Almopias zone subducting to the north (Sharp and Robertson, 2006); (iii) over the obducted Axios/Vardar/Almopias zone (Froitzheim et al., 2014); or (iv) within a collisional wedge that incorporated the obducted Axios/Vardar/Almopias zone (Schenker et al., 2014).

The Kallipetra B~~b~~asin collected coarse detritus, ~~bearing Pelagonian~~ metamorphic and ophiolitic rocks from its shoulders, ~~and deposition was~~ followed by deformation of ~~the sediments~~its deposits, by thermal conditions that locally partially or totally reset the cooling ages, and by cooling during the Late Cretaceous (Schenker et al., 2015). However, the stratigraphic evolution and the depositional age of this basin are so far only partially constrained. Moreover, it remains unclear how thermal conditions (temperatures > ca. 240 °C) and deformation in this basin relate to the apparent tectonic quiescence associated with extensive Late Cretaceous cooling recorded elsewhere in the Pelagonian zone (Schenker et al., 2015) and to the diachronous and complex tectonic evolution of the Hellenides. Finally, the timing of opening and sealing of the basin and the tectonic environment of deposition ~~are~~ can provide fundamental constraints to unravel the Late Cretaceous interval of the long history of accretion, subduction, arc-magmatism and large-scale extension in the Hellenic subduction system (e.g. Jolivet and Brun, 2010; Ring et al., 2010; Burg, 2012 and references therein), therefore allowing us to better define the geodynamic models so far proposed. This study uses conventional geological mapping techniques, stratigraphic analysis, illite crystallinity, and low temperature thermochronology to obtain new constraints on the tectonic evolution of the eastern margin of the Pelagonian zone and to unravel the Late Cretaceous detrital record. Our data indicate that the Upper Cretaceous basin was relatively shallow and tectonically active as testified by the presence of olistoliths, large gravitational features such as rotational growth faults and slumping, and early diagenetic deformation. Rudist bioherms were accumulated on the ~~shallow~~ slopes of the basin with flank deposits dipping into the basin. The bioherms were terminated through environmental restriction or burial due to increased serpentinite sediment input from the south-southwest eroding oceanic~~ophiolitic~~ complex ~~to the south-southwest~~. Moreover, based on illite and petrographic data, we find an inverted, high, non-linear geothermal gradient related to a heating event, which likely occurred during the overriding of the Vardar Oceanic Complex (VOC) in the~~early~~ Late Cretaceous.

2 Background

2.1 Large-scale tectonic setting

Following the Variscan Orogeny and Permian strike-slip and extension (Schenker et al., 2018), the Permian-Triassic rifting led to the creation of the Tethys and its seaways, namely the Pindos, Vardar/Maliac and Meliata basins, that continued to open during the Triassic to Early Jurassic (e.g., Bernoulli and Laubscher, 1972; Schmid et al., 2008; Papanikolaou, 2009). The convergent motion between Eurasia and Adria led to a northward intra-oceanic subduction in the Vardar in the Early-Middle Jurassic that saw the production of magmatic arcs to the north (Dimitrijevic, 1982; Bortolotti et al., 1996; Burg, 2012). In the Late Jurassic, there was south-westward obduction of the Tethys ophiolite from the Vardar Ocean ~~(Axios/Vardar/Almopias zone)~~ onto the passive continental margin of the Pelagonian zone to the south (Bernoulli and Laubscher, 1972; Dimo-Lahitte et al., 2001). Jurassic-to-Lower Cretaceous sediments were imbricated during the accretion of the ophiolitic units (e.g. Robertson and Dixon, 1984; Bortolotti et al., 2005; the complex named Axios/Vardar/Almopias zone in Schenker et al., 2015). Continuous crustal shortening caused the accretion of Rhodope by the latest Jurassic-Early Cretaceous and of the Pelagonian zone by the Early Cretaceous (Figs. 1 and 2; Burg et al., 1996; Ricou et al., 1998; Schenker et al., 2014; Moulas et al., 2017). The buried Pelagonian basement experienced regional amphibolitic-facies metamorphism to the north (U-Pb zircon ~~metamorphic~~ ages from the leucosomes of migmatites at 130-117 Ma; Schenker et al., 2015, 2018) and an upper greenschist- to blueschist-facies metamorphism to the south (Ar-Ar ages on muscovite at 100-85 Ma; Schermer et al., 1990; Lips et al., 1998).

The tectono-sedimentary history during the Early Cretaceous is highly debated. Sharp and Robertson (2006) suggest that the Pelagonian zone and its emplaced ophiolitic rocks underwent extensional exhumation already during the Late Jurassic. Rather, Early Cretaceous tectonic activity has been recorded near Edhessa (Fig. 1) in the Axios/Vardar/Almopias zone, along with late

Aptian-early Albian transgression on both the Pelagonian platform and the Axios/Vardar/Almopias zone (Mercier, 1968; Mercier and Vergely, 2002). To the south, the Aptian-Albian time was characterized by ~~The non-metamorphosed Pelagonian sediments to the south show~~ a sedimentary ~~Aptian-Albian~~ hiatus (~120-100 Ma) over lower Aptian deformed flysch and bauxitic laterites instead ~~testifying deposition and deformation in the frontal part of the wedge, followed by growing topography during the accretion of the lower crustal units of the Pelagonian zone~~ (Nirta et al., 2015; 2018), suggesting a growing topography in the frontal part of the orogenic wedge.

Thereafter, transgressive Cenomanian-to-lower Campanian limestones and deep-water Paleocene turbidites unconformably overlay the eroded Pelagonian and Axios/Vardar/Almopias imbricated units (Mercier, 1968; Mercier and Vergely, 2002; Papanikolaou, 2009) attesting to deepening below sea-level of the Rhodope-Pelagonian crustal-scale orogenic wedge. Moreover, during the Late Cretaceous-to-Eocene and locally since the Campanian, the imbrication of the Axios/Vardar/Almopias units resumed at several locations in relation to thrusting with vergence to the NE and~~mostly~~ to the SW. This has been documented in the central-eastern Vardar near the study area (Paikon Window; Godfriaux and Ricou, 1991; Bonneau et al., 1994; Brown and Robertson, 2003; Katrivanos et al., 2013), in the northwestern Vardar (Grubić et al., 2009; Ustaszewski et al., 2009), in the northeastern Pelagonian zone (Kilias et al., 2010), in the southern Pelagonian zone (Baumgartner, 1985) and in the Pindos zone (e.g. Aubouin, 1959, 1973; Papanikolaou, 1997). Continuous convergence up to the Neogene progressively deformed the continental margin of the Adriatic plate into southwest-verging fold and thrust sheets (Fig. 1; Channell and Hovarth, 1976). Final exhumation of the stacked crustal and oceanic ~~piles~~ slices occurred through extensional metamorphic domes between the Eocene in the north and late Neogene in the south (e.g. Lister et al., 1984; Dinter and Royden, 1993; Gautier et al., 1993, 1999; Brun and Sokoutis, 2007; Jolivet and Brun, 2010; Burg, 2012;).

2.2 Main geologic features of the eastern Pelagonian margin

The Pelagonian basement consists of deformed: (i) orthogneisses crosscut by leucogneisses and leucogranites; (ii) mafic amphibolite bodies; and (iii) interlayered marbles (Schenker, 2013 and references therein). Cooling of the Pelagonian core complex carapace rocks may have started at or after collisional doming at 118 ± 4 Ma (U-Pb metamorphic zircon ages, Schenker et al., 2018). $^{40}Ar/^{39}Ar$ white mica ages from the Pelagonian gneisses show a younging toward the dome core from 111-100 to 80-64 Ma that witness the slow exhumation and cooling of the deeper units of the basement (Schenker, 2013).

The Axios/Vardar/Almopias unit includes a mélange zone made of tectonically superimposed marbles, serpentinites (ophicalcites), flysch-phyllitic series, volcanoclastic sediments, amphibolites and carbonatic sequences imbricated southwestward during the Late Jurassic obduction over the Pelagonian zone ~~to the west~~ (e.g. Smith et al., 1975; Ricou and Godfriaux, 1995; Sharp and Robertson, 2006; Ferriere et al., 2016). In the study area, the Axios/Vardar/Almopias unit is represented by serpentinites that are referred to as the Vardar ~~Ophiolitic~~ Oceanic Complex (VOC), which consists of at least 5 lithologies: (i) ophicalcites; (ii) dark massive fractured to brecciated serpentinites~~hydraulically brecciated serpentinite~~; (iii) sedimentary serpentinite breccias; (iv) sedimentary serpentinite breccia with platform carbonate clasts~~s~~; and (v) foliated serpentinites and limestones. Ferromanganese-rich chert nodules within the VOC, dated further to the south at approximately

175 Ma by Chiari et al. (2013), attest the involvement of this Jurassic oceanic floor in the intra-oceanic Tethys subduction and subsequent obduction.

On the eastern margin of the Pelagonian zone, relatively thick packages of Upper Cretaceous carbonate~~ic~~ and siliciclastic sediments with both a Pelagonian and ophiolitic provenance unconformably cover the VOC and the Pelagonian basement (Sharp and Robertson, 2006; Papanikolaou, 2009; Schenker, 2013; Schenker et al., 2015). In the study area, t~~T~~he sediments belong to a sedimentary basin that here is referred to as the Kallipetra Basin (Fig. 3). It formed as an elongated NNW-SSE oriented belt overlying the VOC and the Pelagonian continent. In this basin, the presence of reworked Lower Cretaceous *Orbitolinids*, *Globotruncana sp.* and ~~mid~~ Turonian *Helvetoglobotruncana helvetica* indicates deposition during the Cretaceous (Schenker et al., 2015). Based on these depositional ages, a ZFT age of 67 Ma from an orthogneiss boulder (sample 10-128) at the top of the Kallipetra Basin was previously interpreted as indicating a very short lag time between cooling of the dome and deposition in the basin (Schenker et al., 2015). Two more samples (10-029 and 10-130) from the Kallipetra B~~b~~asin were interpreted as possibly partially to non-annealed (Schenker et al., 2015).

From the early Oligocene, an overall southwestward tectonic denudation from shallow depths is documented in the Kallipetra B~~b~~asin by AFT ages of 32.7 Ma (sample 10-128) and in the Pelagonian basement by ZFT ages of 24 – 20.7 Ma and AFT ages between 22.9 and 16.1 Ma (Schenker et al., 2015).

3 Methods

3.1 Geologic mapping and stratigraphy

Geological mapping and structural analysis were conducted to reconstruct the geometry of the basin and the ductile and brittle deformation that affected the Kallipetra Basin and the overlying VOC. The paleogeography, depositional environment, and age of the sedimentary sequences were determined based on stratigraphic logging, optical microscopy and biostratigraphy. Planktonic foraminifera and nannoplankton were used to establish ages of the sedimentary succession~~package~~. Simple smear slides were produced using standard techniques to retain the nannofossil assemblages and original sediment composition. Quantitative analyses were carried out using a polarizing light microscope at a magnification of 1250x.

3.2 Illite crystallinity

The Kübler Index of illite crystallinity is a method used to determine diagenetic grade in metapelitic sequences by measuring the changes in shape of the first dioctahedral illite-muscovite basal reflection at a 10-Å X-ray diffraction (XRD) spacing (Kübler and Jaboyedoff, 2000). To analyze illite crystallinity, bulk-rock mineralogy was obtained through the conventional powder XRD method using the ARL Thermo X'tra powder diffractometer at the University of Lausanne. Samples were then de-carbonated, followed by the extraction of <2 µm clay fraction and 2-16 µm fraction that were used for further analysis. Oriented samples were prepared by sedimentation on a glass slide from the suspended fraction. Samples were first air-dried (AD), and then treated with ethylene glycol (EG) to recognize any overlapping effect of smectite peaks. XRD diffractograms were performed on both the AD and EG treatments. The full width at half-maximum height (FWHM) of the illite 10-Å XRD peak that is measured on both AD and EG clay samples (<2µm size fraction) gives the Kübler Index (KI) (Kübler and Jaboyedoff, 2000). KI is expressed as Δ°2θ CuKα. The air-dried KI value is used for the determination of ~~metapelitic~~ low-grade metamorphic zones and approximate temperatures. It should be noted that the KI does not serve as a precise geothermometer, but provides a qualitative indicator of stages that phyllosilicates may have reached through metastable mineral reactions (Merriman and Peacor, 1998; Abad, 2007).

Significant asymmetrical peak broadening, caused by a tail in the 10-Å peak and produced by the presence of smectite and expandable mixed layers, is reduced following EG treatment (Abad, 2007). These peaks may indicate the presence of detrital illite, which gradually decreases with burial and essentially disappears in the anchizone (Kübler and Jaboyedoff, 2000). The decrease of KI values with increasing metamorphic conditions and temperatures is a consequence of the increase in the number of layers and disappearance of expanding layers. The Neuchâtel IC scale was calibrated with the Lausanne diffractometer and therefore produced anchizone limits of 0.18° and 0.36°Δ2θ CuKα, which we use in this study (Jaboyedoff et al., 2000).

