Part I

Background

1

Variability of heat flux through the seafloor: discovery of hydrothermal circulation in the oceanic crust

John G. Sclater

1.1 Introduction

> Never duplicate an oceanic heat flow measurement for fear it might differ from the first by two orders of magnitude!
>
> *(Bullard's Law as stated by Maurice Hill, 1963)*

> The elevation of a suggestion to a hypothesis requires the prediction of testable phenomena separate from the original discrepancy
>
> *(Lister, 1980)*

The heat left over from the formation of the planet combined with that generated by radioactive decay drives the internal engine of the Earth. This heat is the cause of elevated temperatures in mines, and is the ultimate source of energy for volcanoes, hot springs, mountain building, and earthquakes. The heat flux is the product of the temperature gradient and the thermal conductivity. Scientists use temperatures measured in 100-m- to 5-km-deep boreholes coupled with conductivity measurements on the rocks penetrated to derive the heat flux through the continents. At sea, they use the temperature gradient measured by thin probes driven 3–10 m into the soft sediments of the ocean floor multiplied by the thermal conductivity of these sediments. Continental crust is both thicker and has a greater concentration of heat-producing elements than oceanic crust, so if heat is carried from the Earth's interior only by conduction, the continents should have a much greater heat flux than the oceans.

1.1.1 The early oceanic measurements

Hans Petterson, the leader of the 1947–1948 Swedish Deep Sea Expedition, made the first temperature gradient measurement on the ocean floor on November 14, 1947, near the equator between Tahiti and Hawaii (Petterson, 1949, 1957). This and another measurement near the equator on the edge of the Ontong Java Plateau yielded temperature gradients of

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approximately 40 °C km^{-1}, twice that of the average gradient on continents (Petterson, 1949). Even allowing for the differences between the conductivity of continental rocks and soft oceanic sediments, these gradients were incompatible with there being a similar deep conductive flux beneath continents and oceans. It is difficult now to overestimate the importance of the contribution of Petterson. He had recognized that stable bottom-water temperatures, coupled with the soft sediments of the ocean deeps, provided the ideal environment for the easy measurement of the heat flux through the ocean floor. In addition, his measurements stood conventional theory regarding the thermal state of continents and oceans on its head. Surprisingly, no write-up exists in English of the instrument, and Petterson did not turn the temperature gradients into heat flux. When Revelle and Maxwell (1952) and Bullard (1954) reported the first full oceanic heat flux measurements that included sediment thermal conductivity, both cited the pioneering measurements of Petterson (1949), but since then his contribution appears to have been largely forgotten.

Sir Edward Bullard had made substantial contributions to heat flux measurements on continents (Bullard, 1939) and had long wanted to make similar measurements through the ocean floor. He recognized the importance of the efforts of Petterson immediately (Bullard, 1954), encouraged the development of a heat probe device at Scripps Institution of Oceanography (SIO) in the US, and developed a similar device at the National Physical Laboratory in England. Gradients reported by Revelle and Maxwell (1952) were even higher than those of Petterson (1949). Bullard (1952) speculated that “at some not too remote time a convection current rose under the Pacific and brought hot material near the surface,” and that this could account for the higher that expected oceanic flux. With additional measurements in the 1950s, an apparent equality between the mean flux through the oceans and continents emerged (Lee and Uyeda, 1965), despite the much greater contribution of radiogenic heat from continental crust. Early observations also revealed large scatter about the relatively high mean value, particularly over mid-ocean ridges. For example, Von Herzen (1959) and Von Herzen and Uyeda (1963) reported both very high and very low individual values and high average heat flux near the crest of the East Pacific Rise.

I arrived at the University of Cambridge as a graduate student in the autumn of 1962. I joined the Marine Group run by Maurice Hill and planned to work as an observational seismologist on low-frequency surface waves in the ocean crust. In addition, I volunteered, during a 1963 Cambridge expedition to the Indian Ocean on the *RRS Discovery*, to run the outrigger heat probe that Clive Lister had built as part of his Ph.D. thesis (Lister, 1963). The low-frequency seismometer that I built flooded on its first lowering, so I concentrated for the rest of the expedition and ultimately for my thesis on the measurement of heat flux through the ocean floor. I observed high heat flux within the Gulf of Aden (Sclater, 1966b), and a large scatter like that reported by Von Herzen and Uyeda (1963). The scatter troubled me and my supervisor Maurice Hill, who remained skeptical not only of the whole technique but also of the grandiloquent interpretations by Sir Edward of a measurement that could vary so much over so short a distance.

