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Volcanism that pierces plate interiors is characteristically rich in alkalis and volatiles, and its cause and persistence are essentially expressions of the Earth's outgassing. The general balance of mobile elements (such as H, C, F and Cl) rules out recycling of sea floor, hydrosphere, sediments or atmosphere: furthermore, it is not in accord with accepted planet degassing budgets. The typical eruptive mode of volatile-rich magmatism means that the observed regional chemical variations, and even differences between adjacent volcanoes, must largely reflect source heterogeneity.

In a broader context, this magmatism is also at odds with a concept of continental crust underlain by strongly depleted (refractory) mantle. Repetition of activity along crustal zones of weakness shows that the lithosphere mantle (*a*) is structurally complex and (*b*) still holds continuing (or continual) rich reserves of mobile elements. Unbroken lithosphere muffles the evolutionary escape of volatiles from the deep mantle: any lesion that appears then offers easy escape channels, whereby volatiles are drained from a large mantle region and funnelled through the plate. Horizontal movement of thick continental lithosphere releases volatiles from deep sources, imparting some of the special chemical characteristics of the stable continental magmatism. Present evidence requires consideration of the continental lithosphere as a site of primordial heterogeneity that has been accentuated rather than diminished by geological processes.

Introduction

Much of the evidence for chemical heterogeneity in the upper mantle must come from igneous activity, in which gases may play an important role. Yet considerations of igneous processes commonly neglect to mention volcanic gases, or refer to them as if they were of a standard composition. Even some advanced modern treatments have attempted to explain most of the observed gas variations between volcanoes in terms of post-eruptive processes and relate them to a 'standard' composition (Gerlach & Nordlie 1975). Consideration of the enormous variations in the other magmatic variables, and the uncertainties about volcanic gas sources, would suggest that the concept of a standard volcanic gas (even for basalts) is unrealistic. Fortunately, there is now a growing body of observation, both natural and experimental, supporting the idea that volcanic gases vary with magma type (see, for example, Bailey 1974; Anderson 1975). Anderson summarizes the evidence for gas variability between oceanic tholeiites, tholeiites, alkali basalts and andesites. His conclusion that andesite magmatism is the major contributor to the hydrosphere neatly redresses the imbalance derived from the oft-used Hawaiian gas analyses (noted by Holland (1962) and shown here in table 1). A common feature of plate tectonic 'models' is that the hydrous character of andesite magmatism is attributed to recycling of meteoric water carried into the mantle with the subducted slab. Calculations based on Cl abundances (Anderson 1975) and the conclusions drawn from helium isotopes (Craig *et al.* 1978) indicate a good case for most of the H_2O being of juvenile origin. Juvenile H_2O might be released by compression tectonics from shallower storage sites in the leading continental edge, having been previously fixed in hydrous minerals when the geothermal gradient was lower. Whatever the mechanism, the gas output is distinctly different from mid-ocean ridge or intra-plate volcanoes, and must reflect source variations. Once variation of gas composition with major magma types is conceded, however, we are faced with the prospect of kaleidoscopic variations in terrestrial gas output (spatial, temporal and chemical) as the pattern of magmatism has varied throughout the Earth's history. The consequent potential for climatic and biological 'catastrophes' makes recourse to extraterrestrial events less persuasive! But some of the gas differences between broad magma types might be attributable to essential differences in magma forming processes, and others to vertical heterogeneity in the source. Another way to examine the possibility of mantle heterogeneity is to look at the same sort of magmatism in the same tectonic framework. For such a comparison, a mantle magma origin must be unquestioned: moreover, it must be possible to exclude crustal involvement, either by subduction having contaminated the mantle source, or by wall-rock reaction or assimilation during magma ascent. Ideally, the magmas would also be erupted through the crust with little or no differentiation, certainly without modification of the ratios of the gases (which would anyway be largely 'incompatible' with common solid phases). Given these requirements, the alkaline central volcanoes of the plate interiors make the best candidates. Their major element, trace element, and isotope chemistry are consistent with a mantle origin; they penetrate lithosphere of all different kinds, thicknesses and ages; in many instances they carry ultramafic nodules; and they are typically erupted in stable plate interiors, remote from possible subduction zones. Added to this, they are rich in volatile elements and gases, which is reflected in a volcanic style characterized by fragmental eruptions through central vents (mostly vividly exemplified by kimberlite). This combination of properties means that regional chemical variations in the same magma type, e.g. nephelinite, must largely reflect differences in the mantle sources. Detailed studies show that even among an overlapping group of contemporary volcanoes (which would normally be considered parts of the same magma stem) there can be differences reflecting source heterogeneity.

TABLE 1. COMPARISON OF VOLCANIC GASES WITH 'EXCESS' VOLATILES IN ATMOSPHERE, HYDROSPHERE, SEDIMENTARY AND WEATHERED ROCKS

(Values in percentages by mass.)

	H_2O	CO_2	Cl	N	S	H	others
average Hawaiian gases	64.3	23.8	0.16	1.60	9.97	0.05	0.07
'excess' volatiles	92.8	5.1	1.67	0.23	0.12	0.06	0.02

'Excess' volatiles taken from Rubey (1951). Average Hawaiian volcanic gases from Eaton & Murata (1960). Adapted from Holland (1962).

