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Continental Drift: What Driving Mechanism?

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With 5 figures

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Zusammenfassung

Die subduzierte ozeanische Lithosphäre beeinflußt die Konvektion unterhalb der kontinentalen Lithosphäre, weil sie die Rolle einer Wärmepumpe spielt. Experimentelle Versuche zeigen, daß diese thermische Kopplung flache Konvektionsrollen im kontinentalen Mantel erzeugt, mit horizontalen Dimensionen zwischen 3000 und 4000 km. Diese flachen Zellen werden als Ursache der Dehnungstektonik in Gondwana vorgeschlagen (Karroo, Parana, Antarktika). Ihre thermische und mechanische Wirkung führt letztlich zum Zerbrechen des Superkontinents. Die Versuche im Laboratorium zeigen auch Instabilitäten kleinerer Dimensionen, welche thermische Diapire erzeugen, ähnlich den sogenannten „hot spots“.

Abstract

A subducting oceanic lithospheric slab acts as an efficient heat sink which strongly influences the convection pattern in the neighbouring sub-continental mantle. Laboratory convection experiments show that this thermal coupling induces a roll about 5 times broader than deep underneath the continental lithosphere. The experiments are performed in a tank with imposed top and bottom temperature, and with, in addition, one cooled side wall. The convective pattern is observed by differential interferometry. For upper mantle convection one predicts rolls extending 3000 to 4000 km into the continental domain, parallel to the active margin. We show that, for Gondwana prior to the break-up, this simple convection pattern can explain the tensional state of the crust leading to the emission of flood basalts (Karroo, Parana and Antarctica). The thermal and mechanical effect of the large roll also provides a mechanism for the break-up itself and subsequent drift of the continental fragments. This motion of the continental plate leads finally to the closure of existing marginal basins along the Pacific coast of Gondwana. The laboratory experiments throw some light into another phenomenon of possible geodynamical relevance: within the large convection roll a smaller scale circulation is observed in the form of diapiric upwelling produced by thermal instabilities in the boundary layer. This dynamics may apply to hot spot volcanicity.

Résumé

La lithosphère océanique en subduction constitue un puits de chaleur qui influence la convection dans le manteau sous-continental voisin. Des expériences de laboratoire montrent que ce refroidissement latéral crée des rouleaux convectifs sous la lithosphère continentale de 3000 à 4000 km d'extension horizontale pour une convection limitée au manteau supérieur. Appliqué au Gondwana, ceci explique la tectonique en extension accompagnée d'épanchements basaltiques (Karroo, Parana, Antarctique) précédant l'ouverture Atlantique et Indienne. Cette ouverture est elle-même provoquée par l'action thermique et mécanique des grands rouleaux convectifs. Les expériences de laboratoire font également apparaître des instabilités à petite échelle, semblables aux diapirs que l'on pense être à l'origine du volcanisme intraplaque.

Краткое содержание

Субдуцированная океаническая литосфера влияет на конвекционные потоки в материковой литосфере, т.к. она может играть роль теплового насоса. Данные опытов показали, что такая тепловая связь может создавать в материковой мантии горизонтальные конвекционные потоки шириной от 3000 до 4000 км Предполагают, что такое явление тектоники могло возникнуть в Годване и расколоть её (Karoo, парана, антарктика). Именно термическое и механическое воздействие могли привести к распаду гигантского материка. Опыты в лаборатории установили наличие нестабильностей малого масштаба, создающие диапиры, наполинающие т.н. „горячие точки“ (Hot spots) Земли.

Introduction

The break-up of Pangea and the subsequent drift of the various continental fragments (Wegener 1915), has been successfully explained in the framework of plate tectonics (Le Pichon et al., 1973). However, this global model is strictly kinematic and only describes the geometry and velocity of lithospheric plates. The physical mechanisms leading to continental break-up and sustaining the motion of continental plates have not received much attention. Dynamic investigations have mostly been centered on the relationship between the motion of oceanic plates and convection, probably because of the simplicity of the geophysical data: heat flow and topography of oceanic plates exhibit an age relationship (Sclater et al., 1980) which agrees remarkably well with a model of boundary layer cooling combined with isostasy (Turcotte et Oxburgh, 1972). On the other hand, mass conservation requires a sub-lithospheric circulation between the zones of subduction, where the plate re-enters the mantle, and the zones of accretion, where new lithosphere is formed. Thermal convection powered by internal heat sources satisfies the thermal and mechanical observations. It is therefore invoked to explain this large scale evolution of the Earth's surface. The thermal boundary layer is mechanically "rigid" because its temperature is low (Froidevaux et al., 1976). This rigidly of the oceanic lithosphere seems to be responsible for aspect ratios much greater than 1 of some oceanic convection cells (Houston and De Bremaecker, 1975). This quantity is the ratio of horizontal dimension, up to 10.000 km in the case of the Pacific plate, to the depth. It is still uncertain whether this depth is that of the whole mantle, 3000 km, or only that of the upper mantle. Geophysical arguments have not yet settled this problem. They are related to the maximum depth of earthquakes in the subducted oceanic lithosphere, the stress state reflected by these earthquakes, the viscosity vs depth profiles derived from post-glacial rebound studies, possible changes in chemical composition (Davies, 1977; Richter, 1979). More recently some geochemical arguments turned out to strengthen the idea that the upper and the lower mantles form distinct reservoirs (O'Nions et al., 1979; Allègre, 1980). The first could be the source for ridge tholeitic basalts, the second for intraplate volcanism, i.e. alcali basalts. This interpretation would favor a seperate upper mantle convection system. We shall adopt this view arbitrarily to simplify our discussion.

