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Interactive comment on “Numerical model of crustal accretion and cooling rates of fast-spreading mid-ocean ridges” *by* P. Machetel and C. J. Garrido

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Dear colleague,

It seems that it is not possible to keep the italic-blue color formatting we used in our answers to recall your comments. You will find as a supplement a pdf file that gathers our comments and the proposed revised version of our work.

First, we want to thank you for your editorial works. We have taken into account or try to answer positively to all of your comments concerning the opportunity to publish the new code; the discussion and interpretation of the results and the revisions of text. Following your advices several parts of the paper have been rewritten, several

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figures have been modified and new explanations have been added to better justify or improve results presentations. In particular, we followed your suggestion, presenting the temperature patterns obtained for the various accretion geometries as differences to those of the Gabbro Glacier "G" structure. We also clarified in the text and in the new version of Fig. 5 the difference between the instantaneous and average cooling rates that are obtained from the time evolution of tracers along trajectories within the crust with cooling rates obtained by petrologists. In the new version of the paper, all the references to the petrological results have been shift and clearly separated from the numerical model results. We suppress all the reference to “Igneous Cooling Rate, ICR” or “Subsolidus Cooling Rate, SCR” describing our results to emphasize on the average cooling rate that are obtained and are not comparable with the petrlogical ones without cautions. This is why Fig. 6 has been joined to the section describing the numerical results and received new labels. We have improved the discussion to take these restrictions into account. You will find below the detailed answers for each of your comments, which are recalled in blue italic. Thanking you again, for the help you brought us improving the scientific content of our paper, we hope that this new version will find your approbation for publication.

Sincerely yours, Philippe Machetel and Carlos Garrido

?????????????????Global comments: Overall I consider that the manuscript requires minor revisions, because it could present interesting results on the thermal evolution of crustal accretion in mid-ocean ridges, provided that some changes are made before publication. The numerical model with its strengths and limitations has been developed in previous studies. In my opinion, a more robust argumentation is required to justify some rather arbitrary choices in the model setup and interpretation of the results (for example, variation of Phi with depth, viscosity of the crust, melting vs temperature, discussion on cooling rates).

»»»»»»»»»»>This work depicts significant improvements of our computing tool devoted to the exploration of the thermal and dynamic effects for mid-oceanic ridge studies.

However, in spite of their common properties, each ridge is also a particular case, with its own local properties and configurations. This complicates the choice of particular physical values and justifies their large parametric explorations. These needs are emphasized by the open scientific debates that exist among the scientific community about the structure of the ridge itself, the location or the strength of the hydrothermal cooling. These debates are still open for the cracking temperature values, the viscosity contrast in the upper crust but also for the importance of the feedbacks between uncertainties on these variables. Our program has been designed to allow broad, easy (and quite cheap in term of computer time - from a few hours to a few days on modern PC) explorations of these assumptions. This should be considered as an advantage able to bring large possibilities of parameter explorations to who it may be interested. However, it also presents the difficulty of synthetic presentations of numerous crossed possible explorations and cases. The aim of the current paper is not presenting exhaustive explorations of these free parameters, but to present some cases exploring the effects on results of intrusion geometry, hydrothermal cooling location and amplitude, cracking temperature and viscosity. This work illustrates the possibilities of the new version of the code with broadly accepted geophysical parameter values, knowing that the source (Fortran code) and the data files are easy to modify to customize the parameter to explor. New explanations have been added in the introduction and in the abstract of the paper to clarify these points and references have been added and/or modified in the text to justify the choices for crystallization curve, viscosity and cracking temperature hypotheses.

?????????????????Section 5 (thermal history and cooling of the lower crust) should be extensively rewritten because: 1) The discussion on cooling rates is not clear, the concept of cooling rate has limited validity and the definition of opening and closure temperatures are not correct when used in relation to petrological studies;

»»»»»»»»»>We agree that, in the previous version of the paper, our use of cooling rate concept was misleading regarding the “opening and closure” temperature terminology.

