Linear or nonlinear rheology in the mantle: a 3D finite-element approach to postglacial rebound modeling

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Abstract

In a previous work, cast in axisymmetric flat geometry, we have shown that a realistic composite rheology (linear plus nonlinear) for the Earth’s mantle reproduces the postglacial isostatic readjustment of Laurentia significantly better than a purely linear one. In this work we address the same problem in a 3D flat geometry allowing to apply the ice load described by the ICE-3G deglaciation history without manipulations. Computation is numerically carried out through finite elements as the nonlinear formulation prevents the use of spectral methods. The goodness of fit is quantitatively tested by comparing observed and computed Relative Sea Level (RSL) data at 29 North American sites for the last 8 kyr. The mixed rheology model still shows a slightly but significantly better fit (in the statistical sense) than the linear model.

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1. Introduction

Mantle rheology is definitely a multidisciplinary topic among the Earth Sciences domain. Petrologists, looking at deformation microstructures, both in natural xenoliths and in laboratory specimens, discovered traces of various creep mechanisms, the most common being linear diffusion creep and nonlinear dislocation creep (Ranalli, 2001).

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High pressure and high temperature experiments carried out on olivine polycrystals, mineralogically and physically pertaining to upper mantle conditions, showed that power-law creep dominates even though linear creep might locally act a relevant role, if the grain size is small (≤100 μm) and the deviatoric stress level relatively low (Ranalli, 1991, 1998, 2001). Thus, a realistic upper mantle rheology should be composite (Ranalli, 1998). With regard to garnet and spinel, which make up the bulk composition of the transition zone, there is experimental evidence of diffusion creep only in really fine-grained aggregates (Wang and Ji, 2000; Karato et al., 2001). Eventually, macrophysical knowledge on the lower mantle mostly comes from experiments on perovskite analogues, which reported both dislocation and diffusion creep (Karato and Li, 1992; Karato et al., 1995; Li et al., 1996). However, since the pressure dependence of creep for garnet, spinel and perovskite is still unknown, a direct extrapolation of experimental results to the mantle rheology must be avoided (Ranalli, 2001). Recently, Yamazaki and Karato (2002) have made large strain shear deformation experiments on (Mg,Fe)O which have shown dislocation creep to control crystal deformation. Even though a minor constituent of the Earth’s lower mantle (Mg,Fe)O probably has a smaller creep strength than perovskite and therefore its viscosity could control the lower mantle one, but only if it also controls the lower mantle fabric. As elongate flow-induced microstructures, mainly due to dislocation creep, are likely to be the microscopic source of mantle seismic anisotropy at all scales, the deformation fabric of (Mg,Fe)O might cause lower mantle seismic anisotropy (Yamazaki and Karato, 2002).

Approaching rheological parameters from theoretical rate equations (Ranalli and Fischer, 1984; Ranalli, 1991, 1998) leads to a mixed rheology for the upper mantle and a predominant non-Newtonian behaviour in the lower mantle, by assuming a minimum grain size of about 100 μm. However it is worthy to point out that viscosity strongly depends on grain size for diffusion creep and on flow conditions for dislocation creep: both grain size and flow conditions are not well-constrained for the mantle.

For the last few decades, geophysical forward and inverse modeling also have been substantially contributing to the debate on mantle rheology. Researchers concerned with geodynamical processes in general, such as convection, are all aware that their models can properly run if the mantle has non-Newtonian portions (Christensen, 1983; Solomatov and Moresi, 1997; Han and Gurnis, 1999). Postglacial rebound models, conversely, have mostly been implementing a linear viscoelastic mantle. This choice comes from mathematical expediency rather than from physical reality (Lambeck and Johnston, 1998). The different timescale between postglacial rebound and long-term geodynamical processes could make postglacial isostatic readjustment strongly affected by transient creep (Karato, 1998). Nevertheless, the broad agreement of viscosity profiles derived from postglacial rebound data and from density anomalies obtained through seismic tomography and global geodetic features (Mitrovica and Forte, 1997; Čadek and Fleitout, 1999) seems to indicate that postglacial rebound can discern steady-state creep (Ranalli, 2001), thus allowing the application of the rheological properties derived from postglacial rebound modeling to long-term mantle phenomena.

