LETTERS TO NATURE

PHYSICAL SCIENCES

Black Holes and Temporal Ordering

THE "Arrow of Time" has been much discussed by philosophers and by some scientists[1], and various manifestations, which have also been offered as explanations of this directionality, are to be noted in the world around us. For example, asymmetry of time is observed in thermodynamics, an increase in entropy is predicted from statistical mechanics, there is a consistent choice of retarded solutions to time symmetric equations of radiation theory and expansion of the universe is deduced from cosmological theory; in addition a temporal arrow is inferred from the asymmetry of matter and antimatter in the universe. A striking feature of such observations is that the directions of the arrows agree.

Within general relativity it is necessary to impose time orientability on the E_4 manifold such that the arrows placed on timelike world lines agree in sign. Thus an assumption is made concerning temporal asymmetry which may not be derivable within the context of general relativity.

A theory purporting to explain "Time's arrow"[2] generally involves a plausibility argument concerning one of these arrows within a system which is in contact with its complement, the remainder of the universe. The universe is supposed to act as an infinite sink for the dissipation of energy from the system, and, as a result of the interaction or interdependence of all systems and processes, it is concluded that all of the manifestations of temporal asymmetry within the universe agree on direction.

A consequence of this argument is that within a system isolated from the remainder of the universe, asymmetry of temporal order may not be maintained; in other words, the system will reach a state of dynamical equilibrium. To some extent a Black Hole provides such a situation, since world lines and radiation may not escape from a system which has fallen through its Schwartzschild radius[3]. It is, however, possible for exterior particles and radiation to enter the hole, and some of its rotational energy may be extracted from the ergosphere[3].

The Wheeler–Feynman absorber theory of radiation[4] offers an explanation for the appearance of retarded radiation, resulting from initially time symmetric solutions to Maxwells equations, by establishing a connexion with the thermodynamic properties of matter in the universe. Within a Black Hole, however, while retarded signals converge towards the origin of the singularity, it is possible for advanced signals to escape along past pointing null cones. Within the Wheeler–Feynman explanation one would be faced with the possibility of the reversal of temporal direction inside the hole and the emission of advanced radiation.

Thermodynamic arguments within a Black Hole require an unambiguous meaning to be given to the notion of entropy within the hole. It would appear, however, that dissipative processes with the attendant spontaneous increase in "disorder" are not possible within the Hole.

It therefore seems reasonable to question the assumption of a fixed temporal direction for the collapse of a Black Hole and the issue of the final state. Indeed, one may go further and question the meaning of the terms "time" or "proper time" as applied to processes within the Black Hole since, as a result of the bending of light cones towards the origin, it is not generally possible to construct a "clock" in which retarded signals are exchanged between two world lines inside the hole. Thus the nature of temporal flow in regions of pathological geometry is ambiguous.

My object here is to draw attention to one of those classical assumptions as to the nature of time which has remained unexamined in the light of quantum physics and general relativity, and to stimulate discussion directed towards clarification of these matters.

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Is the African Plate Stationary?

THE islands of St Helena, Tristan da Cunha and Gough lie respectively 500 km, 450 km and 450 km east of the crest of the Mid-Atlantic Ridge[1] (Fig. 1). We believe that they overlie hot spots or convective plumes in the mantle and that the Walvis Ridge is the trail of a hot spot marking the relative motion of the African plate over the mantle since the opening of the South Atlantic[2,3]. We suggest that the termination of the ridge at Tristan and Gough records the cessation of this relative motion. That this occurred about 25 m.y. ago is indicated by a spreading rate of 1.7 cm/yr/side and because the two islands lie just east of magnetic anomaly six[4]. Spreading of the sea floor continued and has moved the crest west from the hot spots. The Discovery and Meteor seamount chains are concentric with the Walvis Ridge; they too terminate some distance east of the crest of the Mid-Atlantic Ridge and may also be hot spot trails terminating on the same isochron. The position of Bouvet Island is harder to interpret because of its location at the western end of the Atlantic-Indian Ridge.

On the other side of the African plate, Mauritius and Reunion (200 km apart) also lie on anomaly six at the end of a ridge concentric with the Walvis Ridge[5] which suggests that they also overlie a plume. At the same time that relative motion between the African plate and mantle ceased (25 m.y. ago) the pattern of spreading in the Indian Ocean altered and what had been the Chagos Fracture Zone became the crest of a new Central Indian Ridge[5]. Its subsequent spreading has created young ocean floor east of Mauritius.