You will find in the following more detailed answers to this point that was also developed later in the review. Following your advice, we have extensively rewritten section 5 to focus it on the description of the numerical model results. Fig. 5 has been completed, adding thermal histories of gabbros at specified levels and their instantaneous cooling rates according to the melt accretion geometry. To avoid confusion with petrological models, we no longer use the terms “opening and closure temperatures” but we still keep Eq. 15 to define an average cooling rate useful to portray the differences of cooling versus depths for the various accretion modes. We used “high and low” temperature intervals to name these bounding values and emphasize that these average cooling rate temperature intervals are arbitrary. Fig. 6 is now clearly joined to the section 5, devoted to the description of the numerical results and clearly separated from section 6 where the petrological results are discussed.

????????????????????2) Most importantly this section does not clearly show new results or conclusions, at least not in the format that is currently presented. I would strongly suggest omitting the discussion of petrological cooling models and just present the results of the thermo mechanical model. In particular it would be fantastic to see an x-y plot of T versus time of selected portions of the model, i.e. by following the position of selected tracers at different depths and horizontal displacements. In this way the authors will show the -true-cooling evolution in time and space. This by itself would be a great achievement. Petrologists will decide how their approach to thermal cooling fit into the more general thermal evolution presented here (in an x-y plotting format). In addition, it would be interesting to see how the model from this study would compare with geophysical observations as surface heat flux or topography which are directly affected by the thermal evolution of the upper and lower crust.

»»»»»»»»»»Following your suggestions we have redrawn Fig. 5 to describe the thermal history of cooling gabbros adding two panels for each of the G, M and S crustal accretion modes. Figs. 3 and 4 have also been redrawn. They present x-y plots of the eulerian representation of temperature for the steady state reached at the end of

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the runs. The new Fig. 5 depicts lagrangian representations of the thermal evolutions of tracers that are drift away by the flows. In that sense, this figure answers to your request of a x-y plot of T versus time to show the -true-cooling evolution in time and space. We have improved its readability by adding curves of these thermal evolutions at different depth versus time We also have added more direct information about the thermal evolution of particular trajectories at sampled depth and the values of the instantaneous cooling rate that are obtained.

???????????????????Detailed comments Page 2430: line 12-14, I am not aware of any analogy between the cooling rate defined as ICR and SCR and the cooling rate defined by experimental petrology. What does it means "cooling rates sampled near/far from the ridge"?

»»»»»»»»»»>To avoid confusion we no longer use these terms in the revised manuscript. Cooling rates from petrographic and/or mineral compositional data in samples of the plutonic oceanic crust are integrated cooling rates over T-t interval, which values are intrinsic to the methodologies used to derive the cooling rates. Proxies of magmatic cooling rates derived from the CSD of plagioclase in plutonic rocks (Marsh, 1988; Marsh, 1998) record the cooling of the sample in the T-t interval between the liquidus and the solidus temperature (i.e., the crystallization time). On the other hand, cooling rates based on elemental diffusion in minerals from the plutonic crust, as those based on geospeedometry, record the cooling rate in the T-t interval when exchange diffusion is effective, which depends, among other variables, on the characteristic diffusion temperature of the geospeedometer (i.e., effective diffusion and closure temperature). As most of the geospeedometric formulations these temperatures are below the basaltic solidus, we had used the denomination of “Subsolidus Cooling Rates or SCR” while the first are referred as ÂńIgneous Cooling Rate or ICR”. However, as explained above, we have reorganized the sections 5 and 6 of the paper to clarify and emphasize the differences between the petrological results and our numerical results. Figure 5 shows, the Time-temperature (T-t) trajectories versus the emplacement depth of the plutonic crust at 20 km off-axis. T-t histories of tracers are computed along their flow. However, according to the particular configuration of the tracer trajectories, temperature will not be the same versus time and x-y coordinates during the tracer journeys. This is true for the numerical model but should also be true for gabbros in nature. Then, reaching their final emplacements in the cooled crust, gabbro cooling rates will have received different thermal histories and will be different. This is particularly true if we considered that the final cooling rate represents necessarily an integration of this history. In the new version of the paper we have brought new explanations about the locations where the average cooling rates are sensitive according to their high and low temperature intervals. The locations of the concerned isotherms have also been added in Figs. 3 and 4 to illustrate the areas of the numerical solutions that are recorded by the average cooling rates. The oceanic crust is usually sampled in crustal sections far from the ridge axis, where gabbros record protracted thermal histories since their near-liquidus temperature at their intrusion until temperatures at their final depth of emplacement off-axis.

