PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A
MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

Continental Magmatic Underplating

K. G. Cox

Phil. Trans. R. Soc. Lond. A 1993 **342**, 155-166
doi: 10.1098/rsta.1993.0011

Continental magmatic underplating

By K. G. Cox
Department of Earth Sciences, Parks Road, Oxford OX1 3PR, U.K.

Three arguments based on geological evidence are put forward to support the importance of magmatic underplating processes during continental flood basalt vulcanism. (1) Petrological evidence of gabbro fractionation in erupted basaltic sequences allows estimates to be made of the minimum total mass of concealed cumulate material, which is retained in deep crustal magma chambers, possibly along the Moho, and is comparable in amount to the erupted material. (2) In the Karoo province (southern Africa) large volumes of rhyolite along the S.E. continental margin were generated from basaltic precursors, either as partial melts of already-emplaced solid basic material or as crystal fractionation products of large volumes of basic magma. In either case very substantial volumes of concealed basic rocks are at least locally implied. (3) Studies of geomorphology suggest that the area of the Karoo province experienced at least 1 km of permanent uplift associated with the vulcanism. This appears to be the consequence of the emplacement of an underplated gabbroic layer *ca*. 5 km thick.

1. Introduction

Because of the relatively low densities of crustal rocks, basaltic magmas generated beneath continental areas are probably frequently trapped at or near the Moho, or within the crust, or in complex crust–mantle transition zones. This is the phenomenon that has come to be known as 'underplating'. Thus, although large volumes of magma reach the surface, for example in continental flood basalt (CFB) provinces, a proportion, in some cases possibly a large proportion, solidifies at depth, and the products remain hidden (Cox 1980). The magmas of principal interest are in almost all cases the tholeiites generated in large quantities during CFB vulcanism. Any mantle-derived magma can give rise to underplate material, but the CFB tholeiites are overwhelmingly the most significant in terms of the volumes produced. It is important to understand underplating for two reasons. First, a full appreciation of the amounts of melt generated in an igneous event depends on the quantification of the phenomenon, and second, underplating can lead to significant crustal growth and thickening, which would be unsuspected merely from the examination of the surface products.

There are many ways of approaching the underplating problem, including the theoretical study of the physical problems concerned, the seismological investigation of the lower crust and uppermost mantle, and the study of xenoliths of deep crustal or shallow upper mantle origin (O'Reilly 1988). The present paper, however, reviews the evidence that can be derived from the petrological and geochemical investigation of erupted volcanic sequences in CFB provinces, and also makes a preliminary assessment of the geomorphological evidence for underplating in such areas.

Phil. Trans. R. Soc. Lond. A (1993) **342**, 155–166
Printed in Great Britain

Under the petrology/geochemistry heading, two lines of investigation are pursued. The first may be termed the problem of the missing cumulates (erupted lavas show conclusive evidence of having undergone significant amounts of fractional crystallization at crustal levels. Where are the crystals now? And how much of this material is there?). The second concerns the generation of rhyolites on continental margins. In some cases (e.g. S.E. Africa during the early Jurassic) huge volumes of rhyolite were either generated from basaltic source rocks by partial melting, or were products of the fractional crystallization of large volumes of basaltic magma. In either case, very large volumes of hidden basaltic material are implied.

Geomorphology provides the third line of argument. Long-lived uplift of within-plate continental areas can in some cases be firmly linked to CFB vulcanism, and is difficult to explain without recourse to crustal thickening consequent upon unseen magmatic additions (McKenzie 1984).

2. The missing cumulates

Over the years there has been vigorous argument about the major element composition of primary magmas from the mantle in continental areas, especially about exactly how picritic (olivine-rich or MgO-rich) they might be. Picritic basalts are locally important in some CFB provinces such as the North Atlantic Tertiary province (Clarke 1970), the Karoo province (Bristow 1984), and the Deccan (Krishnamurthy & Cox 1977), and have been assigned a parental role in the generation of the more-evolved, and much more wide-spread, low-MgO basalts typical of these areas (O'Hara 1965; Cox 1980). Conversely, some have argued that the evolved basalts are themselves primary (Wilkinson & Binns 1977; Wright *et al.* 1989). Fortunately, for most of the purposes of the present paper, the precise Mg-content of the primary magmas is unimportant. Picritic magmas readily evolve to basaltic compositions by the fractionation of ferromagnesian minerals, principally olivine. The cumulates produced are not unimportant, but nevertheless they probably rarely constitute more than 25 wt % of the original mass of magma generated (see Cox (1980) for calculation of the amount of olivine fractionation required to generate a basaltic liquid from a typical picritic liquid). In principle, if it were possible to estimate the total amount of *basaltic* material present in a province (i.e. surface eruptives, high-level intrusives, gabbroic underplate material) it would be necessary to augment the total by this factor. However, in terms of crustal growth and thickening, cumulates consisting only of ferromagnesian minerals qualify as mantle, not crust. From the point of view of this question, the important issue is thus, how much plagioclase-bearing cumulate material is present? Such material will count as an addition to the crust, because plagioclase is the low-density phase that most-distinguishes the crust from the mantle.

