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VOLCANISM ON EARTH THROUGH TIME

Kevin Burke and W.S.F. Kidd
Department of Geological Sciences,
State University of New York at Albany
Albany, New York 12222

ABSTRACT

Volcanism is widespread on Earth and apparently always has been. In this respect the Earth contrasts with the Moon, where volcanism stopped about 3 Ga ago, and with Mars, where it may have stopped 1 Ga ago. Although the terrestrial volcanism that occurred before the oldest preserved rocks formed was probably similar to later volcanism, the very earliest volcanic activity on Earth could have been like that on the Moon, if the Earth acquired its water late during the high impact flux.

Volcanism plays a vital part in all three stages of lithospheric evolution active on Earth today. Basalt forms at divergent plate boundaries; tholeiitic and calc-alkaline rocks, most characteristically andesite, dominate where arcs form above subduction zones; highly potassic volcanics are associated with active continental collision, crustal thickening, and fractionation. These three processes appear to have operated at plate margins throughout most of the Earth's history.

Ultramafic komatiites, forming perhaps 5% of basaltic piles and indicating the existence of ultramafic melts, are peculiar to the Archean, and are presumably due to the greater heat generation of the early Earth, although their precise significance is ambiguous. Non-plate margin (hot-spot) alkaline and tholeiitic volcanism is also recorded in old rocks. Remnants of flood basalts and associated sills and dyke swarms formed by rifting episodes are clearly displayed in the Canadian shield up to 2.5 Ga ago, and in Greenland back to 3.6 Ga.

Sea level variations during the Phanerozoic have been interpreted as indicating variations in spreading ridge volume and hence (on an Earth of roughly constant volume) of plate creation and destruction rates. Precambrian sea level fluctuations cannot be interpreted in the same way because the sediment record is incomplete and because timing has not been adequately resolved. Estimates of episodicity in plate activity in the Precambrian depend mainly on the occurrence of peaks in age abundance. This method is highly misleading because the preserved areas of particular ages are much too small to be representative of the world at those times. As far back as the geological record, goes, volcanism has been continuously active on Earth and has occurred mainly at plate boundaries. Phanerozoic history indicates some episodicity, and the Precambrian was probably similar.

RÉSUMÉ

Le volcanisme est très répandu sur toute la Terre et apparemment il l'a toujours été. Sous cet aspect, la Terre contraste avec la Lune où le volcanisme s'est arrêté il y a 3 Ga et avec Mars où il a dû cesser il y a 1 Ga. Bien que le volcanisme terrestre antérieur aux plus anciennes roches préservées ait été probablement semblable au volcanisme plus tardif, l'activité volcanique la plus ancienne sur terre a pu être semblable au volcanisme lunaire si la Terre a acquis son eau plus tard durant le flux élevé d'impacts.

Le volcanisme joue un rôle vital dans les trois stades d'évolution de la lithosphère comme on l'observe sur la Terre aujourd'hui. Le basalte se forme aux limites de plaques divergentes; les roches tholéiitiques et calco-alcalines, en particulier l'andésite, dominent là où des arcs se forment audessus des zones de subduction; on retrouve les volcaniques très potassiques en association avec les zones de collision continentales actives, l'épaississement de la croûte et son fractionnement. Ces trois processus semblent avoir agi aux limites des plaques durant la plus grande partie de l'histoire de la Terre.

Les komatiites ultramafiques, qui forment peut-être 5% des empilements basaltiques et indiquent l'existence de magmas ultramafiques, sont caractéristiques de l'Archéen et on présume qu'elles sont dues à la plus grande production de chaleur dans la Terre primitive; toutefois, leur signification précise est encore ambiguë. Le volcanisme alcalin ou tholéiitique en dehors des bordures de plaques (points chauds) se retrouve aussi dans les roches anciennes. Des vestiges de coulées de basalte de même que les sills et les essaims de dykes associés qui se sont formés durant des épisodes d'effondrement sont clairement exposés dans le bouclier canadien jusqu'à il y a 2,5 Ga et jusqu'à 3,6 Ga au Gröenland.

On interprète les variations du niveau marin au cours du Phanérozoïque comme indiquant des variations dans le volume des crêtes en expansion et par conséquent (sur une Terre de volume à peu près constant) comme un indice des taux de création et de destruction de plaques. On ne peut interpréter les fluctuations de niveau marin au Précambrien de la même façon parce que le registre sédimentaire est incomplet et parce que la chronologie est inadéquate. Les estimations de l'épisodicité de l'activité des plaques au Précambrien dépendent surtout de la présence de pics d'abondance d'âges. Cette méthode porte beaucoup à confusion parce que les régions où les roches de certains âges sont préservées sont beaucoup trop petites pour être représentatives du monde à ces époques. Aussi loin que le registre géologique s'étende, le volcanisme a été continuellement actif sur Terre et s'est produit surtout aux bordures des plaques. L'histoire phanérozoïque indique une certaine épisodicité et c'était probablement semblable au Précambrien.

INTRODUCTION: VOLCANISM ON EARTH COMPARED WITH THAT ON OTHER TERRESTRIAL PLANETS

Active volcanism is widespread on Earth and is recorded in rocks of all ages. Strikingly, the oldest preserved rocks on Earth (at Isua in West Greenland) appear to be volcanic breccias. With the exception of a very small volume produced by partial melting following impact (e.g., basaltic rocks preserved in plutonic facies at Sudbury and the Bushveld, and suevites at numerous localities) terrestrial volcanic rocks appear to be mainly the products of partial melting generated fundamentally by the decay of radioactive heat-generating nuclides.

In this respect the Earth contrasts with some other terrestrial planets and satellites. On the Moon, volcanism ended about 3 Ga ago, and much, if not all, of lunar volcanism was related to impacts about 4 Ga ago or earlier. By 3 Ga ago, radioactive heat generation within the Moon seems to have declined to a rate sufficiently low to have been entirely removed through the surface by conduction. This suggests to us that the Moon's heat-generating nuclides were concentrated close to the surface by that time.

On Mars, earlier volcanism appears to have been impact-dominated. However, the spectacular later volcanism of the Tharsis area and some older similar features more likely resulted from partial melting through radioactive decay of heat-generating nuclides. Martian volcanism seems to have ceased, but there is some uncertainty as to exactly how long ago this happened. We do not yet know about volcanism on Venus, but extremely violent volcanic activity is in progress on Io (Morabito *et al.*, 1979). This volcanism, perhaps unique in the solar system, appears to be the result of tidal forces (Peale *et al.*, 1979). Tidal forces do not appear to be major generators of volcanic heat elsewhere in the solar system, although tidal influences triggering eruptions have been recognized on the Earth (e.g., Mauk and Johnston, 1973).

SECULAR VARIATION OF TERRESTRIAL VOLCANISM

This short review deals only with volcanism, but plutonic igneous rocks are associated with all volcanic rocks, and most plutonic rocks exposed or emplaced at high crustal levels at one time underlay volcanic rocks. In a few, probably exceptional, areas shallow intrusives do not appear to be linked to volcanic rocks. Examples exist in the young, high-level granites of the Himalayas (Gansser, 1964) where the absence of volcanic superstructures may be due to intrusion in a dominantly compressional environment, or to rapid and effective erosion following uplift. This contrasts with conditions on the Tibetan plateau to the north, where compression is now less dominant and young volcanism has been widespread.

Estimates of the variation of heat generation in the Earth through radioactive decay with time are shown in Figure 1. Small additions through such processes as tidal dissipation are significant through all of geologic time, and much larger contributions to heat generation were made before 4 Ga by core formation and impact. Like Turcotte and Burke (1978), we assume that heat escapes from the Earth roughly as soon as it is generated, and generally within 0.5 Ga.

Volcanism is, and apparently always, has been, one of the dominant processes by which heat is removed from the Earth's interior. At present, heat leaves the Earth in three main ways: by conduction, by the eruption and rapid cooling of igneous rocks, and by the longer-term process of the cooling of ocean floor as it ages, subsides, and moves across the Earth's surface. We have shown elsewhere (Burke and Kidd, 1978) that because some of the ancient continental crust is and was of normal thickness and its base did not suffer widespread melting, the continental conductive thermal gradient about 2.5 Ga. ago in the lower crust was not significantly greater than it is now. Since Figure 1 indicates that two or three times as much heat was being generated at that time, this greater terrestrial heat must have been removed by the other two processes: igneous rock emplacement and ocean-floor aging. Ocean-floor aging is linked to divergent plate boundaries; most other igneous activity today also occurs at plate boundaries.

