Pelletal Lapilli in Diatremes – Some Inspiration from the Old Masters

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ABSTRACT: Pelletal lapilli are typically the juvenile component of silica undersaturated, ultramafic and carbonatitic diatreme volcanics; they represent the interface between the erupting magma and the volatile component. In the Monticchio diatremes, Mt Vulture, Italy, unusual pelletal lapilli with shells of melilitite and carbonatite host abundant mantle and not crustal fragments, which indicate that gas exsolution and lapilli formation were dominantly at near mantle depths. The lapilli show a complex history of agglutination and abrasion coupled with consistent change from inner melilitite shells to outer carbonatite shells, which implies an intrinsic process of magma evolution. These features are not consistent with a singular, high-level phreatomagmatic event. The calcite-rich magmatism testifies that the main transporting gas was CO_2 and not H_2O; pyroclastics show no evidence of water-cooling. More commonly occurring pelletal lapilli lack compositional shells but are cemented by serpentine+diopside in kimberlite pipes, or calcite in melilitite diatremes and probably represent magmatic evolution at a shallower level than the Monticchio examples. Inferred ascent rates for ultramafic, xenolith-carrying magmas require a deep-seated gas-driven fracture--conduit; phreatomagmatic lift-off is too shallow. The poor vesicularity of pelletal lapilli indicates that the initial juvenile volatile content of the magma became concentrated as the fluidising medium.

KEY WORDS: diatreme, pelletal lapilli, olivine melilitite-carbonatite, CO_2

Introduction

Formation of tuffisite-filled diatremes, together with their surface expression of maars and tuff-rings, has been the object of debate for over half a century. In 1941, Cloos described the Schwabian diatreme pipes in his classic paper, in which he coined the term "tuffisite" to distinguish the pipe infill of intrusive tuff from extrusive tephra deposits.

Tuffisite material ranges from large blocks to ash, in which clasts are both angular and well rounded and comprise juvenile material together with mantle and crust wall-rock xenoliths (Cloos 1941).

The diatreme suite of volcanic phenomena indicates active participation of volatiles: pyroclast-filled pipe, large explosion crater, base surge deposits. Holmes (1965), drawing on Reynolds' (1954) application of industrial fluidised-bed processes to geological situations, concluded that diatremes are formed through the action of juvenile gas (H_2O and/or CO_2) plus tephra in a fluidised system, drilling their passage through the Earth's crust. In arriving at this hypothesis, Holmes (1965) was strongly influenced by his observation that diatremes are notably typical of silica undersaturated, alkaline ultramafic magmas (olivine melilitites, kimberlites, extrusive carbonatites) with a high proportion of juvenile volatiles, and carbon dioxide in particular. Mitchell's recent (1997) petrographic review of these rock types reiterates that diatreme formation is "commonly an intrinsic part of melilitite magmatism". Holmes also argued that diatreme magmas must contain an important juvenile propellant in order to lift mantle xenoliths to the surface.

With this interpretation, diatremic volcanism is a statement about the history and nature of the erupting melt, the composition of the mantle from which it is derived and the partial melting process that produced it.

Maar and tuff-ring formation by phreatomagmatic processes has been observed in recent times (e.g. Lorenz, this volume). It is commonly supposed that a tuffisite-filled pipe underlies such tuff rings and maars and that this pipe, created by phreatomagmatic explosions, is equivalent to the diatreme of the "magmatists".

