Continental drift and a theory of convection

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ABSTRACT

Early geologists considered that the Earth's surface is rigid and unchanging. They assumed that the whole Earth is static, except for enough sub-surface contraction to build mountains. After seismology developed, most geophysicists agreed. A few scientists, notably Wegener, favoured a more mobile Earth. About 1965 fresh evidence showed that both theories were too simple. This evidence explained why neither theory had been able to relate the whole Earth's behaviour to laws of physics. Hence different aspects of geology had only been solved separately which had fragmented Earth science.

This paper proposes a compromise. It is that the rigid lithosphere fractures according to Navier's law of brittle failure which explains the properties and provides methods for classifying faults, plate boundaries and mountains and that the ductile mantle convects by laws of fluid flow in patterns partly controlled by lithospheric fractures. These dual, interacting influences explain tectonic behaviour. The pattern of currents is hidden. At any one time upwelling beneath continents only affects a few limited areas; today some are in southwestern United States, Central Asia, Botswana, Antarctica and rifts in East Africa, Europe and Siberia. Nevertheless recognition of upwelling currents may revolutionize geology because their cumulative effects have been great and neglected.

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INTRODUCTION

It is indeed a compliment to be invited to give this lecture in honour of Alfred Wegener. He was a great man, a distinguished scientist and the chief architect of a modern plan of the Earth. I thank you.

His ideas pose questions which it seems appropriate to address. What was the state of Earth sciences in the nineteenth century? What led Wegener early this century to advance a theory so different from the generally accepted dogma? Why, in 1928, did the majority of Earth scientists reject his views so vehemently, and then forty years later reach a compromise which has made Wegener's theory of continental drift a central part of plate tectonics? Why have these new ideas, which have been so successful in describing ocean basins and plate motions, not been extended to explain continental features and the causes of motions? Can these be accounted for? If so, can they complete a scientific revolution similar to those which so increased the value of the physical and biological sciences in the 1920s and the 1950s respectively?

Since the 1850s Earth scientists have not been happy with the progress of their subject and the reasons are not hard to discern. In 1850 geologists could claim that their subject was the leading scientific discipline. It has not declined, indeed it has continued to develop, but other sciences have leaped ahead faster. They did so by improving their methods and by discovering and applying new laws and rules of behaviour, including quantum mechanics, nuclear physics, astrophysics and the behaviour of DNA molecules, none of which apply directly to the Earth's behaviour.

The Earth's dimensions, temperatures and pressures are so moderate that it seems likely, indeed almost certain, that the laws of classical physics and chemistry should suffice to describe its behaviour. Those laws are known. Hence it should be possible to apply them and make a similar advance in the Earth sciences.

Several reasons have made that difficult. First, the interior of the Earth has proved hard to investigate. Secondly, it is now realized that the internal behaviour is complex and involves many moving parts. A third difficulty is that the several parts follow different laws and interact with one another to produce complexity. A fourth reason is that so many methods for investigating different parts of the Earth are available on land, at sea and from space that some have become fashionable and others have been neglected.

It might seem impossible for anyone to grasp all that is involved, but fortunately G.W. Wetherill (1989, pp. 110–111) has just written about the even vaster problem of studying the whole universe, 'spanning the domains of many specialists, . . . scientists . . . might find this discouraging. But they shouldn't. Just when it seems that one's mental resources had been spread impossibly thin, there comes the illumination. . . . It is freely given to all those who understand a few simple physical principles.' What have been the illuminating guidelines in geology?

HYPOTHESIS OF A STATIC, CONTRACTING EARTH

To understand what has been discovered about the Earth consider some of the methods employed. On land, geologists have long studied surface rocks. They early resolved the problems of palaeontology, stratigraphy, and structure. They developed a precise relative time-scale, unrivalled in other sciences, and, in spite of objections by physicists, correctly maintained that the Earth is very old. Thus they provided a basis for evolution. They made discoveries of great economic importance and correctly concluded that the surface rocks are rigid and brittle. By 1850 they had become leaders among the world's scientists.

Since no means had been found to investigate the deep interior in detail, many geologists formed the opinion that the land surface is the only important part and that good geological mapping should suffice to explain the Earth's behaviour. In recent years, with the help of oceanographic studies, deep drilling, and the type of seismic reflection surveys used in exploration, detailed observations have been extended to the ocean floors, and to depths of a few tens of kilometres on land. Many wholly new discoveries have resulted, but still only about one percent of the Earth's radius has been explored in detail.

Geophysical studies have also shown that, in complex areas, the finest geological mapping, such as that by Trümpy (1988) near Zurich, may provide a very imperfect view of the deeper structures which seismic and gravity studies by Mueller and Panza (1986) have revealed. Geological and geophysical studies provide equally important data which must be integrated to get as complete an understanding as possible.

Due to the early progress made by geologists, one of them, James Hall (1859), proposed the first widely accepted general theory of tectonic behaviour, the geosynclinal hypothesis of mountain building, which he based upon his observation that the Appalachians had been formed by the accumulation, uplift and folding of a great trough of sedimentary strata. Dana (1873) extended the hypothesis by suggesting that, if the deep interior is static, cooling and contracting of the Earth's outer layers could have built these and other mountains (Fig. 1). Knopf (1948) has discussed the theory in detail.

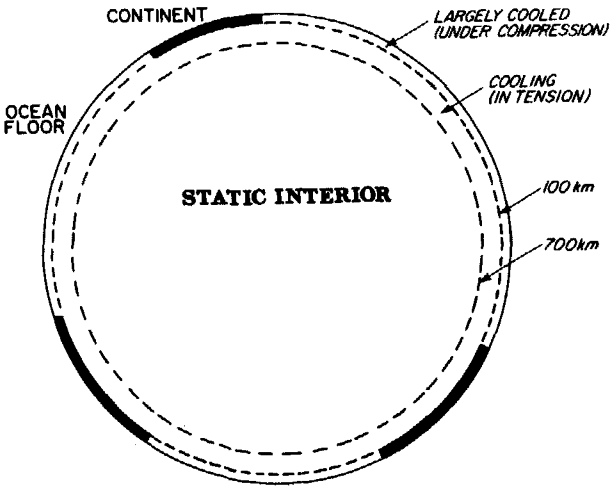


Fig. 1. *Diagram to illustrate the contraction hypothesis of a cooling Earth according to Dana (1873) and Jeffreys (1924).*

Another small, but distinguished, group of scientists had long studied the physics of the whole Earth. Aristotle and Eratosthenes realized that the Earth is approximately a sphere and measured its radius. Newton and Gauss showed that the Earth generates its own gravitational and magnetic fields. Others investigated astronomical and tidal forces on the Earth (Hopkins, 1839) and realized that the interior is hot. Unfortunately at first these methods failed to provide any details. Seismologists were the first geophysicists to produce precise results from the interior. They began to do so early this century after the invention of modern seismometers and the discovery of how to interpret the resulting records.

These records showed that seismic waves, including shear waves, travel at high speed through the mantle, proving it to be rigid, and that layering in its interior reflects waves, making convection less probable (Jeffreys and Bullen, 1935). This is true for short time-scales, but the possibility was largely ignored that, over long periods, the hot and solid mantle might creep like a very viscous fluid (D.L. Anderson, 1989).

In 1924 Jeffreys began a series of encyclopaedic reviews of all that was known about the Earth's interior, particularly from seismology. His conclusions, like all others at the time, required an element of judgment to supplement limited observations. He concluded that, if the Earth had solidified from the centre outwards, the interior should contain little radioactivity. He calculated that below 700 km its dimensions would not have changed, but that a layer above that would have cooled by conduction to produce shrinkage and the folding observed in the uppermost 100 km. (Fig. 1). He therefore supported the geologists' view which Suess (1904–1924) had recently summarized. For a century, the contraction hypothesis was widely accepted as the best unifying theory (Schwab, 1982).

EVIDENCE AGAINST THE CONTRACTION HYPOTHESIS

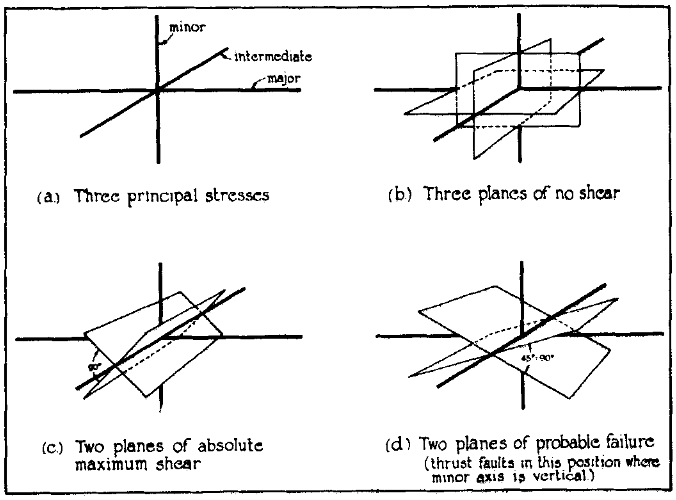
Because neither geologists nor geophysicists could provide much trustworthy information about the Earth's interior, once having accepted the contraction theory most continued to support it, although some had considerable doubts or held alternative views.

Misgivings existed because the contraction theory has never been able to provide a satisfactory general theory of Earth science, so geology became fragmented and now deals with many detailed aspects separately. This was because the contraction hypothesis was based upon the concept of a rigid Earth, in which all the principal stresses are horizontal and can only produce limited motions. These ideas are a century old and have not been modified to meet new discoveries. They have not been precisely related to any pertinent physical theory and must at best be incomplete and partly wrong.