We and our colleagues (Burke and Dewey, 1972; Dewey and Burke, 1973; Burke *et al.*, 1976; Burke *et al.*, 1977) have discussed at length elsewhere why we consider most igneous activity to have been plate-boundary related throughout recorded geologic history (about the last 3.8 Ga). Others have interpreted the early lithosphere as not broken into rigid plates and consequently most tectonic and igneous activity as unrelated to plate margins. It is unnecessary to repeat the arguments for and against these interpretations. Let it suffice to say that the rocks and structures formed in early times so closely resemble later ones, that any radically different process operating then must have been capable of simulating the results of present plate tectonics. It is mainly for this reason that we prefer to regard the ancient world as broken into plates. There are two minor but significant differences between early and present-day plate tectonics. First, the size of suture-bounded areas in Archean terranes (notably the Superior Province) is generally smaller than in later terranes. This is consistent with the idea that greater lengths of plate boundary and/or faster moving plates were needed to dissipate the extra Archean heat (Burke and Kidd, 1978). Secondly, Archean terranes contain most known examples of a unique class of volcanic rocks, the ultramafic komatiites, which form a small proportion of Archean basaltic piles. Archean komatiites are presumably related to the greater heat generation of the early Earth, and their restricted occurrence has been used by various workers as a datum point in analyzing the thermal history of the Earth. Clearly, this is qualitatively

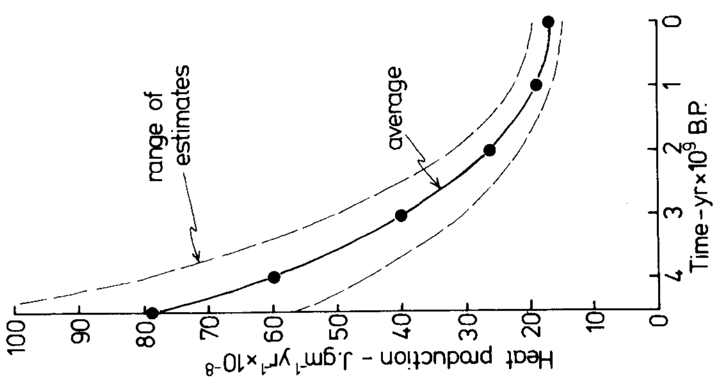

Figure 1. Heat production in the Earth from decay of radioactive isotopes of U, Th, and K through geological time (after Lee, 1967).

correct (the Earth was hotter), but we know too little about the details of the origin, environment, and mechanism of eruption of the Archean komatiites to make quantitative inferences about the significance of these peculiar rocks. In summary, we conclude from the composition, distribution, and structure of volcanic rocks occurring among the oldest of terrestrial rocks that most volcanic activity from 3.8 Ga on was, as now, related to plate margins.

VOLCANISM AT PLATE MARGINS: DIVERGENT MARGINS

There are three types of plate boundaries (Wilson, 1965) and it is appropriate to consider volcanic activity associated with each of them. Tuzo Wilson has long advocated the integration of solid-earth sciences, pointing out that geology, geophysics, and geochemistry are not realistically separable, and are strongest when results from all fields are considered together. There is no better example of this integration than the study of divergent plate-margin volcanism (which takes place at oceanic spreading ridges, and except in anomalous places like Iceland and the Afar, occurs two or more kilometres below sea level). Geophysical methods have dominated the study of oceanic spreading ridge volcanism and have been complemented by geochemical study of dredged pillow-lavas and limited submersible reconnaissance. The realization that ophiolite sequences in mountain belts represent small samples of ocean floor and preserve material produced at divergent plate boundaries has permitted integrated studies of the type favoured by Wilson, which have done much to reveal the essential features of divergent plate-boundary magmatism.

Figure 2 shows the results of one study of this kind (based on Dewey and Kidd, 1977). Basalt rising from partially melted mantle occupies a magma chamber roughly triangular in cross-section; volcanic material is erupted from this chamber to form the pillow lavas of the ocean floor,the underlying sheeted dykes, and the cumulate and non-cumulate plutonic rocks that overlie the depleted mantle.

The recognition of discrete major volcanoes within the axial valley of the FAMOUS area (Ballard and van Andel, 1977; Ramberg and van Andel, 1977) and across-strike compositional variations in basalt (Bryan and Moore, 1977) has led to interpretations of slowly spreading boundaries having along strike diversity and episodic structural development. This kind of interpretation is supported by near-bottom magnetic anomaly studies (e.g., Macdonald, 1977), in contrast to earlier, continuously evolving models, which leaned heavily on magnetic anomaly patterns mapped at or above the sea surface. The small-scale topographic and magnetic structures occurring at oblique angles to regional spreading directions (e.g., Macdonald and Holcombe, 1978) are typical of the kind of complexity being recognized in these detailed studies. The study of small variations in basalt composition, particularly in trace-element distributions (White and Bryan, 1977), has led to the realization that mid-ocean ridge basalts cannot be interpreted as simple products of either fractional crystallization or partial melting, but that a complex interaction of these processes, complicated by episodic magma injection into evolving magma chambers (O'Hara, 1977), is more likely to have taken place.

The differences between fast-spreading ridges (with no axial rift) and slow-spreading ridges (with rifts) have been illuminated by seismic refraction studies that show much stronger evidence of active magma chambers at fast-spreading ridges

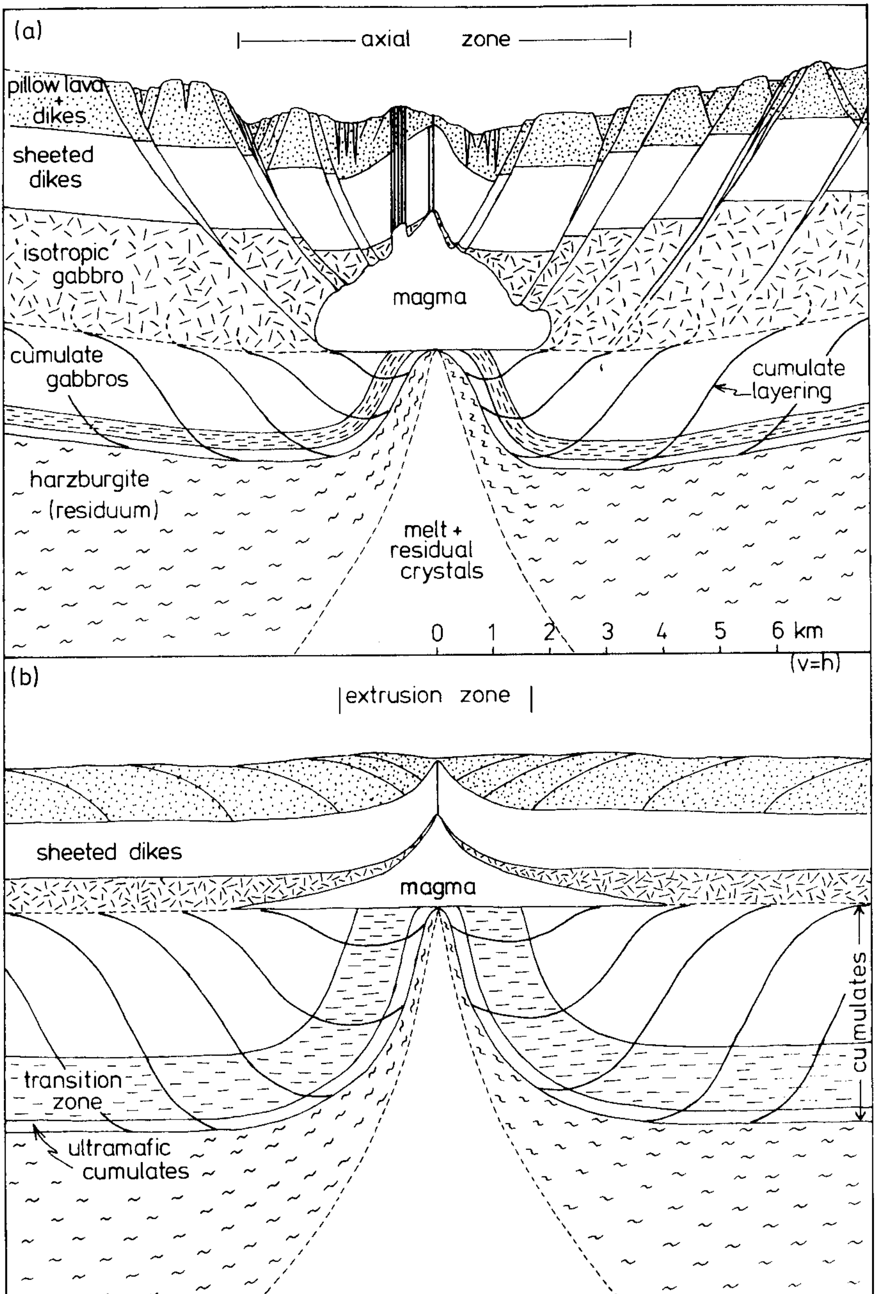

Figure 2. Cross-sections of oceanic spreading ridges (after Dewey and Kidd, 1977). (a) Rifted, slow-spreading ridge. (b) Non-rifted, fast-spreading rise crest.

