Review of “Tectono-thermal evolution of Oman’s Mesozoic passive continental margin under the obducting Semail Ophiolite: a case study Jebel Akhdar, Oman” by Arne Grobe et al. Author’s replies in green

Summarized comments of - M. Zattin (Referee) – Author’s replies in green

Dear Prof. Zattin,

Thank you for your valid comment and feedback.

All comments made in the PDF were accepted as suggested and/or are commented below.

Especially, we extended on the meaning and importance of the study in the Introduction and revised and extended the data description. The discussion now also elaborates on the errors associated with the temperature predictions.

Moreover, we revised the Figures and Tables and enlarged the fonts.

1) First, the figures are in general not clear. The writings are very often too small, keys for acronyms and colors are missing, and some diagrams should be added (see annotated pdf for details). We revised the figures; please keep in mind that the figures appear smaller in the automatically generated preview pdfs than in the later manuscript
2) Fig. 3 mixes stratigraphic and structural information We revised Figure 3
3) Revise tables DONE
4) Emphasize meaning of this work in the introduction – goals are not clear DONE
5) Description of results need improvement in text, figures and tables DONE
6) Relationship of map temperatures and stratigraphic age should be illustrated in a diagram with errors We revised Figure 3 and updated the temperature data accordingly. To keep the number of total figures low, we kept the information in one Figure.

L 54 – Rewrite first paragraph of introduction, expanding the concept DONE

L 72 – How can you say that peak temperatures reached by obduction have not been overprinted Rephrased

L75-79 - You should clear better the goals of the paper, especially focussing on the originality of the results.

Fig 2 – size depict… - Not clear what you mean Size was uniformed to prevent confusion and sentence in the caption was deleted

L 106 - There is a big gap between this paragraph and the previous ones. DONE

L 111 – Batinah Coast - Not in figure DONE

L 112 – Ophiolite exposed subaerial - When? Since the early Paleogene? DONE, text now reads: The sedimentary record in the Batinah coast and the foreland, as well as laterite formation on top of the ophiolite suggest subaerial exposure and a slow-down or stopped obduction in the early Paleogene before lower marine conditions were restored in the Maastrichtian

L129 - I suggest to merge the thermochronology studies in the more general discussion about exhumation that started in the previous paragraph DONE

Figure 3

L 188-190 - This sentence is out of place Deleted as information was not essential for the manuscript

L 202-203 - This sentence is not clear Rewritten, now reads: Duretz et al. (2015) showed in a lithospheric scale thermo-mechanical model that a thermal anomaly c. 100 km northwest of the Arabian margin is necessary to initiate subsea thrusting (Duretz et al. 2015).

L 234 - Which are the errors associated to this equation and the following transformation into temperatures?

L 291/2 – sentence deleted as suggested DONE

L 310 - Actually, from what you write in the legend of figure S2, this is not an assumption but the result of a sensitivity analysis. Text was changed accordingly

L 326 - The relationships between temperature and stratigraphic age are someway visible in figure 3 but I suggest to do a separate diagram. Figure was changed accordingly also taking other reviews into consideration

Table 1

Figures S3, S4 use different sample names, S4 is missing DONE

L 347 - Given the number of analyzed grains, it is difficult to say if two populations are really present or if the broad range of ages is related to other causes (frequent with U-Th/He analysis)

We agree with the reviewer that a spread in ages is commonly observed in U-Th/He analysis. As the reviewer rightly states, this may have multiple causes. We also agree that for a sound statistical analysis of presence of grain age populations many more aliquots would be required (117 is a number determined by Vermeesch). The question the reviewer poses is whether the observed populations are indeed geologically meaningful or may represent factors independent of time-temperature history (such as inclusions, helium implantation or the like). We note that in the data discussed here (i.e. T-5 and T-7), we find reproducing aliquots at roughly 58 and 100 Ma. It seems a stretch to assign this to coincidence / errors in the method, but there have been weirder coincidences reported. We address this in the new version of the manuscript: we do not call this populations anymore, but clusters, preventing the misunderstanding that population implies the ages represent different cooling histories or different annealing kinetics. Secondly, in the discussion, we added a paragraph on uncertainty and age spread of He data.

Figure 4

L 360 – How can you say that this is related to doming - Deleted

L 363 - Are you referring to thermal models obtained by HeFTy? If this is the case, the cooling rates are not meaningful as lower temperature constraints (i.e. AFT and AHe) are missing. Minimum values deleted

L 365 - I see that this sample is a conglomerate. Did you analyze different clasts? If this is the case, it is a bit odd that all the three grains give the same age if the degree of reset is only partial. This is an interesting point. Indeed it came as a surprise the data reproduce so well despite being from a partially reset sample. However, as the apparent age is as old as the formation's stratigraphic age, the data does not allow for post-depositional resetting. If the grains had no reheating at all, they would show much older ages (depending on the lag time between cooling in the orogeny + transportation and deposition). Consequently, the most straight-forward interpretation is a partial reset. We speculate that the source of the dated grains has a rather uniform cooling history, or we dated by chance only one of possibly many existing grain age populations. Here dating of a large amount of grains would provide an answer how many different grain age populations are present. This is an exciting idea, which we leave for a future study. In this manuscript we updated the text accordingly, stating that additional grain age populations could be present.

changed to „ Even though all ages reproduce within error, this indicates partial reset of the ZHe system, as post-depositional reheating above closure temperature would result in younger ages."

L 368 - If only younger ages represent reset zircons (as stated in the previous sentence) the 110-95 age cannot be related to any geological event as it is a partial reset age. A very good point. The question the reviewer rightly asks is whether the obtained age can be a reduced older age instead of an unaffected 100 Ma population. Both interpretations are valid, and only knowing the amount of radiation damage, chemical composition, and possibly other yet unknown factors will be able to resolve this. Consequently, we rephrased the sentence accordingly to "We note that the older ZHe population of 110 95 Ma coincides with timing of forebulge migration through the area, as independently determined in the stratigraphic record in the Wasia-Aruma Break (Figure 3). This may be either pure coincidence due to partial resetting of an older grain age population, or may be a grain age population with higher closure temperature witnessing exhumation. We discuss reasons for different resetting temperatures below. "

L 440-447 This paragraph does not contain any data. I suggest to move these observations to the discussion chapter

Deleted and included in the discussion chapter as suggested

L 454 – change to figures 6 and 7 changed as suggested

L 460 - I would prefer to see this figure S5 in the main text rather than in the supplement. DONE

L 494 - I would not see any major difference between north and south It is a slightly earlier and stronger increase in the thermal maturity data as shown in Figure 9b and 9c

L 566 - I do not understand what is the "sub-thrust thermal overprint" whose effects are limited to 10's of meters.

Rephrased to frictional thermal overprint

L 579 - This could be partly due also to an increase of the heat flow (as you show in figure S2). ADDED

L 600 - Why are you talking about extension? Top-to NNE shearing in the area is associated to tectonic thinning/orogenic collapse and relates to an extensional event (added to clarify)

L 601-5 - This part is not clear. Which are the raw data you are talking about? Why "raw"? Rephrased to "used calibration data" and references added

L 608 - Not clear how this paragraph is linked to the previous ones Better link established

L 641 - This sentence is not clear We rephrased the sentence. Now reads: "Zircon fission track ages witness cooling of the Jebel Akhdar below c. 260 °C between 96 and 70 Ma (Saddiqi et al. 2006)."

L 643 - Why are you introducing the possibility of a Miocene event? References of earlier interpretations added

L 657 – Deleted as suggested

Full comments of – L. Aldega (Referee) – **Author's replies in green**

Thank you for your valid and thoughtful feedback. We adapted the manuscript accordingly and all suggestions are implemented and/or commented below. Especially, we extended on the meaning and importance of the study in the Introduction and revised and extended the data description. The discussion now also elaborates on the errors associated with the temperature predictions.

Moreover, we revised the Figures and Tables and enlarged the fonts.

We hope that after these modifications the manuscript can be accepted.

As most of your comments align with the review of Reviewer 1 we will provide one new document with tracked changes together with our revised manuscript.

1) The introductory parts of the manuscript are weak in explaining the importance of the paper and why it is of broad interest and scientific significance for the Solid Earth audience. It should be strongly highlighted what are the aims and the implications of this work for the international community. The introduction was rewritten, and we extended on the importance of the paper.

2) Results are not sufficiently described and are mixed with literature data. For instance, Section 4.1 provides a mix of literature data (Grobe et al., 2016, Mozafari et al., 2015), that should be moved elsewhere DONE, and undescribed original data. Authors should describe their solid bitumen data for the northern and southern flank of the Jebel Akhdar anticline and then provide paleotemperature values. At the moment only a few lines 325-327 are reported Extended and relationship between temperature and stratigraphic age in figure 3 is not clear Figure was updated. Authors should find another way (different diagram, figure, map) to show their data that have been used for calibrating numerical modelling. Also the results section "fluid inclusion" contains data from the literature and original data. The authors should move data from literature elsewhere and result section should contain only original data. We adjusted most of the manuscript accordingly. For the fluid inclusion section we agree, that some interpretations of other authors are stated to put the analyzed samples into context. Moving this to the Discussion part of the chapter would lead to confusion and repetitions there as we would need to state the fluid inclusion results three times (deepest burial S – deepest burial N and exhumation). Therefore, we kept the data with some minor literature data and renamed the chapter "Results and Interpretation)

3) Kerogen particles are scarce in the study samples due to the types of depositional environments and dominance of carbonate rocks. Table 1 lists the results of measurements for a small number of solid bitumen particles (converted to a vitrinite-reflectance equivalent values). Given the statistical nature of reflectance measurements and the factors that can affect measured values (e.g. organic matter recycling, oxidation, oil staining, etc.), it is desirable to have 50 individual readings per sample to obtain representative mean random reflectance and standard deviation values. Most data in Table 1 have very low number of readings and it is unclear in how these measurements are used or whether they are even used other than to provide qualitative support for the inferred thermal maturity of the studied rock units and calibrate thermal modelling. It is necessary to show the thermal maturity curve fitting the solid bitumen data (individual points with range bars) as a function of depth for the northern and southern flank of the Jebel Akhdar Dome related to your 1D burial models. Without this information, readers cannot be aware about the goodness of your calibrating data and your thermal modelling reconstruction. 1D burial models (now shown as supplementary material) should become part of the main text.

The reviewer suggests to show „the thermal maturity curve fitting, the solid bitumen data as a function of depth". Such information has been published in a previous paper in our group and would be a repetition here. Furthermore, it should be noted that solid bitumen data do not cover a wide stratigraphic range; therefore, a depth plot is less meaningful than in other regional settings. Moreover, the standard diagrams (e.g. VR vs depth) were developed in "normal" sedimentary basins and cannot be applied at such a warm and by obduction overprinted basins. For instance the thermal maturity modelling approach of Sweeney and Burnham's Easy R0 is maxing out above 4.5 % so we had to show the calibration data in Temperature vs. time.

4) Converting solid bitumen data into vitrinite reflectance equivalent and subsequently into a paleotemperature value is very tricky and can be inaccurate. Many studies generated regression equations that used the reflectance of solid bitumen to calculate a vitrinite reflectance equivalent (Jacob, 1989; Bertrand, 1990, Bertrand, 1993; Riediger 1993; Landis and Castano, 1995; Bertrand and Malo, 2001; Shoenherr et al., 2007, Wei et al., 2016; Liu et al., 2017). These equations were derived from samples representing various maturity ranges, lithologies, and basins, and as expected, their results differ from one another. Consequently, depending on which equation is used, late mature and post-mature rocks within condensate-wet gas and dry gas windows may be misinterpreted, and thus may lead to erroneus paleotemperature estimates. Recently, several papers show that solid bitumen is not recommended as indicator of thermal maturity and may have not correlation with vitrinite reflectance values (Petersen et al., 2013- international journal of coal geology, Gonçalves et al., 2015- international journal of coal geology, Kus et al., 2016 – international journal of coal geology). Furthermore, paleotemperatures calculated by Barker and Pawlewicz (1994)'s equation may overestimate the "real" temperature when compared with Basin Maturity Charts from the literature (e.g., Merriman and Frey, 1999 – very low grade metamorphism (book); and Jaboyedoff and Thélin, 1996 – European Journal of Mineralogy 8, 577-592) as the equation groups data from different burial heating environments. I suggest to avoid to talk about temperature in the text but to talk about levels of thermal maturity in terms of solid bitumen data. Temperature estimates may be extracted from your modelling outputs (constrained by your thermal data) without using any equation.

The reviewer is completely correct: Transformation of solid bitumen reflectance to vitrinite reflectance has some pitfalls and should be avoided when possible. However, this is mainly true at low levels of maturation where uncertainties with respect to this transformation are much more important than at high levels of maturation. The reviewer might keep in mind that optical properties of organic particles convert more and more at high levels of maturity.

We think that temperature estimates are helpful, but we agree that we should discuss uncertainties.

5) I am not convinced by the age of the ophiolite emplacement, and Hawasina Nappe thrusting on top of the passive margin units. In authors' reconstruction, ophiolite obduction took place at 84 Ma (Fig. 6d) but its emplacement on top of the Arabian passive margin units was dated 95 Ma by Tilton (1981), 95-93 Ma by Warren et al. (2003) or 88 Ma (Hacker, 1991). Any age chosen, would imply a shift to older ages for the Semail ophiolite and for the Hawasina Nappe and consequently a decrease of tectonic burial.

This is an interesting point, which indeed requires clarification. As the reviewer states correctly, ages of roughly 95 Ma have been reported. However, these ages are formation of the metamorphic sole and initiation of obduction at the mid oceanic ridge. Obduction of ophiolite onto the passive margin occurred only once the Hawasina Ocean was completely overridden. Warren et al. estimate this to be roughly 15 Ma after obduction initiation, also in agreement with the interpretation of Robertson et al. and the stratigraphic ages related to the moving forebulge. This is in line with our modeling (actually we used these time constraints). Moreover, all the ages discussed above are based on data of the Saih Hatat window and no one can predict for sure how to extrapolate this over the Semail Gap to the Jebel Akhdar.

6) Some more details about the exhumation of the passive margin units in the Jebal Akhadar Dome should be given to the readers. The removal by erosion or extensional tectonics of 8-10 km of ophiolite units should have started in Danian time (Hansman et al., 2007) and be completed before the deposition of postobduction deposits of the Jafnain and/or Russayl Formations (early Eocene) that experienced low levels of thermal maturity. To my knowledge, only Late Maastrichtian-early Paleocene conglomerates of the Al Khawd Fm (maximum 350 m thick) contain ophiolite clasts and they occur in depozones of the northern flank of Jebal Akhadar Dome. No occurence has been described for the southern flank of the anticline. Where has all the material coming from the dismantling of such thick ophiolite overburden gone? Which sedimentary deposit has been formed in the southern and northern flank of the Jebal Akhadar Dome? What is their thickness? Furthermore, the explanation about the juxtaposition of the Hawasina and Muti sediments atop the carbonate platform units during extensional shearing sounds to me to be contradicted by your numerical model of figure 6 where both units were buried at depths of 8-10 km since 84-79 Ma and should have experienced similar temperatures than those recorded by the Natih Fm.

We thank the reviewer for this remark. Indeed the Al Khawd Fm contains ophiolite clasts. However, this does not suffice to explain the loss of several km of ophiolite. We argue elsewhere (Grobe et al. 2017, Tectonics) that the ophiolite was significantly thinned during top-to-NNE shear, reducing the amount of material required to be eroded by exogenic forces. Much of the material lost may have been transported to the Persian Gulf. We added a respective sentence in the exhumation history. According to our data the Natih Formation experienced peek peak temperatures of 225 – 260 °C (Natih B and deeper strata) & Hawasina and Muti below 170 °C.

7) Some parts of the discussion are overinterpreted or need clarification (see points line by line below). DONE In general, the short duration of the heating event to explain the discrepancy between temperatures obtained by solid bitumen and clay mineral assemblage fails as the ophiolite units remain atop the passive margin units from 79 to 55 Ma. The time span elapsing between ophiolite thrust stack emplacement and the beginning of tectonic overburden removal is very long and both organic matter and clay minerals acquire similar thermal maturity. Only for time of burials shorter than 1-2Ma and/or in hydrothermal/geothermal settings, clay minerals may have a slow kinetic response when compared with vitrinite or bitumen reflectance, but this is not the case the evolution of mixed layered minerals cannot be considered as an explanation for that discrepancy because I-S in Aldega et al., (2017) shows a trend as function of stratigraphic age either for carbonate or siliciclastic rocks. If the lack of potassium is the key for explaining such discrepancy between paleotemperatures, I-S values would have been scattered and they would not have shown any trend as function of stratigraphic age (or depth).

It is difficult for us to interpret the data in Aldega et. al 2017 but either lack of potassium or very short time heating might be possible explanations. See also paper by Mählmann et. al 2015 , International Journal of Coal Geology. The duration of emplaced ophiolite from 79-55 Ma probably does not exactly represent the time at thermal equilibrium, especially after such deep and rapid burial…

8) It is hard to have confidence in the results presented in Figures 6 and 7 when the authors only provide some general description of how they used Move 2D software for their geological reconstruction, how they use the resulting structure geometries in Petromod 2D and how these results depend on the paleotemperature constraints and 1D modelling method discussed above. We extended parts of the manuscript to clarify the conducted

modelling. The modelling conducted has to be seen as a general attempt, which is due to the uncertainties of the available data.

Technical points:

1) The term “solid bitumen” should be replaced by “pyrobitumen” throughout the text as the reflectance boundary between the two is placed at reflectance values of 0.7% (Hunt, 1978; Jacob, 1989; Landis and Castano, 1995) or 1.5% (Mastalerz et al., 2018). Solid bitumen is an oil window product generated by primary cracking whereas pyrobitumen is a gas-window solid bitumen from secondary cracking,

Solid bitumen is a more general term and is also used in review papers and textbooks. However, we explained now in the beginning that solid bitumen of high reflectance is often called pyrobitumen.

2) Which method of rock decompaction for the passive margin unit has been applied in numerical modelling? This information should be added in the numerical basin modelling section PetroMod uses a forward, event-stepping modeling, starting with the deposition of the oldest layer. Subsequent deposition and burial is leading to differential compaction of the single rock units. Therefore, a decompaction algorithm is not necessary.

Other detailed comments and suggestions to text and figures are listed below.

Introduction

Line 51 – I would replace “sub-thrust sedimentary basin” with “subophiolite units” or “authocthonous passive margin units” changed to subophiolite passive margin units

Line 63 – replace “full” with “whole” or “entire” and replace “Permo” with “Permian” DONE

Line 66- reference is quite old. Recent papers that deal with vitrinite reflectance or organic matter optical analysis in other orogens are: Holy Cross Mountains: Schito et al., 2017 Marine and Petroleum Geology, 80, 112-132 Zagros: Mashhadi, et al., 2015. Marine and Petroleum Geology 66, 978-997. Apennines: Corrado et al., 2010 for a review of the Apennines, Journal of the Virtual Explorer, Electronic Edition, ISSN 1441-8142, vol. 36, paper 15, 1-37 Line 70 – the reference is a bit old with only one paper dated, 2010. Updated accordingly

A selection of more recent papers that integrate thermal constraints and basin modelling to reconstruct tectonic loads or overthrusts in fold-and-thrust belts is: Schito A. et al., 2018. Basin Research, 30, 532-549. Jirman et al., 2018, Journal of Petroleum Geology, 41 (2), pp. 175-188. Aldega et al., 2018. Marine and Petroleum Geology, 93, 376-390 Duschl et al., 2016. Marine and Petroleum Geology, 77, 300-322 Caricchi et al., 2015. Geological Society of American Bulletin, 127 (3-4), 428-442. Updated accordingly

Line 78 – replace “deepest burial” with “maximum burial” DONE

Tectonic setting Lines 90, 92, 98 – replace “Permo” with “Permian” see above DONE and checked in the rest of the manuscript

Line 111-116. I would modify the sentence as the slowing down or ending of ophiolite obduction is early Maastrichtian as indicated by the occurrence of a regional unconformity between the top of the allochthonous units and overlying conglomerates and shales (Al Khawd Fm.). After that in Danian time post-oduction extension took place (64±4 Ma; Hansman et al., 2018). DONE

Stratigraphic sequence

Line 155- Spell out Gp. DONE in whole manuscript

Line 167 – A more detailed description of the hawasina deposits is needed. The Hawasina deposits are not the main focus of this manuscript, therefore we present the most relevant publications, but do not describe it in detail.