3.3 Zircon fission track dating

Two of five collected samples provided enough zircons to date using zircon fission track (ZFT) analysis: V1503 and V1504. These samples integrate our previous samples (10-128, 10-129, 10-130; Schenker et al., 2015). The new samples were collected with the aim of revealing the full age distribution, which in our previous samples was limited by the low number of available zircons. To this goal, the new samples were > 5 kg each. All the samples consist of arenites and~~,~~ conglomerates~~, and sandstones~~. Zircons were separated from the whole rock by initial SELFRAG fragmentation, followed by density-based liquid separation using a Wilfley water table and heavy-liquid separation. The heavy fraction was passed through the Frantz magnetic separator stepwise to remove magnetic minerals from the zircons. Zircons were embedded in PFA Teflon and the prepared mounts were polished to expose the smooth internal zircon surfaces. The polished mounts were etched using a eutectic mix of NaOH and KOH to preferentially damage the fission tracks, enabling them to be fully revealed for optical analysis. To reveal the whole age distribution, we prepared up to four mounts per sample that we etched at very short time steps of 3.5 hours. Fully etched zircons were first recognized after 10.5 hours and then we etched the remaining mounts to 14 hours and 17.5 hours.

4 Results

4.1 The Kallipetra Formation: facies and boundaries

The study area is divided into 3 units: (1) the Pelagonian basement; (2) a stratigraphic unit that we name the Kallipetra Formation, described here for the first time; and (3) the VOC. The Kallipetra Formation is the focus of this study and consists of several lithofacies that collectively characterize a sedimentary basin (Fig. 3). Most field data were collected along two composite stratigraphic sections (the Kallipetra and Sfikia sections, Fig. 4).

The base of the basin is exposed close to the contact with the Pelagonian basement. Locally, the latter consists of a thick package of white, foliated cataclasite containing both serpentinite and gneiss fragments (Fig. 3). Directly overlying the cataclasite is a very dark ~~hydraulically~~ massive fractured to brecciated serpentinite, ~~shortly~~ followed by pebbly sandstones and well bedded dark grey limestones. Elsewhere, the base of the basin is characterized by a thick package of serpentinite-rich conglomerates, breccias, and minor amounts of dark grey limestone (Fig. 4a). The conglomerate is clast-supported and poorly sorted, with a dominance of sub-rounded to rounded clasts greater than 15 cm. The conglomerate is composed of dark green to black serpentinite (~90%), dark grey limestone, marble, and orthogneiss clasts and a fine-grained serpentinite matrix. Thickly bedded, poorly sorted calc-arenites stratigraphically overlie the serpentinite conglomerate. These are openly folded on the meter scale and bedding is deformed around large olistoliths of dark grey veined marble and serpentinite. The occurrence of olistoliths decreases significantly up section (Fig. 4). In the southeast, the basal contact is sharp and consists mostly of marls, shales and subordinate calc-arenites of the same kind as those observed in the central part of the basin, which are described below (Fig. 4b).

Calc-arenites are observed throughout the basin, typically at intermediate stratigraphic levels (Fig. 4b). The arenites range from fine- to coarse-grained, are medium to thickly bedded, and often display slumping folds. Locally, these folds and the synsedimentary gravity faults show a top-to-the NE vergence. The quartz content varies with location, with the highest proportion of quartz being in the north-west region of the study area. Locally, the calc-arenites consist of medium- to coarse-grained poorly sorted pebbly sandstones with 1-6 cm sized clasts of red arenite and red-pink carbonate. Very distinctive thinly bedded and laminated red and green marly limestones occur at intermediate-to-high stratigraphic levels (Fig. 4b). The red layers range from 2-5 cm thick, and green layers typically range from 0.5-2 cm thick. These deposits represent the deepest pelagic facies of the basin.

Towards the top of the basin, massively bedded conglomerates and breccias are often interbedded with the calc-arenites and pebbly sandstones, and consist of limestone, bioclastic limestone, arenite, marl, serpentinite, mudstone, and calcareous mudstone as rounded to sub-rounded clasts in a calcareous matrix.

Lateral variations in facies occur frequently, the most evident being the changes observed from the north-western to the central and south-eastern portions of the mapping area. In the north-west (Fig. 4b), the stratigraphy is dominated by coarse to pebbly sandstones, breccias, and conglomerates whereas shaley-limestones, marls, and mudstones prevail in the south-east (Fig. 4a). In the northwest, lithic fragments of quartz, gneiss, and marble are major components of the coarse sediments, with quartz content ranging from 45% at the base to 90% up section (310 m, fig. 4b), where serpentinite forms a minor component. In addition, olistoliths and evidence of slumping are frequent at high stratigraphic levels in the northwestern sector (Fig. 4b). This differs greatly from the southeastern sector (Fig. 4a), whereby slumped calc-arenites with olistoliths appear only at the base of the section, and the average quartz content is lower.

The top of the Kallipetra B~~b~~asin is marked by the occurrence of rudist mounds, five of which, some ~~hundreds~~ tens of meters thick, were identified in the study area. The mounds produce prominent cliffs and dome-like structures in the topography. Each mound can be separated into 4 different facies associations (Fig. 5): (i) the serpentinite and Kallipetra carbonate breccia (SKB); (ii) the mound core; (iii) mound flank; and (iv) the mound top.

The SKB is a sub-angular, moderately sorted, clast supported breccia that is poorly bedded and massive. Clasts comprise of serpentinite, dark grey limestone, rudist-rich microsparite, pink micrite, and minor lithic fragments like quartz, feldspar, and some dark pyroxenes. The rudist microsparite and pink micrite clasts are identical to the mound core. The matrix is composed of a fine- to medium-grained calcareous arenite. *Orbitolinids* were discovered in a clast by Schenker (2013). The SKB is usually found on the southern side or ~~litho~~stratigraphically below the mound.

The mound core is characterized by light grey to pink, massively bedded micrite and microsparite, in which float abundant whole rudists. *Hippurites* and *Radiolitid* rudists are present along with encrusting sponges and echinoderm fragments. Rudists are scattered throughout the mound and seem to have no preferred orientation. Vertical calcite veins and en échelon veins are frequently observed at the margins of the mound core.

The mound flank is a heterogeneous lithology that varies with distance from the mound core and location within the basin. In general, a moderately sorted, clast-supported breccia containing large, angular clasts of rudists, red limestone, greenish marls, micrite, and minor serpentinite clasts occurs closest to and on the northern side of the mound core. The number of clasts decreases into a matrix-supported breccia with a marly, green-colored matrix. The serpentinite content gradually increases up-section, and gravel-sandstones contain >60% serpentinite in addition to red microsparite clasts and rudists from the mound core. A sharp sub-vertical boundary often separates the mound flank and the mound core. The mound flank facies differ slightly throughout the area depending on the location of the mound core. The flank of the northernmost and youngest mound is first characterized by a massive clast-supported breccia consisting of micrite, rudists, sponges, and echinoderm fragments, dissected by neptunian dykes, with onlapping red pelagic marls. Differential compaction structures (load casts and fluid escape features) can be observed in the pelagic sediments where a stratigraphically higher mound core overlies them. Secondly, the clast-supported breccia passes rapidly into a ~34 m thick sequence of pelagic marly limestones only seen on top of the northernmost mound. The proportion of marls within the mound flank gradually increases from the southerly mounds to the northernmost mound.

Stacking of serpentinite-rich breccias always occurs on the southern slope of the rudist mounds. Flank deposits, either marls or a succession of sandstones and breccias, dip away from the mound core always on the northern mound side.

The mound top, where observed fully, is approximately 6 m thick and is stratigraphically overlying the mound core (Fig. 5). It generally consists of several meters of very poorly sorted, angular to sub-angular gravel of serpentinite and quartz within a white calcareous matrix. A thin layer of rudist-rich, elongated carbonate clasts overlies the gravel. There is a gradual transition into a clast-supported conglomerate with a reddish calcareous matrix, plus arenite and minor serpentinite clasts. The clasts of this conglomerate are very deformed, where the VOC tectonically overlies them. The full stratigraphy of the mound top was only observed at one, the southernmost, rudist mound (Fig. 5).

4.2 Biostratigraphic data

Although significant amounts of sample were collected for biostratigraphic analysis, nearly all of them were barren, or included dissolved, silicified, or recrystallized nannoplankton and foraminifera making most species indistinguishable. Table 1 summarizes the recognizable planktonic foraminifera that were only found near the northernmost mound (Asomata Quarry). The Orbitolinids~~a~~ found in sample M2-TS3, *Mesorbitolina pervia* (A. Arnaud, personal communication), has an older stratigraphic distribution than most of the ages displayed in Table 1, with the minimum age being in the basal late Aptian. However, the fossils are deformed and found in a clast together with other indicators of shallow water platform conditions, ~~deformed and not perfectly preserved,~~ suggesting that they have been reworked and are supplied from elsewhere~~by the VOC~~ (Fig. S1). Indeed, Schenker (2013) discovered Lower Cretaceous o~~O~~rbitolinids~~a~~ in the VOC, located very close to the tectonic contact with the Kallipetra Basin. Late-Jurassic to Lower-Cretaceous limestones directly overlying the Pelagonian basement and the dismembered, eroded ophiolites are the probable source of these fossils (e.g. Brown and Robertson, 2004; Sharp and Robertson, 2006). Therefore, this sample is excluded from discussions about the depositional age of the Kallipetra Basin.

Species abundance and totals of calcareous nannofossil were semi-quantitatively evaluated as F = frequent and R = rare. In the studied section (M2), the major calcareous nannofossil events in stratigraphic order are as follows: the first occurrence of *Quadrum gartneri, Eprolithus octopetalus,* and *Eprolithus eptapetalus* (sample M2/2, 50 cm from the bottom of the section); the first occurrence of *Eiffellithus eximius*, and first and last occurrence of *Kamptnerius magnificus* (sample M2/6B, 2 m from the bottom of the section) (Fig. S2).

Q. gartneri, E. octopetalus, and *E. eptapetalus* can be correlated with the UC7 zone in the Turonian stage, giving the base of the M2 section a minimum age of 93.6 Ma (Burnett et al., 1998). *E. eximius* and *K. magnificus* can be correlated with the base of the UC8 zone in the Turonian stage.

4.3 Post-sedimentary structural data

In the marls and marly limestones of the Kallipetra Basin, the foliation is mostly parallel to the bedding and defined by flat and elongated quartz clasts and clay minerals. Bedding and foliation dip at a very low angle either to the NW or to the SE due to bending around an axis plunging shallowly to the NE (Fig. 6a, b; Table S3). Stretching lineations are observed mostly on lamination surfaces in fine-grained marls, limestones and mudstones and they are formed by the alignment of elongated clay minerals. Mineral lineations occur mainly in the Pelagonian basement where the long axis of elongated quartz and feldspar crystals are aligned. In all the lithologies the lineations strike NNE-SSW at low dip angles (< 20~~-~~°; Fig. 6b). Stretching lineations along with asymmetric interlayered boudinaged beds indicates a top-to-the NNE shear sense within the basin (Fig 7a).

The top of the Kallipetra B~~b~~asin is tectonically covered by the VOC. In the profiles A-A' and B-B' (subparallel to the NE-SW lineations, Fig. 8), the contact appears preferentially flat and dips with shallow angle (< 15°) to NE. Along the profile C-C' (orthogonal to the lineations, Fig. 8), the contact is bent over the mound cores and flanks, forming an undulate surface. To the

NE, the Kallipetra sediments overlie the VOC forming tectonic duplexes (Profile B-B’, Fig. 8). The shear zone in the footwall of the VOC is characterized by 2 to 6 m thick foliated cataclasites and by a strain gradient visible through the increase in the intensity of the foliation. The cataclasite is usually white in colour, clay rich, and often features floating carbonate and/or serpentinite blocks in the matrix. Conglomerates below the contact between the VOC and rudist mounds show a 3 m-thick strain gradient from almost non-deformed clasts at the bottom, to cigar shaped and highly elongated clasts at the contact (Fig. 7b~~c~~; Profile B-B’, Fig. 8). The orientation of the long axis of the cigars is sub-parallel to the stretching lineations observed throughout the study area suggesting that the deformation during the tectonic emplacement of the VOC was penetrative within the basin. Shear bands, stepover structures and sigma-clasts in the cataclasite indicate a top-to-the NE tectonic movement (Fig. 7c~~b~~) synthetic to the intra-basin shearing. However, new growth of syntectonic chlorite (Fig. 9) along the main contact shows that shearing below the VOC occurred at higher thermal conditions with respect to the intra-basin deformation.

Late normal faults trending W-E to NW-SE and two transtensional to strike-slip faults crosscut the Pelagonian basement, the Kallipetra Basin and the VOC (Fig. 3). Most steep normal faults plunge to the NE (Fig. 8). Low-angle fault zones are observed within the VOC dipping approximately 35° towards the NNE with a normal top-to-NE shear sense. This later extensional phase may have locally reactivated the major tectonic contact. The dextral strike-slip component of the fault along the valley of the Aliakmon River reached approximately 50 m in the south and just a few meters in the north. Another transtensional fault causes a small normal displacement of approximately 50 m that uplifts the northernmost mound core.