than at slowly spreading riges (Orcutt *et al.*, 1975; Fowler, 1977). It has even been suggested that magma bodies may only be episodically present (Tapponnier and Francheteau, 1978) at slowly spreading ridges, but the geochemical data do not support this interpretation (Walker *et al.*, 1980). Thermal calculations (Sleep, 1975) suggesting episodic magma chambers along slowly spreading ridges are therefore unlikely to be correct. Clearly, there is some minimum spreading rate below which the cooling effect of circulating seawater will overwhelm the heat supplied by new magma, but this does not seem to have happened along most of the present ridge system.

The hot-spot (i.e., non-plate margin-type) volcanism that occurs in places like the Afar, Iceland, and the Azores will be considered in a later section because we interpret it not so much as an anomalous type of divergent plate-boundary volcanism but as a normal part of the wide spectrum of hot-spot volcanism. Divergent plate boundaries have developed across the sites of these hot-spots.

All but a tiny proportion of oceanic crust has been subducted- that is, permanently removed from the Earth's surface at least in any recognizably original form. Of the tiny sample that has escaped this fate, much is badly shredded and dismembered, particularly the material preserved in steeply-inclined zones and /or at deeper structural levels, even in Mesozoic and Tertiary orogenic belts. The general observation that recognizable ophiolite complexes become scarcer in older orogenic belts is explained by the greater uplift and erosion that have generally occurred there, compared with younger belts. Other reasons for their reported scarcity may include the past unfamiliarity of workers in older belts with the utility of the ophiolite concept, the possibility that major continental collision and suturing was generally more effective and intense further back in time, and the effect of the smaller length of older orogenic belts remaining exposed or preserved compared with younger ones. Well-described ophiolite complexes of Paleozoic age are known from the Appalachians and Caledonides (Bird *et al.*, 1971, 1978; Dewey and Bird, 1971; Church and Stevens, 1971; Sturt *et al.*, 1979), and less detailed descriptions of some of the obviously widespread Paleozoic complexes in the Urals and central Asian orogenic belts are available (for example Abdulin *et al.*, 1974, Makarychev and Shtreys, 1973).

Definite examples of pre-Paleozoic ophiolite complexes have been identified only in Pan-African orogenic belts in Morocco (LeBlanc, 1976) and Saudi Arabia (reported in Brown, 1978), and in the older Baikal orogenic belt in the U.S.S.R. (Klitin and Pavlova, 1974). Many other dismembered pieces surely remain to be identified in Proterozoic orogenic belts, since the well-studied belts, for example the Labrador-Cape Smith-Nelson (Wilson, 1968b) and the Coronation orogenic belts (Hoffman, 1980), so clearly developed through rifting and later collision (Wilson cycles); dated dykes reveal that in both cases rifting began about 2.15 Ga ago. The suggestion (Burke *et al.*, 1976) that oceanic crustal samples (dismembered ophiolite complexes) should exist in Archean greenstone belts has not, to our knowledge, been confirmed. Because there is an extensive greenstone-belt terrane (the Birrimian of West Africa) of similar age to the Coronation orogen, it seems to us very likely that dismembered ophiolites will eventually be recognized in Archean Greenstone belts. Since the Birrimian greestones were formed at the same time that ocean opening and closing (which must have involved sea-floor spreading and subduction) is recorded in the Coronation and other orogens, samples of the oceanic crust of that time may be preserved in the Birrimian terrane. Since this terrane does not differ in any significant way from older Archean greenstone terranes, the inference that oceanic crust may be preserved in Archean terranes seems to us unexceptionable. Extensive areas of mafic volcanics of tholeiitic compositions appropriate to the ocean floor exist in the Archean greenstone belts, but equally widespread plutonic equivalents are generally lacking. Moores (1973) suggested that older Pre-cambrian oceanic crust contained more anorthosite than younger material; this has yet to be verified. It is possible that the extensive tholeiitic submarine lavas of the greenstone belts include, besides lava generated as ocean floor and island arcs, large thicknesses generated by intraplate flood-basalt type magmatism; this is discussed below in the section on intraplate volcanism.

VOLCANISM AT PLATE MARGINS: TRANSFORM MARGINS

Very much less volcanism occurs at transform boundaries than at convergent and divergent plate boundaries and all, or nearly all, of what does occur there is associated with local extensional areas, commonly termed "pull-aparts" "Leaky transforms" are most probably the same features, less well defined because they are submarine. The young alkalic basalts dredged along the St. Paul and Romanche fracture zones are the only rocks presently known that are likely to have been erupted on oceanic transform/fracture zones away from the places where spreading ridge axes abut such zones. Even in these two cases, the tectonic details of their occurrence and the local abundance of the volcanics (or lack of it) are poorly known. It is also hard to prove that these volcanics are not related to areas of "hot-spot" activity, with relatively little associated volcanism, like the Jos Plateau and Air regions of the African plate. These areas are clearly identifiable since they are not submarine, lie within a plate, and are obviously associated with a structurally and topographically defined uplift. The fact that there is an uplift at St. Paul's Rocks perhaps favours the idea that these volcanics are "hot-spot"-related rather than related to secondary extension across the transform/fracture zone.

Pull-apart basins along large strike-slip faults on land (e.g., the Salton Sea, the Dead Sea rift, near the western end of the Altyntagh Fault, and small basins along the North Anatolian fault) reveal that such pull-aparts are not common, that they are usually small relative to the extent of the transform system along which they occur, and that the volume of volcanics directly associated with the pull-apart is also rather minor. It may be that larger volumes of magma occur at depth and that the surface expression is not representative of the amount of magmatism in these pull-aparts; the geothermal activity in the Salton Sea area may be evidence of this.

It has been proposed that other volcanic rocks occurring in some places in the general region of large continental transform fault systems (e.g., the young Arabian basalts, the Hsing-An basalts of China, and some of the young volcanics in the vicinity of the San Andreas Fault) are in a less direct way related to the transform-zone tectonics. Since present evidence for a strong connection is unconvincing, we treat such volcanics under intraplate volcanism.

Perhaps because of the small volume of transform-related volcanics, and their susceptibility to later tectonic disruption, no well-documented examples are known from older, inactive transform zones. For example, well-studied pull-apart basins formed on an extensive, large-displacement Carboniferous strike-slip fault zone (probably an old transform system) through the Canadian Maritime Provinces (Belt, 1969) do not contain any known examples of contemporaneous volcanics. The exposed portion of the possibly correlative (Wilson, 1962) Great Glen Fault system does not show any obvious pull-apart structures. A much older example (around 1.8 Ga) of a preserved piece of large-displacement strike-slip fault, the McDonald Fault, also has no known volcanics associated with its movement, despite having very thick accumulations of coarse clastic sediments (P.F. Hoffman, pers. commun.) which probably were preserved by pull-apart tectonics.

VOLCANISM AT PLATE MARGINS: CONVERGENT MARGINS

In present-day arc systems andesitic volcanism dominates, although overall about 20% is basaltic (Ewart, 1976). The volcanic zone always lies above a subducting slab of oceanic lithosphere, generally where the latter is between 100 and 150 km deep. It is therefore inferred that the descending lithosphere is involved in production of arc magmas, although exactly how and where these magmas are produced is unresolved. While great variability exists in the detailed features of volcanic arcs, the most prominent contrast in volcanism is that silicic, large-volume ignimbrites with high Na and K content are concentrated in, if not confined to, areas underlain by continental-type lithosphere, even though, as in New Zealand and southern Alaska, this may consist of (geologically) recently accreted material. Some involvement of the lithosphere underlying these Andean-type volcanic arcs in the generation of their magmas seems likely.