By considering a low ambient stress non-interacting with rebound stress and employing simple ice histories, Karato and Wu (1993) proposed a 300 km uppermost nonlinear mantle overlying a Newtonian bulk mantle. The use of 2D and 3D finite-element (FE) flat models and of realistic ice histories led to admit the existence of nonlinear portions inside the mantle, even though they confirmed the incompatibility of RSL data with a fully non-Newtonian mantle (Wu, 1993, 1995, 1999).

The application of a spherical FE model showed that a whole nonlinear upper mantle could make long-wavelength postglacial signatures insensitive to the viscosity of the lower mantle and thus to its rheology (Giunchi and Spada, 2000). Recently Wu (2001, 2002) found that models with linear upper mantle ($\eta =$
10^{-36} \text{ Pa s}^{-3} \text{ s}^{-1}) as well as models with thin nonlinear zones ($A = 3 \times 10^{-35} \text{ Pa s}^{-3} \text{ s}^{-1}$) above a linear mantle (ambient stress of about 10 MPa) are able to explain sea level data both outside and inside the Laurentian ice margin.

Several FE simulations of postglacial rebound run by Gasperini et al. (2004), showed how the use of a composite (linear plus nonlinear) mantle rheology (Gasperini et al., 1992) together with the ICE-3G glaciological model (Tushingham and Peltier, 1991), adapted to the axisymmetric geometry, allow to reproduce RSL time histories in North America more accurately than a purely Newtonian rheology. Moreover, the power-law creep component came out to account for 55–85% of the total strain-rate during the numerical analysis (Fig. 1). The linear component, although accounting for a minority of the flow, seems to have a stabilizing effect on power-law rheology singularities.

2. The model

The Earth model we developed is 3D, flat and not self-gravitating. Flat geometry was shown to reproduce quite well the results gained by traditional spectral methods in spherical geometry within or near the ice margin, for an ice load of the size of the Laurentide ice sheet (Wu and Johnston, 1998). Anyhow, we argue that the influence of sphericity and self-gravitation could be of minor relevance for the sake of

![Fig. 1. Stress induced in the mantle by glacial forcing. The solid line represents the effective shear stress produced by glacial forcing during simulation at the depth of 670 km; the dash-dotted line, instead, the percentage of nonlinear component estimated for a model having $\sigma_B = 1.6$ MPa and $\sigma_T = 1.5$ MPa (see text).](image-url)
comparison among different models. The model has a 120 km elastic lithosphere and a 2770 km mantle, whose density and elastic properties vary vertically according to PREM (Dziewonski and Anderson, 1981). The lithospheric thickness we adopted is consistent with the estimates given by Flück et al. (2003) for the Canadian Shield. The mantle is rheologically uniform, both vertically and laterally, and the deformation is controlled by a mixed flow-law (Gasperini et al., 1992), including the linear Maxwell body relation and the power-law equation shown below:

\[
\dot{\varepsilon}_M^{ij} = \frac{1}{2\eta^*} \sigma_{ij} + \frac{1}{2\mu} \dot{\sigma}_{ij} \tag{1}
\]

\[
\dot{\varepsilon}_P^{ij} = A \sigma_{ij}^{n-1} \sigma_{ij} \tag{2}
\]

where \(\dot{\varepsilon}_M^{ij}\) and \(\dot{\varepsilon}_P^{ij}\) are the Maxwell body and the power-law deviatoric strain-rate tensors, respectively; \(\sigma_{ij}\) the deviatoric stress tensor; \(\eta^*\) the Newtonian viscosity (we use this notation since its value differs from the classical estimates of \(\eta\) obtained with purely linear creep laws); \(\mu\) the shear modulus; \(\sigma_E = \sqrt{\frac{1}{2}(\sigma_{ij}\sigma_{ij})}\) the effective shear stress (Ranalli, 1995); \(n\) the power-law exponent; and \(A\) a material parameter that depends on temperature and pressure. Thus, by summing both strain-rate contributions

\[
\dot{\varepsilon}_{ij} = \left(\frac{1}{2\eta^*} + A \sigma_{ij}^{n-1}\right) \sigma_{ij} + \frac{1}{2\mu} \dot{\sigma}_{ij} \tag{3}
\]