4.4 Illite crystallinity data

37 samples for illite crystallinity analysis were taken up-section in the north part of the Kallipetra Basin (Kallipetra section). Four samples were unsuitable for illite crystallinity analysis as the <2µm portions contained no illite. The remaining samples have KI ranging from 0.091 to 0.39~~88~~ (Fig. 4b; Table 2).

Stratigraphically higher samples have KI ranging from 0.09 to 0.25, and stratigraphically lower samples have KI of 0.39~~8~~. The KI appears to increase down-section for samples containing only non-detrital illite. The sample with the lowest KI of 0.091 is characterized by an XRD pattern that reveals the presence of chlorite. The sample with KI of 0.14~~1~~ contains paragonite which indicates epizone conditions.

The samples containing detrital illite are limited to stratigraphic heights between 300 and 350 m~~eter~~s and show a large range of KI between 0.14 to 0.383. Non-detrital illite, on the contrary, is mostly confined to stratigraphic heights above 400 m. Using the anchizone limits as calibrated for our lab (see section 3.2; Jaboyedoff et al., 2000), and given the fact that the effects of detrital micas disappear in the anchizone (~200-300 °C), the results indicate that the Kallipetra sediments experienced higher temperatures (lower KI values) closest to the tectonic contact with the VOC. This is supported by the presence of paragonite at the top of the section. The KI values subsequently increase away from the contact, indicative of an inverse geothermal gradient from >300 °C to 100-200 °C within ~165 m (Fig. 4b).

4.5 Zircon fission track

We collected our samples along a down-section direction within the Kallipetra Basin: the only ones that produced enough countable zircons are from close to the contact with the VOC. Results are reported in table 3. The two successful samples are from the same location but from two different layers: a sandstone and a conglomerate. Both rocks are sheared and contain newly formed chlorite (Fig. 9). In sample V1504, 61 grains could be counted on the 10.5 and 17.5 hour etch. In sample V1503, 79 grains could be counted on four mounts with the 3 different etch times (10.5, 14 and 17.5 hours). Both samples consist of multiple age populations as attested by the χ^2 test that gives a probability of 0 % (Galbraith, 1981). V1504 has grain ages in the range from 75 to 660 Ma with a central age of 156 +/- 10 Ma and V1503 from 74 to 468 Ma with a central age of 177 +/- 13 Ma (Fig. 10; Table S4). At least two to three age populations can be identified using the software DensityPlotter (Vermeesch, 2012). The age distribution of sample V1504 has two major peaks: one centered at 150 +/- 6 Ma contains 84% of the grains, the other at 433 +/- 68 Ma is formed by 16% of the grains. The main younger peak might represent the sum of two populations at 128 Ma +/- 11 Ma and at 183 +/- 19 Ma, respectively. The age distribution of sample V1503 has a major peak with a pronounced shoulder and a long tail towards older ages. The central peak represents the largest age population that consists of 70% of the grain and that has an age of 158 +/- 14 Ma. The shoulder represents a minor population centered at 105 +/- 14 Ma with 19% of the grains. A third population might be located along the tail of the distribution at 252 +/- 50 Ma.

5 Discussion

5.1 Onset and evolution of the Kallipetra Basin

The orthogneiss- and serpentinite-rich composition of the previously described basal cataclasite suggests that it was formed prior to or at the same time with the formation of the Kallipetra Basin and mainly at the expense of the Pelagonian basement and of the VOC. These normal faults crosscut duplicates of Pelagonian mylonitic marble, and must be younger than ca. 120 Ma (Schenker et al., 2014). Normal faulting during or following the exhumation and doming of the Pelagonian zone from the late Early Cretaceous (Schenker et al., 2014; Schenker et al., 2015) probably contributed to subside the deformed wedge below sea level to create the basin. As discussed in section 2.1, the onset of the Cretaceous basins along the Pelagonian zone is diachronous and remains enigmatic. However, some evidence may suggest that the Albian-Aptian topographic response to the Early Cretaceous continental accretion was uneven along strike of the Pelagonian zone, likely due to northward decreasing shortening to a wider Rhodope to the south, thinning out to the north (Fig. 1). Indeed, to the south, non-metamorphosed Pelagonian sediments showing a sedimentary Aptian-Albian hiatus (~120-100 Ma) over lower Aptian deformed flysch and bauxitic laterites testify a growing topography in the frontal part of the orogenic wedge (Nirta et al., 2015; 2018). To the north, where the Rhodope starts to thin out in map view (Fig. 1), the Pelagonian zone and western margin of the Vardar Zone were transgressed during Aptian-Albian times by marine sediments with an eastward deepening that evolved to carbonate-clastic successions (Mercier, 1968; Mercier et al., 1987; Brunn, 1982; Sharp and Robertson, 2006).~~The extension produced an uneven~~

~~paleogeography in which one slope of the basin was prevalently built on Pelagonian basement, and the other on the VOC, allowing detritus from both lithologies to enter the depression.~~

Serpentinite-rich conglomerates represent the first sediments deposited within the Kallipetra Basin through subaerial erosion of the VOC, which created an uneven topography. North of the study area, conglomerates containing serpentinite pebbles and Pelagonian marbles of Albian age are observed on the eastern Pelagonian zone border, demonstrating prior deep erosion of the obducted ophiolitic sheet likely of Pelagonian Zone (Mercier and Vergely, 2002). The occurrence of conglomerates followed by a succession of calc-arenites at the base of the basin indicate shallow marine depths. Marble olistoliths and slumping at the base of the Sfikia section (Fig. 4a) indicate instability during the first phases of basin formation and the presence of a proximal steep slope in which gravitational instability drove slumping. In the north-western part of our study area, the presence of orthogneiss blocks, the dominance of quartz, feldspar, gneiss, and marble lithics in the sediments, and the lack of such components in the southeast, suggest an intrabasinal high, emergent land, or continent existed northwest of the Kallipetra Basin, where the Pelagonian basement was exposed. In the south-eastern part of the study area, the dominance of silty limestones, marls, lime mudstones, and the rare presence of olistoliths indicate that there was~~is~~ a deepening of the basin towards the south-east~~away from the north-west~~. The mid part of the Kallipetra Formation is devoid of serpentinite coarse detritus, suggesting the initial fault scarps were smoothed by sediments. This expansion of the basin toward the southern~~astern~~ slope ~~formed by the VOC~~ is documented by~~produced~~ the transgression of Kallipetra deposits onto the VOC, recorded in the study zone. It is worth noting that this basin widening corresponds to the deepest facies in the basin, likely correlating the Cenomanian-Turonian eustatic sea-level high (e.g. Haq, 2014). Mercier (1968) and Sharp and Robertson (2006) also record marine transgression and eastward deepening of mixed carbonate-clastic successions of the combined Pelagonian and Western Almopias zones.

5.2 The rudist mounds: facies and evolution at the slope of the Kallipetra Basin

Rudists constituted more than 60% of reef frames during the Aptian and Albian and became the most dominant frame-building organism in the Late Cretaceous (Scott, 1988; Voigt et al., 1999). Widespread tectonic extension combined with eustatic continental flooding occurring around the Cretaceous Tethyan Ocean allowed the growth of broad carbonate platform complexes, on slopes from a few ~~degrees~~ up to 40 degrees~~°~~ (Gili et al., 1995). Previously described carbonate mud mounds and rudist biostromes have some similarities to the rudist mounds observed in the study area (e.g. Camoin, 1995; Negra et al., 1995; Sanders, 1998; Sanders and Pons, 1999; Sanders and Höfling, 2000). It has been suggested that bioerosion processes leading to pervasive micritization of invertebrates may result from endolithic microorganism activity, accounting for part of the lime muds (Camoin, 1995). Alternatively, Camoin (1995) also suggest the lime muds are formed through in situ precipitation promoted and induced by microbial activity, and/or the decay of microbial communities. The latter is the most likely option regarding these mounds, with the dense micrite deposited as leiolite (sensu Riding, 2000) in a microbe-rich upper slope. Microbial mud mounds were common in the Late Cretaceous of the western Tethys, especially on the shelf/ramp rimming the Adria microplate (e.g. Picotti et al., 2019). The distinct dome shape of the mounds built mainly from lime mud, suggests that the mounds themselves were sites of increased carbonate productivity. Furthermore, the upward growth of rudists is said to be an adaptation to environments with positive net sedimentation rates (Gili et al., 1995), which may be the case for the Kallipetra Basin. The sub-vertical and sharp nature of some of the contacts between the mound cores and the flank deposits, and the presence of breccia bodies, suggest early diagenetic consolidation allowing stability of the steep mound slopes. By combining the observations of breccia bodies stacking up against the southern flanks of mounds, and the presence of stratigraphically underlying slumping and mass-flow deposits, the rudist mounds were built on a slope environment. Open shelf or shallow-water platforms, conditions suggested by Scott (1988) and Camoin (1995), are unlikely for the Kallipetra Basin due to its dynamic and tectonically active history. The termination of the rudist mounds, found in the upper part of the stratigraphy of the Kallipetra Basin, occurred by environmental restriction due to gradually increased sediment input from the approaching ophiolite talus (Sanders and Pons, 1999; Sanders and Höfling, 2000).

The mound flanks consist of a succession of sandstones, breccias, and occasionally marls. Our observation of polymictic breccias on the south-southwestern mound slopes bear an important paleogeographic meaning. In this case, the presence of serpentinite clasts indicates the breccias were not formed solely from erosion and collapse of mound flanks, but rather they were derived from an ophiolitic source up slope from the mounds, possibly associated to new fault scarps in the south-southwestern slope of the Kallipetra Basin. On the northern flanks of the mounds, the sediments display a shallower dip and are interfingered with the mound talus breccias. The youngest and northernmost mound at Asomata Quarry displays ~~at the northeastern flank~~ pelagic marls and limestones at the northeastern flank, suggesting deeper bottom conditions to the N and NE. On the other hand, the absence of serpentinite detritus in the mound flanks other than the southern ones documents a shadow effect of the mounds with respect to the south-southwestern provenance of the serpentinite clasts. This evidence corroborates the presence of a slope dipping to the north/northeast. North of the study area, Cenomanian-aged *Hippuritid*-bearing rudist mounds have been observed, where Sharp and Robertson (2006) suggest they also developed on an east-facing ramp. These authors also observe younger Campanian-Maastrichtian rudist biostromes that developed on an east-facing ramp-shelf margin in the Pelagonian and Western Almopias zones. However, as discussed in the following sections, these must have formed subsequent to Kallipetra Basin closure, likely in basinal areas not involved in Turonian compression. The increasing serpentinite content in the sandstones and breccias up-section suggests that the ophiolitic source was moving closer to the mound structure and gradually providing material to the slope. The positioning of the flank deposits and the northeastward directed stacking pattern ~~migration~~ of the two or three youngest mounds, with the highest - and therefore youngest - mound being at the Asomata Q~~q~~uarry in the northeast of the study area, suggest that in the upper part of the Kallipetra stratigraphy, there was a movement of the ophiolite (VOC) from SSW to NNE providing at first the slope for the growth of the mounds, then the burial for them (Figs. 12 and 13).

5.3 Stratigraphy and age of the Kallipetra Formation

The Kallipetra Formation was deposited on top of the eroded Pelagonian continent and obducted ophiolite following~~after the end of~~ the collision-related burial and cooling/exhumation of the Pelagonian zone at ~116 Ma (Aptian; Schenker et al., 2014).

The red and green limestones can be loosely correlated across the Kallipetra Basin and they first occur at approximately ~250 m from the base of the Kallipetra construction road section, and 400 m from the base of the Sfikia section (Fig. 4a). These facies indicate deposition in a deep, calm pelagic environment. The distinct red and green alternations are typically attributed to bottom-water redox cycles (*e.g.* Luciani and Cobianchi, 1999), developed around the Upper Cenomanian OAE2 (Luciani and Cobianchi, 1999; Negri et al., 2003; Mort et al., 2007). This event belongs to~~coincides with~~ the global Cenomanian-Turonian sea level ~~transgression~~high (Haq, 2014), therefore explaining the relative absence of clastic input in this interval, that could represent the deepest stage of the basin development. Indeed, this should be the timing of the onlap of the Kallipetra B~~b~~asin toward the southern ophiolitic slope.

Rudist mounds and breccias are lacking in the Kallipetra sediments found on top of the VOC (Figs. 3 and 8), whereas fine sediments dominate. The fine material suggests that the tip of the VOC was under sea level, with a transgressive trend and widening of the basin, allowing onlap of fine material over the VOC slopes at the same time as red and green marl deposition. During this time, the source area for sediments is moving away. This Kallipetra material overlying the VOC is somewhat separated from the main Kallipetra Basin sediments, possibly through a structural high or as perched basins (Fig. 13~~2~~). Alternatively, these deposits represent one flank of the basin that was subsequently tectonically emplaced over the basin, suggesting this movement was just a few kilometers and a local event.