??????????????????????Page 2431: line 29, Theissen-Krah et al (2011) adopted an upper cracking temperature limit of 600C. The 400-1000C temperature range covers the range of values used by several authors; some of them are cited correctly in the next few lines.

»»»»»»»»»»This point is an illustration both of the diversity of opinions that are often applied to particular (but potentially important regarding their consequences on the solutions) geophysical values. Scientist still debate about the bounding limits of the temperature interval over which they observe the effect of hydrothermal cooling but, also debate about the value of the cracking temperature. This is why we have presented two series of cases illustrating possibilities of the code. With the numerical code, it is clear that it is possible to test the sensitivity of these hypotheses in terms of thermal and dynamic properties of the mid-ocean ridges and, hopefully, get clues on the cooling rates that are induced by the thermal structure of the corresponding solutions.

???????????????????page 2435: line 15-16, I don’t see any physical reason that justify the assumption that ïĄŹc = 2 Vp H and ïĄŹlb = 0.5 ïĄŹc = Vp H.

»»»»»»»»»>This result is a direct consequence of the global mass conservation that prescribes the balance between the quantity of mater flowing through the right and left sides of the computation box with the quantity of matter which enters the box from the mantle at the mid-ocean ridge. From its mathematical origin (velocity being a zero divergence field), the stream function is defined to an arbitrary constant. The value of this constant has on the computation since only the stream-function differences (or derivatives) have physical senses. It seem then convenient to set this arbitrary constant in such a way that ïĄŹlb = 0.5 ïĄŹc that leads to a zero stream function value at the surface. A few sentences have been added in the paper to better explain this point.

??????????????????Page 2436: line 22-23, it is not clear to me why the thermal behavior of the sheeted dyke layer is simulated by instantaneous freezing.

»»»»»»»»»The heat that is brought through melt injection is implicitly taken into account by the thermal boundary conditions at the ridge axis which is equal to the injection temperature from the MTZ level to the upper lens level and to the half –space cooling model conditions in the sheeted dyke layer from the upper lens to the surface. However, in this layer, the full energy equation is solved in thermal connection with the lower part of the crust (below the sheeted dyke layer). Then, the lateral propagation of heat is taken into account through the complete temperature equation, from the ridge axis to the lateral boundaries through; the conductive process, the latent heat release and the horizontal advection that occurs in the sheeted dyke layer. The vertical advection of heat is automatically cancelled by the zero vertical velocity condition in the sheeted dyke layer. However, the word freezing, employed in the first version of the paper, was misleading and has been replaced by solidification to describe modeling of the sheeted dyke layer. The Root zone of the sheeted dike complex in the Oman ophiolite goes through very abrupt cooling conditions (Nicolas et al, 2008). This layer is transitional between the magmatic system of the melt lens, convecting at 1200 C, and a high-temperature (<1100 C) hydrothermal system, convecting within the root zone. The whole root zone is a domain of very sharp average thermal gradient (7 C/m) Furthermore, in nature, the injection of the sheeted dykes occurs on a very short time compared to the slow spreading process that affect the whole crust. However, it is clear that an instantaneous freezing is not an instantaneous cooling that remains, as it is shown by the thermal evolutions of the sheeted dyke layer in Figures 3 and 4, based on hydrothermal thermal exchanges with the surface and conductive heat intrusion from the lower crust. The implementation of the sheeted dyke layer has induced deep and significant changes in the functioning of the numerical code that explain it cannot be compared with the previous one published a few years ago (Machetel and Garrido, 2009).

