NEAR-SURFACE EMPLACEMENT OF KIMBERLITES BY MAGMATIC PROCESSES

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Kimberlites are unusual magmas. The differences between kimberlites and other more common rock types results in many unique near-surface emplacement mechanisms. There are two main lines of argument to support this suggestion:

(a) although kimberlite eruptions have never been observed, the magma properties which are evident from rocks indicate that many aspects of kimberlite eruption processes are *not* the same as most other magma types, and

(b) the observed products of emplacement, as indicated by the internal geology and textures within kimberlite pipes (pipe is used here as a non-genetic term), are different from those in more common volcanic rocks, indicating contrasting processes of formation.

(a) Nature of the erupting magmas : Kimberlite magmas have a relatively rapid journey from the mantle to the surface that allows them to carry, and preserve, large volumes of xenolithic mantle material, including diamond. Sub-surface magma chambers are not formed. Kimberlite magmas also retain abundant juvenile gases until they reach surface. These gases are dominated by carbon dioxide (up to at least 20 wt.%) but also include significant amounts of water. Kimberlite magmas also have viscosities lower than many more common volcanic rocks, such as basalts, which allows for greater volatile mobility. Viscosities, however, would be influenced by the high crystal content. Kimberlite textures (e.g. Clement 1982, Clement & Reid 1989) and experimental petrological investigations (e.g. Dreibus et al. 1995) show that the carbon dioxide dissolved in kimberlite magmas must exsolve near-surface (<3 km), i.e. during final emplacement.

(b) Observed products of emplacement : At least three types of kimberlite pipes have been identified: (i) deep (up to 2 km), steep-sided pipes which comprise three distinctive zones (crater, diatreme, root; the term diatreme is used here specifically for this zone in this type of pipe), each of which has a different shape and is infilled by contrasting textural varieties of kimberlite (extrusive crater-facies volcaniclastic kimberlite, intrusive diatreme-facies tuffisitic kimberlite breccia and hypabyssal kimberlite, respectively), (ii) shallow pipes (<500m) which comprise only a crater zone and are infilled exclusively with volcaniclastic kimberlite, mainly pyroclastic material, and (iii) small (<600-700m deep), steep-sided pipes filled predominantly with resedimented material and less common pyroclastic kimberlite or, in a few instances, with hypabyssal kimberlite. The type areas for the different types of pipes are (i) Southern Africa, (ii) the Canadian Prairies, and (iii) Lac de Gras, NWT, Canada, respectively. The kimberlite pipe at Jwaneng in Botswana contrasts with the numerous bodies that conform to type (i) and probably belongs to group (iii). Although the type of kimberlite pipe varies, it is important to note that the nature of the pre-eruption kimberlite magma that reaches near-surface is petrographically uniform world-wide. Variations in magma type, therefore, cannot be the main cause for the different types of kimberlite pipes. Certain aspects of the pipe infill for each type of pipe contrast with those of other more common rock types and thus appear to be unique to kimberlites. Such features, for example, include the microlitic textures of diatreme-facies kimberlites in the type (i) pipes or the mega-graded beds (up to 100m) in the type (ii) and (iii) pipes. There is also an absence of features commonly found in other rock types such as extrusive magmatic rocks, plutonic rocks, calderas or ring faulting.

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Our present knowledge clearly shows :

(1) that kimberlite pipes worldwide have different shapes and contrasting types of infill,

(2) that the kimberlites magmas reaching near-surface prior to eruption are similar worldwide and magma variation cannot explain the diverse products of emplacement,

(3) that each of the contrasting types of kimberlite pipes must result from different emplacement processes,

(4) that more than one emplacement model is required to explain the known pipes,

(5) that any single emplacement model, such as phreatomagmatic processes (as proposed by Lorenz, see companion paper), cannot explain the emplacement of all kimberlite pipes as well as pipes formed by examination of the geology, often for economic purposes, of the first known primary kimberlite pipes in southern Africa (near Kimberley) that led the pioneers of modern kimberlite geology, Roger Clement and Mike Skinner, to propose their landmark textural-genetic classification and emplacement models for those kimberlites (Clement & Skinner 1979, 1985 and Clement 1979, 1982, Clement & Reid 1989 respectively). Since that time, many other kimberlites in southern Africa have been examined in similar detail and there is a great deal of evidence to support their proposals (e.g. Field & Scott Smith 1998a, in press).