Helvetoglobotruncana helvetica indicates that the marls overlying the mound at the top of the Kallipetra stratigraphy are lower Turonian. This agrees with the ~~other~~ nannoplankton that we found in the overlying section that are ~~lower~~ early to middle Turonian. The youngest proven depositional age of the Kallipetra Basin is ~ 92 Ma, but the top 35 m of hemipelagic marls are barren, therefore we cannot exclude a late~~st~~ Turonian or even Coniacian age for the very top of the Kallipetra B~~b~~asin.

The stratigraphic thickness between the red and green marls, and the marls adjacent to the mound core containing the *Helvetoglobotruncana helvetica,* is 200 m. By using an age of 93.9 Ma (Cenomanian – Turonian boundary) for the red and green marls (Cohen et al., 2013), and the youngest age of *Helvetoglobotruncana helvetica* - 91.3 Ma (BouDagher-Fadel and Price, 2019) - for the marls at the top of the section, then the average sedimentation rate of the basin infill is 0.08 mm year^{-1}, a value compatible with the recorded mixture of pelagic and terrigenous sediments. Assuming a constant sedimentation rate during infilling of the basin, the first sediments deposited at the bottom of the basin are lower Cenomanian. This would suggest~~Therefore, there was~~ approximately 20 Ma of erosion and/or subsidence between the final stage of the collisional doming of the Pelagonian basement and subsidence and deposition of the first Kallipetra sediments. This 20 Ma time interval agrees with the Aptian-Albian sedimentary hiatus (~120-100 Ma) described ~~over a lower Aptian flysch observed~~ further south in the Pelagonian zone by Nirta et al., (2015) and Nirta et al., (2018).~~, which is attributed to a growing topography during collision and subsequent subsidence (Nirta et al., 2015; Nirta et al. 2018).~~

5.4 Zircon fission-track age distribution and thermal overprint

Our new ZFT samples come from the top of the Kallipetra Basin where the depositional age should not be older than 92 Ma and therefore should be younger than the ZFT central ages of our samples, which range between 156 and 177 Ma (Fig. 10).

However, both ZFT samples contain a few young grains with ages overlapping with the depositional age of the Kallipetra Formation (Fig. 10). They are located a few hundred meters to the south of a previous sample, 10-029, that is adjacent to the contact with the VOC (Schenker et al., 2015; Fig. 10). The age range of this sample is from 52 to 340 Ma, and it consists of 16 grains that define only one age population centered at 92 +/- 9 Ma, in overlap with the depositional age. Thus, all these samples can be interpreted as partially to non-annealed, and the sample closest to the contact with the VOC has the youngest age. They are all from clastic sediments that contain newly formed chlorite. No illite crystallinity data are available as the rock type of the ZFT samples do not allow the illite method to be applied. However, we observed a NE-SW metamorphic gradient along the section where we collected the dated samples together with others that unfortunately provided no zircons. This gradient is indicated by the fact that the sandstones of V1503, V1504 and 10-029 contain newly formed chlorite, whereas the sandstones (V1505) located 4 km to the SW towards Sfikia show only detrital minerals (Figs. 4 and 9). The presence of newly formed chlorite in samples V1503, V1504 and 10-029 suggest temperature conditions ≥ 250 ºC, which could be within the partial annealing zone (PAZ) for natural zircons bearing radiation damage (Reiners and Brandon, 2006). However, the temperature range of the PAZ depends not only on the degree of radiation damage of the zircons but also on the rate of heating and cooling such that during a short-lived heating event, followed by rapid cooling, higher temperatures are needed to obtain fully reset ages. The fission-track kinetic parameters in natural zircons are constrained only based on exposed fossil annealing zones (Brandon et al., 1998) such that modeling their time-temperature history would not give any deeper insight on the conditions that could have produced the observed age distribution.

Two more samples were previously dated along the Kallipetra section where we collected our new illite crystallinity data (Fig. 10; Schenker et al., 2015). There, 20 grains from the sample at the top (10-128) of the section define an age range between 39 and 102 Ma and a central age of 67 +/-4 Ma; 26 grains from the lower sample (10-130) have ages from 40 to 158 Ma and centered at 72 +/- 5 Ma. These samples come from the top of the Kallipetra section and they were previously interpreted as non-annealed. However, based on the revised depositional age of the Kallipetra B~~b~~asin documented here, the central ages of these samples result younger than the depositional age, but their age ranges partly overlap with the depositional age. Thus, these samples can be defined as partially to fully annealed and they are younger than the samples 10-029, V1503 and V1504. The illite crystallinity data indicate temperatures up to ≥ 300 ºC towards the top of the Kallipetra section. The top ZFT sample 10-128 is from a higher stratigraphic location than that of the illite samples, whereas sample 10-130 comes from the same location as the uppermost illite samples. Thus, the ZFT samples along the Kallipetra section should have been subject to T ≥ 300 ºC but we cannot say if and how much higher these temperatures could have been relative to the other samples.

The different ZFT age ranges and central ages hint to highly variable degrees of annealing. Our petrographic and illite crystallinity data constrain a strong, inverse, vertical (up-section) thermal gradient but they cannot discriminate possible lateral gradients across the basin. However, they indicate that the Kallipetra Basin has been subject to temperatures that locally could have totally or partially annealed our samples. Whether these gradients are reflected by the ZFT central ages or grain-age distributions must be carefully pondered against other factors that could also affect our results. In fact, we processed the new and the old samples purposefully in different ways because, while processing the previous set of samples, we realized that the low number of available zircons limited the applicable etch procedure, which was not optimal to reveal the full age spectra of our samples. However, even though at the time we opted for an etch procedure aimed at maximizing the young grain ages, our results indicated that the annealing degree of our samples might have been incomplete. With the new samples, we aimed at verifying the degree of annealing by maximizing the zircon yield that allowed applying a multiple etch procedure. This in turn revealed that in fact there are wide age distributions in the new samples, which include non-reset ages, and this confirmed our previous observations on a partial degree of annealing. Unfortunately, our new data do not answer all the questions concerning the ZFT ages in the study area but highlight a complex thermal and annealing record.

5.5 The inverted geothermal gradient in the Kallipetra Basin

The KI data constrain an inverse geothermal gradient at the top of the Kallipetra Basin from > 300 °C at the tectonic contact to 100-200 °C ~165 m below the overridden VOC (Figs. 4 and 11). Stratigraphically below this zone, the sediments reached only deep diagenetic conditions. The newly formed syn-tectonic chlorites in the top sediments at the base of the VOC further testify high (> 200 °C; Beaufort et al., 2015) and inverse temperatures that peaked at the time of deformation.

The illitization reaction (i.e. the conversion of smectite-rich I-S into illite-rich I-S) is also dependent on the availability of K^+ ions, sometimes requiring enhanced K^+-rich fluid circulation (Dellisanti et al., 2008). However, the corroboration of temperatures between the chlorite-in reaction and the KI values suggests that the K+ ion were available during the increase of the metamorphic conditions and that other mechanisms influencing the crystallinity of illite such as shear related recrystallization (Merriman and Peacor, 1998; Árkai et al., 2002) were less important in controlling the KI values. Hence, it is likely that the KI values represent metamorphic temperatures recording an ~~dramatic~~ inverse geotherm.

Sedimentary strata within thrust belts are known to sometimes experience transient thermal histories, and 'sawtooth' geotherms with inverse metamorphic fronts from the base of the hanging-wall into the footwall have been recognized in a series of thrust systems (Graham and England, 1976; Furlong and Edman, 1989). ~~The inverted thermal profiles by fault zones require an extra heat source in addition to conductive relaxation after burial (e.g. Barton and England, 1979; Graham and England, 1976). In the Kallipetra Basin several additional heat sources can be envisaged: (i) heat advection through emplacement of the hot VOC or percolation of hot fluids and (ii) in-situ heat production through shear heating (e.g. Barton and England, 1979; Camacho et al., 2005; Graham and England, 1976; Hooper, 1991; Mase and Smith, 1984). In shear zones these mechanisms act contemporaneously, and one heat source may dominate over the other depending on the rheology of the rocks and on viscosity, strain rate, thickness and dip angle of the shear zone. With fast plate velocities (>2 cm/a), the heat surplus is mainly advected by the thrust sheet when viscosities are < 10^{-19} or is produced by in-situ shear heating when viscosities are > 10^{-20} (Duprat-Oualid et al., 2015). With < 2 cm/a, the heat is mainly conducted (Duprat-Oualid et al., 2015), hence at low velocities dramatic inverse thermal gradients such the one of the Kallipetra Basin are probably created by inputs of continuous or spasmodic hot fluids. However, the data collected so far does not allow to calculate the convergence rate, strain rates and thickness of the VOC potentially transporting the heat.~~

~~The sedimentary history suggests that the closure of the Kallipetra Basin by the VOC occurred just after the deposition of the ophiolitic debris that buried the mounds, when the sediments were porous, permeable and saturated. Accordingly, the viscosity of the sediments was low, probably reducing the contribution of heat derived by shear heating, unless the velocities were extremely high. At the microscale, the mechanical feedback between deformation and pore fluid pressurization along fault zones may lead frictional heating to generate fast and transient thermal perturbations with rises of temperature of up to > 500 °C (Vredevoogd et al., 2007) but the influence of these short-term pulses on the long-term thermal overprint results difficult to quantify. Hence, with "normal" convergence rates and low viscosities, the heat surplus is most likely allochthonous either coming from the transported ophiolitic sheet or from the rise of hot fluids. Changes in basin geometry, sediment compaction, uplift, and tectonic loadings from overriding tectonic sheets can all contribute to continuous changes in the groundwater systems, especially in foreland basins (Ge and Garven, 1989). Significant thermal perturbations require focusing of fluids in a spatial or temporal sense, for example, along fault zones (Deming et al., 1992). The overriding unit over the Kallipetra basin would have allowed fluid focusing and differential loading that caused any fluids to flow in the direction of tectonic transport (Fig. 10).~~

Overall, our data document an inverse thermal gradient of the Kallipetra Basin, pointing to a syntectonic heating event that produced a transient, inverse, non-linear and disturbed geotherm (Fig. 11). The sedimentary history suggests that the closure of the Kallipetra Basin by the VOC occurred just after the deposition of the ophiolitic debris that buried the rudist mounds, when the sediments were porous, permeable, and saturated. Although the ultimate sources~~causes~~ of this heat have not been ~~are not clearly~~ established, the non-reset to partially reset FT ages testify that this syn-tectonic heating event formed in the Late Cretaceous, during the closure of the basin in the Turonian. Cooling slightly postdates the deformation as the youngest ZFT population is older than the Turonian closure.

5.6 Sealing of the Kallipetra Basin and large-scale implications

The stacking patten of the rudist mounds documents closure of the Kallipetra Basin through a NE-facing slope and serpentinite detritus supplied from the SW. This pattern cannot be explained by the activity of a normal fault (Fig. 12 (2a)), since, in this case, the stacking patten of the mounds should have been to the SW, following the widening of the basin. Therefore, only a NE verging thrust of the VOC found at the southwestern margin of the basin can explain the observed rudist mound stacking pattern, as well as the serpentinite breccias and the northeast mound shadow (Figs. 12 (2b) and 13). Kinematic indicators, such as shear bands, stepover structures, and sigma clasts along the upper tectonic contact of the Kallipetra Basin, indicate a top-to-the NE tectonic movement. The NE dipping contact of the VOC over the Kallipetra Basin may be interpreted as a Turonian or younger normal fault in the literature (Fig. 12 (2a i); Schenker et al., 2015). However, this interpretation fails to explain the observed cutoff angles, since the tectonic contact should have cut the basinal deposits down-section, and this is not the case (see Figs. 8 and 12 (2a ii)). The cutoff of the Kallipetra deposits is compatible only with a NE directed thrust (Fig. 12 (2b i)). Post-Turonian tectonics is considered responsible for the northeastward block rotation and the normal faulting (Fig. 12 (2b ii)).