????????????????????Page 2437: line 23-25, Can I see some references from literature that support the temperature and the temperature interval for crustal melt used here (1230C, dt= 60C). The experimental petrology studies that I am aware of (Green and Ringwood, 1967, Yasuda and Fujii, 1994), show something different at -1 kbar, T solidus -1100C, T liquidus -1350C.

»»»»»»»»»»»>The values used in our study for crystallization (1230 °C, dt = 60° C) are based on the Kelemen and Aharonov (1998) (fig. 1) in their review paper Periodic Formation of Magma Fractures and Generation of Layered Gabbros in the Lower Crust beneath Oceanic Spreading Ridges. The reference has been emphasized in the text of the new version of the paper.

????????????????????Page 2438: line 23-25, Viscosity of the crust (hot and cold) is extremely low, between 2-4 order of magnitude lower that commonly assumed (list of references is very long. Could the authors explain why they have chosen those values and what are the consequences of such assumption on the thermal and dynamic results?

»»»»»»»»»»>Structural studies conducted in the Oman ophiolite indicate that the gabbro unit located between the diabase sheeted dike complex and the Moho is composed of magmatically deformed and not plastically deformed gabbros, except in the horizon just above the Moho transition where some plastic strain is locally registered[Nicolas,1992]. This demonstrates that below the melt lens a magmatic domain extends down to the Moho and that this domain is magmatically deforming. These studies allow us to conclude that in spite of its much limited melt fraction (5-15%), the LVZ is not a solid domain deforming by plastic flow but a magmatic domain defined by its ability to deform by suspension flow [Nicolas et al., 1993; Nicolas and Ildefonse, 1996].

????????????????????Page 2438 : line 24, I believe low cracking temperature is 400C (Nicolas et al, 2003) therefore the temperature of 700C adopted by the authors cannot be really considered a low T.

»»»»»»»»»»We agree with your remark. It is perfectly true that, according to Theissen-Kraf (2011) or Nicolas et al, (2003), 700C is rather an intermediate cracking temperature than a low one. Changes have been done in the text, figure captions, tables and figures to correct this mistake.

????????????????????Page 2439: line 20, It is very difficult to see from Fig.3 any temperature variations among the 3 models (G, M, S). Wouldn't be better instead to plot the temperature difference with respect to one model, say panel a) T(G), panel b) T(G)-T(M), panel c T(G)-T(S). Page 2440: line 16, Fig. 4 has the same problem of Fig. 3. Plotting the temperature differences may help to visualize better the T variations of the 3 models. Is there any reason why despite a different dynamic evolution, the 3 models show very similar temperature fields?

»»»»»»»»»>We fully agree with your remark and decided to refer the temperature evolution in function of the accretion geometry to the temperature pattern of the Gabbro Glacier "G" solution in the new version of the paper. Figures 3 and 4 have therefore been redrawn to take these modifications in to account. The text and the corresponding

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figure captions have also been changed.

???????????????????Page 2441: line 1 and following. Fig. 5 is not clear at all. Does the plot refer to tracers along the ridge axis (x=0)?, what is the lateral position of the tracers that are plotted in the figure? It would be terrific to see a x-y plot of temperature versus time for selected tracers located at different depths and horizontal positions at time zero.