Most continental tholeiitic magmas begin to crystallize the gabbroic assemblage olivine + clinopyroxene + plagioclase when the MgO content of the liquid has been reduced to *ca.* 7 wt % by the fractionation of ferromagnesian phases. The proportions in which the gabbroic phases crystallize is *ca.* 10–15 % olivine, 30–40 % clinopyroxene, and 50–55 % plagioclase (see Cox & Mitchell 1988; Harris *et al.* 1990). There are exceptions, but they are rare. For example, an abnormally high potassium content (*ca.* 2 wt %) suppresses plagioclase crystallization, and in such cases the MgO content of the liquid can be reduced to as little as 4 wt % without the appearance of this phase (Cox & Bristow 1984).

Many studies give evidence of gabbro fractionation in CFB sequences, and highly distinctive inter-element relationships are seen. Most characteristic is absolute iron-enrichment with falling MgO, because the Fe-free phase, plagioclase, constitutes more than half of the fractionating assemblage. Other typical features are a strong positive correlation between MgO and CaO, and a gentle decline of Al_2O_3 with falling MgO. Amongst the trace elements the behaviour of Sr is particularly distinctive, in that it shows little variation, as a consequence of a bulk K_D close to unity in the fractionating assemblage.

One of the most important features of the fractional crystallization of a gabbroic assemblage from a basaltic liquid is that the removal of relatively large amounts of crystalline material is accompanied by rather small changes in the concentrations of many elements in the residual liquid. For these elements, the bulk composition of the cumulate material is fairly close to that of the liquid. Hence, lava sequences which at first sight look compositionally relatively uniform, may in fact imply the existence of significant quantities of associated cumulates.

To determine the minimum amount of plagioclase-bearing cumulus material associated with an eruptive sequence it is necessary to estimate the average composition of the whole sequence, the composition of the parent magma when it first begins to crystallize the gabbroic assemblage, and the bulk composition of the cumulate assemblage itself. Mass balance requirements for any individual element then lead to the relationship:

$$C_P = C_L X_L + C_C X_C,$$

where C_P, C_L and C_C are the concentrations of the element in parent magma, erupted liquid, and cumulate respectively, and X_L and X_C are the mass fractions of the erupted liquid and the cumulates, totalling the original unit mass of parental liquid. In practice the total mass of the erupted sequence is rarely determinable with any degree of accuracy, because of unknown amounts lost by erosion or concealed by younger deposits. Hence it is not possible to determine the absolute cumulate mass. However, it is extremely useful to determine the relative masses of the erupted sequence and the cumulates, i.e. the ratio X_C/X_L, which is derived from the familiar 'lever rule' equations:

$$X_L = (C_P - C_C)/(C_L - C_C),$$
$$X_C = (C_L - C_P)/(C_L - C_C).$$

It is best to carry out the calculations by using the concentrations of major elements rather than incompatible trace- and minor-elements, which often appear to show anomalous degrees of enrichment during fractionation. One probable reason for this is that the parental magma, as it begins to fractionate gabbro, may itself already be variable in its incompatible element content (see Gill *et al.* 1988), which is equivalent to having an extra enrichment-factor built in, and has the effect of magnifying the apparent enrichment during later fractional crystallization.

The major element calculation can be approached via generalized numerical modelling (Cox 1980) but the example given below is based on one of the much-improved data-sets now available. The rocks considered are those of the Ambenali Formation in the Deccan Traps, selected because they are free from significant crustal contamination, and characterized by numerous analyses. Devey (1986) for example systematically sampled road sections in the Western Ghats, analysing more than 100 samples from the formation. Using average phenocryst compositions he modelled gabbro fractionation for the Ambenali data-set, concluding that the range of compositions erupted (excluding a few more basic rocks which were obviously not on the gabbro fractionation trend) could be generated by the fractionation of olivine, clinopyroxene, and plagioclase in the proportions 14:35:51 from a parent magma containing 7.58 wt % MgO. The most-evolved erupted composition contains 5.64 wt % MgO, and is generated by the crystallization of about 42.5 wt % of the original liquid. In the present study I have selected one of Devey's road sections, at Devrukh, because this is the only one that includes the complete Ambenali section, here 480 m thick. The section is represented by 22 analyses. The average composition of the section can be calculated by weighting each analysis according to the vertical sample spacing, assuming that it represents the column of rock half way up to the overlying sample site, and half way down to the underlying site. The average MgO content calculated in this way is 6.21 wt %. This is of course more basic than Devey's most-evolved composition, so the amount of fractionation required is less than the 42.5 % crystallization required above. In fact it works out at *ca.* 33 %.

Hence, $X_C/X_L \approx 0.5$, which is of course subject to slight errors because of uncertainties in the composition of both the parent and the cumulates. Nevertheless, a significant quantity of hidden cumulus material is implied, and taking the ratio at face value the implication is that for every cubic kilometre of Ambenali magma erupted, another 0.5 km^3 of cumulates exists. In this case the formation is *ca.* 480 m thick in the area sampled, implying the equivalent of a 240 m thick layer of hidden cumulates.