Another question is still considered open: could convection on a smaller scale be superposed to the large scale circulation imposed by the plate geometry? Laboratory experiments show rolls with aspect ratio unity and with axis parallel to the shear motion caused by the large scale circulation (Richter and Parsons, 1975). For the Earth the rigidity of the lithospheric boundary layer could inhibit the formation of these rolls (LUX et al., 1979). If not their existence should yield a small signall in the gravitational field. The geophysical evidence remains uncertain (MARSH and MARSH, 1976, WATTS, 1978).

One striking difference between oceanic and sub-continental convection is that for the latter the lithosphere does not participate to the circulation because of the low density of the continental crust. Thus the upper heat exchanger for sub-continental cells is at the temperature of the base of the lithosphere, say 1200° C (FROIDEVAUX et al., 1977). The presence at the continental edge of a subducting oceanic lithosphere with an average temperature of about 600° C (SCHUBERT et al., 1975) is therefore expected to perturb the sub-continental convective pattern very strongly. Numerical models have shown that the transfer of heat to the cold oceanic slab induces a convection roll with large aspect ratio in the continental mantle (RABINOWICZ et al., 1980). This is sketched on *Figure 1.*

This paper briefly describes some laboratory experiments corresponding to a similar physical situation. They help answering the question: how big is the aspect ratio of the induced cells? Properly scaled laboratory experiments present several advantages compared to numerical experiments. They are 3-dimensional, so that the question of a possible small scale convective mode within large cells can be treated. They reveal non-stationary effects which are often suppressed by computational procedures.

In a more speculative section, the large sub-continental rolls will be shown to be capable of destabilizing large continental masses, leading to widespread rifting, continental break-up and other major geological events. Some evidence in support of the proposed mechanism will be presented. Our proposition is that subduction provides a key mechanism for the global geodynamic evolution of continents. This relates to both the "drift" and the deformation of continental plates.

Convection Experiments with Lateral Cooling

The laboratory experiments described here are not supposed to model sub-continental convection in any detail, but they should provide a sound physical reference frame concerning the basic mechanisms involved. For this, simplified boundary conditions have been choosen. We have built a tank with rectangular

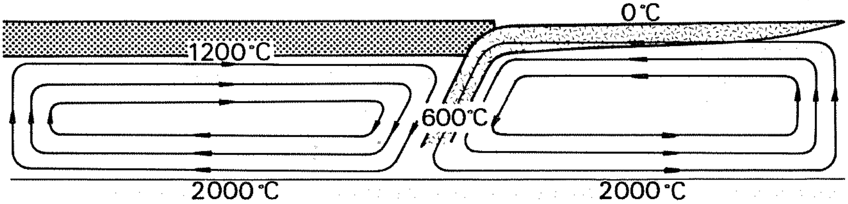

Fig. 1. Schematic representation of oceanic convection (right) and sub-continental convection (left). The figures are approximate temperatures on the boundaries of the 2 systems. For the sub-continental circulation, the cold subducting oceanic lithosphere acts as a lateral heat sink.