»»»»»»»»»>The reviewer's comment show that we failed to provide a sufficiently detailed explanation of what is represented in the Figure 5 (left column). Indeed, the horizontal coordinate of Figure 5 (left column) does not represent a distance “x”, but time, whereas the vertical coordinate represents the “final” depth of emplacement of gabbro in the crust of tracers that have been injected at the ridge axis. During its journey from the ridge axis to its final emplacement (i.e., final time) in the cooled lower crust far from the ridge axis, tracers do not stay at a constant depth. This is particularly true in the case of Gabbro Glaciers “G” accretion model where the melt injected at the shallow melt lens builds the entire lower crust. This obviously induces downward trajectories near the ridge axis that are followed by the tracers. However all the tracers do not sink; some of them follow a nearly horizontal motion until their final emplacement depth in the crust. During accretion of the oceanic crust, the tracers follow the streamlines represented in Figures 3 and 4. Similarly, in the case of a Mixed shallow and transition zone lenses (“M”) structures, the tracers follow down and upstream trajectories that are deciphered by the stream-function. The vertical coordinate of Figure 5 only refers to the final emplacement (final time) of the tracers in the cooled crustal section at the lateral boundaries of the model. That means that looking at the evolution of the temperature field with time in Figure 5 (left column) one can see the evolution of temperature with time of a gabbro that is now emplaced at given final depth and that have travelled along a given stream function and, therefore, the time evolution along each tracer trajectory. In fact, Figure 5 (left column) mostly shows what the reviewer wanted us to show, but having 4-variables (T-t-x-y) the x-y variable is condensed and shown at its final depth (i.e., final time) of emplacement, instead of at its initial time. A better description of this figure has been rewritten in the text and figure captions in order to facilitate the reading of such temperature evolution.

???????????????????page 2441: line 20-21, The concept of opening and closing temperature in this context does not make any sense. The model presented in this study provided much more. It is possible to evaluate the instantaneous cooling rate by simply taking dT/dt at each location over time. If the authors want to make a comparison with petrological cooling models, I would suggest two possibilities: 1) compute the diffusion profiles given in the T-t path retrieved by the thermo-mechanical simulation. The computed profile should match the measured chemical profiles in real mid-ocean rocks. 2) Cooling rates based on chemical kinetics are related to the closure temperature of the geochemical system. Comparison should be done by choosing a particular system (say Ca diffusion in olivine), calculate the closure temperature and the cooling rate and then compare it with the cooling rate at the corresponding temperature from the geodynamic model.

»»»»»»»»»»>We agree with the Reviewer that our numerical models provides much more detail of the cooling rate history of the oceanic crust through the instantaneous cooling rates; petrologically derived cooling rates are obtained from inversion of crystallization kinetic texture or mineral chemical diffusion profiles obtained in natural oceanic gabbro. In order to avoid confusion, we no longer use in the revised manuscript the term closure or open temperature, which are parameters related to the retrieval of cooling rates from chemical diffusion modeling of compositional profiles in minerals. Instead âĂŤas suggested by the ReviewerâĂŤwe now provide in the revised Figure 5 (right panel) the instantaneous cooling rates along the T-t path of tracers as a function of the time and their final depth of emplacement 20 km off-axis (i.e. final time). These instantaneous cooling rates are the numerical derivatives of the T-t history of the tracers that is shown in the mid panel of Figure 5. These two new panels in Figure 5 show that: - Instantaneous cooling rates vary along the T-t flow path. As longer time indicates longer distance from their on-axis intrusion, they also show that instantaneous cooling rates vary as a function of the distance from the ridge axis. - Cooling rates at super-solidus conditions (T > 1050 C) are generally slower that those a subsolidus conditions: it is hence likely that natural proxies of cooling rate at super-solidus conditions (i.e., igneous crystal size) provides different values as those using proxies based on subsolidus intracrystalline diffusion. It is not our intention to make a strict comparison of numerically derived cooling rates with those derived from petrological observations. As pointed out by the reviewer, this comparison would require simulation of crystallization and chemical diffusion along the cooling T-t trajectory employing numerical models of net-transfer and exchange reactions in combination with estimates of intracrystalline diffusion; the large number of variables that can be adjusted in these forward models precludes arguing for the uniqueness of any successful simulation. Such simulation is beyond the scope of our numerical model, which, however, lays the foundation for investigate forward crystallization and chemical diffusion modeling using the T-t path history (Fig.5) of each tracer obtained independently from thermo-mechanical modeling.