One of the earliest and most convincing types of evidence against the contraction hypothesis was produced by careful geological mapping on land. About two centuries ago geologists began to recognize faults in the Alps, and showed that some had offset the strata by many kilometres. Gradually more large faults were identified with offsets too large to be accommodated by contraction (Wellman and Willett, 1942; Wellman, 1945 and 1952; Kennedy, 1946; Menard and Dietz, 1951; Hill and Dibblee, 1953; de Sitter, 1956; Vacquier, 1959; Bolt *et al.*, 1968; Isacks *et al.*, 1969; Wellman, 1969). Correspondents to the Upper Mantle Project produced a list of over 80 faults with very large horizontal offsets (Knopoff, 1969). Offsets of over 100 km had been measured on twenty of them. Many other examples have now been discussed, for example in the Caledonian Mountains (McClay and Coward, 1981), in the Appalachian Mountains (Hubbert and Rubey, 1959; Evans, 1989) and in Precambrian Shields where Stockwell (1926) mapped a most conspicuous example which Jolliffe (1938 and 1942) has illustrated.

The discovery by Wadati (Fröhlich, 1987) and Benioff (1949) that deep earthquakes mark subduction zones posed further problems for the contraction hypothesis.

The work of the Scottish geologist, E.M. Anderson (1951), raised another reason to doubt its validity. For forty years at the beginning of this century, he attempted to apply laws of physics to explain faulting. He showed that, since the Earth's lithosphere is strong and brittle, it should fracture according to Navier's principle of shear failure. Navier and Mohr modified the law which Coulomb originally proposed. In trying to apply Navier's law, Anderson pointed out, since the Earth's surface is a plane of no shear, that at any point on the surface one of the three axes of principal stress must be vertical (Fig. 2). Depending upon whether the principal axis of maximum, of minimum or of intermediate stress is vertical, so normal, thrust or strike-



(a) Three principal stresses

(b) Three planes of no shear

(c) Two planes of absolute maximum shear

(d) Two planes of probable failure (thrust faults in this position where minor axis is vertical)

Fig. 2. *Diagram to illustrate the three axes of principal stress; the three planes of no shear (each of which includes two principal axes and one of which must be the Earth's surface); the two planes of absolute maximum shear; and the two planes of probable failure (according to E.M. Anderson (1951) after Navier).*

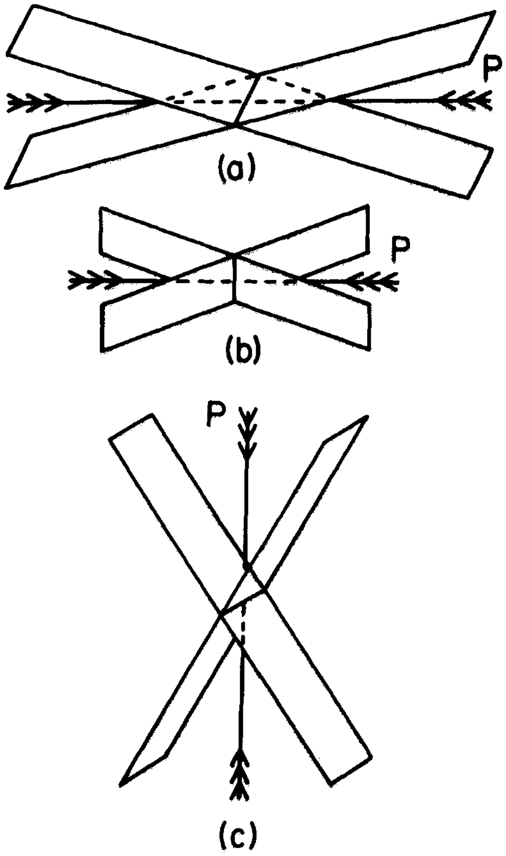


Fig. 3. *Diagram to illustrate the three positions possible for the axis of maximum stress (P) at the Earth's surface and the three kinds of faults which result: (a) thrust faults when axis of minimum stress is vertical, (b) strike-slip or transform faults when the axis of intermediate stress is vertical, (c) normal faults when the axis of maximum stress is vertical (according to E.M. Anderson, 1951).*

Table 1. Some properties of the three types of faults observed by geologists (after E.M. Anderson, 1951).

Principal axis which is vertical	Resulting type of faulting	Direction of greatest pressure	Dip of fault	Plan of strike	Intrusives along fault
Major	Normal	Vertical	Steep	Wavy	Common
Minor	Thrust	Horizontal	Low	Very Wavy	Rare
Intermediate	Wrench, Strike-slip or Transform	Horizontal	Vertical	Straight	Rare

slip faults should form, and exhibit their well-known characteristics (Fig. 3; Table 1). Unfortunately the contraction hypothesis which then prevailed did not provide the vertical forces which Navier's principle requires, and so Anderson's attempt did not succeed. Although it was not appreciated at the time, what he really provided was an interesting example of the impossibility of explaining geology in terms of an erroneous physical theory of the Earth.

HYPOTHESIS OF A MOBILE EARTH

A minority of dissenters never accepted the contraction hypothesis. They favoured a mobile rather than a rigid Earth. Leaders among them were those geodesists and geophysicists who studied gravity and the shape of the Earth. About 1800 Bouguer and others working in Peru, Lapland and later India showed that mountains are not loads on a rigid Earth, but float in isostatic equilibrium upon a mobile interior (Daly, 1949). Other geophysicists agreed and so did some geologists including Dutton, who was one of the first to work in the Basin and Range province of Utah and Nevada, where he noted great instability, extension, faulting and volcanism. He concluded that the cause might be molten magma below the crust and suggested 'that the proximate cause of eruptions is a local increment of subterranean temperature, whereby segregated masses of rocks, formerly solid, are liquified' (Dutton, 1880, p. 120).

One of the geophysicists who favoured a mobile interior was Fisher (1881). In his book, which Jeffreys (1924, p. 138) has discussed, he considered the effects of flow and convection and concluded that convection currents of liquid magma were the most probable way of introducing the excess heat necessary to produce volcanism, as Dutton had recognized.

Most geologists regarded Fisher's views as heresy, but small groups, who worked in disturbed regions or on special problems, continued to keep the idea of mobility in the Earth alive.

One group, including Bouguer, Airy, Pratt, Dutton, Barrell, Bowie, Daly (1949), Heiskanen (Heiskanen and Vening Meinesz, 1958), and Vening Meinesz (Vlaar, 1989) continued to study isostasy. Several Dutch scientists who had worked in Indonesia became interested in mobility. They included Vening Meinesz who discovered that ocean trenches are accompanied by negative gravity anomalies. He introduced Hess to geophysics. Hess (1962) has given references to that work.

Others, including Taylor (1910), considered motion of continents, but ideas were vague until Wegener (1915 and 1966) proposed the theory of continental drift. His colleagues Ampferer (1941) and Schwinner (1941) supported him (Flügel, 1984). They published early cross sections of the mid-Atlantic ridge and of a trench (Figs 4 and 5). Argand (1924) who studied the mobility of the Alpine and Eurasian mountains agreed (Carozzi, 1985). So did Bailey (1929), who suggested possible connections between Europe, Greenland and North America and du Toit (1937) who described connections between the southern continents.

Fig. 4. *Diagram of flow rising under the mid-Atlantic ridge after Ampferer (1941). He stated that flow 'breaks through the continental masses and drives them apart' (Flügel, 1984).*

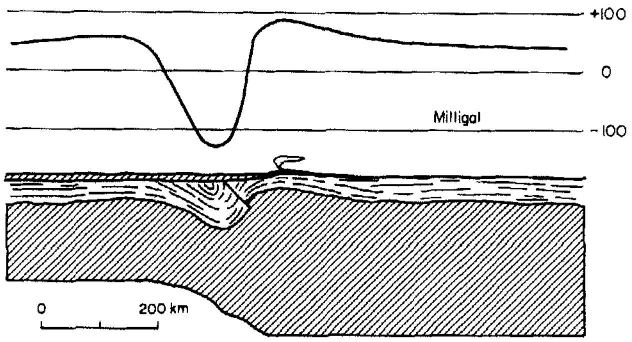


Fig. 5. *Illustration by R. Schwinner (1941) in which he combined Ampferer's views on mantle flow with the gravity research of Heiskanen and Vening Meinesz (1958) and that on deep earthquakes by Gutenberg and Richter (1954). Note the trench, thrust fault and volcano (Flügel, 1984).*

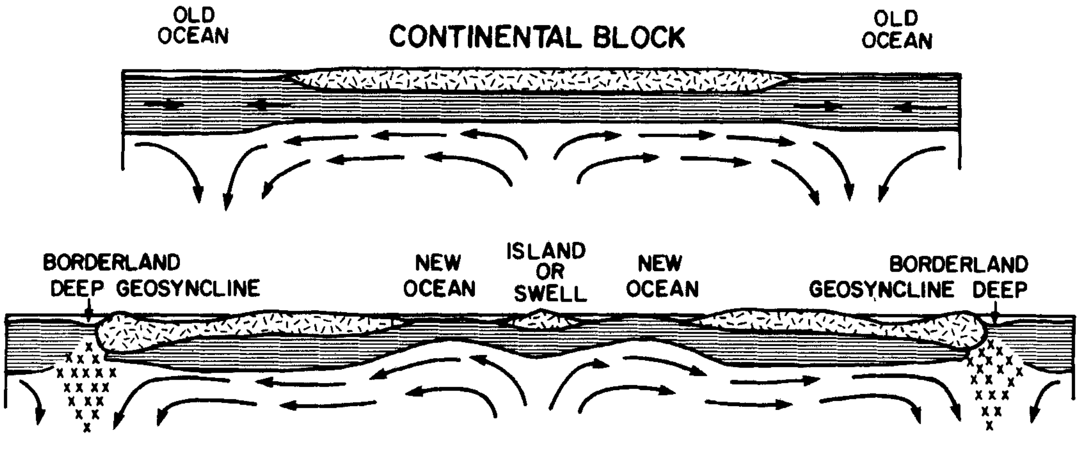


Fig. 6. *Two diagrams by Holmes (1933) showing how mantle extends and breaks the lithosphere and moves continental blocks apart creating new ocean floor. In Holmes (1944) he omitted the continental material from the mid-ocean island.*

Several became interested in convection in the Earth. Holmes (1928–31 and 1933) made important contributions (Fig. 6), to solving the problem. Some attacked his views, while others have claimed that he did not receive due credit. The fault was partly his own. He was so modest that in the first edition of his textbook in geology, (Holmes, 1944) by which he is best known and which Hess told me that he used, Holmes gave no references to his own papers which are many and scattered. Stewart (1964) has published a complete list and Marvin (1985) has reviewed his work.