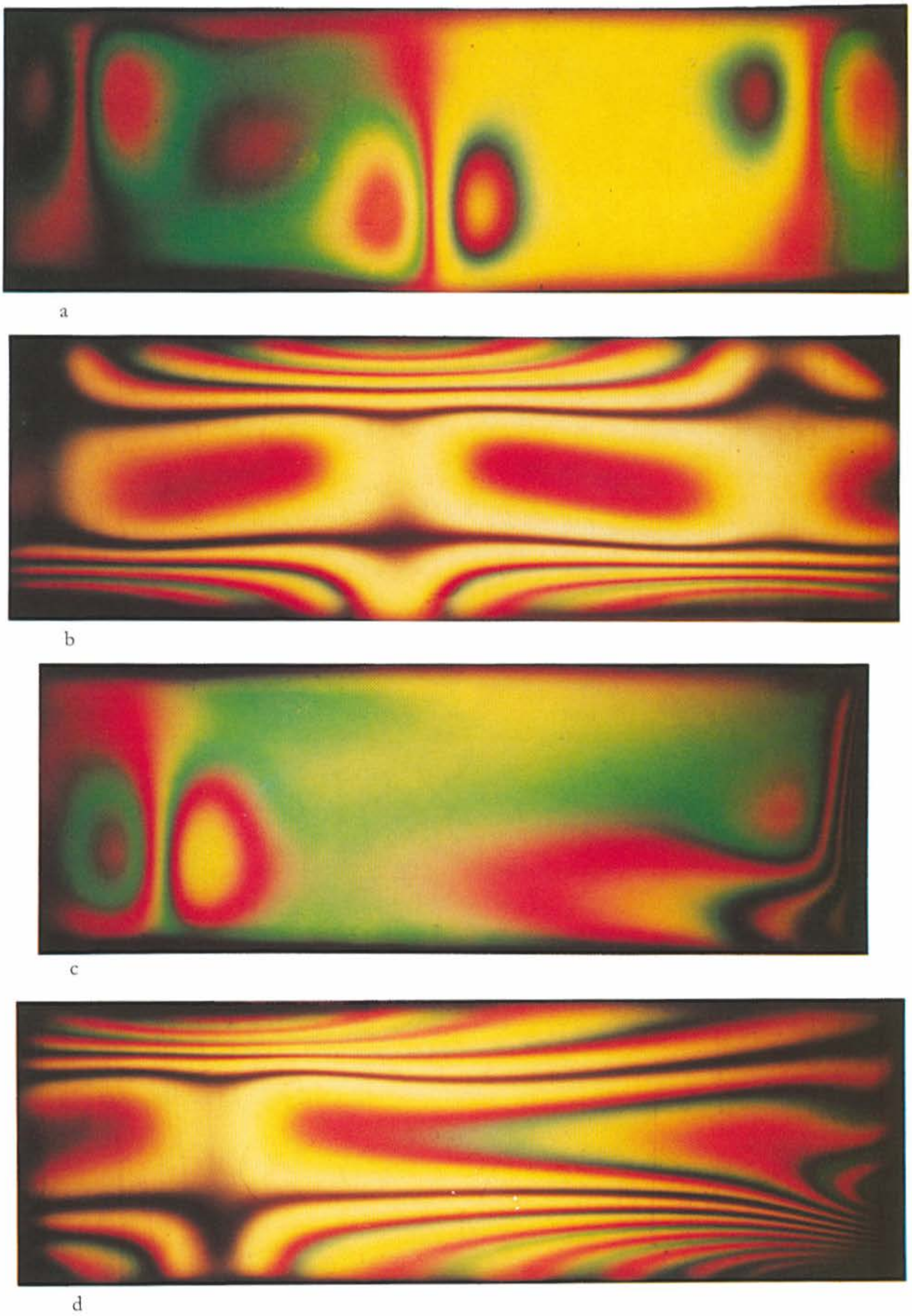

Fig. 2. Steady state convection pattern observed by differential interferometry. The fluid is silicon oil with Prandtl number $Pr = 3100$. The tank has a depth of 2 cm and its base ist 20×10 cm. The pictures only shown a portion of the cross-section. (a) Usual Rayleigh Bénard rolls fo $Ra = 10^4$. Fringes are lines of constant horizontal temperature gradient. (b) Same conditions but with vertical isogradients. (c) Same vertical Ra number as before, but now with lateral cooling: $Ra_{\text{lateral}} = 3.10^4$. Horizontal isogradients. (d) Same conditions but vertical isogradients.