?????????????????Page 2441: eq. 15, The definition of cooling rate given in Eq. 15 is only true for linear cooling otherwise it is useless. If the intent is a comparison with petrological models I would suggest the author to review the definition of closure temperature (Dodson, 1973), it is not an arbitrary concept (temperature at the characteristic time when D decreases by a factor equal to e2/3). Furthermore, cooling rates from petrological models are dependent on the closure temperature and the geochemical system therefore a comparison of cooling rates from this study and petrological studies would require the same critical approach.

»»»»»»»»>To avoid confusion with petrological models, we no longer use the terms opening and closure temperature. As discussed in the previous reply, and pointed out by the reviewer, we agree that a strict comparison with petrological cooling rates would require diffusion modeling along tracers T-t history. As one can see in Figure 5 (panel in the mid and right columns), the T-t path of tracers is nonlinear and hence the cooling rates are not constant during the accretion of the oceanic crust. We still think that Eq.15 is useful to portray relative differences of average cooling rate (Fig. 6) at arbitrary high and low Delta-T temperature intervals; these arbitrary high and low temperature Delta-T portray the strong variations of average cooling rate at high and low T intervals that can clearly be seen by the slope variations of curves in the new panels in the mid and right columns of Fig. 5. The actual values of average cooling rate will depend upon the choice of delta-T, but the point of Figure 6 is to show that relative variation of average cooling rate systematically vary depending on the crustal accretion mode.

?????????????????Page 2445: line 5 and following, I will omit completely this part. It is not clear to me why it is so important to compare the cooling rates from this study with those retrieved from petrological studies. Beside adding a few x-y plots f T versus time, the impact of this would dramatically increase if the results would be compared with mid-ocean ridges observable data rather than numerical results using other methods. For instance, assuming that Fig. 6 does not plot cooling rates computed from Eq. 15 but the true instantaneous cooling rate versus height, it would be interesting to see a discussion on how these extremely low cooling rates affects heat flux on the surface. Mid-ocean ridge topography could be easily computed and compared with available data.

»»»»»»»»>As explained above, we have fully reorganized this part of the paper that has induced a significant reduction of the petrological cooling rate discussion. All the numerical results are now presented in section 5 and new panels in Fig. 5 (mid and right column), while we maintain a shorter discussion of petrological cooling rates in section 6.

Please could you find in the supplement file the formatted version of our comments and the proposed revised version of the paper.

Please also note the supplement to this comment:

http://www.geosci-model-dev-discuss.net/6/C1100/2013/gmdd-6-C1100-2013-supplement.pdf

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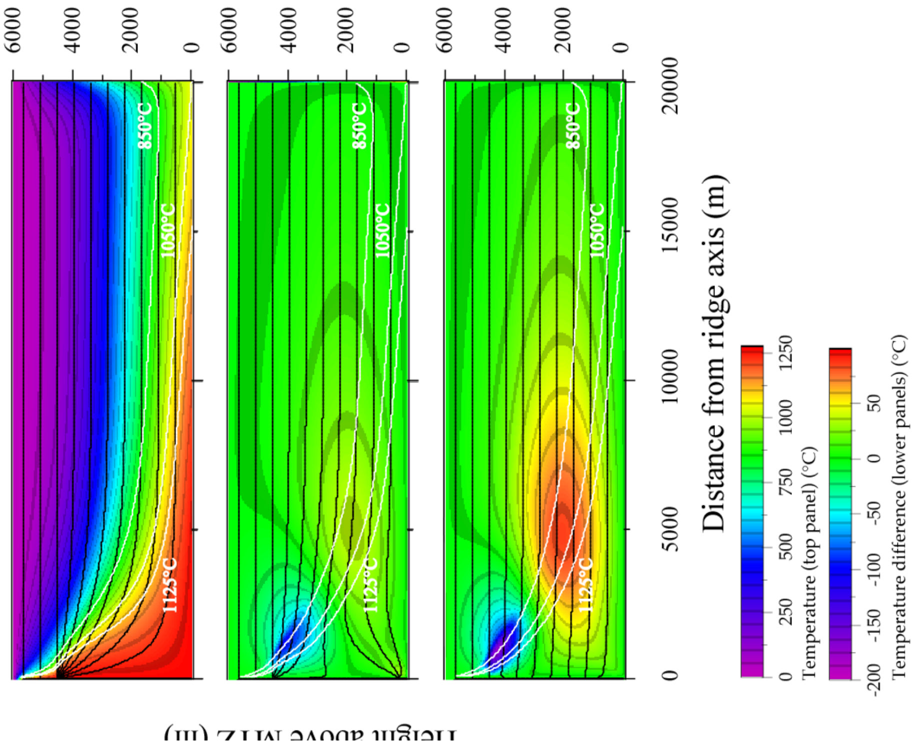