ALKALINE IGNEOUS ACTIVITY AND HIGH CO_2

Some of the features mentioned above are summarized in table 2, which highlights those characteristics that are antithetic to crustal differentiation or assimilation.

It has now become popular to ascribe alkaline magmatism to enhanced volatile activity, especially CO_2 activity (Bailey 1976). Mantle heterogeneity is therefore implicit because current schemes of magma genesis offer no mechanisms for modifying gas ratios. For a long time the widely accepted picture of volcanic gases has been that they consist largely of H_2O, followed by CO_2 and SO_2. This view is now being modified by indications of higher CO_2 and SO_2 (S) in oceanic magmatism, while H_2O is accorded pride of place in orogenic magmatism (for a review, see Anderson 1975). At the same time, studies of the melting of peridotite at high pressures in the presence of CO_2 (Eggler 1974; Brey & Green 1975) have lent experimental authority to the geological observation that nephelinites are the normal silicate magmas associated with carbonatites. The obvious importance of CO_2 in this association has also been continuously emphasized by the high concentrations of this gas emitted by the active nephelinite volcano, Nyiragongo (Chaigneau *et al.* 1960; Bailey 1974). High CO_2 had, of course, long been implicit in the Daly–Shand hypothesis that limestone assimilation was essential for the formation of alkaline magmas. Currently, in the University of Reading, we are examining the gas content of glassy lava from the Nyiragongo lava lake and the preliminary results

TABLE 2. CHARACTERISTICS OF ALKALINE IGNEOUS ACTIVITY

1. Volatile-rich (notably, $CO_2 > H_2O$).
2. Explosive; fragmental; diatremic.
3. Association includes ultrabasic terms: pyroxenite; peridotite; melilitite; etc.
4. Sometimes flushes mantle fragments directly to surface.

Therefore chemical differences indicate differences in the underlying mantle.

TABLE 3. VOLATILES IN NEPHELINITE/CARBONATITE MAGMATISM

gases, Mt Nyiragongo, Zaire (percentages by volume)

	volcanic gas (erupted)	gases from fusion of lava under vacuum			
	(1)	(2)	(3)	(4)	(5)
H_2O	43.20	68.80	55.75	70.66	60.43
CO_2	40.90	21.55	21.61	19.68	20.20
CO	2.45	6.71	—	—	0.10
SO_2	4.40	—	18.16	5.84	14.65
H_2	0.75	2.31	—	—	—
H_2S	—	—	2.02	1.85	1.14
HCl	—	—	0.20	1.14	0.36
HF	—	—	0.10	—	0.13
CH_4	—	—	1.63	1.03	2.95
N_2	8.30	0.62	—	—	—

volatiles in lava (percentages by mass)

	nephelinite, Nnyiragongo (6)	natrocarbonatite, Oldonyo Lengai, Tanzania (7)
CO_2	0.20	31.75
H_2O	0.02	1.86†
F	0.29	2.69
Cl	0.12	3.86
S	0.50	—
SO_3	—	2.00

Sources: (1, 2) Chaigneau *et al.* (1960) (vacuum extraction temperature *ca.* 1000 °C); (3–5) W. F. Price (personal communication, 1978) (vacuum extraction temperature 1100 °C. Note that CO_2 and SO_2 were still increasing at highest temperature, indicating that the CO_2 and S contents shown in (6) are still largely retained in the melt); (6) unpublished rock analysis (analysts: S. A. Malik, K. Ranger, G. Smith (S) and N. Tarrant (S)); (7) Dawson (1966) (analysis 1, table IV, p. 163. †, Average H_2O from analyses 3 and 4.).

indicate that the H_2O content of the erupted gas (Chaigneau *et al.* 1960) may be giving a false impression of the H_2O content of the magma. Normally it would be expected that H_2O would be one of the most soluble gases in the melt (relatively much more soluble than CO_2) and it would therefore be expected that H_2O would be preferentially retained in the quenched liquid. Even by standard analytical techniques this is clearly not so (see table 3) and this is further confirmed by our analysis of the extracted gases. During vacuum fusion, most of the H_2O in the glass is evolved around 700–800 °C, while most of the CO_2 and SO_2 are released at around 1100 °C. Hence, the usual relation that holds for more common melt compositions (that the proportion of H_2O in the erupted gas will be less than its proportion in the retained gas) is reversed, because apparently in this highly alkaline, undersaturated composition, CO_2 and S are more stably bound in the liquid structure. This implies that in much alkaline magmatism not only may enhanced CO_2 activity be expected but H_2O may have a very subordinate role, in contrast with other types of magmatism. Further confirmation of this may be seen in the active carbonatite–nephelinite volcano Oldonyo Lengai, which has been observed to erupt carbonate lavas (Dawson 1966). These are another way of erupting CO_2, but it is easy to be distracted by their remarkable chemistry into overlooking the seemingly mundane fact that they have very low H_2O contents when fresh (table 3). So deficient in water are these rocks that specimens must be sealed from contact with the atmosphere on eruption because they are hygroscopic. All this evidence is simply saying, contrary to general expectations, that H_2O is not a ubiquitous common constituent of magmatic gases. Since it is readily soluble in silicate melts we must conclude that it is not abundant in those parts of the mantle from which these magmas are derived. Any H_2O present in the mantle, either in a free vapour or in hydrous minerals, should preferentially enter early formed melts such as nephelinites: once in the melt, H_2O will be held until there is vapour saturation or a hydrous mineral starts to separate. The low H_2O concentrations retained in nephelinite melts is therefore clear evidence of the heterogeneous distribution of H_2O and CO_2 in the Earth's interior.