Pelletal lapilli are characteristic of the juvenile component of diatreme filling. They are important because they represent the interface between the erupting magma and the volatile component. If formation of pelletal lapilli is concomitant with juvenile gas release and inception of a fluidised gas-debris stream, they should present features that document magma source and evolution. If they are a near surface product of reaction between magma and ground water then deep-seated features should be absent**.**

First this paper reviews the general characteristics and occurrence of pelletal lapilli, and then focuses on some particularly instructive pelletal lapilli that occur in the maar and diatreme rocks of Monte Vulture, southern Italy. These concentric shelled lapilli document stages in the evolution of ultramafic, silica undersaturated magma and separation of immiscible carbonatite. Briefly described in previous papers (Stoppa and Lavecchia 1992, Stoppa and Principe 1998), petrographic details are given for these lapilli that argue cogently for a magmatic origin at mantle depths. Evidence is then provided to show the correspondence between the Monte Vulture lapilli (and other like occurrences in the Umbria-Latium Ultra-alkaline District) and the more common pelletal lapilli found in olivine melilitite and kimberlite diatremes in general. Finally the "gas" phase (fluid or supercritical fluid; or "vapour", as in "V" used in experimental phase diagrams) is discussed, together with the possible mechanism of formation and eruption of Monte Vulture lapilli in particular and pelletal lapilli in general.

General Characteristics and Occurrence of Pelletal Lapilli

According to Mitchell's (1997) definition, pelletal lapilli are discrete, smooth, spherical-elliptical lapilli of primary igneous material, commonly with a single, megacrystic fragment or a lithic at the centre, which is mantled by fine-grained micro-phenocrystal material in which prismatic crystals are flow arranged. A particular emphasis is given to their internal structure, which is composed of several concentric lava layers (Stoppa and Lupini 1993). Pelletal lapilli are dense, with fewer vesicles than typical strombolian lapilli. They are often found mixed with massive acneliths, which are massive lumps of magma and with clasts formed by the fragmentation of pre-existing solid igneous material, typically fine-grained hypabyssal.

Notably, natural occurrence is restricted to eruptive ultramafic rocks such as carbonatites, melilitites, kimberlites and orangeites (Mitchell 1997). Pelletal lapilli are a diatreme-facies phenomenon (Keller 1989, Mitchell 1997). They are found in pipe fillings (tuffisite), e.g.: Schwabian olivine melilitite pipes, Germany (Cloos 1941); Letseng-la-terai kimberlite pipe, Lesotho (Mitchell 1997); Polino carbonatite diatreme, Italy (Stoppa and Lupini 1993) also in surge deposits associated with maars and tuff rings, e.g.: Monticchio Maars carbonatite-melilitite surge deposits, Mt. Vulture, Italy (Stoppa and Principe 1998); Murumuli tuff ring carbonatite-melilitite surge deposits, Katwe-Kikorongo, SW Uganda (Stoppa et al. 2000) and other tuff rings of olivine melilitite in Bunyaruguru and Katwe-Kikorongo, SW Uganda (Lloyd 1985, Lloyd et al. 2002). At the San Venanzo carbonatite-melilitite Celle tuff ring, Italy, pelletal lapilli are found both in the pipe tuffisite and its extrusive (Stoppa 1996). They have also been described from strombolean deposits, as in the melilite-nephelinite Herchenberg volcano (Bednarz and Schminke 1990).

Depth of pelletal lapilli formation and evolution

Mitchell observed (1997) that for olivine melilitites, kimberlites and orangeites, the cores to pelletal lapilli are typically olivine, or sometimes phlogopite and only very rarely country rock microxenoliths. In SW Ugandan olivine melilitite pelletal lapilli, large core-forming mica plates prove to be xenocrysts, probably of mantle origin (Lloyd et al. 2002). Discrete peridotite fragments are a frequent occurrence in diatreme related Italian melilitites and carbonatites (Stoppa and Woolley 1997).

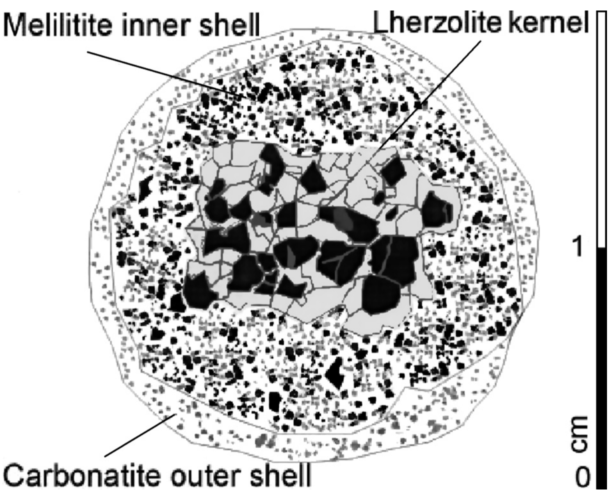

Fig. 1. Drawing traced from a digital image of a cross section of an MLF lapillus with two compositional shells and a lherzolite xenolith core.

