Interactive comment on OESbathy version 1.0: A method for reconstructing ocean bathymetry with realistic continental shelf-slope-rise structures

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We appreciate the many constructive and thoughtful comments by our 2 referees. In our revision we have endeavored to address each comment and editorial suggestion. Below, referee comments are reproduced in **BLACK** text, our responses are in **BLUE** text, and a marked-up revised manuscript is provided in a separate pdf

Response to Benjamin Hell (Referee)

General comments

The manuscript submitted by Goswami et.al introduces a method to model world ocean bathymetry based on today's observed relationships between the age of oceanic crust, the sediment cover of oceanic crust and the geometry of passive continental margins. If these relationships are known for the geologic past, or can be extrapolated from today, the method can reconstruct paleo bathymetry for the World ocean configurations in the geologic past.

Considering the importance of ocean bathymetry for e.g. climate modelling, the question of reconstructing paleo bathymetry is very relevant. The presented approach is comparably easy to apply, because it does not rely much upon observed geologic data other than crustal age and ocean basin geometry.

The authors test their method against the present world ocean bathymetry. The OESbathy model appears to work well for the open ocean, i.e. mid-ocean ridges and abyssal plains. It has limitations when it comes to passive continental margins, especially those heavily shaped by terrestrial sediments. The method does not deal with active continental margins, large igneous provinces, seamounts and other regional "anomalies" such as hotspots.

We excluded river deltas, seamounts and plateaus, and features attributed to dynamic topography, all of which represent separate modeling challenges. Our focus was on open ocean bathymetry, modeled with great success with the age-depth relationship; from this we leveraged an empirical relationship between ocean crust and continental shoreline for a "generalized" shelf-slope-rise structure (**Equation 8**). This modeled structure may be extrapolated back in time to fill in the bathymetric gap between open ocean and shoreline in paleo-worlds. Note: we replaced "realistic" with "generalized" in the manuscript title.

When applying the model for a particular situation in the geologic past, calibration with any existing additional paleo bathymetry data probably increases the significance of the results. It would be good if the authors could test or comment this option in the final version of the article.

In our revision we discuss effects of bathymetry on ocean circulation in more detail, in a new Section 5.3 in the Discussion.

Our methodology offers a convenient way to accomplish multiple tests with its “modular” design of various major bathymetric components: (1) open ocean cooling plate model; (2) open ocean sediment cover; (3) modeled shelf-slope-rise structure; and in the future, important features such as (4) seamounts and plateaus; (5) trenches; (6) dynamical topography from mantle processes; and (7) eustasy.

The manuscript and supplementary material are well-structured and reasonably complete, including the model code. However, a discussion of and references to prior work on the topic of paleo bathymetry modeling are still missing. Also the figures could be improved in order to make it easier for the reader to follow the argumentation in the text.

Apart from a number of suggestions for less significant changes (see below), I believe that the manuscript with these improvements will be mature for publication.

Specific comments

The following more specific comments on the manuscript are structured according to the GMD review criteria.

Scientific significance

Does the manuscript represent a substantial contribution to modelling science within the scope of Geoscientific Model Development (substantial new concepts, ideas, or methods)?
-Does the paper present novel concepts, ideas, tools, or data?
-Does the paper represent a sufficiently substantial advance in modelling science?

Not being an expert in paleo bathymetry modeling myself, I believe that the manuscript introduces a significant advance in at least two ways: (1) The method can be applied to the entire World ocean, and (2) it takes passive continental margins into account.

However, the approach seems not to be fundamentally new, and similar or related reconstructions have been made by e.g. Hayes, Zhang and Weissel (2009; EOS Transactions vol 90/19) or Celerier (1988; Palaios vol 3). The lack of references to such prior work is a major issue of the manuscript that should be fixed in the final article.

In the revised **Introduction** we now provide a brief historical perspective on paleobathymetry reconstruction, including citation to Hayes et al., 2009. We also now cite Célérier (1988) in the **Methods**.

Scientific quality

Are the scientific approach and applied methods valid? Are the results discussed in an appropriate and balanced way (consideration of related work, including appropriate references)? Do the models, technical advances, and/or experiments described have the potential to perform calculations leading to significant scientific results?
-Are the methods and assumptions valid and clearly outlined?
-Are the results sufficient to support the interpretations and conclusions?
-Do the authors give proper credit to related work and clearly indicate their own new/original contribution?
-Are the number and quality of references appropriate?

According to the authors' approach, bathymetry is a superposition of three factors: (1) the underlying oceanic crust, (2) the sediment layers on top of it, and (3) typical passive continental margins comprising shelf-slope-rise structures. Although this of course is a simplification, at least the first two factors are a valid and common assumption. The presented method, however, seems to be limited with regard to the third factor. Passive continental margins vary a lot in comparison to each other, and it seems to be difficult (if not impossible) to derive some kind of "typical geometry" for them. Some specific comments about this can be found below under the technical corrections. But the authors are very honest and quite clear in discussing this shortcoming of their method.

Our approach (**Equation 8**) captures the first order passive margin geometry, which is then evaluated in the Discussion, where we identify limitations to address in future versions of the reconstruction.

The model is verified by applying it to present day world ocean bathymetry. The authors compare the modeled results carefully with the actual present day data, and describe them accurately.

In section 4.2 the reconstructed open ocean regions are described. According to Fig. 10, most areas are modeled to within ± 1000 m of the actual, present day bathymetry. According to Fig. 3, these areas also feature generally less than 1000 m of sediment. The model relies upon a linear regression of sediment thickness data with a lot of variation (Fig. 2), indicating a more complex reality than what the model is capable to simulate. From the figure it is not clear why and how the chosen regression line fits the data best. The question how much the model really is improved by adding the modeled sediment layer is unfortunately not answered.

One can argue about the validity of the reconstructed shelf-slope-rise structures (section 4.1). Also here, the validation is heavily based on a regression line fit to data with large variation (Fig. 8). The authors mention an "anomalous" outlier originating in the Gulf of St. Lawrence. If this point was not taken into account, a simple linear relationship would likely fit the data equally well. However, to me the variation of the points in Fig. 8 indicates that one should not try to find any simple relationship "explaining" the difference between continental slope and rise regimes. Maybe not distinguishing between slope and rise would have yielded equally good (or better) modeling results.

In an earlier version of the model, we considered slopes only, defining the M point at shelf break and P point at closest oceanic crust (usually base of slope) (Goswami et al., 2013). However that approach produced modeled shelves that were consistently too narrow, and led us to redefine the M point at the closest oceanic crust, and the P point at the oceanic edge of the rise (e.g., **Figure 8a**). That is, our model now accounts for slope+rise as a single entity.

The lack of references to prior work has already been mentioned above. Otherwise, the references generally appear to be appropriate and complete.

As mentioned, in the revised **Introduction** we now provide a brief historical perspective on paleobathymetric reconstruction, including citation to Hayes et al., 2009 (among others). We also now cite Célérier (1988) in the **Methods**.

Scientific reproducibility

To what extent is the modelling science reproducible? Is the description sufficiently complete and precise to allow reproduction of the science by fellow scientists (traceability of results)?

5. Is the description sufficiently complete and precise to allow their reproduction by fellow scientists (traceability of results)? In the case of model description papers, it should in theory be possible for an independent scientist to construct a model that, while not necessarily numerically identical, will produce scientifically equivalent results. Model development papers should be similarly reproducible. For MIP and benchmarking papers, it should be possible for the protocol to be precisely reproduced for an independent model. Descriptions of numerical advances should be precisely reproducible.

The methodology is described very thoroughly. This includes a discussion of the data the model is derived from, the formulae for subsidence due to plate cooling, and the sediment model. The supplementary material also includes the program code. To run the programs, proprietary standard software is needed (Matlab, ArcGIS). All input data is open.

Presentation quality

Are the methods, results, and conclusions presented in a clear, concise, and well-structured way (number and quality of figures/tables, appropriate use of English language)?

7. Does the title clearly reflect the contents of the paper? The model name and number should be included in papers that deal with only one model.
8. Does the abstract provide a concise and complete summary?
9. Is the overall presentation well structured and clear?
10. Is the language fluent and precise?
11. Are mathematical formulae, symbols, abbreviations, and units correctly defined and used?
12. Should any parts of the paper (text, formulae, figures, tables) be clarified, reduced, combined, or eliminated?
14. Is the amount and quality of supplementary material appropriate? For model description papers, authors are strongly encouraged to submit supplementary material containing the model code and a user manual. For development, technical, and benchmarking papers, the submission of code to perform calculations described in the text is strongly encouraged.

The title of the manuscript clearly reflects its contents. One could argue about the word “realistic”, as the quality of the shelf-slope-rise structures is the major shortcoming of the model.

We have changed “realistic” to “generalized.”

The abstract is easy to read, appears complete, summarizes methods and findings well, and also includes shortcomings of the model.

The manuscript is structured in the classic way (introduction, methodology, results, discussion, conclusions). I would swap sections 4.1 and 4.2 in order to follow the same structure as under section 3, but that is a minor comment.

Apart from minor issues (see below), the language is clear and the manuscript is very readable. This is also true for (most) formulae, abbreviations etc.

The manuscript in its current form is very comprehensive, and the authors should consider shortening it carefully in order to better support the main findings. One example is section 5.2, that is not strictly related to the OEMbathy model at all, apart from its last paragraph. Also the amount of figures can be overwhelming, especially if one includes the supplementary material. Where appropriate, figures should be combined. In figure series, insignificant figures could be left out. The supplementary material is complete and appropriate, but one could maybe leave out plain reproductions of other scientists' datasets that are easily accessible through the internet.

Although not explicitly mentioned under this section in the review guidelines, I would like to spend a couple of words on the quality of the figures, which I think should be improved in order to make it easier for the reader to follow the authors' argumentation. I believe that the importance of high quality figures cannot be underestimated for the perceived quality of an article.

Many of the figures are too small to be most useful (e.g. the maps, Fig. 8 and Fig. 11). Also, often the color scales chosen are not the most appropriate for its purpose. One problem is very low contrast (e.g. Fig. 3). In other occasions, a color scale (with the same colors) differs in values between figures that are sometimes even being directly compared in the text (e.g. Figs. 12a and 13a). A very common problem (and certainly not only in this manuscript!) is the inappropriate use of the rainbow color scale to express a "positive-neutral-negative" relationship, as e.g. in Fig. 10 (and many more). Such figures are much easier to interpret if the zero or neutral value is plotted in a neutral color (white or grey), and positive and negative values get a specific color of their own. A standard color scale for such cases is e.g. blue-white-red. The rainbow colors with a "floating zero color" (between different figures) are rather confusing. If the authors even stick to a consistent color for the land areas (e.g. grey), the eyes of the readers will be pleased even more…

We agree that the color schemes of some of the maps needed improvement, and have revised them. The revised figures are:

Figure 3: changed to "jet" color scheme.
Figure 11: We increased the fonts in the map and circled those numbers that have profiles.
Figure S1: reversed color scheme.
Figure S2: changed color scheme to match Divins map.
Figure S6: changed color scheme to match Fig. S5 of Muller et al. (2008).

Technical corrections

Please take these corrections as suggestions. Some of them are more significant than others (e.g. the ones regarding section 3), and many are certainly a matter of taste (or nit-picking).

Section 1

Page 3081 Line 27: Name the model "OESbathy", and do not abbreviate it. As the authors state, the abbreviation "OES" is already being used for "Open Earth Systems".

We now use the term " OESbathy" throughout the paper.

P 3082 L 7: Are the confidence levels really "quantitative", or only qualitative? Standard deviation works strictly only for Gauss distributions, and ocean hypsometry is not Gauss distributed.

We have removed the third point about “quantitative confidence levels’ and added text in Section 4.3.1 to indicate that these statistics are used as basic measures of the three bathymetries.

Section 2

P 3082 L 12, P 3083 L 1: Use subsection headings for ocean crust age and sediment thickness data.

Done.

P 3082 L 12 to L 26: The entire section could be shortened significantly.

We have removed some extraneous text.

P 3082 L 12 and L 14: Use the same term, either “ocean crust age” or “crustal age”.

We have now ‘standardized’ the term as “ocean crust age” throughout the text.

P 3082 L 13: Remove the web address from the citation, and put the complete web address to the data into the reference instead (http://www.earthbyte.org/Resources/agegrid2008.html).

We decided to include web addresses of databases in the supplementary file.

P 3082 L 15 and L 18: I would call “reconstruction age” rather “reconstruction time”.

We agree and simplified the text.

P 3082 L 20: Leave out the (self-evident) definition of bathymetry.

