Seismic tomography and the dilemma of the Earth's heat budget

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Until twenty years ago, the predominant view was that the Earth convects in two separate layers, such as to preserve the distinct identity of chemical reservoirs inferred from isotope ratios of basalts and the argon content of the atmosphere. However, after the discovery of slabs penetrating deeply into the lower mantle, this view gave way to the now widely shared perception that upper- and lower mantle easily exchange material. Such a more-or-less one layer convective system had been favoured by many in the geophysical community, who perceived a difficulty in the Earths ability to cool sufficiently rapidly unless heat was advected from the deep interior to the surface.

But even in a one-layer convective system, parametrized convection calculations of the average temperature of the Earth backwards in time lead to a molten mantle at around 3 Gyr (the heat catastrophe), unless the Urey number is higher than acceptable on geochemical grounds. Since the total heat flux out of the Earth is known fairly accurately (about 44 TW), and known sources from crust and upper mantle can be taken into account with reasonable certainty, one relatively hard constraint on convection models is that about 31 TW has to pass through the 660 km discontinuity, again arguing for mass exchange between upper and lower mantle to enable a heat flux that is difficult to accomplish by conduction. The result is an important and puzzling discrepancy between the constraints imposed by geochemical and geophysical data.

A variety of solutions has been proposed to escape from this paradox, but no consensus has evolved: several mechanisms could decrease the dependence of the heat flux on the Rayleigh number in parametrized convection calculations. Others question the geochemical evidence.

Seismic tomography however is beginning to offer observational constraints. Some slabs are seen to rest on top of the 660 km discontinuity. The younger part of the Farallon slab beneath North America has been fragmented, partly along fracture zones, and is only one fragment is subducting to deeper levels. Low velocity zones in the upper mantle beneath those slabs that enter the lower mantle indicate the existence of a return flux at temperatures higher than adiabatic. The imaging of plumes in the lower mantle, while again providing evidence for mass exchange, also show that such exchange must be limited because the lower mantle plumes are much larger than can be inferred from their buoyancy flux.

The tomographic observations could be explained if the 660 km discontinuity caps a significant thermal boundary layer between upper and lower mantle from which secondary plumes may spawn, explaining the discrepancy between plume flux computed from tomography and from bathymetry. To confirm this hypothesis, an improved seismic coverage of the oceans is necessary. Oceanographic floats may be equipped with hydrophones to create dense seismic networks to study the mantle beneath hotspots in the Pacific, Atlantic and Indian Ocean.

Earthquake dynamics: from source to radiation

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The most successful earthquake radiation model, Brune's circular crack, was developed on the basis of a combination of simple geometrical arguments and the amplitude of seismic waves generated by a prescribed instantaneous stress drop. Later this model was shown to model also the radiation from a circular crack running at finite speed and stopping abruptly. Under closer scrutiny, Brune's model actually specifies a particular partition of available strain energy into fracture energy and radiated energy. Seismic efficiency, defined as the ratio between radiated energy and the part of strain energy that can be used for radiation, can be computed for different models of radiation from circular cracks. Efficiency is close to 50 % for Brune's model independently of the size of the earthquake. In order to study energy balance from near field data, we have recently developed a non-linear dynamic inversion method for low frequency weak and strong motion records using the Neighbourhood algorithm of Sambridge and colleagues. We look for source models that have a simple elliptical geometry (one or more ellipses can be used). The forward problem is solved using a finite difference numerical simulation of the seismic rupture process for given distributions of initial stress and fracture resistance (Gc) . We applied the method to a couple of well-studied earthquakes in Japan and Chile showing that seismic waveforms are dominated by a combination of stress drop, energy release rate and the overall earthquake geometry. Only average values of these parameters can be derived from dynamic inversion as suggested by several previous studies. We demonstrate that the general properties of the models retrieved from inversion can be encapsulated by the kappa parameter that controls numerical seismic ruptures. This number derives from the ratio between the strain energy released by the earthquake that is available for radiation and the amount of energy that is required to make the rupture propagate. At low rupture speeds, this number converges to the Griffith criterion of fracture initiation. It is surprising that such a simple number may encapsulate much of the low frequency properties of earthquake radiation. We argue that the reason is that radiation from these simple models are controlled by stopping phases, that is most of the elastic energy radiated by these events comes from the border of the rupture zone, where the ratio of radiated to available strain energy (seismic efficiency) is at a maximum. A consequence of this observation is that energy release rate necessarily grows with earthquake size, so that it is not a property of the fault interface, but that it evolves with the growth of the rupture as suggested by Aki, Ohnaka and others.

Earthquake Forecasting and Prediction: Progress in Model Development and Evaluation

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Forecasting and prediction are the central problems of earthquake system science. This presentation will summarize recent research, which has produced a new generation of time-dependent forecasting models and a new global infrastructure for evaluating prediction experiments. Earthquake forecasts estimate the probability that N fault ruptures with magnitudes ≥ M will occur in a geographic region R during the time interval of length T beginning at t0 ≥ tnpw. Earthquake predictions are alarms derived from forecasts or other information, such as precursory signals, and therefore involve tradeoffs between false alarms (type-I errors) and failures-to-predict (type-II errors).

Long-term earthquake rupture forecasts (T ~ decades to centuries) are the basis for probabilistic seismic hazard analysis. The simplest is a time-independent ERF, a Poissonian model independent of t0 consistent with the long-term occurrence rates in R. The Working Group on California Earthquake Probabilities (2007), in cooperation with the U.S. National Seismic Hazard Mapping Project, has recently developed a new time-independent model for California, and built on top of it a time-dependent Uniform California Earthquake Rupture Forecast. In UCERF, the event probabilities are conditioned on the dates of previous earthquakes using stress-renewal models and calibrated for variations in the earthquake cycle using historical and paleoseismic observations. A second type of time-dependent ERF, appropriate for short-term forecasting (T ~ hours to weeks), conditions the probabilities using seismic-triggering models calibrated to account for observed aftershock activity, such as epidemic-type aftershock sequence models. In California, the Short-Term Earthquake Probability (STEP) model of Gerstenberger et al. (2005) has been turned into an operational forecast that is updated hourly. Unifying the two types of time-dependent models requires a better understanding of medium-term predictability (T ~ weeks to years). This unification is not straightforward, because long-term models based on stress renewal are less clustered than simple Poissonian models, whereas short-term models based on seismic triggering are more clustered. Current research is thus focused on gaining insights into the physical processes that control stress changes and evolution on intermediate time scales.

The SCEC-USGS Working Group on Regional Earthquake Likelihood Models (Field et al., 2007; Schorlemmer et al., 2007) has been prospectively testing of a variety of medium-term forecasts (T = 5 yr, M = 5) in California. Based on this experience, an international partnership has been formed that is extending earthquake prediction experiments to other fault systems in a variety of tectonic environments through a global infrastructure for comparative testing, the Collaboratory for the Study of Earthquake Predictability. CSEP testing regions have been established in California, New Zealand, Japan, Italy, and the western Pacific. An open-source software system has been developed to automate the blind-testing of forecasting and prediction experiments using both likelihood and alarm-based scoring methods. Experiments currently being evaluated at the CSEP testing centers include seismicity-based forecasts updated at 1-day, 3-mo, and 1-yr intervals, as well as time-independent 5-yr forecasts of the RELM type. I will describe how the CSEP infrastructure is promoting rigorous research on earthquake predictability and the challenges of extending this infrastructure to include a wider range of prediction hypotheses.