and substituting for \(A = 1/(2\eta^* \sigma_{ij}^{n-1})\), where the transition stress \(\sigma_T\) is the value of effective shear stress at which diffusion and dislocation creep equally contribute to total strain-rate (Ranalli, 1995, 1998, 2001), the above equation can be written as

\[
\dot{\varepsilon}_{ij} = \frac{1}{2\eta^*} \left[ 1 + \left(\frac{\sigma_E}{\sigma_T}\right)^{n-1}\right] \sigma_{ij} + \frac{1}{2\mu} \dot{\sigma}_{ij} \tag{4}
\]

We also introduced into the rheological equation a term \(\sigma_B\), which simulates the background (or ambient) stress induced in the mantle by other geodynamical processes (mainly convection). The final expression of the flow-law is therefore

\[
\dot{\varepsilon}_{ij} = \frac{1}{2\eta^*} \left[ 1 + \left(\frac{\sigma_E + \sigma_B}{\sigma_T}\right)^{n-1}\right] \sigma_{ij} + \frac{1}{2\mu} \dot{\sigma}_{ij} \tag{5}
\]

As a general analytical method for treating non-Newtonian flow behaviour is not available, we moved to FE analysis and employed the commercial FE code Marc (MSC, 2001).

The 3D FE mesh was developed from the 2D one, used in the previous work (Gasperini et al., 2004), azimuthally repeated a fixed number of times. Its shape is a disk with radius of 12,800 km and thickness of 2890 km. The axial region is occupied by six-node solid elements with triangular base, while all the other elements have eight nodes and trapezoidal bases. In Fig. 2, we show the time evolution of vertical displacement, for the composite rheology, at three sites located at different distances from the centre (0, 2200 and 2550 km). Solid line represents the 2D axissymmetrical model while symbols refer to 3D models with different meshes. For this comparison we loaded the 3D model with a circular paraboloid ice sheet having the same cross section and time history of the 2D load. The mesh we adopted for further computations (stars), having 20 elements radially, 10 vertically and 20 azimuthally, represents a satisfactory compromise between accuracy and computing efficiency.
Fig. 2. Computed vertical displacement as a function of time at three different sites located at the centre of the load ($R = 0\text{ km}$), at the Last Glacial Maximum largest horizontal extension ($R = 2200\text{ km}$) and farther ($R = 2550\text{ km}$). Solid black line refers to axisymmetric mesh with $80 \times 40$ (radially $\times$ vertically) elements; little squares to a 3D mesh $40 \times 20 \times 10$ (radially $\times$ vertically $\times$ azimuthally); dots to a $20 \times 10 \times 10$ mesh; finally, stars concern the mesh $20 \times 10 \times 20$ we chose because it represents the best balance between computing efficiency and precision. As 3D glacial forcing we applied ICE-3G deglaciation history for North America (Tushingham and Peltier, 1991). We stereographically projected ICE-3G disks onto the surface of our flat model (Fig. 3), using the barycentre of the whole deglaciation process (59.1N, 90.8W) as projection centre. Fig. 3 also shows the integration points where the FE model is loaded with a pressure proportional to the height of the disks within which each point is located. Although apparently rough, as some integration points may occur just in spaces between disks or where two disks overlap, this is likely the less speculative way of manipulating the glaciological model not requiring a preliminar interpolation of ice heights (e.g. Wu and Johnston, 1998). We verified, anyhow, that the total applied load, at each step, well corresponds to the balance of ICE-3G disk loads.

3. Analysis and results

We ran simulations for models with both purely linear and composite mantle. The exponent $n$ in Eq. (5) is 3 for the composite rheology while $\sigma_T$ goes to infinity for purely linear behaviour (there is no power-law creep taking place). As a reasonable starting point, we set $\sigma_T = 1.5\text{ MPa}$ and $\sigma_B = 1.6\text{ MPa}$, which are the values of transition and background stresses that better reproduced RSL time histories in our model.
Fig. 3. FE model integration points for elements located within a radius of 3000 km from the stereographic projection centre (see text), with superimposed ICE-3G load disks (units of meters).

runs based on axisymmetric geometry (Gasperini et al., 2004). Predicted vertical displacements were only corrected to account for eustatic sea level variations and then compared to relative sea level sequences of 29 North American sites around Laurentia (see Appendix A), 13 of them inside the former ice margin and 16 outside. The comparison was only carried out for the last 8 kyr, when other terms of the complete sea level equation can be neglected (Wu and Peltier, 1983).

