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Solid Earth Discussions

Interactive comment on "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.

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The manuscript by Grobe et al. presents an integrated approach of ZHe thermochronology, fluid inclusion microthermometry and organic matter thermal maturity analysis that have been used to constrain 1D and 2D numerical models in order to depict the tectono-thermal evolution of the passive margin sedimentary succession in Oman during and after ophiolite obduction. The manuscript requires more work before being considered for publication.

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.

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, 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 and relationship between temperature and stratigraphic age in figure 3 is not clear. 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.

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.

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.

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.

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.

7) Some parts of the discussion are overinterpreted or need clarification (see points line by line below). 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

(see Hoffman and Hower, 1979; Hillier et al., 1995). Also the lack of potassium during 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).

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.

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,

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

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

Introduction Line 51 – I would replace "sub-thrust sedimentary basin" with "sub-ophiolite units" or "authocthonous passive margin units" Line 63 – replace "full" with "whole" or "entire" and replace "Permo" with "Permian" 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. 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.

Line 78 – replace "deepest burial" with "maximum burial"

Tectonic setting Lines 90, 92, 98 – replace "Permo" with "Permian" 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$\pm$4 Ma; Hansman et al., 2018).

Stratigraphic sequence Line 155- Spell out Gp. Line 167 – A more detailed description of the hawasina deposits is needed.

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" Line 177 – replace "is" with "are" and provide reference. Lines 188-190. I would delete these lines as they do not provide useful

information in this section.

Temperature evolution of the Semail ophiolite Nappe/allochthon Lines 198-199. How much is the temperature? Please provide it Lines 199-203. You can use these sentence as well as all the information included in this paragraph in the discussion section.

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.

Methods

I would delete lines 216-217.

Elemental analysis and thermal maturity Line 218 – Thermal maturity is not a method. I would replace “elemental analysis and thermal maturity” with “Raman spectroscopy of carbonaceus material” Line 219 – add “ levels of” in front of “thermal maturity” Lines 220-221 – please define which stratigraphic units were analyzed for organic matter characterization Line 234 – please define “STA” in the equation. Lines 236-238. Move these lines in the basin modelling section

Fluid inclusion thermometry Line 239 – replace “thermometry” with “microthermometry” Line 243- perhaps replace “mineralization” with “crystallization” Line 256- replace “of” with “for” Line 261 – define Tfm

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

Numerical basin modelling Line 287 – replace “R0%” with Ro%. O stands for oil. Line 290 – refer to the supplementary material for lithology and petrophysical rock properties

Line 291 – Which seismic lines? Provide reference Lines 291-292. I would delete this sentence Lines 293-294. The sentence is cryptic. I would delete it as you will discuss this point in the discussion section Lines 201-304. How can you calibrate burial depths for the Adam Foothills where thermal data are lacking? 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

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”. 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 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)

Thermochronology Line 341 – delete “Figure 3” Line 360 – This part needs more details. How can you associated those ages with doming? 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. 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. Line 372 – I would replace “A magmatic sample of an intrusive” with “A sample from an intrusive body”

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. Line 430 - Replace “Sahtan Fm” with “Sahtan Group”

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

Basin Modelling Line 454 – Replace “figures 8 and 9” with “figures 6 and 7” 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 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. Line 457 – it seems that maximum burial conditions are already reached at 84 Ma as shown in figure 6 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. Lines 475- 476- delete 1.8% VR as it is not reported in Mozafari et al., 2015 and revise temperature range Line 475 – Replace “requires” with “require” Lines 494-497 – I do not see any difference in your modelling results for northern and southern flanks 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 Line 513 – replace “deepst” with “maximum”

Discussion Burial history Line 537. Please expand this part. Why? Lines 542-545. delete 1.8% VR as this value is not reported in Mozafari et al., 2015 and revise temperature range/burial depths Lines 566-569. I did not understand these sentences. What is the sub-thrust thermal overprint? 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. Line 575-577.

This is a repetition. Information about heat flow has been already reported in line 513. Please delete it. 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). Line 598 – delete “dated” 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. 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.

Pressure evolution and fluid migration I would delete “fluid migration” from the title as you describe fluid migration in section 5.4. Lines 656-657- please delete the sentence written in german

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.

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

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.

Figure 6 – add a legend for the colours 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

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

Figure 8- revise figure 8a on the basis of my comments on Vr values by Mozafari et al., 2015

Figure 9- the shaded rectangle of calibration data is missing in figure 9c

Table 1 – replace "," with "." in the calculate VR values. Add longitute and latitude to sample location. What do you mean with "below the surface of the matrix"? What did you measure? Please rephrace. Spell out Kh2. Mozafari et al., 2015 show only two data with 1.1 VR%. 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.

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".

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, dolostone

is a rock.

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.

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

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