Fig. 1.1 Department of Geodesy and Geophysics, Cambridge University marine group on board the RRS Discovery in the early 50s. Back row from left: John Swallow, Maurice Hill and John Cleverly. Front row: Tony Laughton, Captain Dalgliesh and Sir Edward Bullard. Photograph by Robin Adams.

1.1.2 Bullard's law

Sir Edward Bullard (Fig. 1.1) had received his Ph.D. in the 1930s as a nuclear physicist under Rutherford at the Cavendish Laboratory in Cambridge, UK. Immediately before World War II and then entirely thereafter, Teddy Bullard had devoted himself to geophysics, ending his career as the Head of the Department of Geodesy and Geophysics at Cambridge. However, he sometimes regretted that he had had to abandon nuclear physics to find a job. He bemoaned especially the fact that unlike most of his contemporaries from the Cavendish, he had had no important physical law named after him. To rectify this oversight, Maurice Hill (Fig. 1.1) formulated Bullard's Law. Maurice, who had worked with Teddy during World War II, knew that he suffered horribly from seasickness and he eventually refused to take him to sea with the marine group for fear his illness would jeopardize the Cambridge expeditions.

In this chapter, I present a personal retrospective of the attempts to explain Bullard's Law, covering early heat flow surveys, the sedimentary observations, magnetic measurements, and physical inferences that led to the realization that fluid flowing through the oceanic crust must be responsible for the variability. I discuss the original discovery of a hydrothermal plume predicted by the physical model, and the later confirmation by Anderson *et al.* (1985) of a layer of high permeability at the top of the igneous crust. I finish by considering the advances that have come from separate considerations of advective flow and conductive thermal flow of heat through the ocean floor. As this is a personal retrospective I have restricted my comments to the papers that I believe influenced or should have influenced my own thinking on this discovery.

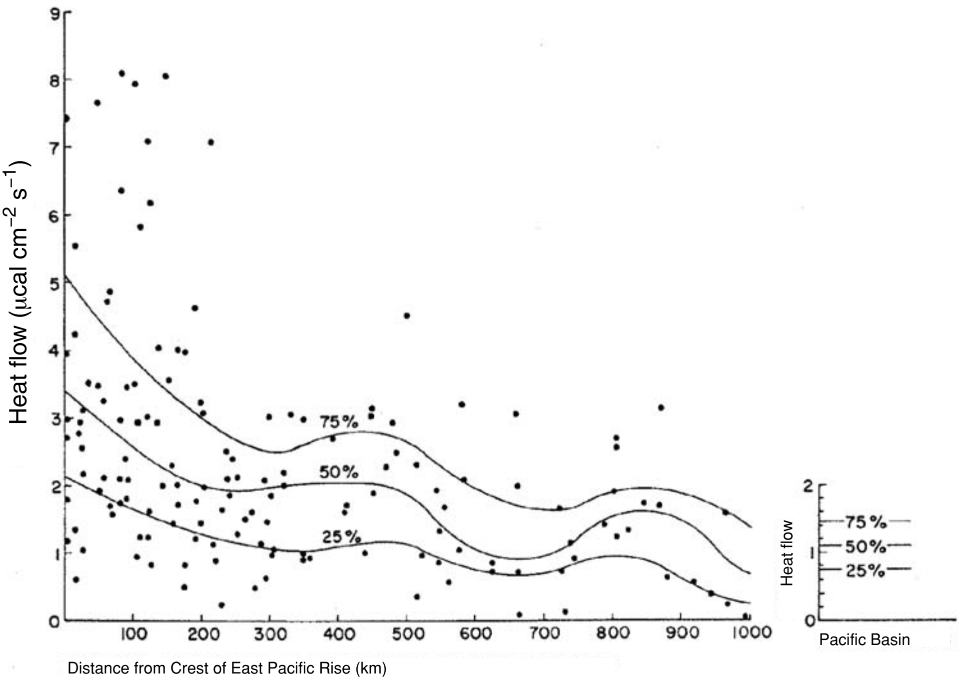

Fig. 1.2 Heat flux values versus distance from the crest of the East Pacific Rise. 75, 50, and 25 percentile bounding lines are given for values from the East Pacific Rise and Pacific Basin. (Reprinted from Lee, W. H. K. and Uyeda, S. 1965. Review of heat flow data. In *Terrestrial Heat Flow*, Geophysical Monograph Series 8, ed. W. H. K. Lee. Washington, DC: American Geophysical Union, pp. 87–190, Copyright 1965 American Geophysical Union.)