Fig. 1. New figure 3

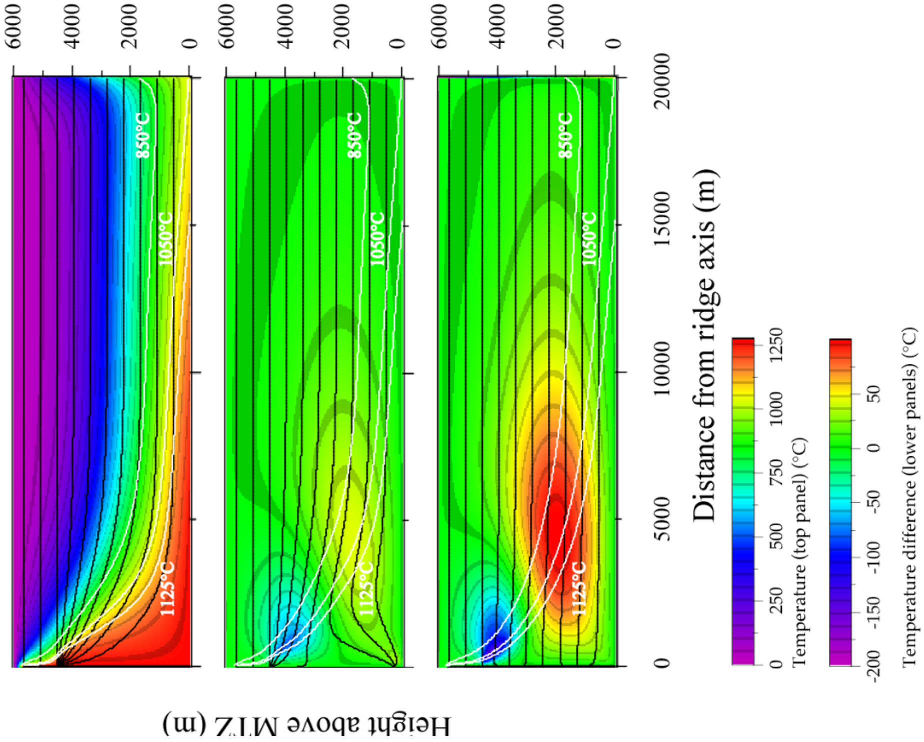

Fig. 2. New figure 4

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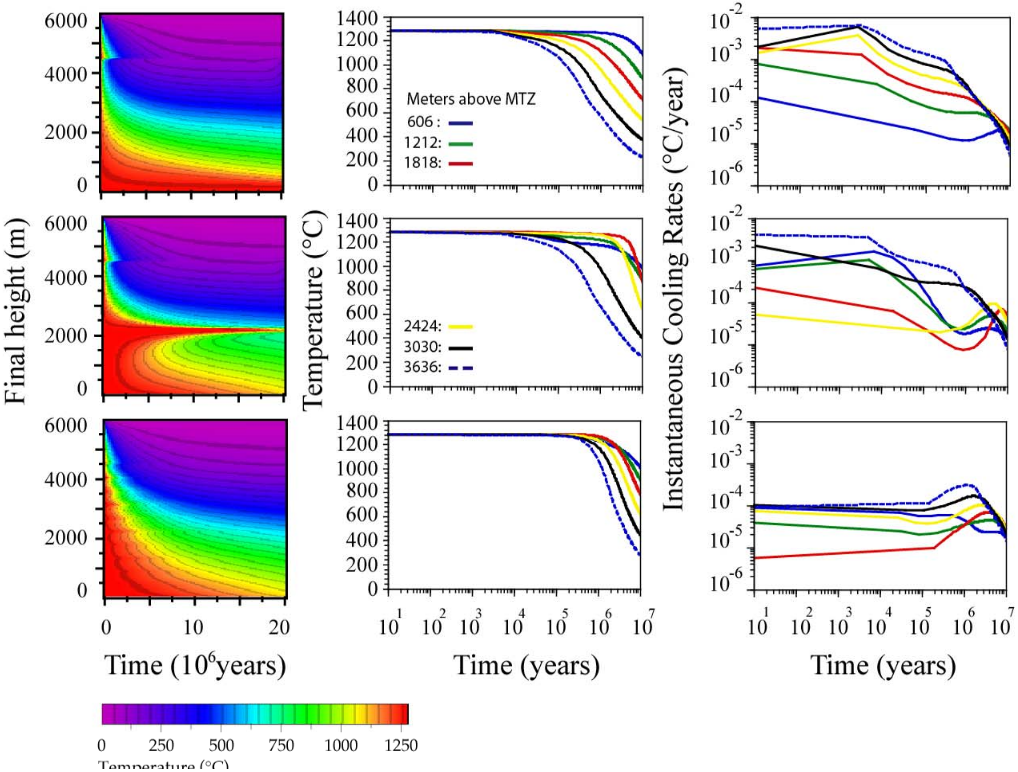