Done.

P 3082 L 24: Which exact version of EB08 was used? The download page lists several versions.

We now indicate the URL in the supplemental file in the Figure S1 caption: ftp://ftp.earthbyte.org/earthbyte/agegrid/Palaeo/2008/Data/

P 3082 L 24: It is irrelevant that the data comes in decimal degree coordinates.

We deleted the phrase.

P 3082 L 26: “0 Ma” instead of “000 Ma”

The terminology “000 Ma” is in anticipation of future (paleo)bathymetries for example at “090 Ma” and “150 Ma.”

P 3083 L 1: Divins (2003) has been outdated since an update was published 2013.

As we understand it, the Whittaker et al. (2013) contribution adds data from the Southern Ocean to the Divins (2003) database. We have added a note about this in the Figure S2 caption.

P 3083 L 6 and L 12: How was the "resampling" (instead of "re-gridding") done?

We mapped ETOPO1 onto the EB08 grid in ArcGIS.

Section 3

P 3084 Eq 2: The use of *m* as counting index is odd. Use *i* instead.

This equation is "copied" from Turcotte and Schubert (Eq. 4.213, 2002 edition, now Eq. 4.211, 2014 edition) and we are reluctant to change from m to i.

P 3084 L 15 to L 18: Spell out the values of the mentioned constants.

These may be obtained from values for beta given in Table 1. For the Global Average ocean:

sqrt(k) = 329.5 (m s^-0.5) x sqrt(pi) = 584.0235 (m s^-0.5)
k=341083.5 m^2/s

yL^2 = 341083.5 (m^2/s) / 4.97 x 10^-2 (s^-1) = 68628.5 x 10^2 m^2
yL=2619.7 m

We have added values next to the constants in Section 3.1:

alpha = 3x10^-5K-1
rho_m=3300 kg/m^3
rho_w=1000 kg/m^3
Tm-Tw = 1300 K

P 3085 L 10 to L 14: These two sentences are hard to understand. This is partly because the figure references could be put in better places. I also wonder what "multicomponent" refers to here. Here is a suggestion for re-phrasing this section (which would eventually also require a re-ordering of Figs. 2-5):
On top of the depth-to-basement $\omega\tau$ (Fig. 4), a parameterized sediment layer was isostatically added to complete the open ocean bathymetry. The OESbathy sediment thickness was parameterized based on a third degree polynomial fit (Fig. 2) between area corrected global sediment thickness data (Whittaker, 2013) and age of the underlying oceanic crust τ. The resulting global sediment thickness is shown in Fig. 3, and Fig. 5 shows the result of adding this sediment layer isostatically to the basement depth.

By "multicomponent" we meant "multi-layer" (see Table 2). We have rewritten the first of the two sentences as: "A parameterized multi-layer sediment cover, called 'OES sediment thickness' (Figs. 2 and 3)…"

P 3085 L 13 and Fig. 2: It remains unclear why this polynomial line fits the data best. From the figure, a linear regression seems to fit the data points equally well (or badly). The data also suggests that the regression line should not (almost) pass through the origin, and that it heavily underestimates sediment thickness for τ > 160 Ma. The modeled sediment layer is a factor for the quality of the overall model, so the assumptions it is based on and its limitations should be explained very clearly.

We found that the polynomial fit gave a slightly lower norm of residual than a linear fit, and the linear fit is slightly lower at old ages. Therefore we used the 3rd order polynomial as shown.

The youngest oceanic crust has little to no sediment cover and should pass through (or close to) the origin. It does look as if the data appear to say otherwise; however, when we plot close to the origin, the data are the ages assigned to the global sediment data (from the underlying ocean crust age) have substantial uncertainty; binning likely mixes ages within magnetic anomalies, which are on average 0.5 myr in duration. At the other extreme, at >160 Ma, the spread of sediment thicknesses is quite large (although not as large as for ~100-125 Ma). Nonetheless the majority sediment thickness at this age indicates a mean value that is represented by the curve fit value at e.g., 160 Ma. We now in the paper, in Section 4.3.2 point to the similarity of our sediment model with the more parameterized sediment model of Muller et al., 2008 (Science): our Figure S6 compares well with their Fig. S5, both are difference maps with respect to Divins sediment. This implies that large global areas are well represented by the simple averaging that we used.

P 3086 L 15 to 16 and Eq 8d: Please explain why geometric relationships between *l*sh and *l*sl + *l*r as well as between *l*sl and *l*r should be assumed overall. The scattered data in Figs. 8B and 8C does not imply a strong correlation between these lengths.

The starting logic was that l_{sh} and $l_{sl}+l_r$ are related: when l_{sh} is short, $l_{sl}+l_r$ is comparatively short. At some large l_{sh}, $l_{sl}+l_r$ will reach a maximum length beyond which it will not lengthen further for even larger l_{sh}. You can see an example of such an extended shelf in Figure 11, Profile 58 where the corresponding slope-rise width is not very extended.

The 34 points (17 sets x 2, shown in Figs. 6, 7 and S4) presented in this work in Fig. 8b seem to bear this out - the relationship shows signs of leveling off at large l_{sh} (Fig. 8b). Thus, we reasoned that a linear model was inappropriate (because it increases upward “infinitely”) and we settled on the quadratic model. In hindsight a logistic model would have been better. Our plan for the future is to assess the individual transects that make up each of the 17 sets and evaluate additional transects in order to populate Figs. 8b and 8c with more data, and to test other curve fitting models.

P 3087 L 1: To my eye the curves fitted to the data in Figs. 8B and 8C are very speculative. As the results show that the model’s shortcomings are mostly in the reconstructed shelf-slope-rise structures, I believe that the data in Figs. 8B and 8C primarily shows that the observed reality is much more complex than a simple geometric relationship. Maybe one could argue that there is a (linear?) relationship in Fig. 8B. But the point cloud in Fig. 8C probably shows that one at least should not distinguish between continental slope and rise when modeling passive margins in the here presented way (i.e. rather assume that *P* = *M* everywhere).

We agree that the data we have collected are sparse, but we began to see a pattern, and once we did, we proceeded with basic fitting and developed the reconstruction methodology. In particular, we discovered from an earlier less successful attempt that slope+rise was an important construct. In that earlier attempt (Goswami et al., 2013), we considered slopes only, defining the M point at shelf break and P point at closest oceanic crust (base of slope). This resulted in shelves that were much too narrow. We redefined the M point at the edge of the ocean crust, and the P point at the toe of the rise (see **Figure 8a**). Thus our model now accounts for slope+rise as a single entity. From this we saw the way forward for in the parameterization.

P 3087 L 8: The statement that "the methodology works well…" is adventurous, considering the fact that even the passive margins that the authors believe are modeled correctly often feature errors of 1000 m or more. Unfortunately *l*sh and *l*sl is not plotted on any of the axes in Fig. 8, so the author's reasoning about "anomalously" wide or narrow shelves cannot be verified. I believe that these problems are a clear sign that nature is more complex than what can be modeled with these simple relationships, or what could be classed as "normal" and "abnormal".

Figure 8b and 8c use data points only from regions where complete rifting history is preserved. A follow-up investigation should examine other shelf-slope-rise structures across the globe to clarify (or disprove) the relationship we have captured, discussed in our response to the previous comment.

Section 4

P 3087 L 17 and P3088 L 13: Swapping the order of subsections 4.1 and 4.2 should be considered.

We decided to keep as is.

P 3088 L 4: The number "-0.003" should be "-0.004" according to Fig. S5.

Corrected.

P 3088 L 10: There is no Fig. S4c. Probably the authors refer to Fig. S4 set 3.

Corrected.

P 3088 L 8-12: If the "anomalous" point originating from the Newfoundland shelf was removed in Fig. 8b, a much less steep linear regression would fit the data better than the than the polynomial.

At this point, we are reluctant to remove any data from this set, without following up with more measurements (see response to comment **P 3087 L 8**).

P 3089 L 10: It would be interesting to know if the authors have made any (unsuccessful) attempts to also model active margins, and why they chose not to reconstruct trenches in the presented model.

We did not attempt to model trenches explicitly. However, in our study of shelf width vs. slope+rise width we forced the parabolic fit to zero to approximate trench geometry near margins.

P 3089 L 12: I believe that standard deviation is used incorrectly in this context. Strictly, standard deviation is a measure of the width of a normal distribution of samples (Gauss curve). Global bathymetry is not normally distributed and a hypsogram is definitely not a Gauss curve. Therefore, a calculated standard deviation for global ocean bathymetry mathematically does not have a meaning. The authors should use a more appropriate statistical measure for the spread of the data.

We used moment-based statistics to compare the three bathymetries, not to characterize the spread of data. We now provide text to emphasize this in Section 4.3.1 where we discuss basic statistics.

P 3090 L 5: Refer to “Sect. 3.3” instead of “Sect. 3”.

Done.

P 3090 L 26: Maybe “profiles” would be a better word than “lines”.

Done.

P 3091 L 1: Figures are labeled with upper-case letters, while references are lower-case.

We will correct the cases in the figures.

P 3091 L 20: Is “hyper-extended shelf” a commonly used phrase? Otherwise a neutral formulation such as “because our parameterization fails to model this extremely wide shelf” would be more suitable.

We substituted in your phrasing.

P 3091 L 25: “enormous layers” instead of “an enormous pile”

“Sediment pile” or “sedimentary pile” is an accepted term in geology (and sediment may not be layered in the delta that is being referred to). So we have kept the term.

Section 5

P 3092 L 21-22: Please explain further why extrapolation back in time produces narrowing of the shelf-slope-rise structures.

Less sediment would have arrived at the continental margins back in time, so presumably the structures were not as built up and out as much as they are today. However, the issue is very complex with presence of rifting, subsidence and basin dynamics.

P 3092 L 25: It is unclear what “far field” means in this context.

We meant “not local”. We have removed the words.

Section 5.2: Apart from the last paragraph, nothing in this long section is about OESbathy.

This is true, and so we have removed most of the discussion.

P 3093 L 2: “reconstructions far back in time” instead of “deep time reconstructions

“Deep time” is an accepted term in geology, and so we have not changed this phrase.

Section 6

P 3095 L 8: Is the shelf-slope-rise reconstruction method really “well established”?

We have rewritten the sentence to separate the well established (ocean crustal age, cooling plate model and global ocean sediment) from the one under development (shelf-slope-rise structure).

P 3095 L 13-14: See comment above regarding the use of standard deviation.

We use statistical moments to compare the three modern bathymetries, and not for quantitative analysis of error.

References

P 3097 L 1 and L 20: Resources from the internet should have a complete web address and access date. Also, the web address in Fig. S3 should point at the original source, not a download site where the data set is mirrored (http://www.ngdc.gov/mgg/sedthick/sedthick.html and http://www.ngdc.gov/mgg/sedthick/sedthick.html, respectively).

In the figure captions we now provide the precise URLs for the figures that use online data.

Figures

Fig. 7: Label the sub-figures in the same way as in Fig. S4 (i.e. Set 4, Set 15 and Set 17).

We kept the labels for Figure 7, however, in the caption we now identify where these transects occur in Figure S4.

Figs. 7 and S4: The many and colorful gridlines are disturbing. What is the color scale for the background data in the middle panels?

These grids were originally important for investigating the shelf, slope and ridge lengths for each margin. We decided to leave them in. In the figure captions we now explain the color scheme for the middle panels.

Fig. 8A: Could be included in or merged with Fig. 1

For convenience we have decided to keep this figure.

Fig. 11: Highlight the labels in the map (e.g. with bold font) for the profiles shown in the lower part of the figure. Otherwise they are very hard to find. I also wonder how the profiles are ordered; maybe there is a more intuitive order that would make it easier to jump between the profiles and the map.

We have increased the fonts of the labels in this map, and circled the ones that appear as profiles.

Fig. 12: Color scale says “Distance”, should be “Depth”.

Done.

General use of units: Mathematically correct is to write e.g. "Depth / m", so that the plotted number becomes dimensionless. "Depth, m" or "Depth (m)" is unfortunately common, but not quite correct.

See also the general comments about the figures under presentation quality.

We have made numerous adjustments to the figures, map color schemes, etc.

Supplementary material

Table S1: The SI unit for density is "kg m-3", not gram-meter per light speed squared ;-)

cc=cubic centimeter. But we have now adjusted to "cm^3"

Fig. S3: Use the same color scale as in Fig. 5. Have the color scale start at zero.

We tried rescaling Fig. S3 to start at zero, and found that it resulted in a very "unpleasant" effect, and so we are keeping as is.