It should be remembered in passing that although there are great similarities in the strongly undersaturated magmatism of the Eastern and Western Rifts, there are also major differences, such as the highly potassic character of many of the Western Rift volcanoes, which must reflect differences in the mantle source (Lloyd & Bailey 1975).

If the small amounts of H_2O in the strongly silica undersaturated alkaline magmas seem remarkable, then the low concentrations of H_2O in silicic volcanics may come as a real surprise. No peralkaline acid volcanic glass yet analysed has contained H_2O in large quantities, and the vast majority have very low water contents, with the maximum in the distribution pressing against the detection limit for this constituent (Bailey 1978). A histogram of the available analyses is shown in figure 1, with comparable histograms for F and Cl. It is possible to demonstrate by the wide variety of sample types and eruption conditions (Bailey 1978), by volatile release experiments, and by experimental melting and crystallization (Bailey & Cooper 1979) that these melts have never contained much higher levels of H_2O than we see at present. It has long been popularly supposed (since Bowen 1937) that such melts are the products of fractional crystallization from the basalts with which they are frequently associated, but all our modern evidence (culminating in the H_2O distributions) refutes this. The low contents of H_2O and high contents of halogens are also inexplicable in terms of closed-system melting of crustal materials (either continental or oceanic). Either these silicic melts are being derived directly from the mantle source, or they are being produced at higher levels in an open system buffered by a juvenile fluid phase from the mantle. Silicic glasses contain very little CO_2 (in keeping with the low solubility of this constituent in silica-rich compositions), but this does not mean that CO_2 is absent from the magma system. In many areas of alkaline magmatism, CO_2 is a common emanation, and along the Kenya Rift, through the areas of active silicic volcanism, CO_2 may be found escaping from the ground. Geologists studying the geothermal areas have taken the view that the steam is a product of ground waters heated by juvenile CO_2 (Walsh 1969). In two places, shallow wells are producing high pressure CO_2 for commercial exploitation. In the Western Rift, methane from the deep waters of L. Kivu (south of the nephelinite volcano of Nyiragongo) is also exploited commercially, and is believed to be part of the degassing in this region (Burke 1963). High proportions of methane at low temperatures would be consistent with high CO_2 in the volcanic gases. These facts imply that all along the East African Rift, regardless of the types of magmatism, the magmatic gases are low in H_2O, and rich in CO_2 and halogens (and possibly sulphur, but this remains to be established). The East African Rift has long been known as a locus of Miocene–Recent magmatism, but a novel view now emerges of the rift as a great gash in the continental lithosphere from which CO_2 has been issuing for the last 23 Ma. During this period, other magmatic régimes, such as fold