Temperature evolution of the authocthon - The title is misleading as the section does not decribe any temperature evolution through time of the passive margin units. You are reporting a set of temperatures from previous studies. In this section you should provide paleotemperature data from other works that you discussed. I would re-title the section “Previous paleothermal data” DONE

Line 177 – replace “is” with “are” and provide reference. DONE

Lines 188-190. I would delete these lines as they do not provide useful information in this section. DONE

Temperature evolution of the Semail ophiolite Nappe/allochthon

Lines 198-199. How much is the temperature? Please provide it Rephrased

Lines 199-203. You can use these sentence as well as all the information included in this paragraph in the discussion section. DONE

Petroleum system: This section should be expanded providing information about, source, reservoir and seal rock together with time of migration and accumulation of hydrocarbons. These information would be useful for understanding and strengthening the discussion part about fluid migration. Adding thermal maturity data (vitrinite reflectance or bitumen reflectance) about source rocks of the Natih and Fahoud fields would strenghten the discussion of your solid bitumen data. At the moment information of solid bitumen can be moved to the temperature evolution of the authocthon section. Extended

Methods

I would delete lines 216-217. DONE

Elemental analysis and thermal maturity

Line 218 – Thermal maturity is not a method. I would replace “elemental analysis and thermal maturity” with “Raman spectroscopyof carbonaceus material” DONE

Line 219 – add “ levels of” in front of “thermal maturity” DONE

Lines 220-221 – please define which stratigraphic units were analyzed for organic matter characterization DONE

Line 234 – please define “STA” in the equation. STA is defined as scaled total area in the line prior to the equation

Lines 236-238. Move these lines in the basin modelling section DONE

Fluid inclusion thermometry

Line 239 – replace “thermometry” with “microthermometry” DONE

Line 243- perhaps replace “mineralization” with “crystallization” DONE

Line 256- replace “of” with “for” DONE

Line 261 – define Tfm DONE

Thermochronology

Line 265- please define which stratigraphic units were analyzed for ZHe analysis. DONE

Numerical basin modelling

Line 287 – replace “R0%” with Ro%. O stands for oil. DONE

Line 290 – refer to the supplementary material for lithology and petrophysical rock properties DONE

Line 291 – Which seismic lines? Provide reference DONE

Lines 291-292. I would delete this sentence DONE

Lines 293-294. The sentence is cryptic. I would delete it as you will discuss this point in the discussion section DONE

Lines 201-304. How can you calibrate burial depths for the Adam Foothills where thermal data are lacking? Clarified in the text – thermal data is lacking south of the foothills but not in the foothills

Lines 309-310 – Is the increase of heat flow an assumption or a result of a sensitive analysis? There is a discrepancy between the text and the supplementary material extended: we assigned the here described heat flow trend and tested it in sensitivity analysis.

Results Thermal maturity and host rock burial temperatures

Lines 324-332. These results refer to previous works, Grobe et al., 2016 and Mozafari et al., 2015 and should be moved in chapter “Temperature evolution of the authocthon”. DONE

Lines 325-327. This part should be expanded as it refers to your original data. Describe results for the northern and southern flanks in terms of solid bitumen data DONE but described in terms of STA and temperature (see comment above)

Line 330 – Provide vitrinite reflectance values, and then temperatures conversion. The sentence is not correct. In Mozafari et al., 2015 there are only two VR data with values of 1.1% and their temperature estimate is 140_C. There is no evidence of a Vr value of 1.8%. Please correct text and table 1. To my knowledge a vitrinite reflectance value of 1.1% should be converted in a lower temperature range (100-130_C) as generally evidenced in other fold-and-thrust belts and by basin maturity charts from literature (see Merriman and Frey, 1999 – very low grade metamorphism book; and Jaboyedoff and Thélin, 1996 – European Journal of Mineralogy 8, 577-592) DONE

Thermochronology

Line 341 – delete “Figure 3” DONE

Line 360 – This part needs more details. How can you associated those ages with doming? This is a good point. We deleted the interpretation here, and interpret the ages in the discussion.

Line 361 – I would not refer to figures S4 and S% as the burial history is not introduced yet. Furthermore see my suggestions for figures S4 and S5. DONE

Line 371 - the zircon partial retention zone (PRZ, Reiners, 2005) is between 130 and 170 _C as you stated in the method section. Please modify the sentence. DONE

Line 372 – I would replace “A magmatic sample of an intrusive” with “A sample from an intrusive body” DONE

Fluid inclusions

Lines 420-421. Why did you assume a depth of 2km? Please explain. Strike-slip faulting should be Paleocene or Eocene in age and from your burial history you should have more than 5km thick overburden atop the Muti Fm. Rephrased – we now refer to the minimum thickness as evidenced by the preserved allochthonous thicknesses

Line 430 – Replace “Sahtan Fm” with “Sahtan Group” DONE and checked in the entire manuscript

Structural observation

Lines 441-447. This section does not contain any data. I suggest to delete it or move it in the geological setting Deleted as suggested

Basin Modelling

Line 454 – Replace "figures 8 and 9" with "figures 6 and 7" DONE

Line 455-How much is the eroded thickness of the Natih Formation? How much is the thickness of the Hawasina Nappe? Add these information in the text DONE

Line 456- ophiolite emplacement is older than 84 Ma as shown in figure 6. The emplacement of Semail ophiolite units onto the Arabian passive margine sediments is dated 88Ma (Hacker, 1991), 95-93 Ma (Warren et al., 2003), 95 Ma (Tilton, 1981). Any age chosen, implies a shift to older ages for the Hawasina Nappe. See comment above (point 6)

Line 457 – it seems that maximum burial conditions are already reached at 84 Ma as shown in figure 6 This age varies along the transect

Line 460 – I would like to see 1D burial histories for the northern and southern flank of the Jebel Akhdar described as part of the main text. DONE

Lines 475- 476- delete 1.8% VR as it is not reported in Mozafari et al., 2015 and revise temperature range DONE

Line 475 – Replace "requires" with "require" DONE

Lines 494-497 – I do not see any difference in your modelling results for northern and southern flanks Slight differences exist, but as they are within the range of error we changed the manuscript accordingly

Lines 507-512. The sentences are unclear to me. If you have a decrease of temperature by 60_C (0% serpentinization) you should require a lower overburden thickness to fit that temperature decrease and not an additional thickness. Please rephrace If modelled temperatures decrease and thermal calibration data remains the same we need to add additional thicknesses to equally match the calibration data (increase modelled temperature)

Line 513 – replace "deepst" with "maximum" DONE

Discussion Burial history

Line 537. Please expand this part. Why? DONE

Lines 542-545. delete 1.8% VR as this value is not reported in Mozafari et al., 2015 and revise temperature range/burial depths DONE

Lines 566-569. I did not understand these sentences. What is the sub-thrust thermal overprint? Rephrased

Line 570-574. This sentence is unclear to me. If 8-10 km of ophiolite units thrust over both passive margin and Hawasina units, why are peak temperatures for these units so different? Peak temperature for the passive margin units is up to 360_C (fluid inclusion data) but they are in the range of 130 to 170_C for the Hawasina sediments as they have not reset the ZHe system. Within their range of error the data is comparable as discussed. Please keep in mind that the fluid inclusion data does not necessarily represent host rock but fluid temperature and we have to compare with thermal maturity data instead.

Line 575-577. This is a repetition. Information about heat flow has been already reported in line 513.Please delete it. DONE

Lines 595–598. The short duration of the heating event to explain the discrepancy between temperatures obtained by solid bitumen and clay mineral assemblage fails as the ophiolite units remain atop the passive margin units from 79 to 55 Ma. The time span elapsing between ophiolite thrust stack emplacement and the beginning of tectonic overburden removal should be shorter than 1-2Ma (hydrothermal/geothermal settings) in order to do not allow clay minerals to record maximum temperature (Hoffman and Hower, 1979, Hillier et al., 1995). Please see comment above (Point 6). It is highly improbable that the maximum temperatures in such a setting of rapid obduction lasted long. Temperature equilibration takes several hundred thousand to few million years and while this is happening as a consequence of ophiolite emplacement, tectonic thinning by top-to-NNE shear already starts. Therefore, we think that short duration of heating is one possible explanation, but there may be other explanations as well.

Line 598 – delete "dated" DONE

Lines 598-600. The interpretation that clay minerals formed during top-to-NNE shearing and does not record maximum temperature associated to burial is a speculation. There are no K-Ar or other geochronological constraints for clay minerals formation. We completely agree with the reviewer. We note there is some discrepancy between different T data, and this may be one explanation. We changed the sentence accordingly to "Alternatively, we speculate that the dated clay minerals…".

Lines 600-606. I do not think the sentence adds value to the discussion and it seems to me very cryptic. I would delete it. If the authors wants to keep the sentence they should expand this part and add more information about that. We rephrased the paragraph accordingly, to make it less cryptic.

Pressure evolution and fluid migration I would delete "fluid migration" from the title as you describe fluid migration in section 5.4. DONE

Lines 656-657- please delete the sentence written in german DONE

Figures and tables

Figure 1 – What is the difference between thrusts in red and thrusts in black in figure 1a? It should be explained in the legend or in the figure caption. Add anticline symbol in the legend Please add latitude and longitude to figure 1b. Furthermore, why do thrusts in figure 1b have different stroke thickness? Please uniform them. DONE

Figure 3 – This figure is confusing and needs a restyling. DONE Thrusting of Hawasina and Semail ophiolite should be placed before the synorogenic sediments of the Fiqa and Muti Fm. DONE It is seems that thrusting is younger than 87 Ma. You can overcome this issue by deleting ages in the Group/Formation column. DONE Zircon ages are too small. DONE Letter size is very small. A legend for lithology should be drawn. I would prefer to see temperature values as points and error bars. DONE

Figure 4 – text in the legend is hardly visible. Please replace it. Provide a legend for the colours in the map. It would be useful to add the trace of the anticline axial plane to better define northern and southern flank of the Jebel Akhdar dome. DONE

Figure 6 – add a legend for the colours in the figure. All units are explained in the figure See my comments in the text for the age of the ophiolite emplacement in order to modify the figure. The figure caption is confusing in the last line as vertical lines show Wadi location as well and not only hydrocarbon fields. Please revise DONE

Figure 7 –vertical lines in the figure caption show Wadi location as well and not only hydrocarbon fields. Please revise DONE

Figure 8- revise figure 8a on the basis of my comments on Vr values by Mozafari et al.,2015 DONE now at 140°C

Table 1 – replace ”,” with “.” in the calculate VR values. DONE Add longitute and latitude to sample location. DONE What do you mean with “below the surface of the matrix”? What did you measure? Please rephrace. DONE Spell out Kh2. DONE Mozafari et al., 2015 show only two data with 1.1 VR%. DONE Please correct the table I would split table 1 into two tables. The first with literature data that can be moved to the temperature evolution section and the other with your original data. To enable a direct comparison of published data and our results we kept the data in one Table, but we visually highlighted the new data and extended the table caption accordingly.

Table 3 – “Replace “Thom” with “Th” in the fifth column. Replace in the figure caption “Data of Holland et al. (2009) is added for comparison and we likewise corrected his homogenization temperatures” with ”Data by Holland et al. (2009) are added for comparison and we likewise corrected their homogenization temperatures”. DONE

Supplementary material

Figure S1 – Provide a better description of the table caption. Furthermore provide the amount of eroded thickness simulated during the Wasia-Aruma break. Are those the inputs for Petromod 2D, 1D basin modelling or Move 2D? Please specify, Replace “dolomite” with “dolostones”. Dolomite is a mineral, dolostoneis a rock. Done – we kept Dolomite as these are the officially defined lithologies as assigned in the software package to keep it transparent.

Figure S5 should become part of the main text and you should provide the thermal maturity curve fitting your solid bitumen data as function of depth. Without this figure the thermal history may have no meaning. Readers must be aware of calibrating data and fitting of the thermal maturity curve. In figure S5, ophiolite emplacement is not at 88 Ma as described in the figure caption. Label the figures as northen and southern flank. Done

Figures S9 and S10 have not been cited in the text. Moved and cited in the main text

Tectono-thermal evolution of Oman's Mesozoic passive continental margin under the obducting Semail Ophiolite: a case study of Jebel Akhdar, Oman

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Keywords: basin modeling, passive margin, obduction, burial, Raman spectroscopy, thermochronology, thermal maturity

Abstract. ~~The Mesozoic sequences of the Oman Mountains experienced only weak post-obduction overprint and deformation and, thus they offer a unique natural laboratory to study obduction.~~ We present a study of the pressure and temperature evolution in the passive continental margin under the Oman Ophiolite, using numerical basin models calibrated with thermal maturity data, fluid inclusion thermometry and low-temperature thermochronometry~~logy~~. Because the Oman Mountains experienced only weak post-obduction overprint, they offer a unique natural laboratory for this study.

Thermal maturity data from the Adam Foothills constrain burial in the ~~foredeep moving i~~I basin in front of the advancing nappes ~~to~~ has been at least 4 km. Peak temperature evolution in the carbonate platform under the ophiolite ~~is~~ depends only weakly ~~dependent~~ on the temperature of the overriding nappes which have cooled during transport from the oceanic subduction zone to emplacement. Fluid-inclusion thermometry yields pressure-corrected homogenization temperatures of 225 to 266 °C for veins formed during ~~progressing~~ progressive burial, 296-364 °C for veins related to peak burial and 184 to 213 °C for veins associated with late-stage strike-slip faulting. In contrast, the overlying Hawasina nappes have not been heated above c. 170 ~~-~~°C, as witnessed by only partial resetting of the zircon (U-Th)/He thermochronometer.

In combination with independently determined temperatures from solid bitumen reflectance, we infer that the fluid inclusions of peak-burial-related veins formed at minimum pressures of 225-285 MPa. This implies that the rocks of the future Jebel Akhdar Dome were buried under 8-10 km of ophiolite on top of 2 km of sedimentary nappes, ~~which is~~ in agreement with thermal maturity data of solid bitumen reflectance and Raman spectroscopy.

~~B~~Rapid burial of the passive margin under the ophiolite results in sub-lithostatic pore pressures, ~~in agreement with observations on~~as indicated by veins formed in dilatant fractures in the carbonates. We infer that overpressure is induced by rapid burial under the ophiolite~~ nappes~~. ~~Obduction-related tilt~~Tilting of the ~~passive margin~~carbonate platform in combination with overpressure in the passive margin caused fluid migration towards the south in front of the advancing nappes.

Exhumation of the Jebel Akhdar as indicated by our zircon (U-Th)/He data, integrated with existing data, started as early as the late Cretaceous to early Cenozoic, linked with extension ~~along~~ above a major listric shear zone with top-to-NNE shear sense~~, together with an early phase of extensional dome formation~~. In a second exhumation

phase~~T~~ the carbonate platform and obducted nappes of the ~~whole~~ Jebel Akhdar Dome cooled together below c. 170 °C between 50 and 40 Ma, before the final stage of anticline formation.

1. Introduction

The Permian~~o~~-Mesozoic platform sediments of north~~ern~~ Oman (Figure 1; e.g. Beurrier et al., 1986; Glennie et al., 1974; Lippard et al., 1982) with hydrocarbon accumulations in the southern foreland of the Jebel Akhdar Dome (Figures 1 and 2) are overlain by the Semail ophiolite nappe complex, the largest and best-preserved ophiolite on Earth. Limited tectonic extension after obduction followed by uplift, folding and deep erosion and the present-day arid climate formed exceptional exposures in three tectonic windows and in the foreland fold-and-thrust belt of the Oman Mountains (Figure 1). The Oman Mountains have been investigated in many studies focusing on tectonic history (Breton et al., 2004; Cooper et al., 2014; Glennie et al., 1973, 1974; Grobe et al., 2018; Loosveld et al., 1996; Searle, 2007), stratigraphic sequences (Van Buchem et al., 2002; Grelaud et al., 2006; Homewood et al., 2008), geodynamic modelling (Duretz et al., 2015), hydrocarbon source rocks (Van Buchem et al., 1996; Philip et al., 1995; Scott, 1990) and reservoir rocks (Arndt et al., 2014; De Keijzer et al., 2007; Koehrer et al., 2011; Virgo et al., 2013). Less well known is the temperature and pressure evolution of the ~~sub-thrust sedimentary basin~~subophiolite passive margin units and the subsequent cooling history of the Jebel Akhdar (Aldega et al., 2017; Grobe et al., 2018; Hansman et al., 2017; Poupeau et al., 1998; Saddiqi et al., 2006). This information is vital for our understanding of~~. A, a better understanding of this would furthe~~further the time-temperature history ~~r~~ and would allow to constrain ~~the~~ obduction dynamics.~~ of obduction A differentiation of peak burial temperatures linked to~~ and forebulge migration~~ and peak burial under the ophiolite obduction would allow to refine phases of obduction stages~~. Combining ~~those~~~~these peak~~ temperatures evolution with cooling ages ~~enables to integrate~~links the burial history with~~-restoration of times an~~phases of orogeny.

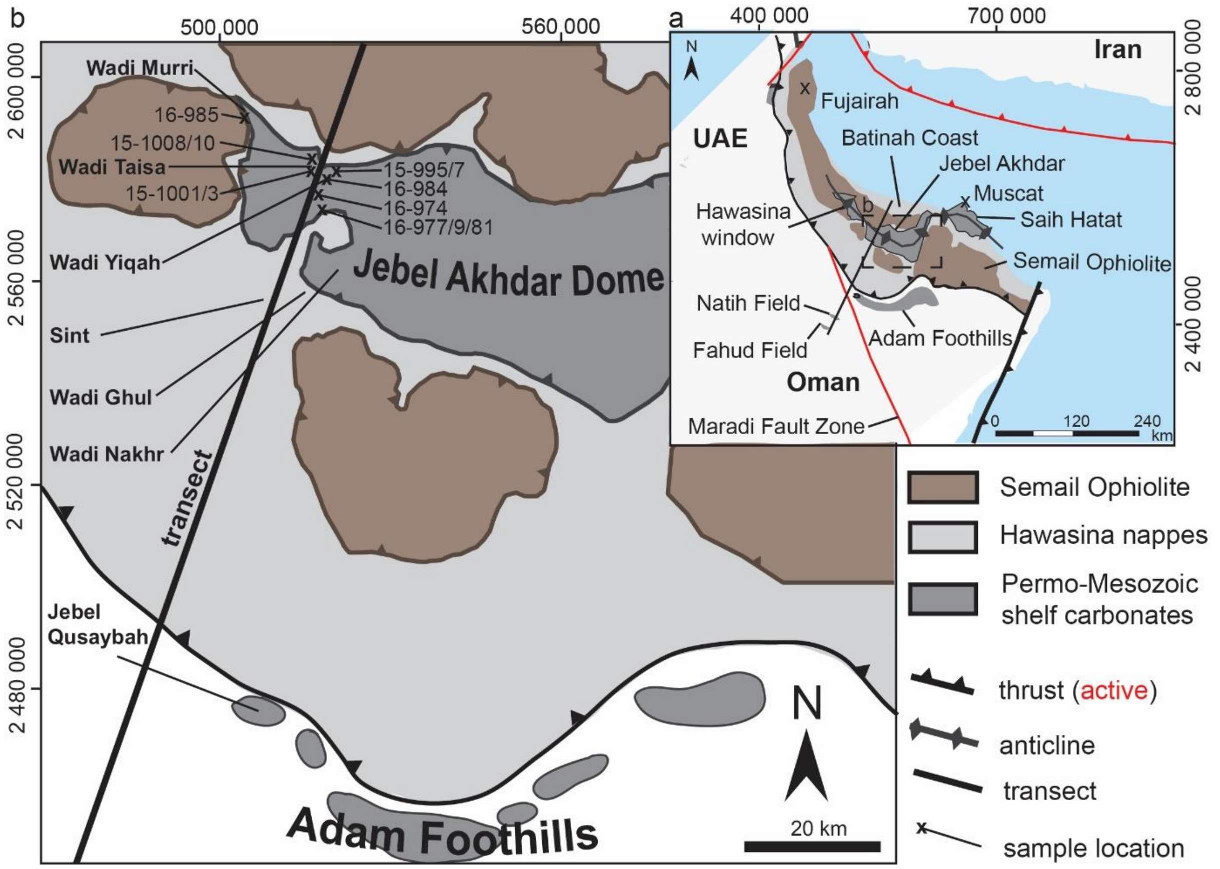

Figure 1: a) Tectonic setting of the Oman Mountains. Shaded in gray are the three tectonic windows of Hawasina, Jebel Akhdar and Saih Hatat as well as the Adam Foothills. Brown areas show the exposed Semail Ophiolite, black lines denote the obduction fronts of Semail and Masirah ophiolites, red lines denote lithosphere-scale, active structures. The modeled transect (black line) crosscuts the Jebel Akhdar window and continues to the Natih and Fahud oil fields in the southwestern mountain foreland. b) Geologic map of the Jebel Akhdar window with the location of the modeled transect (solid black line) and the locations of thermal maturity data (x).