The partially- to fully-annealed ZFT ages combined with illite-crystallinity and crystallization of chlorite, indicating high temperatures at the tectonic contact but only deep diagenetic conditions below, suggest tectonic movement occurred in the Turonian when sediments were not fully compacted and still permeable. Therefore, the Kallipetra Basin was sealed in the Turonian by SSW to NNE tectonic transport of the VOC (Figs. 12 and 13). NE directed thrusting is documented some 50 km north of our study area in the Almopias zone by Vergely and Mercier (2000), although considered Teritary in age by the quoted authors. However, our results differ from previous studies that have documented progressive deepening from the Aptian up to flysch-like Maastrichtian to Paleogene sediments (Mercier and Vergely, 2002), or the development of thick Santonian-Campanian carbonates followed by a foredeep succession indicating dramatic subsidence in the Late Maastrichtian (Sharp and Robertson, 2006). The observed stratigraphy from this study, such as olistoliths, breccias, and slump deposits, suggests deposition very close to steep basin margins. Therefore, it is plausible that the closure of the Kallipetra Basin observed here only affected the margins of a larger-scale basin, which experienced continuous deepening and transgression as observed to the north of the study area by Mercier and Vergely (2002). Alternatively, the Kallipetra Basin may not be laterally continuous and its birth and closure would have only had local significance. ~~According to the sedimentary evolution of the basin and to the kinematic indicators along the tectonic contact and within the basin, the direction of tectonic transport of the VOC sealing the Kallipetra Basin in the Turonian was from the SSW to the NNE (Fig. 12).~~

During the Late Cretaceous-to-Eocene, along the eastern Pelagonian margin, the dominant deformation at the regional scale is SW-verging thrusting (e.g. Schenker et al 2015). Bivergent thrusting occurred locally but later in time during the late Late Cretaceous or Tertiary (Vergely and Mercier, 2000; Brown and Robertson, 2003; Katrivanos et al., 2013). Thus, the sealing of the Kallipetra B~~b~~asin occurred earlier than or in the very early phase of this regional deformation event, although the direction of tectonic transport of the VOC above this basin is opposite to the common SW-vergence of thrusting. This apparent difference may be explained by a localized basin inversion rather than a regional tectonic event that predated the start of the regional convergence in the Late Cretaceous,~~ or~~ Campanian at the earliest (Aubouin, 1973; Baumgartner, 1985; Godfriaux and Ricou, 1991; Bonneau et al., 1994; Papanikolaou, 1997; Brown and Robertson, 2003; Grubić et al., 2009; Ustaszewski et al., 2009; Kilias et al., 2010; Katrivanos et al., 2013; Schmid et al., 2020). ~~In this scenario, the inverted geothermal gradient in the Kallipetra basin was likely produced by heat advection related by the overriding VOC or by hot fluids. The presence of hot fluids could be related to the not too far occurrence of Late Cretaceous oceanic crust that is documented in the Dinarides (Prelević et al., 2017; Ustaszewski et al., 2009), in the Cyclades (Fu et al., 2012) and in Crete (Langosch et al., 2000). However, these basaltic magmatic centers are all dated to the Campanian and this is likely later than the sealing of the Kallipetra Basin that seemingly took place during the Turonian. Overall, independently from the source of heat that caused the inverted geothermal gradient, the closure of the basin anticipates the beginning of resumed ophiolitic imbrication in this sector of the internal Hellenides in the Turonian.~~

Overall, the thermo-tectono-sedimentary history documents a basin that likely formed in the Early Cenomanian over a suture with accreted Jurassic ophiolites in the hanging-wall and an Aptian metamorphic basement in the footwall. This attests its intracontinental position within an orogenic wedge in a tectonic scenario similar to the model proposed by Schenker et al. (2015) (Fig. 2). The extensional phase that opened the Kallipetra Basin remains enigmatic and may be associated with an isostatic re-equilibration of the orogenic wedge or with a far-field plate tectonic reorganization (e.g. Matthews et al., 2012). The closure of the basin anticipates the beginning of resumed ophiolitic imbrication in this sector of the internal Hellenides in the Turonian and is considered a local basin inversion. If the actual Hellenic subduction is considered active since at least the Early Cretaceous (van Hinsbergen et al., 2005), the closure of the Kallipetra Basin could be seen as early evidence in the upper curst of the initiation of the Hellenic slab.

Conclusions

The evolution of the Kallipetra Basin documents the transition from extension to compression during the early Late Cretaceous along the eastern margin of the Pelagonian zone in northern Greece. The history of the Kallipetra B~~b~~asin can be summarized as follows:

- The sediments of the Kallipetra Basin were deposited between the early Cenomanian (~100 Ma) and the latest Turonian (~90 Ma) over the VOC and the Pelagonian basement in a depression deepening to the east and north-east. The depression formed initially by extension as testified by normal faults at the base of the basin.
- As the basin widened, a topographic high located to the NW and exposing Pelagonian basement rocks became the main source of siliciclastic detritus to the basin. ~~Carbonate sediments were produced by pelagic organisms and by rudist mounds growing on the southwestern slopes of the basin (Fig. 12).~~ The basin widened and deepened to the point when no clastic input reached it. This time might correlate with the global Cenomanian-Turonian sea level transgression. Carbonate sediments were produced by pelagic organisms and by rudist-rich microbial mounds growing on the southwestern slopes of the basin (Fig. 13).
- The terrigenous input was later renewed, and the main source were ophiolitic rocks to the south or south-west, which provided breccias stacking up against the southern flanks of the rudist mounds. The progressive increase of detrital input restricted the environments of the rudist mounds.

The ophiolitic rocks overrode the Kallipetra B~~b~~asin from the SW, causing uneven deformation of its sediments (Fig. 12). Thrusting was associated with ~~occurred along with the circulation of hot fluids close to the tectonic contact and imprinted~~ a high inverted geothermal gradient that caused illitization, crystallization of chlorite and partial-to-total annealing of the fission tracks in detrital zircons close to and increasing towards the top of the basin. Deformation, illitization and zircon-fission track annealing occurred during the Turonian and were followed by cooling in the late Late Cretaceous, anticipating the beginning of the resumed tectonics in this sector of the internal Hellenides by about 10 Ma.

Data availability. Additional data is available from the corresponding author upon request.

Supplement. The supplement related to this article is available online at: xx

Author contributions. LRB is the primary author, conducted the study for her MSc thesis at ETH Zurich and wrote the paper. ~~VP contributed to the interpretation and provided supervision and mentorship in all aspects of this study.~~ FLS conceptualized the original research goals and aims of this study, and contributed to the interpretations, introduction and background sections of this paper. MGF conducted the fission track analysis, provided contributions to Sect. 1, 3.3, and 4.5 and to interpretations of data, and also provided mentorship. ~~FLS conceptualized the original research goals and aims of this study, and contributed to the interpretations, introduction and background sections of this paper.~~ MC prepared samples for and conducted all planktonic foraminifera analysis for this study. TA prepared samples for and conducted illite crystallinity analysis and gave constructive suggestions on the final paper draft. VP contributed to the interpretation and provided supervision and mentorship in all aspects of this study.

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Figures and Figure Captions

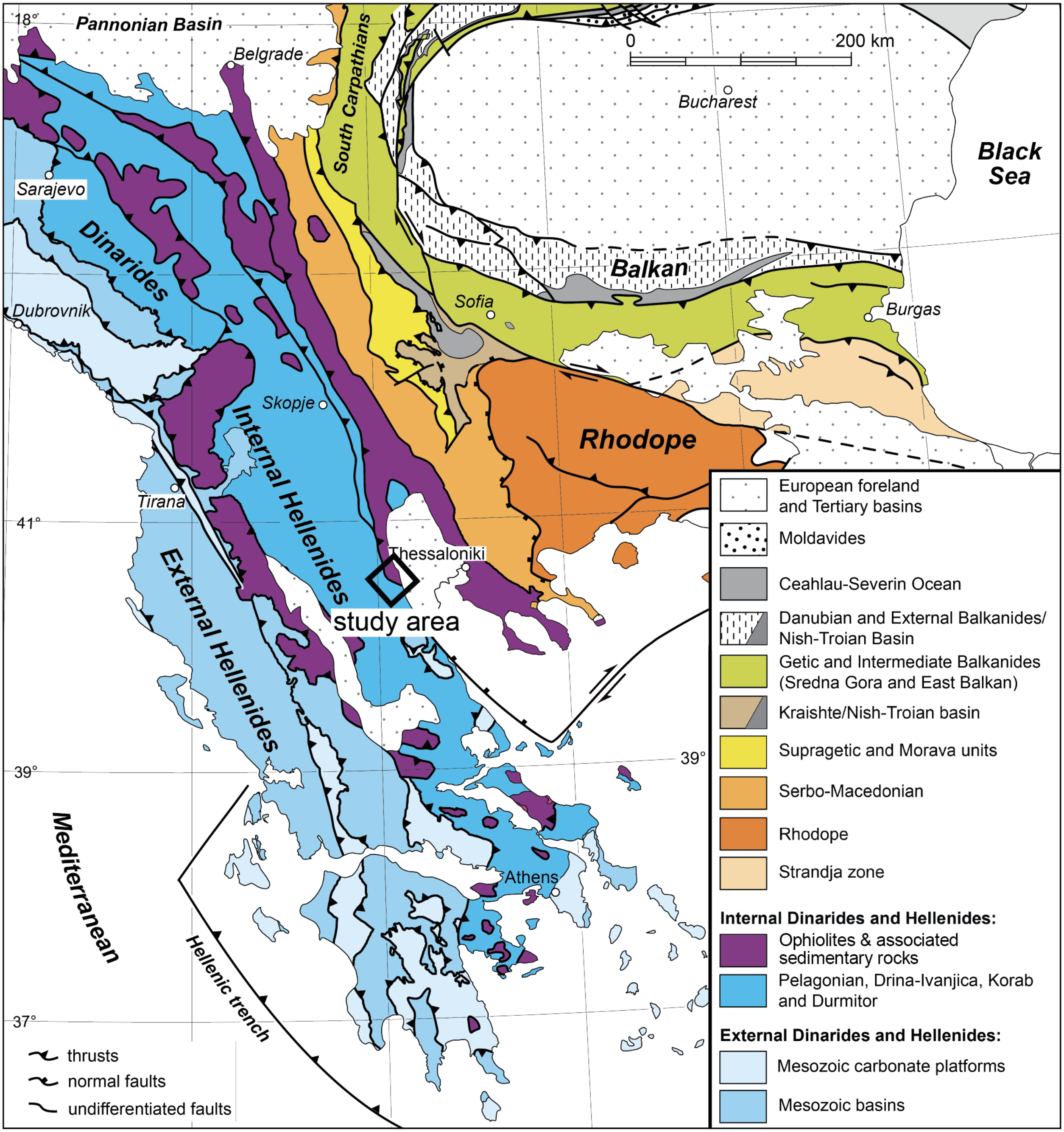

Figure 1: Location of the Hellenides and study area in the Alpine Mediterranean chain. ~~(~~Modified from Burg (~~,~~ 2012).

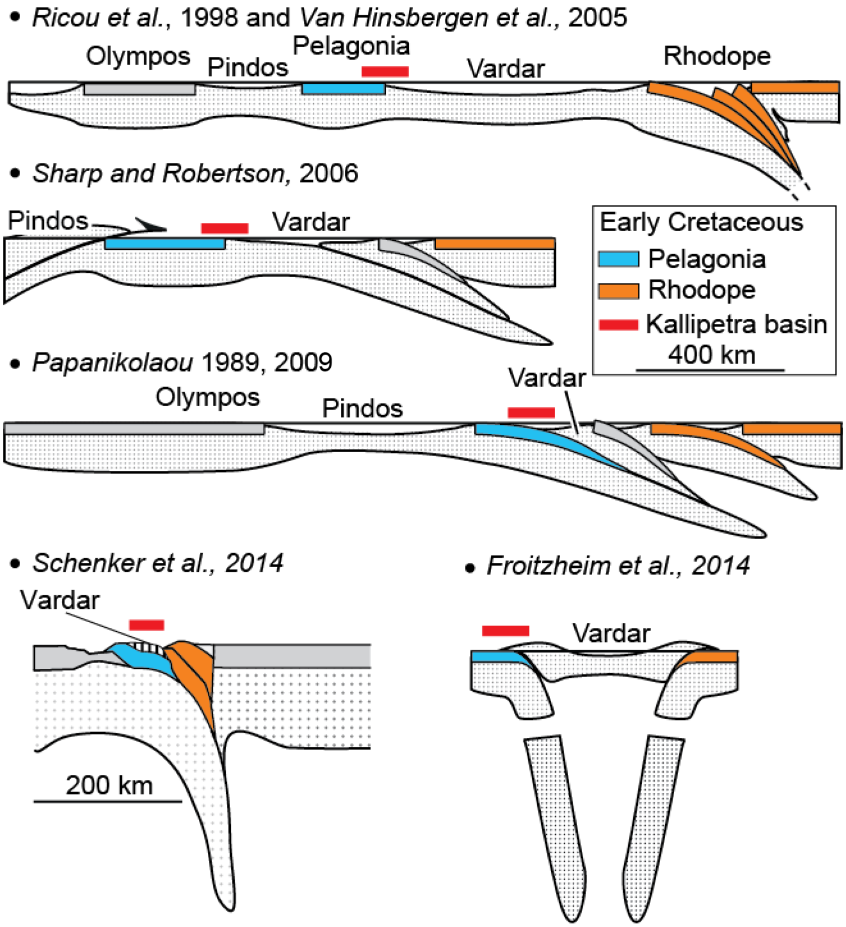

Figure 2: Geodynamic interpretations of the Hellenides in the E~~e~~arly Cretaceous according to different authors. Note that there is no consensus on the E~~e~~arly Cretaceous geodynamic framework at the onset of the Kallipetra Basin ~~of the basins~~ between the Pelagonian zone and the Vardar domain.