The need for a kimberlite-specific textural classification itself shows that kimberlite emplacement results in different textures to most other rock types and must reflect contrasting processes of formation. The textural classification is an essential part of the other magma types,

(6) that the hydrogeological environment into which the different types of kimberlites pipes were emplaced is variable,

(7) that kimberlite magmas are unusual and display their own unique styles of near-surface emplacement.

It is important to note that the *above conclusions are irrespective of any ideas or hypotheses about the nature of kimberlite emplacement processes*. Over the last two to three decades there have been two main emplacement mechanisms proposed for kimberlites: by either magmatic (see references by Clement) or phreatomagmatic processes (see references by Lorenz in companion paper).

Kimberlite textures, and the processes forming them, are complex. The meaningful interpretation of these textures can only be undertaken on extensive three dimensional fresh exposures. Kimberlite pipes are eroded and all known rocks are now found below the original and present surfaces. Fortunately, kimberlites contain diamonds and suitable exposures are provided by mining and evaluation. In addition to megascopic examinations, the detailed petrographic and mineralogical analysis of kimberlites is crucial to an understanding of these rocks and their emplacement mechanisms. It is the modern detailed understanding kimberlite emplacement and is well tested (Field & Scott Smith 1998b). The detailed internal geology and textures of the southern African kimberlite pipes are complex. To explain the many observed features, the emplacement mechanisms proposed by Clement and co-workers include complex intrusive-extrusive magmatic eruptions from closed systems. The country rock geology into which many of the southern African kimberlite pipes were emplaced is similar and schematically shown in Fig. 1. The Clement emplacement model will be briefly described (for more details see Clement 1982, Clement & Reid 1989, Field & Scott Smith 1998a, in press).

During the last ~3 km of its journey to surface, the magma does not rise rapidly, and, prior to final breakthrough, the volatile-rich kimberlite behaves essentially as a closed system. The magma (dashed ornamentation in Fig. 1) rises relatively slowly by stoping and wedging along joints in the country rock. The volatiles migrate to the head of the magma/gas column. Exsolved volatiles concentrate to form a gas cap. The volatiles aid the migration into, and along, discontinuities in the country rock (thin lines within country rock in Fig. 1). There is intensified local fracturing around the head of the intruding magma

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column (thickened joint lines in Fig. 1). The upward journey of the magma toward surface is intermittent. The magma/gas column rises until it encounters a temporary barrier in the country rock such as a Karoo dolerite sill. Where the rising magma meets a barrier, there is a temporary halt in ascent and further build-up of the gas cap. Eventually, after pressure build-up and further fracturing, breaching of the barrier occurs by more explosive brecciation in an envelope around the head of the magma column (triangle ornamentation in Fig. 1). The breccia contains country rock clasts that have moved little or no distance and the local stratigraphy is retained in these sub-surface breccias (shown by wavy lines within the breccias in Fig. 1).

After breakthrough the upward migration of the magma is re-established as a relatively slow intrusive process. Magma and gas rises through the breccia 'front' and starts to move upward along higher level discontinuities in the country rock. The magma column becomes larger and the process is repeated each time a barrier halts the magma migration (three times in Fig. 1). All the intrusion processes (slow wedging and stoping, faster barrier breaching) gradually affect increasingly large areas of the country rock as the surface is approached. This is due to the increasing volume of magma, the increase in volume of exsolved volatiles, the reduced confining pressure, and the related greater penetration of the volatiles into country rock. Prior to breakthrough to surface, a large volume of country rock has been pre-conditioned by successive sub-surface brecciation fronts (the 'embryonic' pipe, Fig. 1).

The thick Stormberg basalts act as the final barrier to magma ascent (Fig. 1). Explosive breakthrough occurs when the volatile pressure exceeds the confining pressure. A crater is excavated. After breakthrough the uppermost part of the magma column begins to degas. After the pressure release, the volatiles rammed into the country rock prior to breakthrough (black arrows in Fig. 1) now migrate inward. This leads to authigenic brecciation, which is an important process in the modification of the 'embryonic' pipe that is about to form.