~~The full~~ whole ~~Permo~~ian ~~Mesozoic sequence of the carbonate platform below the ophiolite is well exposed, providing outcrop samples to study the pressure and temperature history of this rapidly buried passive-margin sequence.~~

In other orogens, peak temperatures related to nappe emplacement were reconstructed by analyzing thermal maturity of finely dispersed organic material (e.g. Teichmüller and Teichmüller, 1986; Zagros: Mashhadi et al., 2015~~;,~~ Holy Cross Mountain: Schito et al., 2017; Eastern Alps: Lünsdorf et al., 2012; Southern Alps: Rantitsch and Rainer, 2003; Apennines: Reutter et al., 1988). However, the number of studies of thermal and pressure effects on overthrust sedimentary basins is limited and modeling approaches to reconstruct such large scale overthrusts are increasing but still ~~rare~~ few (e.g. Aldega et al., 2018; Deville and Sassi, 2006; Ferreiro Mählmann, 2001; Jirman et al., 2018; Oxburgh and Turcotte, 1974; Roure et al., 2010; Schito et al., 2018; Wygrala, 1989). In these studies, a main difficulty is to differentiate between temperature history of ~~obduction~~ overthrusting and overprinting by later phases of orogeny. In the Oman Mountains, peak temperatures reached by obduction have not been overprinted~~, and fluid migration in the thrust belt is predominantly related to obduction~~. ~~-~~The whole Permian-Mesozoic sequence of the carbonate platform below the ophiolite is well exposed, providing outcrop ~~samples~~ to study the pressure and temperature history of this rapidly buried passive-margin sequence.

In this paper we present new thermal maturity, thermochronology and fluid inclusion data, and integrate them in a numerical basin model of the pressure-temperature evolution ~~of~~ along a transect ~~across the entire Jebel Akhdar~~ extending from the undeformed passive margin sequence in the south to the Batinah coast in the north (Figure 2).

This Our dataThis integration allowshelps to better constrain temperature and pressure conditions of deepest maximum burial as well as, and the time of dome formation and exhumation which we linked is linked to the structural and tectonic evolution of the area. HencePresented results of, theOur results for the Oman Mountains can be used as analogue forto understand more deformed orogens, shed light to fluid migration in the early stages of orogeny and on exhumation related to orogenic collapse. and orogenic collapse related exhumation

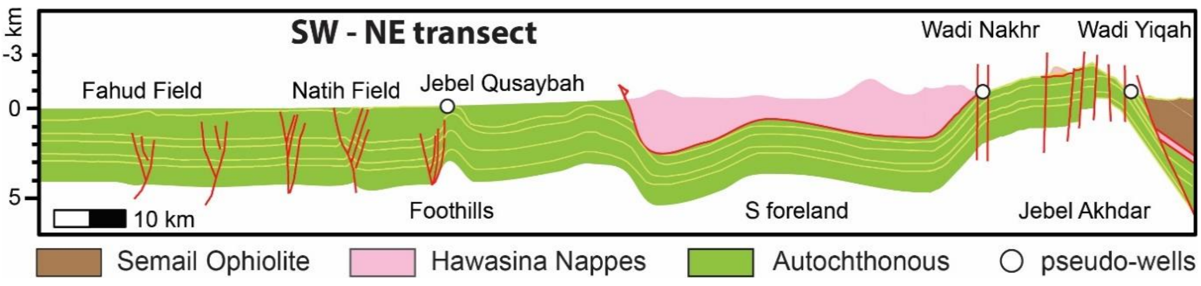

Figure 2: Structural transect used for modeling of the Jebel Akhdar Dome and its southern foreland (Al-Lazki et al., 2002; Filbrandt et al., 2006; Searle, 2007; Warburton et al., 1990). Highlighted are the locations of the pseudo-wells (white circles, size depict area of sample interpolation) in Wadi Nakhr, Wadi Yiqah and at Jebel Qusaybah, Adam Foothills, which were used for model calibration.

2. Geological setting

2.1. Tectonic setting

Along the northeastern coast of Arabia, the NW-SE oriented Oman Mountains form a more than 400 km long anticlinal orogen (Figure 1). The mountain belt consists of allochthonous sedimentary and ophiolitic nappes thrust onto a Permianо-Mesozoic passive continental margin (Breton et al., 2004; Glennie et al., 1973; Loosveld et al., 1996; Searle and Cox, 2002).

This continental margin was formed during opening of the Neotethyan ocean (Loosveld et al., 1996) and the formation of the Permoian-Mesozoic Hawasina Basin (Béchennec et al., 1988; Bernoulli et al., 1990). Cretaceous convergence of Arabia and Iran inverted the rifting and iThe initiation of nitiated subsea thrusting of the later future Semail Ophiolite on topto of the Arabian Plate at 97-92 Ma, as is recorded by U-Pb geochronology (Rioux et al., 2013, 2016; Warren et al., 2005) and $^{40}Ar/^{39}Ar$ dating of the metamorphic sole (Hacker et al., 1996). Obduction initiation and tThe advancing ophiolite resulted incaused a flexural forebulge that moved southwestwards through the passive margin during the Upper Cretaceous (Robertson, 1987). Forebulge migration induced up to 1100 m of uplift of the Permianо-Mesozoic Arabian Platform and erosion of the Cretaceous platform sediments (Searle, 2007). In the field this can be observed at, causing the Wasia-Aruma Break (Robertson, 1987). During northeastward directed subduction of the Arabian margin, pDuring this convergence, parts of the Hawasina ocean sediments and volcanics units became detached and became accreted in front of and beneath the ophiolite nappe (Béchennec et al., 1988, 1990; Glennie et al., 1974; Searle et al., 2003; Warburton et al., 1990). Palinspastic reconstructions of the Hawasina Nappes locate the position of the initial ophiolite thrusting 300-400 km offshore the Arabian coast (Béchennec et al., 1988; Glennie et al., 1974).

Initiated BbIn the carbonate platform, burial under the Hawasina and ophioliticadvancing nappes the allochthonous sequences led to the generation of overpressure cells and the formation of three crack-seal calcite vein generations in the margin sequence, which represent overpressure build-ups and releases (Gomez-Rivas et al., 2014; Grobe et al., 2018; Hilgers et al., 2006; Holland et al., 2009; Virgo, 2015). Peak The highest grades of metamorphism of the subducted margin is recorded by eclogites exposed in the As Sifah region (E Saih Hatat, Figure 1a), where the burial triggered thermal climax resulted in zircon and rutile recrystallization at c. 79 Ma (Warren et al., 2003).

The sedimentary record in the Batinah coast and the foreland, as well as laterite formation on top of the ophiolite suggest subaerial exposure and a slow-down or stopped obduction before lower marine conditions were restored in the Maastrichtian suggest that obduction slowed or stopped in the early Paleogene, and the ophiolite was exposed subaerially (Coleman, 1981; Forbes et al., 2010; Nolan et al., 1990). This slowdown might relate to the formation of the Makran subduction zone at c. 35 Ma (Agard et al., 2005; Grobe et al., 2018; Hassanzadeh and Wernicke, 2016; Jacobs et al., 2015; Mouthereau, 2011). This shift of deformation to the north resulted in preservationing the initial early stage of the obduction orogen in northern Oman.

Regional In the Jebel Akhdar, post-obduction extension took place along ductile top-to-NNE shear zones, dated toat 64 ± 4 Ma (Grobe et al., 2018; Hansman et al., 2018), followed by NW-SE striking normal fault systems (Al-Wardi and Butler, 2007; Fournier et al., 2006; Grobe et al., 2018; Hanna, 1990; Hilgers et al., 2006; Holland et al., 2009 a and b; Loosveld et al., 1996; Mattern and Scharf, 2018; Virgo, 2015).

Renewed Arabia-Eurasia convergence during the Cenozoic formed the three dome structures with the associated tectonic windows. Timing of formation and exhumation of the Jebel Akhdar Dome is still debated. Stratigraphic arguments for a late Cretaceous doming are Maastrichtian rocks unconformably deposited on Hawasina (Bernoulli et al., 1990; Fournier et al., 2006; Hanna, 1990; Nolan et al., 1990), while inclined Miocene strata at the northern fringes of the dome points to a younger Miocene doming (Glennie et al., 1973). Consequently, some models suggest a two-phased exhumation in Cretaceous and Miocene (Grobe et al., 2018; Searle, 1985, 2007), in agreement with forthermochronological constrains and an interpreted two-stage cooling with possible reheating in late Miocene (Poupeau et al., 1998; Saddiqi et al., 2006). More recent studies, however, have shown that the data of Poupeau et al. (1998) and Saddiqi et al. (2006) can also be explained by a cooling-only scenario with exhumation in the Eocene (Hansman et al., 2017). This is in agreement with structural observations suggesting early dome formation and later amplification of the structure (Grobe et al., 2018).

2.2. Stratigraphic sequence

Sediments in the Jebel Akhdar area consist of a pre-Permian sequence (Autochthonous A, Figure 3) unconformably overlain by a Permiano-Mesozoic sequence (Autochthonous B, Figure 3; Beurrier et al., 1986; Breton et al., 2004; Glennie et al., 1974; Rabu et al., 1990). During the late Cretaceous, Hawasina nappes and the Semail Ophiolite were emplaced onto the passive margin, and neo-autochthonous rocks of Cenozoic age were deposited on top of the ophiolite after obduction (Béchennec et al., 1988; Forbes et al., 2010; Loosveld et al., 1996).

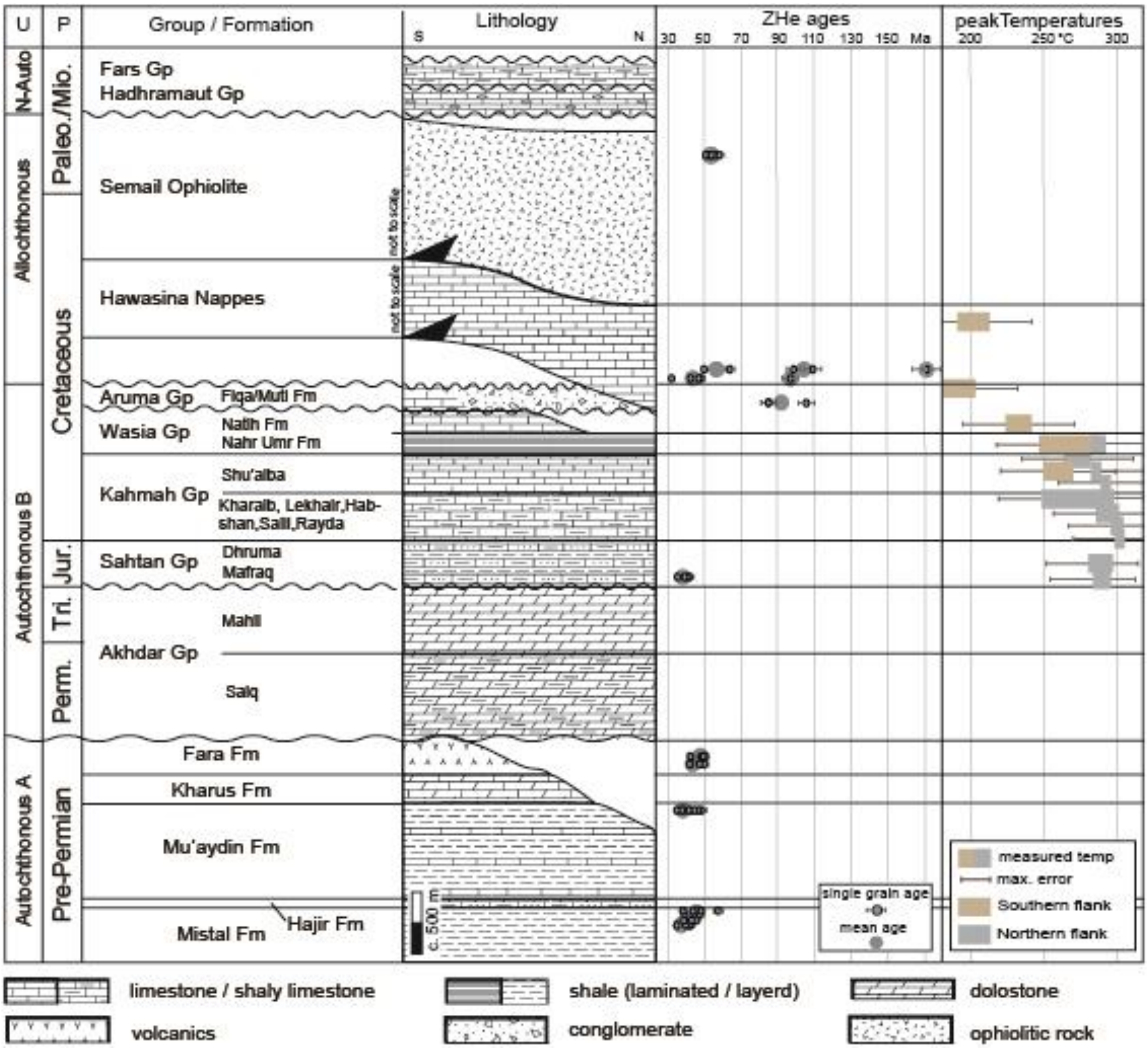

Figure 3: Stratigraphy of the Jebel Akhdar area with its two passive margin sequences Autochthonous A and B overthrust by Hawasina and Semail Nappes and unconformably overlain by neo-autochthonous units. ~~Ages (Forbes et al. 2010) are basin modeling input data. In addition, t~~Thermal calibration data is shown: ZHe ages (Table 2) show two different grain age ~~populations~~clusters. ~~Maximum~~ Peak burial temperatures from organic matter maturity (~~black,~~ Table 1) outline the temperature increase with stratigraphic age. Temperature data was supplemented by values from *Mozafari et al. (2015) and +Grobe et al. (2016). (U = Unit, P =Period). Note that the Semail and Hawasina nappes are shown in their structural rather than stratigraphic positions; ~~. D~~lithological data is compiled from Beurrier et al. (1986), Loosveld et al. (1996), Terken et al. (2001) and Forbes et al. (2010).

Autochthonous A deposits are exposed in the Jebel Akhdar window down to the Mistal Fm. (Beurrier et al., 1986). Black limestones of the Hajir Fm., mudstone rich carbonate beds of the Mu'aydin Fm. and lime- and dolostones of the Kharus Fm. conformably overlie the Mistal Fm. (Beurrier et al., 1986; Glennie et al., 1974). Platform break-up is recorded by laminated cherts and volcanoclastics of the Fara Fm. (Beurrier et al., 1986) followed by an unconformity representing a gap from Cambrian to Permian times (Loosveld et al., 1996). After establishment of the Neotethyan Ocean during the Permian, northern Oman returned to stable passive margin conditions and the carbonate platform of the Autochthonous B developed, with the Akhdar G~~p.~~roup at its base (Koehrer et al., 2010; Pöppelreiter et al., 2011). This is unconformably overlain by limestones with clastic interlayers of the Jurassic Sahtan Group ~~Gp.~~ (Beurrier et al., 1986; Pratt et al., 1990). Limestones with marly, frequently organic-rich intercalations of the Cretaceous Kahmah (Habsi et al., 2014; Vahrenkamp, 2010) and Wasia groups (Grelaud et al., 2006; Homewood et al., 2008; Philip et al., 1995) form the youngest platform sediments (Robertson, 1987; Warburton et al., 1990).

The obduction-related moving forebulge and associated uplift ended passive margin deposition and eroded the topmost Wasia Group ~~Gp.~~ (Natih Fm.) in the Jebel Akdhar (Figure 3), and deeper in the Saih Hatat region. Deposition in the foredeep basins in front and behind the forebulge was dominated by the syn- and postorogenic, conglomerate-rich sediments of the Muti Fm., Aruma ~~Gp.~~ Group (Beurrier et al., 1986; Robertson, 1987). Towards the south, in the Adam Foothills, this laterally grades to calcareous foreland sediments of the Fiqa Fm. (Forbes et al., 2010; Robertson, 1987; Warburton et al., 1990).

Hawasina sediments accreted in front and beneath the ophiolite represent marine slope and basin facies, time equivalent to the Autochthonous B (Béchennec et al., 1990). After obduction of oceanic crust on top ~~of~~ the passive margin, neo-autochthonous evaporites and carbonates of the Paleocene to Eocene Hadhramaut Gp. and bivalve-rich dolomites and limestones of the Oligo- to Pliocene Fars Group~~Gp.~~ were deposited south of the mountains (Béchennec et al., 1990; Forbes et al., 2010). Paleogeographic~~al~~ reconstructions show that the Oman Mountains had high relief after obduction, followed by a low relief landscape until the early Eocene (Nolan et al., 1990). In the middle Eocene marine transgression caused widespread deposition of limestones, as witnessed e.g. by the Seeb and Ruwaydah Formations (Nolan et al., 1990). Post Eocene times show renewed relief development and continued uplift until recent times (Glennie et al., 1974; Searle, 2007).

2.3. ~~Temperature evolution of the Autochthon~~Previous paleothermal data of the Autochthon

Only limited paleo-temperature data are~~is~~ available from the carbonate platform (Fink et al., 2015; Grobe et al., 2016; Holland et al., 2009; Stenhouse, 2014). Peak-burial temperatures of 226-239 °C for the top of the platform were measured using solid bitumen reflectance (also referred to as pyrobitumen reflectance) and Raman spectroscopy of carbonaceous material (RSCM) in the Jebel Akhdar (Grobe et al., 2016). ~~Data correspond to~~Results indicate peak-burial temperatures of 266 to 300 °C (Grobe et al., 2016; Table 1). Temperature estimates based on RSCM and solid bitumen reflectance (Grobe et al., 2016) yielded similar temperatures for the southern flank of 248-280 °C for the Nahr Umr, 226-239 °C for the Natih B and 172-206 °C for the Muti, respectively (Table 1, Figure 3).

Vein crystallization temperatures of 166-205 °C at the top of the Natih A (near Al Hamra) were measured by quartz-calcite thermometry in veins formed during ophiolite-induced burial (Gen. III of Grobe et al., 2018), and approximately 255 °C for veins associated with a later normal fault network (Gen V of Grobe et al., 2018; Stenhouse, 2014). Fluid inclusions (FI) of bedding parallel pinch-and-swell veins (top-to-NNE shear after peak burial, Gen. IV of Grobe et al., 2018) show uncorrected minimum trapping temperatures of 134-221 °C in the lower beds of the Sahtan Group at Wadi Nakhr (Holland et al., 2009). Reflectance measurements of solid-bitumen-containing veins in the Wadi Ghul (Gen I of Grobe et al., 2018), which are interpreted to be associated with fluid mobilization during forebulge migration, showed maximum temperatures of 230 °C (Fink et al., 2015).

Vitrinite reflectance data of Mozafari et al. (2015) shows temperatures of c. 140 °C for the Natih B in the Jebel Qusaybah, Adam Foothills, an area not overthrust by the ophiolite complex.

~~**Reconstructions of the thermal history using numerical basin modeling were presented for the southern foreland and the contained Natih Fm. outlining its extreme efficiency interpreted to be a result of thrusting**~~

induced lateral migration (Terken, 1999; Terken et al., 2001) and the Proterozoic hydrocarbon source rocks (Visser, 1991).