Mathematicians studied internal flow (Pekeris, 1936; Fig. 7) and the effects of mobility upon rotation (Munk and MacDonald, 1960). Griggs (1939 and 1954) and Verhoogen

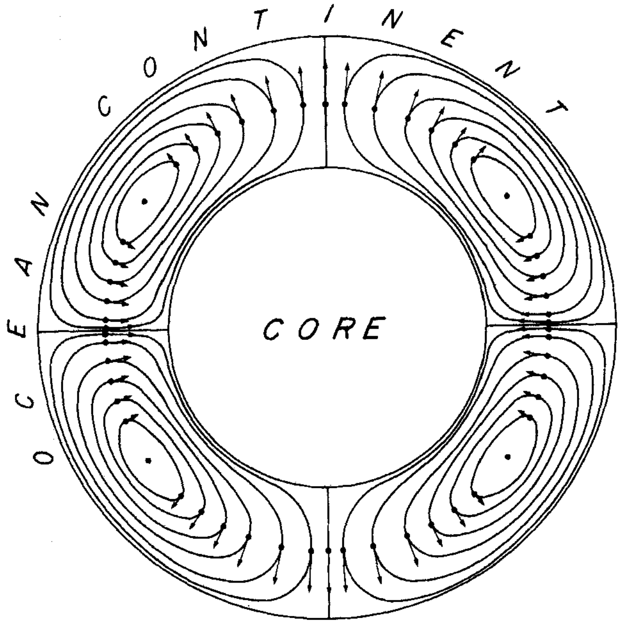


Fig. 7. *One posible solution to the mathematical problem of whole mantle convection (Pekeris, 1936).*

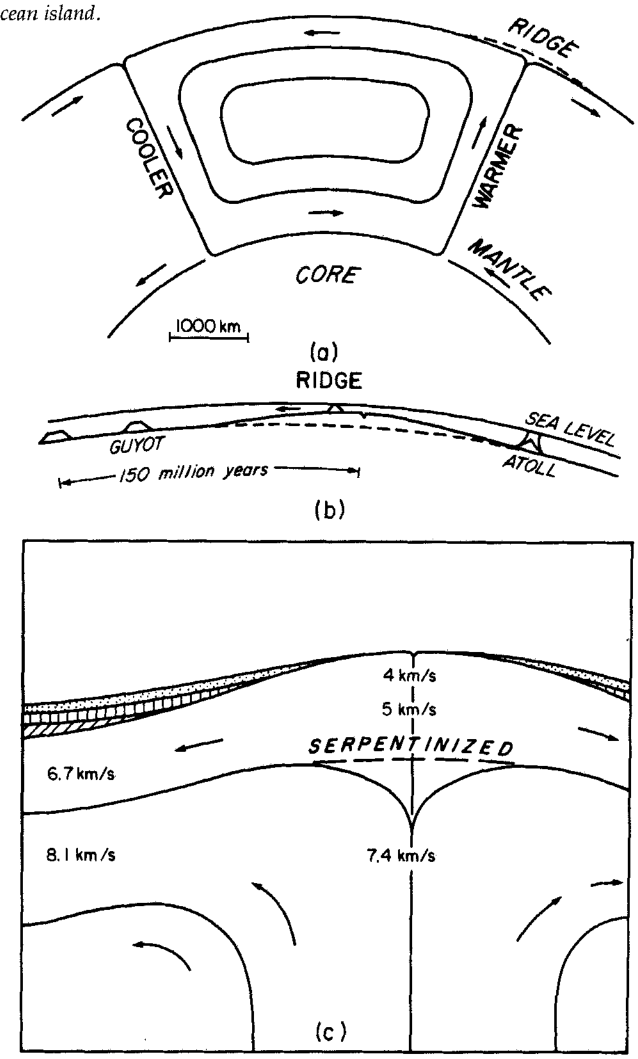


Fig. 8. *Three diagrams after Hess (1962) showing how (a) whole mantle convection uplifts mid-ocean ridges and splits the surface so that plates move apart, (b) how upwelling generates volcanic islands, atolls, seamounts and guyots which subside as they move off hot ridges, and (c) how sediments accumulate and thicken away from the ridges.*

(1954) made important contributions to the relationship between convection and mountain building.

Several scientists realized that the surface rocks are not mobile, but strong. In effect, as their illustrations show, they introduced the concept that the lithosphere and the mantle behave in different ways as is advocated in this paper. Following the exploration of the Pacific basin largely by American and Japanese scientists (Revelle and Maxwell, 1952; Dietz, 1961; Menard, 1986; Sugimura and Uyeda, 1973) and the extension of the mid-Atlantic ridge into a worldwide system (Ewing and Heezen, 1956; Menard, 1960), Hess (1962) introduced the important idea that

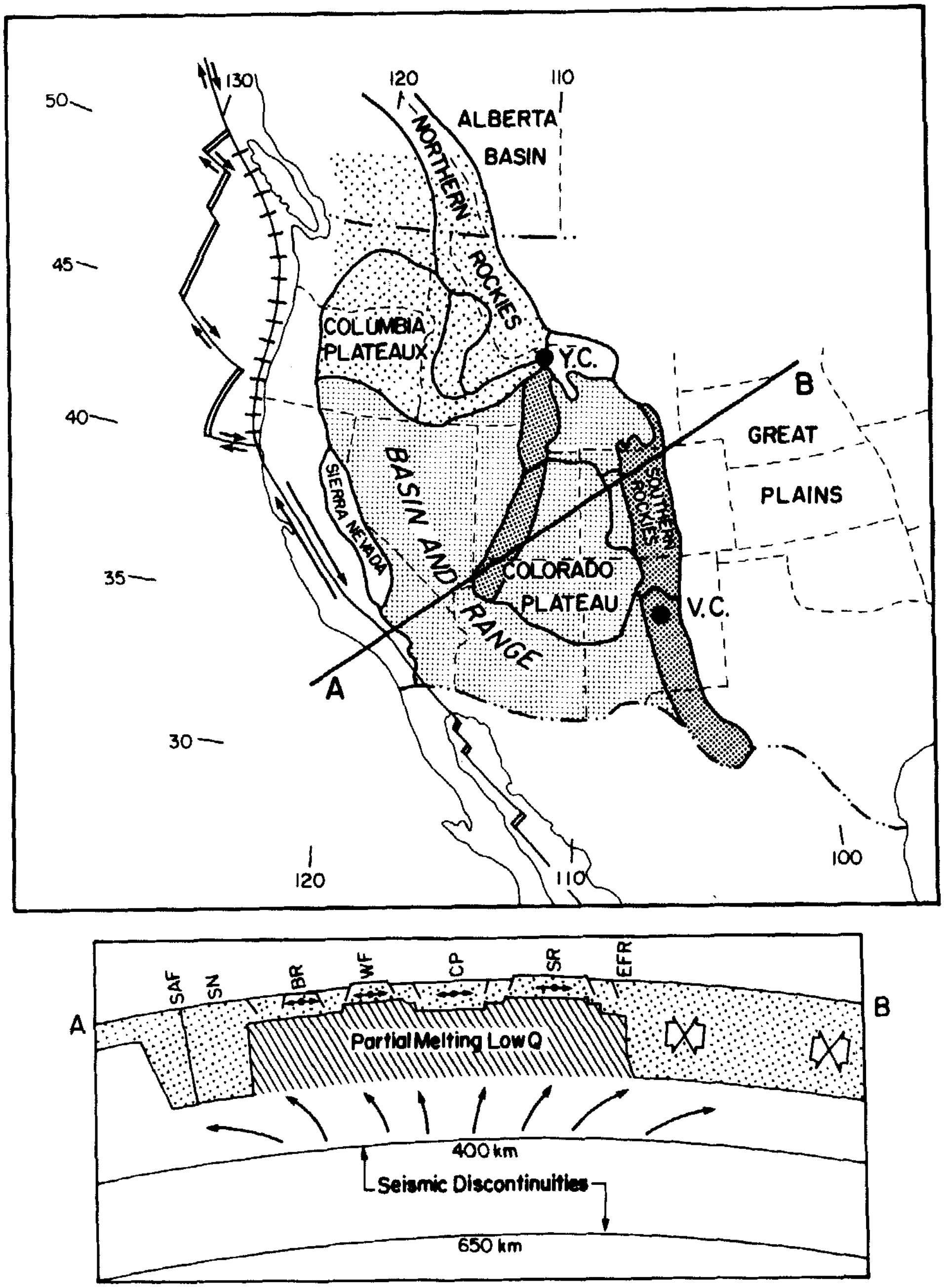


Fig. 9. *Sketch map and section after Gough (1984) of western North America showing magnetotelluric observations. These indicate by increasing shading regions underlain by layers of greater conductivity at depths of a few tens of kilometres. Note on the map and along section A–B how the Wasatch Front (WF) and the Southern Rockies (SR) are underlain by the most highly conducting regions. YC and VC are the Yellowstone and Valles calderas. Note how the basement thickens east of the East Front of the Rockies (EFR). Note the tension over the region of higher conductivity. SAF is San Andreas fault, SN is Sierra Nevada, BR is Basin and Range province, CP is Colorado Plateau.*

upwellings split the ocean floor and thus produce sea-floor spreading (Fig. 8).