Arcs built on oceanic crust tend to contain proportionately more mafic and less silicic volcanics, although precise estimates are difficult to make since most of these arcs are submerged, and preservation is biased against pyroclastic and clastic materials. Burke *et al.* (1976) pointed out that the collision and accretion of this kind of arc, together with remnants of the intervening marginal basin floors and fill, will produce greenstone-granodiorite belt geology like that of the Archean Superior Province and similar terranes elsewhere. These include at least one that is of post-Archean age (the Birrimian of West Africa - 1.8 Ga), and thus contemporary with orogenic belts clearly formed from the operation of the Wilson cycle. The present southwestern Pacific contains areas that we envisage as close analogues to those that formed the greenstone terranes. Andesites in present arcs do not have any significant geochemical differences from andesites in Archean greenstone belts. As the overwhelming bulk of andesites is made at convergent margins today, possibly in response to the liberation of water from hydrated phases in the subducted slab at significant depths in the mantle, we see no good reason to suppose that they were made in any grossly different way in the past. Greenstone-type terranes are not unique to the Archean. We pointed out above (see also Burke and Dewey, 1972) the example of the Birrimian, and smaller analogues can be found in Paleozoic and Mesozoic orogenic belts (Burke *et al.*, 1976). More extensive analogues probably exist, awaiting proper description, in the Paleozoic orogenic area of Central Asia (Burke *et al.*, 1978a). The area of older orogens preserved intact from the tectonic effects of younger orogenies decreases with age. It is entirely possible that the sample we have of Archean

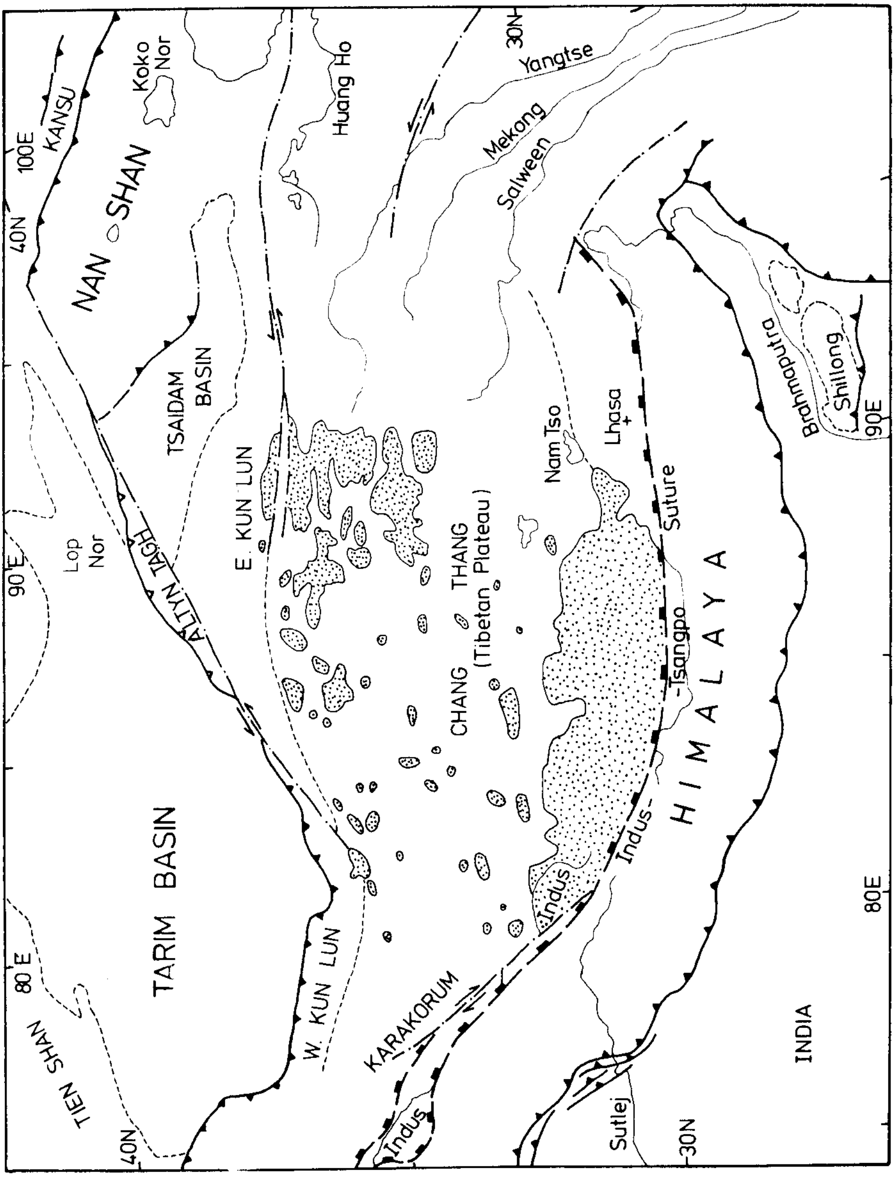

Figure 3. Tectonic sketch map of the Tibetan Plateau and surrounding regions, emphasizing the Neogene-Recent volcanic rocks (stippled). Lines with black triangles – active thrust boundaries; line with open triangles – inactive thrust boundary; dot-dash lines – active transcurrent faults.

orogenic terranes is not representative of their original proportions, due to the accidents of the siting of later rifts and, hence, collisions (Wilson cycles). Assuming, however, that the greater abundance of greenstone belts in the Archean reflects a real secular tectonic change, then it is reasonable to suppose that it is connected with the Earth's greater heat production in the past, which, as suggested above, resulted in faster plate motion and greater length of plate boundary. Such properties would most probably have led to more arc generation in a given time, thus accounting for the greater abundance of greenstone-type terranes in the past without excluding them from post-Archean terranes.

Plate convergence eventually leads to continental collisions. These, in recent examples (Fig. 3), give rise to volcanics very similar to those found in Andean arcs (Burke *et al.,* 1974; Kidd, 1975; Sengör and Kidd, 1979). Older examples of such calc-alkaline, K-rich volcanics and/or their subjacent post-kinematic granites are well known in collisional orogens up to about 2 Ga, e.g. the granites and other plutons of the Appalachian-Caledonian belt (Dewey and Kidd, 1974); the post-kinematic granites and local rhyolites of the Pan African; the rhyolites of the St. Francois Mountains (Bickford and Mose, 1975), related to the Elsonian orogeny which we suggest is collision-induced; and the volcanics of the Bear Province (Hoffman *et al.,* in prep.), related to collision about 1.8 Ga ago at the end of the Wilson cycle on the site of the Coronation orogen. Pieces of continental crust older than 1.8 Ga are either too small or too deeply uplifted and eroded to distinguish collisional from arc-related magmatic products with any confidence, but we see no reason to suppose their absence.

INTRAPLATE TYPE VOLCANISM: HOT SPOTS AND FLOOD BASALTS

Young volcanism not related to plate boundaries is widespread (Burke and Kidd, 1975). Despite the great variety in its expression, we feel that there are sufficient common elements among different instances of non-plate margin volcanism that it is inappropriate not to treat them in a single category. Many areas of active intraplate volcanism are well-exposed in Africa and have been well studied; the association in them of volcanics and a structurally and topographically high area is well established (Burke and Whiteman, 1973; Thiessen *et al.,* 1979). The volcanics of Dakar, near sea level, are not an exception, since subsurface data (Spengler and Deteil, 1966) reveal an underlying youthful structural elevation. There is a complete spectrum of intraplate volcanic areas in Africa, from uplifts without any volcanism (e.g., Fouta Djallon), through minor volcanism of alkaline type (e.g. Air), to more abundant alkaline volcanism (e.g., Tibesti), to areas of voluminous tholeiitic flood basalts together with comparatively minor alkaline volcanics (e.g., Ethiopia). In all cases a structural uplift is associated with the volcanic area; the size of this uplift varies, although most tend to be 100 to 200 km across (Burke and Whiteman, 1973). There seems to be a tendency for the areas with larger volumes of volcanics to have larger diameters of uplifts, although it becomes possible to resolve subsidiary uplifts within the larger ones (e.g., Ahaggar; Black and Girod, 1970). Thus it is not wholly clear whether the larger uplift structures are merely groups of smaller ones, or whether the smaller diameter uplifts in them are secondary to the larger, but generally lower amplitude uplifts.