Fig. S6: Unclear which data set was subtracted from which one. What about positive values on the color scale? They seem to exist at least in the Pacific Ocean. A positive-neutral-negative color scale would be easier to interpret (see above).

We have changed the color scale so that we can compare with Fig. S5 in Muller et al. 2008 (Science).

Fig. S8: The color scales should be white for values between 0 and 1000 or 2500, respectively. Fig. S8B does not add any information above what is shown in Fig. S8A.

But it does highlight the dramatic anomalous elevation of some areas, e.g., Iceland.

Fig. S9: Typo ".diagram". The figure is not explained anywhere in the text, and it is rather complex. Therefore it should be explained better in the caption, e.g. summarizing the general workflow and stating that the numbers refer to the numbers of the scripts in the supplementary material.

We corrected the typo and now refer to this figure in the Methods section.

3 Response to Anonymous Referee #2

This paper describes a method for reconstructing the bathymetry of the seafloor, using only the age of the seafloor and its proximity to a continental margin (which can be estimate from a tectonic reconstruction model). A method like this could be useful for estimating the bathymetry of the seafloor at past times, which can be useful for developing the boundary conditions for paleo-climate or paleo-oceanographic models. The authors give several examples (in the introduction), where the topography of the seafloor affects ocean circulation, and is therefore of interest to paleoclimate studies.

The method presented is extremely simple, and consists of two parts. In the first part, they estimate the depth of the open ocean from the age of the seafloor. In the second part, they estimate the bathymetric variations along the edge of the continental shelf.

They then apply their methods to the present-day seafloor to evaluate the success of their models.

Although the model does a reasonable job of reproducing the topography of the present-day seafloor, I am not convinced that this study represents a significant advancement in "geoscientific model development", for two primary reasons, which I describe briefly below and in more detail later:

Our motivation was to take cues from the modern world and parameterize and apply them to the past (principle of uniformitarianism). We committed to a simple approach, and present a nominal output with very little to no enhancement. We envision gradually improving and adding complexity to the model for specific applications, e.g., paleoclimate simulation.

The reconstruction methodology is "modular" with the following components: (1) open ocean cooling plate model, (2) open ocean sediment cover, and (3) modeled shelf-slope-rise structure. In the future, other important components can be added such as (4) seamounts and plateaus, (5) trenches, (6) dynamical topography, and (7) eustasy.

First, the "models" developed are merely simple equations – this is not so much an advancement in modeling but instead an application of current understanding of bathymetric variations on the seafloor. For example, the equation they develop for the bathymetry of the open ocean (equation 2) is taken directly from the Turcotte & Schubert 2002 Geodynamics textbook. The sediment correction (section 3.2) is expressed merely as a function of seafloor age, whereas previous authors have developed more sophisticated expressions that take into account latitude or basin-specific variations (see below). The expression for the shelf-slope rise (equation 8) is simply an empirical exercise in slope-fitting for the present-day shelf structures. This is seemingly the newest part of the work, but the authors do not present anything particularly sophisticated– it is just an empirical analysis.

The shelf-slope-rise equation (**Equation 8**) develops an empirical relationship between shelf width and slope-rise width using two points, one defining the distance from shoreline to nearest ocean crust (M point) and the other defining the oceanward extent of the shelf-slope-rise (P point). This constitutes a reality-based approach for determining the shelf-slope-rise structure for any juxtaposition of continental and oceanic crust with respect to the shoreline. In deep-time applications, ocean crust (i.e., from modeled age) and shoreline (i.e., from paleogeographic reconstruction) are the only parameters required to reconstruct the structure.

This brings up a second concern: A study like this is only useful if it can be usefully applied to other studies. I don't think that is the case here. In a sense, the models are so simple that they could be developed "on they fly" as part of a larger study on an application of a model like this. Indeed this is already true for the open ocean – there is a long history of various authors developing expressions for seafloor bathymetry as a function of age, and Muller et al 2008 and Conrad 2013 have already applied such expressions for the geologic past. For the continental shelf, I am not sure that the model presented here is particularly useful, but because the model (equation 8) does not take into account any local knowledge of the continental shelf (e.g., presence of a sediment source, whether it is a passive or active margin). This part of the study would mostly only be useful for estimating the shelf topography of a particular margin (instead of an average over all margins) – and thus some information about local geology would be available and useful for any practical uses. It would be better to develop a region specific analysis for different types of margins (sediment-rich vs. sediment starved, active vs. passive), and then apply the correct one as necessary when it is necessary to reconstruct the bathymetry of a margin. In short, I don't see enough here that couldn't be done better on a case-by-case basis in individual regional studies.

In the **Introduction**, we suggest that OESBathy 1.0 can be used in modern applications to assess the influence of the reconstructed bathymetry with respect to actual bathymetry on climate, e.g., the influence of dynamic topography on climate. We are undertaking CESM climate modeling experiments to investigate such influences. Moreover, we have applied our methodology to reconstruct Cretaceous bathymetry (Goswami et al., 2014), which is now being prepared for CESM paleoclimate simulation.

The referee suggests that our model could be developed "on the fly" as part of a larger study. However, we found that careful human intervention is required for accurate and high-resolution definition of shorelines, selection of P points, and other tasks still to be developed (e.g., instituting seamounts and plateaus).

The referee is concerned that our model does not take into account local knowledge about the continental shelf. The M and P points provide first order constraints for local shelf-slope-rise structure; both passive vs. active margin architectures are thereby taken into account. That said there are outstanding problems for shelves wider than ~400 km, and when M and/or P cannot be clearly distinguished, e.g., around the Arctic Ocean. Improvements may be possible by fitting the slope and shelf-slope data to another equation and/or collecting additional data.

Our open ocean sediment model (**Figure 3**) does not take latitudinal differences into account or contributions from large coastline deltas and productivity. Nonetheless, our model performs reasonably well, as shown in **Figure S6**, the difference map between it and Divins global sediment, now revised to a color scheme that can be compared with Fig. S5, Müller et al. (2008). The major difference between the Müller model and our model is in the eastern Pacific Ocean, where our model significantly overestimates sediment thickness, because we average over all ocean basins, i.e., including the much thicker sediments of the Atlantic Ocean basin. Otherwise, the two models compare well.

I have more specific comments below. I am recommending reject for the paper because I don't see enough "model development" to merit a new publication. Possibly if the authors did much new work to make their sediment and shelf-slope models much more sophisticated (for example, by taking into account sedimentation processes), then they might consider resubmission – but this would be a different type of study than what is presented here. I would be much more excited to see these expressions developed as part of a paper about the eventual application of these models to a geologic problem.

Since submission of this paper, we have developed OESbathy 1.0 for the mid-Cretaceous (Goswami et al., 2014), now being used in NCAR's CESM for paleoclimate. We consider that this paper is an important foundational paper for our unique approach in deep time Earth system simulations.

Specific Comments:

page 6, line 12 – the authors are citing an outdated version of Turcotte and Schubert (2002). It would be better to cite equation 4.211 of the 2014 version of this book.

The updated equation on page 320 of Turcotte and Schubert (2014), is now cited for Equation (2).

Page 6, line 22 – the authors choose omega_e = 5875 m as the midpoint of the range of the oldest part of the Pacific. This seems rather arbitrary - why did they choose this? Why exclude the oldest Atlantic, which is also about 180 Myr old? It would be even better to find the best-fitting value for this parameter from empirical fits to the seafloor. Also, shouldn't the authors subtract the sediments from this old seafloor before estimating a value for omega_e – because they are handling the sediment contribution separately.

We agree that there are other ways to find an appropriate value for omega_e. For convenience we chose to rely on Crosby et al. (2006, p. 559), who indicate a range between -5750 m and -6000 m, which is sediment-corrected (pp. 555-556). We arbitrarily selected the midpoint, 5875 m. Finding an empirically based best fit value to the seafloor would finely tune the bathymetry. We could institute such a procedure in a future version of OESbathy.

Page 6, line 8 - Similarly, the choice of omega_0=2639.8 m is taken unquestioned from Crosby et al 2006 – is this the best value? Again, it seems that it would be better to invert for these parameters, rather than just assign them – but there have been many studies over the years that discuss this problem.

Our selected depth of 2639.8 m shows some problems in the difference map of Fig. 12b, where significant negative values are recorded for example in the Southwest Indian Ridge, indicating that the value of 2639.8 m is not deep enough. In other regions however, the value appears to be adequate (e.g., Atlantic MOR).

5 References

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OESbathy version 1.0: A method for reconstructing ocean bathymetry with generalized continental shelf-slope-rise structures

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Abstract

We present a method for reconstructing global ocean bathymetry that combines a standard plate cooling model for the oceanic lithosphere based on the age of the oceanic crust, global oceanic sediment thicknesses, plus generalized shelf-slope-rise structures calibrated at modern active and passive continental margins. Our motivation is to develop a methodology for reconstructing ocean bathymetry in the geologic past that includes heterogeneous continental margins in addition to abyssal ocean floor. First, the plate cooling model is applied to maps of ocean crustal age to calculate depth-to-basement. To the depth-to-basement we add an isostatically adjusted, multi-component sediment layer, constrained by sediment thickness in the modern oceans and marginal seas. A three-parameter continental shelf-slope-rise structure completes the bathymetry reconstruction, extending from the ocean crust to the coastlines. Parameters of the shelf-slope-rise structures at active and passive margins are determined from modern ocean bathymetry at locations where a complete history of seafloor spreading is preserved. This includes the coastal regions of the North, South, and Central Atlantic Ocean, the Southern Ocean between Australia and Antarctica, and the Pacific Ocean off the west coast of South America. The final products are global maps at 0.1° x 0.1° resolution of depth-to-basement, ocean bathymetry with an isostatically adjusted, multicomponent sediment layer, and ocean bathymetry with reconstructed continental shelf-slope-rise structures. Our

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reconstructed bathymetry agrees with the measured ETOPO1 bathymetry at most passive margins, including the east coast of North America, north coast of the Arabian Sea, and northeast and southeast coasts of South America. There is disagreement at margins with anomalous continental shelf-slope-rise structures, such as around the Arctic Ocean, the Falkland Islands, and Indonesia.

Keywords global ocean bathymetry, depth-to-basement, ocean sediment, shelf-slope-rise, residual bathymetry, reconstruction

1 Introduction

Reconstructing paleobathymetry represents a challenge for modelling past climates. The modern ocean bathymetry influences global climate in numerous ways. As examples, the present-day Southern Ocean bathymetry blocks flow through Drake Passage, which has effects on the magnitude of the circumpolar current (Krupitsky et al., 1995) and the stability of the thermohaline circulation (Sijp and England, 2005). Similarly, in the northern hemisphere, variations in the depth of the Greenland-Iceland-Scotland Ridge have been proposed to modulate North Atlantic Deep Water formation (Wright and Miller, 1996). On the global scale, tidal dissipation is concentrated in shallow marine environments, while the generation of tides over rough ocean bathymetry has been proposed to play a major role in driving deep ocean mixing (Simmons et al. 2004).

Quantifying these processes in the geologic past requires detailed knowledge of paleobathymetry. The geometrical rules of plate tectonics and seafloor spreading provide an objective method for paleobathymetric reconstruction in the open ocean, and much progress has been made in reconstructing this part of paleobathymetry younger than ~200 Ma. In particular, the relationship discovered between ocean crust age and depth-to-basement (Parsons and Sclater, 1977) was quickly exploited to estimate paleobathymetry of the Atlantic and Indian oceans (Sclater et al., 1977a,b). Pacific Ocean paleobathymetry proved to be more challenging with its multiple spreading centers, plates of various sizes, ages and orientations, and active subduction zones (Müller et al., 1997), as well as the now lost Tethys Ocean (Heine et al., 2004). Despite these difficulties, today a convincing case has been made for the

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general validity of paleobathymetric reconstructions of oceans that overly oceanic crust of known age (Xu et al., 2006; Müller et al., 2008a,b; Hayes et al., 2009).

An important element missing from these reconstructions is the shelf-slope-rise region between oceanic crust and continental shoreline. For near-present day reconstructions, this region can be adapted from modern bathymetry. However, further back in geologic time the structure of the continent-ocean transition becomes increasingly less certain or unknown. Yet this region represents a critical zone for many biological, sedimentary, and oceanographic processes that influence the Earth system.

In this work we develop a method to model shelf-slope-rise structure back through geologic time that is based on modern-day geometric relationships between ocean crust and shoreline, and takes into account the heterogeneity of these compound structures. Modern open ocean bathymetry, a parameterized open ocean sediment thickness and shelf-slope-rise structure are joined together to form a modern ocean bathymetry. We name this reconstructed bathymetry 'OESbathy' (OES = Open Earth Systems; www.openearthsystems.org).