2.4. Temperature evolution of the Semail Ophiolite nappe / Allochthon

Initial intra-oceanic ophiolite thrusting and associated metamorphism at its sole took place at peak temperatures of 840 ± 70 °C at 97-92 Ma measured at several locations in the Oman Mountains (Gnos and Peters, 1993; Hacker and Mosenfelder, 1996; Rioux et al., 2013; Searle and Cox, 2002; Warren et al., 2003). At 90-85 Ma the base of the ophiolite cooled to 350 ± 50 °C (white mica Ar/Ar dating, Gnos and Peters, 1993). At around 80 Ma the deepest burial of the Oman margin beneath the ophiolite was reached (Hacker and Mosenfelder, 1996; Warren et al., 2005) with temperatures in the metamorphic sole below 300 °C (Le Metour et al., 1990; Saddiqi et al., 2006). Due to the at least 2 km thick imbricated Hawasina Nappes between the ophiolite and the passive margin sequence, the thermal overprint did not affect the of the nappe temperature on the top of the carbonate platform was low. Limited thermal overprinting of the units underlying the ophiolite is supported by the fact that the sediments of the nappes directly below the ophiolite do not show signs of regional metamorphism in the Jebel Akhdar region (Searle, 1985). Duretz et al. (2015) showed in A lithospheric scale thermo-mechanical model of the thrusting in northwestern Oman includes a thermal anomaly c. 100 km northwest offshore the Arabian margin to initiate subsea thrusting (Duretz et al., 2015).

2.5. Petroleum system elements

Several petroleum systems developed in the carbonate platform of northern Oman with important source rock horizons in the Natih Fm. (Natih Members B and E). Both members contain Type I/II kerogen with total organic carbon contents up to 15 % in the Natih B and up to 5 % in the Natih E, respectively (Terken, 1999). Source rock maturity is restored based on biomarker analysis to c. 0.7 %VR within the Fahud reservoir and c. 0.9 %VR in the Natih reservoir (Terken, 1999). In the southern mountain foreland Natih oil generation started in the middle Cretaceous and continuous until present (Terken, 1999). Ophiolite obduction in the Jebel Akhdar area of northern Oman led to over-mature Natih source rocks (Grobe et al., 2016). The Natih Fm. is classified as supercharged, laterally drained, foreland petroleum system (Terken et al., 2001). However, the thermal impact of the moving forebulge and the importance of tectonic processes for fluid migration below and in front of the obduction orogen are not clear. At least three different generations of solid bitumen particles in veins and source rocks on the southern slope of the Jebel Akhdar suggest pulses of hydrocarbon generation and migration in front of the Oman Mountains (Fink et al., 2015; Grobe et al., 2016). In central Oman, Shu'aiba and Tuwaiq oils are produced out of Kahmah and Sahtan Gp. Group reservoirs, sealed by argillaceous shales of the Nahr Umr Fm. (Terken et al., 2001). All Tthese units are all well-exposed in the Oman Mountains.

3. Methods

Samples for thermal reconstruction were collected during several field campaigns between 2013 and 2016 in the Jebel Akhdar Dome (Figure 2).

3.1. Elemental analysis and thermal maturityRaman spectroscopy of carbonaceous material

To determine levels of thermal maturity, over 100 dark, unweathered and organic-rich samples were taken from different stratigraphic units in the Jebel Akhdar (ADDSahtan Group, Kharaib Fm., Shu'aiba Fm., Nahr Umr Fm., Natih Fm., Muti Fm. STRATIGRAPHIC LEVELS,, Figure 3). Based on total organic carbon (TOC) content as determined by Grobe et al. (2016), 13 samples were selected for thermal maturity analysis on surfaces cut perpendicular to bedding. Results were used to calibrate peak-burial temperatures of the numerical basin models. The organic particles lack sufficient size or surface quality for reflectance measurements and are therefore investigated by confocal Raman spectroscopy of carbonaceous material. The technique measures vibrational energies of chemical bonds which change during temperature induced reorganization of amorphous carbonaceous material (kerogen) to graphite (e.g. Aoya et al., 2010; Beyssac et al., 2002; Kouketsu et al., 2014; Mair et al., 2018). Measurements were conducted at the Geoscience Center, Göttingen, on a Horiba Jobin Yvon HR800 UV spectrometer attached to an Olympus BX-41 microscope and a 100× objective. A high-power diode laser with a wavelength of 488 nm and an output power of 50 mW was installed and a D1 filter avoided sample alteration by heating. Each spectral window (center at 1399.82 cm^{-1}, grid of 600 lines/mm) was measured 5 to 10 times for 2 to 10 seconds with a Peltier CCD detector at activated intensity correction. For quality control, the 520.4 cm^{-1} line of a Si-wafer was measured every 30 minutes without observable drift of the measurements. To transform the measured data into VR_r values the scaled total area (STA) approach of Lünsdorf (2016) was applied with the equation of Grobe et al. (2016):

$$VR_r = -\frac{STA - 280.13}{24.71} \quad [\%]$$

Absolute errors of the applied calibration are in the order of ±40 °C, based on comparing neighboring samples (Grobe et al., 2016) we can resolve the relative differences down to ±30 °C which also represents the residual error interpreted to relate to within-sample heterogeneity (Lünsdorf et al., 2017; Nibourel et al., 2018).

3.2. Fluid inclusion thermometry

Doubly-polished wafers (c. 200 µm thick) of four vein samples (FI-N1, -N2, -M1, -M2) have been prepared according to the procedure described by Muchez et al. (1994). Fluid inclusion (FI) petrography and microthermometry was performed to analyze the temperature-pressure conditions and fluid's salinity. FIs represent paleofluids accidentally trapped in a crystalline or amorphous solid during ~~mineralization~~crystallization, lithification or both (Diamond, 2003). If unaffected by later changes, trapping pressure and temperature is given by the homogenization temperature (Barker and Goldstein, 1990). Based on the time of trapping primary (mineral growth), secondary (fracture-related) and pseudosecondary inclusions are distinguished (Barker and Goldstein, 1990; Diamond, 2003; Goldstein, 2001; Van Den Kerkhof and Hein, 2001):

Two calcite vein samples of the Natih Fm. (FI-N1 and 2, Locations Figure 4) represent conditions related to early burial (FI-N2, structural generation I of Grobe et al., 2018), and burial beneath the ophiolite (FI-N1, structural generation III of Grobe et al., 2018). Two quartz-rich calcite veins of the Muti Fm. (FI-M1 and 2, Locations Figure 4) are related to late, NE-SW striking strike slip faults (generation IX of Grobe et al., 2018). FI assemblages were defined and fluid inclusions measured with a Linkam THMSG600 thermostage (accuracy ± 0.1 °C) attached to an Olympus BX60 microscope at the KU Leuven, Belgium. Calibration was performed using CO_2, H_2O-NaCl, H_2O-KCl, and H_2O standards. Homogenization temperatures (T_h) were measured prior to temperatures of complete freezing (T_f), first melt (T_{fm}), and complete melting of ice ($T_{m(ice)}$) to avoid stretching or leakage due to the volume increase during ice formation. All measured temperatures were recorded during heating, except ~~of~~ for the freezing temperature (T_f). Pressure corrections of T_h were conducted with the program FLINCOR (Brown, 1989) for 280 and 340 MPa, assuming 8 to 10 km of ophiolite overburden (see model results, ρ= c. 3070 kg/m³) and 2 km of sedimentary Hawasina Nappes (ρ= c. 2450 kg/m³), and for 45 MPa, assuming 2°km of sedimentary overburden (Al-Lazki et al., 2002; Grobe et al., 2016). Fluid salinities were calculated from the $T_{m(ice)}$ values considering a H_2O-NaCl composition (Bodnar, 1993), which is based on the T_{fm} values.

3.3. Thermochrono~~logy~~metry

Zircon (U-Th)/He (ZHe) dating allows to reconstruct the ~~tectono-~~thermal history of the topmost few kilometers of the Earth's crust. Helium retention in less metamict zircon crystals is sensitive in the temperature range between c. 130 and 170 °C, i.e. the zircon partial retention zone (PRZ, Reiners, 2005). 11 rocks sampled above (Muti Fm., Hawasina and Semail nappes), below (Mistal Fm., Muaydin Fm., Fara Fm.) and within (Sahtan Gp.) the carbonate platform were selected for ZHe dating. Zircon crystals were released using high voltage pulse crushing (http://www.selfrag.com) and concentrated by standard mineral separation processes (drying, dry sieving, magnetic and heavy liquid separation). Three to eight clear, intact, euhedral single crystals were selected per sample and transferred into platinum micro-capsules. They were degassed under high vacuum by heating with an infrared diode and extracted gas purified using a SAES Ti-Zr getter at 450 °C. Helium was analyzed with a Hiden triple-filter quadrupole mass spectrometer. Degassed zircons were subsequently dissolved in pressurized teflon bombs, spiked and U, Th and Sm measured with a Perkin Elmer Elan DRC II ICP-MS equipped with an APEX micro flow nebulizer.

Time-temperature histories were reconstructed using the HeFTy 1.8.3 software package (Ketcham, 2005) applying kinetic zircon properties of Guenther et al. (2013). For samples with reset zircons the only constraint used was a minimum temperature above 200 °C between deposition and the calculated ZHe age. Thermal modeling was conducted until 100 statistically good time-temperature paths were achieved (goodness of fit: 0.5, value for acceptable fit: 0.05). In cases where this was not possible, at least 10,000 independent paths were calculated.

3.4. Numerical basin modeling

Structural evolution was palinspastically reconstructed starting from the present-day profile using Move 2D (2016.1, Midland Valley Exploration). Geometries and relative ages of the structures were supplemented with subsurface data (Al-Lazki et al., 2002; Filbrandt et al., 2006; Searle et al., 2004; Warburton et al., 1990). The reconstruction workflow is based on restoring the pre-deformation layer continuity ~~was~~ as follows: (1) faulted layers in the southern foreland were restored, (2) doming was retro-deformed by vertical simple shear, before (3) normal faults in the Jebel Akhdar were restored. This sequence is based on our tectonic model (Grobe et al., 2018). The resulting geometries were used as pre-thrusting input geometries for 2D PetroMod 2014.1 (Schlumberger) basin modeling, enabling thermal maturity reconstruction for vitrinite reflectance values of 0.3 to 4.7 % by the use of the EASY % R_{o}~~$_{\theta}$~~ approach (Sweeney and Burnham, 1990). The numerical basin model is based on a conceptional definition of events. Based on this sequence of events (sedimentation, erosion, hiatus) a forward, event-stepping modeling ~~is~~ was performed, starting with the deposition of the oldest layer. Subsequent deposition and burial is leading to differential compaction of the single rock units. For each event lithologies and related petrophysical rock properties ~~are~~ were assigned (Figures S1, S2). ~~The final basin model (representing the present day) fits the geometries deduced from seismic interpretation and geology. This is the first time that ophiolite obduction is reconstructed using a petroleum system modelling software such as PetroMod. To simulate obduction we used a rapid, stepwise laterally-advancing emplacement, i.e. sedimentation, of ophiolitic rocks. This is reasonable, as we will show that the ophiolite did not thermally overprint the passive margin sequence from above.~~

For our conceptual model the following sequence of events was implemented (Figure 3): (1) passive margin carbonate sedimentation from Permian until late Cenomanian times (Forbes et al., 2010; Loosveld et al., 1996), interrupted by a short erosional period at the Triassic-Jurassic boundary (Koehrer et al., 2010; Loosveld et al., 1996), (2) a moving forebulge associated with a paleo-water depth increase in its foredeep and erosion of the top of the carbonate platform in the north of the transect (Robertson, 1987), (3) the emplacement of allochthonous sedimentary nappes and (4) subsequent obduction, i.e. stepwise, rapid sedimentation, of the ophiolite with deepest burial reached at c. 79 Ma (Warren et al., 2005). The area of the Adam Foothills, represented in the transect by the Jebel Qusaybah, is a relic of the moving forebulge not overthrust by allochthonous units – this was used to calibrate burial depth of the foredeep at this point in the transect. The south of the foothills is unaffected by foredeep and obduction, but also lacks thermal calibration data. Absolute ages, thicknesses, lithologies and related petrophysical properties as well as source rock properties were associated according to results of our own field mapping and the compiled data from Forbes et al. (2010; Figure S1).

Thermal boundary conditions of the model have been defined for each time step by the basal heat flow (HF) and the sediment water interface temperature (SWIT), representing the upper thermal boundary (Figure S3). To account for active margin tectonics and uplift and exhumation of the Jebel Akhdar, we assume an increase in basal heat flow since the late Cretaceous. The resulting heat flow trend (Figure S3, Terken et al., 2001; Visser, 1991) has been assigned to the entire transect and was tested in the sensitivity analysis. Paleo-surface temperatures were estimated based on Oman's paleo-latitude (after Wygrala, 1989) corrected by the effect of the paleo-water depth (PWD) derived from the facies record (Van Buchem et al., 2002; Immenhauser et al., 1999; Immenhauser and Scott, 2002; Koehrer et al., 2010; Pratt et al., 1990; Robertson, 1987).

This set-up has been iterated until modeling results fit the thermal calibration data (Table 1). From VR_r calculations peak-burial temperatures were determined following the approach of Barker and Pawlewicz (1994). For calibration of the numerical basin models, data was supplemented by thermal maturity and peak-burial temperature data of 63 Natih B source rock samples, taken around the Jebel Akhdar Dome (Grobe et al., 2016), and two data points in the Adam Foothills on Jebel Qusaybah (Mozafari et al., 2015).

Main modelling uncertainties derive from the unknown thickness of paleo-overburden (Muti Fm., Ophiolite, Hawasina Nappes) and uncertainty of paleo-basal heat flow. Present-day heat flow was calibrated by data and borehole temperatures of Visser (1991) and Rolandone et al. (2013) and peak-burial temperatures determined by Raman spectroscopy and solid bitumen reflectance data (Table 1). From surface samples and their position in the stratigraphic column various pseudo-wells were created (e.g. Nöth et al., 2001) and used as control points for the 2D model (Figure 2). The model was used for sensitivity analyses of different input parameters.

4. Results and Interpretation

4.1. Thermal maturity and host rock burial temperatures

New Raman spectroscopy data of the northern flank give scaled total areas of 78-172. This correspond to peak temperatures of 270-300 °C in the Shu'aiba Fm., 268-305 °C in the Kahmah Group, 283-286 °C in the Sahtan Gp., 270-288 °C in the Nahr Umr Fm. and 266 °C at the base of the Natih Fm. Based on the calculation to VR_r and temperature an absolute error of ±30 °C has to be considered for the single values.

Table 1: Thermal maturity data and calculated peak temperatures of northern Oman (new data highlighted by bold sample name). Temperatures from Raman spectroscopy of carbonaceous material are calculated based on the STA approach of Lünsdorf (2016) and the ~~formula~~ equation ~~published by~~ of Grobe et. al (2016). M/P indicate if measurement was conducted on solid bitumen particles (P) or ~~below the surface of the~~ if organic rich matrix (M). Errors shown are related to the measurement, calculation errors are in the order of +/-30 °C. Data of Mozafari et al. (2015) are used for Jebel Qusaybah, Adam Foothills.

~~From Raman spectroscopy, integrated deformation peaks (D-peaks) give scaled total areas of 90-156 which correspond to peak-burial temperatures of 266 to 300 °C (Grobe et al., 2016; Table 1). The maximum temperatures increase with stratigraphic age and are similar on the northern and southern flanks of the Jebel Akhdar Dome (e.g. Natih Fm.). Nahr Umr and Shu'aiba Fm. show slightly higher peak temperatures in the north of the transect (Figure 3). Temperature estimates based on RSCM and solid bitumen reflectance (Grobe et al., 2016) yielded similar temperatures for the southern flank of 248-280 °C for the Nahr Umr, 226-239 °C for the Natih B and 172-206 °C for the Muti, respectively (Table 1, Figure 3). Vitrinite reflectance data of Mozafari et al. (2015) shows temperatures of c. 145-182 °C for Natih B in the Jebel Qusaybah, Adam Foothills, an area not overthrust by the ophiolite complex.~~

sample No.		location (UTM 40Q)					No. of measurements	mean D_STA	calculated VR_r [%]	mean Temp.
15_995	northern flank	Wadi Yiqah	516683	2582911	Sahtan Gp.	M	14	113 +/- 14	6.52	286 +/- 6 °C
15_997		Wadi Yiqah	517815	2583645	Shu'aiba Fm.	M	10	115 +/- 5	6.69	289 +/- 3 °C
15_1001		Wadi Taisa	516538	2584640	Kahmah Gp.	M	1	78	8.19	305 °C
15_1003		Wadi Taisa	516538	2584640	Kahmah Gp.	M	8	96 +/- 9	7.44	297 +/- 4 °C
15_1008		Wadi Taisa	516562	2584727	Kahmah Gp. (top)	M	8	113 +/- 15	6.78	290 +/- 7 °C
15_1010		Wadi Taisa	516693	2584882	Shu'aiba Fm.	M	13	98 +/- 11	7.28	295 +/- 5 °C
15_1010		Wadi Taisa	516693	2584882	Shu'aiba Fm.	P	4	149 +/- 15	5.31	270 +/- 9 °C
16_974		Tr- Jur fault	515839	2582229	base Sahtan Gp.	P	6	125 +/- 17	6.29	283 +/- 9 °C
16_977		Kharb Plateau	520420	2577490	base Natih Fm.	M	10	156 +/- 9	5.04	266 +/- 6 °C
16_979		Kharb Plateau	519305	2577363	top Nahr Umr Fm.	M	2	117 +/- 4	6.60	288 +/- 2 °C
16_981		Kharb Plateau	519933	2577201	top Nahr Umr Fm.	M	1	149	5.30	270 °C
16_984		Wadi Taisa	518069	2583462	Kahmah Gp.	M	3	172 +/- 26	5.29	268 +/- 22 °C
16_985		Wadi Murri	505508	2592709	Shu'aiba Fm.	M	2	90 +/- 4	7.69	300 +/- 2 °C
Grobe et al. (2016)_SV10	southern flank	Wadi Nakhr	521260	2560364	Natih	P	6	-	2.83	227-231 °C
Grobe et al. (2016)_AG22		Wadi Nakhr	521255	2560362	Natih	M	4	-	3.72	225-260 °C
Grobe et al. (2016)_AG01		Wadi Nakhr	520375	2562026	Shu'aiba (Kh 3)	M	4	-	4.49	251-269 °C
Grobe et al. (2016)_AG11		Sint	505627	2564136	Hawasina	P	5	-	2.45	193-213 °C
Grobe et al. (2016)_AG25		Balcony Walk Nakhr	520913	2565658	Nahr Umr	M	4	-	4.23	226-267 °C
Grobe et al. (2016)_AG26_1		Balcony Walk Nakhr	521052	2565560	Nahr Umr	P	2	-	(2.58)	(211-213 °C)
Grobe et al. (2016)_AG26_3		Balcony Walk Nakhr	521052	2565560	Nahr Umr	M	2	-	4.96	275-280 °C
Grobe et al. (2016)_AG27		Balcony Walk Nakhr	520879	2565342	Nahr Umr	M	3	-	4.61	248-266 °C
Grobe et al. (2016)_AG30		Balcony Walk Nakhr	520756	2565030	Nahr Umr	M	3	-	4.25	248-257 °C
Grobe et al. (2016)_AG37		Jebel Shams	514821	2568047	Muti	P	3	-	2.16	191-208 °C
Grobe et al. (2016)_AG38		Jebel Shams	514930	2567334	Muti	P	2	-	1.99	172-206 °C
reference		location (UTM 40Q)					No. of measured particles	measured BR_r [%]	calculated / measured VR_r [%]	calculated T_{burial} (Barker and Pawlewicz, 1994)
Grobe et al. (2016)	south. fl.	Wadi Nakhr area	521216	2560308	Natih B	BR_r	253	3.08-3.59	3.08-3.59	226-239 °C
Fink et al. (2015)		Wadi Nakhr area	518550	2561000	Natih B	BR_r	200	3.10-3.14	-	c. 225 °C
Fink et al. (2015)		Wadi Nakhr area	514800	2565950	Natih A Vein	BR_r	c. 250	3.40-3.76	-	-
Grobe et al. (2016)		Al Hamra area	531024	2557020	Natih B	BR_r	20	2.95-3.34	2.95-3.34	223-233 °C
Grobe et al. (2016)	N	Wadi Sahtan	531010	2585640	Natih B	BR_r	6	3.32	3.32	232 °C
Mozafari et al. (2015), measured at RWTH		Jebel Qusaybah	507930	2491600	Natih B	VR_r	20		1.1	c. 140 °C

4.2. Thermochronology

Results of the ZHe dating are shown in Figures 3 and 4; time-temperature paths modeled with HeFTy are included in the electronic supplement (Figures S4 and S5). Samples from the carbonate platform (stratigraphically older than Muti Fm.) have been entirely reset after deposition, as witnessed by Neogene apparent ages ~~(Figure 3)~~. ~~This~~ Similarly, cooling ages from ~~coincides with~~ the center of the Jebel Akhdar Dome ~~in which all cooling ages~~ fall in the range of 48.7 ± 1.8 to 39.8 ± 3.0 Ma (Table 2, Figure 4). Sample T4, collected in the Muti Fm., yields an apparent mean age of 93.8 ± 6.9 Ma and samples T5 and T7 of the Hawasina Nappes collected at the northern and the southern slope of the dome, show two grain age ~~populations~~ clusters of 43.0 ± 3.7 / 99.2 ± 8.5 Ma, and 58.9 ± 7.0 / 106.0 ± 5.2 Ma, respectively. In sample T5, an additional single grain age ~~population~~ of 172.9 ± 14.9 Ma was obtained.

