PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A
MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

The World-Wide Oceanic Rise-Ridge System

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Phil. Trans. R. Soc. Lond. A 1965 **258**, 109-122
doi: 10.1098/rsta.1965.0026

X. The world-wide oceanic rise-ridge system*

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About half the length of the 'oceanic' rise-ridge system is centred in ocean basins. On the other hand, almost the whole system is approximately disposed in circles around continental shields.

Exceptional heating of the system is indicated by high heat flow and the extrusion of extraordinary volumes of flood basalts. The concentration of volcanoes, however, is little greater than normal for ocean basins.

Longitudinal normal faulting and transverse wrench faulting are characteristic of the system. Both types formed early in the life of the system and are still active. Wrench faults offset belts of normal faulting and the crests of rises and ridges in many places but are not themselves known to be offset by normal faults.

The ancient Darwin Rise has subsided in the southwestern Pacific. Its history differs in some respects from other rises although it too was heated and faulted.

A hypothesis of origin of the system is briefly discussed.

Location of the rise-ridge system

The rise-ridge system consists of a number of parts of which one, here called the main system, is by far the largest. The main system extends through the Atlantic, south of South Africa, into the Indian Ocean, south of Australia, and across the Pacific to Mexico (figure 1). For this distance it is an essentially continuous, and, after it was pointed out by Ewing & Heezen (1956), rather obvious feature. The main system has several branches and spurs. The largest extends into the Arabian Sea where it splits again and continues northwest into the Red Sea and southwest into the African rift valleys. Smaller spurs include the Walvis Ridge and related features in the South Atlantic.

Identification of the other parts of the system are more difficult. They lie in little sounded regions or are largely covered by continents, or are obscured by complex topography and structures as in the southwestern Pacific. Various criteria may be used for identification. Depth is the most obvious and is reliable where the topography is relatively simple. The occurrence of longitudinal ridges and troughs or of transverse fracture zones is also suggestive, as are seismicity and high heat flow.

A fragmented rise as wide as the Mid-Atlantic Ridge and half as long has been identified in the southeastern Pacific on the basis of shoal depth, ridge and trough topography, seismicity, and some high heat flow (Menard, Chase & Smith 1964). Soundings are very scarce in some places and connexions between the known fragments are somewhat conjectural. However, it appears that the sections extending from Panama to Chile are all parts of one feature which has been grossly faulted by transverse fracture zones. The southern section, or Chile Rise, curves southeast into Chile. East of the narrow continental strip of southern South America, this rise seems to continue as the Scotia Ridge and almost reaches the Mid-Atlantic Ridge. Far to the north, the rise may also extend into the Atlantic in the form of the seismically active ridge east of Honduras. This 'Galapagos–

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* Contribution, Scripps Institution of Oceanography, University of California, San Diego, New Series.

Chile Rise' lies parallel to the East Pacific Rise for a long distance and the flanks overlap thus giving a much more complicated global pattern than the main rise system alone.

Another rise extends through Melanesia in the southeastern Pacific (Menard 1964). It is divided into three major sections by fracture zones. Various parts of the rise are known to have ridge and trough topography, and high seismicity as well as extensive areas shallower than 4 km. The southern section includes the plateaus and rises around New Zealand and also the Lord Howe Rise and Norfolk Island Ridge. The middle section, bounded by fracture zones, is centred on the so-called North Fiji Basin, which is generally shallower than 4 km and has the other characteristics of an oceanic rise. The northern section is the Caroline–Solomon Ridge which is little known.