This spectrum of intraplate volcanism can be seen less well displayed on other continents, but it is more significant that it is also developed in the oceans, and that the alkaline and tholeiitic volcanics in oceanic hot spots are essentially indistinguishable from those in continental hot spots. Again, the African plate provides many of the best examples. Oceanic intraplate volcanic areas also show a variation in volume from the largest, like Hawaii, with abundant tholeiite and minor alkaline volcanics, to relatively small edifices, like Ascension, that are mainly alkaline volcanics. Intraplate volcanic areas of very small volumes, like some of those on the African continent, are harder to detect in the oceans, and uplifts without accompanying volcanism harder still. Nevertheless, careful study has detected them in one area (Menard, 1973).

Because alkaline magmas are erupted in places within present island arcs and collisional orogens, it is not possible to detect "intraplate" type or "hot-spot" type activity unambiguously within such zones of convergence even though it may well occur. However, it is possible to detect such volcanism along divergent plate boundaries because of the alkaline character of some of the magmas, the excess volume of magma, and the associated structural uplift. The occurrence of "hot-spot" type volcanism at discrete and long-lasting sites along divergent plate boundaries is, we suggest, one of the most significant properties of their distribution, and helps considerably in winnowing the many hypotheses put forward for their origin. In particular, since the lithosphere is thin to virtually non-existent at spreading ridge crests and is created progressively away from them, it is unlikely that either the crack propagation hypotheses of Turcotte and Oxburgh (1973) and Oxburgh and Turcotte (1974), or the dense anchor-asperity hypothesis of Shaw and Jackson (1973) is correct. An "active mantle" hypothesis for hot-spot origin, such as proposed by Wilson (1963), is more satisfactory.

A similar spectrum of size and volume of magmas can be seen in those hot spots located on divergent plate boundaries. The central and north Atlantic contains the best examples. These range from the anomalously elevated area at 45°N on the ridge, where there seems to be relatively little excess volcanism, through the Azores, with mostly alkaline volcanism constructing small islands above sea level, to the extreme of Iceland, with its voluminous excess tholeiitic volcanism and, in relative terms, minor alkaline magmatism. Anomalous (with respect to spreading-ridge basalt) geochemical signatures, particularly $^{87}Sr/^{86}Sr$ (White *et al.*, 1976) correlate exactly with discrete, anomalously elevated ridge crest areas in Iceland, 45°N, the Azores, and near 34°N (Colorado Seamount). The distinctive geochemistry of the "excess" magmas argues strongly for a separate (deeper) source for them (Schilling, 1973) compared with normal spreading-ridge basalts. It is because the latter are usually produced in a fairly constant amount through a wide range of spreading rates that the "excess" character of the hot-spot magmatism along ridge axes can be easily detected.

The connection between flood basalts and the largest hot spots is clearly shown by Iceland. The island itself consists of flood basalts, and the hot-spot tracks that lead away from Iceland go to large areas of flood basalts in East Greenland and the northern British Isles (Fig. 4). These basalts were erupted during the initial rifting that lead to successful sea-floor spreading in the northern Atlantic beginning about 60

Ma ago. The relics of associated central alkaline volcanoes of that age are well known from Scotland. A younger but similar situation is seen in the Afar (Fig. 3), where the Ethiopian Traps erupted before and up to the opening of the Red Sea and Gulf of Aden. If the Pacific plate were not moving so rapidly with respect to the source of the Hawaiian magmas, the accumulation of igneous material at present rates of production would clearly rival Iceland, and although the Hawaiian Emperor hot-spot trace (Fig. 4) does not lead back to a site of rifting and a large flood basalt pile, it is

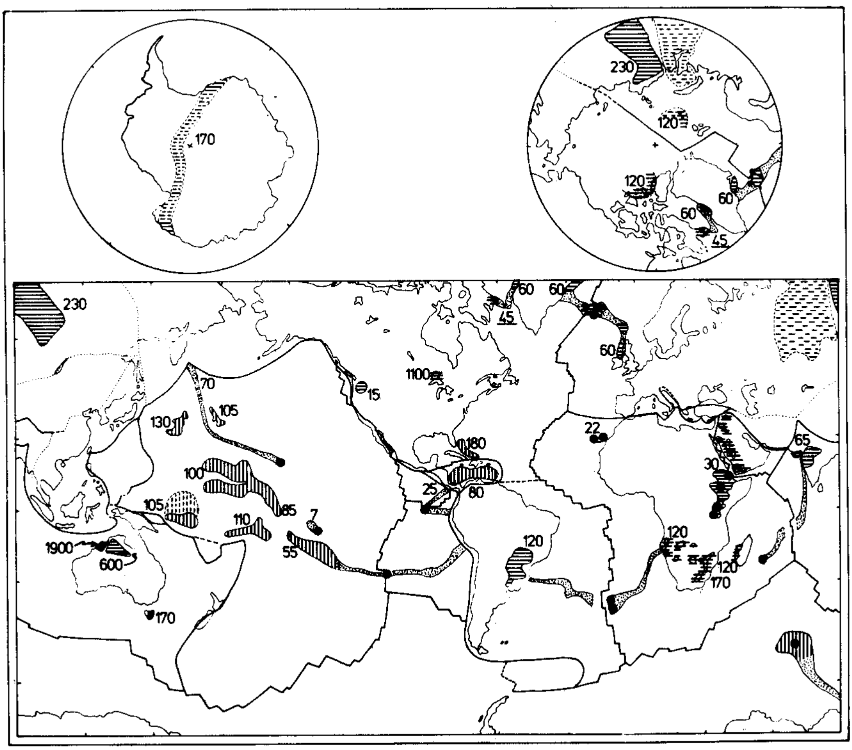

Figure 4. World map with plate boundaries showing larger active hot spots (black circles); their tracks, i.e., volcanic accumulations left behind hot spots on moving plates (stipple); large areas of flood basalts and associated sills (horizontal ruling, dashed where basalts mostly subsurface); submarine equivalent of flood basalts, mostly sill complexes (vertical ruling – dashed where tentative). Approximate ages of flood basalts and sills given in millions of years, as are the ages of the oldest portions of some hot-spot tracks. Number underlined is age of youngest part of Davis Strait hot-spot track.

appropriately grouped with other flood basalt-producing objects. Several other large hot spots do have tracks leading back to rifting sites and accumulations of flood basalts (Fig. 4), in particular Tristan/Gough to the Kaokoveld and Parana basalts, which were erupted just before and up to the opening of the South Atlantic 120 Ma ago; and Reunion to the Deccan Traps, which were erupted about 65 Ma ago just before rifting in the Gulf of Khambat and removal of the Seychelles from India (McKenzie and Sclater, 1971). The Galapagos hot spot, although its tracks do not lead back to preserved flood basalts, is sited on a spreading ridge that started about 25 Ga ago by rifting across older oceanic crust generated at the East Pacific Rise (Hey, 1977).It may not be a coincidence that the Galapagos hot spot, as shown by its area and the volume of magmatic products in its tracks, is a relatively large one, like others that have been listed as associated with flood basalt production and initial ocean opening. Ocean opening in the Labrador Sea-Baffin Bay was accompanied by the flood basalt volcanism (about 60 Ma) that is now preserved on Disko Island, and Cape Dyer of Baffin Island. The hot spot that produced this volcanism made the shallow sill to Davis Strait as a track, but is now obviously extinct. Perhaps it is also not a coincidence that spreading ceased in the Labrador Sea-Baffin Bay at the same time or shortly after the hot spot died. This case illustrates the point emphasized by Vogt (1972), that the volumes of magma generated in hot-spot site's vary with time, although, unlike him, we do not think there is strong evidence for synchroneity in this variation among many hot spots. Thus, the amount of magma produced by the Hawaiian hot spot, judged by the volume of the track, was very small at the time of and shortly after the bend formed in the Hawaiian-Emperor chain. Its volume may have been no more impressive at that time than one of the smaller present ocean island hot spots, like St. Helena. The point we wish to make here is that voluminous flood basalt-producing hot-spots are the same kind of object as the smaller ones, and that one can change into the other, and back again, with time. They may also die out, in terms of their volcanic expression, temporarily or permanently. They vary a great deal in the length of time during which large quantities of tholeiitic magma are produced, from the short burst of the Columbia River basalts (Baksi and Watkins, 1973) and Deccan Traps (Wellman and McElhinny, 1970) to the more extended histories of Iceland and Hawaii.