Calculations of this sort do not characteristically yield very large values for the ratio X_C/X_L, though Cox (1980) estimated that many erupted CFB sequences were probably accompanied by approximately equivalent amounts of hidden cumulates. Estimates of the latter become larger as the rocks become more evolved, and there are for example substantial tracts of CFB provinces made up of more evolved lavas than the Ambenali Formation (e.g. an average MgO of *ca.* 5.5 wt % for the Sabie River Basalt Formation of the Zululand is reported by Duncan *et al.* (1984)). However, the significance of these estimates does not lie in the fact that the amounts of hidden cumulate indicated are particularly large. Rather, they demonstrate the existence of hidden magma chambers of significant size, that the conditions necessary for underplating existed, and that at least *some* underplating must have taken place. The calculations furthermore can only give *minimum* estimates of the amount of hidden material. They depend on the assumption that all fractionated liquids produced are available for sampling on the surface. Unknown additional amounts of magma may have solidified completely in the sub-surface environment, leaving no trace in the eruptive record.

In the next section a different line of petrological evidence will be examined, suggesting that, at least locally on continental margins, massive amounts of underplate material may exist, probably in much larger volumes than indicated by the calculations above.

3. Rhyolites on continental margins: evidence from S.E. Africa

Several instances are known of CFB provinces that contain substantial amounts of acid rocks, often in the form of relatively small plutons, but occasionally in the form of rhyolitic extrusives. At the present level of erosion the latter are developed on a small scale in the Deccan (e.g. on Salsette Island near Bombay (Sethna & Battiwala 1980)), on an areally extensive scale, though not very thick, in the Paraná Province

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

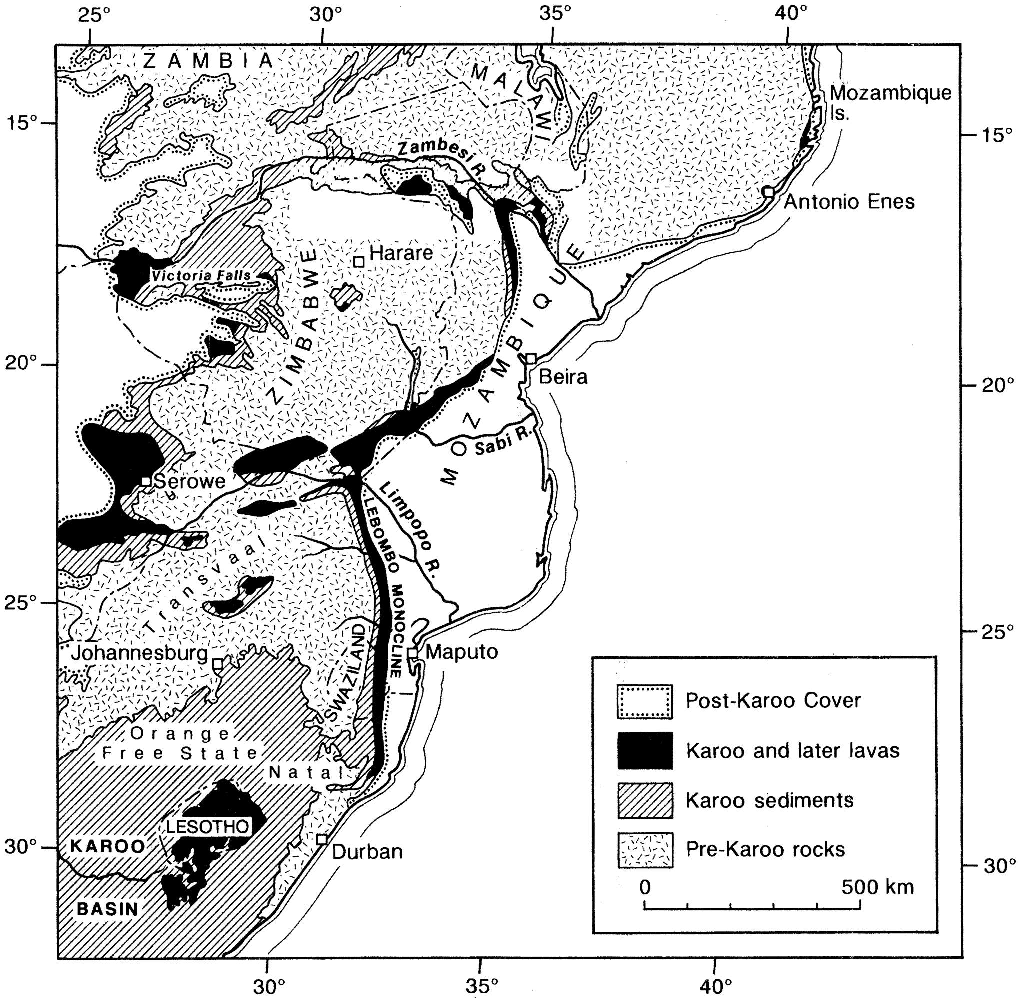

Figure 1. Geological map of South-East Africa showing distribution of Karoo rocks.