Another group including several geologists from the United States Geological Survey revived the views of Dutton and Fisher that a mobile, and at least partially melted layer in the upper mantle underlies the Basin and Range province in the southwestern United States (Menard, 1960; Gilluly, 1963; Pakiser and Zeitz, 1965; Cook, 1969; Scholz *et al.*, 1971). Gilluly (1963, p. 159) wrote 'that the Basin Range faults are the result of lateral transfer of crustal material from beneath the province to the area of the (Colorado) plateau' and that this was done by flowing currents. Gough (1984) and his colleagues mapped the region using magnetotelluric methods which showed that conductors, probably fluid, underlie the region (Fig. 9).

ECLIPSE OF THE HYPOTHESIS OF A MOBILE EARTH

In spite of this support, Wegener's views remained contrary to the strongly entrenched opinions of the majority of Earth scientists who favoured the contraction hypothesis. Between 1923 and 1926 several meetings were held to discuss the rival opinions. Wegener had made mistakes; information about the interior was vague; most scientists denounced his ideas (Lake, 1923; De Golyer, 1928; Marvin, 1974; Le Grand, 1988). The strength of the opposition appears somewhat odd, because everyone admitted that some evidence demanded mobility of at least part of the interior.

At the meetings, opinions were so hostile that for the next thirty years few, particularly in North America, mentioned mobility. It required the development of new methods and the advent of plate tectonics to change attitudes.

SUCCESS OF PLATE TECTONICS: THE CONVECTION THEORY

Thus for a century or more some authorities insisted that the Earth behaves as a rigid body while others held that it acted as a mobile one. Curiously enough both groups agreed that some evidence supported the opposite view. Thus those who favoured a rigid Earth admitted that part of the interior was fluid and many of those who favoured a mobile Earth published illustrations showing a thin, strong outer skin (Figs 4, 5, 6 and 8).

This partial agreement between the two opposing views has suggested the solution here advocated. It is that the bulk of the Earth, its mantle, flows as a very viscous fluid, and that it interacts upon an outer shell, the lithosphere, which is rigid and brittle and which fails by shearing (Davies, 1988). That dual concept is now supported by abundant fresh data. In the 1950s and 1960s many new discoveries were published especially about ocean floors by Ewing and Heezen, (1956) and Menard, (1960 and 1986); about movements of surface plates by Carey (1958), Hess (1962), Vine and Matthews (1963), and Morley (see Glen, 1982) and about palaeomagmatism by Cox *et al.* (1964) and Irving (1964). Together these led to the concept of plate tectonics (Bullard *et al.*, 1965; Wilson, 1965a; McKenzie and Parker, 1967; Le Pichon, 1968). The essence of that concept is that the lithosphere and the mantle have different properties, but interact, and, in more detail, that two other smaller features of the Earth are also involved in tectonic behaviour. These features are plumes which rise through the mantle from the core–mantle boundary (Fig. 10), and small detached flakes at the surface, including both thrust sheets (Fig. 11) and the caps over mantle plumes (Figs 9 and 12).

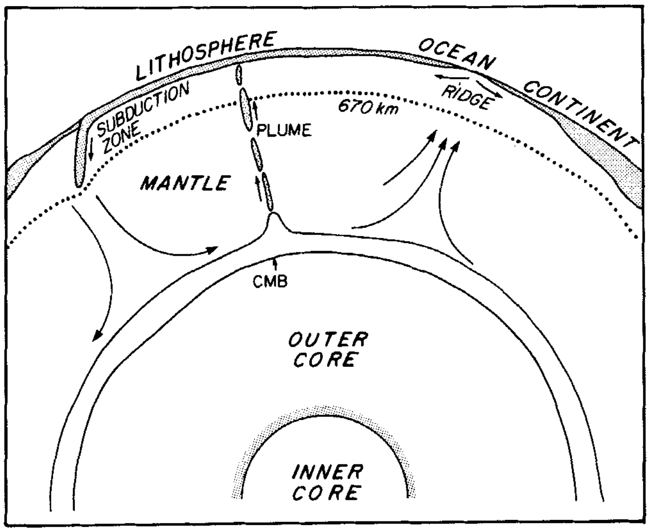


Fig. 10. *Section through the Earth after Lay (1989) showing how plumes rise from the lower mantle or the core-mantle boundary (CMB), while mid-ocean ridges arise from higher levels within the upper mantle beneath mid-ocean ridges. A subduction zone is also shown where lithosphere sinks.*

The lithosphere, thrust sheets and detached flakes are well exposed and have been much studied by geologists. All are rigid and all obey Navier's principle. The mantle and plumes are largely concealed and have to be studied by indirect means. They obey the laws of fluid flow. The plumes themselves have not been mapped, but the existence of about 40 of them is assumed in order to explain the properties and nourishment of a peculiar class of volcanoes which mark their presence. These were named hot spot volcanoes when little was known about them except their energy, longevity, and the observation that they form a nearly stationary frame of reference for plate motions (Minister and Jordan, 1978). They have also been called ocean island volcanoes, although some are on continents; and mantle plume volcanoes, although the plumes have not been mapped. None of the names is wholly satisfactory.

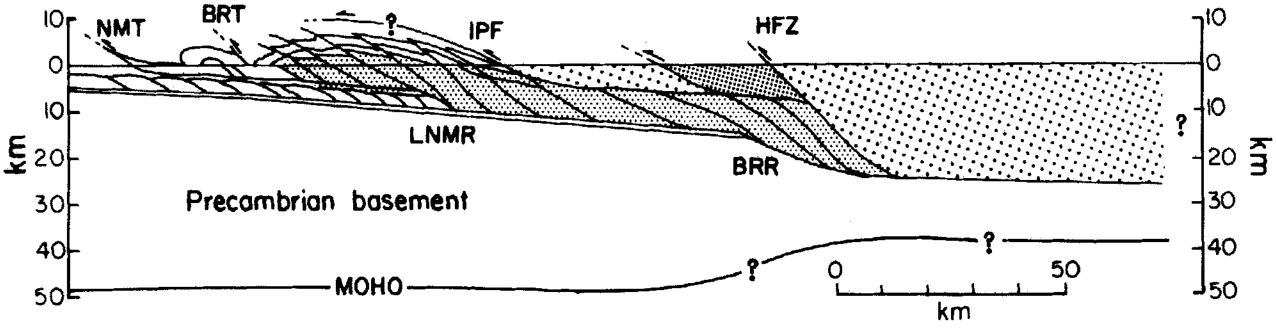


Fig. 11. *Section after Evans (1989) of thrust faults and thrust sheets across the Appalachian Mountains. Some have been moved 100 km horizontally, which now appears impossible, but, if a high hot welt had moved inland it could have produced temporary uplift, tilting and motion before it cooled and subsided. NMT and BRT are North Mountain and Blue Ridge thrusts. IPF and HFZ are Inner Piedmont and Hylas fault zones. LNMR and BRR are lower North Mountain and Blue Ridge ramps.*

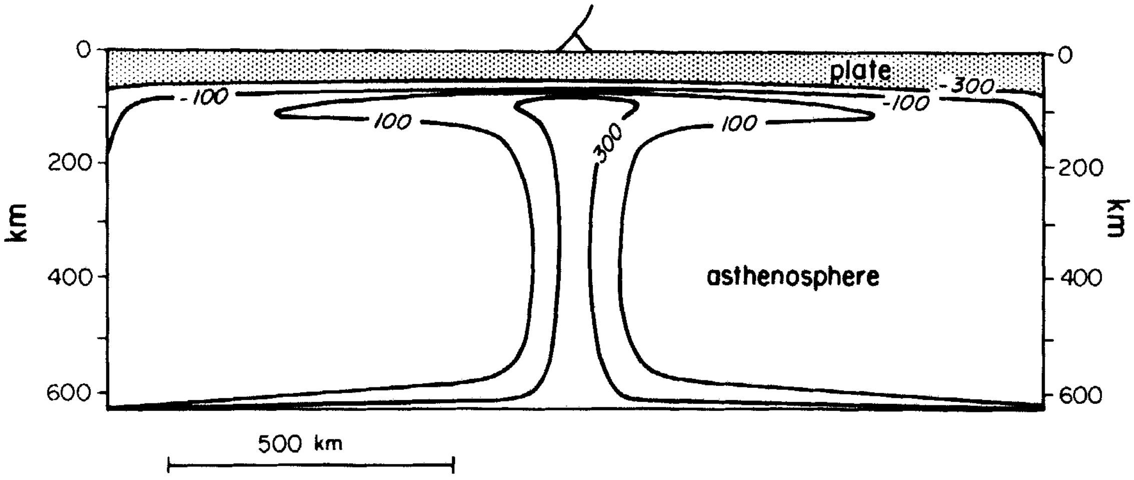


Fig. 12. *Temperature variations in a diagrammatic cross section of a cap generated by a mantle plume which is rising through a plate stationary over the plume (White and McKenzie, 1989).*

This proposal for a convection theory may also solve a long-standing argument about the possible vertical uplift of some mountains or ranges (Crough, 1983 and Sleep, 1990).

Long ago Soviet and Chinese geologists published accounts of vertical tectonics in Central Asia, a type of behaviour which western geologists did not recognize in their countries (Beloussov, 1962; Knopoff, 1969; Gliko *et al.*, 1985). However, Cloos (1939), Stephansson (1975), Witschard (1984), de Beer *et al.*, (1975 and 1976) and authors in Morgan and Baker (1983) have since produced much evidence for vertical uplift in Europe, East Africa and Botswana (Fig. 13). Ramberg (1981), Bhattacharji and Koide (1987) and Rönnlund (1989) have supported field evidence by modelling. Smith and Drewry (1984) have noted vertical uplift in Antarctica. Stern and ten Brink (1989) have agreed that 'one of the principal uplift mechanisms for the Transantarctic Mountains is considered to be a thermal uplift'. Wilson (1988, 1990a and 1990b) has discussed some cases.