1.2 Measurement scatter and the search for its cause

Early workers such as Bullard and Day (1961) and Von Herzen and Uyeda (1963) investigated the heat flow anomaly at the crests of the mid-ocean ridges. After the accumulation of a substantial body of data, Lee and Uyeda (1965) showed that the mid-ocean ridges had an overall flux well above the global average (Fig. 1.2). However, great scatter in the measurements prevented a confident quantitative interpretation of the results.

In their compilation of heat flux measurements from the Pacific, Von Herzen and Uyeda (1963) noted that the values ranged from essentially zero to 400 mW m^{-2} and discussed in detail local factors that might affect them. Bullard *et al.* (1956) had shown already that bottom-water temperature changes had a negligible effect. Von Herzen and Uyeda (1963) examined four other factors and demonstrated that none could reasonably account for the observed scatter and individual low values. These were: (a) rapid sedimentation, (b) local sediment slumping, (c) thermal refraction through rugged basement and around sediment ponds, and (d) a downward flow of water through the sediments.

The conclusion that local environmental effects could not explain the low values set the stage for my thesis (Sclater, 1966a). In 1965, I investigated the combination of sediment

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ponds and sharp topographic slopes in the North Atlantic (Sclater *et al.*, 1970a), and, in 1966, I carried out a similar investigation north of the Hawaiian islands (Sclater *et al.*, 1970b). My coauthors and I concluded that only a series of recent slumps of sediment from nearby hills could explain the low values. This explanation was unrealistic, however, so the low values remained problematic.

1.3 Early thermal models of the oceanic lithosphere without good thermal constraints

Harry Hess and Tuzo Wilson spent a sabbatical at "Madingley," the English manor housing the Department of Geodesy and Geophysics at Cambridge, during my last year at Cambridge. I was so caught up in dealing with the variability of the measurements that I failed to realize the importance of either seafloor spreading (Hess, 1962) or plate tectonics (Wilson, 1965) for understanding oceanic heat flux. When the concept of seafloor spreading was proposed, heat flux measurements had played a major role. Hess suggested that huge igneous intrusions caused the high values at the crests of the mid-ocean ridges. The combination of Von Herzen's measurements showing high average values over the crest of the East Pacific Rise (Von Herzen, 1959), Bill Menard's concept of a world-encircling set of mid-ocean ridges (Menard, 1959), and the insight of Bruce Heezen (1960) regarding normal faulting at the crest of the Mid-Atlantic Ridge led Hess directly to the concept of seafloor spreading. Additional measurements by Nason and Lee (1962), Vacquier and Von Herzen (1964), and Von Herzen and Vacquier (1966) confirmed the correlation of high average heat flux (and high scatter) with the crests of all of the mid-ocean ridges.