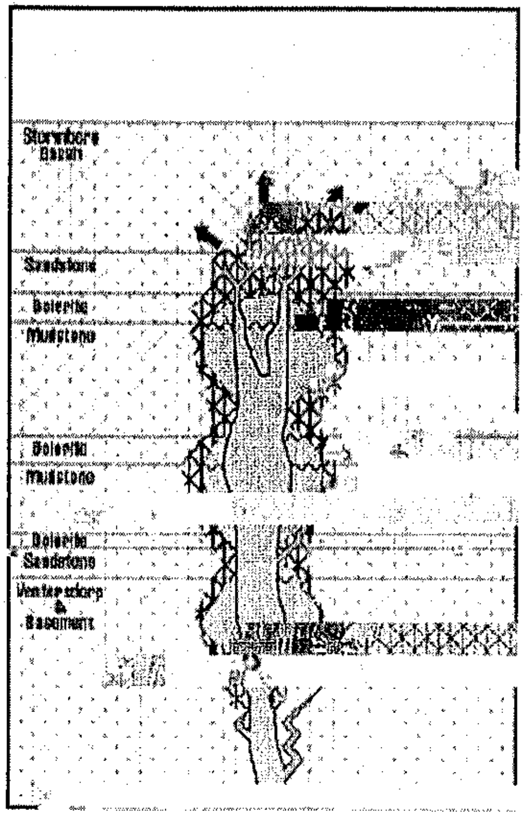

Figure 1 The third figure from a series of six which schematically illustrate the near-surface emplacement model for southern African kimberlites (from Field & Scott Smith in press. After drawings by C.R. Clement, based on Clement

1982, Clement & Reid 1989, Field et al. 1997). This figure illustrates the nature of the pre-breakthrough 'embryonic' pipe in relation to the country rock geology (see text for more details).

The carbon dioxide and other volatiles continue to rapidly exsolve from the magma. This massive volatile streaming causes fluidisation of the magma and the formation of magma droplets (pelletal lapilli) in a volatile-rich host. As degassing progresses, the interface between gas and liquid, or the degassing front, moves downward in the magma column while the magma continues to move upward.

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The powerful and turbulent fluidisation process aids the implosion and causes erosion of the country rock to form the smooth-sided diatreme. The diatreme excavation process moves downward with the degassing front and the diatreme is gradually widened. Abundant angular fragments of the country rock are incorporated into the fluidised magma. Thorough mixing occurs. Sinking particles are buoyed upward by the fluidised system. Only larger blocks of country rock move downward. Most of the carbon dioxide is lost from the fluidised system. The fluidisation stage is not long lived. The system cools rapidly. The remaining vapour phase condenses to produce quenched microlitic textures in the matrix of the fluidised kimberlite (for example see Plate 12.7(a) in Clement & Reid 1989; Plates 69 & 70 in Mitchell 1997 and numerous figures in Clement 1982). Much of the country rock, on the

The PK may be poorly bedded. Any remaining vacant areas in the crater are infilled by post-eruption resedimentation processes. The nature of resedimented material is very varied and distinct from the PK below. For example the resedimented volcaniclastic kimberlite (RVK) is commonly well bedded.

The primary pipe infill shows a gradual and progressive change in kimberlite textures with depth from partly bedded PK to intrusive monotonous TKB to HK. Each of these textural types of kimberlite dominates a different shape zone within the pipe. HK and the associated breccias occur in the irregular root zone (up to 500m deep), TKB in the steep-sided diatreme (up to 1000m deep) and PK +/- RVK in the shallower crater (up to 500m deep).

Lorenz (see companion article) has proposed that the same southern African kimberlite pipes were formed by a very different emplacement mechanism, namely by phreatomagmatic maar-like processes.

order of 50%, remains within the diatreme, ranging from small xenoliths to floating reefs. Fluidisation has shaped the diatreme by incorporating most of the pre-brecciated areas and material produced by authigenic brecciation. The pelletal lapilli, the abundant small angular mixed country rock xenoliths and the magmatic microlitic matrix together form the diatreme infill (usually termed tuffisitic kimberlite breccia or TKB).