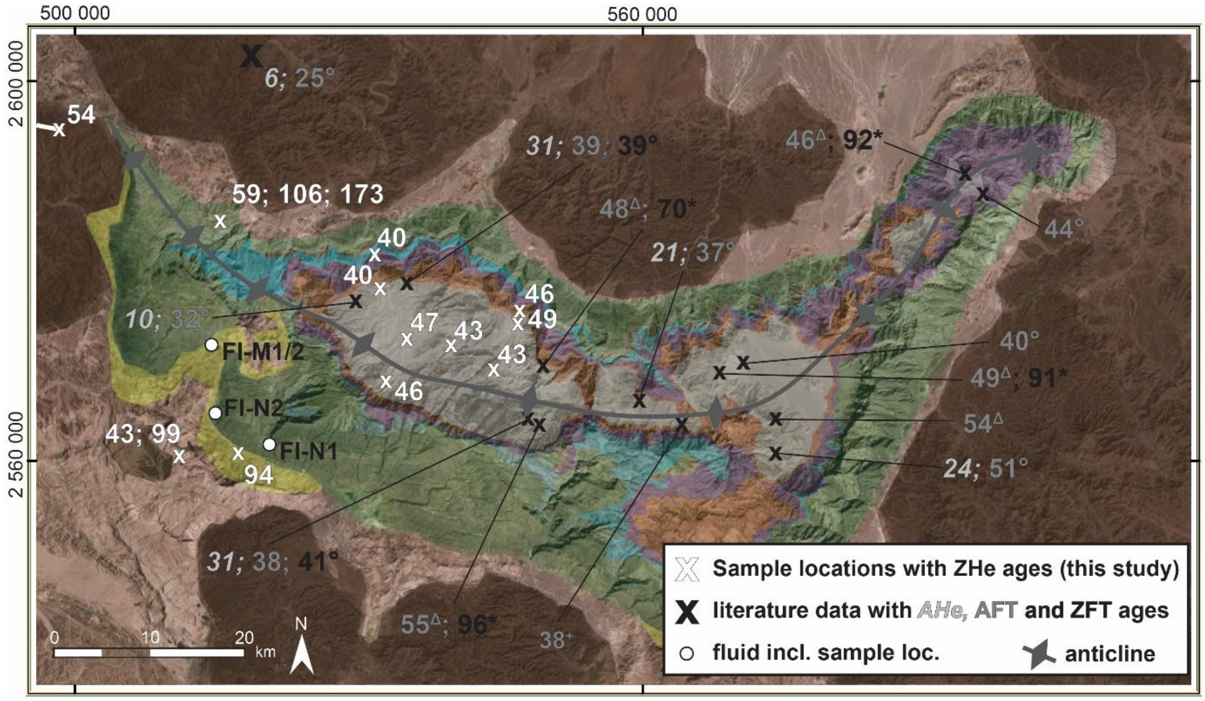

Figure 4: Map view of ZHe ages (in Ma) ~~sampled below, in and above the carbonate platform of the Jebel Akhdar Dome~~. Data outlines a general cooling between 58.9 ± 7.0 and 39.8 ± 3.0 Ma. Some samples outside of the dome show two age ~~populations~~clusters, with an additional age ~~population~~ of c. 100 Ma. Additional temperature data refers to zircon fission track ages of (*) Saddiqi et al. (2006), Apatite fission track ages of (Δ) Poupeau et al. (1998) and (+) Mount et al. (1998), and AHe, AFT and ZFT ages of (+, grey) Hansmann et al. (2017). Moreover, the locations of samples used for fluid inclusion measurements are shown. Colors in the background depict geological units (brown: ophiolite, pink: Hawasina units, light green: Muti Fm., dark green: Wasia and Kahmah Gp., blue: Sahtan Gp., purple: Mahil Fm, orange: Saiq Fm, grey: pre-Permian, shaded DEM from Esri, Digital Globe, swisstopo, and the GIS user Community).

Table 2: Results of zircon (U-Th)/He dating.

sample	lithology / location		He		^{238}U			^{232}Th			Th/U	Sm			ejection	uncorr ected	FT corrected			mean age [Ma]		
aliquot	Easting	Northing	vol. [ncc]	1 σ [%]	mass [ng]	1 σ [%]	conc. [ppm]	mass [ng]	1 σ [%]	conc. [ppm]	ratio	mass [ng]	1 σ [%]	conc. [ppm]	correct. (Ft)	He age [Ma]	He age [Ma]	2σ [%]	2σ [Ma]			
T1-Z1	sandstone		5.31	0.83	1.04	1.81	212.00	0.38	2.41	77.66	0.37	0.03	10.43	6.44	0.754	38.90	**51.60**	8.20	4.20	**48.70**	**+/-**	**1.80**
T1-Z2	547533	2574875	6.05	0.84	1.31	1.81	323.34	0.33	2.41	80.49	0.25	0.01	21.24	2.97	0.737	36.10	**49.10**	8.70	4.30			
T1-Z3	Fara Fm.	Autochthon A	3.45	0.87	0.84	1.81	212.21	0.30	2.41	74.73	0.35	0.02	14.08	3.83	0.719	31.30	**43.60**	9.20	4.00			
T1-Z4			3.15	0.86	0.64	1.82	178.10	0.34	2.41	95.86	0.54	0.01	15.61	4.16	0.72	36.30	**50.50**	9.10	4.60			
T2-Z1	tuffite		9.23	0.83	2.04	1.81	352.85	1.03	2.41	178.16	0.50	0.04	9.53	7.26	0.778	33.40	**42.90**	7.60	3.20	**46.10**	**+/-**	**2.00**
T2-Z2	547533	2574875	8.58	0.83	1.99	1.81	376.54	0.88	2.41	166.07	0.44	0.07	7.63	14.20	0.757	32.30	**42.70**	8.10	3.50			
T2-Z3	Fara Fm.	Autochthon A	12.48	0.83	2.32	1.81	377.81	1.01	2.41	163.95	0.43	0.03	11.07	5.44	0.789	40.20	**51.00**	7.30	3.70			
T2-Z4			6.16	0.83	1.26	1.81	186.92	0.52	2.41	76.65	0.41	0.03	10.98	4.83	0.768	36.80	**48.00**	7.80	3.80			
T3-Z1	sandstone		3.69	0.86	1.04	1.81	361.71	0.41	2.41	142.73	0.39	0.02	15.90	6.29	0.689	26.90	**39.10**	10.00	3.90	**42.60**	**+/-**	**1.70**
T3-Z2	544722	2570255	2.82	0.88	0.63	1.82	254.57	0.22	2.42	87.47	0.34	0.02	12.85	9.07	0.694	34.20	**49.40**	9.90	4.90			
T3-Z3	Muaydin Fm.	Autochthon A	1.54	0.90	0.35	1.85	116.01	0.23	2.42	75.70	0.65	0.02	17.64	5.19	0.67	31.80	**47.50**	10.50	5.00			
T3-Z4			4.71	0.84	1.20	1.81	309.13	0.70	2.41	180.18	0.58	0.05	9.18	12.12	0.74	28.50	**38.50**	8.60	3.30			
T3-Z5			8.91	0.83	1.95	1.81	262.57	1.30	2.41	175.08	0.67	0.07	9.00	9.29	0.761	32.60	**42.90**	8.00	3.40			
T3-Z6			9.80	0.83	2.52	1.81	283.31	1.13	2.41	127.16	0.45	0.06	7.80	6.56	0.816	29.00	**35.60**	6.60	2.30			
T3-Z7			11.83	0.83	2.41	1.81	219.27	1.23	2.41	111.66	0.51	0.11	7.31	10.01	0.794	36.10	**45.50**	7.10	3.20			
T3-Z8			8.41	0.83	1.85	1.81	224.86	1.04	2.41	125.92	0.56	0.07	9.09	8.40	0.784	33.10	**42.20**	7.40	3.10			
T4-Z1	conglomerate		18.23	0.83	1.79	1.81	380.98	0.44	2.41	93.57	0.25	0.02	13.79	3.77	0.736	79.30	**107.60**	8.70	9.40	**93.80**	**+/-**	**6.90**
T4-Z2	517510	2560808	10.68	0.83	1.36	1.81	392.55	0.35	2.41	100.65	0.26	0.02	15.99	5.30	0.703	61.20	**86.90**	9.60	8.40			
T4-Z3	Muti Fm.	Autochthon B	5.24	0.85	0.56	1.82	137.78	0.48	2.41	118.23	0.86	0.04	8.48	11.06	0.738	64.20	**86.90**	8.60	7.50			
T5-Z1	turbiditic sandstone		34.15	0.82	3.38	1.81	502.17	0.79	2.41	117.95	0.23	0.10	7.97	14.16	0.781	78.70	**100.80**	7.50	7.60	**106.00**	**+/-**	**5.20**
T5-Z2	512934	2561691	13.52	0.83	1.28	1.81	333.42	0.27	2.41	69.42	0.21	0.02	16.57	4.11	0.744	82.70	**111.20**	8.50	9.50			
T5-Z3	Matbat Fm.	Hawasina N.	8.95	0.83	1.30	1.81	254.43	0.78	2.41	153.35	0.60	0.01	16.47	2.78	0.754	49.70	**65.90**	8.20	5.40	**58.90**	**+/-**	**7.00**
T5-Z4			9.21	0.84	1.75	1.81	416.93	0.69	2.41	163.29	0.39	0.04	9.44	9.25	0.766	39.80	**51.90**	7.90	4.10			
T5-Z5			37.88	0.80	51.13	2.33	1.81	561.72	0.37	2.41	90.14	0.16	0.02	11.59	0.741	128.10	**172.90**	8.60	14.90			
T6-Z1	granodiorite		6.55	0.83	1.00	1.81	241.80	1.28	2.41	311.91	1.29	0.29	5.62	69.36	0.747	41.60	**55.60**	8.30	4.60	**53.70**	**+/-**	**1.20**
T6-Z2	478301	2592360	6.39	0.85	0.97	1.81	288.96	1.32	2.41	394.16	1.36	0.28	5.31	84.38	0.719	41.10	**57.20**	9.10	5.20			
T6-Z3	Trondjemite	Semail Ophio.	7.07	0.83	1.06	1.81	314.75	1.79	2.41	528.55	1.68	0.19	5.49	57.19	0.751	39.20	**52.30**	8.20	4.30			
T6-Z4			12.11	0.84	1.79	1.81	347.26	3.35	2.41	649.55	1.87	0.31	5.55	61.00	0.769	38.60	**50.20**	7.70	3.80			
T6-Z5			6.78	0.84	1.08	1.81	273.36	1.46	2.41	368.85	1.35	0.27	5.75	68.70	0.738	39.10	**53.00**	8.60	4.50			
T7-Z1	quarzite		14.91	0.84	1.56	1.81	427.30	0.43	2.41	118.20	0.28	0.05	9.26	12.45	0.744	73.80	**99.20**	8.50	8.50	**99.20**		
T7-Z2	514817	2586049	4.14	0.87	1.35	1.81	428.75	0.38	2.41	119.50	0.28	0.02	12.47	7.90	0.729	23.70	**32.50**	8.90	2.90	**43.00**	**+/-**	**3.70**
T7-Z3	Matbat Fm.	Hawasina N.	6.37	0.85	1.33	1.81	274.36	0.30	2.41	62.67	0.23	0.03	10.62	6.71	0.769	37.50	**48.80**	7.90	3.80			
T7-Z4			9.66	0.81	12.43	2.13	1.81	539.06	0.15	2.45	38.38	0.07	0.01	17.24	0.777	36.90	**47.50**	7.70	3.70			
T7-Z5			4.03	0.83	5.46	0.94	1.81	232.12	0.47	2.41	115.05	0.50	0.02	12.63	0.738	31.70	**43.00**	8.60	3.70			
T8-Z1	tuffitic sandstone		4.60	0.86	1.34	1.81	450.89	1.11	2.41	374.66	0.83	0.16	5.81	53.52	0.759	23.70	**31.20**	8.00	2.50	**39.80**	**+/-**	**3.00**
T8-Z2	532600	2578681	2.92	0.85	0.56	1.82	147.09	0.86	2.41	226.75	1.54	0.28	5.14	73.06	0.715	31.40	**44.00**	9.20	4.00			
T8-Z3	Mistal Fm.	Autochthon A	2.21	0.89	0.46	1.83	168.48	0.57	2.41	208.48	1.24	0.05	8.65	16.66	0.716	30.90	**43.20**	9.20	4.00			
T8-Z4			3.46	0.85	0.85	1.81	212.57	0.41	2.41	103.10	0.49	0.01	14.27	3.65	0.74	30.30	**41.00**	8.60	3.50			
T9-Z1	quarzite		2.90	0.86	0.61	1.82	238.35	0.50	2.41	198.12	0.83	0.01	16.09	5.23	0.705	33.10	**46.90**	9.50	4.50	**45.50**	**+/-**	**2.40**
T9-Z2	532595	2568258	0.72	0.98	0.18	1.94	109.52	0.13	2.43	76.58	0.70	0.05	10.52	29.38	0.674	27.50	**40.80**	10.50	4.30			
T9-Z3	Mistal Fm.	Autochthon A	2.04	0.89	0.41	1.84	147.39	0.28	2.41	101.51	0.69	0.01	18.70	3.60	0.718	35.10	**48.80**	9.20	4.50			
T10-Z1	sandstone		5.09	0.85	0.93	1.81	213.39	0.95	2.41	217.83	1.02	0.02	13.41	4.93	0.754	36.40	**48.20**	8.10	3.90	**46.90**	**+/-**	**4.10**
T10-Z2	534779	2572636	6.71	0.83	1.37	1.81	267.61	1.24	2.41	241.07	0.90	0.04	9.18	8.32	0.763	33.30	**43.70**	7.90	3.40			
T10-Z3	Mistal Fm.	Autochthon A	8.97	0.83	2.25	1.81	568.33	1.79	2.41	452.52	0.80	0.04	8.74	10.22	0.723	27.70	**38.40**	9.00	3.50			
T10-Z4			2.26	0.88	0.35	1.85	118.10	0.39	2.41	131.18	1.11	0.02	14.08	5.39	0.727	41.80	**57.50**	8.90	5.10			
T11-Z1	quarzite		4.70	0.84	1.01	1.81	188.02	0.57	2.41	106.02	0.56	0.01	19.39	2.18	0.746	34.00	**45.60**	8.40	3.80	**42.50**	**+/-**	**2.00**
T11-Z2	540394	2572230	1.55	0.90	0.39	1.84	109.55	0.33	2.41	93.99	0.86	0.01	20.85	2.31	0.706	27.30	**38.80**	17.60	6.80			
T11-Z3	Mistal Fm.	Autochthon A	1.50	0.94	0.37	1.84	110.19	0.19	2.42	56.69	0.51	0.01	17.25	3.39	0.693	29.90	**43.20**	9.90	4.30			
T12-Z1	sandstone		5.35	0.85	1.21	1.81	355.93	1.09	2.41	320.43	0.90	0.02	16.47	5.58	0.706	30.10	**42.70**	9.50	4.00	**40.10**	**+/-**	**1.50**
T12-Z2	531776	2582871	4.28	0.86	1.12	1.81	286.68	0.16	2.42	40.59	0.14	0.01	27.93	1.79	0.736	30.70	**41.70**	8.80	3.70			
T12-Z3	Sahtan Gp.	Autochthon B	3.80	0.86	1.06	1.81	349.54	0.14	2.43	44.41	0.13	0.01	22.03	2.70	0.719	28.70	**39.90**	9.20	3.70			
T12-Z4			1.51	0.89	0.38	1.84	92.50	0.32	2.41	76.60	0.83	0.01	15.61	3.53	0.758	27.30	**36.10**	8.10	2.90			

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These ages indicate a large-scale cooling signal that affects the entire ~~study~~Jebel Akhdar area~~ area and is associated with doming; ~~. ~~T~~the ZHe age pattern and 1D thermal models ~~(Figures S3 and S4) ~~indicate a phase of rapid cooling below 170 °C in the early Cenozoic (58.9 ± 7.0 and 39.8 ± 3.0 Ma). The range of modeled cooling paths outline ~~minimum and ~~maximum cooling rates of 2-8 °C/Myr. This is followed by slower cooling until the present day.

Data from the Muti Fm. and the Hawasina units differ partly from this trend: the apparent ZHe ages of clast in the Muti sample T4 (mean: 93.8 ± 6.9 Ma) is as old as its respective stratigraphic age (Robertson, 1987)~~ indicating only partial reset of the ZHe system~~. Even though all ages reproduce within error, this indicates partial reset of the ZHe system, as post-depositional reheating above closure temperature would result in younger ages. Samples of the lower Hawasina Nappes contain two grain age ~~populations~~clusters. Older ages coincide with higher uranium concentrations suggesting that only the younger ages represent thermally reset zircons. ~~Even thought, T~~t~~he~~We note that the older ZHe ~~population ~~ages of 110-95 Ma coincide~~s~~ with timing of forebulge migration through the area, as independently determined in the stratigraphic record ~~in ~~by the Wasia-Aruma Break (Figure 3). This may be either pure coincidence, due to partial resetting of an older grain age population, or may be a grain age population with higher closure temperature witnessing exhumation. We discuss reasons for different resetting temperatures below. However, ~~P~~partial reset of ZHe ages suggests that the Hawasina samples have not experienced temperatures exceeding the partial retention zone (PRZ) of 13~~5~~0-170 °C.

A ~~magmatic ~~sample ~~of ~~from an intrusive body of~~from ~~the Semail Ophiolite yields ZHe ages of 53.7 ± 1.2 Ma (T6) with a modeled cooling path gradually decreasing into the PRZ until c. 55 Ma. This time interval of passing the PRZ is comparable to the Hawasina nappe samples beneath the ophiolite but occurs slightly earlier than cooling of the Autochthonous. Nevertheless, Semail Ophiolite, Hawasina Nappes and the autochthonous margin sequence were affected by the same cooling event that was possibly initiated by exhumation of the Jebel Akhdar Dome.

4.3. Fluid inclusions

The Muti veins' samples FI-M1 and M2 of the southern Jebel Akhdar show evidence of crack and seal processes (youngest parts in the center of the vein, Ma-2010-11b and 14a of Arndt 2015) with blocky quartz grains that contain two kinds of roundish primary FIs with sizes of 3-20 µm. They are mainly aligned along dark zones and are interpreted as growth zones or form bright clusters in the central part of the crystals. A third set of fluid inclusions (FIs) appears in large, grain-crosscutting trails interpreted to be of secondary origin. Calcite crystals within the Natih veins contain bright FIs with sizes of 2-20 µm and are edgy, often rectangular or trapezoidal in shape. Identified primary FIs are aligned parallel to crystal growth zones.

All measured FIs are two-phase, liquid-vapor inclusions with ice as last phase to melt. The Muti samples show $T_{fm(ice)}$ between -5.1 ± 0.5 and -4.6 ± 0.3 °C and $T_{m(ice)}$ at -2.2 ± 0.2 to -1.9 ± 0.1 °C, the Natih sample T_{fm} of -18.4 ± 1.9 to -20.2 ± 2.1 °C and $T_{m(ice)}$ of -7.1 ± 0.3 to -8.9 ± 1.8 °C (Table 3). First melting temperatures of all inclusions correspond to an H_2O-NaCl system and complete melting temperatures of ice indicate salinities similar to seawater (3.0 ± 0.5 to 3.5 ± 0.3 wt.-% NaCl eq., Muti Fm., Figure S6) or three times higher (10.3 ± 0.3 to 12.5 ± 2.0 wt.-% NaCl eq., Natih Fm., Figure S6).