The fact that igneous pheno/xenocrysts, or a mantle nodule, are *typical* cores, rather than country rock fragments, points to a great depth of lapilli formation.

Pelletal lapilli from the Monticchio Lakes Formation (MLF), Monte Vulture in Southern Italy are remarkable in that they have concentric shells that document, from deep-seated to sub-surface, stages in evolution of ultramafic, silica undersaturated magma and separation of immiscible carbonatite liquid (see Figs. 1–3, below). The eruption style and petrology of this carbonatite-melilitite tuff sequence have been fully described (Stoppa and Principe 1998). The tuffs represent the latest activity (0.13 my) in the Umbria-Latium Ultra-alkaline District

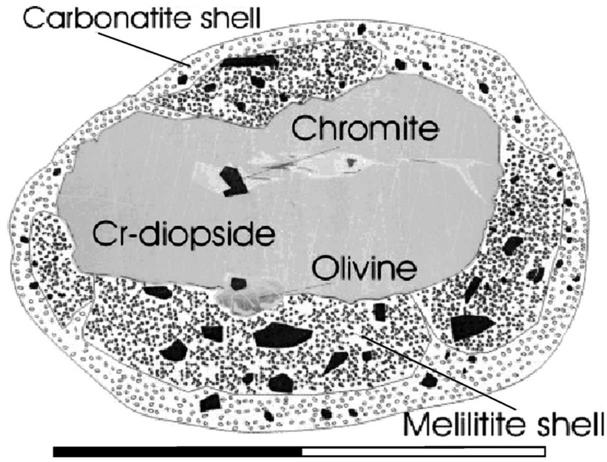

Fig. 2. Drawing traced from a digital image of a cross section through an MLF lapillus with two compositional shells and a Cr diopside megacryst core. Scale bar as in Fig. 1.

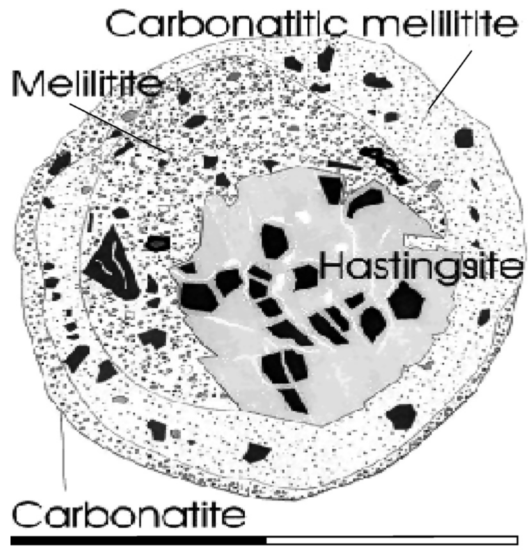

Fig. 3. Drawing traced from a digital image of a cross section through an MLF lapillus with 3 compositional shells and a hastingsite megacryst core.

(ULUD: Stoppa and Lavecchia 1992, Stoppa and Lupini 1993, Stoppa and Cundari 1995, Stoppa and Woolley 1997). The lapilli occur in surge deposits that rim the Monticchio depression, which encloses two lake-filled maar craters (Lago Grande and Lago Piccolo). The primary nature of the carbonatite has been well established in terms of stable and radiogenic isotope ratios and compatible and incompatible element contents (Stoppa and Principe 1998), which are typical for calciocarbonatites (Deines 1989, Woolley and Kempe 1989). Group 1 mantle xenoliths (lherzolite, wehrlite, harzburgite and dunite), up to 8 cm across, testify to high velocity eruption from mantle depths (Stoppa and Principe 1998). Geothermobarometric analysis of MLF group 1 xenoliths indicates final equilibration at about 14-22 kbar and 1050–1150 °C, i.e. in the lithospheric mantle (Jones et al. 2000).