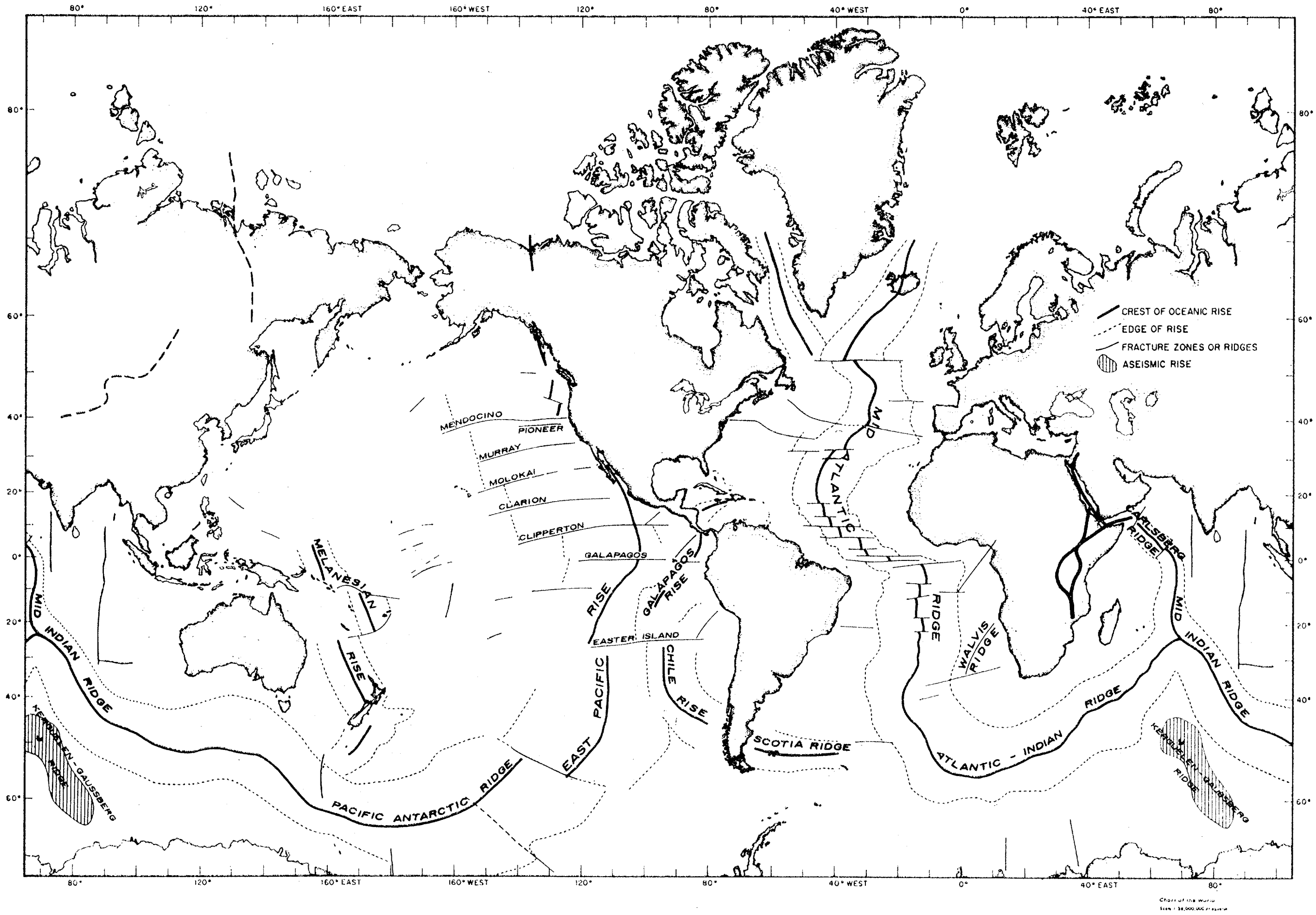

FIGURE 1. The world-wide system of rises and ridges with related features.

Elsewhere, fragments of overlapping or branching rises may or may not be parts of less obvious but more extensive rises. A branch from the Mid-Atlantic Ridge between Greenland and North America was predicted by Wilson (1963) and found as a sub-bottom feature by Drake, Campbell, Sander & Nafe (1963). The 'branch' may be a small fragment of a rise marked by earthquakes extending through the Canadian Arctic to Alaska and thence south to the northern East Pacific Rise. Yet another largely continental rise may lie under central Asia. One section can be traced as a topographic and seismic feature joining through the Arctic Basin with the Mid-Atlantic Ridge (Heezen & Ewing 1961). A gap exists between this section and the section which apparently trends from Lake Baikal to Gibraltar. The latter section is marked by plateaus, fault troughs, and a distinct seismic belt (Gutenberg & Richter 1954).

RELATIVE POSITIONS OF THE RISE-RIDGE SYSTEM

The rise-ridge system does not appear to be randomly distributed on the face of the globe but rather is related in some way to the positions of continents and ocean basins. The general location of the main system of rises and of some parts of other rises is known. However, few parts are surveyed in detail and some gaps are unsounded. With regard to origin, the junctions between or changes in trend of rises may be most revealing but these are little known. The location of continental extensions of oceanic rises is also crucial but partially obscure. The system cannot now be seen to lie in any unique, consistent, global pattern. Perhaps none exists, but perhaps further exploration will establish such a pattern. Meanwhile, some elements of one or two patterns can be dimly perceived and even these may help to guide speculation about origin of some of the major features of the surface of the Earth.

Large sections of the main system obviously are in the centres of ocean basins. This fact is difficult to explain unless rises form in the centre of ocean basins or else shape ocean basins around themselves. However, important sections of even the main system lie under the continents of Africa, North America, and at least part of Asia. Moreover, the smaller rises such as the Galapagos–Chile Rise and the Melanesian Rise are nearer the margins than the centre of an ocean basin. Thus it is quite as definite that rises and ridges exist away from the centres of ocean basins as in them. A quantitative evaluation can be made by considering rises as centred if they are within 1000 km of the median line of an ocean basin (Menard 1958). The total length of all rises identified in this paper is 84700 km. Of this, only 42400 km or 50% is centred in an ocean basin. If the doubtful Asiatic rise is excluded from consideration, the centred portion is 56%. Thus the distribution of rises has the curious property that about half the system is almost exactly centred and the other half is not centred at all.

The rise-ridge system conforms to another pattern unrelated to the centre of ocean basins, namely long sections follow arcs of circles centred on continental shields (Menard, in the press). This relation is not very clear on a Mercator projection map or radial projections, but is less obscure if rises are plotted on a large globe. South America is almost completely circled by the Galapagos, Chile, Scotia, and Mid-Atlantic rises and ridges (figure 2). Antarctica is surrounded by rises and Africa almost so, but the pattern is only partially circular. From more fragmentary data it appears that the continental nuclei of both North America and Europe may be surrounded by roughly circular rises. For a quantitative evaluation, the crest of a rise is taken as corresponding to an arc of a circle of uniform radius around a continental centre if it is no more than 1000 km away. By this criterion, 87% of the rise-ridge system lies on circles around continental shields. Excluding the questionable Asiatic rise, the correspondence drops to 85%. Thus the distribution of rises corresponds much more closely to circles around continental shields than to centres of ocean basins. Moreover, most of the circles around shields have about the same radius namely between 1600 and 2200 km.