Modern ocean bathymetry reconstructed with this methodology is used as a test case, as it offers the following advantages: 1) differences can be assessed between actual ocean bathymetry and the reconstruction; 2) when applied to coupled climate models, it can be used to assess the influence of the reconstruction with respect to actual ocean bathymetry; and 3) specific components of the reconstructed bathymetry, e.g., continental shelf-slope-rise structures, can be investigated to examine their roles in the Earth system.

2 Data

2.1 Ocean crust age

For the age distribution of the oceanic crust (hereafter 'ocean crust age' represented by τ) we use the data from Müller et al. (2008a) who provide global reconstructions of ocean crust age in one million year intervals for the past 140 Ma (Ma = Megaannum). For each reconstructed age in Müller et al. (2008a), ocean crust age, depth-to-basement, and bathymetry are given. The reconstructed bathymetry based on Müller et al. (2008a) is referred to hereafter as EB08 (EB = EarthByte). The data are in 0.1° x 0.1° resolution (3601 longitude x1801 latitude points). For this project, 000 Ma (modern) crustal age reconstruction data are used (Figure S1).

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2.2 Modern ocean sediment thickness

We use modern ocean sediment thickness data from Divins (2003) and Whittaker et al. (2013). These data are derived from seismic profiling of the world's ocean basins and other sources. The reported thicknesses are calculated using seismic velocity profiles that yield minimum thicknesses. Data values represent the distance between sea floor and 'acoustic basement'. The data are given in 5' x 5' resolution and have been re-gridded to 0.1° x 0.1° resolution values (Figure S2), to match the EB08 grid.

2.3 ETOPO1

To construct the shelf-slope-rise structures, ETOPO1 modern bathymetry (Amante and Eakins, 2009) is used. We use the 'Bedrock' version of ETOPO1, which is available in a 1' x 1' resolution (earthmodels.org), re-gridded to 0.1° x 0.1° resolution (Figure S3) in order to match the EB08 grid (Figure S1). This version of ETOPO1 includes relief of earth's surface depicting the bedrock underneath the ice sheets. However, we use only the oceanic points in this dataset, so that this has no impact on the reconstructed bathymetry.

3 Methods

Modern ocean basins have different types of crust, including oceanic crust, submerged continental crust, and transitions between these two types. In our reconstruction, the regions underlain by oceanic crust to which an age has been assigned are termed 'open ocean' regions. The parts of the ocean basins that occupy the transitional zone between oceanic crust and the emerged continental crust are termed 'shelf-slope-rise' regions. These regions typically extend from the boundary of open ocean regions to the coastline. Accordingly, the OES ocean bathymetry model involves the merging of open ocean regions and shelf-slope-rise regions (Figure 1). To accomplish the merging, map-based operations such as computing distances between locations were carried out in ArcGIS 10.1, whereas local calculations such as interpolation and statistics were carried out in Matlab R2014a. The workflow is diagrammed in Figure S9.

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3.1 Reconstruction of Open Ocean Regions

Reconstruction of open ocean bathymetry starts with ocean crust age. This information is available only at locations where oceanic crust is preserved or has been reconstructed. The ocean depth-to-basement is the distance between mean sea level and the top of the basaltic layer of the oceanic crust. Calculation of depth-to-basement is based on a cooling plate model in which the vertical distance between mean sea level and basement ω_τ is expressed as:

$$\omega_\tau = \omega_0 + \omega_d \qquad (1)$$

where the ω_0 = -2639.8 m is the area-weighted average of mid-oceanic ridge depths from the North Pacific, Eastern Atlantic and Southeast Atlantic reported in Crosby et al. (2006), and ω_d is the change in depth due to plate cooling. Here we adopt a negative sign to denote depths below mean sea level. The change in depth due to cooling of the oceanic plate ω_d is given by (adopted from Equation 4.211 in Turcotte and Schubert, 2014):

$$\omega_d = \frac{-\alpha\rho_m(T_m - T_w)y_L}{(\rho_m - \rho_w)}\left[\frac{1}{2} - \frac{4}{\pi^2}\sum_{m=0}^{\infty}\frac{1}{(1+2m)^2}\exp\left(\frac{-\kappa}{y_L^2}(1+2m)^2\pi^2\tau\right)\right] \qquad (2)$$

where α (=3 x 10^{-5} K^{-1}) is the volumetric coefficient of thermal expansion of the mantle, ρ_m is (=3300 kg/m^3) is density of the upper mantle, ρ_w is(=1000 kg/m^3) is density of sea water, $T_m - T_w$ (1300 K) is the difference between upper mantle and ocean temperature, κ (=3.410835 x 10^5 m^2/s) is thermal diffusivity, y_L (=2619.7 m) is equilibrium plate thickness, all assumed to have constant values.

The equilibrium depth-to-basement ω_e corresponds to the limit of $\tau \to \infty$ in (2), appropriate for the oldest crust:

$$\omega_e = \frac{-\alpha\rho_m(T_m - T_w)y_L}{2(\rho_m - \rho_w)}. \qquad (3)$$

In our reconstruction we use ω_e = -5875 m, the mid-point of the range -5750 to -6000 m in the oldest part of the North Pacific (Crosby et al., 2006). We assign an area-weighted average value to the parameter β (Table 1):

$$\beta = \frac{2\alpha\rho_m(T_m - T_w)}{(\rho_m - \rho_w)}\sqrt{\frac{\kappa}{\pi}} = 329.5\, m \cdot s^{-\frac{1}{2}} \qquad (4)$$

so that

$$\frac{\kappa}{y_L^2} = \left(\frac{\beta\sqrt{\pi}}{2\omega_e}\right)^2 = 4.97\text{x}10^{-2} s^{-1}. \qquad (5)$$

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In terms of ω_e and β, (2) becomes

$$\omega_d = \omega_e \left[\frac{1}{2} - \frac{4}{\pi^2}\sum_{m=0}^{\infty}\frac{1}{(1+2\mathrm{m})^2}\exp\left(\frac{-\beta\sqrt{\pi}}{2{\omega_e}^2}(1+2m)^2\pi^2\tau\right)\right]. \quad (6)$$

We include the first 25 terms in the sum of (6) to ensure convergence. Lastly, the depth-to-basement is calculated with (1).

3.2 Reconstruction of ocean sediment thickness and isostatic correction

The addition of sediment and an isostatic correction from sediment loading of the oceanic crust (e.g., Célérier, 1988) is needed to complete the bathymetry. A parameterized multi-layer sediment cover, called 'OES sediment thickness' (Figures 2 and 3), was isostatically added on top of the depth-to-basement ω_τ; (Figure 4) to complete the open ocean bathymetry (Figure 5). OES sediment thickness (Figure 3) was parameterized based on a third degree polynomial fit between area corrected global sediment thickness data (Divins, 2003; Whittaker et al., 2013) and age of the underlying oceanic crust τ. Sediment loading was calculated using a multicomponent sediment layer with varying sediment densities given in Table 2 in 100-meter increments of the sediment. The variable sediment densities were calculated from a linear extrapolation of sediment densities in Crosby et al. (2006) (Table S1). For the isostatic correction, in each 100 meter sediment layer we calculate an adjusted thickness given by

$$D_z = \frac{100(\rho_m - \rho_z)}{(\rho_m - \rho_w)} \quad (7)$$

where ρ_z is the density of the zth layer, ρ_m= 3300 kg/m^3 and ρ_w= 1000 kg/m^3. The sediment model has a total of 16 layers in which the basal layer includes all sediment deeper than 1500 meters. For a given location we sum D_z to obtain the isostatically adjusted total sediment thickness, which is then added to the depth-to-basement to obtain the open ocean bathymetry. This loading correction is similar to procedures used by Crough (1983) and Sykes (1996).

3.3 Reconstruction of shelf-slope-rise structures

To model the shelf-slope-rise structure, profiles from various modern shelf-slope-rises at active and passive margin regions from ETOPO1 were examined, along with their corresponding sediment thicknesses taken from Divins (2003). As a representative active margin, the west coast of South America was chosen (Figure 6). For passive margins, the

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Atlantic Ocean (north, south and central) and part of the Southern Ocean were chosen as representatives, because their complete rifting history is preserved (Figures 7, S4).

Profiles from these representative regions were used to parameterize the widths of the continental shelf, slope and rise as follows. The basic parameters of the shelf-slope-rise structure (Figure 8a) include continental shelf width l_{sh}, continental slope width $l_{sl,}$ and continental rise width l_r. The location of the maximum extent of oceanic crust according to EB08 is labeled as M, and another anchor point labeled as P marks the boundary between the shelf-slope-rise structure and the open ocean. These are related by:

$$l_{sh} + l_{sl} = M \tag{8a}$$

$$l_{sh} + l_{sl} + l_r = P \tag{8b}$$

$$l_r = -0.290 l_{sl} + 437.2 \tag{8c}$$

$$l_{sl} + l_r = -8.28\text{x}10^{-3} l_{sh}^2 + 5.486 l_{sh,} \tag{8d}$$

where M and P are the distances of coastline from points M and P, respectively.

The numerical coefficients in (8a) - (8d) were obtained from fits to ETOPO1 profiles (Figures 6, 7 and S4). In Figure 8b we plot the width of the slope + rise versus the width of the shelf from a set of passive margin regions that span a range of shelf widths. We then fit a parabola to this data, constraining the parabola to pass through the origin in order to model the structure at active continental margins. We apply this parabolic fit to active margins and to passive margins where the shelf width is less than the parabola maximum, approximately 350 km. Shelves having widths greater than this maximum are treated individually as special cases.

To determine the corresponding depths, we work outward from the coast. First we apply a uniform gradient of 3.2° in depth over the width of the shelf. This value of the shelf gradient was obtained from analysis of 17 ETOPO1 transects (Figures S4). For the depth distribution along the slope and rise, we assume another uniform gradient as illustrated in Figure 8a, joining the depth at the shelf break with the depth calculated for the open ocean at point P.

This methodology works for all shelf-slope-rise regions except where the shelf is anomalously extended, for example, north of Siberia, the Falkland Islands region, and the complex regions in Southeast Asia. If the M point is too far from the coastline, so that $l_{sh} + l_{sl} > 800$ km, or too close to the coastline, so that $l_{sh} + l_{sl} < 100$ km, then the relationship among the three widths

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no longer holds. For these regions we assume that $P=M$ (Figure 1c). To complete the reconstruction, these regions were filled by interpolation from neighboring regions.

4 Results

4.1 Reconstructed shelf-slope-rise structures

ETOPO1 bathymetry reveals that active margins lack extensive shelves (Figure 6), and their slope gradient is anomalously large. Likewise, sediment thickness profiles show that active margins have little sediment cover, either near or far from the coast. In particular, sediment thickness on the shelves of active margins rarely exceeds 250 meters and gradually thins out beyond the subduction zone towards the open ocean.

In contrast to active margins, passive margins are characterized by significant shelf–slope-rise regions. Three out of the sixteen passive margin cross sections studied are shown in Figure 7. The extent of the shelf region varies substantially along passive margin coastlines, which accounts for the scatter among the profiles in Figure 7. For example, in the profile between the southern tips of Africa and South America, the South American side has a very wide, platform-like shelf region that extends for more than 500 km, whereas on the African side the shelf is at most 100 km wide.

The bathymetric gradients at passive continental margin slopes in Figure S5 vary significantly, from -0.004 to -0.018. Compared to active margins, passive margins are characterized by greater thickness of sediments and more lateral variability. The greater sediment thickness on passive margins and its greater lateral variability are evident in the thirteen passive margin transects shown in Figure S4.

Figure 8 shows the relationship between the widths of the shelves and the widths of the adjacent slope-rise. A transect east/northeast of Newfoundland in the northern part of the Atlantic Ocean (Figure S4, Set 3, center panel) includes a 300 km of continental shelf and nearly 900 km of continental slope-plus-rise. The presence of the widely extended Gulf of St. Lawrence may contribute to this anomaly.

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4.2 Reconstructed open ocean regions

Our depth-to-basement reconstruction is shown in Figure 4. The isostatically adjusted, sediment-loaded model bathymetry of the open ocean is shown in Figure 5, for which only ocean basin areas with ocean crust ages have an assigned bathymetry. The gap between the coastline and open ocean bathymetry is reconstructed with the shelf-slope-rise model described in Section 3.3.