Stratigraphic evidence and K/Ar dates from widely separated areas on the African plate indicate a roughly simultaneous upsurge in volcanic activity about 25 m.y. ago (Table 1). If this volcanism was generated over plumes and the African plate has moved laterally over them during the past 25 m.y., then the volcanoes should form parallel lines across Africa.

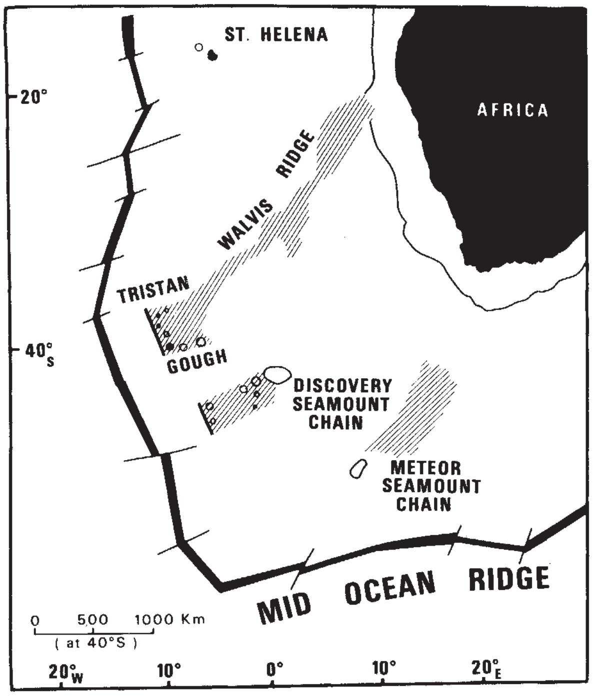

Fig. 1 St Helena, Tristan, Gough, and the ends of the Discovery and Meteor seamount chains lie some hundreds of km east of the crest of the Mid-Atlantic ridge. This could be the result of relative motion between the African plate and hot spots stopping about 25 m.y. ago.

Table 1 Neogene Volcanism on the African Plate

Volcanic group	Approximate length (km)	Approximate azimuth (degrees)	Age range	Ref. No.
Tristan	—	—	18 m.y. to Recent	27
			20–25 m.y. to Recent	28
Gough	—	—	6 m.y. to 2 m.y.	27
Cape Verde	300	Circular	Mio-Pliocene to Recent	29
Madeira	50	110	Cenozoic	—
St Helena	—	—	14 m.y. to 7 m.y.	33, 34
Canary Islands offshore	300	110	22 m.y. to Recent	30
Canary Islands inshore	250	45	22 m.y. to Recent	30
Dakar	50	—	Miocene (?) to Lr Pleistocene	31
Air	100	—	Cenozoic	32
Edgere, Hoggar	60	45	Cenozoic	32
Ajjar, Hoggar	100	75	Cenozoic	32
Atakor and Anahef, Hoggar	250	45	Cenozoic	32
Jos	100	135	Pliocene to Recent	35
Benue	500	45	22 m.y. to Recent	35
Biu	80	125	5 m.y. to Recent	35
Cameroun Zone (8 uplifts)	1,100	30	25 m.y. to Recent	35
Tibesti	400	120	Post-Eocene to Recent	36
Haruj	400	120?	Pliocene to Recent	37
Jebel Marra	200	0	Tertiary to Recent	38
SE Uganda older group	60	10	30 to 25 m.y.	39
E Uganda younger group	300	0	22 to 12.5 m.y.	39
Kavirondo rift	200	60	22 to 2 m.y.	39
Kenya rift	800	0	Miocene to Recent	40
Ethiopian rift	400	50	Eocene to Recent, mainly less than 25 m.y.	41
Rungwe	80	140	Pliocene to Recent	42
Comores	200	120	? Miocene to Recent	43
Mauritius	60	30	12 m.y. to Pleistocene	44
Reunion	75	130	Pleistocene	45

Although the volcanoes are arranged in lines these lines have no consistent trend nor do they get younger in any one direction. Where age data are available they show that the volcanism either started or became greatly intensified at the beginning of the Miocene about 25 m.y. ago. Volcanoes at plate margins are omitted.

If the motion averaged 1 cm/yr the lines of volcanoes would be 250 km long and all would become younger in the same direction. Fig. 2 and Table 1 indicate that although African Neogene volcanoes are commonly arranged in lines the lines are not parallel and there is no evidence of consistent age variations from one end to another. This pattern of volcanism is consistent with the hypothesis that the African plate halted and has been virtually at rest for the past 25 m.y. with each Neogene volcanic area overlying a different plume.