(Bellieni *et al.* 1984), and on a truly huge scale in the southeastern part of the Karoo Province in southern Africa (Cleverly 1979; Cleverly *et al.* 1984)). In the latter area the rhyolites are exposed continuously over a distance of *ca.* 600 km along the Lebombo monocline (see figure 1) and a maximum thickness of as much as 7.5 km has been estimated in Swaziland from surface dip measurements and outcrop width (Cleverly 1979). Had the monocline been below sea-level, it would certainly have been identified as a sequence of seaward dipping reflectors by marine geophysicists. For whatever reasons (see Cox 1992) it is exposed above sea-level now, and is available for inspection. A geological map of the Lebombo in Swaziland and neighbouring parts of Mozambique is given in figure 2 and illustrates the fundamental features of the present argument. Using observed dip measurements on the surface, the volcanic sequence exposed appears to be approximately 15 km thick (see figure 3), of which about half consists of rhyolite. The volcanic sequence rests in the west on Karoo sediments overlying Archaean basement. To the east the nature of the basement is unknown, though basement is faulted up on the seaward side of the

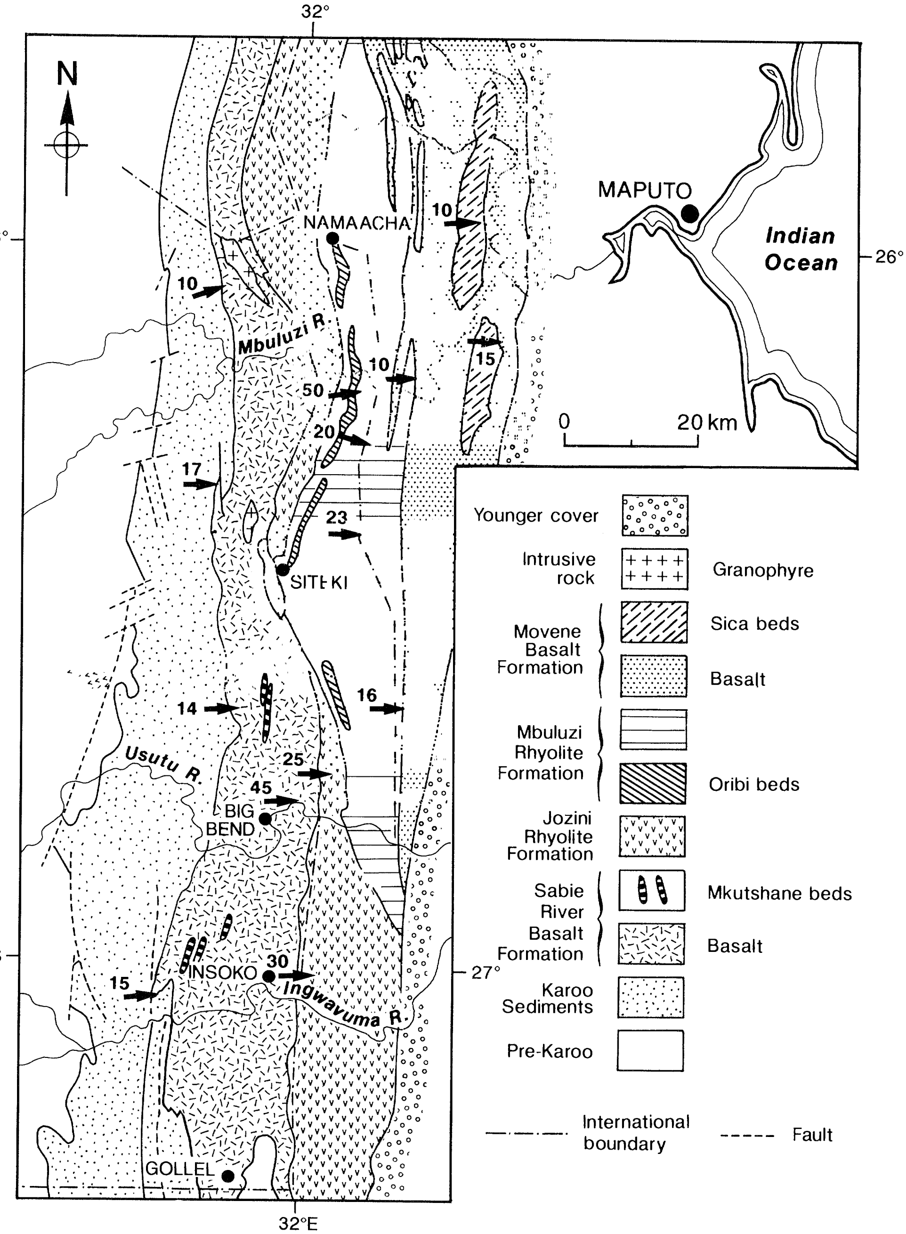

Figure 2. Geological map of the Lebombo Monocline in Swaziland (after Eales *et al.* 1984).

monocline in Zululand at the southern end of the province, forming a half-graben. The area east of the monocline has been referred to as the Mozambique Thinned Zone (Cox 1992), an area possibly of new oceanic crust, or of thinned continental crust, or a mixture of both, overlain by younger sediments and produced during the early stages of the break-up of Gondwanaland in the L. Jurassic. The Lebombo can perhaps not strictly be regarded as a continental margin, but it is clearly the boundary between crustal areas respectively unaffected by and strongly affected by the early stages of continental break-up. It is not possible to estimate the total