Fig. 3. New figure 5

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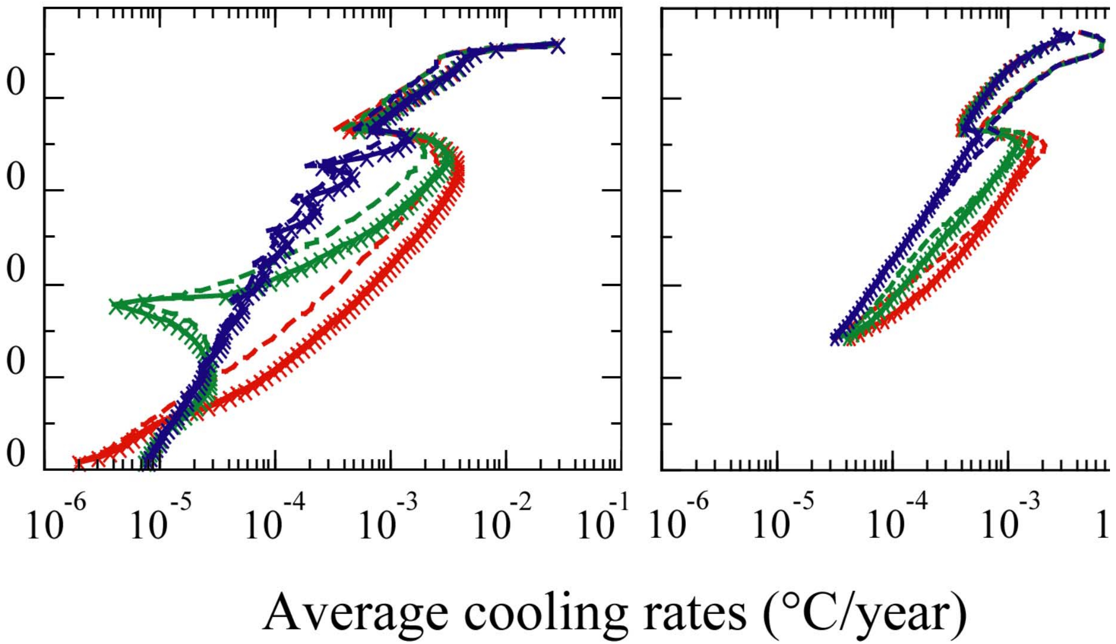

Fig. 4. New figure 6