The mid-oceanic ridge systems in our open ocean bathymetry in Figure 4 have an average depth of approximately -2675 meters. Away from the mid-ocean ridges, ocean depth increases systematically, and reaches a maximum depth of approximately -5575 meters at old crustal ages. In Figure 5, the open ocean bathymetry is shown with the modeled sediment cover from Figure 3 isostatically loaded on to it. With this sediment cover added, the bathymetry ranges between -2675 meters to -4900 meters in the open ocean regions and the maximum depth of the reconstructed bathymetry is approximately -6500 meters. The depth range between -4900 and -6500 meters is associated with old ocean crust (crustal age in the range of $\tau = 100 - 120$ Ma) along the flanks of the Atlantic, Pacific, Southern and Indian Oceans, and the Bay of Bengal.

4.3 Model evaluation

The addition of the shelf-slope-rise model completes the OESbathy (Figure 9), except for ocean islands, seamounts, trenches, plateaus and other localized anomalies plus the underlying dynamical topography. Below we evaluate the modeled OESbathy with respect to ETOPO1 and EB08.

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4.3.1 Statistics

Basic statistics of the OESbathy, ETOPO1 and EB08 are summarized in Table 3, which highlight major differences among the bathymetries. Compared to the -10714 meter maximum depth of ETOPO1, OESbathy maximum depth is -6522 meters, while the deepest point of EB08 is only -5267 meters. These differences from ETOPO1 are due to the absence of trenches in the reconstructions. The average ocean depths for the ETOPO1, OESbathy and EB08 are -3346, -3592 and -4474 meters, respectively, signifying that EB08 in particular is very deep compared to ETOPO1. The standard deviations of the ETOPO1, OESbathy and EB08 are 1772.25, 1668.52 and 785.08 meters, respectively. These values suggest that

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compared to ETOPO1, the EB08 is overall very smooth, whereas OES bathymetry has a variability that is comparable to ETOPO1.

We also assessed the skewness and kurtosis of the three bathymetries. Skewness is a measure of the asymmetry of data around their mean, and is zero for a symmetric distribution. The skewness of OESbathy (1.34) lies between ETOPO1 (0.67) and EB08 (1.81), indicating a closer fit of OESbathy to ETOPO1 than EB08 to ETOPO1. Kurtosis is a measure of how outlier-prone a distribution is. Kurtosis equals to 3 for a Normal distribution, whereas outlier-prone distributions have a kurtosis greater than 3, and less outlier-prone distributions have kurtosis less than 3. For the three bathymetries the kurtosis values are 2.30 (OESbathy), 3.26 (ETOPO1) and 7.69 (EB08). It should be noted that OESbathy does not take into account large igneous provinces (LIPs), seamounts, or plateaus, whereas EB08 has incorporated some of the major LIPs.

4.3.2 Difference maps

To assess the quality of our results, we difference OESbathy from ETOPO1 in Figure 10, with positive values corresponding to regions where OESbathy is deeper than ETOPO1 and negative values corresponding to regions where OESbathy is shallower than ETOPO1. As described in Section 3.3, interpolations were used in certain regions to complete the reconstruction, for examples, the Falkland Island regions, north of Siberia, and the complex regions around SE Asia. These regions show significant deviations from ETOPO1; in general, OESbathy is much deeper. Some shelf-slope-rise structures are shallower in OESbathy than ETOPO1, such as around the margins of the central Atlantic, whereas in other areas OESbathy is deeper, such as along the east coast of Africa, the Bay of Bengal and the Arctic Ocean margin. Owing to the absence of seamounts and plateaus in OESbathy, those areas display large positive anomalies.

A difference map between the OES sediment thickness (Figure 3) and the Divins (2003) global ocean sediment (Figure S2) has been calculated for the open ocean regions. Figure S6 shows that the most noticeable differences occur close to the continent margins (edge of the ocean crust), where large negative values indicate that the modeled sediment thicknesses are much less than actual sediment thicknesses. Otherwise, over a substantial part the open ocean, especially on ridge flanks, the differences in Figure S6 are close to zero, indicating a good fit between OES sediment thickness and Divins sediment thickness. In the Atlantic abyssal plains, however, OES sediment thickness generally exceeds the Divins sediment thickness.

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Likewise, OES sediment thickness exceeds Divins sediment thickness (up to 0.5 km) in the eastern Indian Ocean (offshore Australia) and significantly exceeds (by more than 1 km) measured sediment thickness throughout the western Pacific Ocean. Figure S6 can also be compared with Figure S5 in Müller et al. (2008b), which is an equivalent difference map between their more detailed sediment model and Divins sediment thickness.

4.3.3 Shelf-slope-rise profiles

Randomly selected shelf-slope-rise cross sections from all continents, here referred to as "profiles", are compared for OESbathy, EB08 and ETOPO1 (Figure 11 and Figure S7). The profiles shown in Figures 11b, c, g, j agree well with ETOPO1, while those in Figures 11d, e, are partial fits, and the profiles in Figure 11f, h, i are poor fits. In all profiles, EB08 is shown only for the deep oceans with no continental shelf or slope, and as a result none of the EB08 profiles reach the coast. Of the 64 profiles depicted, nearly 50% fit well with ETOPO1.

Along Profile 1 from the North Pacific (Figure 11b), OESbathy is in good agreement with the ETOPO1, especially for the shelf and slope. Beyond 550 km, OESbathy is deeper and lacks the local variations of ETOPO1, such as from the seamounts. EB08 is even deeper than OESbathy along this profile with a similar lack of local variation. Along the northeast coast of South America and Australia (Figure 11c, g), Profiles 12 and 39, OESbathy agrees with ETOPO1, whereas the EB08 is deeper than both OESbathy and ETOPO1. Figure 11j shows Profile 61 off the coast of Delaware, USA. Here, there is good agreement between ETOPO1 and OESbathy from the shelf-slope-rise to the open ocean region out to ~600 km from the coast.

Profiles 20 and 22 (Figures 11d and 11e) are taken from coastal Nigeria and the southern tip of Africa. Here, OESbathy has a partial fit with ETOPO1. The OESbathy shelf in both profiles is wider than ETOPO1, and as a result, the OESbathy slope+rise is too steep. However, the fit improves in the open ocean along both profiles.

Profiles 58 and 60 (Figures 11h and 11i) are from the northern part of Eurasia. This region was filled in by interpolation from nearby regions, because our parameterization fails to model this extremely wide shelf. Hence, along these two profiles there is poor agreement between ETOPO1 and OESbathy. The ETOPO1 shelf is very shallow (<1000 m below sea level), whereas the OESbathy shelf is deeper with a steeper gradient on the slope-rise. Similar deviations occur in Profile 33 (Figure 11f) from the Bay of Bengal, where an enormous pile

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of sediment from the Ganges system has accumulated, resulting in a much shallower ETOPO1 compared to OESbathy.

5 Discussion

5.1 Shelf-slope-rise internal architecture

Examples of the global ocean sediment thickness data of Divins (2003) are displayed as cross-sectional profiles from the coastline to the abyssal ocean in Figures 6, 7 and S4. In these profiles, the sediment thickness contribution is shown separately from ETOPO1. These profiles highlight the fact that the greatest sediment accumulations occur in the shelf-slope-rise regions, whereas open ocean regions accumulate far less. Active margins as in Figure 6 have thin sediment cover, whereas passive margins as in Figures 7 and S4 have much thicker sediment cover. On the passive margins, lateral heterogeneity in sediment thickness reflects a complex buried topography of the seafloor on which the sediment accumulated. This topography consists of rifted, stretched and sagged lithosphere in km-scale relief, first in-filled by syn-rift sediment and then buried by post-rift sediment (e. g, Watts et al., 2009; Davison and Underhill, 2012). The thickness profiles of the Atlantic margins reflect subsurface graben structures related to the Jurassic-Cretaceous rifting of Pangea (Peron-Pinvidic et al., 2013; Franke, 2013).

The shelf-slope-rise model in Figures 1 and 8 is based on modern-day bathymetry with three well-defined gradient changes from the coast to the open (deep) ocean. There is no accounting in the model for the complex types of internal architecture in shelf-slope-rise structures just described.

For paleo-ocean reconstructions, extrapolation back through time will produce proportionate narrowing of shelf-slope-rise geometry at passive margins. Highly variable internal structures strongly suggest that simple backward extrapolation may not accurately produce paleo shelf-slope-rise bathymetries, especially for the oldest paleo-oceans. Rifting depends on local lithospheric strength, mantle dynamics, and global tectonics, all contributing to the evolution of a passive margin in ways that are not easy to parameterize (Ziegler and Cloetingh, 2003; Corti et al., 2004). Thus, additional data such as from seismic profiling and ocean margin drill cores must be consulted before applying these types of corrections for deep time reconstructions.

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Lastly, we point out that our shelf-slope-rise formulation constitutes a marked improvement over simple bathymetric interpolation between the coastline and oldest oceanic crust. Bathymetric interpolation would not resolve the extreme differences in slope between shelf and rise, nor would it faithfully represent the heterogeneity in shelf lengths found in the modern ocean.

5.2 Residual bathymetry

The Divins sediment thickness (Figure S2) may be isostatically subtracted from ETOPO1 (Figure S3) to yield a sediment-stripped bathymetry that should be in isostatic equilibrium with the mantle (Figure 12a). To detect deviations in this bathymetry from isostatic equilibrium, the OESbathy modeled depth-to-basement (Figure 4), which is in isostatic equilibrium with the mantle (Equations 2 and 3), is subtracted from the sediment-stripped bathymetry. This residual bathymetry (Figure 12b) is comparable to the residual basement maps of Müller et al. (2008a; their Figure 11), with differences attributable to the isostatic corrections applied to sediment removal and the predicted crustal (depth-to-basement) models.

OESbathy subjected to the same treatment as ETOPO1 provides a secondary check of our methodology (Figure 13a). Removing sediments, including their loading, results in a difference map with deeper values than ETOPO1 with the same sediment correction applied (compare Figure 12a and 13a). This difference also appears in the residual OESbathy (Figure 13b), which shows slightly negative mid-ocean ridges, mostly positive coastlines, and very negative terrigenous sediment fans.

5.3 Bathymetric impacts on climate

It remains unclear whether the differences between true and reconstructed bathymetry produce qualitatively important impacts on climate. One fundamental process for which bathymetry is potentially important is ocean tidal amplitude, which depends sensitively on basin resonances (which in turn depend sensitively on the ocean depth affecting the speed of gravity waves, Arbic et al., 2009). As noted above, both lateral (Krupitsky et al., 1996) and vertical (Sijp and England, 2005) ocean circulation have also been hypothesized be sensitive to the details of bathymetry. Work to evaluate these sensitivities in modern models will be a future focus of research.

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Another key issue concerns reconstructed paleo-bathymetry with simple vertical ocean margins, i.e., no realistic shelf-slope-rise structures, which if applied to paleo-oceans could result in substantially inaccurate paleoclimate simulation. Shelf-slope-rise structure is known for present-day ocean models, but not for paleo-ocean models; the "modular" aspect of the OESbathy reconstruction provides a convenient means to test the effect of shelf-slope-rise structures on modern climate simulation. Obviously such a test could be undertaken by simply removing the actual shelf-slope-rise structures from ETOPO1, but to our knowledge this has never been done.

6 Conclusions

The reconstruction method described in this paper was applied to modern data in order to test how well simple parameterizations of the deep and coastal oceans replicate actual modern ocean bathymetry. Our method uses well established oceanic crust ages, a cooling plate model, a parameterized sediment cover for the open oceans, and a parameterized shelf-slope-rise structure based on modern bathymetry of ocean margins. The reconstructed bathymetry is called 'OESbathy'.

Comparison of OESbathy with ETOPO1 shows global scale agreement (Figure 10; Table 3): OES average depth is -3592 ±1668 m versus ETOPO1 average depth of -3346 ±1772 m, a 7.35% difference; OES median depth is -4321 m versus ETOPO1 median depth of -3841 m. ETOPO1 is shallower, owing to seamounts and underwater plateaus (LIPs) that are not included in OESbathy. OESbathy maximum depth is -6522 m versus ETOPO1 maximum depth of -10714 m, reflecting the absence of a full trench model in OESbathy. Significant differences also occur in complex coastal regions north of Siberia, the Falkland Islands, and Indonesia.

OES sediment thickness for the open oceans was parameterized as a multi-layer sediment cover, with total thickness based on a third order polynomial fit between the global ocean sediment thickness data of Divins (2003) and age of the underlying ocean crust. OES sediment thickness fits well to Divins sediment thickness in the open oceans, but underestimates Divins sediment thickness at greater ages, especially where terrigenous sediments have accumulated (e.g., Bay of Bengal, Amazon Fan).