Nor is the idea of vertical uplift of mountains entirely new in North America, Dutton (1880) and Fisher (1881) hinted at the possibility, and Gilluly (1963) proposed that currents flowing in the mantle have uplifted the Colorado Plateau. Cook (1969), Scholz *et al.* (1971) and Gough (1984 and 1986) have illustrated regions of melting and flow under the Basin and Range province and the Omineca province in British Columbia (Fig. 9). Suppe *et al.* (1975), Blackwell (1989), Fournier (1989) and Smith *et al.* (1989), have postulated great uplifts and horizontal migration of the Yellowstone volcanic region and the Colorado Rocky Mountains (Fig. 14), and Morgan (1983) has suggested that uplifts have migrated across the Canadian Shield and across other continents.

BEHAVIOUR OF THE LITHOSPHERE: ANDERSON'S THEORY EXTENDED

The outermost shell of the solid Earth is a thin, brittle lithosphere which averages a few tens of kilometres thick,

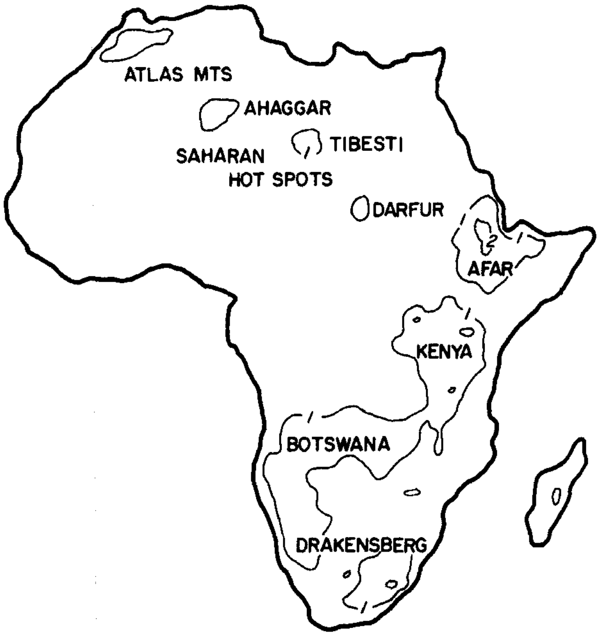


Fig. 13. *Hypsometric map (after Cogley, 1985) of averaged topography of Africa with generalized contours at 1 km intervals. Note how hot spot volcanoes and rifts all lie on elevated regions, suggesting that rising currents formed the uplifts.*

Fig. 14. *Hypsometric map (after Cogley, 1985) of North America with generalized topographic contours at 1 km intervals. Note that the largest high region (> 2 km) in North America lies between the Yellowstone and Valles calderas (YC and VC) which are two of the greatest centres of volcanic heat on the continent and which are believed to mark mantle plumes.*

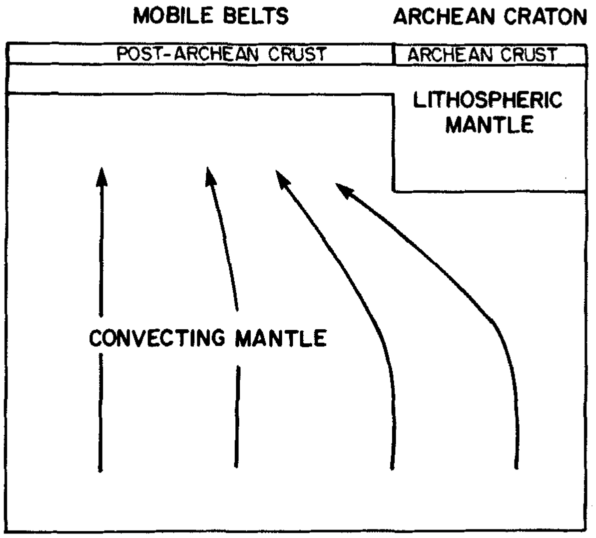


Fig. 15. *Sketch cross section across one side of a craton showing how the low heat flow in the old and thick craton distorts the upward flow of mantle currents (after Ballard and Pollack, 1989).*

but which varies from zero under the crests of mid-ocean ridges to a few hundred kilometres under the oldest cratons (Fig. 15), (Ballard and Pollack, 1987; Lerner-Lam and Jordan, 1987; White, 1988). The oceanic and continental sectors have different properties and isotopic compositions (Walker *et al.*, 1989).

Fisher (1881, p. 213) E.M. Anderson (1951, pp. 26–27) and Speight *et al.* (1982) have all suggested that large faults and dyke swarms may cut right through the crust. When convection currents were recognized, vertical stresses became acceptable and so did Anderson's explanation for the three classes of faults in terms of Navier's principle (Fig. 3, Table 1). As has been suggested elsewhere that theory can be extended to explain the three types of plate boundaries and the three classes of mountains (Tables 2 and 3). (Wilson, 1990a and 1990b). If this is so then all these features follow the rigorous and predictable laws of shear failure in brittle solids.

Jeffreys (1952, p. 348) stressed the difficulty of breaking the lithosphere, but he also mentioned the possibility, for which there was then no evidence, that strong uplift might suffice (Marvin, 1974, p. 52). Later Cloos (1939) produced evidence for vertical uplift of basement by hot spot volcanoes and Crough (1983) argued that mantle plumes rising beneath them can provide a way to start fracturing. Thus there is no physical argument against the possibility that currents flowing in the mantle may uplift the lithosphere vertically, and therefore fracture it to generate faults, plate boundaries and ranges. Once fractures start, interplay betwen plates can extend them.

It is important here to avoid an argument which might arise because of semantics about the words 'mountains'

Table 2. Classifications of plate boundaries according to Navier's principle (after E.M. Anderson, 1951).

Principal axis of stress which is vertical	Resulting type of faulting		Types of plate boundary	Examples
Major	Normal	Increasing age ↓	Hot spots	Hawaii
			Rift valleys	East Africa rifts
			Axes of narrow expanding seas	Axis of Gulf of Aden
			Crests of mid-ocean ridges	Crest of mid-Atlantic ridge
Minor	Thrust		(a) Coastal trenches (with young ocean floors)	Trench off western South America
			(b) Island arc trenches (with older ocean floors)	Aleutian Is. trench
Intermediate	Transform		Vertical shear faults along coasts	San Andreas or Jordan Valley faults

Table 3. Classification of ranges (mountains) according to Navier's principle (after E.M. Anderson, 1951).
Note the use of word 'range' for mountains in general, because some scientists still think that all mountains have been built by compression, thrusting and folding, and not by uplift or horizontal shearing.

Principal axis of stress which is vertical	Predominant type of faulting		Types of range formed	Examples
Major	Normal	Increasing age ↓	Hot spots and tracks	Hawaii, Tristan du Cunha
			Rift valley margins	Ngong Hills, Kenya
			Coasts of young expanding seas	Coasts of Norway and East Greenland
			Crests of mid-ocean ridges	Mid-Atlantic Ridge
Minor	Thrust		(a) Ranges along island arcs	Japan, or Java, Sumatra and Timor
			(b) Ranges along subducting coasts	Andes, Cascade Mountains
Intermediate	Transform		Ranges along coasts with vertical shears	Mountain of Lebanon or those south of Los Angeles

and 'ranges'. Molnar and Lyon-Caen (1988, p. 180) have pointed to two extreme views held about mountain buildings. One is that 'virtually all mountain ranges in the world are a consequence of crustal shortening'. The other which they quote is that of John Rodgers who concluded, after a study of central Asian mountain belts, 'that essentially all mountain ranges evolve differently from one another and that no mountain belt should serve as a model for others'.

The first view, that mountains are built by compression became widely adopted as the general explanation. This arose because the Alps and the Appalachians, which were among the first mountains to be studied in detail, were observed to have been compressed and folded, and because the contraction theory applies to most mountains on continents. The aberrant behaviour of a few ranges, like those in Central Asia or in coastal California, were for a time largely ignored, but the discovery of the system of mid-ocean ridges which has sometimes been called 'the greatest mountain system on earth' drew attention to ranges built, not by compression, but by sea-floor spreading and upwelling. Since it would be unwise, as well as unnecessary, to suppose that the tectonics of ocean basins are wholly different from the tectonics of continents, this paper suggests that there are three causes of mountain building. Since most continental geologists have so long held the view that all mountains are due to compression, this paper will use the term mountains for those built by compression and will use the term ranges as a more general term to include also those built by vertical uplift and by horizontal shearing.

FLOW IN THE MANTLE

The lithosphere rests upon and obscures a much thicker shell, the mantle, which is difficult to investigate. Recently, seismic tomography has provided a powerful fresh method (Woodhouse and Dziewonski, 1984; Anderson and Dziewonski, 1984). Mantle convection is now believed to be the chief cause of surface motions (Kellogg and Turcotte, 1990). Because the mantle is hot, its behaviour follows laws of fluid flow, in patterns still subject to debate.

Many have proposed convection in two layers. Richter and McKenzie (1981) and Anderson (1989) placed the boundary at about 700 or 650 km, while Mörner (1990) considered that most of the flow occurred in an asthenosphere 50–150 km thick beneath a lithosphere 100–300 km thick. Forte and Peltier (1987) preferred whole mantle convection which is hard to distinguish from a system with only a thin, viscous lower mantle (Lay, 1989; Bercovici *et al.*, 1989). The last configuration provides a way to anchor roots of plumes, but so might thermal properties (Peltier, pers. comm.).

The upper layer appears to convect in three patterns (Fig. 10). That complexity resembles the fluid flow in the atmosphere which follows different patterns at different altitudes and also, in the lowest layer, simultaneously forms weather fronts, thunderstorms and tornadoes. In the mantle, flow may be unstable, non-linear, and possibly chaotic. It is not neatly predictable like the type of failure which most of us expect in the lithosphere, but Keilis-Borok (1990) has published a note of caution. In the mantle the paths of flow are not confined by rigid walls, as is the case in the lithosphere with brittle failure, but flow in streams which may move about like the funnel of a tornado.