Almost the whole system lies along circles around continental shields, and almost half lies very close to the centres of ocean basins. If this distribution has meaning, it appears that the location of continents exerts a primary control over the position of rises, even though rises shape the ocean basins in which they lie.

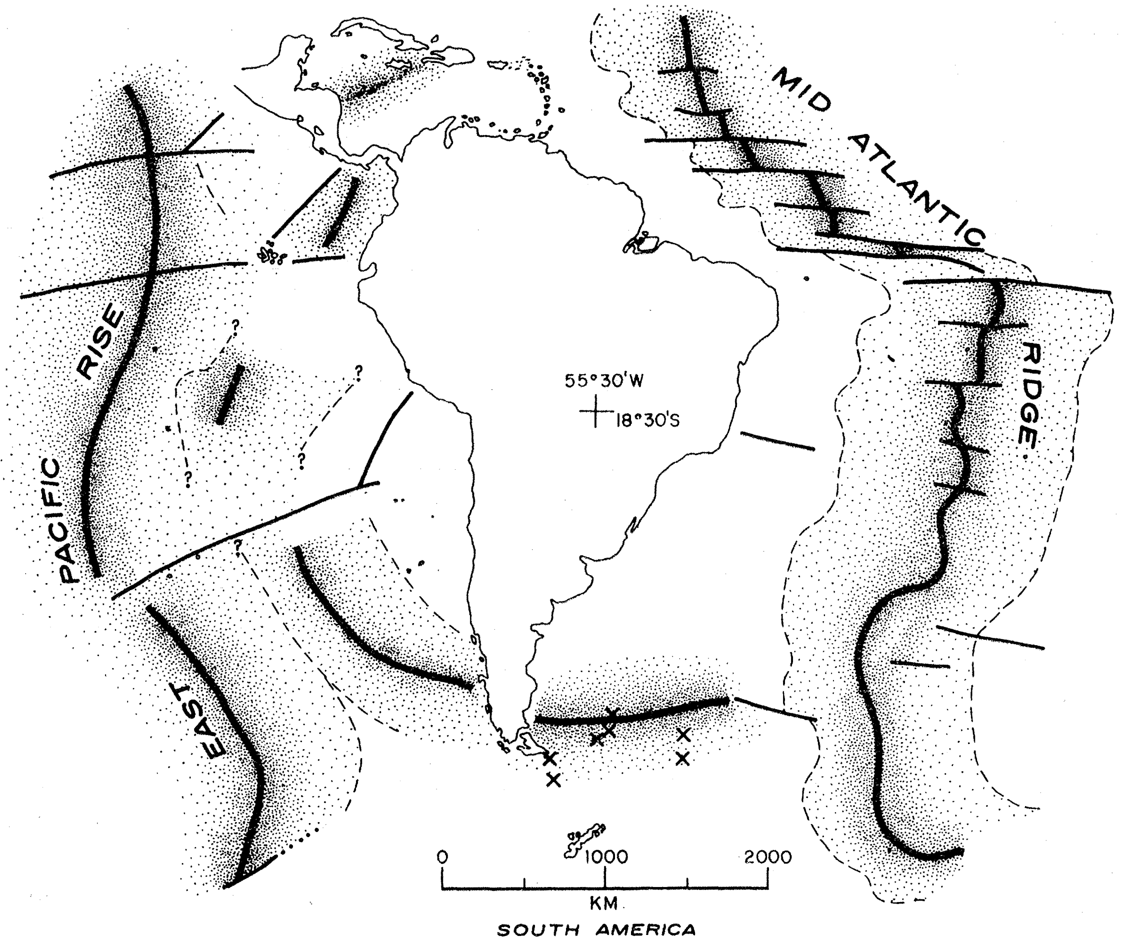

Figure 2. Polar projection of rises and ridges around South America. Epicentres shown only in the vicinity of the Scotia Ridge. Note subparallel rises west of South America.

Heating of rises

The Mid-Atlantic Ridge had hardly been discovered before submarine volcanic eruptions were noted near the crest. They were so common near the equator that Lyell predicted that a new island would rise above the waves. It was soon observed that flood basalts occur on the ridge in Iceland which stands directly on the crest. More recently high heat flow has been found at the very crests of some rises. Thus by the evidence of heat flow and vulcanism it appears that the rise-ridge system is the locus of exceptional heating from the interior of the Earth. The mode and timing of this heating give some useful information about the origin and development of the system.

Exceptionally large heat flow associated with the system was first found in the northern Mid-Atlantic Ridge (Bullard, Maxwell & Revelle 1956) and since confirmed in the central and southern Mid-Atlantic Ridge, and in numerous places on the East Pacific Rise (Von

Herzen 1959). The band of high heat flow is only 200 to 300 km wide in the best surveyed regions and lies directly on the crest. Very high heat flow is further restricted to two linear zones only a few tens of kilometres wide in one place in the East Pacific Rise (Von Herzen & Uyeda 1963) and it appears that dikes are the sources of the exceptional heat flow. Correlation of the high heat flow with dikes, however, merely indicates how some more basic source of heat is localized. The reason why dikes of molten rock at relatively shallow depths are so common on the crests of oceanic rises remains to be explained.