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The modeled shelf-slope-rise structure for connecting the reconstructed open ocean regions to the continental coastlines was parameterized with respect to adjacent ocean crust age and present-day geometry of the continental shelf-slope-rise. The results show good fits to ETOPO1 for one half of the 64 profiles examined from around the world oceans; the other half of the profiles examined show moderate to poor fits to ETOPO1.

Residual ocean bathymetry computed from ETOPO1 consistently highlights positive anomalies in the North Atlantic Ocean, offshore southeast Africa, and the west Pacific Ocean, where actual bathymetry is elevated more than 1.5 km with respect to that produced by a cooling model of the oceanic lithosphere.

Acknowledgements

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1 **Tables**

Regions	**% of Analyzed Ocean**	**ω_0 (m)**	**β ($m.s^{-1/2}$)**
North Pacific	6.80%	-2821	-315
Eastern Atlantic	3.38%	-2527	-336
Southeast Atlantic	4.35%	-2444	-347
Global Average		-2639.80	-329.50

2 Table 1. Values for ω_0 and β from Crosby et al. (2006) by ocean basin, and percentage of
3 global ocean areas used to calculate weights for the global averages.

Depth (meters)	Density of sediment (kg/m^3)
0-100	1670
100-200	1740
200-300	1810
300-400	1880
400-500	1950
500-600	2020
600-700	2090
700-800	2160
800-900	2230
900-1000	2300
1000-1100	2370
1100-1200	2440
1200-1300	2510
1300-1400	2580
1400-1500	2650
>1500	2720

Table 2. Profile of sediment density vs. depth below sea floor used in our reconstruction. These sediment densities were calculated from a linear extrapolation of the data in Table S1.

Bathymetry	Max	Min	Average	Median	Mode	Std. Dev.	Skewness	Kurtosis
OESbathy	-6522.17	204.5	-3591.83	-4321.07	-6.22	1668.52	1.34	3.26
ETOPO1 (ocean only)	-10714	3933	-3346.41	-3841	-1	1772.25	0.67	2.30
EB08	-5266.97	422.75	-4473.83	-4678.47	-4231.85	785.08	1.81	7.69
ETOPO1- OESbathy	8812.7	-9231.41	242.53	1.43	5.22	1270.46	0.53	5.71
ETOPO1- EB08	9129.19	-6349.64	380.93	151.92	108.01	1009.99	1.22	6.40
OESbathy - EB08	5264.95	-4769.50	216.31	169.99	94.59	921.59	1.31	17.12

Table 3. Statistics of three global ocean bathymetries: ETOPO1 is from Amante and Eakins (2009), EB08 is from Müller et al. (2008a), and OESbathy is the result of this study. Mean, median, mode, minimum, maximum and standard deviations are in meters; skewness (measure of horizontal symmetry of data distribution) and kurtosis (tall and sharpness of the central peak of data distribution) are dimensionless.

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Figures

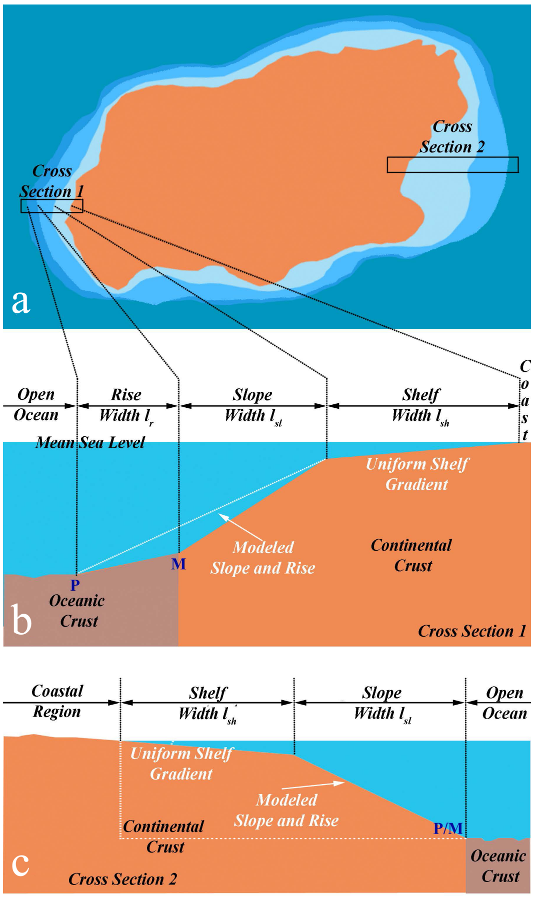

Figure 1. Bathymetric model geometry. a: Map view showing two passive continental margins. Section 1 is a standard passive margin, Section 2 is a passive margin with an extended continental shelf. b: Cross section of the standard passive margin with model geometry. c: Cross section of the passive margin with extended continental shelf model geometry.

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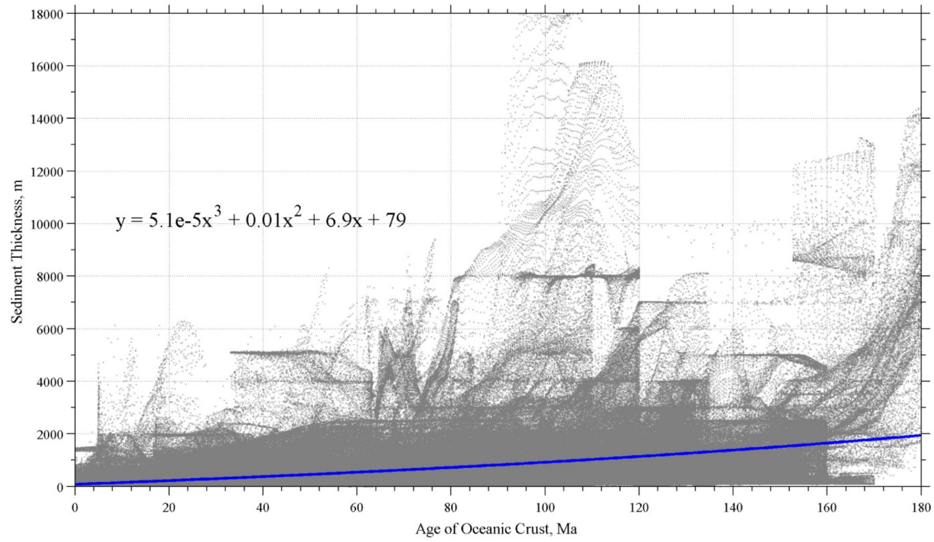

Figure 2. Polynomial fit of sediment thickness as a function of ocean crust age using area-corrected global sediment data from Divins (2003) and Whittaker et al. (2013) (Figure S2) and age of the underlying oceanic crust from Müller et al. (2008a) (Figure S1).

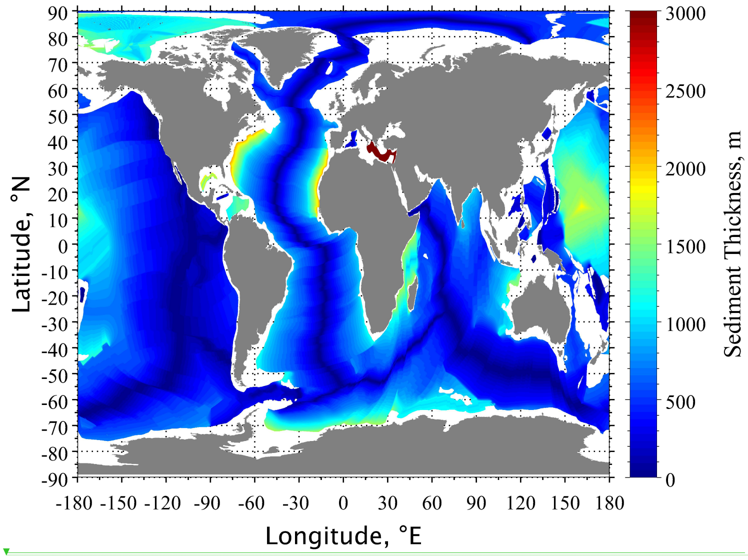

Figure 3. OES model sediment thickness based on the sediment thickness parameterization in Figure 2.

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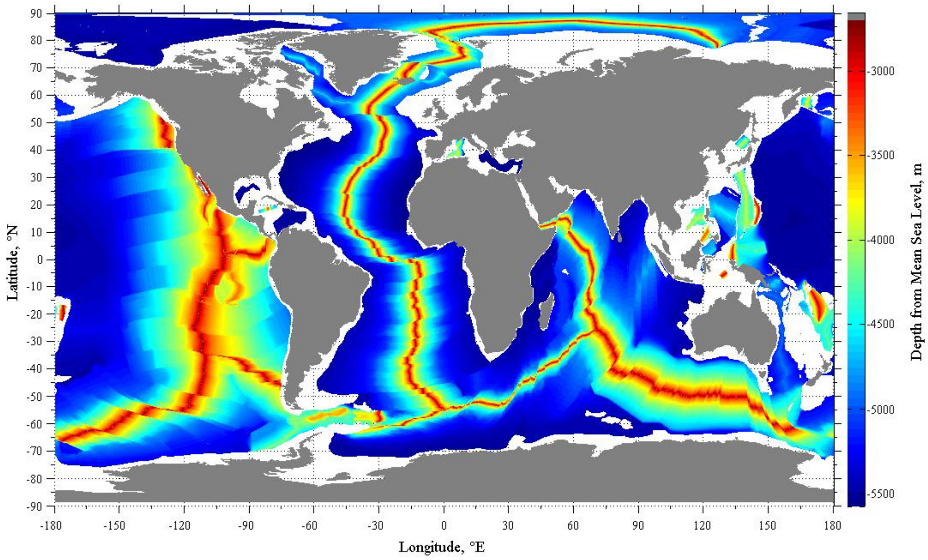

Figure 4. OES model depth-to-basement calculated using (1), (6) and Table 1 in open ocean regions underlain by ocean crust of known age.

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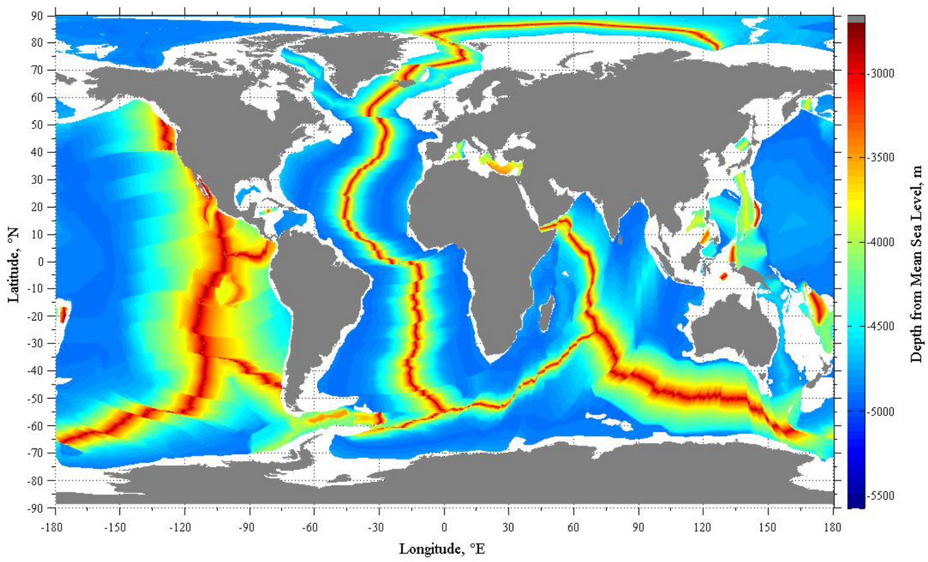

Figure 5. OES model bathymetry for the open ocean regions with isostatically adjusted multi-layer sediment of varying densities shown in Table 2. The sediment thickness was parameterized as in Figure 2. The varying sediment densities are from Table 2.