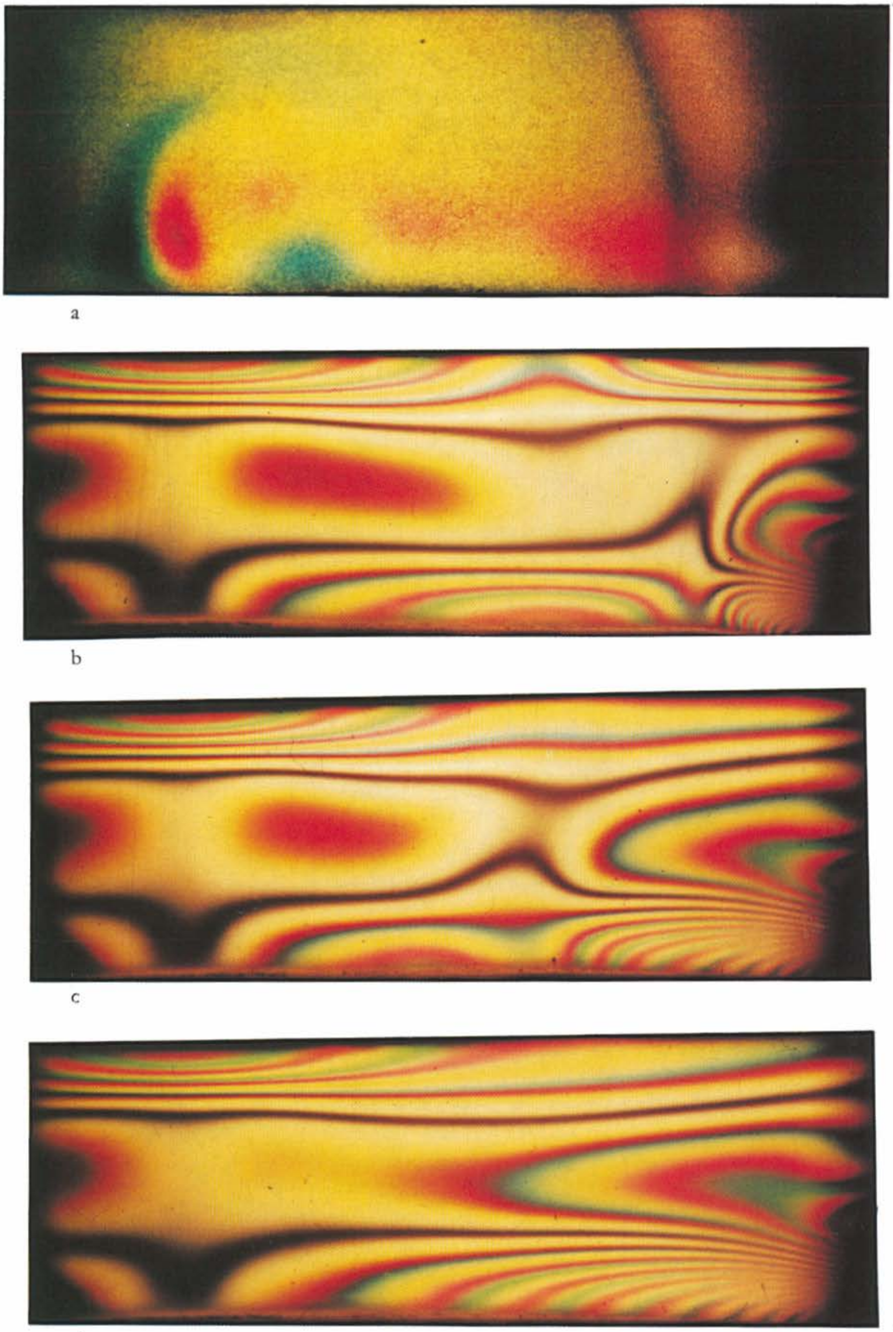

Fig. 3. Time dependent features. (a) Thermal instability in the lower boundary layer in the central portion of a wide roll. $Pr = 440$, $Ra_{vertikal} = 10^5$ and $Ra_{lateral} = 3.3\ 10^5$ The rising diapir is made apparent by weak horizontal isogradients. (b) Birth of a roll with large aspect ratio after the right hand side wall has suddenly been cooled ($Ra_{lateral} = 3.7\ 10^4$). The initial state is that shown in Figure 2 b. This shot is at time 100 sec. (c) Second shot 4 minutes after lateral cooling started. (d) Third shot at time 6 minutes. One approaches the steady state configuration with aspect ration 2.7.

top and bottom isothermal plates defining T_{top} and T_{bottom}. The long side walls and one of the short side walls are thermally insulating. The other short side wall is maintained at a controlled temperature $T_{lateral}$ and should provide the effect of lateral cooling (Nataf, 1980). Without lateral cooling this set-up produces Rayleigh-Bénard convection cells in the viscous fluid filling the cavity. A meaningful comparison with mantle conditions can only be tempted if the experiment is scaled properly. For the Rayleigh-Bénard case, two hydrodynamical numbers, the Prandtl number Pr, and the Rayleigh number Ra, must have the right magnitude. For the mantle, Pr is practically infinite. To simulate this in the experiment a very viscous fluid must be taken. Ra depends upon the fluid properties (ν the kinematic viscosity, K the thermal diffusivity and α the thermal expansivity) and upon the depth d of the tank, the gravity constant g and the temperature difference $\Delta T = T_{bottom} - T_{top}$. It is defined by:

$$\mathrm{Ra} = \frac{\alpha g \Delta T d^3}{K \nu}$$

For upper mantle convection Ra approches 10^6 (McKenzie et al., 1974). For a tank with lateral cooling, it has been established that an additional Rayleigh number was sufficient to characterize the convection pattern (Nataf, 1980). This parameter called $\mathrm{Ra}_{lateral}$ is defined according to the above expression by putting $\Delta T = T_{bottom} - T_{lateral}$. We therefore call $\mathrm{Ra}_{vertical}$ the usual parameter. $\mathrm{Ra}_{lateral}$ is harder to estimate for the Earth, but *Figure 1* suggests that it is about twice as big as $\mathrm{Ra}_{vertical}$.

A new method of visualization of the convection structure is used in this work: differential interferometry (Françon and Mallick, 1971; Oertel and Buhler, 1978). Light crosses the fluid horizontally parallel to the cold side wall of the tank. Pairs of neighbouring rays are recombined to form interference fringes. Each fringe corresponds to a given temperature difference between the pathes sampled by the 2 rays. If the latter are split horizontally, resp. vertically, the fringe pattern yields lines of equal horizontal, resp. vertical, gradients. Such isogradients are shown on *Figure 2* for simple Rayleigh-Bénard convection at low Ra value. The rolls have axes parallel to the light beam. Notice that the location of ascending or descending currents is best located in the first picture (a) whereas the presence of the top and bottom thermal boundary layer is particularly well marked in the second picture (b). The experimental tank has an aspect ratio of 10 but the optical system only samples one portion of the total width.

The effect of lateral cooling is also illustrated in *Figure 2* with the cold wall at the right hand side. One wide roll has formed. The downwelling current looses heat along the cold wall where a thermal boundary layer is now present (c). Hence the high density of horizontal isogradients. The material has therefore to travel a longer distance along the tank bottom before it absorbs enough heat to become buoyant again und rise (d). Other cells remain similar to those of the previous pictures. The aspect ratio of the large cell is function of both Rayleigh numbers. It gets bigger for increasing $\mathrm{Ra}_{lateral}$ values and for decreasing $\mathrm{Ra}_{vertical}$ values. The complete analysis of this dependence will not be presented here.

Experiments with Rayleigh numbers comparable to those of the upper mantle yield aspect ratios of about 5 (NATAF et al., 1980).

One important new feature appears when $Ra_{vertical}$ exceeds 10^5. The large cell induced by lateral cooling still exists. However its lower thermal boundary layer becomes unstable, giving rise to ascending plumes, diapirs or blobs. These smaller scale features drift in the global horizontal circulation and their ascension is not purely vertical. They often reach the surface close to the upwelling extremety of the large cell, although their generation at depth takes place closer to the cold wall. This can be seen in *Figure 3a* which shows the central part of a large cell. The existence of these instabilities is best revealed by horizontal isogradients. Instabilities also exist in the upper thermal boundary layer, giving rise to downward diapiric motion. If heating from below is replaced by internal heating, the lower boundary layer does not exist, neither do the upwelling diapirs. These experiments confirm the existence of a small scale component in the large cell. It consists of up and downwelling diapirs, rather than parallel rolls. This was verified by observing the circulation in 3 dimensions. Similar features have been reported in 2 dimensional time dependent models (LUX et al., 1979; MCKENZIE et al., 1974).

Figure 3 also shows the time dependence of the onset of the large cell. The starting pattern is that of Figure 1b with square section rolls filling the whole tank. The sequence of pictures (b, c and d) illustrates the penetration of the cold front after the side wall has suddently been cooled. This front progresses at a speed of comparable magnitude with the final horizontal convective velocity. For the Earth the above time dependence implies a considerable time lag before a large cell could approach its steady state dimension. The evolution is however rapid enough to ensure the relevance of the experiments described here for a variety of geological events. The simplicity of the experimental conditions restricts this relevance to global effects of course.

Speculations on the Geodynamics of Continents

What has been shown in the laboratory experiments will now form the basis of some proposals concerning the evolution of continents. For a convective layer confined to the upper mantle, the experiments for the appropriate Ra numbers, predict large cells with aspect ratio of 5. This corresponds to a zone of 3000 to 4000 km behind the active margin. The time of build-up of such a cell is about 200 Ma, as the progression of the cold front caused by a new subduction is expected to occur at a velocity of order 2 cm/yr.