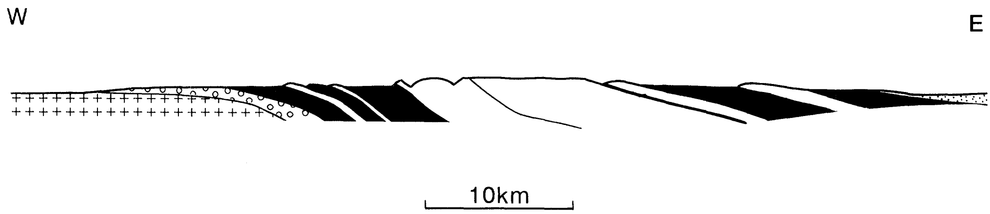

Figure 3. Sketch section across the Lebombo along the line of the Mbuluzi R. (see figure 2). From west to east ornaments are: crosses, Archaen basement; circles, Karoo sediments; black, basalts; un-ornamented, rhyolites; stipple, post-Karoo cover. Horizontal and vertical scales are the same.

volume of the rhyolites because extents are unknown both up-dip (to the west) and down-dip. They are, however, absent from the inland Karoo volcanic sequences in the Transvaal and Lesotho, approximately 200 km west of the monocline. On the seaward side the extent to which half-graben systems, and general thinning towards the ocean, may affect the sequence is unknown.

The origin of the Lebombo rhyolites has been extensively discussed in the literature, since Manton (1968) carried out the first Sr-isotopic determinations and discovered that they display initial ratios typical of mantle-derived rocks ($^{87}Sr/^{86}Sr_I = 0.7044 \pm 2$ (Bristow *et al.* 1984)) and indeed ratios similar to the basalts which they overlie. A small sequence of stratigraphically lower rhyolites (the Mkutshane Beds, see figure 2), are in complete geochemical contrast to the main rhyolite sequence, and have all the expected geochemical features of remelts derived from Archaean basement. The existence of the Mkutshane Beds thus reinforces the conviction that the main sequence is, somehow, related to its associated basalts rather than to remelting of the basement.

Rhyolites cannot be derived from the mantle in a one-stage process, but they can be generated by the further processing of first-stage products, e.g. by the remelting of basalt or by the fractional crystallization of basaltic magma. Betton (1978; and see Cleverly *et al.* 1984) carried out detailed modelling calculations and concluded that most of the rhyolites of the main sequence were generated by the partial melting of source rocks similar to Karoo dolerites, having a mineralogy dominated by clinopyroxene and plagioclase, with subordinate magnetite, quartz, and potash feldspar. For various specific rhyolite types the amount of melting required varied from 11 to 16 wt % of the source rock. Essentially similar conclusions have been reached for the Deccan rhyolites of Salsette (Lightfoot *et al.* 1987). Betton also modelled fractional crystallization of typical Swaziland basaltic magmas and concluded that this too was a permissible mechanism for generating the rhyolites. It was however regarded as a less-likely origin, because the rhyolites occur only in the specific setting of the Lebombo – implying some sort of special conditions of formation – not in the continental interior, where basalts alone occur. If fractional crystallization were the answer, then at least some rhyolite should be expected in all areas.

However, from the point of view of the present argument, it is actually immaterial whether the rhyolites were generated by the remelting of previously solidified basaltic material or by the fractional crystallization of basaltic magma. Nor is the mechanism by which remelting might occur particularly relevant (Betton (1978), for example, suggested that uplift, implying decompression, of hot underplated material during crustal thinning might suffice. Alternatively, injection of fresh magma into the underplate zone might promote partial melting). In either case, the rhyolites erupted onto the surface require the existence of perhaps 6–10 times as much basaltic material, either as their source rocks or as their accompanying gabbroic cumulates. A rhyolite sequence of this type, up to 7.5 km thick, implies the existence of very large volumes of such hidden material, which was probably emplaced as an underplate, analogous to the prisms of high-velocity lower continental crust identified beneath some volcanic continental margins. For example the prism identified by White *et al.* (1987) on the Hatton Bank margin in the N. Atlantic, and interpreted by them as underplated basaltic material, extends for *ca.* 100 km normal to the margin, and reaches a thickness of 15 km. Partial remelting of a source of this size would clearly be capable of generating impressive quantities of rhyolite.

To reinforce the argument, in the next section the topographic evidence for uplift in southeast Africa will be interpreted to imply that in fact underplated material probably extends for several hundred kilometres into the continental interior beneath pre-existing crust.

4. The topographic argument

Uplift of within-plate continental areas can be generated by the dynamic and thermal effects of plume activity, or by crustal thickening, which in the absence of folding and thrusting is perhaps most likely to take place by the magmatic addition of rocks with densities lower than that of the mantle (McKenzie 1984). Dynamic plume effects can, however, be discounted in most CFB provinces, because hot spot tracks indicate that plumes, even if still active, are now large distances away from the provinces created (e.g. the Deccan plume now under Réunion, the Paraná-Etendeka plume now under Tristan da Cunha). Equally, thermal effects are unlikely still to be in evidence in Mesozoic provinces such as the Karoo and the Paraná, because the time constants of thermal decay are too short. Thermal affects are probably, however, still of some significance in the early Tertiary N. Atlantic province (White & McKenzie 1989), and may still have some small influence in the Deccan.

The Karoo province, however, provides evidence that the uplift which took place either during or after vulcanism is still clearly expressed, i.e. it is the type referred to as 'permanent uplift' (McKenzie 1984; in contrast to 'impermanent' uplifts caused by dynamic and thermal effects), and seems therefore most likely to be related to magmatic crustal thickening. The uplift involved is the 'surface uplift' of Molnar & England (1990), i.e. the average surface elevation was increased, and it is not to be confused with the upward movement of bed-rock during the isostatic response to erosion, during which average surface elevation decreases. The argument for southeast Africa has been discussed by Cox (1989). Briefly, the salient points are:

1. The area is topographically very high compared with most anorogenic continental regions (maximum elevation *ca.* 3.5 km, large areas at 1.5–2 km above sea level).