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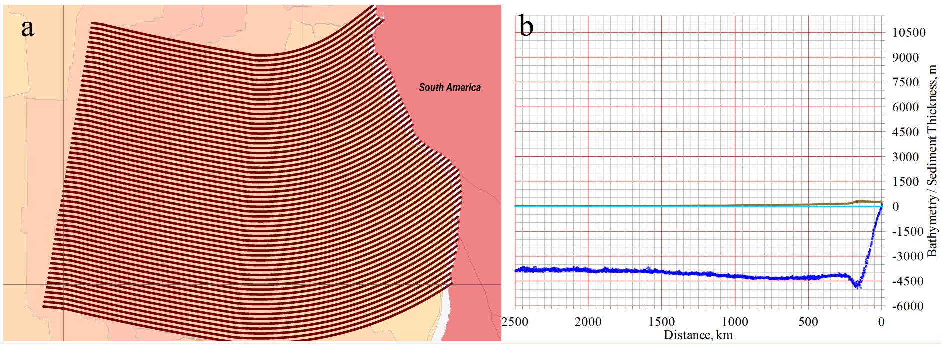

Figure 6. Representative active margin profile off the west coast of South America. a: Transects (brown lines) drawn by smoothly connecting transform fault segments using maps by Scotese (2011). Ocean color represents ocean crust age from the PALEOMAP Project (Scotese, 2011). Continents are from the ESRI standard shapefile data library in ArcGIS 10.1. b: Average profile based on all transects in a. Light blue line represents mean sea level (MSL), brown points represent sediment thickness obtained from Divins (2003) and dark blue points represent bathymetry from ETOPO1.

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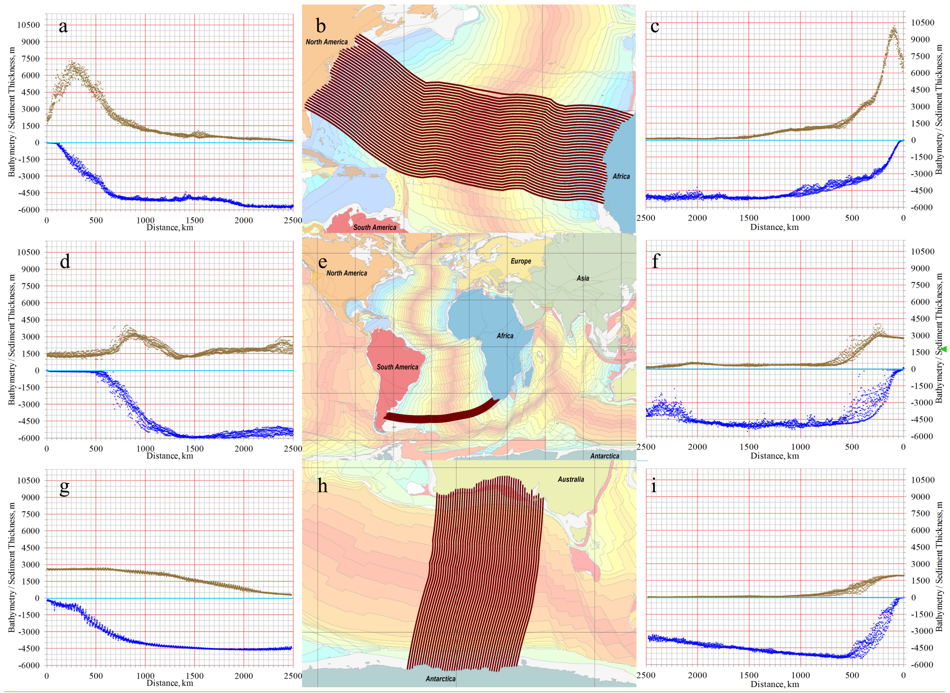

Figure 7. Representative passive margin profiles (shelf-slope-rise structure) from the Atlantic and Southern oceans. Ocean colors represent ocean crust age from the PALEOMAP Project (Scotese, 2011). Continents are from the ESRI standard shapefile data library in ArcGIS 10.1. b, e and h: Transects (brown lines) drawn by smoothly connecting transform fault segments using maps by Scotese 2011. a, c, d, f, g and : Average profiles based on west and east part of all transects in B, E and H. Light blue line represents MSL, brown points represent sediment thickness obtained from Divins (2003) and dark blue points represent bathymetry from ETOPO1. Figure S4 displays all 17 transects used, where the ones displayed here appear as Set 4 (A-C), Set 15 (D-F) and Set 17 (G-I).

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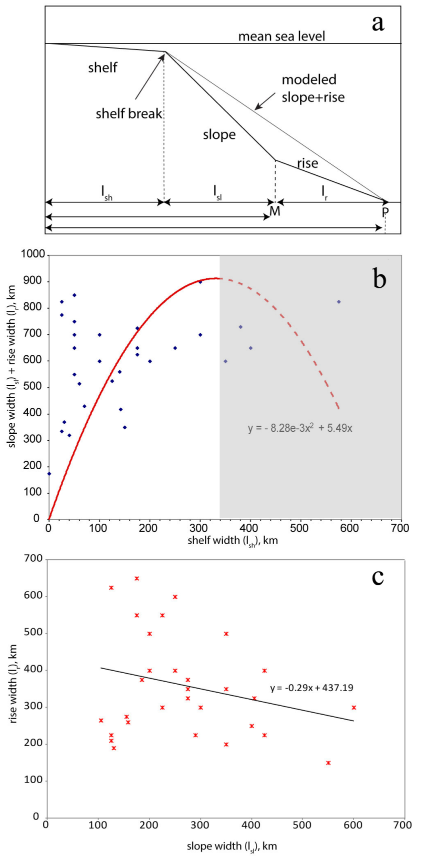

Figure 8. Modeling shelf-slope-rise structure as in Figure 1. a: The shelf-slope-rise parameterization shown in cross section through a passive continental margin. Parameters are: l_{sh} = continental shelf width; l_{sl} = continental slope width; l_r = rise width; M = maximum extent of oceanic crust (closest to the coastline) from EB08; P = the boundary between the shelf-slope-rise structure and the open ocean. b: Relationship between shelf width (l_{sh}) to slope width + rise width (l_{sl} + l_r) in the modern oceans from ETOPO1. Diamonds represent measurements from the east/west coasts of the Atlantic Ocean, and north/south coasts of the Southern Ocean between Australia and Antarctica as shown in Figure 5. The red line is a parabolic fit; only the solid portion of the fit was used; shading indicates region requiring reconstruction by hand. c: Relationship between slope width (l_{sl}) and rise width (l_r) in the

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modern oceans from ETOPO1. Red crosses represent measurements at the same locations used in Figure 8b. The black line is a linear fit.

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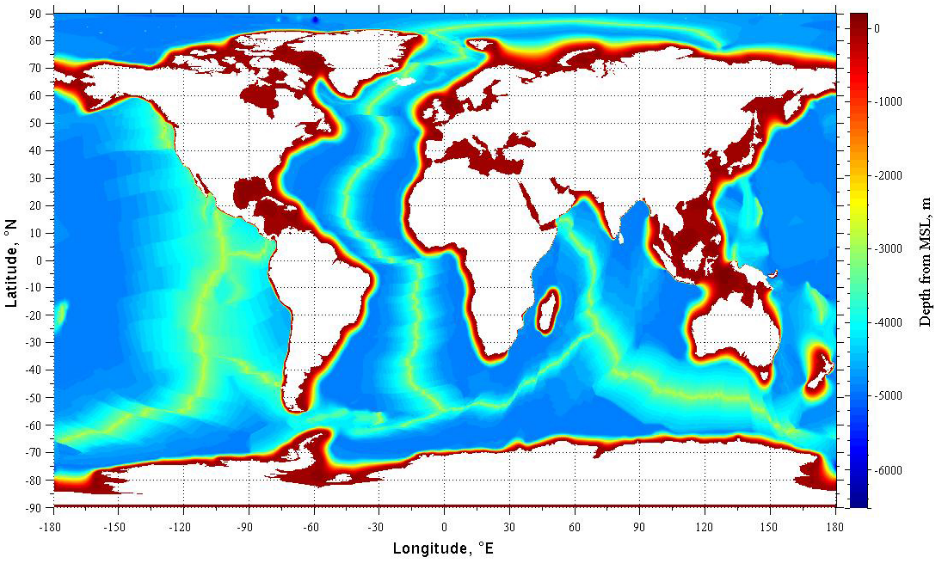

Figure 9. The full OESbathy model including open ocean regions and shelf-slope-rise structures.

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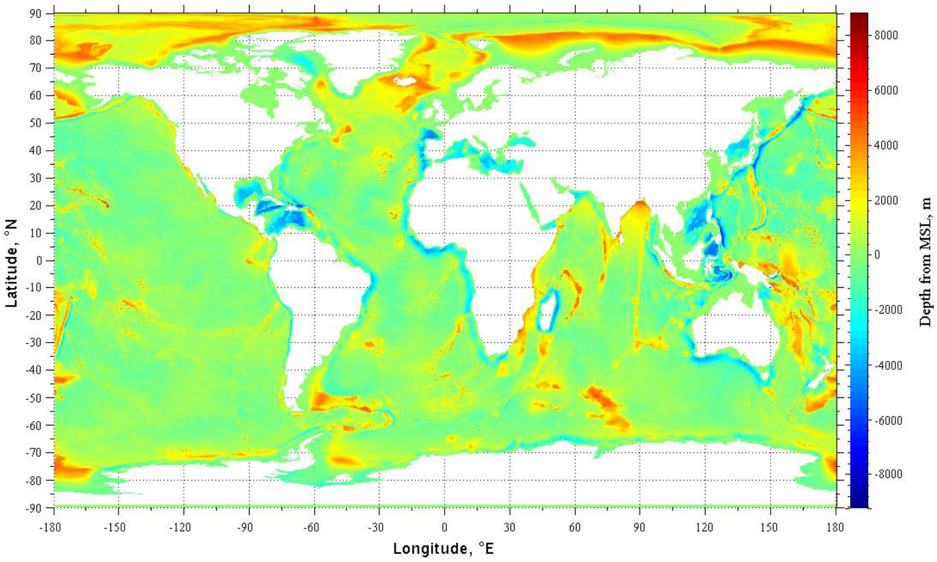

Figure 10. ETOPO1 minus OESbathy. In regions with positive values OESbathy is deeper than ETOPO1, and in regions with negative values OESbathy is shallower than ETOPO1.

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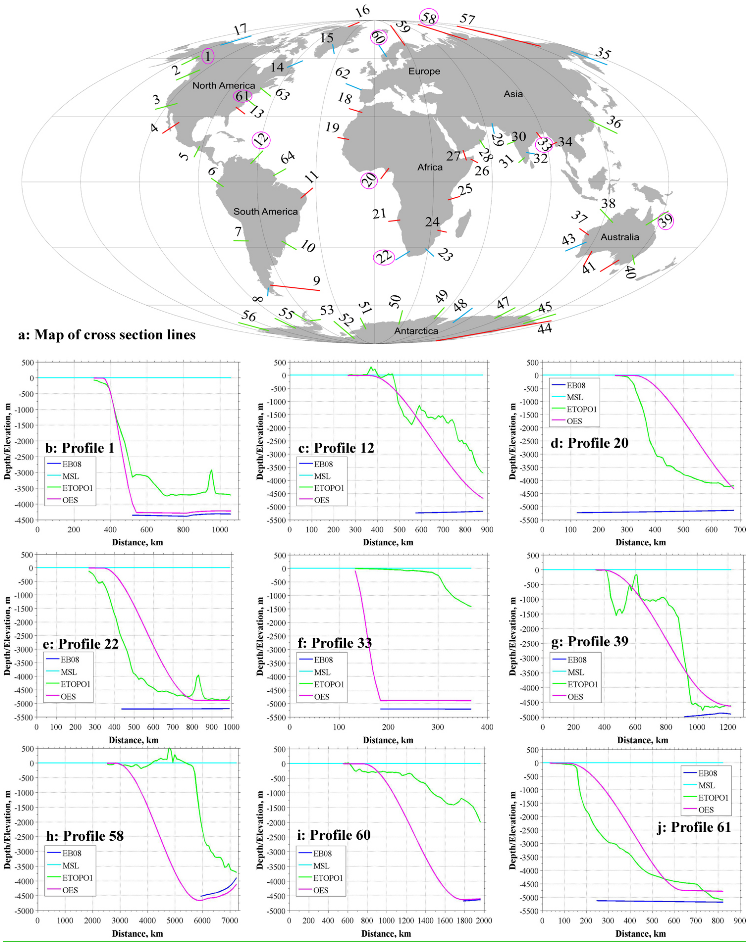

Figure 11. a: Location of sixty-one profiles comparing OESbathy (Figure 9) with ETOPO1 and EB08. b - j: Representative profiles at locations shown in Figures 6 and 7.

