Palaeoclimatology

Climate's carbonate cypher

For the best part of 50 years, palaeoceanographers have been exhuming marine sediments and meticulously decoding the isotopic signals locked into the ancient carbonate shells of buried animals, such as the microscopic foraminifer, *Orbulina universa*, pictured here. The fruits of this cryptographic endeavour are detailed pictures of past climates and ocean conditions stretching back hundreds of millions of years. But have the right codes been used? Not always, according to new experiments on *O. universa* and another foraminifer, *Globigerina bulloides*, reported elsewhere in this issue (H. J. Spero *et al. Nature* 390, 497–500; 1997).

Pioneers in this field worked out that the oxygen-isotope ratio, $^{18}O/^{16}O$, of shell carbonate depends not only on the ratio in the surrounding sea water, but also on the temperature at which the shell formed. A shell's carbon-isotope ratio, $^{13}C/^{12}C$, seems to reflect that of the ambient sea water, overprinted with the effects of physiological processes, such as respiration and the photosynthesis of symbiotic organisms.

It is no secret that other processes affect isotope fractionation, but their identity and extent of influence have proved largely elusive. Spero *et al.* show that the concentration of dissolved carbonate ions in sea water has a marked effect on the fractionation, and consequently argue that present understanding of some past climate changes will need to be revised. For example, the glacial–interglacial shift in shell $^{13}C/^{12}C$ — thought to be due to a large transfer of terrestrial carbon to the ocean — could simply reflect known changes in the surface ocean's carbonate ion concentration; and oxygen-isotope-based estimates of tropical sea-surface temperature during the last glacial period might need to be lowered.

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Simons and Hager[1] have carried out an innovative analysis of the global free-air gravity field which explores the geographical variation in the spectral content of the field. The approach provides fresh insights and a powerful, gravity-based datum for inferring Earth structure. Specifically, as regards Hudson Bay, it confirms proposals that the post-glacial rebound of Canada is consistent with a significant increase of material strength (or viscosity) with depth in the mantle, and shows that 50% of the peak anomaly from this region is due to incomplete post-glacial rebound.

Associating the entire observed peak free-air gravity anomaly over Canada with post-glacial disequilibrium is highly problematic. It has long been recognized[2,3] that the relatively large gravity anomaly is inconsistent with the short relaxation time (some 2,000–3,000 years) inferred from the post-glacial uplift record from the same region. Simply put, the uplift record indicates that the post-glacial adjustment is nearly complete, whereas the gravity anomaly suggests that a significant level of disequilibrium remains. To reconcile this apparent inconsistency, Walcott[2] proposed an adjustment defined by two relaxation times; however, Cathles[3] argued convincingly that Earth models characterized by a double relaxation time would not fit other glaciation-related data sets in the region. Cathles was, to my knowledge, the first to suggest that a significant portion of the observed anomaly may derive from an entirely different source — namely, mantle convection.

The idea of a double relaxation time was revived by Peltier and Wu[4] in the early 1980s. These authors argued that the buoyancy associated with the deflection of the density discontinuity at 670 km depth, the boundary between the upper and lower mantle, would be characterized by long decay times and would contribute significantly to the peak anomaly over Hudson Bay. Subsequent analysis[5] showed that the free-air anomaly had been incorrectly calculated and that the contribution from the adjustment of the 670-km boundary would be very small. It now appears inescapable that the amplitude of the Canadian anomaly cannot be explained by remnant post-glacial disequilibrium alone[6,7]. Indeed, direct predictions of the mantle convection signal, using methods established to predict long-wavelength variations in the geoid[6], indicate that convective flow may support over 75% of the observed anomaly.

How can this uncertainty be resolved? One approach is to simply ignore the regional gravity data from such areas and test preferred models by their ability to account for the observed peak gravity signature. Forte and I inverted data associated both with mantle convection and with post-glacial rebound, and found that a single viscosity profile, characterized by a significant increase with depth, is able to reconcile the two[8]. Our calculations indicated that the predicted peak free-air gravity anomaly fitted the observed anomaly, with one-third of the signal arising from post-glacial disequilibrium.

Simons and Hager[1] outline a second approach. They use a so-called spatio-spectral localization method[9], which involves spectral decomposition of data spatially windowed around a specific geographical site. Repetition of the procedure for sites around the globe provides a measure of the geographical variation of this spectral content. The method gives an incredibly rich representation of the gravity field (see Fig. 1 on page 501), in which tell-tale fingerprints of various geophysical signatures (such as variations in crustal thickness, and mantle convection and incomplete rebound) are clearly evident. Simons and Hager find that, over Hudson Bay, the amplitude of the spatio-spectral representation of the gravity field is uniquely localized in space and in length scale. They also show that near-surface seismic tomographic images do not have this feature in the vicinity of Hudson Bay, which provides convincing evidence that the post-glacial rebound contribution to the gravity field in this region cannot be small.

But how large is this signal? The answer is an outcome of a second aspect of Simons and Hager's analysis, in which they define a global transfer function, $\tilde{F}$, determined by spatially averaging local correlations between the observed gravity field and any arbitrary spatial distribution. If this distribution reflects the spatial geometry of post-glacial rebound, then the transfer function is a much less 'contaminated' measure of the rebound signal than either a peak gravity anomaly or a traditional spectral decomposition. Indeed, the global transfer function derived by Simons and Hager (see their Fig. 2b on page 502) is an important new data set in studies of post-glacial rebound and one that can be used directly to infer Earth structure.

As a first step in this direction, the authors compute synthetic transfer functions using a set of previously published viscosity models as well as a new model ('SH') which provides a reasonable fit to their estimate of $\tilde{F}$. The SH model shares many of the main features of the viscosity profile inferred by Forte and me[8], including a stiff asthenosphere, an anomalously weak transition zone and a high-viscosity deep mantle (see Fig. 2a, page 502). This agreement is remarkable because the data sets used in the two studies are essentially independent, and it adds strong support to a growing consensus in the geodynamics community that the mantle is characterized by a large increase in viscosity with depth. It is on the basis of the SH model that Simons and Hager argue that 50% of the peak free-air gravity anomaly over Hudson Bay is due to incomplete glacial rebound.

Overall, the authors have resurrected the