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Preface to Response to the Earth's lithosphere to extension. A Discussion Meeting held at the Royal Society on 20 and 21 May 1998.

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Preface

The idea of holding a meeting to act as a forum for presenting some of the many exciting new results that were emerging from studies of rifted continental margins was conceived during a discussion between two of the organizers (R.S.W. and R.B.W.). It also seemed timely to include a commercial viewpoint in view of the hydrocarbon industry's increasing expansion of exploration into water depths traditionally regarded as the province of academics, and of recent discoveries of metal-rich, massive-sulphide deposits in the oceans that are potentially of great economic importance. The concept was subsequently broadened further to attract a wider audience and led to a Discussion Meeting on 'Response of the Earth's lithosphere to extension' held at the Royal Society in May 1998. The following collection of papers resulted from the Meeting.

Before discussing the response of the Earth's lithosphere to extension, it is necessary to agree on the definition of 'lithosphere' since this commonly causes misunderstandings and semantic problems. R. S. White reviews the thermal, rheological and compositional definitions of the lithosphere in oceanic and continental settings, with particular reference to rifted areas. Next Hawkesworth *et al*. present the oceanic lithosphere as being simpler, more homogeneous and hence probably stronger than continental lithosphere. Their subsequent discussion focuses on the continental lithosphere and in particular on the differences between Archaean and younger lithosphere. A problem here is to find uncontaminated samples that can provide evidence of the mantle composition; even dating these samples is quite difficult. It is concluded that in general the Archaean lithosphere has a less mafic lower crust, a thicker mantle lithosphere and a thinner crust, is more depleted in Fe and other major elements and is richer in SiO_2 than younger Proterozoic crust.

The mechanical or rheological behaviour of the lithosphere when under stress was the nub of the Meeting since it defines the response of the Earth's lithosphere to extension. The next group of papers presents ways in which we can attempt to explore and predict the Earth's response using numerical and analogue models. It ends with a presentation of a newly discovered form of extension on the Mid-Atlantic Ridge.

First, Buck *et al*. consider the competing processes that, on the one hand, tend to concentrate rifting in one place and, on the other hand, allow rifting to become 'delocalized' as in the case of a wide rift. Examples of the first sort of process are lithospheric necking, magmatic accommodation (intrusion of dikes) and the loss of cohesion on faults. The first mechanism seems to be the more important. Examples of the second sort of process are viscous flow, regional isostasy and local isostasy, of which probably only the last is important. The authors then report the results of numerical experiments to investigate the conditions that favour wide rifting and the 'boudinage' of the lithosphere. These experiments, along two-dimensional profiles normal to the direction of extension, are based on finite deformation that goes beyond earlier work on such models that used perturbation analysis alone. The authors incorporate the localizing effect of lithospheric necking and the delocalizing effects of slow extension, viscous effects and local isostasy. The conclusions are that wide rifting can occur when the viscosity varies slowly with depth and boudinage can happen if there is a density contrast at the Moho.

An alternative, but complementary, approach to modelling extension is taken by Brun who reviews the results of 15 years of analogue modelling. Although analogue models cannot allow for the temperature-dependent rheology of rocks, they can incorporate the bulk and internal mechanical instabilities that are inherent in extension. Brun's models consist of two to four layers of alternating 'brittle' and 'ductile' materials that approximate the rheological properties of crust and mantle. These models, with layers of varying thickness (strength), are exposed to different rates of extension including free spreading under gravitational forces alone. The models are used to investigate the development of narrow rifting (such as the continental rifts that often develop into rifted continental margins) and wide rifting (that occurs during, or after, lithospheric convergence that leads to lithospheric thickening). In the first case it is demonstrated that the thicknesses (strengths) of both the brittle and ductile layers affect the final result. An important conclusion from these models is that they do not support the concept of simple shear of the whole lithosphere; rather they suggest a form of pure shear with local internal structural asymmetries, such as boudinage of the uppermost mantle, that can lead, in the models, to the exhumation of the underlying ductile mantle. In the case of wide rifting different rates of extension are shown to generate either horsts and graben or tilted fault blocks. It is this class of model, with the addition of a local viscous heterogeneity just below the brittle–ductile transition, that is proposed as an explanation of the development of metamorphic core complexes.

In complete contrast, and in apparent contradiction with the above view associating core complexes with thickened crust, is the paper by Karson that describes an example from the Kane Transform Fault on the Mid-Atlantic Ridge of a new class of recently discovered dome-like massifs, which the author calls 'oceanic core complexes'. These massifs are characterized by a lineated upper surface and have similar forms and dimensions to core complexes on land. The Kane Transform Fault massif has been studied using sidescan sonar images, deep-towed cameras and manned submersibles. The massif was formed in thick gabbroic crust or in serpentinite with gabbroic intrusions, the gabbro being syntectonic in origin. Evidence of ductile stretching is seen in mylonites and shear zones. The massif shows small-scale fault-bounded ridges that apparently are responsible for the linear terrain that previously has been attributed to prolonged displacement along a detachment fault surface. Clearly, these are features that deserve considerable further study.

The next group of papers describes some of the different styles of tectonic expression found in continental rifts and on rifted continental margins. Ebinger *et al.* document the style of rifting that is found within the East African Rift, a classic example of a continental rift system. These authors present an extensive tabulation of the lengths and widths of active continental rift basins in the East African Rift together with estimates of the elastic thickness (T_e, ranging from 5 to 50 km) and the thickness of the seismogenic zone (T_seis) under the basins in different parts of the Rift. There appears to be an almost linear relationship between T_e, T_seis, basin width and border-fault length. The same relationship appears to be valid also for basins in the Baikal Rift and the Aegean area. Only the longer border faults seem to have re-occupied basement trends; shorter faults usually cross-cut such trends.