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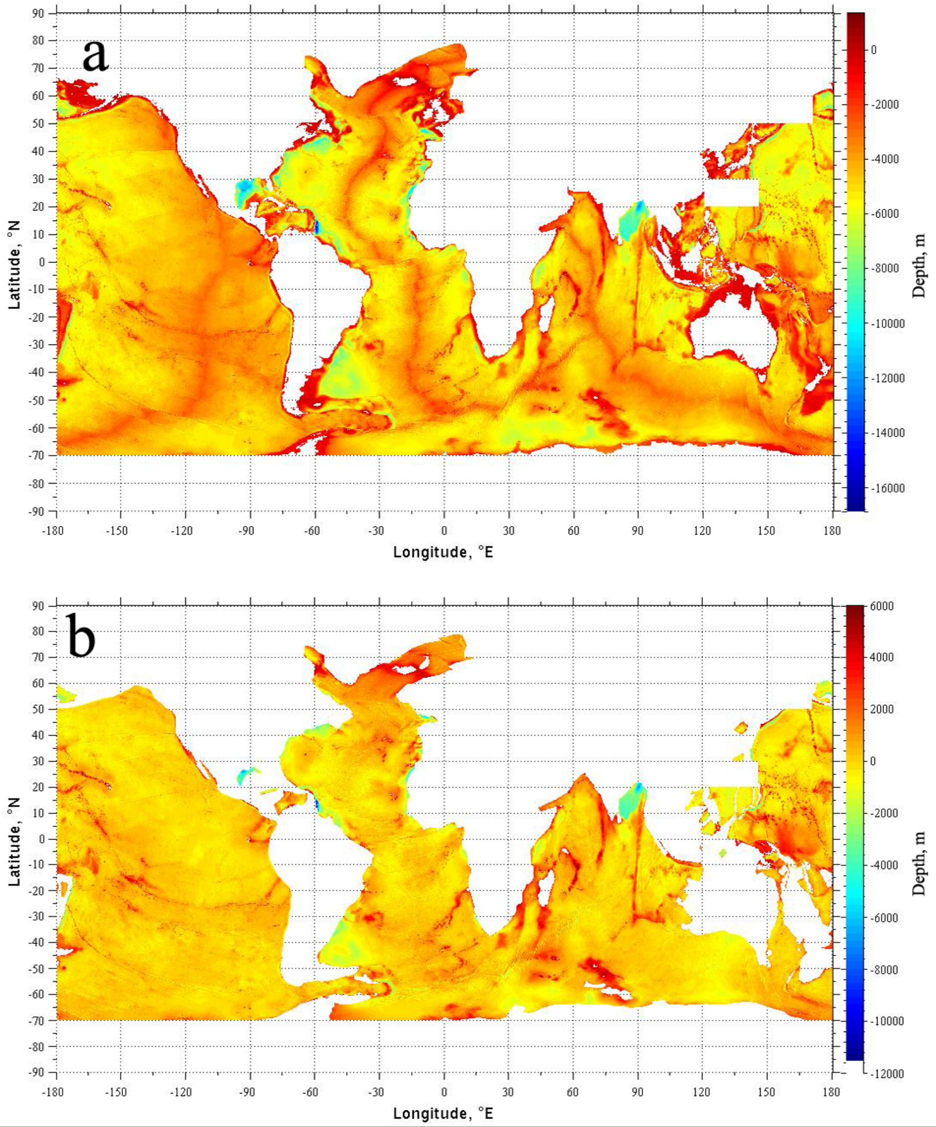

Figure 12. Residual ocean bathymetries: a: ETOPO1 bathymetry minus the global oceanic sediment thickness from Divins (2003) with isostatic re-adjustment applied. : The bathymetry from a minus the depth-to-basement bathymetry shown in Figure 4.

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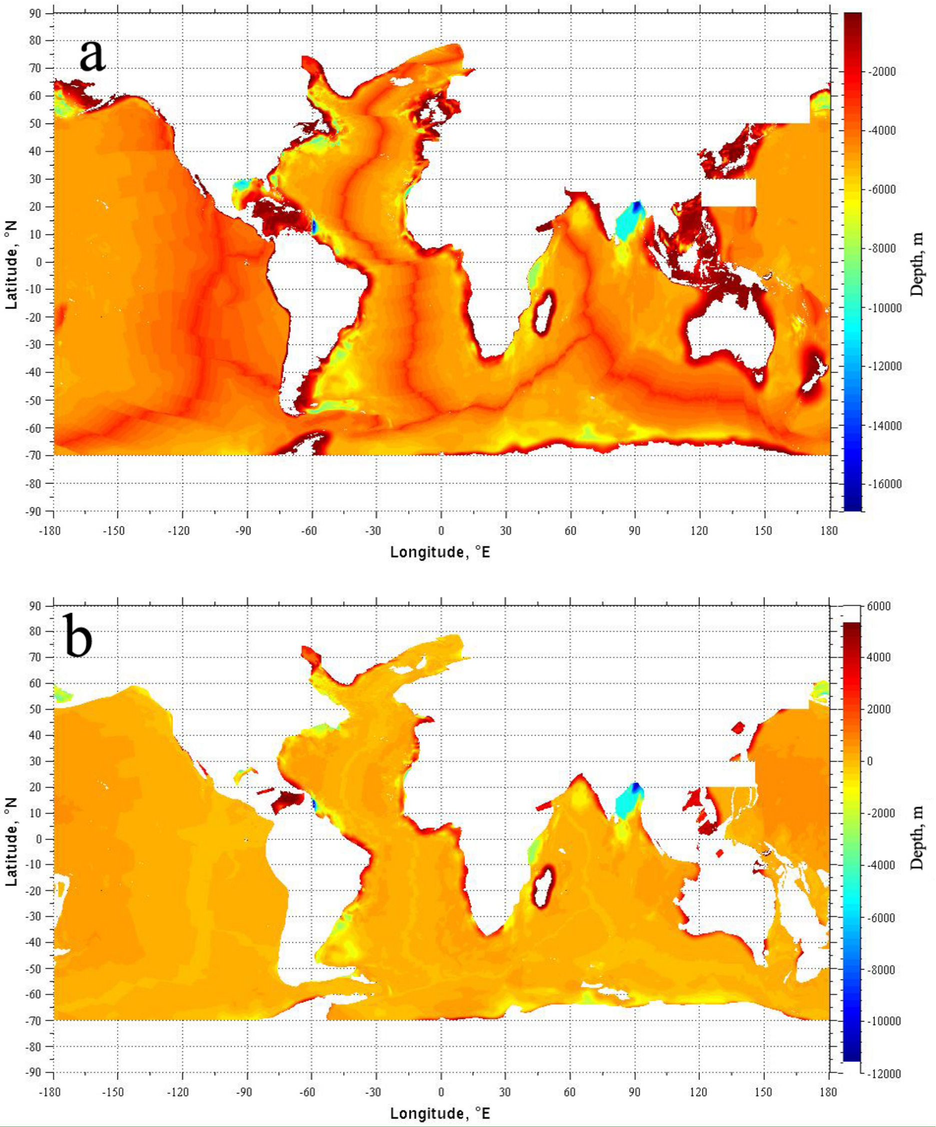

Figure 13. a: OES model bathymetry minus the global oceanic sediment thickness from Divins (2003) with isostatic correction applied. b: The bathymetry from a minus the depth-to-basement bathymetry shown in Figure 4.

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Examining such processes under past climate, however, is difficult. Analysis of the distribution of ages for the modern oceanic crust reveals that 46% of the crust is younger than 50 Ma, 31% is 51 to 100 Ma old, and the remaining 23% is older than 100 Ma (Müller et al. 2008). Because older ocean crust is recycled through subduction processes, direct reconstruction of bathymetry for the paleo-ocean is problematic. Apart from benthic fossil and sediment paleo-depth interpretations (Holbourn et al., 2001), there is little by way of a geologic record to quantify paleobathymetry where ocean crust has been subducted.

The past decade has witnessed vast improvement in the quality of high-resolution global ocean bathymetry, ocean sediment thickness, and ocean crustal age data, important refinements to models of the lithosphere. These advancements provide an opportunity to revisit the question of what the ocean bottom looked like in the past. In this work we apply these new data and modeling tools to develop a method that can be used to extend ocean bathymetry back through geologic time. Modern ocean bathymetry, sediment thickness, and continental shelf-slope-rise structure are parameterized to reconstruct a realistic ocean bathymetry, tied to age of the oceanic crust and idealized representations of marginal marine sediment structures. We name this reconstructed bathymetry 'OESbathy', abbreviated to OES for this paper (OES = Open Earth Systems; www.openearthsystems.org).

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Examining such processes under past climate, however, is difficult. Analysis of the distribution of ages for the modern oceanic crust reveals that 46% of the crust is younger than 50 Ma, 31% is 51 to 100 Ma old, and the remaining 23% is older than 100 Ma (Müller et al. 2008). Because older ocean crust is recycled through subduction processes, direct reconstruction of bathymetry for the paleo-ocean is problematic. Apart from benthic fossil and sediment paleo-depth interpretations (Holbourn et al., 2001), there is little by way of a geologic record to quantify paleobathymetry where ocean crust has been subducted.

The past decade has witnessed vast improvement in the quality of high-resolution global ocean bathymetry, ocean sediment thickness, and ocean crustal age data, important refinements to models of the lithosphere. These advancements provide an opportunity to revisit the question of what the ocean bottom looked like in the past. In this work we apply these new data and modeling tools to develop a method that can be used to extend ocean bathymetry back through geologic time. Modern ocean bathymetry, sediment thickness, and continental shelf-slope-rise structure are parameterized to reconstruct a realistic ocean bathymetry, tied to age of the oceanic crust and idealized representations of marginal marine sediment structures. We name this reconstructed bathymetry 'OESbathy', abbreviated to OES for this paper (OES = Open Earth Systems; www.openearthsystems.org).

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In all oceans, central rift valleys of the mid-ocean ridges have a negative residual bathymetry, not having been modeled by our depth-to-basement procedure. Major transform fault lineaments are negative for the same reason. Otherwise, ridge crests have been successfully removed. Along the central rift valleys there are significant variations, with especially deep values in the southern South Atlantic and Indian Oceans. There is almost no signature of the central rift in the Southern Ocean mid-ocean ridge (between Australia and Antarctica), where sediment cover was underestimated (Divins, 2003).

Most of the eastern Pacific Ocean is close to isostatic equilibrium, but there is broad, low amplitude positive and negative variability throughout the abyssal plains. Elsewhere, hot spots are expressed by long tracks of seamounts, for example the long arcs crossing the southern Pacific Ocean such as the Pukapuka and Louisville seamount chains. The Hawaiian Island chain is surrounded by a pronounced positive swell that is maintained over the entire chain. The western Pacific Ocean has a large and widespread positive anomaly, some of which is associated with the Ontong-Java Plateau (Taylor, 2012).

Anomalies at ocean margins are evident in the cross-section profiles of Figure S7, e.g., where ETOPO1 is much shallower (by more than 1.5 km) than OES or EB08. Notable examples are from Newfoundland (Lines 14 and 15) and southeast Africa (Lines 23 and 24), while other examples should not be confused with incompletely modeled delta systems, e.g., the Bay of Bengal (Line 33), or anomalously wide shelves, e.g., the Arctic Ocean margin (Lines 16, 57-59).

Some of the anomalies in the ETOPO1 residual bathymetry may be related to dynamic topography, usually defined as the deviation of surface topography from that expected for the lithosphere in isostatic equilibrium with the underlying mantle (Hager et al., 1985; Braun, 2010; Flament et al., 2013). Dynamic topography is attributed to effects from mass anomalies in the mantle related to mantle convection. Evidence for such mass anomalies comes from the global geoid, which exhibits three large positive anomalies centered on Iceland, the western Pacific Ocean and Southern Ocean near the southern tip of Africa (Cazenave, 1995). Comparison of the residual bathymetry (Figure 12B) and two slices at +1000 m and +2500 m (Figure S8) identify these three regions as those with the largest positive topographic anomalies worldwide. The northern Atlantic Ocean has the largest positive anomaly, in excess of 2 km, associated with Iceland. Some of this anomaly may be ascribed to the igneous province that comprises Iceland, but the remainder has been explained as dynamic topography resulting from a deep mantle upwelling (Conrad et al., 2004). The western flank of the northern Atlantic Ocean has a large positive anomaly associated with the Bermuda hotspot (Vogt and Jung, 2007). Residual bathymetry also captures part of the African Superswell (Lithgow-Bertelloni and Silver, 1998) around the coast of South Africa and Mozambique, as well as the multiple N-S-trending positive ridges extending offshore from seamounts and hotspot tracks.

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