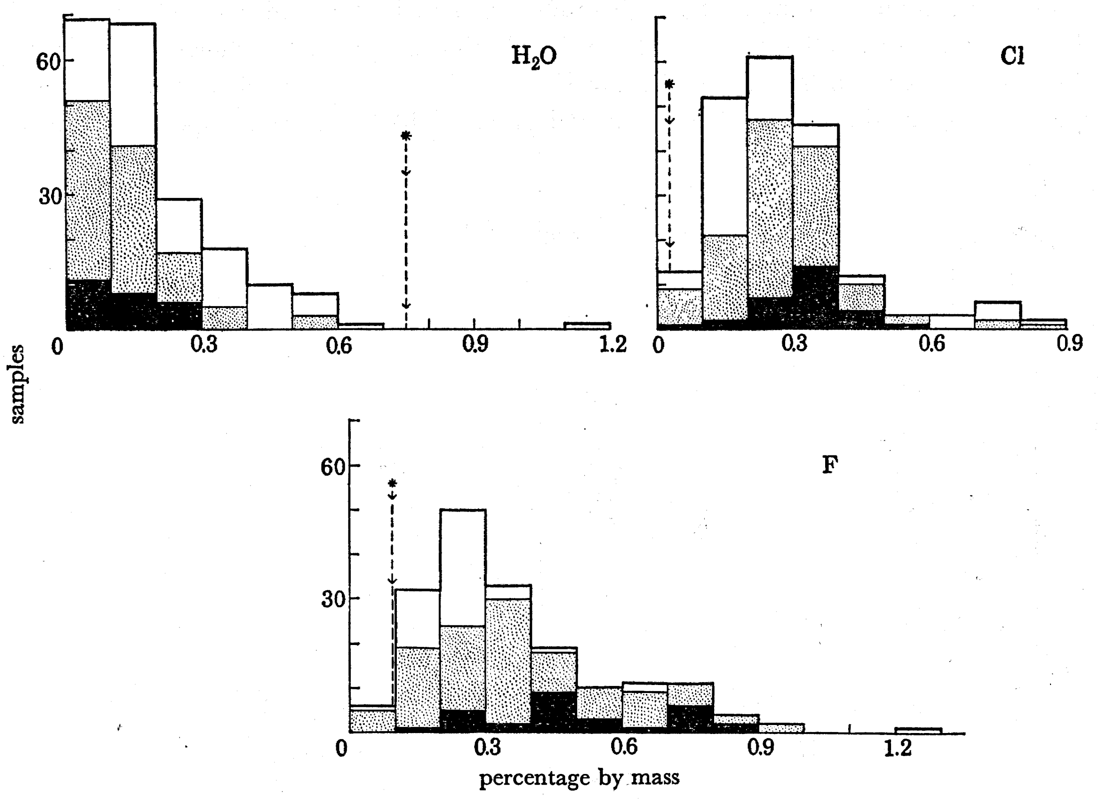


Figure 1. Histograms of the distributions of H_2O, Cl and F, in oversaturated peralkaline volcanic glasses from all available sources (analyses made in the University of Reading, and from Eburru volcano, Kenya, are identified by stippled and solid filling, respectively). The Badlands basalts (asterisks) are adjacent to Eburru volcano, and contemporaneous with the Eburru lavas: the sample shown on the histogram is a glassy specimen which would generally be taken to represent parental magma from which the Eburru lavas were derived by fractional crystallization.

mountain belts and mid-ocean ridges have been bringing their own characteristic gases to the surface, giving expression to different kinds of existing heterogeneity in the mantle and leaving new heterogeneities in their wake.

FLUORINE, CHLORINE AND POTASSIUM

If we stay with alkaline magmatism and look closely at some of the concentrations of gaseous elements, it is possible to discern variations even in overlapping contemporaneous volcanoes. Around Lake Naivasha, in the central part of the Kenya Rift, there are several contemporaneous silicic volcanic complexes, ranging through trachytes, pantellerites and comendites. In each complex there is a distinctive pattern in the distribution of F and Cl, shown in figure 2*c*. The distinctions may also be seen in the covariations of selected trace elements. It must be emphasized that, on the basis of general chemical similarity, these contemporaneous melts

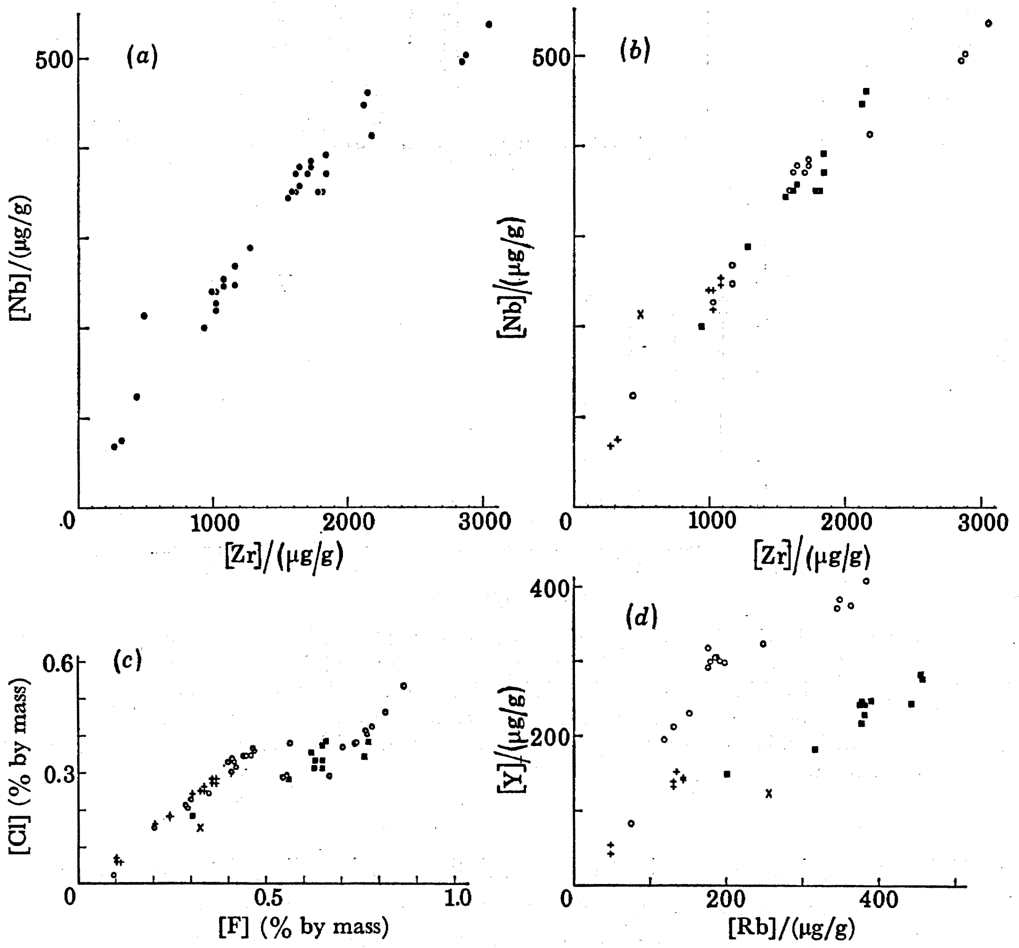


FIGURE 2. Distribution of Zr with Nb, F with Cl, and Y with Rb in Holocene peralkaline glassy lavas, from complexes around Lake Naivasha in the central part of the Kenya Rift. (*a*) Plot of Zr against Nb, with individual complexes not distinguished. (*b*) Plot of Zr against Nb, with the main volcanic complexes identified (+, Longonot; ○, Eburru; ▪, Naivasha), showing that there are subtle differences. (*c*) Plot of F against Cl. (*d*) Plot of Y against Rb, showing that different complexes may be clearly discriminated by using these elements. The first example of a fourth distinct group near L. Naivasha is marked by × in (*b*), (*c*) and (*d*).