The authors argue that the elastic thickness of the lithosphere controls the style and dimensions of surface deformation.

From a different perspective Louden & Chian discuss the tectonic style involved in the formation of non-volcanic rifted margins that evolve from the rifting and break-up of continental crust (the evidence for what happens tectonically at volcanic margins is almost invariably obscured on seismic reflection profiles by a thick surficial layer of extrusive volcanic rocks). Louden & Chian present multichannel seismic reflection profiles and velocity models from seismic refraction profiles across three pairs of conjugate rifted margins in the North Atlantic Ocean (Goban Spur–Flemish Cap, West Greenland–Labrador and Galicia Bank/southern Iberia Abyssal Plain–Newfoundland). Only in the case of the southern Labrador Sea is there a complete pair of profiles from both sides; elsewhere the data-set is incomplete. Even so, it is evident that a characteristic of all these margins is a wide ocean–continent transition zone with common features such as shallow high-velocity (greater than $7.2\ \mathrm{km\,s^{-1}}$) material, low velocities (*ca.* $4.0\ \mathrm{km\,s^{-1}}$) at the top of acoustic basement and a lack of strong normal-incidence and wide-angle Moho reflections. The margins differ slightly in the number and extent of fault blocks of continental crust, in the presence or absence of a strong subhorizontal reflection near the base of these blocks, and in the width of the ocean–continent transition zone. The authors conclude that the ocean–continent transition zone appears to consist of exhumed and variously serpentinized upper mantle.

Next, two papers discuss the vertical motions of the lithosphere that can be inferred from two different data-sets. Newman & N. White focus attention on how kinematic observations (of stratigraphic sections in sedimentary basins) can constrain dynamic models of lithospheric extension. They do this by considering the strain rate history of individual sedimentary basins because this history depends on the interaction of extensional forces and lithospheric rheology, which together, they argue, determine the final extension factor, β. They demonstrate that subsidence history can be used as a proxy for strain rate history in a sedimentary basin. After justifying the use of a one-dimensional dynamic model of extension for their purposes they examine the consequences of a number of scenarios and complicating factors on such a model. One important result is that extension in an earlier stretching event can apparently control the (shorter) duration of any subsequent extension at the same place. The principal result, however, is that when over 2000 stratigraphic sections from sedimentary basins are inverted to provide a strain rate history, and the results are plotted in the form of strain rate versus final extension factor, all plots give the same systematic relationship and range of strain rates. The authors argue that this observation tends to support a viscosity-controlled model of extension better than a force-controlled model.

Gallagher & Brown tackle the difficult, but complementary, problem of estimating the vertical motion of rifted margins from the evidence provided in the post-rift development of subaerial topography adjacent to a margin. The problem is difficult because there is no obvious record of the vertical motion and erosion tends to destroy the evidence provided by the few available diagnostic markers. There are three classes of model for the evolution of the subaerial landscape on higher-elevation, rifted margins. These models can be tested against the different predicted patterns of erosion normal to a margin. The apatite fission-track method, which enables estimates to be made of when the apatite cooled through a temperature of 50–120 °C, can provide this information. An intensive study of the western margin of South Africa indicates that, there at least, the data do not support the downwarp model of landscape evolution but that the 'scarp retreat' and 'pinned divide' models may operate on geological time-scales. The inferred denudation history allows the authors to calculate the margin's isostatic uplift history for a range of assumed effective elastic thicknesses of the lithosphere, and to reconstruct the palaeotopography, but, at present, with no allowance for post-rift tectonic effects.

The significance of lithospheric extension for world commerce was highlighted by two contributions that discussed massive sulphide deposits, principally at accretionary plate boundaries, and the role of sedimentary basins in the accumulation, maturation and trapping of organic carbon to produce reserves of hydrocarbons.

In the first of these contributions, Herzig points out that the main commercial interest of presently active massive sulphide deposits in the oceans is their use as analogues of the creation of sulphide deposits mined on land; the closest analogues have been found in some of the backarc basins of the Pacific Ocean. Land deposits that occur as volcanogenic massive sulphides or as sedimentary exhalative massive sulphides can be of enormous commercial significance as sources of copper, lead, zinc, tin, gold, silver and a number of other special metals. However, the more than 100 relatively small sulphide deposits discovered worldwide in the oceans in the past two decades are unlikely to be of commercial interest, at least in the short term, for reasons of accessibility and economic viability. Nevertheless, under certain special circumstances, including those accompanying the recently discovered deposits in a forearc setting off Papua New Guinea, there could be commercial interest in some of these deposits.

Finally, Lambiaise & Morley develop the thesis that the stratigraphic succession of syn- and post-rift sedimentary sequences in rift basins determines the occurrence and distribution of hydrocarbons there. Most reserves occur in rifts with post-rift sag (thermal subsidence) basins and in rifts dominated by a marine fill because such rifts tend to have the best distribution of seals. Simple rifts, i.e. those without post-rift sediments, and rifted continental margins, are much less prolific in hydrocarbons. The factors that control non-marine syn-rift sequences are tectonics and climate; the same factors, plus relative sea-level, control marine syn-rift sequences. Tectonics is the most important factor; it can also influence topography, and hence, in quite subtle ways, the local climate. The authors conclude that because source, reservoir and seal rocks are not randomly distributed in rift basins, but occur preferentially in certain geographical and stratigraphic positions, it is possible to develop strategies for hydrocarbon exploration based on the geometry of a post-rift basin and the nature of its sedimentary fill.

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