Figure 4 schematically illustrates the growth of the large cell and its possible geological consequences. This diagram includes the formation of a marginal basin behind the volcanic arc soon after the onset of subduction. This marginal basin is not assumed to be caused by the growing cell; it is more likely to follow from the retreat of the oceanic slab foundering into the mantle (CHASE, 1978). As the width of the large roll tends to stabilize, two important mechanical phenomena affect the base of the continental lithosphere. Firstly the new upwelling current, produces a stronger heat input which tends to thin the lithosphere. Secondly a coherent drag is exerted by the convective circulation towards the

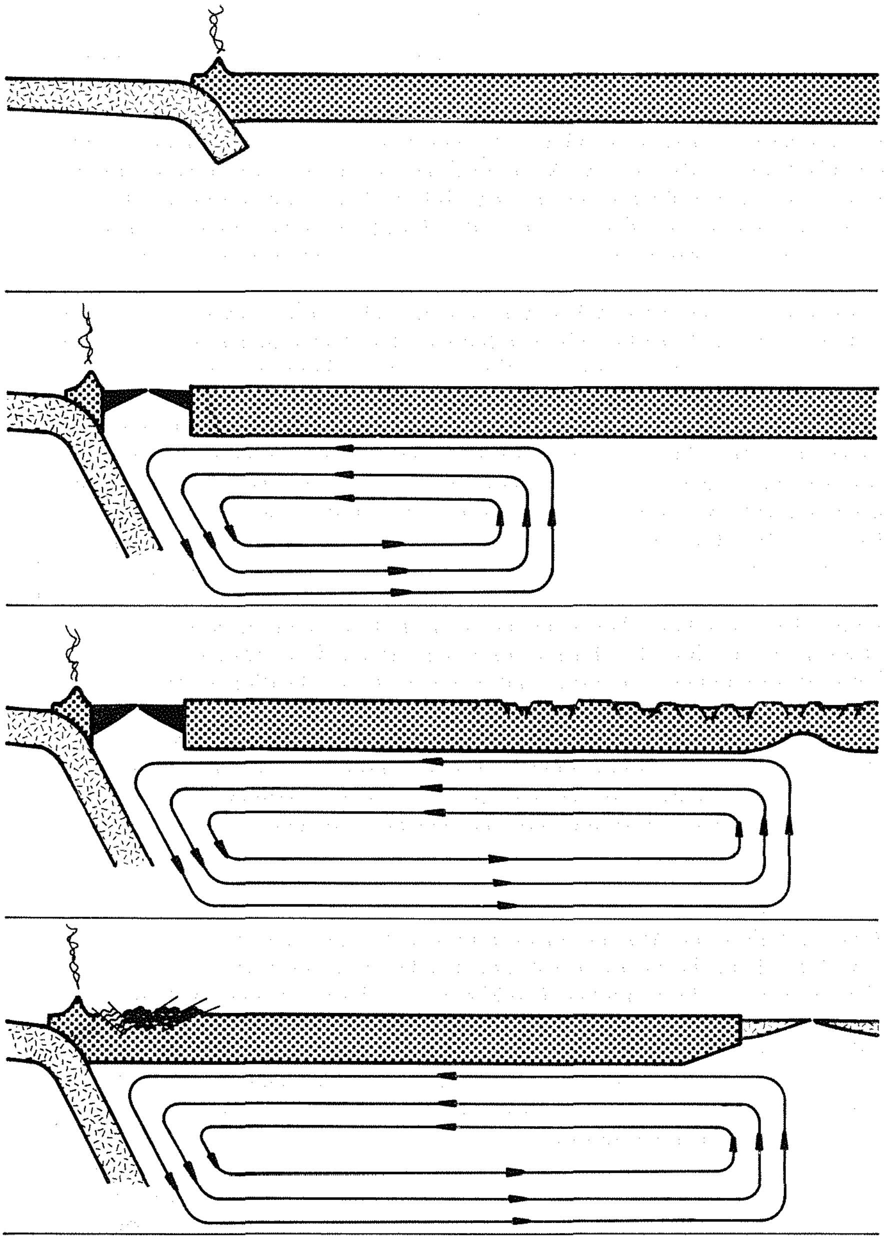

Fig. 4. Evolution scheme related to the growth of a large roll underneath the continental lithosphere. Stage 1: beginning of subduction. Stage 2: the trench retreats from the continental edge and a marginal basin forms behind the island arc; simultaneously the growth of the thermally induced roll begins. Stage 3: drag force generates extension of the continental lithosphere; break-up is initiated. Stage 4: new ocean opens and the continental plate drifts towards the trench; closing of the marginal basin with ophiolite obduction.