Table 3: Results of FI microthermometry. Identified FI types, their measured homogenization temperatures and results of the pressure correction for 280 and 340 MPa accounting for 8 and 10 km of ophiolite with partly serpentinized mantle sequence and 2 km of sedimentary nappes, and for 45 MPa accounting for 2 km of sedimentary overburden for samples unaffected by ophiolite obduction. First melting (T_{fm}) and final melting of ice ($T_{m\ ice}$) temperatures and salinities are given. Data by Holland et al. (2009) are added for comparison and we likewise corrected their homogenization temperatures~~Data of Holland et al. (2009) is added for comparison and we likewise corrected his homogenization~~

~~temperatures for pressures of 280 and 340 MPa, as his samples were originally covered by the ophiolite complex~~. **(* further heating was avoided to prevent fluid inclusion damage)**

sample No.	vein orient., location and host mineral	FI kind	No. of FIA	T_h [°C]	pressure corrected T [°C] for 45 MPa		T_{fm} [°C]	$T_{m\ ice}$ [°C]	salinity [wt.-% NaCl]
FI-M1	NE-SW striking	primary	21	166 +/- 7	189 +/- 7		-4.7 +/- 0.2	-2.2 +/- 0.2	3.5 +/- 0.3
	strike-slip vein (IX), Muti Fm.	primary	22	189 +/- 3	213 +/- 3		-4.6 +/- 0.3	-2.0 +/- 0.3	3.2 +/- 0.4
	Gorge area, quartz	secondary	18	> 200*	> 224		-4.6 +/- 0.2	-2.0 +/- 0	3.2 +/- 0
					pressure corrected T [°C] for 45 MPa				
FI-M2	NE-SW striking	primary	24	161 +/- 3	184 +/- 3		-5.1 +/- 0.5	-1.9 +/- 0.1	3.0 +/- 0.2
	strike-slip vein (IX), Muti Fm.	secondary	12	116 +/- 12	138 +/- 12		-	-	-
	Gorge area, quartz	secondary	24	150 +/- 2	172 +/- 2		-	-	-
					for 280 MPa	for 340 MPa			
FI-N1	Natih Fm., NW-SE	primary	14	90 +/- 5	235 +/- 5	266 +/- 5	-18.4 +/- 1.9	-7.1 +/- 0.3	10.3 +/- 0.3
	burial vein (III), Wadi Nakhr, calcite	primary	26	(114 +/- 7)	(264 +/- 7)	(297 +/- 7)	-20.2 +/- 2.1	-8.9 +/- 1.8	12.5 +/- 2.0
FI-N2	Natih Fm., early E-W vein (I) Al Raheba, calcite	primary	10	80 +/- 4	225 +/- 4	256 +/- 4	-	-	-
					for 280 MPa	for 340 MPa			
Holland et al. (2009)	Sahtan Gp., bedding parallel shear vein, top-to-NE (IV), Wadi Nakhr, quartz	primary and pseudosec.	n.a.	134-141	296-303	357-364	from -19	-3.7 to -2.3	3.8 to 6.0

Primary inclusions in quartz crystals from the Muti Fm. show minimum trapping temperatures of 161 ± 3 to 166 ± 7 °C (Table 3, FI-M2 and middle of FI-M1) with a second primary population of 189 ± 3 °C (sides of vein FI-M1). T_h of secondary inclusions in FI-M1 are above 200 °C. In sample FI-M2, two generations of secondary inclusions were observed, both reflecting lower T_h than the primary inclusions. No hints of necking down, leakage or stretching were observed at the measured inclusions and over 90 % of the measured FIs in one assemblage are in the range of 10-15 °C representing a good quality of the measurements (Goldstein, 2001).

Samples FI-N1 and N2 of the Natih Fm. in the southern Jebel Akhdar (Figure 4) contain primary inclusions hosted by calcite crystals giving T_h of 80 ± 4, 90 ± 5 and 114 ± 7 °C (Table 3). The latter population is often characterized by elongated, possibly stretched FI, and is not considered for further interpretations. Assuming vein formation during burial (Grobe et al., 2018; Hilgers et al., 2006; Holland et al., 2009; Virgo, 2015) under 8 to 10 km of ophiolite including partially serpentinized peridotite and 2 km of Hawasina Nappes, results were pressure corrected for 280 and 340 MPa leading to corrected homogenization temperatures of 235 ± 5 and 266 ± 5 °C (FI-N1), and 225 ± 4 and 256 ± 4 °C (FI-N2, Table 3). Signs of strong deformation such as twinning or cleavage were not observed in the measured inclusions; secondary inclusions were present but not measured.

These temperatures represent minimum trapping conditions of a paleo-fluid and do not necessarily represent burial temperatures of the host rock. It should be noted that the analyzed Natih veins formed bedding confined (Grobe et al., 2018; Holland et al., 2009; Virgo, 2015) and show host rock buffered carbonate isotope signatures (Arndt et al., 2014; Hilgers et al., 2006). This corroborates the idea that analyzed veins were in thermal equilibrium with their host rocks.

FI microthermometry of late strike-slip veins in the Muti Fm. are interpreted to have formed after dome formation (Grobe et al., 2018; Virgo, 2015) at an assumed minimum depth of 2 km (preserved allochthonous thickness). A pressure correction for the related 45 MPa corresponds to minimum fluid trapping temperatures of 184 ± 3 °C (FI-M2) and 213 ± 3 °C (FI-M1) with a later phase of primary inclusions outlining 189 ± 7 °C and even cooler secondary inclusions of 138 ± 12 to 172 ± 2 °C (FI-M1 and M2, Table 3). These cooler fluid temperatures can be explained by further exhumation of the Jebel Akhdar and, hence, cooling of the fluids' reservoir during crack-seal vein formation. Isotope studies on the vein calcite do not support an open system with fluid exchange (Stenhouse, 2014; Virgo and Arndt, 2010), hence, we interpret the formation of strike-slip related veins as having formed during exhumation following peak burial.

Based on the assumption that fluid and host rock were in thermal equilibrium, we can use maturity data in combination with fluid inclusion data to estimate the pressure at vein formation. Peak temperatures of the Sahtan ~~Fm~~Group~~.~~ revealed by RSCM reached 283 ± 9 to 286 ± 6 °C (Table 1, Figure 5 red line) and enable to solve the pressure-temperature couples of FIs measured in Sahtan veins formed at deepest burial by Holland et al. (2009, black line). This results in minimum trapping pressures of 254 ± 30 MPa at times of vein formation (Figure 5 blue line), which correspond to times close to or at deepest burial of the carbonate platform.

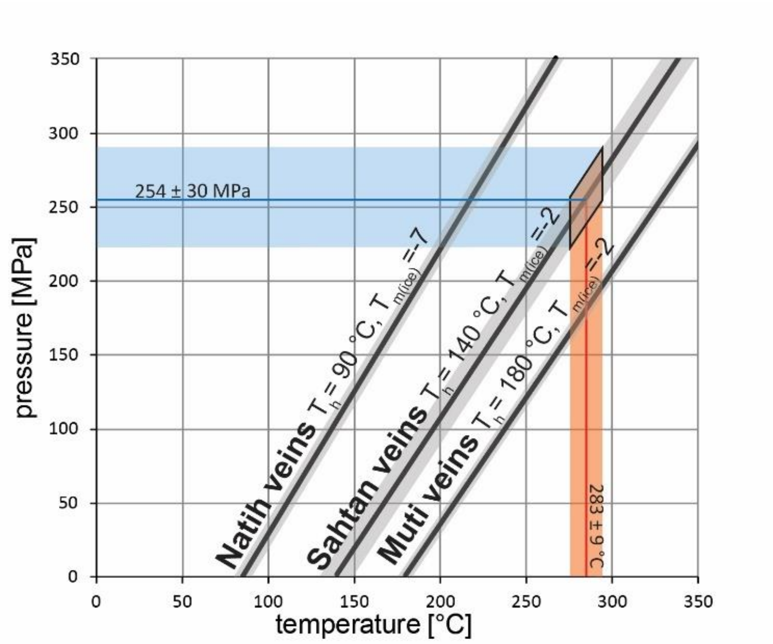

Figure 5: Fluid inclusion isochores (solid black lines) of analyzed fluid inclusion populations with corresponding std. deviations (shaded areas, for Sahtan ~~Gp.~~ Group data of Holland et al., 2009, conservatively ± 10°C are assumed). To estimate the pressure conditions during vein formation, calculated temperatures from thermal maturity data are added for the Sahtan ~~Gp.~~ Group (red line with error) and result in minimum trapping pressures of 254 ± 30 MPa during peak burial (blue line with error).

~~**4.4. Structural observations**~~

~~**The reconstructed transect (Figure 2) shows the dome structure of the Jebel Akhdar covered with ophiolite nappe remnants in the northeast, the thrusted southern foreland and the salt basins in the southeast that contain the fault-bound hydrocarbon reservoirs of the Fahud and Natih fields. Structures shown are related to large scale normal faulting in the mountain area, where faults are subsequently rotated and bent by doming (Jebel Akhdar), and later strike-slip faulting crosscut domed layers (Gomez-Rivas et al., 2014;**~~

~~Grobe et al., 2018; Virgo, 2015). Reactivation and inversion of some of the strike-slip faults caused formation of hydrocarbon traps in the southern foreland (Natih and Fahud field, e.g. Al-Kindi and Richard, 2014).~~

~~4.5.~~4.4. Basin modeling

Numerical basin modeling integrates all data and tests the individual interpretations in the thermal and geodynamic framework. Deepest burial was constrained with thermal maturity data and exhumation with thermochronological data. In the following we present our best fit model, considering a mixed ophiolite lithology (Searle and Cox, 2002) consisting of strongly serpentinized peridotites. Then, the sensitivity of important results to changes of relevant input parameters are discussed.

Modeled evolution of the transect over time is given in Figures ~~8~~ 6 and ~~9~~7, showing (a) final deposition of the Autochthonous B, (b) erosion of the Natih Fm. in the North by a moving foredeep (no erosion in S, full erosion in N), (c) emplacement of 1400 –m of Hawasina Nappes, and d-e) ophiolite obduction reconstructed by rapid, stepwise sedimentation. After maximum burial beneath the ophiolite complex at c. 80 Ma (Warren et al., 2005) exhumation is assumed to start slightly prior to 55 Ma (Saddiqi et al., 2006) with a rapid phase of cooling below c. 200 °C at 55 Ma leading to lower temperatures in the Jebel Akhdar region. 1D burial plots of two pseudo-wells created out of point data in Wadi Nakhr and Wadi Yiqah are shown in Figure 8.

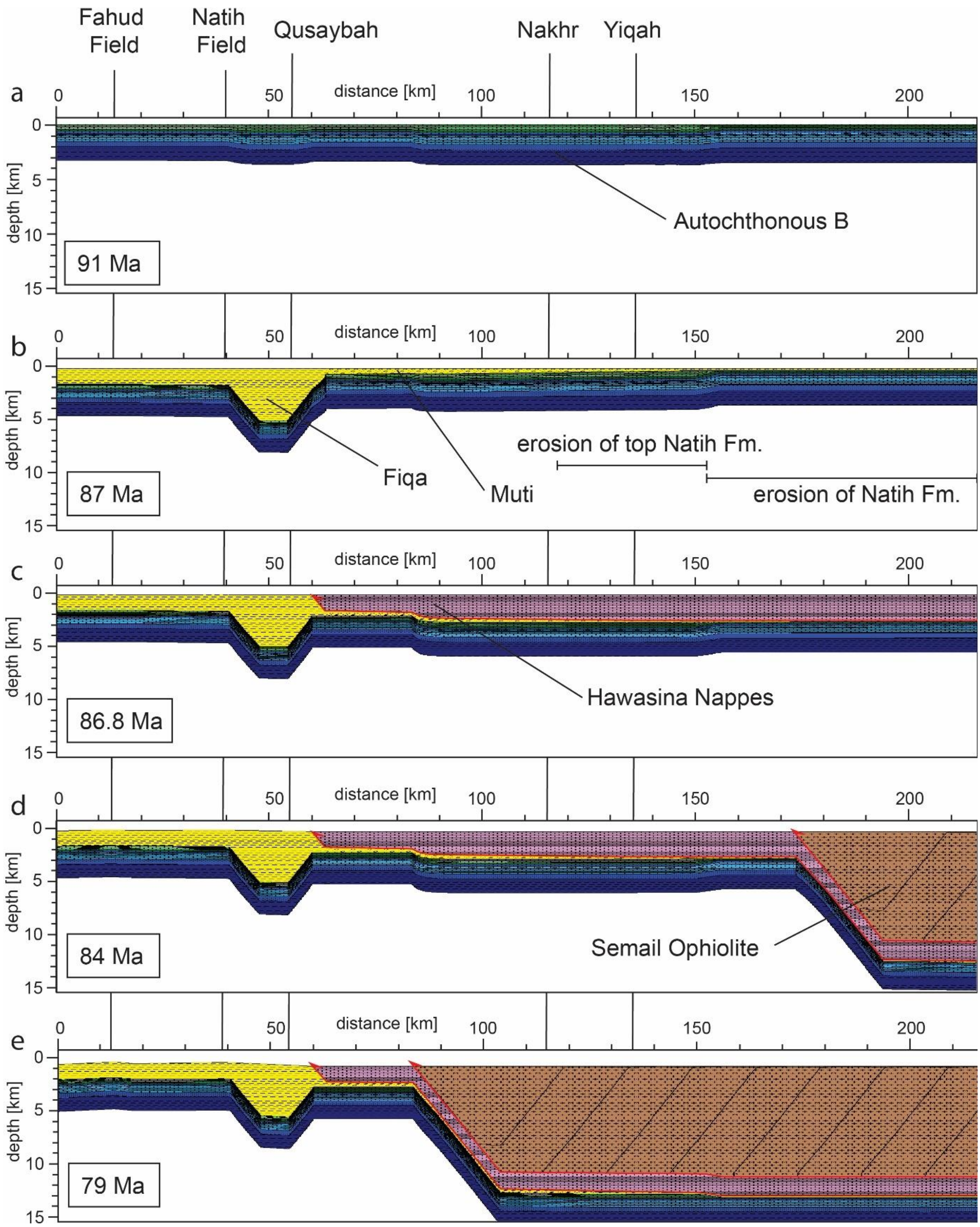

Figure 6: Modeling results: Transect evolution from sedimentation of the Autochthonous B at stable passive margin conditions (a), to moving foredeep that finally filled with Fiqa sediments (b, peak burial as calibrated by thermal maturity data), Hawasina Nappe (c) and ophiolite emplacement (d) leading to deepest burial (e). Highlighted with vertical lines in the background are the locations of present-day oil fields and sampled valley locations~~sing sites~~.

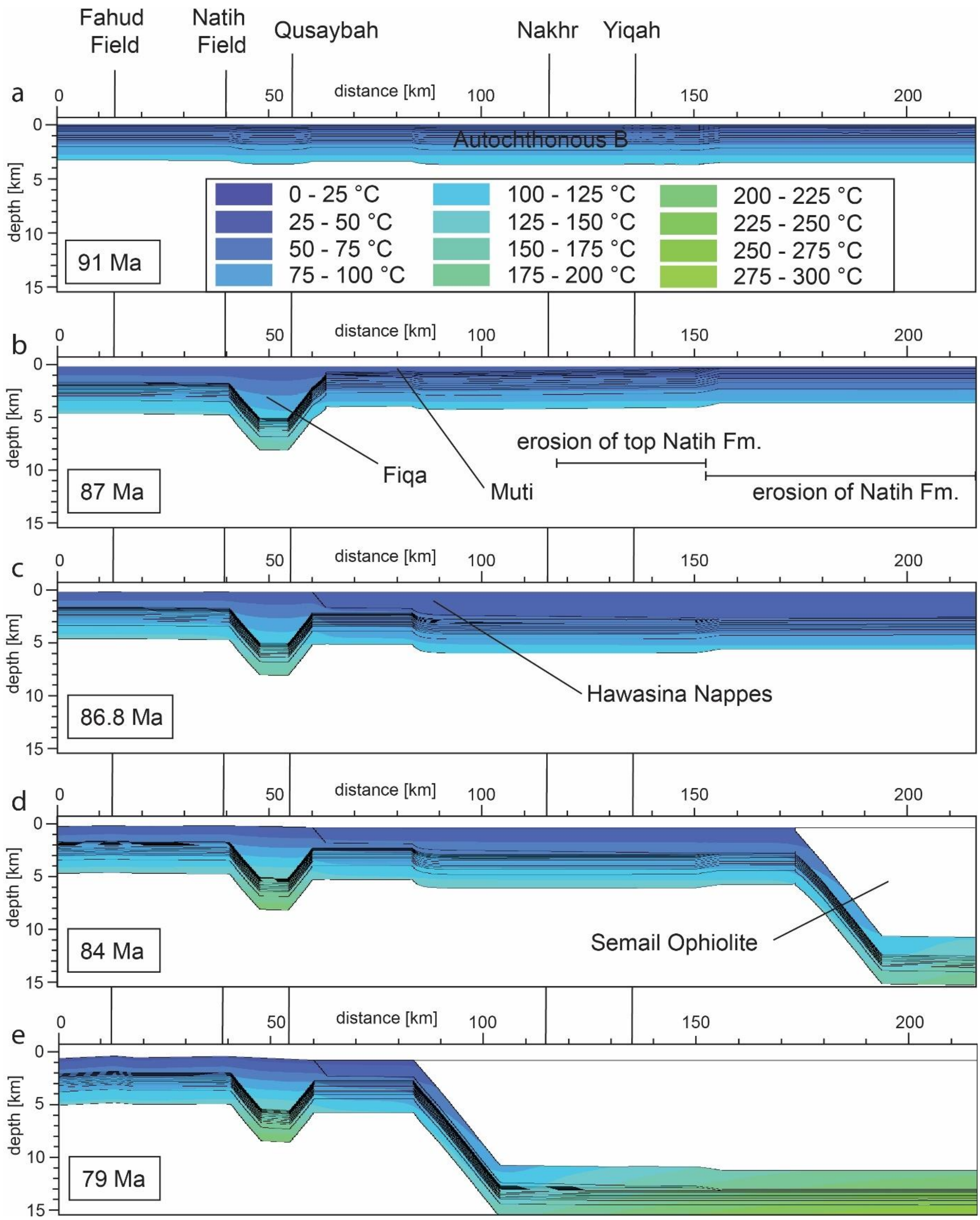

Figure 7: Modeling results: Temperature distribution and temporal evolution alongof the transect of Figure 6. Highlighted with vertical lines in the background are the locations of present-day oil fields and and sampled valley locationsssampling sites.

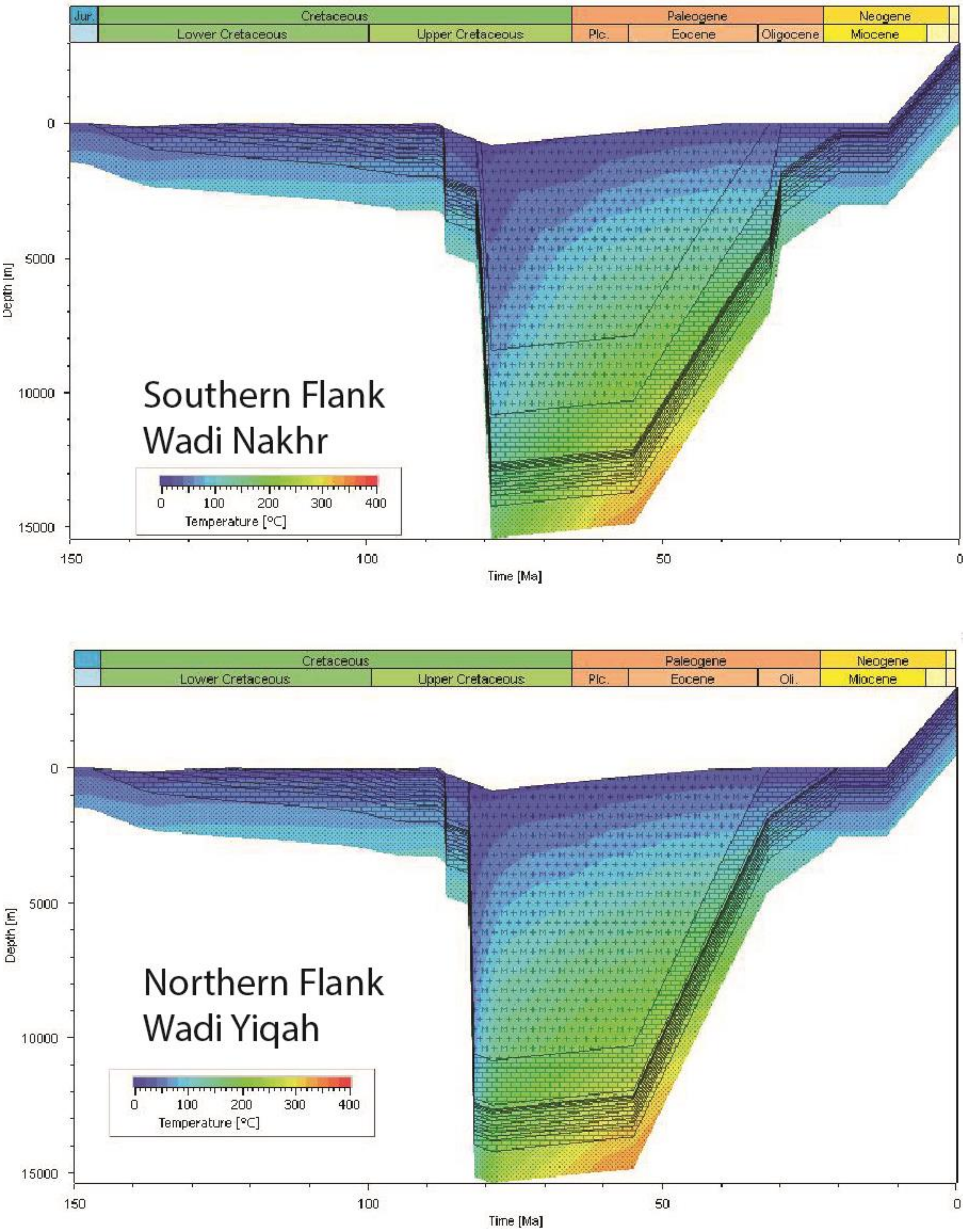

Figure 8 Modeling results: Two representative burial plots for two pseudo-wells created near the entrances of Wadi Nakhr and Yiqah (Figures 1, 6 and ,7) show two phases of rapid burial related to Hawasina and Semail Nappe emplacement and c. 88 Ma and ophiolite emplacement at c. 78 Ma. Burial in the North (Wadi Yiqah) starts c. 2 Myra earlier due to ophiolite obduction taking place from N to S.

