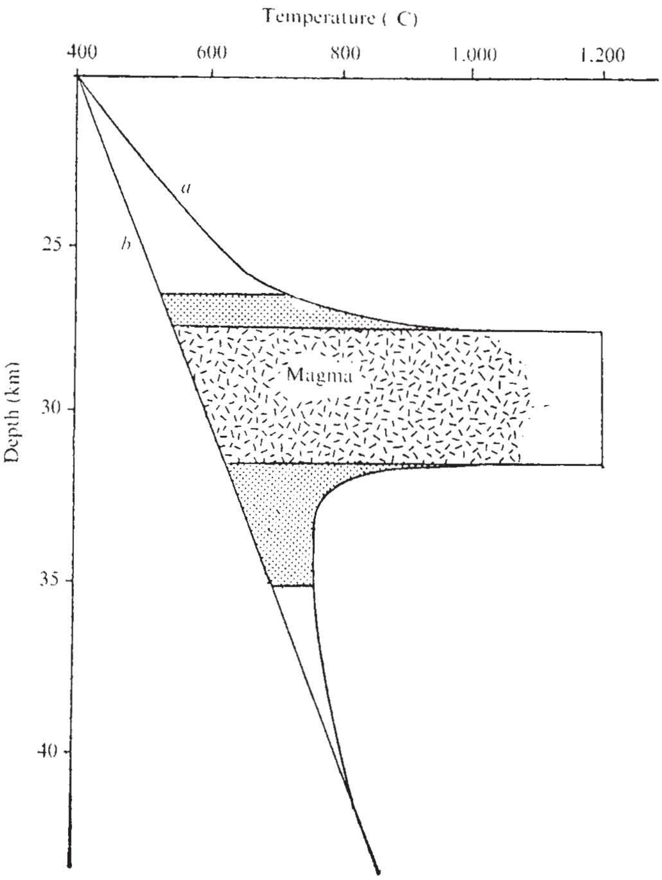

Fig. 3 Temperatures around an intrusive which is 4 km thick, and centred on a depth of 30 km: *a*, maximum temperatures; *b*, geothermal gradient; stippling, zone of partial melting. Initial temperature of magma = 1,200° C; *H*, = 50 calorie g^{-1}.

significantly different from that indicated by the model in Fig. 1. An asymmetrical orientation of the heat fluxing from the top and the bottom of the magma is produced. Taking an initial geothermal gradient of 20° C km^{-1}, and a magma slab 4 km thick emplaced at 30 km depth, the country rock temperatures below the magma would be at least 80° C more than above the magma, and those temperatures would increase with depth (Fig. 3). In this thermal model the values of the parameter given already define the initial boundary conditions, and crustal rocks initially hotter than 700° C (35 km depth) are assumed not to undergo partial melting. The maximum temperatures achieved in the country rock in a case such as that are shown in Fig. 3. About 1 km of country rock above the upper contact, and about 4 km below the magma, would undergo partial melting. The total width of the zone of partial melting would exceed the initial thickness of the magma. In that case, the total heat flux from the top of the magma would be about twice that from the bottom. As much as 5 km of the country rock would have been melted partially, whereas in the model shown in Fig. 1, the partially melted zone is only 1.6 km thick adjacent to a slab of magma of the same size, with initial country rock temperatures of 500° C.

The process of partial melting and solidification of the country rock adjacent to an intrusive, takes approximately 2×10^5 yr in the cases discussed. Solidification of the mafic parent rocks at 900° C takes about 10^4–10^5 yr. Thus, the zones of partial melting adjacent to a magma may have a higher mobility for a considerably longer period of time than either the solidified magma or the lower crustal material that has not undergone partial melting. These zones of partial melting may serve as sites for the emplacement of other material derived from the mantle, and further partial melting in the lower crust may follow.