We estimated the goodness of fit of the model to the RSL data through a chi-square analogous statistics (Wu, 1999; Gasperini et al., 2004):

$$\chi^2 = \frac{1}{N} \sum_{i=1}^{N} \left( \frac{rsl_o - rsl_i}{err_i} \right)^2$$

where $rsl_o$, $rsl_i$, and $err_i$ are, respectively, the observed and computed relative sea levels and the corresponding errors of each single RSL observation, while $N$ is the total number of observations. The Newtonian viscosity was varied iteratively in order to minimize the chi-square value for both linear and composite models.

The lowest chi-square value for the linear rheology, obtained with $\eta = 1.9 \times 10^{21}$ Pa s, is $\chi^2 = 8.1$, thus expressing a strongly better fit with respect to previous axisymmetric models which could only get $\chi^2 = 13.1$, with a viscosity $\eta = 2.6 \times 10^{21}$ Pa s (Gasperini et al., 2004). The composite rheology, with $A = 4.04 \times 10^{-38}$ Pa$^{-3}$ s$^{-1}$ ($\sigma_T = 1.5$ MPa and $\sigma_b = 1.6$ MPa), gave a slightly better value of chi-square.
Fig. 4. Chi-square values vs. viscosity for linear (dashed line) and best composite (solid line, with $\sigma_T = 1.8$ MPa and $\sigma_B = 1.6$ MPa) models. $(\chi^2 = 7.9)$, which however is very close to the minimum value of 8.3 got in axially symmetric geometry. The greater improvement for linear rheology when switching from axisymmetric to 3D models probably depends on the linearity assumption which characterizes ICE-3G. In fact, a linear mantle model is likely to overfit the deglaciation details, that were inferred by Tushingham and Peltier (1991) using the same linear rheology.

We also ran some other simulations with only varying $\sigma_T$ in the neighbourhood of the axisymmetric best-fit value of 1.5 MPa, because we had found, from the previous analysis, that the fit is more sensitive to this parameter rather than to $\sigma_B$. The parameters of the models we have run are summarized in Table 1. The behaviour of the misfit function with respect to viscosity is plotted in Fig. 4 for the best-fit model ($\sigma_T = 1.8$ MPa). However, the statistical significance of this fit needs to be tested because the composite rheology includes two free parameters more than the linear one. We thus analyzed the variance explained by the best composite and the linear models, properly accounting for the number of free parameters (Draper and Smith, pp. 97). The statistics for “extra sum of squares” $F = 11.7$ (with 2 numerator and 179 denominator degrees of freedom) indicates that the variance reduction (7.4%) of the best composite model ($\sigma_B = 1.6$ MPa, $\sigma_T = 1.8$ MPa, $A = 3.43 \times 10^{-35}$ Pa$^{-3}$ s$^{-1}$) with respect to the linear one is significant with confidence level $>99\%$.

The preference among models having different numbers of parameters can also be assessed by using the Bayesian Information Criterion (BIC). This criterion compares the log-likelihood function of different
Table 1
Chi-square and BIC values for linear and composite models