Before the acceptance of plate displacement it seemed appropriate to relate surface structures directly to those of the underlying asthenosphere but this is no longer realistic unless a plate can be shown to be temporarily at rest.

Krenkel[6] was the first to draw attention to the basin and swell structure (Fig. 2) which is peculiar to Africa, and Cloos[7] linked these structures to rift valley formation. Burke and Whiteman[8] have postulated a genetic sequence, discernible in Africa, from uplift, through rifting and triple junction formation to continental separation. We suggest that these peculiarities of Neogene African structure (in no other continent are they so prominent) may be a consequence of the standstill of the African plate over the asthenosphere.

Fig. 2 is a sketch of the Neogene volcanoes, basins and swells of Africa and these features may reflect the structure below the bottom of the lithosphere. The basins and swells shown in the figure (which are generalized from topographic maps) have wavelengths of about 2,000 km and amplitudes of about 1 km. Smaller scale uplifts about 1 km high average about 100 km across and 200 km in length[8]. These smaller scale features are associated with major negative gravity anomalies and lines of volcanoes which show no consistent ageing pattern (Table 1).

Nine volcano crested uplifts are tangentially disposed about the Chad basin and another eight or nine arranged in a straight line form the Cameroun Zone, half on the continent and half in the ocean. The Eastern and Western rifts are marked along their lengths by local uplifts of the same scale and the rifts themselves show a rude tangential disposition within the East African Swell. It appears that structures of two orders of magnitude, the smaller with a marked horizontal asymmetry, may be making their presence felt through the African plate.

There appear to be systematic differences between various parts of the continent which may reflect differences deep in the mantle. Higher ground is concentrated to the east and south of the Congo basin and there is no Neogene volcanism south of that basin. Rifting is restricted to the north-east and Bouguer anomalies are about 60 mgal lower in the centre of the continent than in the north[9]. Earthquakes are closely linked to the rift system although a line of epicentres extends south down the axis of the continent[10].

Although the present phase of uplift, volcanism, rifting and continental break-up began in Africa only about 25 m.y. ago, earlier activity between 100 and 200 m.y. ago when Gondwanaland broke up was similar[8,11]. The absence of a consistent ageing pattern along lines of African Mesozoic intrusives may also record a former standstill. If this is generally true fossil rifts and aulacogens up to 2,000 m.y. old may record local plate standstills as far back as the beginning of the plate tectonic regime[12]. Because oceanic lithosphere is only two-thirds as thick as continental lithosphere[13] more volcanoes related to plumes may form in ocean basins except in the case of stationary continents.

We relate most if not all volcanoes to plate boundaries or to plumes because of evidence in Hawaii and because there are at

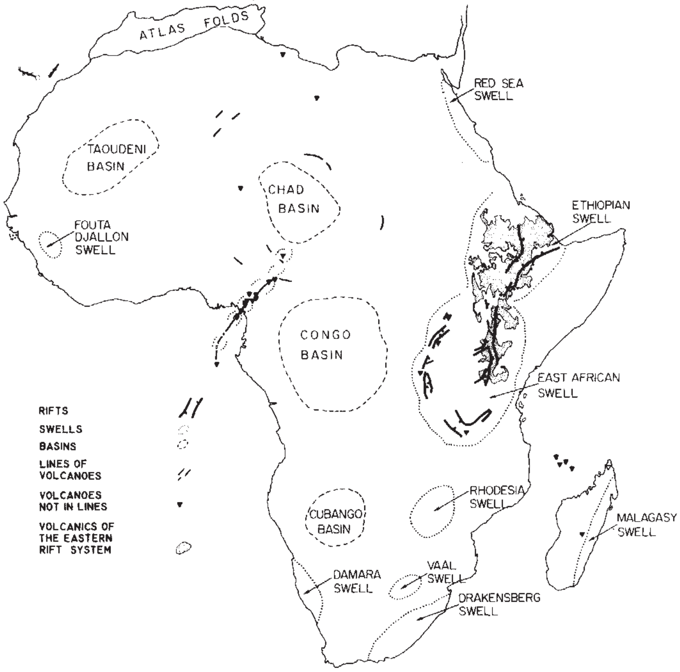

Fig. 2 Neogene basins, swells, volcanic uplifts and lines of volcanoes on the African plate. The lines are not concentric and do not get younger in consistent directions. This can be interpreted as indicating that the African plate is at rest over the deep mantle.

least two indications that African Neogene magmas originate from below the lithosphere. First, the continental lithosphere is about 110 km thick and the alkali basaltic composition which characterizes most African Neogene volcanism requires partial melting at this or greater depths[14]. Second, the huge volume of material in the Neogene volcanics of East Africa (600,000 km^3) would be hard to derive from within a 110 km thick lithosphere[15].