2. Karoo sedimentation immediately before the onset of vulcanism was largely aeolian and fluviatile, but it was unlikely to have taken place at more than *ca.* 0.5 km above sea-level.

3. Over large areas of the Transvaal and Orange Free State the Karoo lavas have largely been eroded away but the underlying sedimentary sequences are preserved. Thus any contribution to topographic height made by the lava pile itself has been

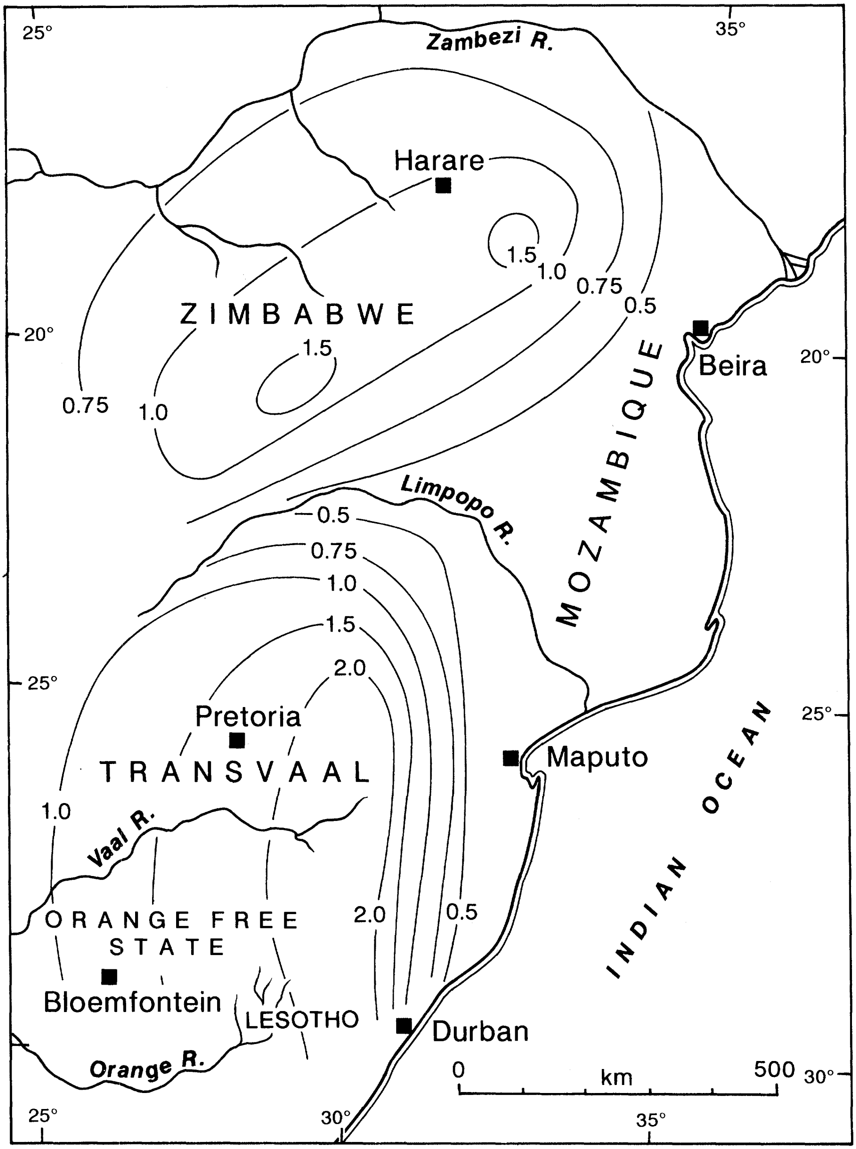

Figure 4. Sketch map showing estimated elevation above sea-level of the present-day sub-Karoo Basalt unconformity in S.E. Africa. Reference to figure 1 will indicate degree of certainty (i.e. where the unconformity is actually exposed). In some cases high-points have been inserted in the map so that the unconformity can pass above high areas of pre-Karoo rocks, e.g. 200 km S.E. of Harare (Marandelas), 400 km S.W. of Harare (Matopo Hills), and 200 km N.E. of Pretoria (the Berg). Elevations above 0.5 km above sea-level are probably the consequence of surface uplift. The half-dome pattern of the uplift (see Cox 1989) is bisected by the Limpopo rift.

removed. In the absence of any other factor, isostatic readjustment should have restored the sub-basalt unconformity to its original elevation. It is, however, now preserved patchily, or can be inferred to have been recently only a little above the present ground surface, over wide areas of South Africa and Zimbabwe at more than 1 km, and in some areas, more than 2 km above sea-level (see figure 4). Evidently there *is* another factor, and that is likely to be the contribution to crustal thickness made by the underplate. For example, in the area of figure 4 where the unconformity is inferred to be 2 km above sea-level, at least 1 km of uplift can safely be invoked. The density assumptions of McKenzie (1984; i.e. density of *gabbroic* underplated material of 2.7 Mg m^{-3}, mantle density of 3.3 Mg m^{-3}), imply an underplated layer including *ca.* 5.5 km of gabbro in this area. The total amount of underplated material is of course likely to be substantially higher than this because of additional ultramafic cumulates. White & McKenzie (1989), for example, assumed an overall density of 3.0 Mg m^{-3} for the underplated material, which leads to an increase by a factor of two in the calculated thickness. However, as pointed out earlier, the included ultramafic material does not affect the uplift argument.