The largest flow pattern reported consists of two vast slow overturns rising in turn under the central Pacific and Africa, and marked by the Dupal isotope anomaly which is not illustrated here (Dupré and Allègre, 1973; Castillo, 1988).

A second major pattern of convection rises under mid-ocean ridges through the whole mantle, or more probably only through its upper part (Bercovici *et al.*, 1989), while corresponding subduction zones sink around the margin of the Pacific and across southern Eurasia with the downward flow of the great Dupal overturns. When the convection pattern was first proposed it seemed that it should affect both continents and oceans alike, but that is not so. Atwater (1970) proposed that mid-ocean ridges are cut off and transformed into great shear faults at continental coasts and thus do not enter continents. There are some exceptions, of which the Gulf of Aden is one, which will be discussed below, but in most places her conclusion appears to be valid. As a result the mantle beneath continents is less affected by convection than that beneath ocean basins. Walker *et al.*, (1989) found supporting evidence of small but distinct differences in the isotopic composition of osmium between suboceanic and subcontinental mantle.

It also seems that the lower temperature gradient and the great thickness of the roots of cratons further restrict and guide the flow of currents beneath continents so that most currents, plumes, rift valleys and fractures tend to avoid cratons and follow gneiss belts, old collision zones and other lines of weakness in the lithosphere (Figs 15 and 16). McConnell (1972) has mapped those features in East Africa (Fig. 16). He described the belts as having been repeatedly 'reactivated during orogenic periods' from at least 2700–

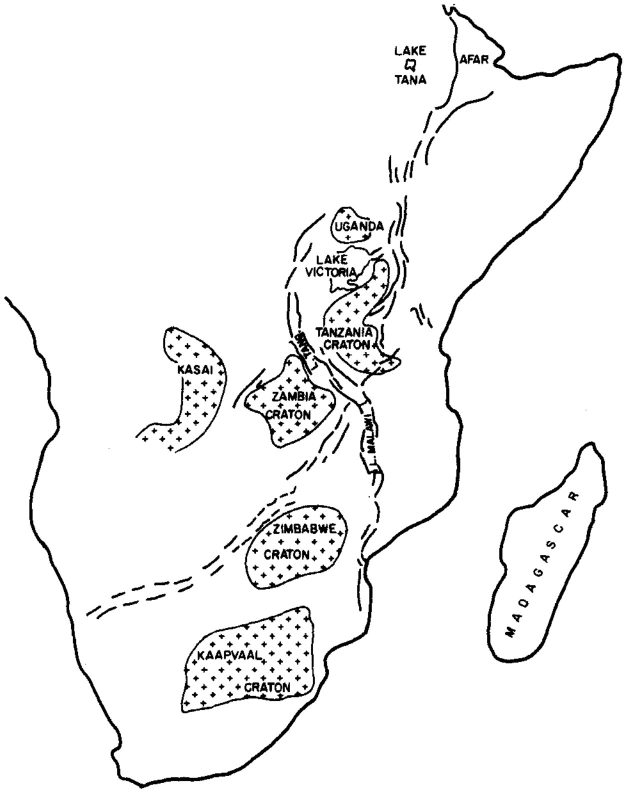


Fig. 16. *Simplified map of East Africa, showing how Tertiary rift valleys and plumes avoid the named cratons (> 2800 Myr old). They follow gneiss belts (after McConnell, 1972). The double dashed line northwest of Zimbabwe craton is the Botswana uplift. L. Tang. is Lake Tanganika.*

2300 Ma to the present. The belts separate the still older cratons. Ballard and Pollock (1987) drew a section to illustrate the effects of the roots of cratons (Fig. 15).

A third system of convection is supplied by about forty narrow, active plumes, each only a few hundred kilometres in diameter. They are believed to uplift and rift the lithosphere and to erupt as volcanoes (Crough and Jurdy, 1980). Those which fracture the lithosphere are evidently very energetic. The importance of their role, especially on continents, has been neglected, so they will be discussed first.

BEHAVIOUR OF MANTLE PLUMES

Cloos (1939) mapped large volcanoes in Africa and suggested that the flow which fed some of them had uplifted the basement and fractured it to form rift valleys. There is no agreement upon how many of the great volcanoes in East Africa are over plumes, but all of them lie along gneiss belts. Hence it is not known to what extent rift valleys spread from volcano to volcano and to what extent they lengthened along belts of weakness (Figs 13 and 16).

Dana (1849; Stearns, 1985) had already commented on the fact that in ocean basins the chain of the Hawaiian Islands appears to increase in age towards the northwest, and that the ages of the Society and Samoan islands also change as if all had formed at ends of spreading faults (Betz and Hess, 1942). After Hess (1962) had proposed sea-floor spreading in the Pacific, Wilson (1963, 1965a and b) and Morgan (1971) suggested that surface flow over plumes rising from a deep stationary source could explain the increase in age of the extinct volcanoes backwards along the tracks of these volcanoes.

Acceptance of the importance of mantle plumes was slow until it had been demonstrated that these volcanoes share many striking characteristics which may be summarized. Sleep (1990) has just published a fuller account.

(1) Most plume volcanoes leave tracks, which may be straight like the Hawaiian Islands, or they may change direction as do the Emperor Seamounts (Dietz, 1954; Morgan, 1972) or branch so as to explain the peculiar patterns of some groups of islands, like Rodriguez and Reunion Islands, like Darwin, Wolf and Galapagos Islands (Morgan, 1978) or like Oeno, Henderson and Ducie Islands and Crough Seamount relative to the Southern Tuamotu hot spot plume (Okal and Cazenave, 1984 and 1985). There has been debate about the existence and number of plumes which have formed parallel or branching lines of volcanoes in the Tasman Sea and Eastern Australia (Sutherland, 1983; McDougall and Duncan, 1988; Johnson, 1989).

(2) Morgan (1983) suggested that some plumes only break through intermittently, thus leaving discontinuous tracks, for example across the ocean floor to Bermuda and across the Canadian Shield. He proposed that, if they do not break through, they may leave ridges to mark their passage, but this seems to require further examination especially since it has also been suggested that flow, without plumes, may form uplifts as in Botswana (Wilson, 1988).

(3) A few plumes, like those in the Sahara, (Fig. 13) have left no tracks, either because they had not enough energy (Morgan, 1981) or because the African plate was stationary when they were formed (Burke and Wilson, 1972).

(4) The lithosphere around most hot spots has been raised, as Fig. 13 shows in Africa, and as is true for the Yellowstone and New Mexico calderas, which as Suppe *et al.* (1975) have shown lie close to the two ends of the largest region of high elevation in North America (Fig. 14).

(5) Crough (1983) has argued that plume volcanoes tend to uplift and break through the continental lithosphere, but not through the oceanic lithosphere unless plates have migrated to move continents over them. Minster and Jordan (1978) have shown that there is little relative motion between plumes which thus form a worldwide frame of reference.

(6) So long as only a few volcanoes were known to have uplifted the basement or to have left tracks, little attention was paid and the existence of this special group was generally ignored (Anon, 1973). Then chemical analyses by Schilling (1973a and b), Schilling and Noe-Nygaard (1974) and later by isotopic analyses Dupré and Allègre (1973), O'Nions and Oxburgh (1983) and O'Nions (1987) showed that plume volcanoes were derived from a different source than MORB (mid-ocean ridge basalts).

(7) Measurements of heat flow and of the volumes of ash erupted from volcanic calderas have demonstrated that some volcanoes may erupt with an energy at least two orders of magnitude greater than any historical eruptions. Thus 2 Ma a single violent eruption ejected 2500 km^3 of rhyolitic ash to create Island Park caldera about 50 km west of the present Yellowstone volcanic centre (Blackwell, 1989). In comparison, in 1980, Mount St Helens emitted only 1 or 2 km^3 of ash.

Thus, recent discussions which have held that only impacts by meteorites or asteroids could be large enough to have been the cause of biological extinction, have underestimated by two or three orders of magnitude the power of those rare volcanic eruptions due to mantle plumes and failed to appreciate that since the plumes arise at the core–mantle boundary they may have similar compositions to those of meteorites and asteroids.

(8) The combination of a stationary frame of reference, of extreme energy and of a special isotopic composition different from MORB are the features which suggest

that plumes rise from the core-mantle boundary or close to it (Fig. 10). Kellogg and Turcotte (1990, p. 430) have explained the origin of plume lavas in the following way: 'The rapid convective mixing in the mantle indicates that this more primitive material cannot persist through the entire history of the Earth as blobs in a mantle which convects as a whole. Instead, the upper mantle, which is the source of MORB, is probably convectively isolated from the lower mantle, which is less depleted than the upper mantle. The more primitive material seen at the Hawaiian hot spot comes from the lower mantle by entrainment in upwelling plumes'.

If the lower mantle is more viscous than the upper mantle, it could serve to anchor mantle plumes rising from it and, if it forms a thin layer, it would be hard to detect. There is at present no way to solve this problem to everyone's satisfaction, but Bercovici *et al.*, (1989) and Kellogg and Turcotte (1990) have proposed a solution which seems to meet most arguments. It is that mid-ocean ridges are generated higher in the mantle than the plumes which rise from the less disturbed lower part and which have a different composition (Fig. 10).

In addition to this pattern of general circulation, Frank (1968) has proposed a simple physical explanation for the shape of island arcs.