would be regarded in most quarters as stages in a common line of magmatic evolution. A popular choice to illustrate a closed-system line of descent is Zr/Nb (Weaver *et al.* 1972), but figure 2 shows that other, equally 'incompatible', elements falsify any simple conclusion that may be drawn from Zr/Nb linearity. The distinctions shown in figure 2 are presumed to reflect fine structure heterogeneity in the mantle source of the volatiles.

Covariation of F and Cl presents an even more spectacular picture if we compare widely separated complexes of the same magma type. Glassy lavas from Eburru, Kenya, may be compared with closely similar rocks from the type area for pantellerite. Major element chemistry for two rocks of almost identical SiO_2 contents are shown in figure 3, the only essential difference

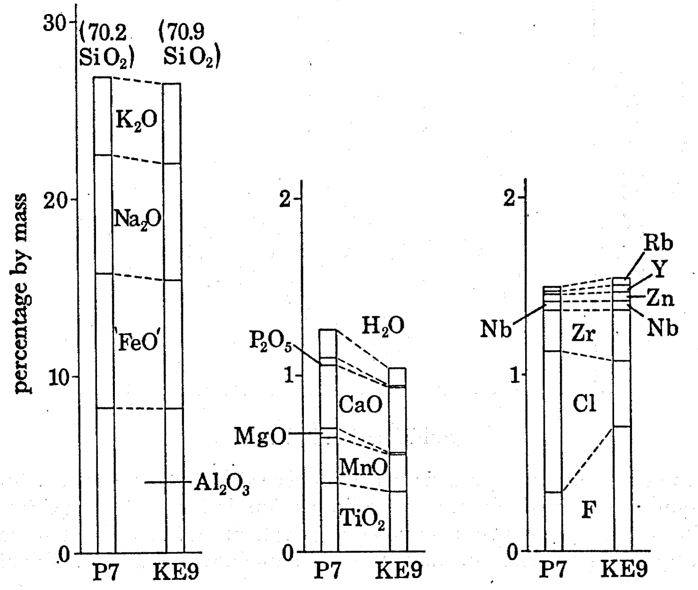


FIGURE 3. Graphical comparison of major element analyses for two glassy lavas with almost identical SiO_2 content, from Pantelleria, Mediterranean (P7) and Eburru, Kenya (KE9).

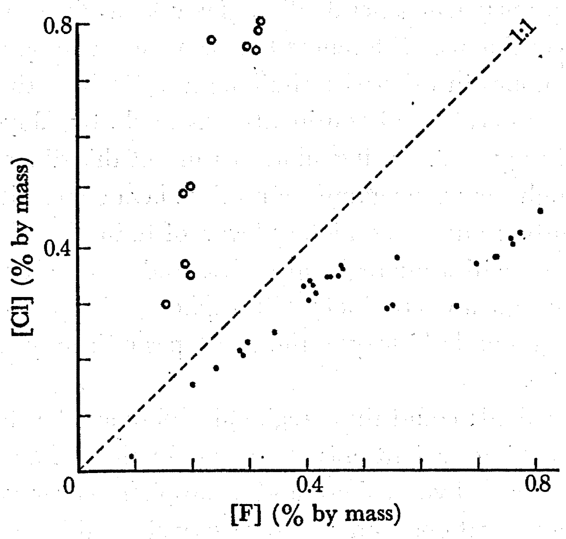


FIGURE 4. Cl–F distributions in suites of lavas from Pantelleria (○) and Eburru (●). The major element chemistry shows a similar range for both suites. The 1:1 line also discriminates between continental (below the line) and oceanic glassy lavas (above the line).

being in the reversal of the ratio of F:Cl. This difference is maintained through the two suites of rocks, as shown in figure 4. These two elements are highly soluble in silicic liquids, and there are no phenocrysts containing F or Cl recorded in the rocks. Once in the magma, therefore, F and Cl must be retained in any residual liquid. Because the major element chemistry of pantellerites is so consistent (Macdonald & Bailey 1973) and their magmatic association reproduced in many complexes, we must conclude that the magma-generating mechanism is essentially the same (and independent of continental crust), but that the sources have different proportions of halogens. The reversed proportions of Cl/F seen for Pantelleria and Eburru also emerge (with few exceptions) when peralkaline glassy lavas from oceanic volcanoes are compared with those from continents. Differences between the two regions of lithosphere are also discernible in the Sr isotopes in otherwise similar lavas, such as tholeiites. A test of the distribution of K-rich lavas in oceans and continents was made by Lloyd (Hough 1972), the results of which are shown in figure 5. An ingenious feature of this diagram is that it permits comparison of K levels through the whole gamut of possible lava compositions, and thus shows that the continents consistently produce the highest levels of K in all magma-types. These are indications of mantle heterogeneities on regional scales, and must reflect the differences in age and thickness between oceanic and continental lithosphere, with the consequent differences in thermal, tectonic and metasomatic history of the two types of lithosphere mantle (Lloyd & Bailey 1975).