In the area discussed above, the maximum preserved thickness of surface lavas is *ca.* 1.5 km, e.g. in Lesotho (Cox & Hornung 1967), suggesting that the underplate is much thicker than the surface sequence. Furthermore, the area affected by uplift appears to be much wider than those including typical uplifted rift-shoulders (e.g. East Africa) for which there might be other explanations. There is a strong implication that at least *some* underplated material was emplaced far inland of the continental margin.

5. General remarks

This inference above conjours up interesting speculations about crustal growth over geological time spans. During the past 250 Ma, there have been half a dozen or more CFB episodes akin to the Karoo (e.g. Siberia, Paraná, Deccan, N. Atlantic, Ethiopia–Yemen, Columbia River). On that basis, if such a mechanism operated in earlier times, a not insignificant fraction of the continental crust could perhaps have been generated by underplating in addition to the marginal accretion of island arcs. White & McKenzie (1989) estimated that the crustal accretion rate from extensional magmatism was *ca.* 0.4 $km^3\ a^{-1}$, compared with an average Phanerozoic rate of perhaps 1 $km^3\ a^{-1}$. However, for these figures to be meaningful, the high density lower crust produced by extensional magmatism must not be preferentially lost back into the mantle.

Since many of the arguments presented have been based on the Karoo province the extent to which this case acts as a general model for CFB vulcanism is of some interest. In general, it has to be said, the effects appear to be smaller in most other provinces, because the areas simply are not so topographically high as S.E. Africa. Areas comparable in elevation do exist in Ethiopia and Yemen, where extensive tracts are more than 2 km above sea-level. However, these are likely to be still dynamically supported by the Afar plume. An additional general problem lies in the fact that quantification of surface uplift is extremely difficult, because it is necessary to estimate both the original elevation of the surface onto which the basalts were erupted, and the present elevation at which the sub-basalt unconformity would lie if the basalts had been just eroded off, and the underlying topography remained as an un-canyoned plateau surface. The latter is a requirement because any substantial dissection of the sub-basalt rocks results in the renewed uplift of the unconformity, e.g. preserved locally on interfluves, by isostatic adjustment.

Surface uplift has, however, almost certainly affected areas of the North Atlantic Tertiary Province on both sides of the present ocean, in Greenland, Norway, and Scotland, but it is not clear at present how much of it is 'permanent' as in the Karoo case. In Scotland, Watson (1985) put forward a closely argued case, demonstrating that the western part of the Scottish craton was uplifted in the Eocene by

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

0.5–1.5 km, an event which she specifically related to the co-eval N. Atlantic vulcanism. Brooks (1979, 1985) has described the Eocene uplift of the sub-basalt unconformity inland of Skaergaard in E. Greenland, which resulted in an extensive inlier of basement gneisses. However, a second uplift-episode later in the Tertiary also seems to have taken place, suggesting that rejuvenation of initial uplifts is possible. In Norway, Torske (1975) has ascribed reversals of drainage directions to plume activity associated with the opening of the N. Atlantic in the Mesozoic, i.e. *before* the North Atlantic vulcanism, but there is also an episode of Tertiary uplift. The latter is, however, difficult to quantify by using the arguments developed above. Norway is now devoid of the volcanic sequence, if it were formerly present, and is deeply dissected, probably making the isostatic effects important. Nevertheless, it is clear that the geomorphology has a continuing role to play in the study of the vulcanism of within-plate continental regions.

References

Bellieni, G., Brotzu, P., Comin-Chiaramonti, P., Ernesto, M., Melfi, A. J., Pacca, I. G. & Piccirillo, E. M. 1984 Flood basalt to rhyolite suites in the southern Paraná plateau (Brazil): palaeomagnetism, petrogenesis and geodynamic implications. *J. Petrol.* **25**, 579–618.

Betton, P. J. 1978 Geochemistry of Karoo volcanic rocks in Swaziland. D.Phil. thesis, Oxford University.

Bristow, J. W. 1984 Picritic rocks of the North Lebombo and south-east Zimbabwe. In *Petrogenesis of the volcanic rocks of the Karoo province* (ed. A. J. Erlank), *Spec. Publ. geol. Soc. S. Afr.* **13**, 105–123.

Brooks, C. K. 1979 Geomorphological observations at Kangerdlugssuaq, East Greenland. *Greenland Geosci.* **1**, 3–21.

Brooks, C. K. 1985 Vertical crustal movements in the Tertiary of central East Greenland: a continental margin hot-spot. *Z. Geomorph. N.F., Suppl.-Bd.* **54**, 101–117.

Clarke, D. B. 1970 Tertiary basalts from Baffin Bay; possible primary magma from the mantle. *Contr. Miner. Petrol.* **25**, 203–204.

Cleverly, R. W. 1979 The volcanic geology of the Lebombo monocline in Swaziland. *Trans. geol. Soc. S. Afr.* **82**, 343–348.