High heat flow and, apparently, dikes are characteristic of the crest of rises at present and it might be expected that oceanic rises would also be sites of unusual concentrations of volcanoes. Despite the well known submarine vulcanism of the Mid-Atlantic Ridge, this expection is not correct. The location, and general size of several thousand oceanic volcanoes, chiefly seamounts, are known. Volcanoes are more common in some parts of the ocean than in others, and in some places they are typical. However, the provinces are not correlated with oceanic rises. For example, the Murray fracture zone lies on the flank of the East Pacific Rise and in the region to the south volcanoes are common but to the north they are rare. Similarly, volcanic provinces are widely distributed in the Atlantic and are not confined to the Mid-Atlantic Ridge. Although modern rises lack concentrations of volcanoes, the ancient Darwin Rise of the southwestern Pacific certainly did not. The majority of the large oceanic volcanoes of the Pacific, now mostly guyots and atoll platforms, formed on this rise. This may indicate that the Darwin Rise is unique in this respect, or possibly, volcanoes may be characteristic of a declining phase of rise development not yet reached by modern rises.

In their most fluid form basaltic lava flows build not volcanoes but lava plains by flooding large regions. Individual flood basalt provinces, such as the Deccan traps or Columbia basalts, have volumes of 5 to 6×10^5 km^3 (Rittmann 1962). The total volume of continental flood basalts in the whole geological record may be 10^7 km^3 (Verhoogen 1946). Equally large accumulations of flood basalts closely associated with oceanic rises appear to exist in ocean basins, although they cannot be directly sampled (figure 3). Such accumulations are the archipelagic aprons which form plains around existing and ancient island groups in the western Pacific (Menard 1956). Consideration of the volume of material in the aprons indicates that extrusion of flood basalts on the sea floor is the only possible source. The total volume of archipelagic aprons is roughly 2×10^7 km^3 (Menard 1964) which is the same order of magnitude as Verhoogen's estimate for continental basalts. The aprons lie on the ancient Darwin Rise, and apparently accumulated while the rise was in existence. This point will shortly be discussed. Thus the Darwin Rise was the locus of extraordinarily intense outpouring of flood basalts—perhaps unmatched in the geological record.

The Mid-Atlantic Ridge in the North Atlantic has also been the site of quite exceptional basalt flooding which may be continuing locally in Iceland. The early Tertiary basalts of the Thulean volcanic province occur on islands spanning the North Atlantic in layers 1 to 4 km thick (Tyrrell 1937). The second seismic layer under the sea floor in the same region has about the same thickness (Ewing & Ewing 1959). This thickness is exceptional for the Atlantic and the only plausible source for the unusual quantity of material is accumulation of flood basalts. This province can be traced to the south by the presence of a thick second seismic layer at numerous stations. It occurs only along the Mid-Atlantic Ridge. The volume of flood basalts defined by seismic techniques is $1{\cdot}5 \times 10^7$ km^3 or about the same as the estimates for the Darwin Rise or for all the continents.

The extent or even existence of large accumulations of flood basalts associated with other parts of the rise-ridge system is unknown. The second seismic layer is quite normal under the East Pacific Rise, but elsewhere pertinent data are scarce. It may be suggestive that flood basalts, including the Deccan traps, are common where the Carlsberg Ridge approaches Asia and Africa, and that the Columbia basalts lie where the East Pacific Rise overlaps western North America.