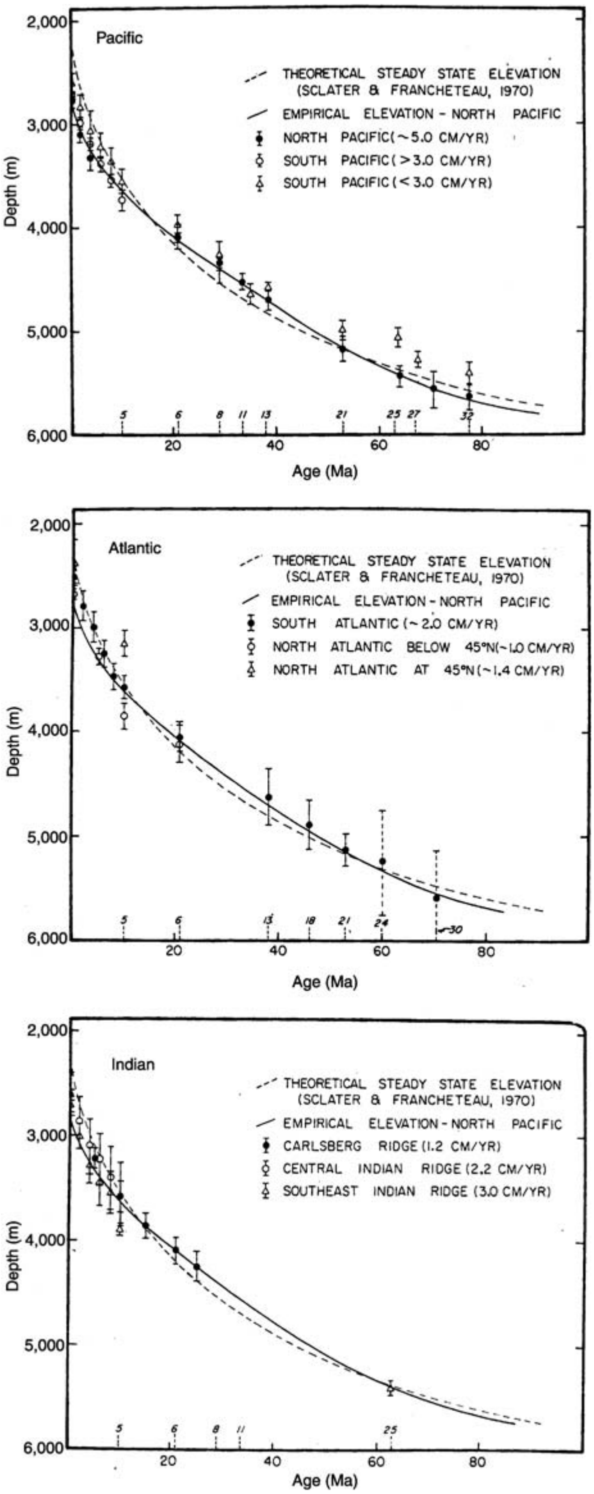
Soon after the publication of Hess' paper, Wilson (1965) introduced the idea of transform faults from which the quantitative theory of plate tectonics developed. Lyn Sykes (1967) showed from earthquake first-motion studies that only normal faults occurred at the crest of the Mid-Atlantic Ridge and that all the strike–slip fault-plane solutions lay on the cross-cutting fracture zones, consistent with the transform fault hypothesis. At the same institution, Lamont Doherty Geological Observatory of Columbia University, Marcus Langseth (Fig. 1.3*a*), Xavier Le Pichon, and Maurice Ewing introduced the concept of a constant thickness lithosphere, created by a zone of intrusion and subsequently cooled by conduction through its upper surface (Langseth *et al.*, 1966). They pointed out that the cooling of this plate would lead to a decrease in heat flux and a subsidence due to contraction as the newly created plate moved away from the place of creation, the mid-ocean ridge. While this early model was to become a cornerstone for quantitative plate-tectonic theory, it is interesting that the authors were forced to argue against the possibility of "continuous continental drift of the spreading-floor type in the Cenozoic" in the Atlantic Ocean on the basis of the lack of a wide heat flow maximum over the Mid-Atlantic Ridge. The knowledge of unaccounted-for advective heat loss from the lithosphere was yet to come.

Stimulated by this paper, McKenzie (1967) showed that by reducing the plate thickness and the axial and lower boundary temperatures, the plate model could be made to match the heat flux data in a general way. Other attempts that followed involved more reasonable plate thicknesses and initial and lower boundary temperatures, and more sophisticated treatments

Fig. 1.3 Marcus Langseth (*a*) on board the JOIDES *Resolution* drill ship in 1991 (photograph by Andy Fisher), and Clive Lister (*b*) jogging on the *R.V. Thomas Thompson* in 1973. (photograph by Earl Davis). Reproduced with permission.

of isostatic compensation and axial boundary conditions (McKenzie and Parker, 1967; Vogt and Ostenso, 1967; Isacks *et al.*, 1968; Le Pichon, 1968; Morgan, 1968; McKenzie and Sclater, 1969; Sleep, 1969; Sclater and Francheteau, 1970). These established many quantitative aspects of plate tectonics, but all suffered from the same unrecognized problem that the heat flux data did not reflect the total flux from the lithosphere in young regions. Ironically, those that were most successful used heat flux as a constraint only semi-quantitatively or not at all (as in the case of Sclater *et al.*, 1971; Fig. 1.4).