Large flood tholeiite events in the oceans seem, in some instances, to produce huge sill complexes, probably because of the limited abilities of even mafic lava to travel underwater before chilling. Such sill complexes (Fig. 4) have been identified underlying large portions of the Caribbean (Burke *et al.*, 1978b) and the submarine plateaus of the western Pacific (Winterer, 1976). The Mid-Pacific Mountains, one of the latter, may perhaps be traced to the hot spots of Easter Island and/or Pitcairn Island through the Tuamotu-Line Islands track. Sill complexes are, of course, also important components of may continental flood basalt events, particularly the early early Jurassic Karoo and Ferrar dolerites of South Africa and the Antarctic, and the mid-Cretaceous Isachsen diabase of the Canadian Arctic (Fig. 4).

It is of note that all major flood basalt events (where at least some of the extensive lavas and/or sills are still preserved) were connected with extensive rifting and, in most cases, with successful opening of an ocean. Two large and well known ones not associated with successful ocean opening are the Columbia River basalts and the Siberian Traps.

Well-preserved remnants of older flood basalt and/or sill complexes are seen back to 2.15 Ga. Most remnants are found within old rifts and aulacogens because the accidents of erosion through geological time have claimed any more extensive basalts lying relatively higher outside them. The most prominent flood basalt remnants of Paleozoic or older age lying outside old rifts and of any significant extent are the 600 Ma-old Antrim basalts of N.W. Australia, the 1100 Ma-old Keweenawan lavas and sills north of Lake Superior, and the 1900 Ma-old Kimberly Plateau basalts and sills, also in N.W. Australia. Within old rifts there are many more examples; prominent ones in North America are the rifts of about 1100 Ma, which include the Coppermine River (N.W. Territories), part of which may be outside the rift defined by Burke and Dewey (1973), Seal Lake (Labrador), Gardar (S. Greenland), Keweenawan and its extension in the mid-continent rift and gravity high, and various aulacogens along the Cordilleran margin of the North American craton, including one exposed in part in the Grand Canyon. Another prominent rifting episode is that shown by the extensive tholeiitic sill complex (about 2.15 Ga old) that invades what we interpret as the initial rifting facies clastics and volcanics (arkoses, sandstones and basalts, etc. of the Seward and part of Attikamagen Formations) preserved in the fold and thrust belt of the Labrador Trough (Baragar, 1967).

Associated with this 2.15 Ga rifting and ocean opening event is an extensive dyke swarm (Fahrig and Wanless, 1963; Stevenson, 1968) that runs (in Archaen basement) subparallel with the northern end of the Labrador Trough and then turns to run obliquely along the Cape Smith belt, the continuation of the Labrador Trough in northern Ungava. This dyke swarm is the last relict of a flood basalt event; a very similar although smaller example is seen close to and subparallel with the western margin of the Appalachians in northern Newfoundland (Williams, 1967), where it (and nearby small relicts of flood basalts) was associated with the early Cambrian or slightly older opening of the ocean that Tuzo Wilson called the Proto-Atlantic (1966), now termed the Appalachian Ocean or Iapetus. Dyke swarms as relicts of flood basalt and rifting events are common. The MacKenzie dykes, which extend a great distance NNW across the western part of the Canadian shield are of the same age as the Keweenawan rifting and flood basalt event. There are no well-preserved segments of continental rifted margins older than 2.15 Ga, the opening age of the Labrador Trough and Coronation oceans. However, there are examples of extensive tholeiitic dyke swarms, from which we infer that rifting events like those recorded in younger rocks took place. The Ameralik dykes in West Greenland (McGregor, 1973), which are at least 3.0 Ga and perhaps as much as 3.6 Ga old (Pankhurst *et al.*, 1973) are evidence of the oldest rifting event directly recorded. The nature of the older rocks they cut, containing calc-alkaline volcanics, is to us indirect evidence of subduction, sea-floor spreading and yet older rifting.

One feature of low-metamorphic grade Archean volcanic terranes is that they do not – with very minor exceptions which could be younger than Archean (Cooke and Moorhouse, 1969) – contain alkaline volcanic and plutonic rocks like those that have been emplaced at present hot-spot sites and are preserved sparingly in rocks up to about 2.5 Ga old. Judging by the largest present hot spots, perhaps most of them were large in the Archean and erupted huge quantities of flood basalt-type tholeiite. Lavas and sills generated in this way, if preserved from subduction, might be represented within the extensive basalts in greenstone belts. Alternatively, efficient subduction of Archean oceanic lithosphere may have removed essentially all the hot-spot material and may have preferentially preserved island arc edifices, which even today contain only rare occurrences of alkalic volcanics. Added to the small area of preserved Archean rocks, this small chance of preservation of alkalic volcanics may explain why they are so rare in such terranes.

FLUCTUATION IN VOLCANIC ACTIVITY?

An important question is whether, and if so by how much, the amount of volcanism on Earth has fluctuated with time. This question is fraught with difficulties. Older rocks are generally preserved in smaller proportions relative to younger ones, so that the occurrence of volcanic rocks per unit time could be expected to be less. Long ago, however, since heat generation was greater, volcanism may also gave been greater, and these effects may partly cancel. Because oceanic rocks are destroyed by subduction and obduction, the record is necessarily incomplete; generally only arc and continental rocks are preserved. In spite of these difficulties, some workers have discerned episodicity in igneous activity, especially in the Precambrian. The crude technique, popular twenty years ago, of plotting histograms of isotopic ages has fallen into disuse with the recognition of the complexity of the record. A particularly significant observation is that the proportions of continental area representative of a particular time interval and available for study are so small. For example, the Superior Province, which is the largest Archean area on Earth, representing about half the total area of Archean rocks not obscured by later events, amounts to only 1% of continental area. A more sophisticated approach considering the isotopic compositions of Nd, Sr, and Rb has been used by several authors (e.g., McCulloch and Wasserberg, 1978) to show that many Precambrian continental rocks became isolated from the main mantle resevoir during an interval of about 200 Ma ago roughly 2.7 to 2.5 Ga ago. This is a most interesting and unexpected result.

Turcotte and Burke (1978) used an indirect method to estimate volcanic fluctuation with time during the Phanerozoic. Realizing that sea level responds to the volume of the mid-ocean ridges, they inferred that the times when the continents were most flooded were times when the ridges were most active. By crudely calculating the proportions of heat escaping through conduction and ocean-floor aging, they were able to estimate that nearly twice as much heat was escaping the Earth through the cooling of aging ocean floor during the late Cretaceous episode of continental flooding as is escaping in this way now. In order to keep the Earth at roughly the same volume, they inferred that plate consumption also peaked at this time, which is consistent with the familiar high concentration of circum-Pacific batholithic emplacement during the Late Cretaceous and the Late Cretaceous concentration of emplacements of Tethyan ophiolites.

CONCLUSIONS

It has been impossible to cover all aspects of volcanism through time in such a short review, but it seems appropriate to point out that the history of volcanic activity on Earth as summarized here is best viewed as Tuzo Wilson (1968a) first proposed, in the context of cycles of ocean opening and closing. Not only can rift, plate-margin, and collisional volcanism be well accommodated within the framework of "Wilson Cycles" (Dewey and Burke, 1974), but so can the role of hot spot (intraplate type) volcanism, especially of the Hawaiian kind (Wilson, 1963).

REFERENCES

Abdulin, A.A., Bespalov, V.P., and Shelepova, T.N., 1974, Ophiolite belts of Kazakhstan, Doklady Akad. Nauk. SSSR., v. 218, p. 159-162 (20-22 in translation).

Baksi, A.K. and Watkins, N.D., 1973, Volcanic production rates: comparison of oceanic ridges, islands and the Columbia River basalts: Science, v. 180, p. 493-496.

Ballard, R.D. and van Andel, T.H., 1977, Morphology and tectonics of the inner rift valley at 36°50'N on the Mid-Atlantic Ridge: Geol. Soc. America Bull., v. 88, p. 507-530.

Baragar, W.R.A., 1967, Wakuach Lake Map area, Quebec Labrador (230): Geol. Survey Canada, Mem. 344.

Belt, E.S., 1969, Newfoundland Carboniferous stratigraphy and its relation to the Maritimes and Ireland: in Kay, M., ed., North Atlantic Geology and Continental Drift, Amer. Assoc. Petrol. Geol. Mem. 12., p, 734-753.