As fluidisation wanes, the kimberlite magma below the fluidised system crystallises to form hypabyssal kimberlite (HK). The gradational HK to TKB boundary represents the preserved degassing front at the time of solidification. Some of the early formed irregular intrusive contacts and pre-cursor sub-surface breccias are preserved in this root zone when fluidisation has not persisted long enough and deep enough to remove all traces of sub-surface pre-breakthrough activity or the 'embryonic' pipe. Contemporaneous with the post-final breakthrough events described above, some juvenile and xenolithic material is ejected from the crater and forms a pyroclastic eruption cloud and the crater is infilled by pyroclastic kimberlite (PK). Extra crater deposits will also form. The PK is composed of the same constituents as, and resembles, the TKB below. The boundary between the PK and TKB is gradational.

In Lorenz's interpretation, the pipes are explosion craters that were back-filled by erosion of the crater rim deposits. In general, evidence for phreatomagmatic maar/crater formation processes is provided by the nature of the resulting base-surge deposits, which occur mainly in extra-crater deposits surrounding maars. No such deposits are preserved at any known kimberlite locality, so direct evidence does not exist for the southern African or other kimberlite pipes. Lorenz also suggests that one process, namely phreatomagmatism, explains the formation of maars, kimberlites, lamproites and other diatremes (sensu lato), irrespective of magma type and nature of the pipe infilling. It is clear that, in certain circumstances, phreatomagmatism is important in crater excavation, but only the sudden release of confined juvenile gases can lead to the formation of the southern African kimberlite diatremes as well as the concomitant fluidisation of the magma. The latter is a magmatic process. Clement (1982) also posed the question "How does sufficient water enter the system sufficiently rapidly to be vapourised and maintain fluidised conditions in major diatremes?", to which there is no ready expla

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nation.

textures on a megascopic scale from

There is abundant evidence that shows that the main mechanism forming and infilling the southern African kimberlite pipes was not phreatomagmatism. Most maars are shallow craters filled with mainly resedimented material. Resedimentation processes are diverse so the internal geology of each maar is different. In maars, an underlying diatreme is seldom proven/present. Most southern African kimberlite pipes have proven diatremes which are deep, steep-sided and filled with a specific type of *magmatic* material (TKB) that is remarkably uniform worldwide. Also, in his model, Lorenz relies on numerous individual phreatomagmatic blasts to produce the numerous base surge beds in the crater rim deposits. Kimberlite diatremes by contrast commonly display good evidence for one major eruption.

The southern African pipes comprise three zones that have different shapes and contrasting material filling them, which indicates that they formed by varying processes within the one overall emplacement event (root zones by stoping etc., diatremes by fluidisation and craters by explosive breakthrough). The nature of the infilling of both kimberlite diatremes and the few known overlying craters contain no evidence for phreatomagmatism. These features include the monotonous nature of the kimberlite in the diatreme with a distinct lack of sedimentary structures, the consistent presence of magmatic inter-clast matrices in the TKB and some PK, the consistent nature of that matrix (diopside and less common phlogopite microlites set in a serpentinous carbonate-poor base), the absence of exotic fines that are typically present in reworked material, the consistent pelletal not blocky shape of the juvenile lapilli, the lack of accretionary lapilli, the complete range crater-facies PK to diatreme-facies TKB to root zone HK with depth in the pipe. Also, in the root zones the sub-surface breccias preserve the local stratigraphy and have clearly never been ejected. Kimberlite diatremes are constantly smooth-sided, irrespective of the country rock geology. In contrast, pipes which remain vacant for periods of time during resedimentation have complex shapes depending on the angle of repose of the different country rock units in the pipe wall.