continental margin; it generates a tensional state in the continental lithosphere, in particular far away from the margin. This mechanical action contrasts with the state of stress produced by a convection pattern organized in small cells in the absence of lateral cooling. At some stage a large continental segment is detached and starts moving. As its leading edge moves trenchward, the marginal basin closes and ophiolite terrains are obducted onto the continent which collides with the island arc. The continental lithosphere is no more in tension, but a new oceanic opening has started at the continental trailing edge. Has this speculative scenario any connection with the real world? *Figure 5* is a map of Gondwana at the time when the Indian and South Atlantic oceans had just started opening (115 Ma). The subduction zone drawn along the coastline should have been in operation prior to this continental berak-up for our model to be valid. Indeed many authors (STUMP, 1973; CRADDOCK, 1977; COX, 1978; IRVING, 1979) see the Pacific coast of Gondwana as an active margin at least since the Devonian (400 Ma). In the Jurassic, before the initiation of the opening, widespread extension affects South Africa and Antartica. Crustal thinning is accompanied by massive basaltic flows: the Karroo and Kirkpatrick in early Jurassic (180 Ma). Somewhat later, in early Cretaceous (140 Ma), similar tectonic and magmatic activity occurs in South America: the Paraná basaltic flows. The continental break-up that follows is roughly parallel to the Pacific coast line, some 4000 km inland. However the break follows some lines of weakness of the lithosphere, leaving the Karroo province attached to Africa. This relationship between subduction and intra-continental tectonics leading to the creation of a new oceanic opening has been noticed before (ELLIOT, 1975; COX, 1978). Our dynamical model offers a possible basic mechanism. What is known of the history of marginal basins in South America seems compatible with our scenario: in Chile their opening is dated 140 Ma and their closure with ophiolite obduction occurs in the mid-Cretaceous (100 Ma). For the Northern section of the Andes, the marginal basins open in the lower Jurassic and also close at 100 Ma (BURKE et al., 1977).

For Laurasia we are not aware of widespread extensive tectonics in North-America before the Atlantic opens. Subduction may have started in the Devonian (380 Ma) along the Pacific coast, about 4000 km away from the future break-up. Compression in the Canadian Cordillera and closure of marginal basins seem to occur in phase with the opening of the central Atlantic (MONGER and PRICE, 1979). In California and Oregon closure happens somewhat later in the Cretaceous (130 Ma) (JONES, 1976; ROURE, 1979). Thus, although some of the features of the scenario proposed in *Figure 4* may be present, we considere Laurasia a less favourable test than Gondwana.

For present-day Asia, important graben tectonics in Baikal and in China could well be explained by the action of a large sub-continental convective cell induced by subduction under Japan and Kampchatka. This would be superposed to the effect of the Indian collision in the South (TAPPONNIER and MOLNAR, 1976). As rifting in Baikal starts in Eocène (50 Ma), the formation of the large cell requires subduction since the Jurassic. This is exactly what the data suggest (KIMURA, 1974). Marginal basins are of course still active at present and one is only witnessing the first stage of the evolution towards break-up. This idea is reinforced by the observation of geoid anomalies with wavelength of about 4000 km