As a model set up only presents one possible solution out of several, sensitivity analyses with varying paleo-overburden thicknesses (Figures 9 and 10), changing degree of serpentinization of the ophiolite and varying basal heat flow during deepest burial (Figure 11) are presented and discussed below.

Thermal maturity data of the Natih B at Jebel Qusaybah (1.1 % VR_r), Adam Foothills, require~~s~~ peak temperatures of c. 14~~5-182~~0 °C (Table 1). Sensitivity analys~~z~~es of the overburden above the Natih Fm. ~~outlined~~ show that at least 4 to 4.5 km of sedimentary overburden (Figures 9a and 10a) ~~are~~ is needed to match the calibration data (Figures 9a and 10a).

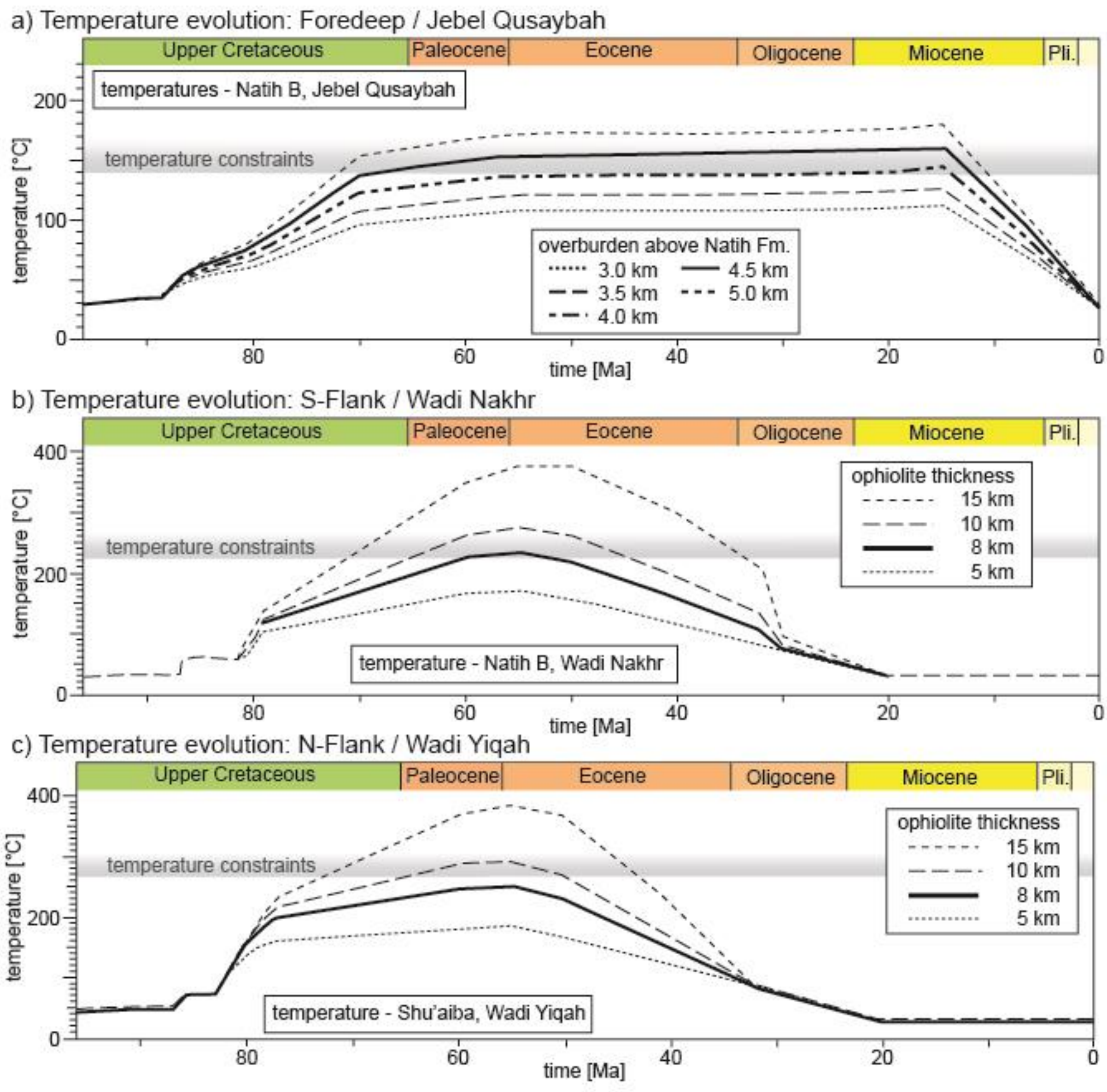

Figure 9: Sensitivity analysis of paleo-overburden and its influences on temperature in comparison to calculated peak temperatures (gray area) for pseudo-wells at Jebel Qusaybah (a), Wadi Nakhr (b) and Wadi Yiqah (c).

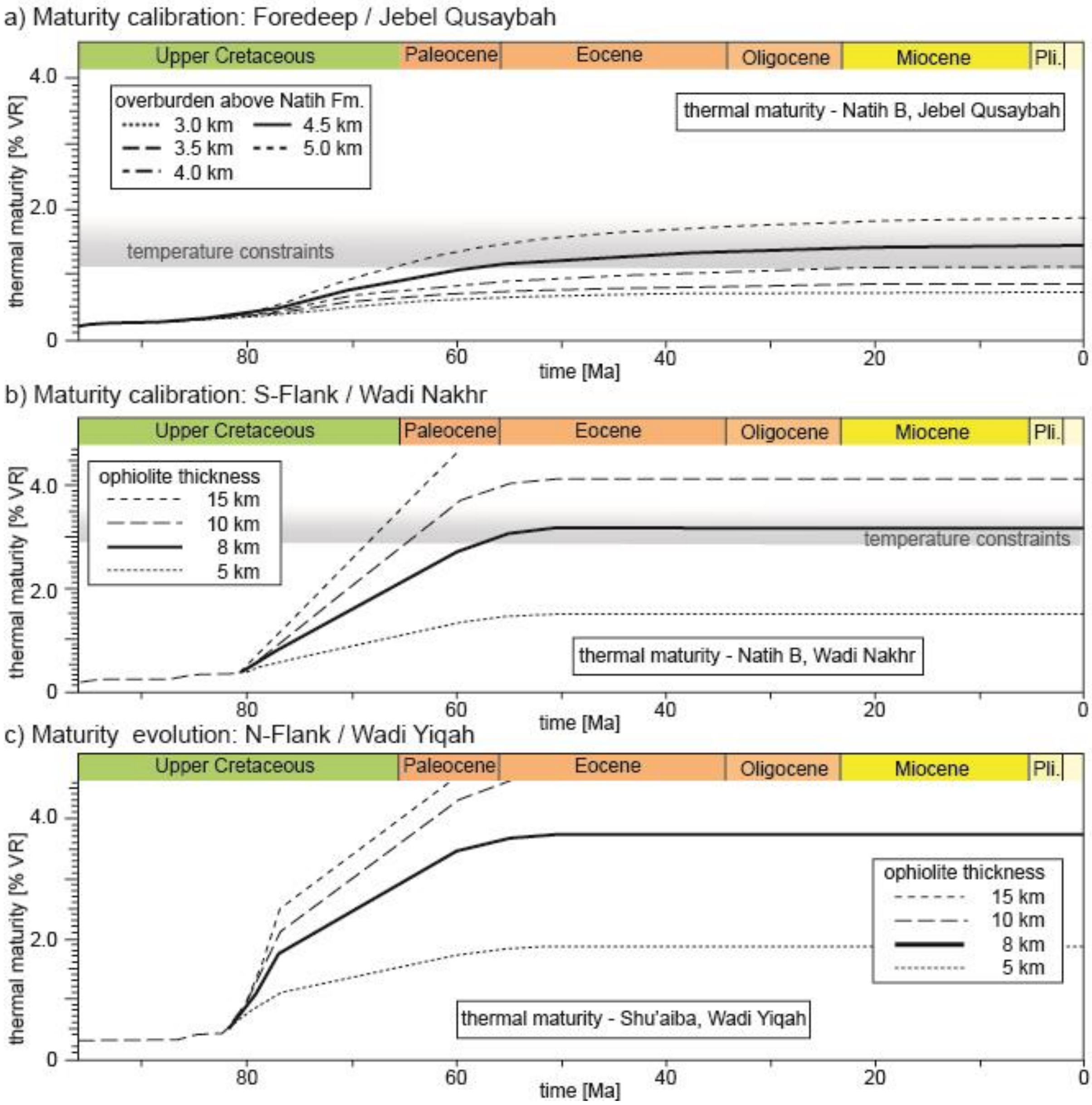

Figure 10: Sensitivity analysis of paleo-overburden and its influences on thermal maturity in comparison to calibration data (gray area). Data is used to calibrate burial depth of the foredeep at the Jebel Qusaybah (a) and the ~~,~~ paleo-ophiolite thickness at the southern flank of the Mountains at Nakhr (b). ~~and at i~~Its northern counterpart at Yiqah (c) is in agreement with the temperature data of Figure 9, however to mature to be reconstructed by standard maturity modelling (Sweeney and Burnham, 1990).

To restore the former minimum thickness of the Semail Ophiolite, the thickness of the Hawasina Nappes along the transect was fixed to 2 km, ~~representing its minimum thickness~~ as suggested by the maximum present-day thickness of the Jebel Misht exotics. To reach the required thermal conditions measured at the entrance of the Wadi Nakhr (Natih B: 2.83-3.72 % VR_r, 225-260 °C; Grobe et al., 2016), 8-10 km of original, total thickness of strongly serpentinized ophiolite sequence are needed in addition to the ~~assumed~~ 2 km of Hawasina Nappes (Figures 9b and 10b). These thicknesses are also sufficient to reach peak temperatures calculated for older stratigraphy at the northern flank of the Jebel Akhdar Dome (Shu'aiba Fm. at Wadi Yiqah: 270-295 °C by RSCM, Figures 9c and 10c). Modeling results show an earlier heating and ~~onsetting longer-lasting~~, ~~quicker~~ more rapid increase in maturity ~~and temperature~~ in the north. We associate this~~,~~ ~~which we interpret as associated~~ with the 2 Mys earlier onset of obduction and, hence, a longer burial of the

northern carbonate platform (Wadi Yiqah) under the active ophiolite obduction compared to is southern counterpart (Béchennec et al., 1990; Cowan et al., 2014).

Another factor influencing the modeling results is related to the lithology of the overburden and its compaction. In the special case of burial under an ophiolite, serpentinization of peridotite and its impact on ophiolite density and thermal conductivity must be considered. Sensitivity analysis of ophiolite serpentinization shows the temperature and thermal maturity effects on our model (Figure 11). A model-case of ophiolite without any serpentinized peridotite (0 %-case, ρ_{ophio}=3133 kg/m³) would represent the largest deviation compared to our best-case model assuming complete ophiolite serpentinization (100 %-case, ρ_{ophio}=3069 kg/m³). This density is based on Al-Lazki et al. (2002). Even if the upper part of the ophiolite ~~is~~ was missing in the Jebel Akhdar area (Nicolas and Boudier, 2015), this and the ~~observations~~ field data of Searle and Cox (2002) in the Saih Hatat support strong serpentinization. A less serpentinized ophiolite means higher densities and related higher thermal conductivities of the overburden and thus lower peak temperatures in the sediments below. In ~~a~~ the case of no~~-~~ serpentinization ~~case~~, peak temperature of Natih B in the Wadi Nakhr would decrease by c. 60 °C resulting in a maximum thermal maturity decrease of 1.5 % VR. The best fit model with an ophiolite thickness of 8-10 km would need additional 3 km of overburden at 0 % serpentinization to equally match the measured thermal maturities. Additional thicknesses of 0.75 km (75 % serpentinization), 1.5 km (50 % serpentinization) and 2.25 km (25 % serpentinization) apply for lower degrees of serpentinization, respectively.

Results depend strongly on basal heat flow (Figure S3). The best fit model of 40 mW/m² at ~~deepst~~ maximum burial is typical for a passive continental margin setting. If this heat flow at peak burial would be lowered to 30 mW/m² an additional amount of 1.2 km of ophiolitic overburden would be required to achieve a match with thermal calibration data (Figure 11). Increased heat flow values to 50, 60 or 70 mW/m² would result in ~~less~~ lowering of overburden ~~of~~ by ~~-~~1.3, ~~-~~2.4 and ~~-~~3.5 km, respectively (Figure 11).

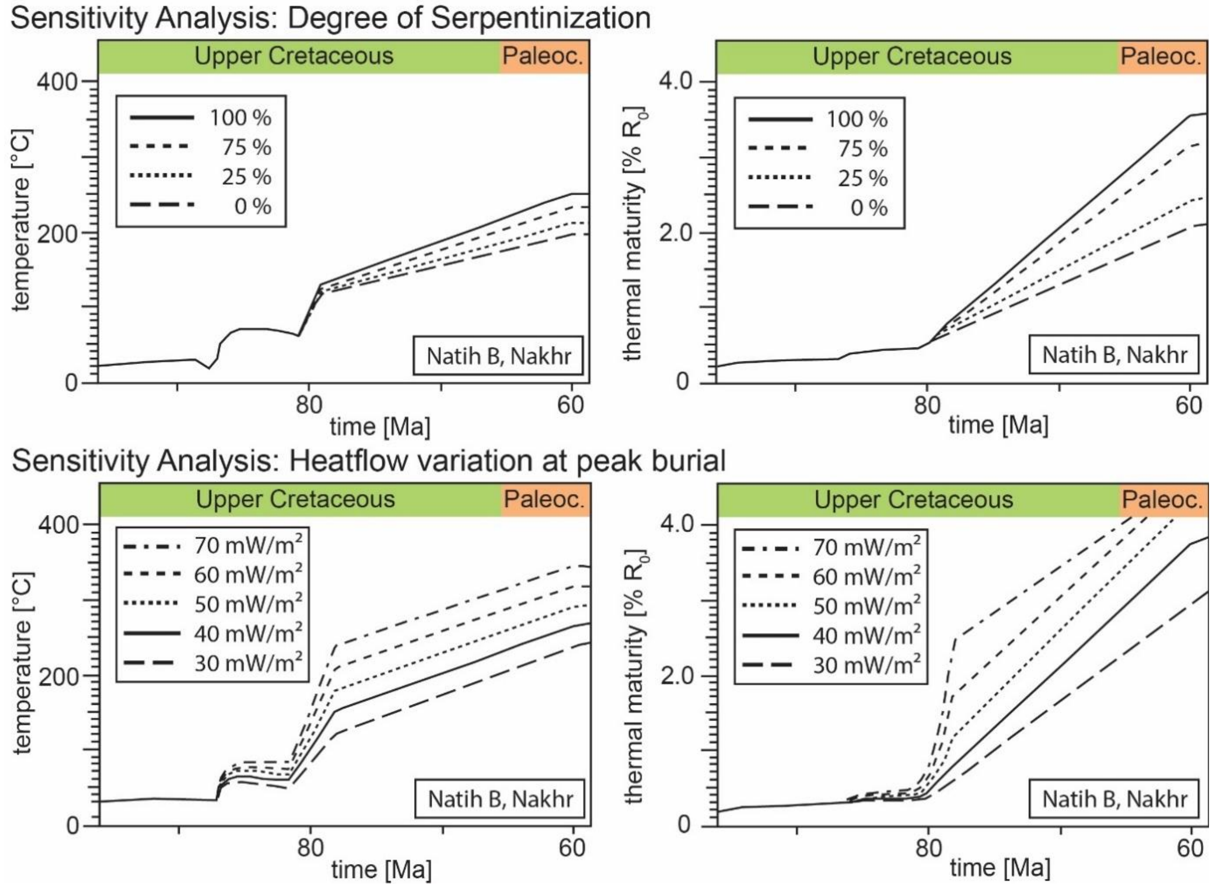

Figure 11: Sensitivity analysis: Top: Different degrees of serpentinization of the peridotite within the Semail Ophiolite affect the temperature (left) and thermal maturity (right) evolution (modeled for Natih B Fm. at Wadi Nakhr). Pure peridotite (0 % serpentinization) require additional 3 km of ophiolite in addition to the 8-10 km of the best-fit model to equally match the calibration data. 100 % refers to complete serpentinization of the peridotite in the ophiolite. Bottom: The influence of variable heat flow values at peak burial on temperature (left) and thermal maturity (right).

5. Discussion

~~Any~~Evaluating uncertainties in basin and petroleum system models ~~has to deal with uncertainties, in~~is especially important ~~particular~~ for complex areas such as the Jebel Akhdar, where sedimentary rocks reached high temperatures and maturities due to deep and rapid burial. In the following, we discuss these uncertainties with respect to temperature and burial history, overpressure build-up and induced fluid flow. For all presented basin models of the study area, the following ~~limitations~~ assumptions apply: (1) decompacting the present-day lithologies does not consider rock volume lost by pressure solution. This is probably of minor importance in our study area as host-rock buffered isotope ratios of the veins were interpreted as local sinks for nearby dissolved calcite (Arndt et al., 2014; Hilgers et al., 2006), so that the overall rock volume remains approximately constant, (2) decompaction only accounts for burial, whereas a possible tectonic compaction is neglected (Neumaier, 2015) and (3) calculated overpressure does not include a rock volume decrease due to pressure solution.

5.1. Burial history

Little is known about the very early phase of burial, before 91 Ma (Figures 6 and 7, Grobe et al., 2018). The assumptions for this period are based on hypotheses on the tectonic evolution of the passive continental margin as well as data on thickness of sedimentary units but are not strongly constrained by petrographical data.

In Turonian times (Robertson, 1987) a southwest-ward-moving forebulge, related to plate convergence, affected northern Oman. It eroded the northeastern platform edge and migrated southwest-ward to the present-day position of the Adam Foothills (Robertson, 1987). Measured thermal maturities of 1.1~~-1.8~~ % VR_r were used to reconstruct peak temperatures during burial in Jebel Qusaybah, Adam Foothills to c. ~~, which range between 145 and 182~~140 °C. Numerical basin modeling results reveal that additional paleo-overburden of at least 4 to 4.5 km (Natih B, Qusaybah, Figure 10) is required to reach these temperatures. The exhumation history of the Adam Foothills is not well known; our model is based on an interpreted late exhumation during the Miocene (Claringbould et al., 2013). Earlier exhumation would shorten the time span of the rock at higher temperatures (Figure 7), lead to decreased thermal maturity and, hence, would require additional overburden to match the measured thermal maturity data. Therefore, the resulting burial of 4 to 4.5 km has to be regarded as minimum value~~, which would increase by pre-Miocene exhumation of the Jebel Qusaybah~~. South of the Adam Foothills basin geometries ~~-~~do not show tilting and are interpreted as not affected by the moving foredeep. Here peak burial was reached under c. 3 km of Fiqa, Hadhramaut and Fars formations. This is based on the assumption that present-day burial equals deepest burial as no thermal calibration data of the area south of Jebel Qusaybah was achieved, which is in agreement with interpretations of Terken (1999) and Warburton et al. (1990).