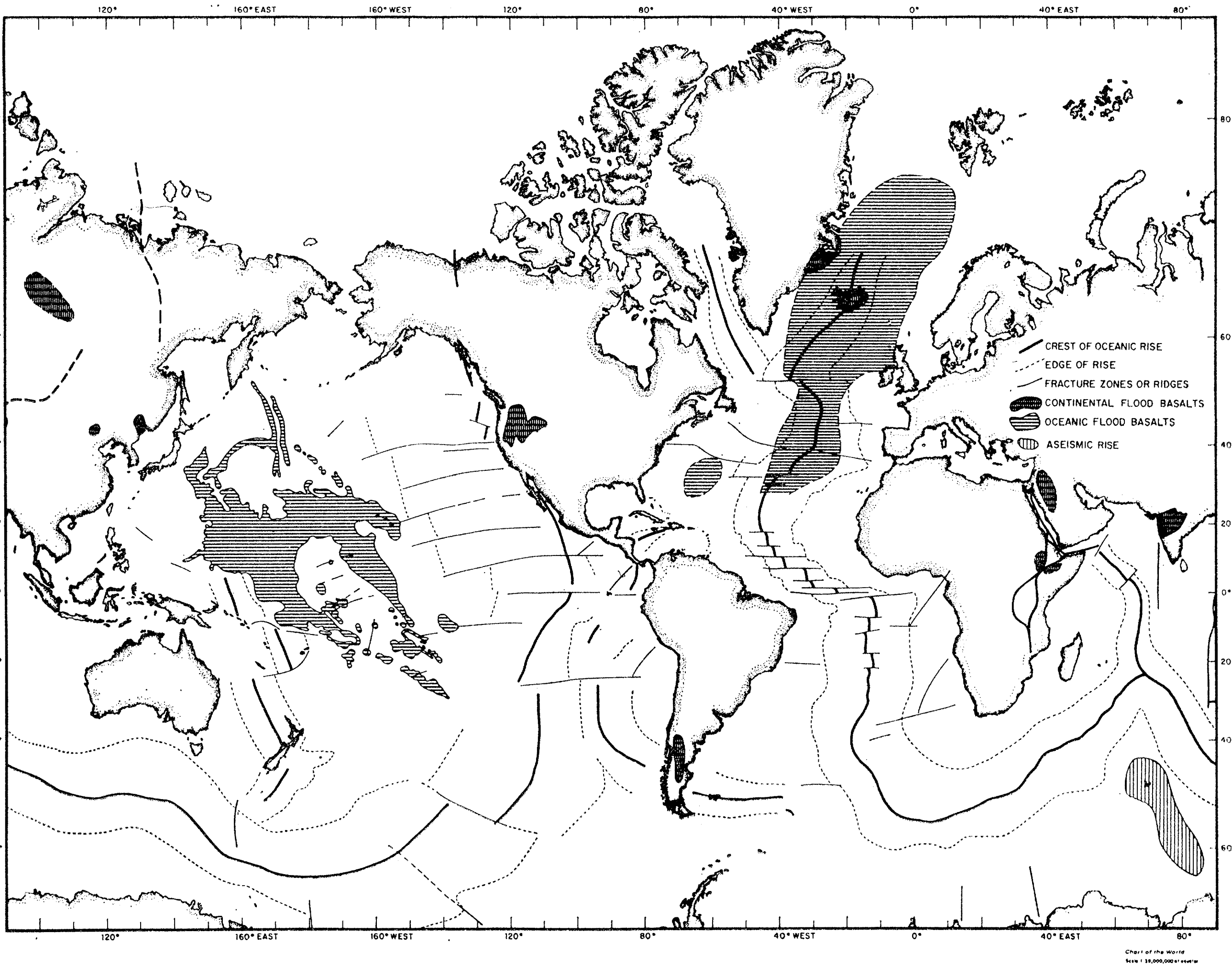

FIGURE 3. Association between late Mesozoic and Cenozoic flood basalts and oceanic rises and ridges. Archipelagic aprons, which formed of flood basalts, in the western Pacific are associated with the ancient Darwin Rise (see figure 6).

NORMAL FAULTING

Provinces of narrow ridges and troughs are common features on the rise-ridge system but rare elsewhere in ocean basins. Individual features and whole provinces of ridges and troughs generally follow the same trend as the rises on which they occur. Thus they are clearly associated with the rises. A conspicuous feature of this type of topography is a deep rift which occurs in many regions in the very centre of the rise-ridge system (Ewing & Heezen 1956). Notable examples are known in the North Atlantic and southwestern Indian Ocean and off Chile. Even in these regions, the rift is not a continuous feature but is interrupted by volcanoes or is offset in an *en echelon* pattern or transversely by fracture zones. Elsewhere the central rift does not exist. It is not identifiable on detailed surveys of the crest of the rise-ridge system in the South Atlantic (Vacquier & Von Herzen 1964) nor at most places in the Pacific (Menard 1964).

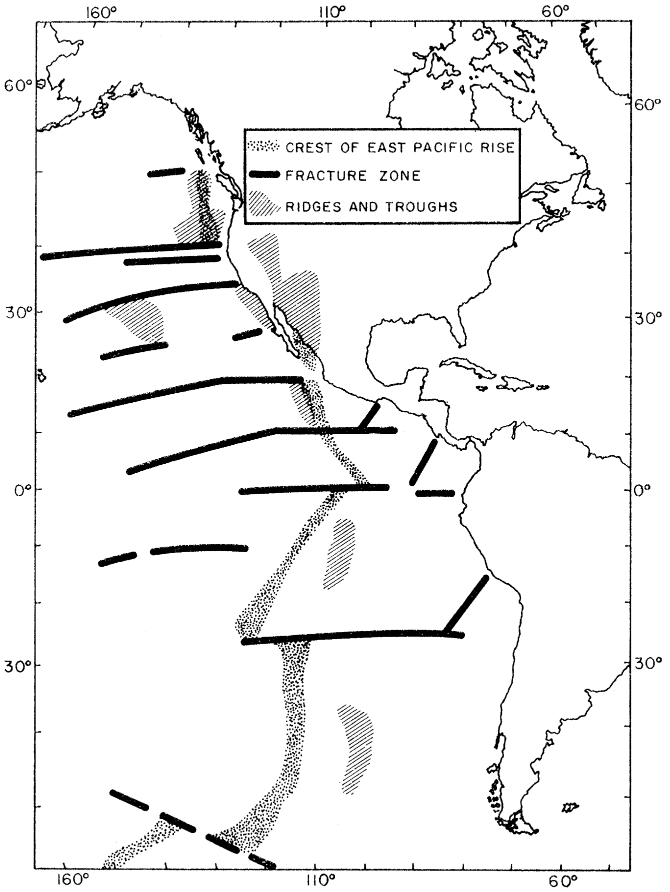

Figure 4. Distribution of prominent ridges and troughs on the East Pacific Rise. They are far more common on the flanks than on the crest (from Menard 1964).

Provinces of ridges and troughs are more extensive and continuous than any single feature, even the median rift. Thus a mountainous belt of asymmetrical ridges and troughs can be traced for long distances along the crest of the Mid-Atlantic Ridge in the North Atlantic (Heezen, Tharp & Ewing 1959). Similar median mountain belts are widespread in the Indian Ocean and in the southwestern Pacific but they are not continuous around the world. Gaps have been identified in the South Atlantic and the Eastern Pacific. In the latter region, at least, ridges and troughs appear not on the crest of the East Pacific Rise but on both flanks (figure 4). They occur as elongate but intermittent provinces for the whole length of this rise. Individual ridges and troughs and individual provinces have about the same dimensions and trend as the faulted blocks of the Basin Range Province of western North America (Menard 1960). Indeed this province may be similar to the ones on the sea floor; it appears to lie on the flank of the East Pacific Rise which overlaps the continent in this region.