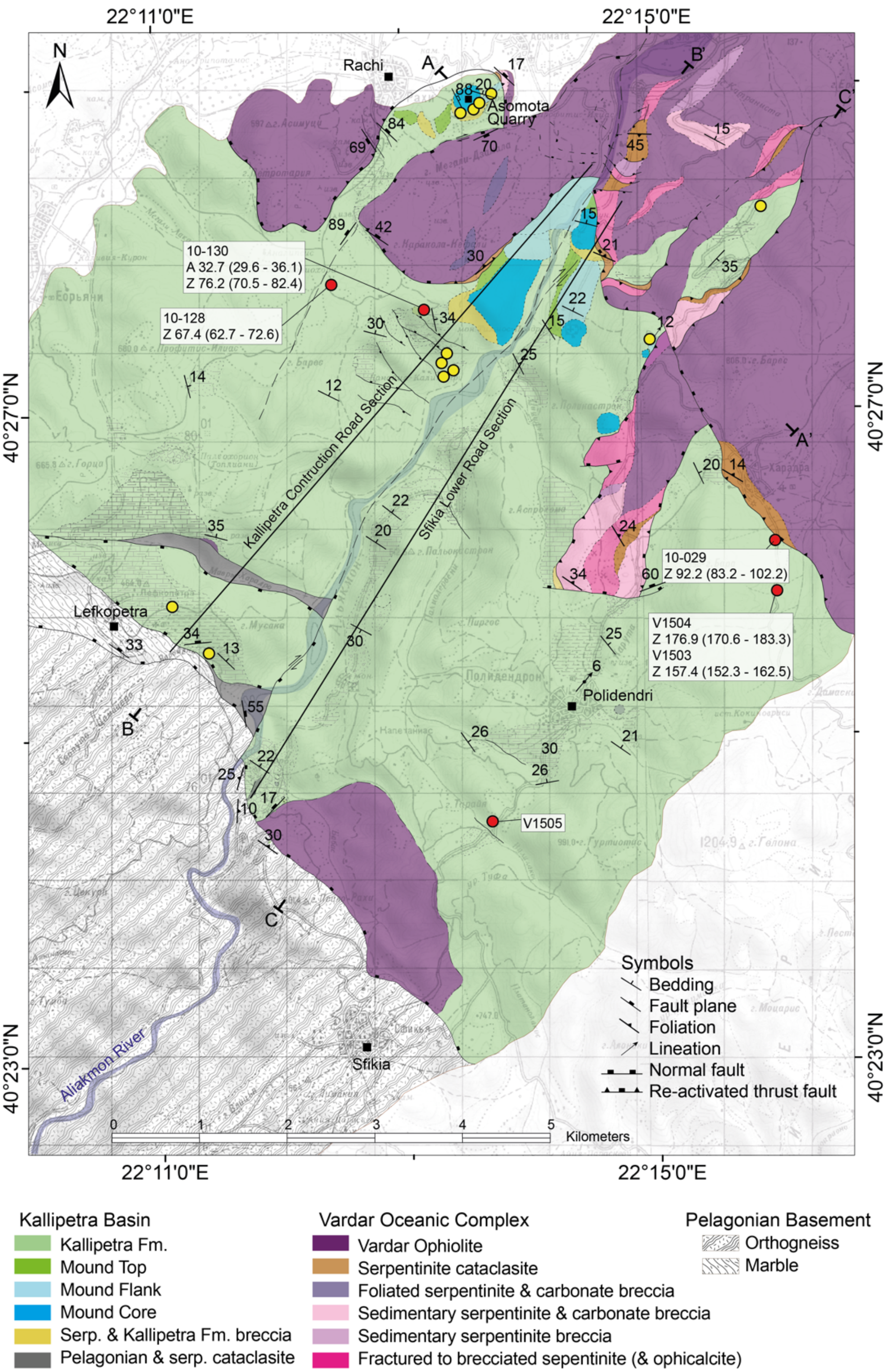

Figure 3: Geological map of the study area. ~~Dark blue~~Yellow circles indicate locations of illite samples, ~~black~~ red circles indicate location of ZFT samples and their respective ages.

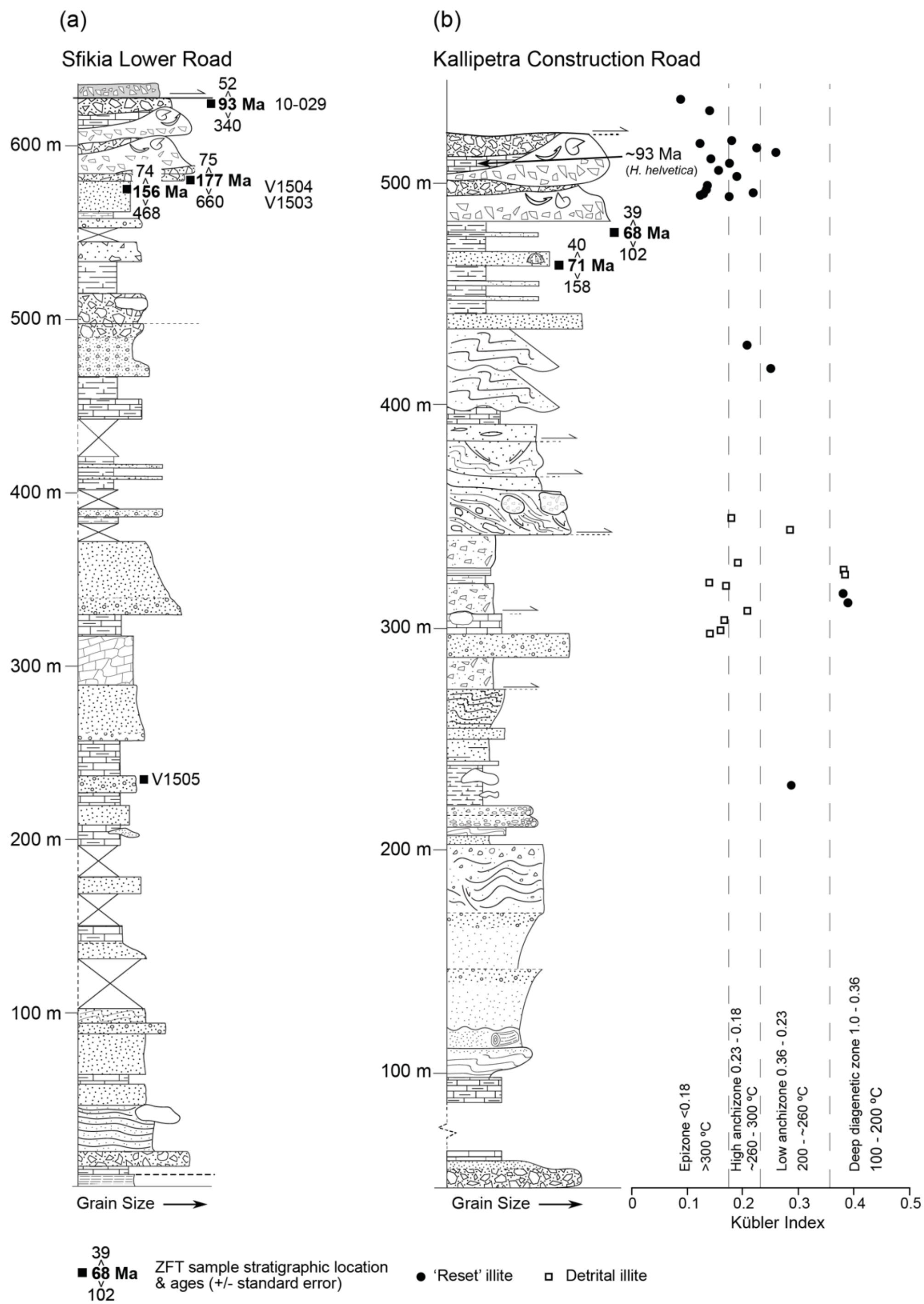

Figure 4: (a) Stratigraphic column taken along the lower road leading to Sfikia, located directly south of the Aliakmon River, and stratigraphic locations and ages of ZFT samples; (b) Stratigraphic column taken along the Kallipetra Monastery construction road, located north of the Aliakmon River, the ages and stratigraphic locations of ZFT samples, and illite crystallinity samples. Illite crystallinity samples are plotted against Kubler Index and diagenetic zone.

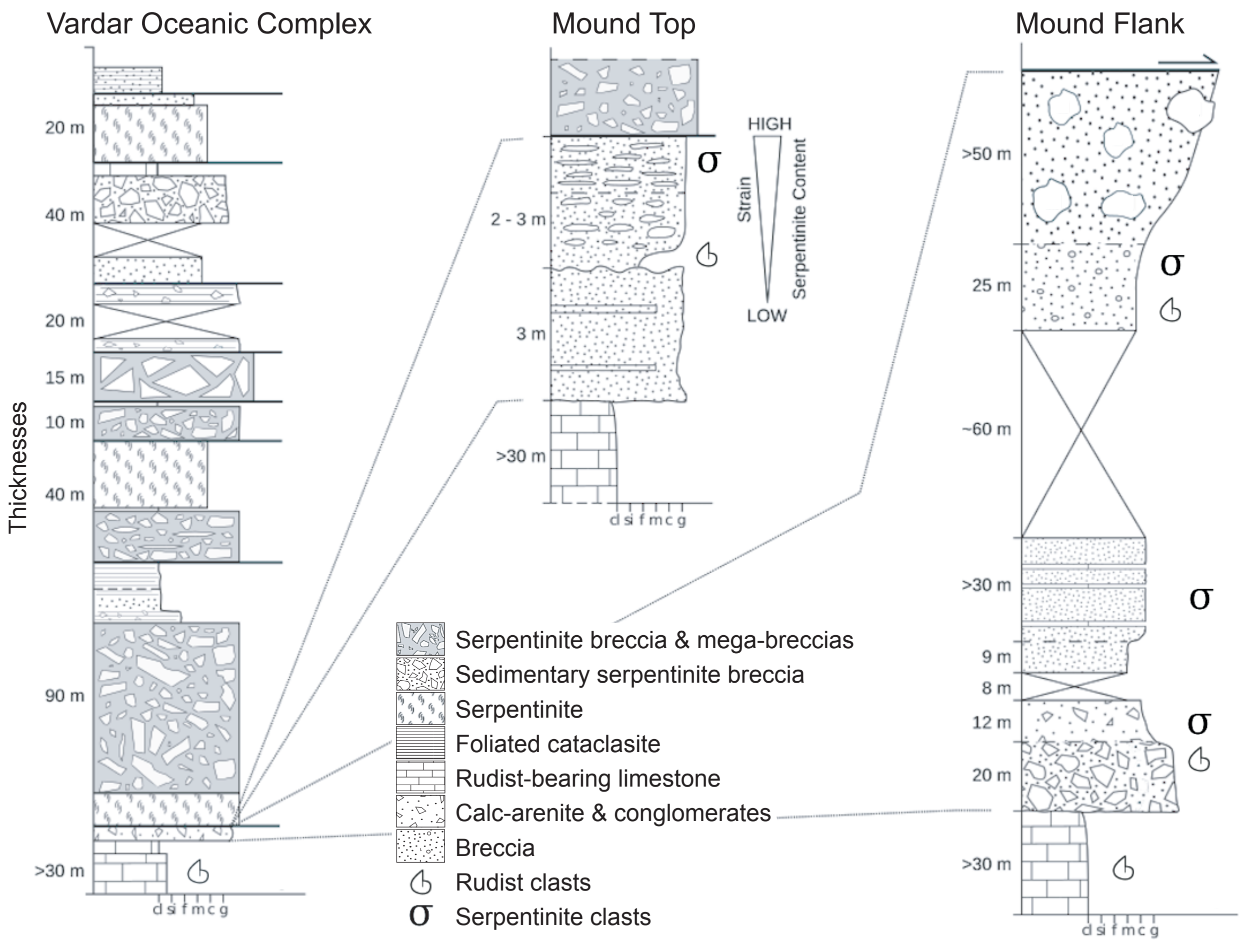

Figure 5: Stratigraphic sections of the Vardar ophiolitic complex, mound top and mound flank.

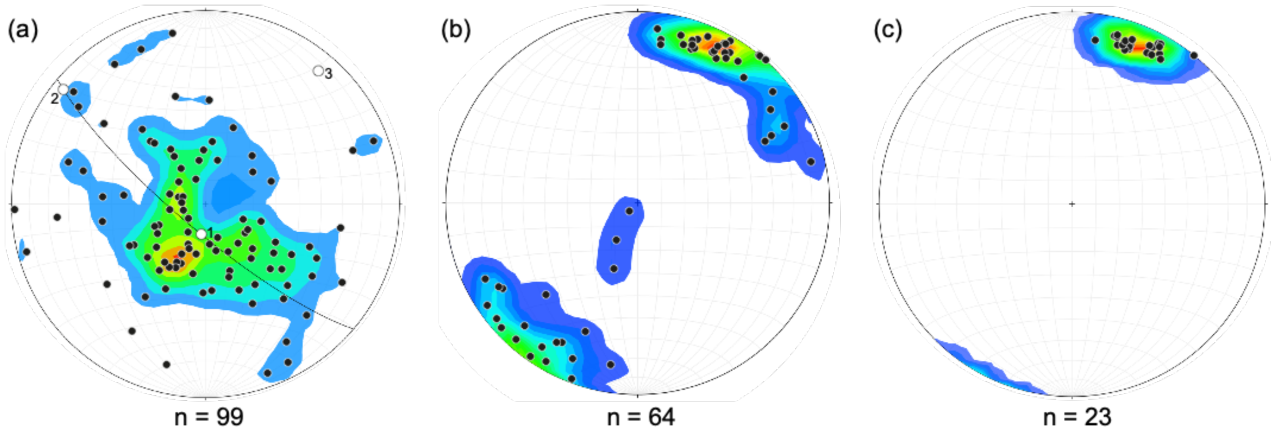

Figure 6: Lower hemisphere stereoplots of: (a) foliation poles whereby measurements were taken from marls and limestones; (b) mineral and stretching lineation measurements of the mapped area; and (c) stretching lineations of the strained conglomerate at grid reference N40° 27' 23" E022° 15' 00". These measurements do not include foliations observed in foliated cataclasites.