<table>
<thead>
<tr>
<th>Model</th>
<th>(\sigma_T) (MPa)</th>
<th>(\sigma_B) (MPa)</th>
<th>(\eta^*) (Pa s)</th>
<th>(A) (Pa (^{-3}) s(^{-1}))</th>
<th>(\chi^2)</th>
<th>BIC</th>
</tr>
</thead>
<tbody>
<tr>
<td>LIN</td>
<td>0.0</td>
<td>(\infty)</td>
<td>(1.9 \times 10^{21})</td>
<td>0.00</td>
<td>8.1</td>
<td>-665.61</td>
</tr>
<tr>
<td>C14</td>
<td>1.6</td>
<td>1.4</td>
<td>(5.7 \times 10^{21})</td>
<td>(4.51 \times 10^{-15})</td>
<td>8.0</td>
<td>-667.84</td>
</tr>
<tr>
<td>C15</td>
<td>1.6</td>
<td>1.5</td>
<td>(5.5 \times 10^{21})</td>
<td>(4.04 \times 10^{-15})</td>
<td>7.9</td>
<td>-666.70</td>
</tr>
<tr>
<td>C16</td>
<td>1.6</td>
<td>1.6</td>
<td>(5.0 \times 10^{21})</td>
<td>(3.91 \times 10^{-15})</td>
<td>7.8</td>
<td>-665.54</td>
</tr>
<tr>
<td>C17</td>
<td>1.6</td>
<td>1.7</td>
<td>(5.0 \times 10^{21})</td>
<td>(3.54 \times 10^{-15})</td>
<td>7.7</td>
<td>-664.36</td>
</tr>
<tr>
<td>C18</td>
<td>1.6</td>
<td>1.8</td>
<td>(4.3 \times 10^{21})</td>
<td>(3.43 \times 10^{-15})</td>
<td>7.5</td>
<td>-661.97</td>
</tr>
</tbody>
</table>

models giving a penalty for the extra parameters (Main et al., 1999). It is based on the BIC estimator

\[
\text{BIC} = L(z) - \frac{k}{2} \ln \left( \frac{N}{2\pi} \right)
\]

where \(k\) is the number of parameters fitted in the model (1 for the linear, 3 for the composite), \(N\) the number of observations (182), and \(L(z)\) the log-likelihood function of estimated parameters \(z = [x_1, x_2, \ldots, x_k]\). The latter can be expressed as

\[
L(z) = -\frac{1}{2} N \ln (S_R^2)
\]

where \(S_R^2\) is the residual sum of squares which is simply given by \(S_R^2 = N \chi^2\), in our (weighted) minimization scheme. The higher the BIC value the better the evaluated model. The two best composite models (C17 and C18) have BIC = \(-664.36\) and BIC = \(-661.97\), respectively and appear both clearly preferable with respect to the best linear one (LIN) giving BIC = \(-665.61\). Conversely, models C14 and C16 perform worse than LIN, while C15 is almost equivalent. Although we did not explore the whole parameters space with regard to \(\sigma_T\) and \(\sigma_B\), the statistically significant better fit of our best composite models with respect to the linear one, appears to confirm the findings obtained in axially symmetric geometry.

A visual inspection of model predictions at four RSL sites (Fig. 5) shows how locally important the choice of rheology can be. At Churchill the linear model fits RSL data more nicely than the composite rheology, but the latter gets better for Ottawa Island, where it performs particularly well on the data with smaller observational error (and higher weights in Eq. (6)). Moreover, the composite model is able to well explain relative sea level variations just outside the ice margin. This is an encouraging aspect as RSL sequences at these sites have shown to be the most difficult to reproduce for nonlinear models in past works (Wu, 1993, 1995, 1999, 2001, 2002).

4. Discussion and conclusions

The application of a mixed rheology for the mantle to a 3D FE model is able to reproduce RSL variations in North America slightly better than a purely linear behaviour, thus confirming what previously found through analyses conducted in axially symmetric geometry (Gasperini et al., 2004). A rather nice fit was also possible for sites located a little outside of the former Laurentide ice sheet, which has always been a challenging task for people working in postglacial rebound modeling (Wu, 1993, 1995, 1999, 2001, 2002).
Fig. 5. Matching predicted and observed relative sea levels at two sites inside the area formerly covered by Laurentide ice sheet (Churchill, Manitoba and Ottawa Is.) and two outside (Brigantine and Boston).

Our adoption of a more complicated rheology (with two parameter more than the linear one) might raise the question about the statistical significance of the obtained fit as the fit improvement could be too low for allowing the choice of a higher number of parameters. For that reason we applied the $F$-test and the Bayesian Information Criterion to the best-fit linear and composite models and found out that the improvement of the fit for the composite rheology is statistically significant with regard to the higher number of free parameters.