In case of the Jebel Akhdar, peak temperatures were reached as a consequence of burial below the ophiolite (Loosveld et al., 1996; Searle et al., 2003; Searle, 2007; Warren et al., 2005). Here the sedimentary rocks reached high temperatures and maturities as shown by solid bitumen reflectance, RSCM, FT-IR and Rock-Eval pyrolysis data (Fink et al., 2015; Grobe et al., 2016). Pre-obduction burial by sedimentation is not sufficient for such high thermal maturities, and it likewise cannot be explained by increased basal heat flow before 91 Ma or after 55 Ma. Influence of local hydrothermal effects cannot be excluded, but because the entire Jebel Akhdar reached high temperatures, short-term, local events are unlikely to have been dominant. A regional thermal overprint on the passive margin sediments by warm ophiolite obduction can be excluded~~ as the peak temperatures in the Jebel Akhdar Dome are increasing with stratigraphic age~~. Due to the at least 2 km thick imbricated Hawasina Nappes between the ophiolite and the passive margin sequence, the thermal overprint did not affect the top of the carbonate platform. Limited thermal overprint~~ing~~ of the units underlying the ophiolite is supported by the fact that the sediments of the nappes directly below the ophiolite do not show signs of regional metamorphism in the Jebel Akhdar region (Searle, 1985). This is in agreement with models of Lutz et al. (Lutz et al., 2004) ~~outlining~~ that show th~~at even in subduction zones the isotherms of the~~e thermal evolution of rapidly buried sediments~~ are not adjusting to the surrounding temperatures instantaneously~~. Moreover, the thermal imprint as observed by the metamorphic sole in northern Oman ~~is~~ only affect~~s~~ing 10’s of meters in the sub-thrust Hawasina Nappes (Searle and Cox, 2002) and not the carbonate platform sediments below. This ~~only~~ minor ~~sub-thrust thermal~~frictional ~~thermal~~ overprint ~~-~~is also observed in other ~~thrust zones~~areas (e.g. Wygrala, 1989).

To reach the measured maturity ~~data~~ values in the Jebel Akhdar~~mountain, area of the transect~~ a paleo-thickness of the ophiolite in the order of 8-10 km on top of 2 km of Hawasina Nappes is required (Figure 10); this ~~would account for~~corresponds to 280 to 320 MPa of lithostatic pressure~~ and is~~, in rough agreement with the pressure reconstructed by combining fluid inclusion data and independently determined thermal rock maturity temperatures (cf. FI results: 254 ± 30 MPa). ~~Depending on lithological effects, such as a less pronounced serpentinization of the ophiolite, this value might increase by up to 3 km (Figure 10). Basal heat flow values at deepest burial are estimated to c. 40 mW/m². This seems realistic as passive margin conditions prevail, and no magmatism or rifting is reported in the area.~~

Basin modeling indicates that highest temperatures were reached much later than deepest burial under the ophiolite (Figure 7), directly prior to uplift. This difference is interpreted as the time the rock needed for thermal equilibration after rapid burial. Deep burial under the ophiolite represents the only time ~~in~~ in the basin's evolution when ductile limestone deformation was possible (Grobe et al., 2018). However, there is uncertainty concerning the exact timing of deepest burial in the Jebel Akhdar (we used 79 Ma according to U-Pb dating of eclogites in the Saih Hatat window; Warren et al., 2005), the related basal heat flow (discussion, Fig. S2) and the beginning of early uplift (we used 55 Ma, as discussed below).

Our peak temperatures are in ~~principal~~ agreement with temperatures of c. 200 °C suggested for the top of the carbonate platform by Breton et al. (2004), and non-reset zircon fission tracks in the pre-Permian basement indicating peak temperatures up to 280 °C (Saddiqi et al., 2006). Moreover, thermal maturities of the same stratigraphic units show similar values along the transect and around the dome (Grobe et al., 2016). Hence, we assume a similar burial history for the entire Jebel Akhdar. The temperatures used in our models are in contrast with recent results on mixed illite-smectite layers and clay mineral assemblages from the Jebel Akhdar by Aldega et al. (2017) who argue for peak temperatures of 150-200 °C on the northern flank of the Jebel Akhdar and 120-150 °C on the southern flank. These values are incompatible with our solid bitumen and Raman spectroscopy data, as well as with the overmature Natih B source rock on the southern flank (data presented here and in Grobe et al., 2016). Independent data on temperatures from fluid inclusions confirm the higher temperature range. At present, there is no clear explanation for this discrepancy. However, it has been shown that the vitrinite reflectance system is more sensitive to rapid temperature changes than clay mineralogy (e.g. Hillier et al., 1995; Velde and Lanson, 1993). If burial was short enough, the clay minerals may not have time to recrystallize, possibly due to a lack of potassium, whereas vitrinite reflectance increases. Alternatively, we speculate~~Another possible explanation may be~~ that the ~~dated~~ clay minerals were transformed during top-to-NNE shearing, thus their state do not show peak burial. Indeed it has been shown that deformation associated with this early extension reaches deeply into the passive margin sequence, and includes the Rayda and Shuaiba Formations (Grobe et al., 2018; Mattern and Scharf, 2018). Furthermore, Aldega et al. (2017) ~~suggest~~ argue that the ~~thermal evolution during uplift of~~cooling history proposed by Grobe et al. (2016) indicates temperature in the basement < 70°C during the Eocene-Oligocene, thus not ~~does not~~ accounting for thermochronological data in pre-Permian basement rocks. ~~(Poupeau et al., 1998; Saddiqi et al., 2006), arguing the 1D thermal models indicate temperature in the basement had to be lower than 70°C during the Eocene-Oligocene.~~ In fact, the ~~raw~~ ~~used~~ calibration data we used ~~from~~ ~~of~~for the basement indicate rapid cooling at 55 ± 5 Ma (Poupeau et al., 1998; Saddiqi et al., 2006), in agreement with models of Grobe et al. (2016) and the exhumation presented in this work.

This exhumation might be a result ~~Temperatures~~ of the ductile top-to-NNE shearing event (64 ± 4 Ma, Hansman et al., 2018). Its onset~~,~~ markings the time of deepest burial and related peak temperatures measured in bedding parallel veins~~, were~~ ~~reconstructed to~~estimated at 186-221 °C by Holland et al. (2009) assuming an ophiolitic overburden of 5 km (Sahtan Fm., Wadi Nakhr). If we adjust this pressure correction for higher values of 280 to 340 MPa accounting for the here elaborated 8 to 10 km of ophiolite and 2 km of sedimentary nappes, trapping temperatures would increase to c. 296-364 °C (Table 3), which are in the order of the maximum burial temperatures as deduced from organic matter maturity.

Figure 12 presents a summary burial ~~plot~~ graph indicating temperature and age constraints. Highlighted in gray is additional information gained by fluid inclusion thermometry. These data indicate paleo-fluid temperatures in the range of 225 ± 4 (280 MPa) to 266 ± 5 °C (340 MPa) during burial under the ophiolite (bedding-confined veins),

c. 296-364 °C at peak burial (top-to-NNE sheared veins) and 213 ± 3 °C during exhumation with a later phase of primary inclusion outlining 184 ± 3 to 189 ± 7 °C (both strike-slip related veins). Temperature decrease within the latter formed parts of the strike-slip veins might relate to a change of fluid source or to exhumation during vein formation. In combination with our thermochronology data the second possibility appears more likely and would imply strike-slip faults developed after c. 55 Ma.

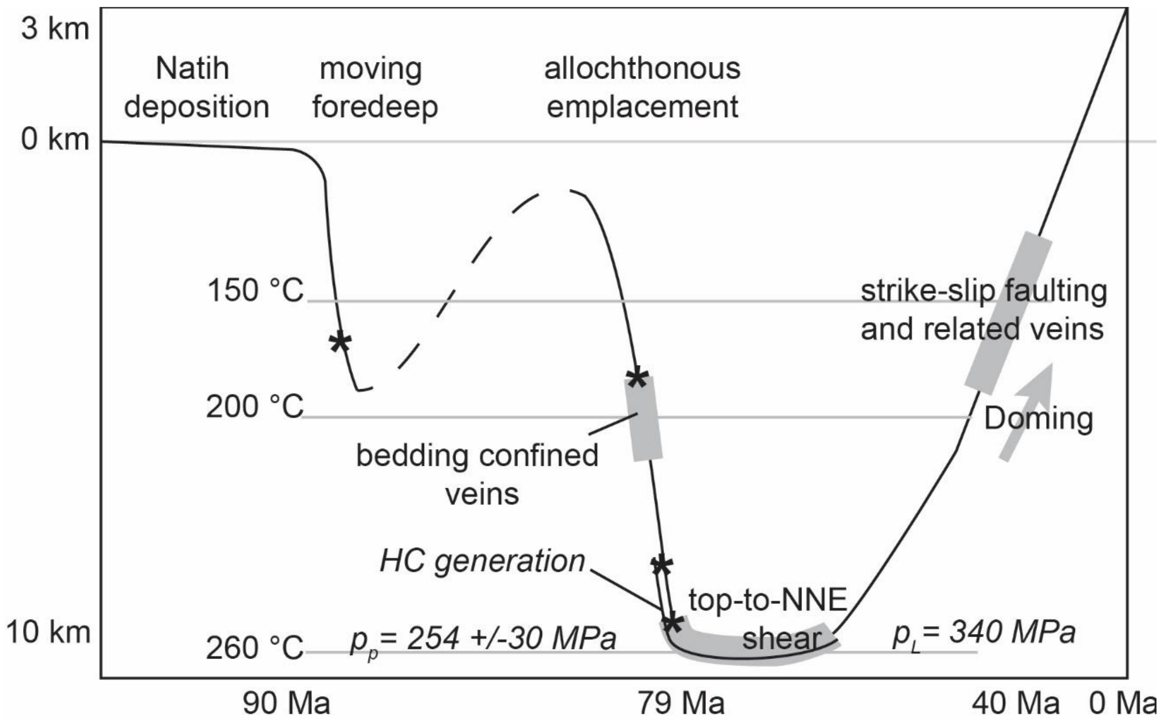

Figure 12: Summary burial sketch for the top of the carbonate platform (Natih Fm.). Shown temperatures are based on RSCM and FI thermometry, pressure data calculated out of FI measurements and independently determined temperature data. The ~~uplift~~ exhumation history is restored by ZHe ages. (* indicate times of overpressure formation, gray areas depict vein formation)

5.2. Exhumation history

Our new thermochronology data from the central part of the Jebel Akhdar Dome suggest~~s~~ cooling below the reset temperature of the ZHe thermochronometer (c. 130-170 °C) between 48.7 ± 1.8 and 39.8 ± 3.0 Ma (Table2, Figure 4). The small variation in cooling ages for the different stratigraphic levels indicates rapid passage of the entire rock suite through the ZHe partial retention zone, and consequently rapid exhumation of the Jebel Akhdar Dome. This Eocene cooling is in agreement with ZHe ages of pre-Permian strata of Hansman et al. (2017) ranging between 62 ± 3 and 39 ± 2 Ma. Apatite fission track (AFT) ages measured in the basement of the Jebel Akhdar range between 55 ± 5 Ma and 48 ± 7 Ma (4 samples, Poupeau et al., 1998) and 51 ± 8 Ma to 32 ± 4 Ma (Hansman et al., 2017). The temperature of resetting the AFT system (i.e. the depth of the base of the partial annealing zone) may vary depending on annealing kinetics. For different apatite crystals this temperature ranges between 100 and 120 °C (Carlson et al., 1999; Fitzgerald et al., 2006). Hence, these AFT ages reproduce within error with our ZHe results, despites the fact that both systems are sensitive to different temperature intervals (100-120 °C and 130-170 °C, respectively This supports the interpretation of rapid exhumation of the Jebel Akhdar at c. 55 Ma. Zircon fission track ages witness cooling of the Jebel Akhdar below c. 260 °C between 96 and 70 Ma (Saddiqi et al., 2006). This implies slow cooling thereafter (c. 100° between 70 and 55 Ma) until rapid exhumation at c. 55 Ma. ~~).~~ ~~This supports the interpretation of rapid exhumation of the Jebel Akhdar. In combination with zircon fission track~~

~~ages of Saddiqi et al. (2006), indicating the rocks cooled below c. 260 °C between 70 and 96 Ma, modeled cooling paths indicate rapid exhumation initiated at c. 55 Ma.~~ Earlier exhumation would not result in required thermal maturities as exposure of the rock to highest temperatures would be too short for thermal equilibration. A reheating event in the late Miocene is not required to explain the data.

Our ZHe data from the Muti Formation and the Hawasina Nappes show a spread in ages, between 173 and~~ranging from~~ 43 ~~to 173~~ Ma, i.e. partly much older than the ages observed in the stratigraphically lower units in the center of the dome.

A spread in (U-Th)/He-ages is often observed, and has been attributed to radiation damage density, uneven distribution of mother isotopes in the dated crystal, broken grains, grain chemistry, among other causes (e.g. Flowers et al., 2009; Guenther et al., 2013). Several studies show that samples from sedimentary rocks are particularly prone to spread in ages (e.g. von Hagke et al., 2012; Ketcham et al., 2018; Levina et al., 2014). This is because transported grains are subject to abrasion, which influences age correction for grain geometry and may obscure presence of inclusions within the crystal. Additionally, dated grains can originate from different sources, and thus have a different chemical composition and a different pre-depositional ~~time-~~temperature history. This may result in different reset~~ting~~ temperatures, and consequently different grains (or grain age populations) represent different thermochronometers.

It is difficult to prove the existence of such multiple thermochronometers, as independent parameters indicative for different kinetics have not yet been established. Indeed, statistical analysis of different grain age populations requires dating of multiple grains (e.g. to be 95 % certain that a population representing 5 % of the grains is not missed 117 single grain ages need to be dated, Vermeesch (2004)). In any case, reproducing ages determined in different samples indicates the data is geologically meaningful, i.e. the observed spread is the result of partial resetting and/or different kinetics and not the result of factors independent of the time-temperature history, such as undetected inclusions or external helium implantation. We thus interpret the system as ~~This indicates the system has been~~ only partially reset, implying these units were not heated above the reset temperature (approximately 130-170 °C) after deposition. This interpretation is corroborated by ~~Units exposed in the Hawasina Window (Figure 1) also show~~ unreset ZHe ages in the Hawasina Window (Figure 1~~(~~, Csontos, pers. comm.). The top of the Natih Formation has seen temperatures above 220 °C. We suggest that this apparent contradiction may be explained by juxtaposition of the colder Muti and Hawasina units against the top of the carbonate platform during extensional top-to-NNE shearing. This implies that at least 50 °C of cooling are associated with post obduction extension, i.e. before doming. A two-stage exhumation history of the Jebel Akhdar Dome has also been inferred from structural data (Grobe et al., 2018; Mattern and Scharf, 2018) and the stratigraphic record (Fournier et al., 2006; Mann et al., 1990). Top-to-NNE shearing is associated with tectonic thinning of the ophiolite (Grobe et al., 2018). This tectonic denudation will also result in cooling, and may explain why so little ophiolite is found in the post-obduction sediments. Additionally, ophiolitic material may have been lost to the ~~Persian~~ Gulf of Oman.

5.3. Pressure evolution ~~and fluid migration~~

Evolution of pore pressures was modelled (Figures S7 and S8) assuming a ~~perfect~~ seal on top of the Natih Fm. ($k_{Muti}=10^{-23}$ m^2). Porosity was lost during Muti deposition in the moving forebulge (top seal) and related burial, the emplacement of the Hawasina Nappes and the ophiolite, which induced compaction and a remaining very low porosity of c. 1 %. Hydrostatic pressure increased with burial under the moving forebulge at 88 Ma to 40 MPa, after Muti deposition to 60 MPa and after ophiolite emplacement to 120 MPa. Calculated pore pressure ~~exceeded~~ rise above hydrostatic pressure in response to Hawasina Nappe and ophiolite emplacement.

Formation of tensile fractures, as inferred from bedding confined, Mode-I veins in the Natih Fm. (Arndt et al., 2014; Grobe et al., 2018; Holland et al., 2009; Virgo, 2015), require internal fluid pressures (P_f) exceeding the sum of the stress acting normal on the fracture surface (σ_3) and the tensile stress of the rock (T): $P_f > \sigma_3 + T$, and a differential stress (σ_1 - σ_3) below 4T (Secor, 1965). Host-rock buffered vein isotope compositions indicate that the veins were formed by local fluids (Arndt et al., 2014) and, hence, require local overpressure cells.

Sensitivity analyses of reduced permeabilities of Muti, Natih and Nahr Umr formations show that overpressure generation, necessary for rock fracturing, requires a very good top seal and also a reduced horizontal permeability of the Natih Fm. of 10^{-23} m² (Figure S7 and S8). A top seal on its own is not sufficient for overpressures initiating rock failure. This case results in pore pressures up to 300 MPa within the top Natih and localized overpressures of 195 MPa in front of the obducting ophiolite.

All results indicate that without low horizontal permeabilities of the Natih Fm. $\leq 10^{-23}$ m² overpressure cells required for vein formation cannot be generated. The reduced permeabilities in the Natih Fm. are necessary to prevent an early, tectonically-driven horizontal pressure release.

5.4. Fluid migration

Numerical basin modeling shows that rapid burial of sedimentary rocks below the ophiolite (88-80 Ma) caused under-compaction, i.e. a porosity too high with respect to burial depth, and consequent pore pressure increase. Two example model results of fluid migration in front of the obducting ophiolite are shown in the electronic supplement Figure S9. If low permeabilities are assigned to the non-source-rock members of the Natih Fm., migration will mainly take place within the source rocks and at layer interfaces within the Natih Fm. If the complete Natih Fm. has low permeabilities, fluids will leave the source rock vertically first, before lateral migration localizes along layer boundaries. The pressure gradient between overpressures below the allochthonous nappes and the less deeply buried southern foreland initiates tectonically-driven fluid migration in front of the obducting nappes, an idea that was first introduced by Oliver (1986). Solid bitumen accumulations in black stained calcite veins are in agreement with this interpretation (Fink et al., 2015).

Dome formation of the Jebel Akhdar anticline around 55 Ma initiated layer tilting and consequent southward migration of the generated hydrocarbons as observed by secondary low reflective solid bitumen generations in Natih veins and host rocks at the southern flank of the Oman Mountains (Fink et al., 2015; Grobe et al., 2016).

6. Conclusions

This study provides insights into the temperature evolution during obduction, prior to subsequent orogenesis.

Arabia’s passive continental margin was buried to at least 4 km at times of foredeep migration and afterwards under 8-10 km of Semail Ophiolite and 2 km of sedimentary Hawasina Nappes. Burial under the ophiolite resulted in peak temperatures of up to 300 °C (Shu’aiba Fm.) with sub-lithostatic pore pressures. Ophiolite obduction and overpressure cells expelled fluids towards the foreland, through matrix and fracture porosity.

ZHe data show cooling associated with forebulge migration, as well as with exhumation of the Jebel Akhdar Dome.

Exhumation of the Jebel Akhdar Dome took place in two stages. A first stage is associated with top-to-NNE shearing, which is responsible for at least 50 °C of cooling, as witnessed by juxtaposition of units including partially reset ZHe ages against units that experienced more than 220 °C. ZHe data show the second exhumation phase, associated with doming of the Jebel Akhdar occurred between 49 and 39 Ma.

Author contribution

JLU, RL and AG ~~conceived of~~initiated and planned the study. AG planned and carried out fieldwork as well as thermal maturity measurements (VR, solid bitumen reflectance, Raman spectroscopy), structural interpretations and basin modelling. AG, CvH, JU, ID and FW carried out fieldwork and structural interpretations. FW and ID conducted the thermochronological measurements with help of CvH. PM and AG performed fluid inclusion thermometry.

AG and CvH prepared the manuscript with contributions from all co-authors.

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