The provinces of ridges and troughs appear to result from normal faulting caused by extension of the crust perpendicular to a rise. Great importance has been attached to this evidence of extension by a group of geologists who see the median rift, typical of the North Atlantic, as a crack along which rises have formed and the Earth has expanded (Heezen 1960). It is difficult to see how this hypothesis explains the many rises which lack a median rift, or the many ridge and trough provinces on the flanks of rises. However, the evident extension does not require expansion of the Earth. Any process which forms a rise by elevation from below will extend the crust and produce tension cracks parallel to the rise.

Wrench faulting

Zones of fracturing cut transversely across rises in many places. Typical examples are the fracture zones of the northeastern Pacific which are relatively narrow belts of asymmetrical ridges and troughs and large volcanoes which follow very straight trends for 1000 km or more. Many fracture zones separate regions with different depths and different physiography. The spacing of fracture zones seems to be relatively constant in the whole eastern Pacific (Menard 1960) and in the equatorial Atlantic (Heezen, Bunce, Hersey & Tharp 1965) but it is very different in the two regions. Both the uniformity in large regions, and the variations between regions of such large scale strain patterns are important to an understanding of sea floor deformation, but they are only recently discovered and are little understood.

Fracture zones in ocean basins are rare except on existing or ancient rises and ridges. Moreover, fracture zones are roughly transverse to the crest of a rise regardless of its trend. Thus it appears that such zones are formed by the same forces as rises and ridges. It is not yet clear whether all rises or sections of rises are transversely fractured, because surveys are not adequate to check the point. However, forty fracture zones occur on existing rises and ridges in the North and South Atlantic Oceans, western Indian Ocean, Antarctic Ocean, and both western and eastern Pacific. In addition, several probable fracture zones have been found associated with the ancient Darwin Rise. Known fracture zones are most common in the best sounded regions and probably many more will be discovered.

Offsets on fracture zones, or at least the three where detailed measurements are available, are almost purely horizontal. In the northeastern Pacific, a pattern of distinctive north-trending magnetic anomalies is offset 150 to 1170 km on west-trending fracture zones on the west flank of the East Pacific Rise (Vacquier, Raff & Warren 1961). Bathymetric contours in the region are offset in the same direction and by roughly the same amount (Menard 1960) indicating that the slope of the flank of the rise existed before the displacement, and also that the displacement was almost precisely horizontal. The absolute direction of movement on a few fracture zones can be deduced with some assurance from the relative movement and from the stretching of the crust indicated by thinning of crustal blocks bounded by the zones. Off California and Baja California it appears that the absolute motion of three blocks of the oceanic crust has been away from the crest of the East Pacific Rise (Menard, in the press). Detailed evidence of this sort is not available elsewhere although thinning of the crust in the middle of oceanic rises may be taken as evidence of average movement of the flanks away from the centre.

The feature most commonly observed to be offset on fracture zones is the crest of the rise-ridge system. It is relatively easy to identify from soundings and also from associated earthquakes; consequently offsets are recognizable even in relatively remote and little known regions (Sykes 1963). Offsets of hundreds or as much as 1000 km occur at a score of places in the Atlantic (Heezen *et al.* 1965), Indian (Matthews 1963), and Pacific ocean basins (Menard 1960). Offsets of the crest are so large and so common that they can be taken as typical (figure 1). This may be interpreted as indicating that a single, perhaps an elongate convection cell, creates rises and is capable of breaking itself into displaced fragments and still functioning, or contrarywise, that rises are formed by a line of smaller agents, perhaps equidimensional convection cells, and that offsets of the rise crest occur in the zone of interaction of the smaller agents.

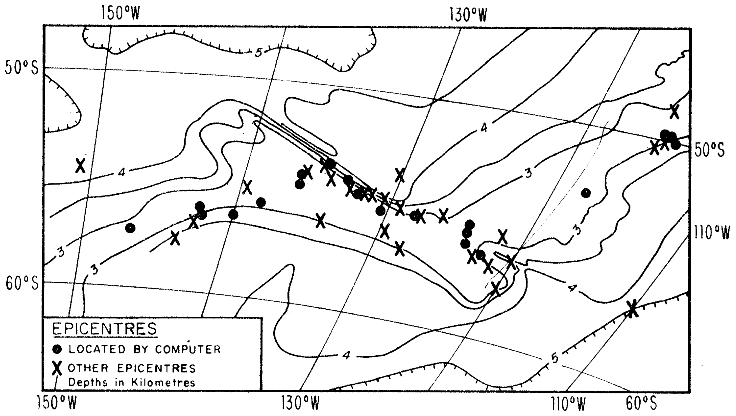

Figure 5. Topography and epicentres of part of the southeastern Pacific. Note the epicentre at about 110° W, far out on the flank of the rise and apparently on a transverse fracture zone (from Menard, in the press).

Relative ages of faulting

The longitudinal normal faults associated with a median rift or a median belt of ridges and troughs on rises are conspicuously active seismically (Ewing & Heezen 1956). Transverse wrench faults are also active (Tolstoy 1951; Menard 1955) but for a number of years it appeared that they were active only where they intersected the longitudinal earthquake belt, implying rejuvenation of older faults. This relationship came into increasing conflict with the evidence of actual offsets. The crest of the rise-ridge system and longitudinal ridges and troughs are offset by transverse fracture zones in many places but there is no known example of the reverse offset. From offsets, therefore, the transverse faults appear younger than the longitudinal ones. This problem is not yet solved but new observations show that fracture zones are active far out on the flanks of rises (figure 5) and thus are not merely older faults rejuvenated in the belt of longitudinal faulting (Menard, in the press). On present evidence, both types of faulting are active in many places reflecting differential movement of blocks of the crust away from the crest of the rise-ridge system.