These thermal models suggest that there are a number of possible ways in which an intermediate rock type could be derived from the mixing of a mantle derived parent with partially melted lower crustal rocks that are adjacent to the intrusion. Dense refractory material in the zone of partial melt, as well as in the parent magma, will tend to sink and lighter granitic fractions will tend to migrate upward. Granitic material may be formed from the partial melt zones above and below the magma and from differentiation of the original magma. These lighter granitic liquids could accumulate into large magmas in the lower crust and then migrate and collect to form plutons of batholithic proportions in the upper crust. In this two stage model of the origin of granitic batholiths along continental margins, the production of the intermediate granitic rocks may be intimately associated with the production and migration of magmas of andesitic to basaltic composition from active subduction zones at the continental margins.

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Thermal contraction joints in a spreading seafloor as origin of fracture zones

IF newly formed oceanic crust is moving away from a spreading axis, it can be expected to contract by cooling. Vertically, the cooling is expressed in the existence and cross-sectional shape of the mid ocean ridges, where there is a relationship between depth of the ocean and age of the crust[1]. A steady state solution for a model of a lithospheric plate which cools while moving[2–4] is compatible with data on topographical height.

Horizontally, in the direction of spreading, cooling will result in the formation of superficial horst and graben structures parallel to the median rift[5,6]. Also in the third direction—that of the ridge axis—internal stresses will arise which are much larger than the breaking strength of rock. If the thermal expansion coefficient λ, is 1.5×10^{-5} ° C^{-1}, and Young's modulus, E, is 1×10^6 kg cm^{-2}, a decrease in temperature of 1,000° C gives an internal tension of 15,000 kg cm^{-2}. Faulting can therefore be expected to occur perpendicular to the direction of the ridge axis, and I propose that fracture zones are the topographical expression of those faults (Fig. 1 and refs 7–10).

The hypothesis provides a model for an orthogonal median rift–fracture zone system[11]. The actual shape of the ridge as a whole will be dictated by other causes, such as the shape of the initial rift. That is exemplified by the parting of North America and South America from Africa. A change in spreading direction can also place constraints on the shape of the ridge. Straight ridges with fracture zones and no offset could be explained using this model:

the thermal contraction character is primary, and the transform fault function[13] is secondary.

Additional evidence of thermal contraction in the direction of the ridge axis comes from the distribution of fracture zones in the central North Atlantic and the equatorial Atlantic. There, the Mid-Atlantic Ridge is far from straight. The active sections of the fracture zones do not obey strictly the small circle pattern dictated by purely geometric or kinematic considerations[14]. The departures from that pattern are significant and apparently systematic (Fig. 2). Fracture zones and median rift segments still form an orthogonal system but the pattern as a whole becomes fanned, following to some degree the bends of the ridge.

The segments of the median rift and the fracture zones therefore form a complex dovetail construction, interlocking opposing lithospheric plates. Thus, in order to free the plates, about 6% of shortening in the direction of the ridge axis is needed. That is of the right order of magnitude compared with the maximum depth of the ocean, which in these parts varies between 5.5 and 6 km. That would lead to a total vertical contraction of 3–6%, depending on the thickness assumed for the lithosphere.