The accumulated data suggest that the rise of swells in Africa may be due to convection plumes in the mantle which by lifting parts of the continent have resisted and halted eastward motion from the Mid-Atlantic Ridge and have held Africa stationary for about the past 25 m.y. Meanwhile sea floor spreading has caused the crest of the Mid-Atlantic Ridge in the South Atlantic to move westwards, off the plumes which originated it. The implication that fresh plumes rising under continents are more vigorous than older plumes in oceans may also explain why mid-ocean spreading rates slow down as oceans broaden. If Africa halted with only a minor contemporary change in the Atlantic spreading rate[16], the rate of rotation of the Americas plate westward over the mantle must have doubled about 25 m.y. ago.

Dott[17] noted many examples of tectonic changes around the Pacific at that time. Jackson *et al.* hold that the Hawaiian–Emperor Chain is the trail formed over a persistent melting spot or plume in the mantle[18] and ascribe the sharp bend in the chain to a sudden increase 24.6 ± 2.5 m.y. ago in the westward component of motion of the Pacific plate to a rate of 14.8 cm/yr in a direction west-north-west. Others favour a somewhat slower rate[19]. The East Pacific Rise at the corresponding position of about 10° S has a total spreading rate of 12 cm/yr, suggesting that the crest of East Pacific Rise is moving westwards over the mantle at 8.8 cm/yr or less. If stationary plumes underlie Galapagos and Easter Islands this could explain why these islands now lie east of the crest, although their separation from the crest seems to be rather small. Also the Nasca plate should be moving westward at 2.8 cm/yr or less and may be nearly stationary. Perhaps the acceleration of the Americas plate halted it, in spite of the intervening subduction zone. Molnar and Sykes[20] note only "a minor belt of activity" between the Nasca and Caribbean plates near Panama so that the latter may also be nearly stationary.

Relative to Africa, Eurasia is rotating southwards about poles at 9° N, 46° W and 9° S, 134° E[21]. The second is at the eastern end of Indonesia and any part of the Eurasian plate over it would be stationary relative to Africa. A series of faults crossing China from Burma to Korea give indications of left hand motion implying that the China plain is rotating southward less rapidly than the rest of Eurasia. Thus much of China and all of South-east Asia between the Indian Ocean and Philippine Sea may be halted. As in Africa, China has much volcanism that started in mid-Tertiary time and the Ordos Plateau appears to be a dome which is rising rapidly with a rift valley system around it from Sian through Taiyuan to Peking (ref. 22 and personal communication from Chinese scientists). Another seismic line extending from the Pamirs to past Lake Baikal may mean that Sinkiang, Mongolia and the Lake Baikal rifts are moving only slowly over the mantle, again like Africa.

If these absolute motions over the mantle are approximately correct it is possible to generalize that circular island arcs have formed where ocean floors are advancing over the mantle towards the convex sides and continents are retreating from or stationary behind their concave sides (North-east Asia, Aleutian, West Indian and Scotia arcs and Indonesia from the Andaman to Javas Seas). On the other hand, arcs have not formed off coasts which are advancing over the mantle and ocean floor which is nearly stationary over it (Chile–Peru and Mindanao).

The orocline concept[23] is incompatible with strong plates and offers no reason why arcs should be circular. Frank's explanation[24] might be expected to apply where an oceanic plate is advancing over the mantle and free to shape its own subduction zone but not where a continent is advancing over the mantle and overriding the zone. Plafker[25] supports this interpretation for the Aleutians, but is uncertain about the motion in Chile although recognizing great structural differences.

It should be noted that two ridges, the South Atlantic Ridge and East Pacific Rise, seem to have spread smoothly about crests and poles stationary relative to the mantle throughout later Mesozoic and Palaeogene time.

The South Atlantic and Pacific oceans could expand without interfering with one another because subduction zones around the Pacific separated them but they would have interfered with the development of other oceans not so separated from them. For example, if the pole for spreading between Africa and the Americas was fixed near Greenland, the Americas and Eurasian plates, their rotation pole, now near New Siberian Islands, and the Arctic spreading ridge, must all have been moving over the mantle. This could explain why the spreading axis of the Arctic Sea has jumped to a new location at about 20 m.y. intervals[26] and similar arguments could explain the complex patterns of the Northern Atlantic and Indian Oceans and Tasman Sea.