Development of individual rises

The Darwin Rise is the only one which is known to have subsided and consequently is the only one in which a complete development can be studied. The sequence of events related to the Darwin Rise appears to be the following (Menard 1964):

1. Earlier than about 100 My ago, a rise roughly 10000 km long, 4000 km wide, and 2 to 3 km high developed in the southwestern Pacific in water more than 5 km deep. The rise extended in a northwesterly direction from the Tuamotu Islands to the Marianas Islands (figure 6).
2. During the early stages of its development the Darwin Rise was faulted into longitudinal ridges and troughs near the crest, and cut by transverse fracture zones at least in the central region.
3. About 100 My ago the rise was dotted with a great number of volcanic island archipelagoes which were gradually truncated after they became inactive.
4. The load of the growing archipelagoes cracked the surrounding crust and opened fissures for vast floods of basalt which collected in archipelagic aprons, and partially buried the older faulted topography.
5. During or after the accumulation of aprons, the Darwin Rise began to subside and has now completely disappeared. Subsidence has continued at a relatively constant rate for roughly 100 My but has been interrupted at least locally by short periods of minor elevation.

The end products of the elevation and subsidence of the Darwin Rise are a few faults in the sea floor, a very large accumulation of volcanic rock, and abnormal velocities averaging 8·4 km/s in the upper mantle. In terms of origin, the rise apparently was formed by a very large, ephemeral, process which heated the whole region enough to produce exceptional vulcanism, and then gradually subsided during a prolonged period.

The known history of other rises is quite incomplete but a few fragments of information exist to compare with the development of the Darwin Rise and thus, perhaps, gain some insight about the development of rises in general. The faulting of the Darwin Rise apparently is older than the vulcanism and may have developed either simultaneously with the rise or after it had been elevated. Consequently it is worthwhile to examine existing rises to try to resolve this question. The whole rise-ridge system is faulted either longitudinally or transversely or both. It is possible that all existing rises have passed through some initial unfaulted stage of development but it seems probable that rises are faulted from the beginning. This in turn implies lateral extension and differential movement of blocks and of the crest itself from the beginning.

The next event following faulting of the Darwin Rise was formation of a large number of linear volcanic archipelagoes. Similar archipelagos are rare elsewhere and thus this may be is a unique event. Either it is not a normal part of rise development or else it has not yet occurred on younger rises. The next stage in development of the Darwin Rise was the extrusion of flood basalts which were localized around archipelagoes because of cracking of the crust by the load of the volcanoes. Flood basalts are also known on the northern Mid-Atlantic Ridge and possibly the Carlsberg Ridge but they do not ring volcanic archipelagos. Quantitatively the significant volcanic event is the extrusion of flood basalts rather than the formation of archipelagos and the two events may be independent. In the North Atlantic the volcanic cone stage of development of the Darwin Rise has been eliminated. However, the flood basalts of the northern Mid-Atlantic Ridge are faulted both longitudinally and transversely in sharp contrast to the unfaulted archipelagic aprons of the Darwin Rise. Evidently the rise-ridge system is faulted when it first develops, and the faulting may or may not cease if basalt flooding occurs in a region.