These results are not surprising from either the microphysical or the convection modeling point of view as both linear and nonlinear deformation mechanisms are largely recognized inside the mantle. Such an awareness, however, is not equally widespread among investigators involved in postglacial rebound. This probably comes from the fact that Newtonian viscoelastic creep can be beautifully treated with rigorous
analytical methods (Farrell and Clark, 1976; Peltier and Andrews, 1976; Yuen et al., 1986) which unfortunately break down, for the inadequacy of the superposition principle, when approaching a nonlinear problem. Also, several decades of studies in this field have shown that linear rheology is able to reproduce quite well the observations within experimental uncertainties. Thus the linear rheology might appear preferable, at least mathematically. Moreover, the ambient stress field induced in the mantle by thermal convection may mask the nonlinear behaviour of mantle rock subjected to the glacial forcing, hence postglacial rebound alone could not be able to discern the true mantle creep mechanism. On the other hand, experimental evidences and microphysical studies suggest that non-Newtonian creep must play a prominent or at least equivalent role with respect to linear creep, in viscous deformation of rocks. Although the microphysical approach is known to have important limitations, it represents a piece of knowledge that cannot be overlooked in setting models of Earth dynamics which always must agree with the laws of solid-state physics (Drury and Fitzgerald, 1998).

Our results are not conclusive about the nature of mantle rheology and further analyses, considering for example more realistic geometries (spherical), a rheological stratification, and the modeling of other observables (gravity, rotation, etc.), are required to demonstrate that composite rheology fits better than linear one in all cases. However they clearly indicate that the preference for a linear model, assumed in the most of postglacial rebound investigations, is far from being demonstrated, even because exhaustive comparisons between purely linear and nonlinear (or composite) rheologies have been only seldom addressed in the past literature.

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Appendix A. RSL sites used for comparison with model prediction

RSL data are taken from the global database by Tushingham and Peltier (1992) and consists of a total of 182 observations (82 inside and 100 outside the former ice margin). The sites listed in Table A.1 do not exactly coincide with those (27) used (but not listed) by Wu (1999, 2001, 2002), although our selection is based on an “unofficial” list referring such papers.