Bickford, M.E. and Mose, D.G., 1975, Geochronology of Precambrian rocks in the St. Francois Mountains, southeastern Missouri: Geol. Soc. America Spec. Paper 165, 48 p.

Bird, J.M., Dewey, J.F., and Kidd, W.S.F., 1971, Proto-Atlantic ocean crust and mantle: Appalachian/Caledonian ophiolites: Nature Phys. Sci., v. 231, p. 28-31.

_______________, 1978, The Mings Bight ophiolite complex, Newfoundland: Appalachian oceanic crust and mantle: Canadian Jour. Earth Sci., v. 15, p. 781-804.

Black, R., and Girod, M., 1970, Late Palaeozoic to recent igneous activity in West Africa and its relationship to basement structure: in African Magmatism and Tectonics: Clifford, T.N. and Gass, I.G., eds., Edinburgh, Oliver and Boyd, p. 185-210.

Brown, G.F., 1978, Arabian-Nubian shield discussed on the spot: Geotimes, v. 23, p. 24.

Bryan, W.B., and Moore, J.G., 1977, Compositional variations of young basalts in the Mid-Atlantic Ridge rift valley near 36°49'N: Geol. Soc. America Bull., v. 88, p. 556-570.

Burke K.C.A. and Dewey, J.F., 1972, Orogeny in Africa: in Dessauvagie T.F. and Whiteman, A.J., eds., African Geology Univ. Ibadan Press, p. 583-608.

_______________, 1973, Plume-generated triple junctions: key indicators in applying plate-tectonics to old rocks; Jour. Geol. v. 81, p. 406-433.

Burke, K.C.A., and Kidd, W.S.F., 1975, Earth, heat flow in: in McGraw-Hill Yearbook of Science and Technology, McGraw-Hill, New York, p. 165-169.

_______________, 1978, Were Archean continental geothermal gradients much steeper than those of today?: Nature, v. 272, p. 240-241.

Burke, K.C.A. and Whiteman, A.J., 1973, Uplift, rifting and the breakup of Africa: in Tarling, D.H. and Runcorn, S.K., eds., Implications of Continental Drift to the Earth Sciences, v. 2: Academic Press, London, p. 735-755.

Burke, K.C.A., Dewey, J.F. and Kidd, W.S.F., 1974, The Tibetan Plateau: its significance for tectonics and petrology: Geol. Soc. America Abstracts with Program 6, v. p. 1027-1028.

_______________, 1976, Dominance of horizontal movements, arc and microcontinental collisions during the later permobile regime: in Windley, B.F., ed., The Early History of the Earth: Wiley, London, p. 113-129.

_______________, 1977, World distribution of sutures – the sites of former oceans: Tectonophysics, v. 40, p. 69-99.

Burke, K.C.A., and Delano, L., Dewey, J.F., Edelstein, A., Kidd, W.S.F., Nelson, K.D., Sengör, A.M.C. and Stroup, J., 1978a, Rifts and Sutures of the World, Contract Rept.

NAS5-24094: Geophysics Branch ESA Division Goddard Space Flight Center, Greenbelt, MD, 238 p.

Burke, K., Fox, P.J., and Sengör A,M.C., 1978b, Buoyant ocean floor and the evolution of the Caribbean: Jour. Geophys. Res. v. 83, p. 3949-3954.

Church, W.R. and Stevens, R.K., 1971, Early Palaeozoic ophiolite complexes of the Newfoundland Appalachians as mantle-oceanic crust sequences: Jour. Geophys. Res., v. 76, p. 1460-1466.

Cooke, D.L. and Moorhouse, W.W., 1969, Timiskaming volcanism in the Kirkland Lake area, Ontario, Canada: Canadian Jour. Earth Sci., v. 6, p. 117-132.

Dewey, J.F. and Bird, J.M., 1971, Origin and emplacement of the ophiolite suite: Appalachian ophiolites in Newfoundland: Jour. Geophys. Res., v. 76, p. 3179-3206.

Dewey, J.F. and Burke, K.C.A., 1973, Tibetan, Variscan and Precambrian basement reactivation: products of continental collision: Jour. Geol., v. 81, p. 683-692.

____________, 1974, Hot spots and continental break-up: implications for collisional orogeny: Geology, v. 2, p. 57-60.

Dewey, J.F. and Kidd, W.S.F., 1974, Continental collisions in the Appalachian-Caledonian orogenic belt: variations related to complete and incomplete suturing: Geology, v. 2, p. 543-546.

____________, 1977, Geometry of plate accretion: Geol. Soc, Amer. Bull., v. 88, p. 960-968.

Ewart, A., 1976, Mineralogy and chemistry of modern orogenic lavas – some statistics and implications: Earth Planet. Sci. Letters, v. 31, p. 417-432.

Fahrig, W.F. and Wanless, R.K., 1963, Age and significance of diabase dyke-swarms of the Canadian shield: Nature, v. 200, p. 934-937.

Fowler, C.M.R., 1977, Crustal structure of the mid-Atlantic ridge crest at 37°N: Geophys. Jour. Royal Astron. Soc., v. 47, p. 459-491.

Gansser, A., 1964, The Geology of the Himalayas: New York, Wiley-Interscience, 289 p.

Hey, R., 1977, Tectonic evolution of the Cocos-Nazca spreading center: Geol. Soc. America Bull., v.88, p. 1404-1420.

Hoffman, P., 1980, Precambrian Wilson Cycle: in Strangway, D.W., ed., The Continental Crust of the Earth and Its Mineral Deposits: Geol. Assoc. Canada Spec. Paper 20.

Kidd, W.S.F., 1975, Widespread late Neogene and Quaternary calc-alkaline volcanism on the Tibetan Plateau: EOS, Trans. American Geophys. Union, v. 56, p. 453.

Klitin, K.A. and Pavlova, T.G., 1974, Ophiolite complex of the Baikal fold zone: Doklady Akad. Nauk SSR, v. 215, p. 413-416, (p. 33-36 in translation).

LeBlanc, M., 1976, Oceanic crust at Bou Azzer: Nature, v. 261, p. 34-35.

Lee, W.H.K., 1967, Thermal history of the Earth: Unpub. Ph.D. Thesis, University of California, Los Angeles.

Macdonald, K.C., 1977, Near-bottom magnetic anomalies, asymmetric spreading, oblique spreading, and tectonics of the Mid-Atlantic Ridge near 37°N: Geol. Soc. America Bull., v. 88, p. 541-555.

Macdonald, K.C. and Holcombe, T.L., 1978, Inversion of magnetic anomalies and sea-floor spreading in the Cayman Trough; Earth Planet. Sci. Letters, v. 40, p. 407-414.

McCulloch, M.T. and Wasserburg, G.T., 1978, Sm-Nd and Rb-Sr chronology of continental crust formation; Science, v. 200, p. 1003-1011.

McGregor, V.R., 1973, The early pre-Cambrian gneisses of the Godthaab district, West Greenland: Phil. Trans. Royal Soc. London, v. A 273, p. 343-358.

McKenzie, D. and Sclater, T.G., 1971, The evolution of the Indian Ocean since the late Cretaceous: Geophys. Jour. Royal Astron. Soc., v. 24, p. 437-528.

Makarychev, G.I. and Shtreys, N.A., 1973, Tectonic position of ophiolites of the southern Tien Shan., Doklady Akad. Nauk. SSSR, v. 210, p. 1164-1166 (P. 92-93 in translation).

Mauk, F.T. and Johnston, M.J.S., 1973, On the triggering of volcanic eruptions by Earth tides: Jour. Geophys. Res., v. 78, p. 3356-3362.