Above the several subduction zones the surface breaks in one or other of two different forms. One pattern is marked by arcs, many of which are circular and all of which, except for the three in the Alaska and the Antarctic peninsulas and in southern Chile, lie off shore. In other places the break in the lithosphere follows ocean trenches close to continental coasts. An illustration by Vine (1970) and a discussion by Renkin and Sclater (1988) serve to explain how the crust increases in density (Fig. 17). No arcs form where the subducted oceanic crust is young, but arcs always form where it is old. The change in age occurs about 60 Ma, close to the Tertiary–Cretaceous boundary.

Scheidegger and Wilson (1950) examined the shape of island arcs and showed that a dozen are precisely circular. They were unable to provide an explanation, but Frank (1968) has suggested that the reason is, if the surface of any sphere (for example, a soft tennis ball) is pushed inwards, the least distortion and the least energy are required when the boundary of the depression is circular. Fukao and Yamaoka (1987) have discussed why multiple arcs occur.

Karig's (1970, 1971) statement that back-arc intrusions accompany arc formation is of course true. These are probably connected with the offshore movement of the arcs, but this fact does nothing to explain why any arcs are circular. Hence an explanation along the lines of Frank's is still necessary.

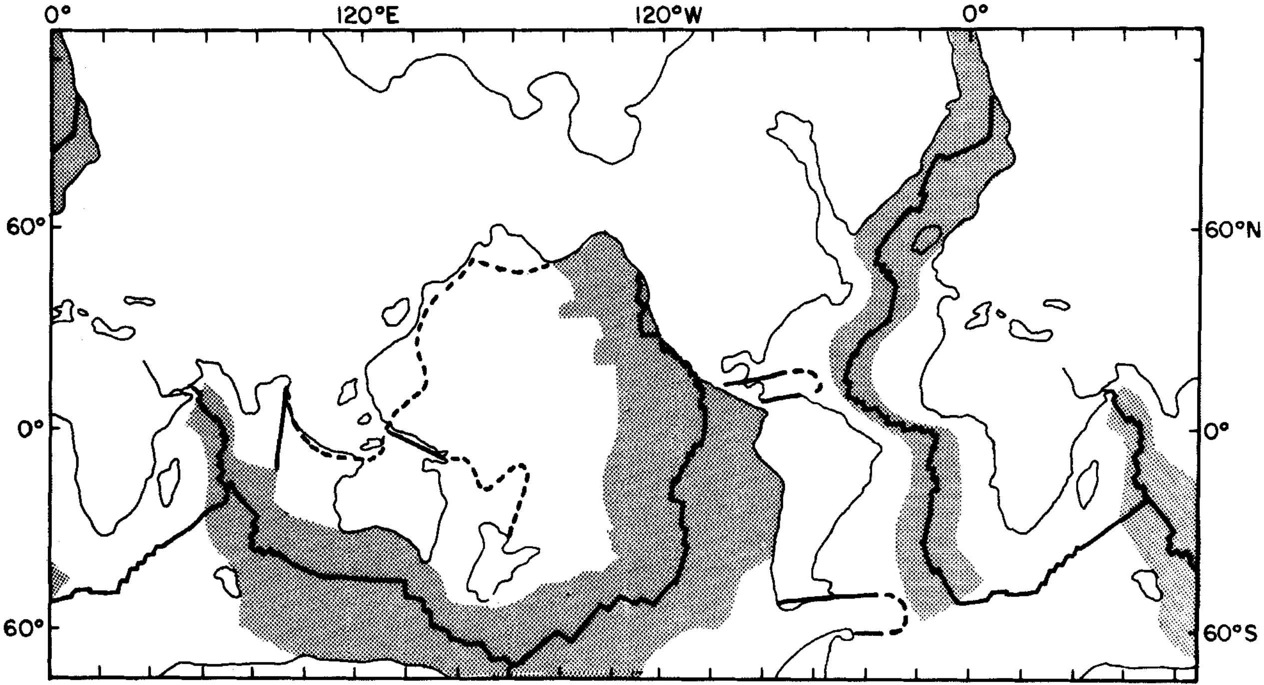


Fig. 17. *World map showing by a line the boundary between areas of continental and oceanic crust, and by shading areas of ocean floors formed during the Tertiary and latest Cretaceous periods. Unshaded ocean floors are older (after Vine, 1970). Note that, in the contracting Pacific Ocean, island arcs have formed where older ocean floor is being subducted and coastal trenches where younger floor is being subducted.*

COLLISIONS BETWEEN SURFACE FEATURES: RIDGES AND CONTINENTS

The acceptance of plate tectonics involves recognition that surface features migrate and hence may collide with one another. Consideration of the subject reveals that collisions have been frequent and that many factors combine to produce a wide variety of types.

One factor which has influenced collisions is that different features on the Earth's spherical surface rotate at different rates about different poles. Minster and Jordan (1978) have shown that hot spot plumes maintain approximately the same relative positions and thus provide a fixed reference frame. Rifts and mid-ocean ridges form over plumes and hence, when they first form, they are also stationary in that frame , but if two such ridges are parallel and have no subduction zone between them, their spreading must cause one or both of them to leave the founding plumes.

When plates move away from ridges, they carry continents with them and the movement of continents and their margins will carry subduction zones about. Also island arcs may separate from continental coasts. Thus most features of ocean basins and their margins are in constant, slow motion and so to a lesser extent are some continental features.

Important in any collision is the question of whether a surface feature is an inactive body like an ocean floor, or whether it is actively upwelling like a hot spot volcano or a mid-ocean ridge. Also important is the question of whether the feature is thick and buoyant, like continents, or shallow and dense like ocean floors. Because continents are thick and light, subduction at their margins will create a larger tectonic disturbance (e.g. the Andes or the Himalayas) than the subduction of ocean floor or even a mid-ocean ridge beneath an island arc (Grow and Atwater, 1970). Most mountain ranges have involved collision. (The East Africa Rift Valley margins are one exception). Hence consideration of the types of surface features involved in collisions may aid in the classification of mountains. This paper will only discuss two examples, first, ranges formed by collisions between a mid-ocean ridge and a continent and second, the role of collisions in the transport of thrust sheets.

The simplest case of a collision between a mid-ocean ridge and a continental coast can arise, paradoxically, when neither is migrating. This is possible because besides moving laterally, mid-ocean ridges, rifts and subcontinental ridges (like the Botswana uplift) may extend end-on. This process of end-on extension seems to have been repeated many times, as happened when the Atlantic and Indian Oceans extended northwards (Wilson, 1988). This type of growth enables mid-ocean ridges to collide with continents on coasts along which there is no subduction. Such a collision may enable a mid-ocean ridge to penetrate into a continent, as occurred in the Gulf of Aden (Matthews *et al.*, 1967; Morgan, 1981), but alternatively a lengthening ridge may fail to do so, as happened further south along the same coast (Coffin and Rabinovitz, 1987; Cochran, 1988).

Most features, except hot spot volcanoes, are elongate in shape and, if so, the angle at which collision occurs should be considered. Thus Menard (1960) showed that the East Pacific Rise meets the coast of California at an obtuse angle. At that time he did not believe in continental drift and so did not realize that the migration of North America could have caused the collision. Nevertheless he considered that the rise continues beneath the continent to reach the North Pacific, but Atwater (1970) and Atwater and Molnar (1973) held that the ridge was transformed into the San Andreas fault which cut it off. Atwater (1970) noticed that besides the San Andreas fault a broad band of disturbance extends inland across the Basin and Range and Colorado Plateau provinces. The disturbance had formed opposite to the San Andreas fault and was contemporaneous so she attributed the disturbance to the collision, without much explanation. Dixon and Farrar (1980) and Farrar and Dixon (1980) have discussed other possible complexities.

Other similar examples of collisions of mid-ocean ridges with continents, at acute and obtuse angles respectively, are those of the Chile Rise with the coast of southern Chile (Nelson and Forsythe, 1988) and of the Explorer Ridge and plate with the coast of British Columbia (Yorath and Chase, 1981; Dehler and Clowes, 1988; Bérubé *et al.*, 1989). The Chile Rise and the Explorer Ridge both appear to be cut off respectively by the great Liquiñe–Ofqui and Queen Charlotte Islands coastal faults, which resemble the San Andreas fault (Fig. 18). In neither case is there any indication of large disturbances inland, which raises the question of why the Basin and Range province which formed in the southwestern United States has no equivalent in these places (Fig. 9). Can the United States case be related to the Yellowstone and Valles caldera mantle plumes which appear to feed the uplifts of the Wasatch and Southern Rocky Mountains and which were only recognized in the 1970s (Morgan, 1971; Suppe *et al.*, 1973; Gough, 1984)? Zoback and Zoback (1980 and 1989) and Gough (1984) have shown that the disturbed region coincides with a change in the crustal stress pattern (Fig. 9) and is related to the locations of the two calderas.

A fourth collision of a ridge with the west coast of the Americas is where the Cocos plate has impinged upon the coast of Central America orthogonally producing a complex collision without any large horizontal shear fault (LeFevre and McNally, 1985; Adamek *et al.*, 1987). Clearly the history of past collisions is a vast subject which has been neglected and which may have had large effects upon historical geology.