High-pressure megacrysts or mantle debris *invariably* form the cores to the MLF concentric lapilli (Figs. 1–3), despite the fact that crustal debris far exceeds mantle fragments in the tephra. This is difficult to explain except by lapilli initiation at near mantle depths. The kernel is often angular and irregularly bounded (Figs. 1 and 2); as might be expected if mantle fragments have been incorporated at depth and protected from abrasion during prolonged transport. In an example where the core is rounded it has been abraded after being coated with melilitite magma (Fig. 3).

Melilitite surrounds the nucleus, the fine-grained groundmass being composed of melilite laths (±calcite), which may/may not show concentric arrangement, together with microphenocrysts of spinel, apatite, häuyne and perovskite (Stoppa and Principe 1998). There is also xenocrystic debris with deformation features such as kink bands and undulose extinction, comprising olivine, clinopyroxene, amphibole and phlogopite (Stoppa and Principe 1998), which are all minerals typical of Monte Vulture xenolith suite assemblages (Jones et al. 2000, Rosatelli et al., in review). Clearly the melilitite melt was disrupted and subsequently nucleated while mantle, not crustal material prevailed.

The boundary to the melilitite shell in general describes an ellipse (Figs. 1–3). This form may be related to rapid rotation of the lapillus in the gas stream. Embayments, which have been preserved by "deposition" of the outer shell of calciocarbonatite (Figs. 1 and 2), point to abrasion by a particle-loaded gas stream. In some cases the melilitite shell is discontinuous and appears to consist of several sites of accretion (Fig. 2) that remain more or less discrete, rather than flowing into each other. This is explicable by very rapid quenching due to adiabatic supercooling of the melt. A supercooled state can explain the ability of the melt to adhere to the kernel and has been advocated for the formation of Schwabian pelletal lapilli (Lorenz 1979). The combination of observed features advocates concentric-shelled lapilli formation by agglutination of small melt droplets onto a crystal or lithic core.

The compositional changes from melilitite to carbonatite (Figs. 1 and 2), and from melilitite to carbonatitic melilitite and then to carbonatite (Fig. 3) reveal a complex history of accretion and erosion, which otherwise might not be visible. A consistent change in magma composition from inner to outer shells, i.e. calciocarbonatite is always the final coating, implies lapilli development concomitant with separation of silicic and carbonatitic fractions, over vertical distance and time. Moreover, crustal fragments are absent from the outer, calciocarbonatite shell, which similarly to the inner melilitite shells, contains phlogopite flakes and olivine fragments. This lack of crustal xenocryst debris in both inner and outer shell compositions advocates that lapilli development was largely confined to the mantle. None of these features is explicable by a singular, intra-crustal explosive event.

Associated features of the Monte Vulture Pyroclastics

The Monticchio Lakes Formation (MLF) is a small volume product spread over a wide area by violent, maar-crater forming eruptions. This is a scenario compatible with gas-powered eruptions at initial magmatic/near magmatic temperatures (Mastin 1995). In addition to concentric lapilli, massive lumps of carbonatite or melilitite, irregular and vesiculated carbonate lapilli, carbonate ash and crystal fragments compose the juvenile product. Mantle xenoliths of lherzolite, wehrlite, harzburgite and dunite, up to 8 cm across and typically without a magma jacket are also found. Country rocks occur in accessory proportion. No indication of H_2O quenching of magma is observed and evidence for significant H_2O during eruption, such as accretionary lapilli, or ash-matrix vesiculation, is absent (Stoppa and Principe 1998). Lapilli, other than pelletal, are irregular and vesiculated. The lumps of carbonatite or melilitite are interpreted as low-pressure acneliths produced by lava fragmentation at the vent during a period of strombolian activity. The lack of magma coating to mantle xenoliths could imply carriage to the surface in a fluid.