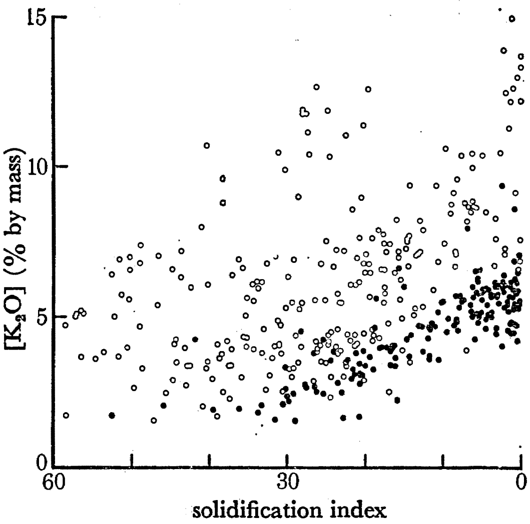


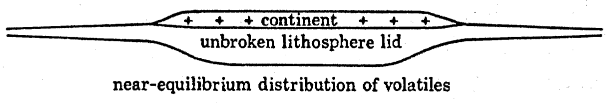
FIGURE 5. The K_2O contents of the most potassic volcanics recorded from the oceans (solid symbols) and the continents (open symbols) plotted against the solidification index ($100 \times MgO/(MgO+FeO+Fe_2O_3+Na_2O+K_2O)$, all in percentages by mass; Kuno *et al.* 1957). From F. E. Lloyd (1972, and personal communication, 1972). By kind permission of the author. See appendix for sources of analyses.

A question could then be raised: could these regional differences be the results of contamination by surface materials during ancient episodes of subduction? The answer must be that no mixture of sea floor, sediments, hydrosphere and atmosphere can provide halogens, CO_2, alkalis and H_2O in the concentrations and ratios observed in this magmatism. If further evidence were needed, the helium isotopes will probably provide the corroboration (Kaneoka *et al.* 1978).

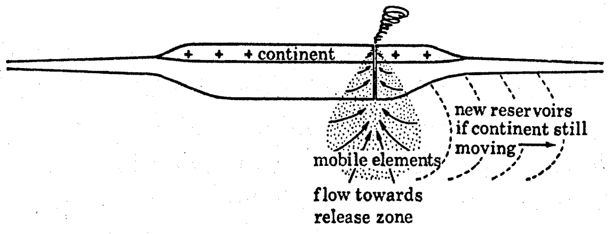
Episodic degassing of the mantle

In the ancient continental plate interiors there is preserved a record of repeated alkaline magmatism in the same place from the Precambrian onwards (Bailey 1977). Here we see evidence of episodic degassing of an underlying mantle that has either acted as a continuing reservoir, or has been periodically replenished. Additional piquancy is provided by the fact that in many places the continental basement consists of granulite facies rocks. By definition such basement has already been exhausted of volatiles, either by anatectic melt extraction (Fyfe 1973) or by crystallization under conditions of high p_{CO_2} (Greenwood 1976) with subsequent loss of the ambient vapour. Granulites, too, generally have low contents of incompatible elements, especially K, Rb, Th and U (Tarney & Windley 1977) presumably depleted by melt and vapour losses from the rock mass. A good illustration of this may be seen in the Zomba area of Malawi where the Precambrian granulite basement is pierced first by a ring complex of Precambrian perthosite (Ntonya), and then by the Mesozoic syenite ring complex of Zomba Mountain (Morel 1961 *a*, *b*). The Zomba syenite is part of the classic Chilwa province of carbonatites/alkaline rocks in southern Malawi, and must represent production from the underlying mantle of magmas rich in volatiles and incompatible elements. If the deep granulite crust had previously been exhausted of these elements, it may be expected that the immediate underlying upper mantle lithosphere had also suffered regional depletion. Subsequent episodes of alkaline magmatism through this same segment of the plate indicate that a potential exists for the regeneration or collection of gases and volatile melts in the mantle. One possibility is that during periods of stability the lithosphere plate in general acts as a lid over the underlying

1. *pre-displacement, pre-rifting*



2. *initial fissuring of lithosphere lid*



3. *escape channel acts as heat focus, distillation and ion-exchange column*, resulting in:
   (*a*) metasomatism (vertical mineral zoning)
   (*b*) lithosphere expansion (surface uplift)
   (*c*) steepening of geotherm, culminating in partial melting at various levels (nephelinites, early/deep; felsics, late/shallow)

Figure 6. Schematic diagram showing fissuring of the lithosphere forming an open system through which mantle volatiles migrate to the surface. The section would apply equally to a linear zone of rifting or an equidimensional zone of perforation.