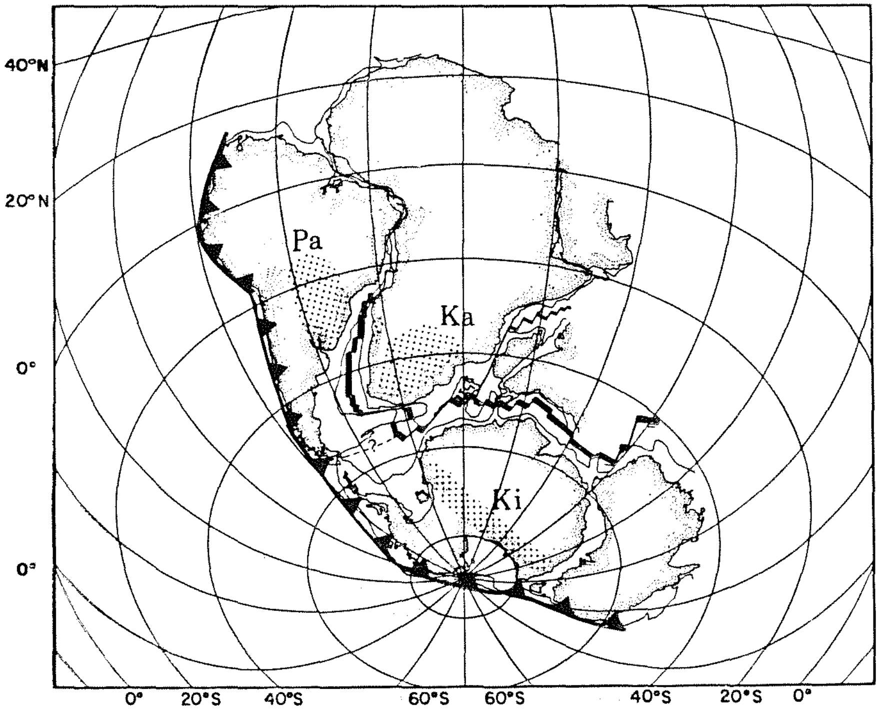

Fig. 5. Gondwana at 115 Ma after NORTON and SCLATER (1979) with location of tectonics events. The assumed location of the subduction along the Pacific coast is for the time period preceeding the break-up. The dotted areas suffer widespread extension with emission of flood basalts: Ka = Karroo, Ki = Kirkpatrick and Pa = Paraná. This occurs before break-up along the new ocean ridge (Indian and South Atlantic).

between Japan and the region NW of Baikal (BALMINO and al., 1978). The shape and amplitude of these anomalies corresponds to what a numerical model of the wide convective rolls predicts with a maximum along the continental edge and a minimum above the upwelling end of the sublithospheric roll (RABINOWICZ, 1980). Exactly the same anomalous pattern exists in the geoid between the Western coast of South America and the middle portion of the South Atlantic.

Conclusion

Simple convection experiments with lateral cooling scaled to mantle conditions suggest the existence of convective rolls of large horizontal dimension underneath a continental lithosphere bordered with a subduction zone. The transfer of heat to the neighbouring plunging oceanic slab provides the physical mechanism. At Rayleigh numbers of the oder of 10^6 the width to depth ratio of the thermally induced roll is about 5. For a depth scale comparable to that of the upper mantle the rolls should extend beyond 3000 km into the continental domain. Their thermal and mechanical action upon the overlying continental lithosphere may yield a global explanation for the break-up of large continental masses like Pangea. The model also accounts for extended rifting phenomena and widespread magmatism preceeding the break-up, and for the subsequent closure of back arc basins and emplacement of ophiolites. More geological data concerning the time relationship between these events are needed in order to confirm or infirm the proposed geodynamical time sequence. Those we have quoted for Gondwana appear favourable. Present day Asia also offers a possible illustration.

The boundary layer instabilities seen in the experiments could correspond to the thermal anomalies leading to intraplate volcanism (hot spots). They could also be connected with kimberlite erruptions. This type of small scale diapiric motion deserves further investigations. If the mantle has 2 levels of convection, instabilities in the thermal boundary layer situated at their interface could provide a mechanism to extract blobs of material from the deeper convective layer. Such a system could correspond to the 2 reservoirs suggested by the different isotopic signatures of oceanic ridge tholeites and "hot spot" alcali basalts. The observed preferential emergence of the thermal diapirs in the upwelling extremity of the large roll in the laboratory experiments could explain the relatively high density of hot spots along the mid-Atlantic ridge.

The cold downwelling diapirs created by instabilities in the upper thermal boundary layer of the large cell may also exist in the Earth. They could well form underneath the continental lithosphere, but are less likely in oceanic convection. This difference relates to the fact that in the latter case the upper thermal boundary layer is "rigid" being the lithosphere itself (Yuen et al., 1979).

Despite of the various differences between sub-continental and oceanic convection, one comes to the conclusion that cells of large aspect ratio can be present in both situations. For the oceanic case, of course, the rigidity of the upper layer may be the primary cause. However once the old oceanic plate founders into the mantle, it is only partially thermalized during its descent. Thus relatively cold material penetrates the return flow towards the oceanic ridge. The deep thermal structure of a large oceanic cell (Kopitzke, 1979) is therefore quite similar to the large cells described here.

The view that oceanic plates directly take part in the global convection process has often led to the impression that continental plates on the other hand just move in order to accomodate with the global kinematic pattern imposed by the fast oceanic plates. Indeed mechanical interactions between neighbouring plates constitute an important input into the problem of plate dynamics and intraplate deformations (Richardson et al., 1976). Our message here is that subcontinental convection can be just as important as a driving mechanism. After applying the laboratory models to the Earth and comparing with global geological events, we have suggested that large cells are at the origin of the creation of a new plate boundary inside a large continental mass. They initiate the drift of the splitted continental fragments and are the cause of some of their widespread internal deformations. The evolution of Gondwana and possibly of Eastern Asia were found to support our model. Other geological cases deserve further consideration.

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