Fig. 1.4 Average depth in the Pacific, Atlantic, and Indian Oceans plotted against age of the ocean floor. The theoretical profile (dashed line) is that for a lithosphere 100 km thick with a base temperature of 1,475 °C. The thick black line is a curve drawn by eye through the North Pacific data. (Reprinted from Sclater, J. G., Anderson, R. N., and Bell, M. L. 1971. The elevation of ridges and the evolution of the central eastern Pacific. *J. Geophys. Res*. **76**: 7,888–7,915, Copyright 1971 American Geophysical Union.)


Pacific
THEORETICAL STEADY STATE ELEVATION (SCLATER & FRANCHETEAU, 1970)
EMPIRICAL ELEVATION - NORTH PACIFIC
NORTH PACIFIC (~5.0 CM/YR)
SOUTH PACIFIC (>3.0 CM/YR)
SOUTH PACIFIC (<3.0 CM/YR)
Depth (m)
2,000
3,000
4,000
5,000
6,000
5
6
8
11
13
21
25
27
32
20
40
60
80
Age (Ma)
Atlantic
THEORETICAL STEADY STATE ELEVATION (SCLATER & FRANCHETEAU, 1970)
EMPIRICAL ELEVATION - NORTH PACIFIC
SOUTH ATLANTIC (~2.0 CM/YR)
NORTH ATLANTIC BELOW 45°N (~1.0 CM/YR)
NORTH ATLANTIC AT 45°N (~1.4 CM/YR)
Depth (m)
2,000
3,000
4,000
5,000
6,000
5
6
13
18
21
24
30
20
40
60
80
Age (Ma)
Indian
THEORETICAL STEADY STATE ELEVATION (SCLATER & FRANCHETEAU, 1970)
EMPIRICAL ELEVATION - NORTH PACIFIC
CARLSBERG RIDGE (1.2 CM/YR)
CENTRAL INDIAN RIDGE (2.2 CM/YR)
SOUTHEAST INDIAN RIDGE (3.0 CM/YR)
Depth (m)
2,000
3,000
4,000
5,000
6,000
5
6
8
11
25
20
40
60
80
Age (Ma)

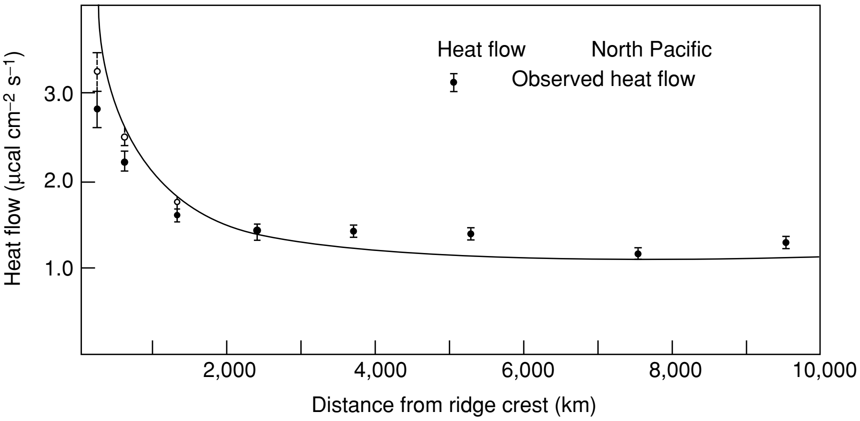


Fig. 1.5 A comparison of the observed heat flux averages in the North Pacific (filled points) with the theoretical profile for a 75-km-thick lithosphere. Open points reflect a 15% shift applied to the observed averages to account for a possible bias from environmental effects. (Reprinted from Sclater, J. G. and Francheteau, J. 1970. The implications of terrestical heat flow observations on current tectonic and geochemical models of the crust and upper mantle of the earth. *Geophys. J. Roy. Astron. Soc.* **20**: 509–537, Copyright 1970 The Royal Astronomical Society.)