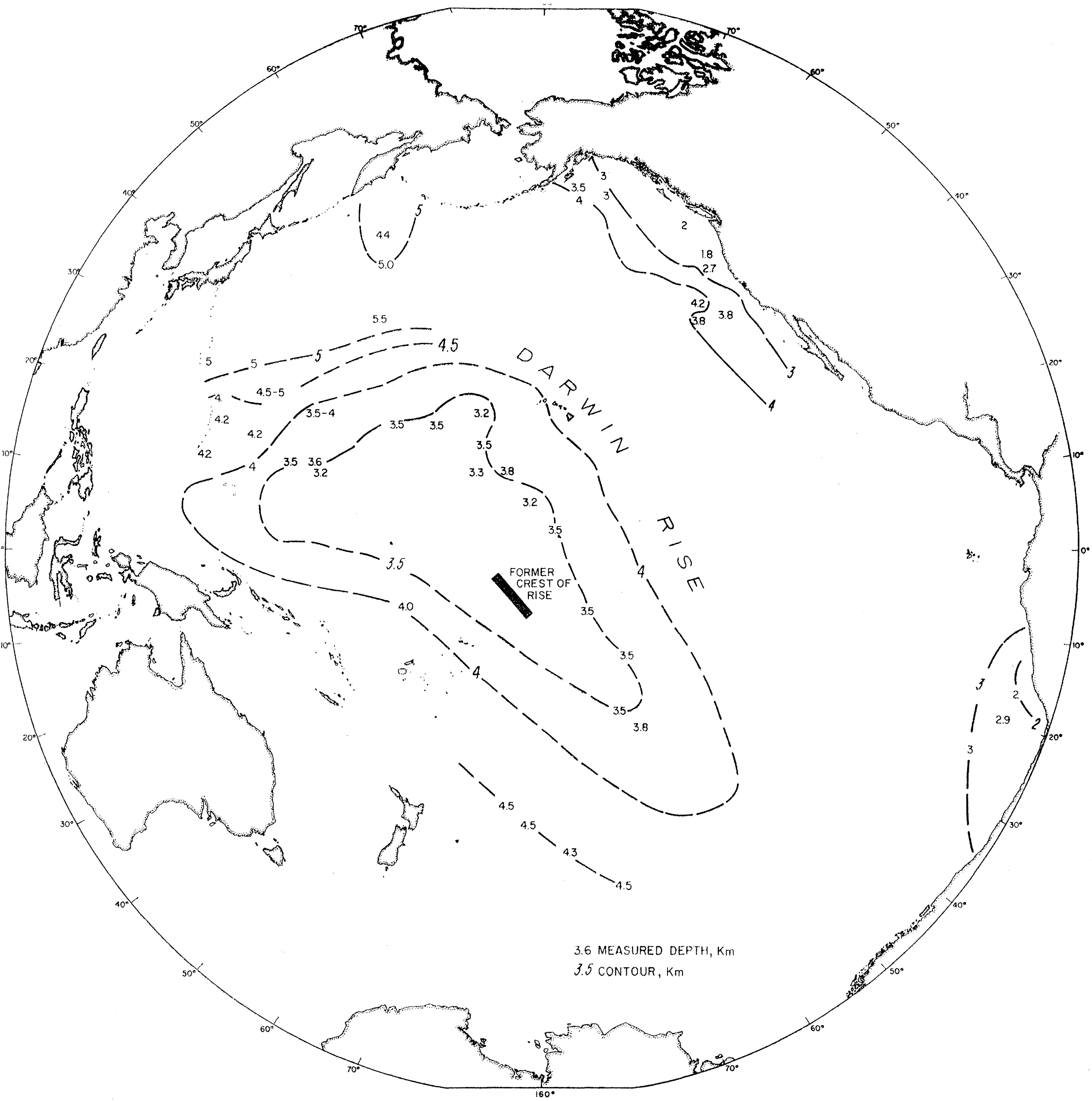

Figure 6. Paleobathymetry of the Pacific at different times. Contours of the Darwin Rise indicate depths roughly 100 My ago (from Menard 1964).

Flood basalts have not been extruded on all parts of rises, at least as yet. The East Pacific Rise has a normal thickness of the seismic second layer and there is no other evidence of exceptional vulcanism.

During or after the main volcanic stage, the Darwin Rise began to sink. Have other parts of the rise-ridge system also subsided? Guyots and atolls rise from various places on the rise-ridge system in the Atlantic, Indian, and eastern Pacific oceans although they are scarce compared to the region of the Darwin Rise. Nevertheless, it is clear that many parts of rises have been higher than they are at present and epirogenic movements are commonplace.

In summary, the development of even individual oceanic rises is complex and differs from rise to rise. Large scale faulting, vulcanism and epirogenic movement may occur simultaneously or in various sequences. The simple submarine welts suggested by small scale bathymetric maps do not exist and never have.

Origin of the rise-ridge system

Field evidence has suggested to many geologists that large convection currents move horizontally under the crust and stress it. Such currents, for example, offer a simple explanation for the extensive horizontal movement of crustal blocks on oceanic rises, or the folding found in island arcs or many mountain ranges. The evidence for a vertical component of convection is more tenuous and rests mainly on arguments connected with high heat flow or negative gravity anomalies. There is, of course, no evidence from field geology of any deep return flow. Thus neither the shape nor even existence of organized convection cells in the mantle has ever been suggested by field geology. This is not true of field geologists.

Geophysicists have been of two minds. One group presents mathematical models of the motion of circular convection cells that extend through the whole mantle and evidence, other than field geology, supporting the existence of such motion. The other group denies the existence of mantle convection because of stratification, indicated by seismology, that would prevent large scale vertical movement. By default it has appeared that the field geology evidence for convection is opposed by the seismological evidence of stratification. A recent paper resolves this conflict by showing that nearly horizontal advective motion is at least as probable as circular motion and that it would not be prevented by a stratified mantle (Elsasser 1963).

If mantle convection forms the rise-ridge system, many of its characteristics can be deduced. The chief conclusion to be derived from the distribution of rises is that they roughly circle continental nuclei which suggests that some phenomenon related to continents exerts a primary control over their location (Menard, in the press). Continuing differentiation of continents from the underlying mantle might be such a phenomenon. Separation of a light component of the mantle which rises to form a continent may leave a dense residue which sinks. Ramberg (1963) has shown experimentally that a heavy body sinking through a viscous material produces flow around it and that an overlying competent crust is stretched in a ring around the sinking body. If this occurred under Africa and South America the rings of stretching would meet at the Mid-Atlantic Ridge in the middle of the Atlantic basin. The flow around the sinking bodies is shallow convection of a sort and it has the right motion to produce the observed faulting and stretching of the Mid-Atlantic Ridge, and the high heat flow on the crest. On the other hand, it cannot explain the western motion of crustal blocks away from the crest of the East Pacific Rise in the northeastern Pacific. This requires some secondary thermal convection cells rising and spreading from the crest and with positions determined by the location of a belt of stretching around the North American continental shield.

The existence of primary convection acting from each side of a rise or from secondary local centres along the rise seems to offer a natural explanation for the numerous offsets of the crest of the rise-ridge system which are so puzzling if the system is produced by convection cells in the form of long horizontal rollers centred on the rises. Moreover, in this model all the convection cells are roughly circular in plan view, although shallow in cross-section, which agrees with convection experiments in which rotational effects are negligible.

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