mantle: this lid is split in episodes of continental rifting. The openings so formed then act as focusing channels towards and through which gases and volatile elements migrate to the Earth's surface. An open system is created, with the outflow losses setting up gradients between the surface and the mesosphere, and the rift zone then functions as an exhaust system for a broad region of the upper mantle as shown in figure 6. Such a system has the attribute of a very large mantle reservoir, which, even with initially low concentrations of volatiles, could nonetheless provide relatively large amounts when these are focused into the comparatively tiny volume of the rift segment. The source volume providing the volatiles is thus vastly greater than any consequent high level eruptives. In this way it may be possible to explain the paradox of the most volatile-rich magmatism piercing the most volatile depleted segments of the continental plates. The escaping volatiles focus heat in the escape channels (Bailey 1970) and under appropriate P–T conditions can metasomatize and replenish the lithosphere in volatile and incompatible elements (Bailey 1978). A further attribute of the system is that after one episode of rifting the continental plate may move horizontally again, reopening the rift and providing a fresh reservoir (as indicated in figure 6). Thus the mechanism permits episodic degassing, and replenishment of the lithosphere, that may be correlated with major changes in plate configurations.

It may be noted that the exhaust system just described would function as well through an equidimensional lesion in the lithosphere, and centrally disposed magmatic provinces would result, e.g. Tibesti and Atakor. In three dimensions, the system would then have the form of an inverted funnel, releasing volatiles from a broad region into a narrow feeder through the lithosphere (analogous to the function of the culinary utensil, the pie-funnel, venting hot vapours from below a large area of pastry). In the mantle exhaust system, seen in section in figure 6, volatiles migrate continuously upwards only while there is active degassing at the surface. On the continents, the system can remain open, venting directly into the atmosphere, even when magma eruption is minimal. In the ocean basins, on the other hand, the system can be fully open for gases only while a volcanic orifice is maintained near or above sea level: volcano construction must keep pace with subsidence and erosion if continuous gas venting is to be sustained. This may be the controlling factor in the development of island volcanism, and could be especially pertinent to cases like Iceland, where not only the chemistry, but also the volume of the magmatism are clearly anomalous compared with the submarine mid-ocean ridge (Flower *et al.* 1975). The chemical anomalies have been attributed to a mantle plume (see, for example, Schilling 1973; Unni & Schilling 1978), but the weight of evidence is against fixed mantle plumes, and, for Iceland, either the plume must migrate with the Mid-Atlantic Ridge, or it uniquely coincides with a null point (Bailey 1977). Note that the exhaust system (the 'pie-funnel' effect) is the exact reverse of a plume, which is supposed to rise as a narrow column (and possibly spread radially as it nears the surface); the volcanic funnel taps a large volume of mantle radially and focusses the extracts into a narrower region. The volcanic funnel has the further advantage that it can migrate permissively with the mid-ocean ridge, which seems to be demanded by the Iceland example. To maintain itself subaerially, the Iceland segment of the Mid-Atlantic Ridge must produce a greater volume of magma than equivalent submarine segments, yet the products (tholeiites and transitional alkali basalts) are commonly taken to represent a smaller fraction of mantle melting than mid-ocean ridge basalts. This paradox in magma production rates is explained if the island volcanoes are subaerial degassing points drawing on a broad region of the deeper underlying mantle, while the ridge basalts are the products of high-level decompression melting in a narrow convective wedge. Eruption rates are thus logically related to the different total volumes of contributing mantle, as well as the fraction of melting. It is the different *modes* of melting that impart the distinctive chemistry to the different volcanic régimes (Bailey 1979).

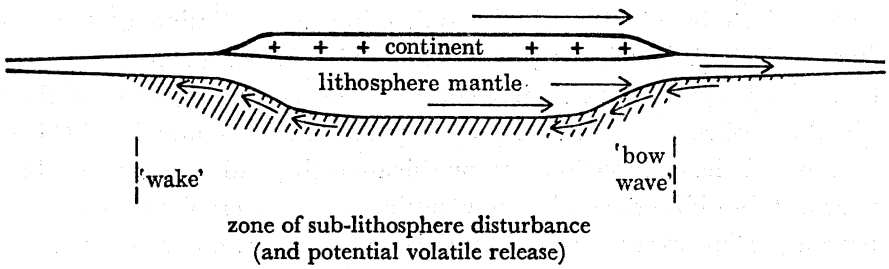


Figure 7. Schematic diagram showing possible disturbance and volatile release from the deep mantle by horizontal movement of a continental plate with a thick lithosphere keel.

Another feature of the horizontal movement of continental plates should not be overlooked. It is generally held that the continental lithosphere is much thicker than that of the oceanic plates, possibly very much thicker. Horizontal movement of the thick keel of the continent must therefore cause deep mantle perturbations of a type not associated with moving oceanic plates. Perturbations of this kind may trigger the release of volatile elements from the deeper part of the mesosphere, and thus account for some of the distinctive peculiarities that are found in the magmatism of continental plate interiors. An abnormal richness in CO_2 in continental alkaline magmatism may be partly explained by the 'massaging' effect of the continental keel moving through the mesophere, as illustrated schematically in figure 7.