These four examples demonstrate that the apparently simple case of a collision of a mid-ocean ridge with a con-

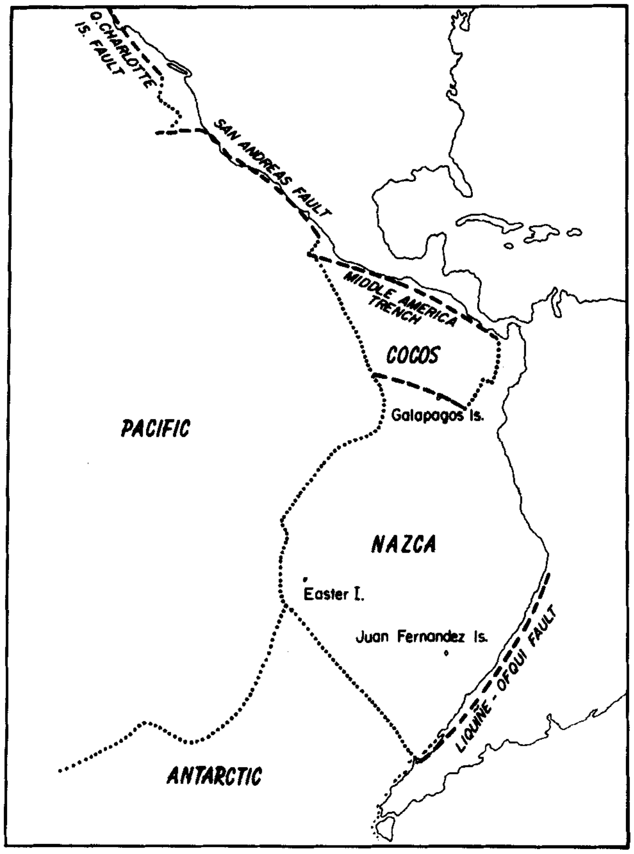


Fig. 18. *Sketch of west coast of North America, showing that the great Liquiñe–Ofqui, San Andreas and Queen Charlotte Islands transform fault-zones strike north from junctions of ocean ridges with continents. The Middle America Trench, which is a subduction zone not a transform fault, is also shown (after Simkin* et al., *1989).*

tinent at a coastal subduction zone can produce three different effects. Not only can such collisions take the forms noted, a simple coastal shear, a coastal shear with a broad belt of disturbance inland and a subduction with no coastal shear, but one can imagine other cases. One example would be the collision of a ridge with a coastal trench to which it is parallel. That could produce no transform shearing parallel to the coast, but might result in the ridge being subducted as a hot welt parallel to the coast and moving inland at depth. One can suggest other possibilities. If a ridge had one or more mantle plumes on it when it collided, what would happen to the plumes when the ridge was cut off or subducted?

TRANSPORT OF THRUST SHEETS AND OTHER DETACHED FLAKES

The problem of how to transport thrust sheets is nearly as old as structural geology itself, and although many scientists have proposed partial solutions and palliatives the problem keeps recurring. The difficulties were well stated by Smoluckowski (1909) and Evans (1989). If a welt rises or if one migrates then Hubbert and Rubey (1959) have shown how good lubrication may enable a sheet of rock to slide down the rising slope and do so at a small angle, but that solution will not suffice if there is no slope to enable gravity to work. Price (1988) and Dahlen and Suppe (1989) have proposed other solutions for other cases, but not all thrust sheets meet the conditions they require.

The proposal that actively upwelling mid-ocean ridges or hot spot plumes may collide with coasts and may migrate inland also seems to be worth exploring as a cause of transport of thrust sheets. One reason for being hopeful is that all major thrusts seem to have been initiated at a coast and to have moved inland from the sea. Some apparent exceptions like the Moine thrust in Scotland and the thrusts on the extreme eastern coasts of Canada and New England can be explained by transposition of the thrusts, which were apparently formed in the normal manner during the closing of the Iapetus Ocean, and were then transferred to the opposite coasts of the opening Atlantic Ocean (Wilson, 1988).

On the west coast of the Americas a series of disturbances formed due to a variety of collisions (Fig. 14). The oldest to be considered produced a great series of batholiths which formed for the most part close to the west coasts of the Americas during the Jurassic period. Subduction of ocean floors produced abundant andesitic lavas, metamorphism and uplift.

It might seem paradoxical that these, the oldest disturbances, lie so close to the coast, while belts of rocks which were disturbed more recently lie further inland, but Bateman and Eaton (1967) have offered an explanation in the case of the Sierra Nevada. They agree that the rocks there had been disturbed in the Jurassic period, but state that the present uplift was only 'formed by the westward tilting . . . in late Cenozoic time, of a huge block of the Earth's crust'.

Crough and Thompson (1977) have suggested that the cause of the delay and recent uplift may have been due to recent thinning of the lithosphere as progressive warming of the mantle underlying the Sierra Nevada followed the motion of the Mendocino triple junction northwards (Atwater, 1970). This converted sub-Sierra lithosphere to asthenosphere.

Armstrong (1988) has broadly agreed. He has reported from a study of 3000 isotopic age determinations that beginning at about 230 Ma in late Triassic time, extensive magmatism widely affected many exotic terranes of the Canadian Cordillera, becoming most extensive from 200 to 155 Ma and reaching into North America as far as the Omineca Belt in eastern British Columbia in early Late Jurassic time, that is about 180 Ma. After 155 Ma plutonism diminished.

On totally different stratigraphic evidence Bally (1975) suggested that at the time of the Jurassic magmatism the cover and basement of the eastern Canadian Cordillera became detached, and Price and Mountjoy (1970) 'suggested that the basement moved vertically and the cover rocks flowed under the pull of gravity away from a rising dome of metamorphic rocks in the central zone of the eastern Canadian Cordillers' (Struik, 1988). Struik considered that these movements began between Early Jurassic and mid-Cretaceous time (200 to 100 Ma) so that the stratigraphic evidence agrees with Armstrong's isotopic dates for magmatic events.

Armstrong (1988, p. 56) found a recurrence of widespread plutonism between 110 and 90 Ma followed by 'a distinct lull in magmatism' and he also states that 'from 55 to 45 Ma (latest Paleocene to Middle Eocene), widespread and voluminous magmatism occurred in all terranes. While Struik (1988, p. 729), for different reasons, found that at the same time 'the thrust stack was further compressed and metamorphosed during mid-Cretaceous to Eocene time (100 to 50 Ma) and now makes up the Eastern Canadian Cordillera' (shown as Northern Rockies in Fig. 9).

Commenting upon these dates Armstrong (1988, pp. 85–86) states that 'Implicit . . . is the concept that magmas arise from subduction of Pacific Ocean floor under North America and that explanations for magmatic episodes must include changing geometry and rate of subduction'.

More specifically, Armstrong states that 'a specific plate-convergence event along the west coast of North America is the Farallon pulse (Jurdy, 1984). . . . It corresponds so exactly to the Eocene magmatic event as to make a cause-and-effect relationship seem inescapable'.

Both Armstrong and Struik provide details of the effects of many moving, exotic terranes in British Columbia, but it appears likely that plate tectonics can explain other details of Cordilleran structure as well. It is suggested that, if a continent collides at a subduction zone with a mid-ocean ridge which is parallel to it, the result may be that the overriding generates a hot welt which migrates inland. Such migrating uplifts may have raised thrust sheets and stacks of strata in the Canadian Rocky Mountains (and in their extension into the northern United States) and thus provided slopes which have enabled gravity to transport the sheets and stacks inland. Gough (1986) has reported that a conducting welt which may be the dying stage of such a moving ridge may lie beneath the Omenica Range today. Eventually all such welts cool and subside so that evidence of their activity will be lost and the motion of the thrust sheets becomes a mystery. This could apply in many ranges.

It should be noted that if a mid-ocean ridge and a trench are parallel when they collide, horizontal shear faulting cannot in that configuration cut off the ridge, so a ridge may be subducted and penetrate far inland. This would not contradict Atwater's view (1970) that collision at other angles may cut off a mid-ocean ridge at the coast.

This paper has tried to show that flow and vertical upwellings in the mantle have played an important part in the structure of continents. On the ocean floors it is widely accepted that great uplifts, particularly mid-ocean ridges and hot spot volcanoes, are due to upwelling currents in the mantle. The currents elevate the lithosphere over the region where they are rising. Likewise ocean trenches mark the descent of currents at subduction zones. This relationship between topography and underlying upwellings has been clearly shown by recent work on seismic tomography (Anderson and Dziewonski, 1984; Woodhouse and Dziewonski, 1984; Bercovici *et al.*, 1989).

On continents such connections are rarely mentioned, but can such effects be seen? In Fig. 13 the major uplifts of the three hot spot volcanoes in the Sahara and of the rift valleys and ranges through Afar, Ethiopia, East Africa and Botswana may all be attributed to upward flow in the mantle. The Atlas Mountains are related to and are part of Alpine subduction in the Mediterranean region. Hence all the high regions in Africa, except perhaps the Drakensburg uplift in the southeast, can be related to mantle upwelling or subduction.

An examination of Figs 9 and 14 shows that the Yellowstone and Valles calderas lie on the great Wasatch Uplift and on the Southern Rockies respectively and mark either end of the most extensive high region in North America. Surely this cannot be due to chance. Strange and Woollard (1964) quoted by G.P. Eaton *et al.* (1978) have made two of the scarce references to such a relationship between topography and tectonics in North America. Cogley (1985) by drawing hypsometric maps (i.e. averaged topography) of all the continents has made these connections easy to study.

ACKNOWLEDGEMENTS

This paper is based upon sixty-six years of experience which began with field work on the Canadian Shield as a schoolboy assistant and included studying classical physics and geophysics at the Universities of Toronto and Cambridge, before modern physics had been developed. At Princeton University I mapped a thesis area lying across the high Beartooth Mountains north of Yellowstone Park. During visits to one hundred countries, Earth scientists have welcomed me most hospitably and described much of what is reproduced here. I cannot thank them individually or adequately. I can only mention my gratitude for some major opportunities including this and many earlier visits to Europe and longer stops to Ohio State University, University of Cambridge, Australian National University, Institute of Geophysics and Planetary Physics, San Diego, (as a C.H. and Ida Green Fellow), California Institute of Technology (as a Fairchild Fellow) and Mobile Research Laboratories in Texas. I have been a guest in many places with many fascinating tours in Antarctica, Africa, China, Eastern and Western Europe, India, Japan and South America. Colleagues, especially Professors R.M. Farquhar, A.E. Litherland, L.W. Morley, Professor D. York and Dr J. Mitrovica, have read and made comments on this manuscript which was prepared by E. Khan and Moira Arnot. I extend thanks to them all, and to the University of Toronto and York University for use of facilities.

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