Cleverly, R. W., Betton, P. J. & Bristow, J. W. 1984 Geochemistry and petrogenesis of the Lebombo rhyolites. In *Petrogenesis of the volcanic rocks of the Karoo province* (ed. A. J. Erlank), *Spec. Publ. geol. Soc. S. Afr.* **13**, 171–194.

Cox, K. G. 1980 A model for flood basalt vulcanism. *J. Petrol.* **21**, 629–650.

Cox, K. G. 1989 The role of mantle plumes in the development of continental drainage patterns. *Nature, Lond.* **342**, 873–877.

Cox, K. G. 1992 Karoo igneous activity, and the early stages of the break-up of Gondwanaland. In *Magmatism and the causes of continental break-up* (ed. B. Storey & A. Alabaster), *Spec. Publ. geol. Soc. Lond.*

Cox, K. G. & Bristow, J. W. 1984 The Sabie River Basalt formation of the Lebombo Monocline and south-east Zimbabwe. In *Petrogenesis of the volcanic rocks of the Karoo province* (ed. A. J. Erlank), *Spec. Publ. geol. Soc. S. Afr.* **13**, 125–147.

Cox, K. G. & Mitchell, C. 1988 Importance of crystal settling in the differentiation of Deccan Trap basic magmas. *Nature, Lond.* **333**, 447–449.

Cox, K. G. & Hornung, G. 1966 The petrology of the Karoo basalts of Basutoland. *Am. Mineralogist* **51**, 1414–1432.

Devey, C. W. 1986 Stratigraphy and geochemistry of the Deccan Trap lavas, western India. D.Phil. thesis, Oxford University.

Duncan, A. R., Erlank, A. J. & Marsh, J. S. 1984 Regional geochemistry of the Karoo igneous province. In *Petrogenesis of the volcanic rocks of the Karoo province* (ed. A. J. Erlank), *Spec. Publ. geol. Soc. S. Afr.* **13**, 355–388.

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

Gill, R. C. O., Neilsen, T. F. D., Brooks, C. K. & Ingram, G. A. 1988 Tertiary volcanism in the Kangerdlugssuaq region, E. Greenland: trace element geochemistry of the Lower Basalts and tholeiitic dyke swarms. In *Early Tertiary vulcanism and the opening of the NE Atlantic* (ed. A. C. Morton & L. M. Parson), *Geol. Soc. Spec. Publ.* **39**, 161–179.

Harris, C., Marsh, J. S., Duncan, R. A. & Erlank, A. J. 1990 The petrogenesis of the Kirwan basalts of Dronning Maud Land, Antarctica. *J. Petrol.* **31**, 341–369.

Krishnamurthy, P. & Cox, K. G. 1977 Picrite basalts and related lavas from the Deccan Traps of western India. *Contr. Miner. Petrol.* **62**, 53–75.

Lightfoot, P. C., Hawkesworth, C. J. & Sethna, F. F. 1987 Petrogenesis of rhyolites and trachytes from the Deccan Trap: Sr, Nd, and Pb isotope and trace element evidence. *Contr. Miner. Petrol.* **95**, 44–54.

McKenzie, D. P. 1984 A possible mechanism for epeirogenic uplift. *Nature, Lond.* **307**, 616–618.

Manton, W. I. 1968 The origin of associated basic and acid rocks in the Lebombo-Nuanetsi igneous province, southern Africa, as implied by strontium isotopes. *J. Petrol.* **9**, 23–29.

Molnar, P. & England, P. 1990 Surface uplift, uplift of rocks, and exhumation of rocks. *Geology* **18**, 1173–1177.

O'Hara, M. J. 1965 Primary magmas and the origin of basalts. *Scott. J. Geol.* **1**, 19–40.

O'Reilly, S. Y. 1988 Evolution of Phanerozoic Eastern Australian lithosphere: isotopic evidence for magmatic and tectonic underplating. *J. Petrol.* (Special Lithosphere Issue), pp. 89–108.

Sethna, S. F. & Battiwala, H. K. 1980 Major element geochemistry of the intermediate and acidic rocks associated with the Deccan Trap basalts. In *Proc. 3rd Ind. geol. Cong. Poona*, pp. 281–294.

Torske, T. 1975 Possible Mesozoic mantle plume activity beneath the continental margin of Norway. *Norges geologiske undersøkelse* **322**, 73–90.

Watson, J. 1985 Northern Scotland as an Atlantic–North Sea divide. *J. geol. Soc. Lond.* **142**, 221–243.

White, R. S., Spence, G. D., Fowler, S. R., McKenzie, D. P., Westbrook, G. K. & Bowen, A. N. 1987 Magmatism at rifted continental margins. *Nature, Lond.* **330**, 439–444.

Wilkinson, J. F. G. & Binns, R. A. 1977 Relatively iron-rich lherzolite xenoliths of the Cr-diopside suite: a guide to the primary nature of anorogenic tholeiitic andesites. *Contr. Miner. Petrol.* **65**, 199–212.

Wright, T. L., Mangan, M. & Swanson, D. A. 1989 Chemical data for flows and feeder dykes of the Yakima Basalt sub-group, Columbia River Basalt Group, Washington, Oregon, and Idaho, and their bearing on a petrogenetic model. *U.S. geol. Surv. Bull.* 1821, 71 pp.