Early catastrophic outgassing of the Earth

> 'For reasons that are not quite clear philosophically, all hypotheses about the Earth's beginning postulate a time when its substance was part of a homogeneous sample of average cosmic matter.'
>
> K. B. Krauskopf (1967)

In the short time since the above was written, there have been an increasing number of advocates for heterogeneous accretion of the Earth, with even the possibility of a significant contribution from outside the solar system (see Smith, this symposium). But we should be wary that in our new-found enthusiasm for heterogeneity we have not substituted a concept subject to the same reservation as that expressed by Krauskopf. Mantle heterogeneity has clearly changed and developed with time, but we should distinguish the quite separate cases of whether the Earth has ever approximated homogeneity, or whether it has never seriously departed from its accretionary heterogeneity. Some hypotheses for Earth evolution require an early period of rapid mantle convection and wide-scale melting, leading to early formation of continental lithosphere. But a consequence of this would also be mantle homogenization. Mantle-wide melting would require catastrophic outgassing, and indeed, this is sometimes an essential part of the hypothesis, whereby the early oceans are the result of H_2O expulsion (Fanale 1971). There is little firm evidence to support such a concept – quite the opposite.

Using gas contents of glassy sea floor basalts, and glass inclusions in andesite phenocrysts, and applying Cainozoic rates of magma production, Anderson (1975) shows that for H_2O, Cl, Br, CO_2, S, B, I and Hg, the surface reservoirs would have filled to their present levels during the Earth's history. Schilling *et al.* (1978) have updated the budget calculations for Cl and Br. These computations accord with the deductions of Hogbom (1894, cited by Rankama & Sahama 1950) and calculations by Goldschmidt (1933) using accumulation of limestone through geological time, and by Rubey (1951), who compared volcanic gas proportions with 'excess volatiles' at the Earth's surface. A similar constraint on early outgassing of the bulk of the constituents in the surface reservoir is imposed by the large amounts involved, especially of CO_2, which is generally less soluble in common silicate melts, and hence expelled preferentially with respect to H_2O. But if all the carbon now in the surface reservoirs were converted to CO_2, this would have a partial pressure exceeding 11 bar (1.1 MPa): no evidence of an early atmosphere of this extreme character has been reported from the oldest rocks. Therefore, if it is proposed that the early Earth thoroughly outgassed most of its H_2O, we should ask why and how it has gradually outgassed other volatiles, such as CO_2, Cl and F, and is still doing so. Certainly in a mantle-wide episode we could expect the less soluble gases to have been preferentially eliminated, especially light unreactive ones like He. The present-day regional variations in the He flux and $^3He/^4He$ ratios require continuing output of juvenile gases from a mantle that is still heterogeneous (Jenkins *et al.* 1978). It may also be noted in passing that the contents and ratios of rare gases on Earth are orders of magnitude different from all known meteorites, and require other sources or rates of supply to a heterogeneously accreting Earth (Bogard & Gibson 1978).

Thus, whatever thermal processes were at work in the early Earth, present evidence conspires to show that they failed to eliminate inhomogeneities. We should therefore ask if there is any evidence that wholesale melting happened – or is this merely the corollary of an assumption about the early distribution of heat or radioactive elements in the Earth? Perhaps this notion of early homogeneity is an antecedent truth that we should question and keep on questioning. Otherwise, our understanding of this planet may be an artefact of the notion of *primordial homogeneity* of the mantle.

It is obvious that continental lithosphere has been the site of heterogeneity (horizontal and vertical) since its earliest formation, and much of the evidence assembled at this Meeting illustrates that the heterogeneities are being made ever more complex by melt extractions and metasomatism in crust and mantle. Perhaps the first continents were not formed by some early 'event' that swept them out of the mantle as a 'scum' onto the surface. An alternative is that they mark the sites of accretionary regional heterogeneities that subsequent mantle processes have never been able to eliminate. If, for instance, the late accretions to the Earth were of lower density from the outset, by what process could this primordial 'lithosphere' ever have been rendered homogeneous? Primordial lithosphere heterogeneity would be difficult to disprove, but the real merit of the suggestion lies in the fact that it can account for persistent regional patterns in continental magma chemistry, magma types (e.g. kimberlite provinces) and metallogenesis (Watson, this symposium). Some of the chemical and thermal differences between oceans and continents would also be explicable in these terms.

Appendix 1. Sources of analyses used in figure 6

Oceanic analyses

Chayes's (1971) RKNFSYS Data Library for Cenozoic Volcanics. All oceanic analyses with more than 1.5% K_2O (by mass) are examined (this constitutes 745 analyses). Of the lava analyses 168 have molecular $K_2O:Na_2O > 0.5$ and are plotted in figure 6. Another nine analyses, unclassified in the bibliography, or unnamed in Chayes's system, but with molecular $K_2O:Na_2O > 0.5$, have been included in figure 6. Seven plutonic analyses that have molecular $K_2O:Na_2O > 0.5$ have been omitted.

Continental analyses

SW Uganda and Kivu (Denaeyer & Schellink 1965; Lloyd 1972); E Uganda – the Toror Hills (Sutherland 1965); the Roman Province (Washington 1906; Savelli 1968); southern Spain (Borley 1967); the Kaiserstuhl, Germany (Sutherland 1967); the Leucite Hills, Wyoming (Carmichael 1967); Kimberly, Australia (Wade & Prider 1940). A total of 245 analyses are plotted.

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