References

Table A.1

<table>
<thead>
<tr>
<th>Site</th>
<th>Latitude</th>
<th>Longitude</th>
<th>Distance</th>
<th>IN/OUT</th>
<th>N.DA TA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Richmond Gulf, Quebec</td>
<td>57.0</td>
<td>−77.0</td>
<td>845.01</td>
<td>IN</td>
<td>9</td>
</tr>
<tr>
<td>James Bay, Quebec</td>
<td>53.0</td>
<td>−79.0</td>
<td>997.39</td>
<td>IN</td>
<td>7</td>
</tr>
<tr>
<td>C. Henrietta Maria O</td>
<td>55.0</td>
<td>−82.5</td>
<td>679.39</td>
<td>IN</td>
<td>7</td>
</tr>
<tr>
<td>Churchill, Manitoba</td>
<td>58.0</td>
<td>−94.0</td>
<td>220.94</td>
<td>IN</td>
<td>7</td>
</tr>
<tr>
<td>Keewatin, Northwest Territory</td>
<td>64.5</td>
<td>−95.0</td>
<td>637.35</td>
<td>IN</td>
<td>4</td>
</tr>
<tr>
<td>Ottawa Is., Northwest Territory</td>
<td>59.8</td>
<td>−80.3</td>
<td>599.67</td>
<td>IN</td>
<td>10</td>
</tr>
<tr>
<td>Southampton Is., Northwest Territory</td>
<td>64.5</td>
<td>−84.0</td>
<td>697.60</td>
<td>IN</td>
<td>7</td>
</tr>
<tr>
<td>Goose Bay Lab</td>
<td>53.0</td>
<td>−60.0</td>
<td>2001.91</td>
<td>IN</td>
<td>7</td>
</tr>
<tr>
<td>C. Tanfield Baf.</td>
<td>63.0</td>
<td>−70.0</td>
<td>1193.68</td>
<td>IN</td>
<td>4</td>
</tr>
<tr>
<td>Melne Inlet Baf.</td>
<td>72.0</td>
<td>−80.0</td>
<td>1508.48</td>
<td>IN</td>
<td>6</td>
</tr>
<tr>
<td>Igplik Bay Baf.</td>
<td>69.0</td>
<td>−75.5</td>
<td>1318.52</td>
<td>IN</td>
<td>6</td>
</tr>
<tr>
<td>Igoolik Is. Northwest Territory</td>
<td>69.0</td>
<td>−82.0</td>
<td>1176.35</td>
<td>IN</td>
<td>7</td>
</tr>
<tr>
<td>Rimouski, Quebec</td>
<td>48.5</td>
<td>−68.5</td>
<td>1860.27</td>
<td>IN</td>
<td>1</td>
</tr>
<tr>
<td>NW, Newfoundland</td>
<td>51.5</td>
<td>−56.5</td>
<td>2288.44</td>
<td>OUT</td>
<td>8</td>
</tr>
<tr>
<td>Halifax, Nova Scotia</td>
<td>44.7</td>
<td>−63.7</td>
<td>2411.57</td>
<td>OUT</td>
<td>4</td>
</tr>
<tr>
<td>Bay of Fundy, Nova Scotia</td>
<td>43.0</td>
<td>−65.0</td>
<td>2322.88</td>
<td>OUT</td>
<td>6</td>
</tr>
<tr>
<td>St. John, New Brunswick</td>
<td>45.3</td>
<td>−66.0</td>
<td>2249.18</td>
<td>OUT</td>
<td>4</td>
</tr>
<tr>
<td>Addison, Maine</td>
<td>44.5</td>
<td>−67.7</td>
<td>2239.74</td>
<td>OUT</td>
<td>8</td>
</tr>
<tr>
<td>Isles of Shoals, New Hampshire</td>
<td>43.1</td>
<td>−70.7</td>
<td>2238.16</td>
<td>OUT</td>
<td>7</td>
</tr>
<tr>
<td>Boston, Massachusetts</td>
<td>42.8</td>
<td>−70.8</td>
<td>2262.40</td>
<td>OUT</td>
<td>6</td>
</tr>
<tr>
<td>New Haven, Connecticut</td>
<td>41.2</td>
<td>−73.0</td>
<td>2332.75</td>
<td>OUT</td>
<td>6</td>
</tr>
<tr>
<td>New York, New York</td>
<td>41.0</td>
<td>−74.0</td>
<td>2317.40</td>
<td>OUT</td>
<td>9</td>
</tr>
<tr>
<td>Hudson R., New York</td>
<td>41.3</td>
<td>−74.0</td>
<td>2287.60</td>
<td>OUT</td>
<td>7</td>
</tr>
<tr>
<td>Brigantine, New Jersey</td>
<td>39.5</td>
<td>−74.5</td>
<td>2451.00</td>
<td>OUT</td>
<td>6</td>
</tr>
<tr>
<td>Bowiers, Delaware</td>
<td>39.0</td>
<td>−75.5</td>
<td>2476.53</td>
<td>OUT</td>
<td>8</td>
</tr>
<tr>
<td>C. Charles, Virginia</td>
<td>37.0</td>
<td>−76.0</td>
<td>2660.81</td>
<td>OUT</td>
<td>8</td>
</tr>
<tr>
<td>Southport, North Carolina</td>
<td>34.0</td>
<td>−78.0</td>
<td>2921.62</td>
<td>OUT</td>
<td>4</td>
</tr>
<tr>
<td>Myrtle Beach, South Carolina</td>
<td>33.7</td>
<td>−78.7</td>
<td>2937.46</td>
<td>OUT</td>
<td>4</td>
</tr>
<tr>
<td>Savannah, Georgia</td>
<td>32.0</td>
<td>−81.0</td>
<td>3072.27</td>
<td>OUT</td>
<td>5</td>
</tr>
</tbody>
</table>

LAT and LON are the geographical coordinates in degrees, DIST is the distance from the barycentre of the ice sheet in km. IN or OUT indicate whether the site is located inside or outside the former ice margin. N.DA TA is the actual number of RSL observations in the last 8 kyr.


Han, L., Gurnis, M., 1999. How valid are dynamic models of subduction and convection when plate motions are prescribed? Phys. Earth Planet. Inter. 110, 235–246.