Plumes seem to have average lives of the order of 100 m.y. Competition between vigorous fresh plumes and older ones appears to be the major cause of plate motion and of its changing patterns and rates, and hence the mainspring of geological history.

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Glaciation in the Somerset Levels: the Evidence of the Burtle Beds

KELLAWAY has postulated[1] an ice stream of Wolstonian (Saale) age moving from the Bristol Channel, across the lowlands of Somerset and into Wiltshire. He suggested that erratic rocks, including the "bluestones" from the Prescelly Hills of Pembrokeshire, subsequently erected in the Stonehenge monument, were carried into the chalk upland by this, or the earlier Anglian, ice sheet. At least one piece of the evidence he cites to support this hypothesis can be subjected immediately to critical examination. Kellaway described the Burtle Beds of Somerset in the following terms: "Other residual masses of glacial sand and gravel ('Burtle Beds') rise out of the marshes at Catcott Burtle, Weston Zoyland and Othery". Their marine origin is cursorily dismissed in the phrase "These outwash deposits, previously thought of as marine. . . . ". These deposits have, in fact, recently been the subject of detailed re-investigation[2,3]. This new work supports the conclusion by Bulleid and Jackson[4,5] that the sands and gravels of the Burtle Beds are of marine origin. If that is the case then Kellaway's "glacial" hypothesis is much weakened. It is, therefore, important to review the grounds for re-asserting the marine character of the Burtle Beds.

The Burtle Beds are confined to the valleys of the Rivers Brue, Parrett and Tone. Although the Kenn gravels[6] and the "marine Pleistocene" deposits in the Vale of Gordano[7] have been tentatively correlated with the Burtle Beds, this correlation has not been confirmed. Hawkins and Kellaway[8] conclude that the Kenn gravels are of glacial origin but do not give their detailed evidence. The distribution of the Burtle Beds proper (Fig. 1) is precisely that which would be expected to result from a marine incursion into the Somerset Levels. The known Holocene marine sands conform to a similar pattern if lower sea levels are taken into account. In no case are the Burtle sands and gravels found on the interfluves above the 50 foot contour, as could be expected if they were of glacial or fluvio-glacial origin. Their characteristic surface form reminds us of the sandbanks in the present Parrett estuary. So striking is the similarity that a comparison on both petrological and faunistic grounds seems desirable. Dr M. R. Dobson, of the Geology Department of the University College of Wales, compared the Burtle gravels with those from various locations in the estuary. He found that they are indistinguishable on petrological grounds. Dr J. D. Fish, of the Zoology Department, examined a collection of marine shells from the Burtle Beds and agreed with Prestwich's[9] original conclusion that they represent a fauna similar to that now inhabiting the British seas. It is pertinent to repeat Prestwich's assessment that "There is a marked absence of such northern shells as *Astarte borealis*, *Leda permula*, *Fusus islandica*, *Natica groenlandica* and others common in the Glacial drifts".

The upper surface of the Burtle sand and gravel deposits has clearly been subjected to non-marine erosion. The absence of surface cryoturbation phenomena, in spite of some evidence of solifluction, suggests that this erosion was dominantly fluvial rather than glacial or periglacial. The deposits give the appearance of having been dissected by streams flowing to the Parrett and Brue. This dissection has not disturbed the structures within the Burtle Beds which make it impossible to accept a glacial origin. Everywhere within the area south of the Mendips, the deposits are horizontally or nearly horizontally bedded. Shell layers, most often composed mainly of *Macoma baltica*, are almost totally undisturbed. A high proportion of the bivalves are still articulated. Occasionally locations are found where forms common on rocky shores occur in great numbers. A general picture emerges of a range of habitats comparable to that of the present estuary and without any of the signs of re-sorting and re-distribution which a glacial or fluvio-glacial disturbance would cause.

There are, however, much more substantial grounds for concluding that they are undisturbed marine deposits. A series of boreholes has been sunk through the Burtle Beds (Fig. 1 shows the locations at Catcott Burtle, Brickyard Farm and Cutley). The results are given in Fig. 2. The sands and gravels of the Burtle Beds are shown to rest conformably on clays of similar age, the microfaunas of which indicate a progressive marine transgression.

We examined ten selected samples from four of the boreholes