Pelletal lapilli without concentric shells of different composition

Similar concentric pelletal lapilli where shells of carbonatite alternate with kamafugite (phenocrysts of forsterite, melilite, kalsilite and leucite) are found at the Late Pleistocene carbonatite-melilitite maar and tuff ring of San Venanzo-Pian di Celle, Umbria-Latium Ultra-alkaline District (ULUD), Italy (Mittempergher 1965, Stoppa 1996). However, pelletal lapilli with concentric structure defined by flow-aligned microphenocrysts (Gurney et al. 1991, Stachel 1995), or faint mineral or colour banding and slight grain-size changes (Ferguson et al. 1973, Plate 69A; Lorenz 1979, Fig. 5; Riley et al. 1996) are much more common than the compositional shells seen in the Italian ULUD examples.

Such lapilli are typical of olivine melilitite effusives, e.g. Katwe-Kikorongo and Bunyarurguru, SW Uganda (Lloyd 1985), Laetolil beds, Tanzania (Hay 1978), Schwabian tuffisite pipes, Germany (Cloos 1941), where they are often cemented by carbonate-rich ash. In SW Uganda this ash is carbonatitic (Lloyd 1985; Stoppa et al. 2000). Pelletal lapilli are a feature of extrusive carbonatites, e.g. Auf Dickel, W Eifel, Germany (Riley 1994), Gross Brukkaros, Namibia (Stachel et al. 1995), and Rufunsa, Zambia (Bailey 1989), and they are also relatively common in diatreme-facies kimberlite (Ferguson et al. 1973; Gurney et al. 1991; Mitchell 1997) where they are cemented by microlitic diopside and serpentine (quenched kimberlitic transporting fluid phase, Gurney et al. 1991), sometimes with dolomite and calcite, usually in subordinate amounts.

Mantle xenolithic material forms a significant proportion of the lapilli nuclei, but crustal debris is also quite common as core material, as are the larger phenocrysts, for example, melilite and olivine (Lorenz 1979 for Schwabian lapilli; Lloyd, personal observation for Ugandan lapilli). In these examples some nucleation was taking place at shallower-than-mantle levels (melilite is stable to 10 kbar in melting experiments on Ugandan olivine melilitite, Arima and Edgar 1983).

A higher level of nucleation and involvement of crustal material has been interpreted as support for phreatomagmatic origin, especially where the geomorphology and sedimentary stratigraphy suggest presence of copious groundwater (Lorenz 1973, 1979, 1994, Schminke 1977, Stachel et al. 1995). None-the-less, the SW Ugandan examples (Lloyd 1985, Stoppa et al. 2000) document evolution and segregation of a primary carbonate-rich, silica undersaturated ultramafic magma, in a similar manner to the ULUD examples, albeit at a higher level.