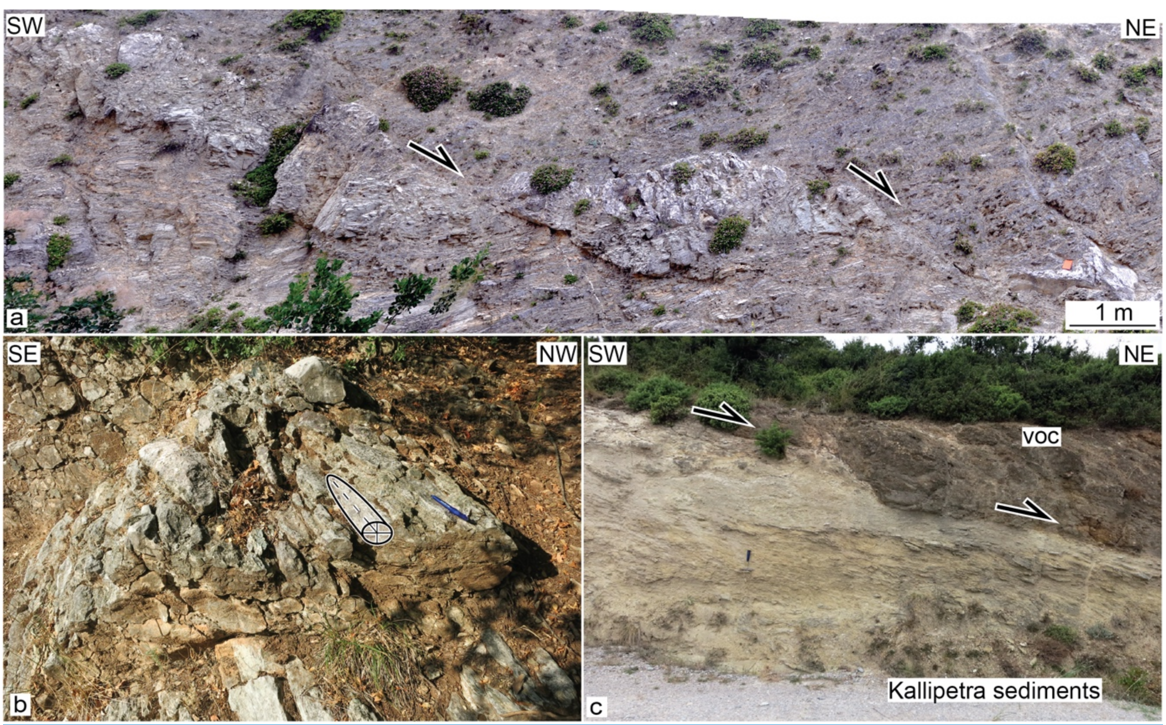

Figure 7: (a) Asymmetric boudin of a limestone showing top-to-the NE shear sense. (b) Cigar-shaped clasts in a polymictic conglomerate of the mound top within the shear zone below the VOC (with sketch of the uniaxial ellipsoid mimicking the shape of the clasts). The stretch axis (X) of the prolate finite strain is parallel to the regional mineral and stretching lineation. (c) Tectonic contact between the Kallipetra B~~b~~asin and the VOC with a top-to-the NE shearing.~~(c)~~

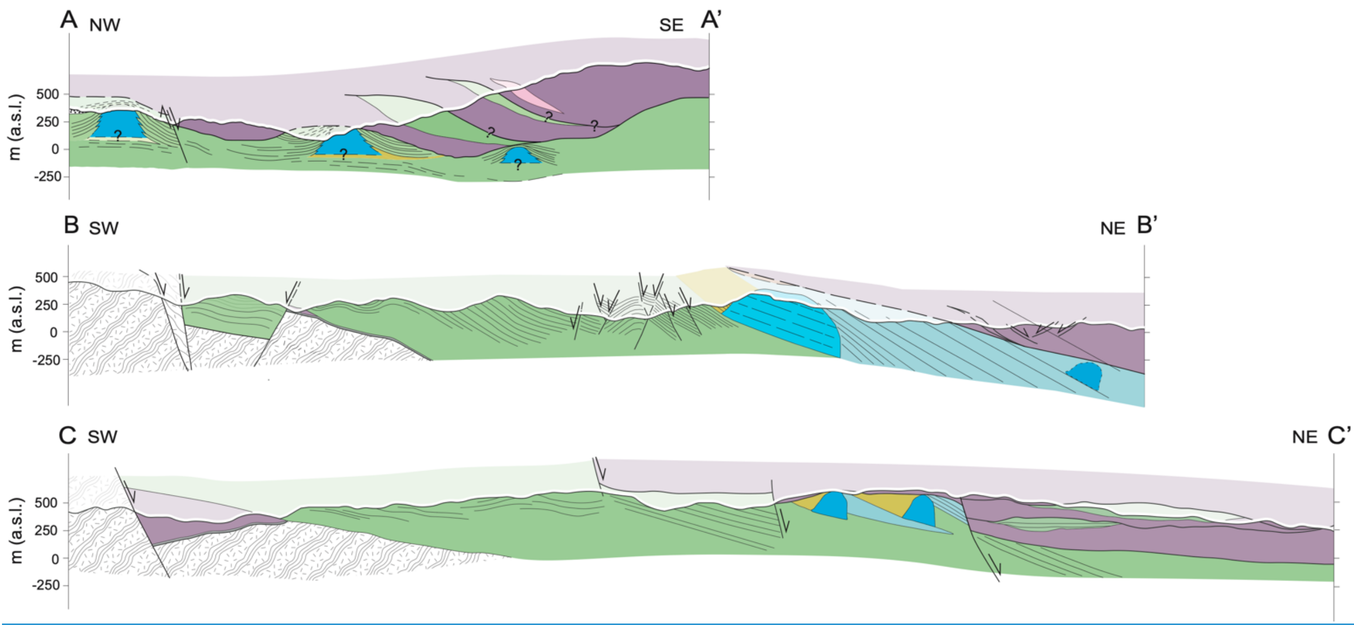

Figure 8: Geologic cross-sections of the mapped area, colors corresponding to those on the geological map (Fig. 3).

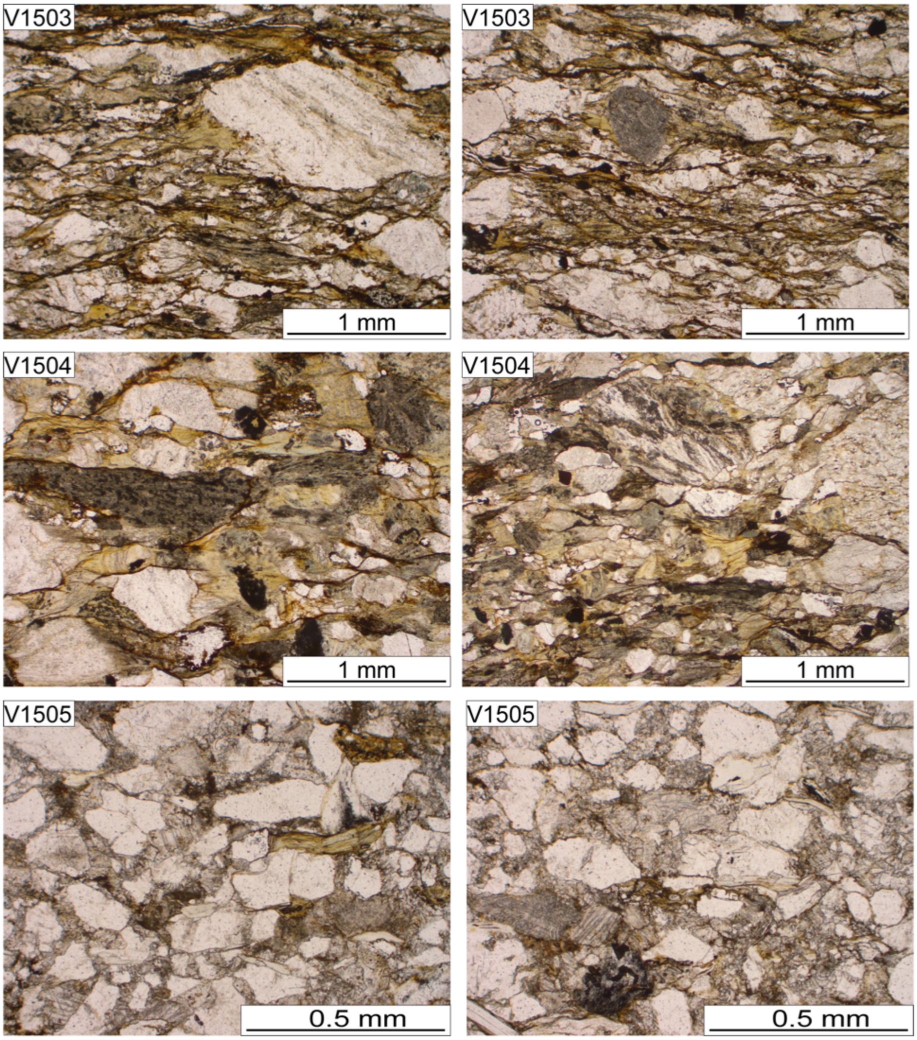

Figure 9: (a) Sample V1503, newly formed chlorite; (b) Sample V1503, newly formed chlorite; (c) Sample V1504, newly formed chlorite; (d) Sample V1504, newly formed chlorite; (e) Sample V1505, detrital chlorite; (f) Sample V1505, detrital chlorite.

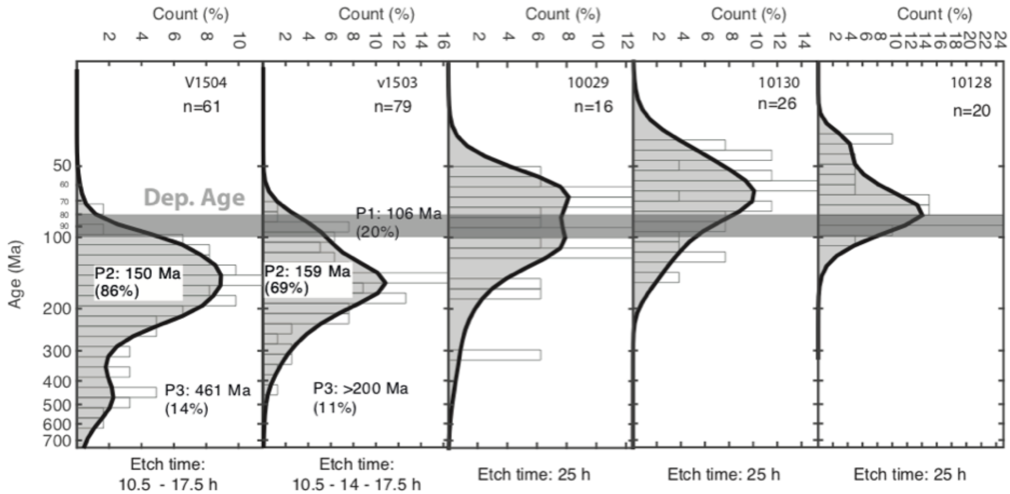

Figure 10: Zircon fission track ages of samples taken in the mapped area.