Menard, H.W., 1973, Epeirogeny and plate tectonics: EOS, Trans. American Geophys. Union, v. 54, p. 1244-1255.
Moores, E.M., 1973, Plate tectonic significance of Alpine peridotite types: in Tarling, D.H. and Runcorn, S.K., eds. Implications of Continental Drift to the Earth Sciences: v. 2: Academic Press, London, p. 963-975.
Morabito, L.A., Synnot, S.P., Kupferman, P.N. and Collins, S.A. 1979, Discovery of currently active extraterrestrial volcanism: Science, v. 204, p. 972.
O'Hara, M.J., 1977, Geochemical evolution during fractional crystallization of a periodically refilled magma chamber: Nature, v. 266, p. 503-507.
Orcutt, J., Kennett, B., Dorman, L. and Prothero, W., 1975, a low-velocity zone underlying a fast-spreading rise crest: Nature, v. 256, p. 475-476.
Oxburgh, E.R. and Turcotte, D.L., 1974, Membrane tectonics and the east African rift: Earth. Planet. Sci. Letters, v. 22, p. 133-140.
Pankhurst, R.J., Moorbath, S. and McGregor, V.R., 1973, Late event in the geological evolution of the Godthaab district, West Greenland: Nature Phys. Sci., v. 243, p. 24-26.
Peale, S.J., Cassen, P. and Reynolds, R.T., 1979, Melting of Io by tidal dissipation: Science, v. 203, p. 892-894.
Ramberg, I.B. and van Andel, T.H., 1977, Morphology and tectonic evolution of the rift valley at 36°30′N, Mid-Atlantic Ridge: Geol. Soc. America Bull., v. 88, p. 577-586.
Schilling, J.G., 1973, Iceland mantle plume: Nature, v. 246, p. 141-143.
Sengör, A.M.C. and Kidd, W.S.F., 1979, Post-collisional tectonics of the Turkish-Iranian plateau and a comparison with Tibet: Tectonophysics, v. 55, p. 361-376.
Shaw, H.R. and Jackson, E.D., 1973, Linear island chains in the Pacific: result of thermal plumes or gravitational anchors?: Jour. Geophys. Res., v. 78, p. 8634-8652.
Sleep, N.H., 1975, Formation of oceanic crust: some thermal constraints: Jour. Geophys. Res., v. 80, p. 4037-4042.
Spengler, A. de E. and Delteil, J.R., 1966, Le bassin secondaire-tertiare de Cote d'Ivoire: in Reyre, Du, ed., Bassins sedimentaires du littoral africain 1e partie: Assoc. Serv. Geol. Afr. Paris, p. 99-113.
Stevenson, I.M., 1968, A geological reconnaissance of Leaf River map area, New Quebec and Northwest Territories: Geol. Survey Canada Mem. 356.
Sturt, B.A., Thon, A. and Furnes, H., 1979, The Karmoy ophiolite, southwest Norway: Geology, v. 7, p. 316-320.
Tapponnier, P. and Francheteau, J., 1978, Necking of the lithosphere and the mechanics of slowly accreting plate boundaries: Jour. Geophys. Res., v. 83, p. 3955-3970.
Thiessen, R., Burke, K. and Kidd, W., 1979, African hotspots and their relation to the underlying mantle: Geology, v. 7, p. 263-266.
Turcotte, D.L. and Burke, K.C.A., 1978, Global sea-level changes and the thermal structure of the Earth: Earth Planet Sci. Letters, v. 41, p. 341-346.
Turcotte, D.L. and Oxburgh, E.R., 1973, Mid-plate tectonics: Nature, v. 244, p. 337-339.
Vogt, P.R., 1972, Evidence for global synchronism in mantle plume convection and possible significance for geology: Nature, v. 240, p. 338-342.
Walker, D., Shibata, T. and DeLong, S.E., 1980, Abyssal tholeiites from the Oceanographer Fracture Zone: Contrib. Mineral. Petrol., in press.
Wellman, P. and McElhinny, M.W., 1970, K-Ar age of the Deccan Traps, India: Nature, v. 227, p. 595-596.
White, W.M. and Bryan, W.B., 1977, Sr-isotope, K, Rb, Cs, Sr, Ba and rare-earth geochemistry of basalts from the FAMOUS area: Geol. Soc. America Bull., v. 88, p. 571-576.
White, W.M., Schilling, J.G., and Hart, S.R., 1976, Evidence for the Azores mantle plume from strontium isotope geochemistry of the central North Atlantic: Nature, v. 263, p. 659-663.

Williams, H., 1967, Geological Map of Newfoundland 1:1m: Geol. Survey Canada Map 1231A.
Wilson, J.T., 1962, Cabot Fault, an Appalachian equivalent of the San Andreas and Great Glen Faults and some implications for continental displacement: Nature, v. 195, p. 135-138.
________________, 1963, A possible origin of the Hawaiian Islands : Canadian Jour. Phys., v. 41, p. 863-870.
________________, 1965, A new class of faults and their bearing on continental drift: Nature, v. 207, p. 343-348.
________________, 1966, Did the Atlantic close and then reopen?: Nature, v. 211, p. 676-681.
________________, 1968a, Static or mobile Earth: the current scientific revolution: Proc. Amer. Phil. Soc., v. 112, p. 309-320.
________________, 1968b, Comparison of the Hudson Bay arc with some other features: in Beals, C.S., and Shemstone, D.A., eds., Science, History and Hudson Bay: Dept. Energy, Mines, and Resources, Ottawa.
Winterer, E.L., 1976, Anomalies in the tectonic evolution of the Pacific: in The geophysics of the Pacific Ocean Basin and its margin: Amer. Geophys. Union Mono. 19, p. 269-278.

THE GEOLOGICAL ASSOCIATION OF CANADA SPECIAL PAPER 20

THE CONTINENTAL CRUST AND ITS MINERAL DEPOSITS

The Proceedings of a symposium
held in honour of
J. Tuzo Wilson
held at Toronto, May 1979

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D.W. Strangway

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D. W. Strangway
Department of Geology
University of Toronto
Toronto, Ontario M5S 1A1

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D.W. Strangway, J.T. Wilson and Sir Edward Bullard
on the occasion of the Wilson Symposium.

PREFACE

In May of 1979 a group of friends and colleagues gathered to honour J. Tuzo Wilson, a long time member of the faculty at the University of Toronto and now the Director of the Ontario Science Centre. The papers in the symposium on "The Continental Crust and its Mineral Deposits" were presented under the following groupings: i) The Early Earth; ii) Evolution of the Precambrian Crust; iii) Vertical Geometry of the Crust; iv) Crustal Motions; v) The Global View; vi) Ore Deposits. From a study of the Table of Contents, one can see that the conference covered a wide range of topics on the current view of the Earth and its processes ranging from its formation to the movements of fluids leading to the concentration of useful mineral deposits.

It is particularly fitting that this conference should have taken place in Toronto with this broad range of topics, since Tuzo's views of the Earth have had a profound influence on models of terrestrial processes and since there is a great deal of mineral exploration work based in Toronto. Tuzo's early work involved field mapping in the Canadian shield and in Montana. He was instrumental in compiling the first glacial map of Canada and was among the first to recognize how isotopic dating could be used to divide the shield into various age provinces. He used this as the base for his models of stable, fixed continental nucleii. He compiled information on island arcs and championed the contracting Earth theories. This was converted later to support of the expanding Earth hypothesis, but eventually after a thorough synthesis of all known information on ocean islands, he became one of the staunch supporters of the new plate tectonics. He predicted transform faults and championed the concept of hot spots.

There is no doubt that Tuzo's thinking on Earth processes has contributed in a major way to our present models of the Earth. This conference was about this topic and how these models have affected geologic thinking. Each speaker was asked to give his view of current thinking in his sector of the discipline. They were not asked to give a history. In a sense then, the conference was really about the second generation of the plate tectonics revolution. Forty-three papers were presented at the conference with adequate time for discussion. There were no multiple sessions, so that workers from all of the Earth Science disciplines, listened to papers from other disciplines and participated in animated discussion. We have been able to publish in this volume thirty-nine of these papers. This volume represents a snapshot of the 1979 view of the Earth and we hope it will stand as a useful reference work.

Over 300 people attended the conference representing industry, government and university and they came from Canada, the United States, Britain, India, Belgium, Venezuela, Japan and Australia. During the conference, a banquet was held in Tuzo's honour. The featured speaker was Sir Edward Bullard. It was particularly appropriate that Sir Edward was able to come to this conference. Sir Edward had been head of the Physics Department at Toronto when Tuzo was a struggling young professor. He had been at Cambridge when the transform fault theory was generated and sea floor lineations were recognized. Sir Edward himself was a pioneer, who had been responsible for much of the data on which Tuzo's models were built. In fact, one even supposes that Sir Edward may have helped in the conversion of Wilson, when he jumped on the moving continents. Sir Edward passed on the Albatross award to Tuzo at this meeting. His "unusual contribution to oceanography" was "making the faults run backwards". It is therefore with much regret that we record that early in 1980, Sir Edward passed away after a struggle with cancer.

D.W. Strangway
June 1980