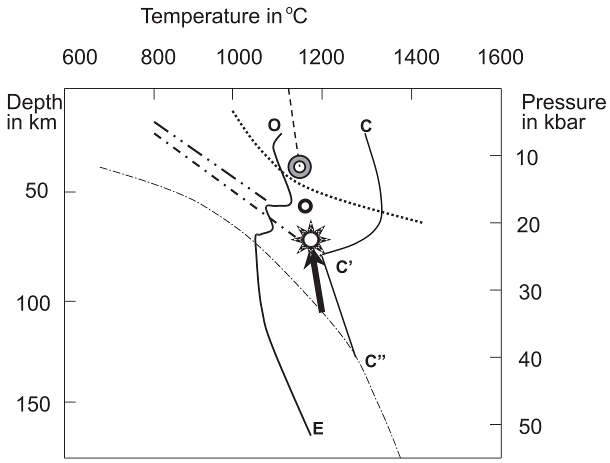

Fig. 4. Pressure-temperature diagram to show the ascent of MLF melt, CO_2 diatresis and hypothetical formation of MLF concentric lapilli (based on Bailey 1985, Fig. 4). **0-E** is the peridotite solidus in the presence of H_2O and CO_2 (Olafsson and Eggler 1983); **C-C'-C"** is the carbonate peridotite solidus and the *heavy dot-dash line* from **C'** the decarbonation boundary of Wyllie (1979), the *dot-dot-dash line* parallel to this is the equivalent boundary of Olafsson and Eggler (1983). The *thick black arrow* marks accumulation and ascent of liquid on geotherm (*light dot-dash line*) along an adiabatic path (*heavy dashed line*) with origin at 1150°C appropriate for San Venanzo liquid (Stoppa and Cundari 1998). As the liquid passes through the melt structure transition where CO_3^{2-} becomes unstable (*heavy dot-dash line*: decarbonation boundary of Wyllie, 1979), massive gas exsolution induces high velocity eruption (melt diatresis), marked by *starburst*. The liquid fragments into droplets that accrete on mantle debris to form lapilli of carbonated melilitite composition (*thick black circle*). Lapilli, fragmented liquid and mantle debris ascend in a CO_2 fluidised stream and pass through the immiscibility boundary for silicate and carbonate fractions (*heavy dotted line*; Kjarsgaard and Hamilton 1989) and unmixing leads to deposition of outer carbonate coatings on lapilli (*double circle with unfilled centre and grey outer shell*). Note that 100% decarbonation of the rising liquid does not occur because carbonate clearly remains in the melt to erupt as carbonatite. The CaO released during decarbonation should encourage precipitation of melilite and clinopyroxene in the silicate melt.

Consideration of the gas phase: nature of gases in pelletal-lapilli forming magmas

The "gas" under discussion is essentially a fluid or supercritical fluid (or "vapour", as in "V" used in experimental phase diagrams) that can exist as a separate phase from a silicate or carbonate melt. Carbon dioxide is the major volatile phase in all the igneous compositions from which pelletal lapilli have been reported. In the Italian ULUD cases it appears that CO_2 is overwhelmingly present and evidence for H_2O, juvenile or otherwise, is generally lacking (Stoppa 1996, Stoppa and Principe 1998). In olivine-melilite tuff-rings and diatremes and in kimberlite pipes, there is a notable presence of magmatic carbonate, which represents a high proportion of mantle-derived CO_2 (e.g. Brey 1978, Dawson 1980, Lloyd 1985, Kirkley et al. 1989, Brey and Ryabchikov 1994). Hydrous phases such as phlogopite and serpentine indicate some juvenile H_2O as well, while significant F and Cl is found in the SW Ugandan melilitite lapilli (Lloyd 1985).

With respect to meteoric water, in SW Ugandan pelletal-lapilli-bearing tuffs, the presence of acneliths, the lack of accretionary lapilli and glassy or bread-crust surfaces point to high-temperature largely "dry" eruption conditions (Field work by Eby, Lloyd, Stoppa and Woolley; Stoppa et al. 2000). Kobelski et al. (1979) considered interaction with meteoric water to be responsible for enrichment in the heavier stable isotope content of fragmental kimberlite, but Kirkley et al. (1989) observed the same trends in fresh, hypabyssal facies, which they interpreted as carbon isotope fractionation by CO_2 degassing and oxygen isotopic exchange with juvenile water.

Eruption mechanism: requirements

Ultramafic, silica undersaturated, carbonate-rich volcanism requires the mechanism to erupt both magma and mantle xenoliths from depths of up to ~200 km, in the case of kimberlite (Dawson 1962, Boyd and Nixon 1973, Bailey 1985). Ascent needs to be rapid, 10-30 m/sec for kimberlites, based on factors such as preservation of diamond without graphitisation (Anderson 1979) and xenolith settling rates (Spera 1987). Only a fractureconduit flow mechanism is sufficient, diapiric ascent and melt percolation are too slow (Anderson 1979, Spera 1987). The only realistic agent of acceleration at depth is gas (Anderson 1979, Bailey 1985).