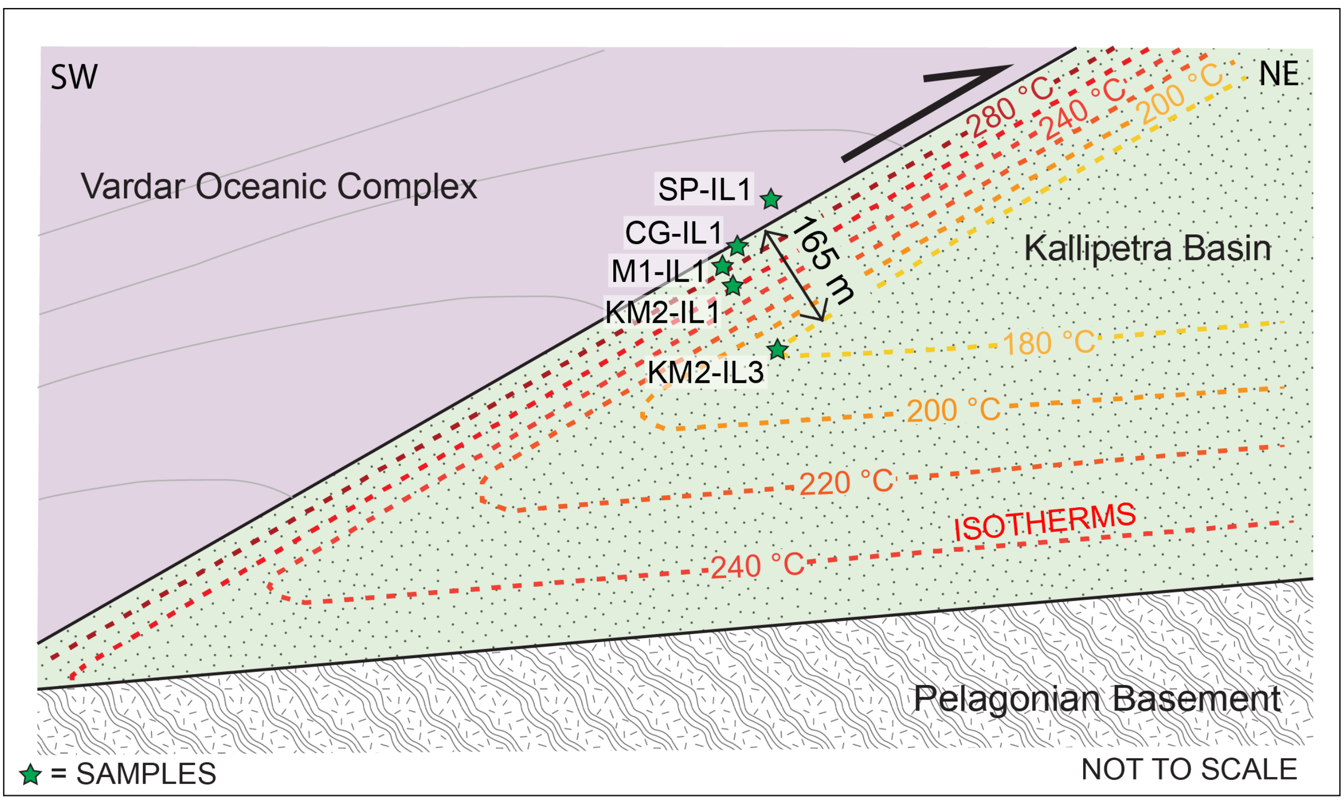

Figure 11: Schematic diagram showing the inverse geothermal gradient at the contact between the VOC and Kallipetra Basin.

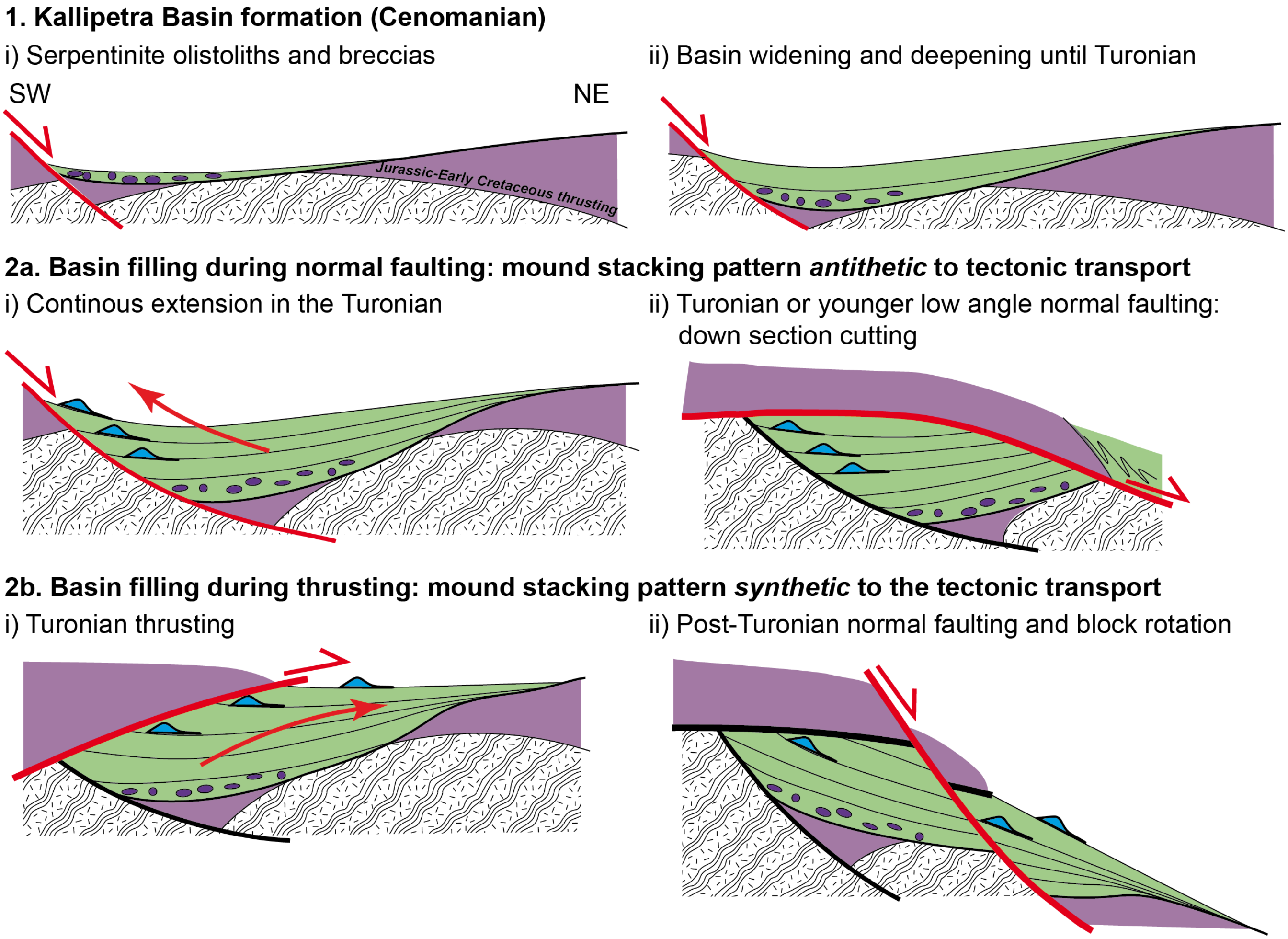

Figure 12: A series of sketches to demonstrate the opening of the Kallipetra Basin in the Cenomanian, and the closure of the Kallipetra Basin under normal faulting or thrust faulting conditions. Only a NE verging thrust of the VOC found at the southwestern margin of the basin can explain the observed rudist mound stacking pattern, as well as the serpentinite breccias and the northeast mound shadow. Colors and patterns correspond to those on the geological map (Fig. 3)

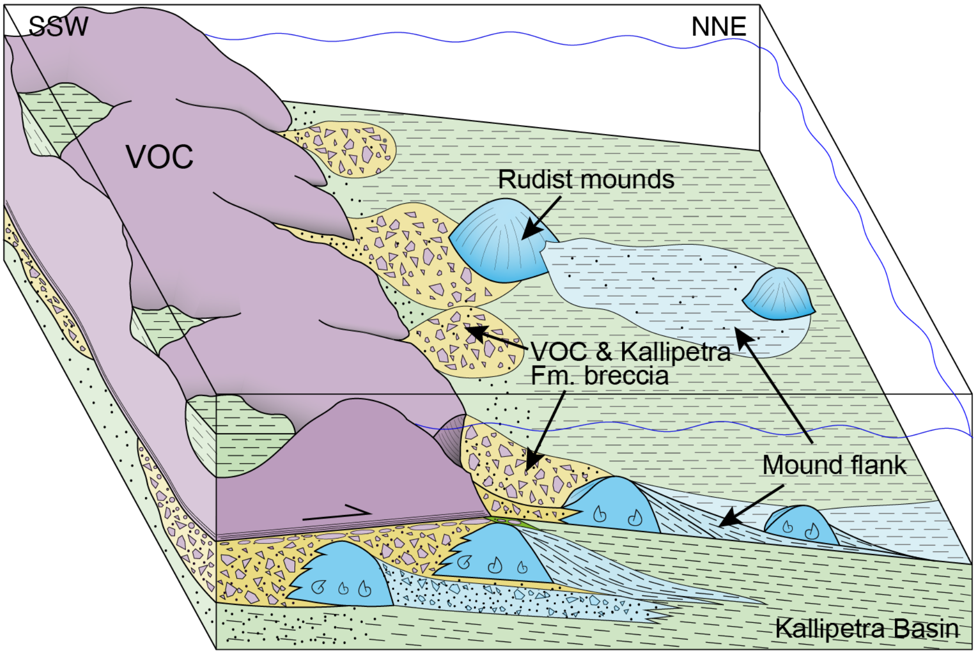

Figure 13~~2~~: Schematic diagram showing the sedimentary and tectonic environment of the Kallipetra Basin during the Turonian, and the overriding of rudist mounds by the resumed thrusting of the VOC. Colors correspond to those on the geological map (Fig. 3).

Sample	Location	Foraminifera	Stratigraphic Distribution	Age
M2-TS1	N 40° 28' 53" E 022° 13' 38"	*Helvetoglobotruncana helvetica*	Lower-Middle Turonian	93.5 - 92.7 Ma
M2-TS1	N 40° 28' 53" E 022° 13' 38"	*Dicarinella hagni (?)*	Lower Turonian - Coniacian	93.52 - 86.71 Ma
M2-TS3	N 40° 28' 53" E 022° 13' 39"	*Whiteinella* sp.	Upper Cenomanian - Campanian	100.5 - 72.05 Ma
M2-TS2	N 40° 28' 55" E 022° 13' 42"	*Whiteinella (inornata?)*	Cenomanian-Turonian boundary - Santonian	94.03 - 84.19 Ma
M2-TS3	N 40° 28' 55" E 022° 13' 42"	*Mesorbitolina pervia*	Mid - upper Aptian	

Table 1: Table of observed ~~planktonic~~ foraminifera.

Sample	Depth (m)	KI (AD)	KI (EG)	Metapelitic zone	Approx. T (°C)
SP IL1	540	0.091	0.109	Epizone	310
CG IL1	535	0.141	0.122	Epizone	300
M3/2	527	no illite			310
M3/1	525	no illite			310
M2/16	520	0.181		Low epizone	295
M2 IL3	519	0.126	0.11	Epizone	305
M2/13	517	0.225		High anchizone	280
M2 IL2	515	0.258	0.131	Low anchizone	230
M2/10	512	0.145		Epizone	300
M2/7	510	0.175		Epizone	290
M2/4	507	0.157		Epizone	295
M2/1	504	0.192		High anchizone	290
M1/7	500	0.137		Epizone	300
M1/5	498	0.131		Epizone	300
M1/3	497	0.22		High anchizone	285
M2 IL1	496.5	0.131	0.122	Epizone	300
M1 IL1	496	0.127	0.116	Epizone	300
M1/1	495	0.176		Epizone	290
CRN1/1	428	0.209		High anchizon	285
CRN1/3	418	0.25		Low anchizone	275
CRS1/2	350	0.18		High anchizon	290
CRS1/1	345	0.286		Low anchizone	230
CRS1/3	330	0.191		High anchizon	290
KM2 IL3	327	0.383	0.188	Detrital	250
KM2 IL2	325	0.383	0.224	Detrital	250
KM1/2	321	0.14		Smectite	200
KM1/1	320	0.168			200
KM1 IL1	316	0.383	0.353	Deep diagenetic zone	160-200
KM2 IL1	312	0.388	0.164	Deep diagenetic zone	160-200
KM2/8	308	0.209		Diagenetic	160-201
KM2/6	304	0.166		Diagenetic	160-202
KM2/4	300	0.16		Diagenetic	160-203
KM2/2	298	0.14		Diagenetic	160-204
CRS1/4	230	0.286		Low anchizone	230

Table 2: Illite crystallinity data.

Sample ID	UTM	E	N	Elevation	Mount ID	Etch time	N. grains	n_D	ρ_D	n_s	ρ_s	n_i	ρ_i	$P\chi^2$	Age Dispersion	Central Age	$\sigma 1$
		m	m	m		hr		tracks	e+05 tracks cm^{-2}	tracks	e+06 tracks cm^{-2}	tracks	e+06 tracks cm^{-2}	%	%	Ma	Ma
V1503	34T	607415.37	4476334.86	800	a	17.5	10	6594	5.290	5628	12.226	1353	2.939	0	24	155.99	10.07
					b	14	19	6579	5.279								
					c	10.5	27	6565	5.267								
					d	10.5	23	6551	5.256								
V1504	34T	607415.37	4476334.86	800	a	17.5	18	6523	5.233	5101	13.396	1083	2.844	0	34	176.65	13.22
					c	10.5	43	6537	5.245								

Table 3: Zircon fission-track data. Variable amounts of zircons were analyzed on multiple mounts for each sample that were etched for different times. As a fluence monitor, a glass standard CN1 with a U concentration of 39.8 ppm was used. Central ages were calculated using a ζ calibration value of 145.39 ± 7.04. n_D and ρ_D: number and density of induced tracks from the fluence monitor. n_s and ρ_s: number and density of spontaneous tracks in the zircons. n_i and ρ_i: number and density of spontaneous tracks from the zircons. $P_{\chi 2}$: $\chi 2$ probability.