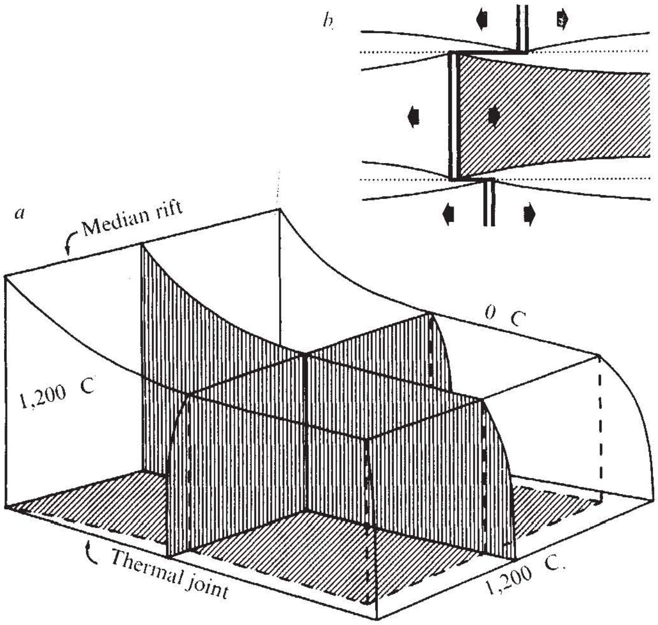

Fig. 1 *a*, Seafloor spreading implies cooling of newly formed lithosphere. A plate moving from the median rift will contract as shown. Thermal joints develop at right angles to the ridge axis. *b*, Plan view of thermal joints accommodating transform faults; arrows indicate spreading directions.

The fanning of fracture zones can be understood by considering the mechanism which makes the plates move. Thinking in terms of gravitational sliding, the analogy to glacier flow[15] may be extended by comparing the 'bights' of the Mid-Atlantic Ridge to a firn or névé: the shape of the bights would determine the flow pattern of the lithosphere which slides passively downwards to both sides, coagulating into rigid plates in which the stress trajectories are roughly parallel to the fossil fracture zones and to the growth lines of the lithosphere, that is, the magnetic lineations. The stress trajectories would then converge off the concave sides of the ridge, thus accounting for the fanning. A pull, exerted by the sinking lithosphere in the subduction zones and/or by a friction exerted by the upper mantle at the base of the lithosphere may be added to this. If the latter effect were dominant, however, fanning still occurs because the ridge represents a curvilinear zone of weakness in the lithosphere. A zone such as this (with a lower Young's modulus) in an elastic plate under tension would be reflected in the stress distribution. Experiments with a sheet of pararubber have shown that the longer axes of the strain ellipsoids are deflected towards the normal to the weakened zone.

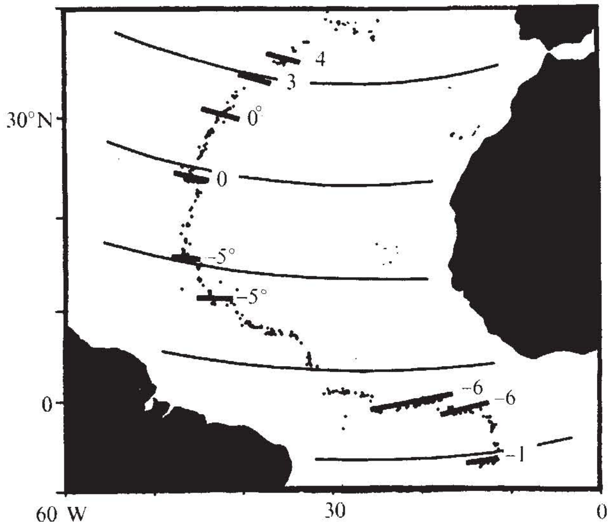

Fig. 2 Departure of fracture zone azimuths from a small circle pattern with a pole spreading at 63°N and 27°W.

Once the pattern has been established and the fracture zones begin to function as transform faults, the stress distribution will be affected if some form of welding occurs along the plane of the fracture zone. Extrapolation of the results of the experiments with pararubber, indicates that the larger principal stress may be expected to become deflected towards the normal to the fracture zone, thus releasing the normal stress in the plane of the fracture zone, and easing the movement.

The observation that fracture zones may be fanning implies that, although statistically and on a global scale the small circle concept[14,16] remains valid, poles derived from individual fracture zones or from a number of close fracture zones do not necessarily represent the true spreading pole. True spreading poles can only be found by averaging weighted azimuths of all of the fracture zones in a given area. The degree of fanning is also a function of age, with the fanning reaching its maximum at the ridge axis. The present data on the central North and equatorial Atlantic do not yet allow a final analysis.

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