Fluidisation of mantle rocks by CO_2 diatresis, formation of pelletal lapilli and evolution of ultramafic silicate-carbonate magmas during ascent

The low compressibility of CO_2 at high pressures means that exsolution of gas from the melt at depth does not provide much acceleration (Spera 1987). However, initial melts start out with high CO_2 contents (as argued above) and those that follow an adiabat will exsolve gases and pass through Olafsson and Eggler's (1983) carbonate-out boundary, leading to massive CO_2 exsolution (Bailey 1985). At the same time the melt temperature approaches the liquidus where major gas foaming (CO_2 and H_2O) occurs (Hampton and Bailey 1985) leading to extensive fragmentation of the melt in a gas-fluidised system.

In the ULUD volcanoes of Monticchio Lakes and San Venanzo, the initial percolating melt was of a carbonatitic-melilititic nature. The ascent of MLF melt (based on San Venanzo liquid, Stoppa and Cundari 1998), CO_2 diatresis and hypothetical formation of MLF concentric lapilli are shown in Fig. 4 (based on Bailey 1985, Fig. 4). It is proposed that fluidisation and consequent "lift off" of the melt by CO_2 diatresis took place at a minimum depth of ~66 km, according to the lherzolite xenoliths carried to the surface (see above). The carbonate fraction probably segregated at P<20 kbar (Stoppa and Cundari 1998) based on phonolite-carbonatite immiscibility experimental results of Kjarsgaard and Hamilton (1989). Some carbonatite liquid adhered to the already formed lapilli and the rest was sprayed as ash-sized droplets. The magmatic origin of the concentric-shelled lapilli at mantle depths and the important role of CO_2 in their formation and eruption are fully substantiated by the petrographic evidence, even if the exact mechanism(s) that formed MLF lapilli are a matter for debate.

Pelletal lapilli of olivine melilitite in carbonate ash and of kimberlite in calcite plus serpentine are considered to represent similar phenomena, but where lapilli nucleation and segregation of the matrix phase took place at a higher level.

Vesicularity of pelletal lapilli and gas-content

In the CO_2 diatresis model of Bailey (1985), foaming at mantle depth in near conjunction with the carbonate-out boundary has two effects: (i) production of minute droplets when melt is fragmented; (ii) very rapid quenching of these droplets, which seals in some volatile and discourages further vesiculation, though some volatile may diffuse out of the smallest particles. Poor vesicularity of pelletal lapilli need not indicate that their magmas were low in initial juvenile volatile component as suggested by Lorenz (1973, 1979, 1994), but rather that the juvenile gases have been concentrated as the fluidising medium (Scott Smith 1999).

Phreatomagmatism manifestly does occur and can be superimposed on earlier tuffisite phenomena to boost maar formation. Pellet-shaped lapilli, reported from basanites and nephelinites of W Eifel maar deposits (e.g., Lorenz 1979), are unusual in that some show marked surface cooling cracks (ibid, Fig. 6) that could indicate H_2O cooling. Schminke (1977) interpreted these as products of eruptions transitional between purely magmatic and phreatomagmatic.

Summary

1. Pelletal lapilli are typically a juvenile component of ultrabasic, ultramafic and carbonatitic diatreme volcanics; they represent the interface between the erupting magma and the volatile component, which is dominated by CO_2.
2. The Monticchio pelletal lapilli document a deep-seated process of formation in a CO_2 fluidised stream of fragmented melt that was concomitant with melilitite-carbonatite magma evolution.
3. Poor vesicularity of pelletal lapilli indicates that the initial juvenile volatile content of the magma became concentrated as the fluidising medium.
4. The high concentration of juvenile propellent implicit in the nature of the ULUD lapilli resulted in extremely violent volcanic activity, which means that the potential volcanic risk implied by the ULUD occurrences along the Apennine structural trends must be re-evaluated in terms of this factor.

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