The lack of vesicles in the pelletal lapilli within the diatreme-facies kimberlite is used by Lorenz to argue that the lapilli cannot have formed from a melt that was exsolving volatiles. In contrast, in the magmatic model it is proposed that the lapilli form as a result of massive, and usually complete, degassing of the carbon dioxide above the root zone. The degassing is clearly illustrated at the interface between the root zone and the overlying diatreme. There is a gradual progression from uniform HK, to segregationary HK to TKB. The well crystallised volatile-rich segregationary HK contains abundant irregular pools or segregations of late crystallising primary serpentine and calcite. As the interface is approached, the abundance of segregations (and volatiles) increases. The individual segregations begin to coalesce, thus isolating discrete bodies of the silicate matrix which, after degassing, form the pelletal lapilli in the TKB. The inter-pelletal lapilli matrix, which is composed of microlitic clinopyroxene set in a base of serpentine, crystallised rapidly, or quenched, from the residual magmatic fluids. No carbonate is present in the TKB indicating that the carbon dioxide has been lost from the upper part of the magma. These textural variations clearly illustrate the transition from volatile-bearing HK to fluidised and degassed TKB within a single overall diatreme-forming in size of xenolithic material from small to very large floating reefs, the carbonate cement in xenoliths which were brecciated prior to incorporation into the kimberlite, and the absence of ring faults surrounding kimberlite pipes.

Another important feature that contradicts phreatomagmatic processes is the gradation in magmatic event. The interface represents a degassing front preserved at the time when the kimberlite condensed and emplacement ceased.

The above discussion is based on the long known, and well studied, kimberlites of southern Africa. Other kimberlite pipes elsewhere in the world are

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similar and must have been emplaced by similar processes. Comparable products of emplacement also occur in melilitite pipes, suggesting that they were emplaced by similar processes. The fact that melilitites are the only other silicate magma which contains abundant carbon dioxide during eruption offers support for the magmatic model discussed above. Over the last decade intense exploration has led to the discovery of many new kimberlites, particularly in Canada. It is clear that many, but not all, of these kimberlites are different from those of southern Africa. The contrasting types of pipes must result from different types of emplacement mechanisms, which will only be discussed briefly here.

There appears to be a correlation between the type of kimberlite pipe and the nature of the country rocks into which they were emplaced (Field & Scott Smith 1998a, in press). The pyroclastic kimberlite is texturally very different from that found in the southern African pipes, indicating that a different style of magmatic eruption must have occurred. Fluidisation and diatreme-formation did not occur. Based on the nature of the pyroclastic kimberlite, it is proposed that because of the absence of any barrier-forming igneous or other rocks, the magmas erupted from open systems by more 'normal' processes (Hawaiian/Strombolian-like) as well as other kimberlite-specific more explosive styles of eruption (e.g. producing mega-graded beds). With the absence of any preserved extra-crater deposits, there is no direct evidence to indicate the nature of the initial crater excavation event. Based on circumstantial evidence only, it seems likely that the craters were excavated by phreatomagmatic eruptions relating to well known aquifers in the poorly consolidated sediments into which they were geological settings for the three types of pipes listed in section (b) above are: (i) competent country rocks that commonly contain igneous rocks, (ii) poorly consolidated sediments, and (iii) basement covered by a veneer of poorly consolidated sediments (respectively). This correlation suggests that the near-surface geological setting is a major factor in determining the emplacement process of each kimberlite. Different emplacement mechanisms are proposed that take into account the combination of pipe variety and geological setting. Setting (i) provides the closed systems that are an integral part of the proposed intrusive-extrusive magmatic eruption mechanisms for the emplacement of the southern Africa pipes discussed above. Competent country rock barriers result in the sub-surface build up of juvenile volatiles, and after breakthrough, massive degassing of carbon dioxide with fluidisation of the magma below and the contemporaneous formation of the deep steep diatreme.

In contrast, the kimberlites in setting (ii) are formed by a two stage process: complete crater excavation and subsequent, separate crater infilling. The magmatic eruptions which formed the predominantly pyroclastic infilling are clearly not of phreatomagmatic origin (e.g. lack xenoliths and fines, contain vesicular and/or amoeboid juvenile lapilli as well as mega-graded beds up to 100m). The emplaced. The evidence includes the fact that the shape and size of the craters are comparable to maars and that they flare from the known aquifer. This is the only instance among the many kimberlites examined to date by this author where it appears justified to propose that phreatomagmatic processes may be involved in kimberlite emplacement.

A third mechanism that does not conform to either of the other two processes, but is as yet poorly constrained, must apply to kimberlites emplaced into setting (iii). Other emplacement mechanisms may be required to explain other well exposed kimberlites, such as in Yakutia.