1.4 Hydrothermal circulation at mid-ocean ridges

Even after omitting very low values, Sclater and Francheteau (1970) found that the mean heat flux near the ridge axes lay well below that predicted by plate theory (Fig. 1.5). An explanation that involved an arbitrary rejection of low values and even then did not match the observations was inherently unsatisfactory. To be taken seriously, the geothermal community needed an explanation of the low average values (relative to plate theory) and large scatter. The explanation came from sedimentary geochemistry and from the work of my predecessor at Cambridge, Clive Lister (Fig. 1.3*b*).

1.4.1 Geochemical evidence

The cause of variability in ocean heat flux received little attention from most of the geophysics community. However, geochemists had long been searching for an explanation for both the global and local variations in metalliferous metals in sediment samples from the ocean floor. Many (von Gumbel, 1878; Murray and Renard, 1895; Arrhenius, 1952; Petterson, 1959) had suggested hydrothermal solutions were responsible. However, none had related the phenomena to the mid-ocean ridges until Skornyakova (1964) linked the formation of iron–manganese–carbonate-rich sediments with modern volcanism and hydrothermal action at the crest of the southern East Pacific Rise. Arrhenius and Bonatti (1965) related the high barite concentration on the East Pacific Rise to active magma reservoirs, and Bonatti and Jeonsuu (1966) argued that hydrothermal activity concentrated mineral deposits right on the crest of the Rise. In their classic paper, Bostrom and Peterson (1966) related sediment enrichment in iron and manganese to the high heat flux at the crest of the Rise (Fig. 1.6). They argued for ascending solutions of deep-seated origin, and that hydrothermal activity "is the only explanation that seems reasonable."

1.4.2 Geophysical arguments

John Elder (1965) was the first geophysicist to tackle the question of hydrothermal circulation in the hard rock at mid-ocean ridges. When interpreting the Tuscan steam zone in Italy and the Taupo hydrothermal systems of New Zealand, he considered a body of freely circulating hot water and discussed the problem in terms of convection within a porous medium. He noted that the boundary conditions in an oceanic system would differ from those on land: no air–water interface, and seawater existing both above and below the ground surface. He simulated the conditions in a laboratory Hele–Shaw cell, a device that simulates flow in a porous medium with flow in a thin vertical slot bounded by parallel insulating plates. With heat applied uniformly from below, he observed that heat flux at the surface was concentrated above a narrow zone of convective up-flow. This was bordered by a broad region where the flux was zero corresponding to the area of recharge.

The Mid-Atlantic Ridge includes Iceland, where famous hot springs and geysers abound at the surface. Appropriately, the first publication linking hydrothermal circulation to the cooling of a mid-ocean ridge appeared in an Icelandic publication (Palmason, 1967). Talwani *et al.* (1971) made a similar suggestion to account for some very low values near the crest of the Reykjanes Ridge. Irving *et al.* (1970) provided further support for this hypothesis by arguing that hydrothermal alteration reduced the magnetization of the near-surface lava flows as they move away from the crest of a mid-ocean ridge.

However, only after Clive Lister (1972) carried out two detailed heat flux surveys over the variably sediment-covered Juan de Fuca and Explorer Ridges did a coherent hypothesis with testable predictions develop. As observed in other studies, the heat flux in this young area was anomalously low and variable. Carbon-14 studies of the sediments in the ponds with low heat flux showed a constant deposition rate with no evidence of major slumping. Clearly, environmental disturbances could not explain the low and variable values. Lister argued that only hydrothermal circulation in the hard rocks of the oceanic crust could explain the low values in the sediment ponds and the overall missing heat over this ridge crest. He also concluded that a thin drape of low-permeability sediments would impede water flow, and predicted in a now famous cartoon the flow pattern in three cases of differing hydrologic structure: a permeable crust where exchange with the ocean is uninhibited, a permeable crust blanketed by a uniform drape of low-permeability sediments, and a permeable crust buried by flat lying abyssal plain sediments (Fig. 1.7). He also argued that up-flow would be highly focused and create hot springs at ridge crests, but that detection of them would be difficult because of the great dilution of the springs that would take place as they mixed into the open ocean.

In a parallel development, Bodvarsson and Lowell (1972) demonstrated how easily a pipeline type of convection system could modify the heat flow of a region. Cracks as small as 3 mm wide and a kilometer deep could convect away a large amount of heat, and minute amounts of thermal contraction in the oceanic crust could generate them. This became the