Concluding remarks

This brief discussion should help to dispel the notion that the emplacement of the different types of kimberlite pipes that have been recognised can all be explained by phreatomagmatic processes as suggested by Lorenz. At the very least, the review shows that contrasting emplacement processes must have been involved to form the different types of kimberlite pipes, irrespective of the nature of the processes. The complex intrusive-extrusive magmatic emplacement model of Clement and Skinner best explains the observed nature of the majority of

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the southern African kimberlite pipes (and some pipes elsewhere in the world). This author believes that the evidence supporting this magmatic model is overwhelming and that workers who suggest that phreatomagmatic processes are essential in the emplacement of these, and many other known, kimberlites are ignoring the geological evidence.

It is time to move on from the detrimental, two decade stalemate between the opposing models and to advance the understanding of kimberlite emplacement using other aspects of volcanological research. Perhaps an impartial, independent detailed review of the two models is required. Much of the data for kimberlites are collected by economic geologists (such as myself) whose priority is not publication. As a result much of the detailed information is not in the public domain, however, it would probably be available for review. Also the detailed observations and ideas on the emplacement of these unusual carbon dioxide-rich magmas should have a contribution to make to the understanding of explosive volcanic processes in general.

Roger Clement reviewed an earlier draft of this article (on the day of his retirement) and added the following comment : "Lorenz's erroneous and simplistic elevation of phreatomagmatism to the status of the universal, unquestionable explanation of the formation and infilling of kimberlite (and other rock types) pipes reflects a glaring omission in his approach. Lorenz has failed to examine and understand the detailed petrography and mineralogy of the rocks he seeks to interpret".

Roger Mitchell, author of three books able, when considering the real structure of diatremes, to extend such processes to depths of 1-2 km. Further it is unrealistic to claim that experimental studies of water-magma interactions at low pressures (1-30 bar) are suitable models for high pressure (>1000 bars) fluid-magma interactions in carbon dioxide-rich systems. The current impasse between magmatists and phreatomagmatists will only be resolved by new approaches. It would be particularly useful if volcanologists and petrologists with experience of other magmatic systems could bring novel, and hopefully bias-free, recommendations and concepts to the resolution of the problem of kimberlite emplacement. "

Although it is proposed here that the main emplacement mechanisms for kimberlites are magmatic and driven by juvenile volatiles, this does not exclude the possibility that phreatomagmatic processes may contribute and, sometimes, be important in certain circumstances (e.g. crater excavation in the kimberlites of the Canadian Prairies).

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on kimberlites (e.g. Mitchell 1997), wrote the following after reviewing this article : "I consider that the weight of the observational evidence provided by the actual geological structure and petrographic character of kimberlitic volcaniclastic rocks currently favours hypotheses of emplacement which are dominated by magmatic processes. These studies have clearly indicated that more than one process must be involved in near-surface emplacement. There is no doubt that phreatomagmatic processes may occur in some near-surface environments but it is unreason

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In this Issue....

In this issue, we have decided to try eliciting a debate among our readers. One of the biggest debates at the CEV symposium on maars, diatremes and kimberlites at the meeting in South Africa last year was whether kimberlites are truly different from phreatomagmatically formed maars. Volker Lorenz argued for a phreatomagmatic origin for all kimberlites, citing striking similarities between his group's experiments on fuel/coolant interactions, field data on maars around the world, and descriptions of kimberlites. Barbara Scott Smith argues for a magmatic volatile component causing the explosivity of kimberlites, and sees little to no evidence for fuel/coolant interactions, at most diatremes. It seemed to us that the debate was worth extending to all of our members, so we invited Volker and Barbara to submit articles arguing for their models. They graciously agreed, and their articles make up the bulk of this issue. We would welcome discussion on their models in future issues. If enough people write, we can post comments on the CEV home page to continue the debate.

In addition to the kimberlite debate, we also have an article by Paola Del Carlo, Mauro Coltelli, and Luigina Vezzoli on their work on the Etna Plinian basaltic eruption of 122 BC. They present a model designed to explain how a basaltic magma can have the explosive force to sustain a Plinian eruption column. Their model finds that magmas of compositions similar to those from the 1996 eruption can cause tremendous explosions with little warning. They suspect that there are more basaltic Plinian deposits around the world, and want to alert other workers to look for them. Comments on their work are also welcome.