LA-UR- 04-5750

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QA: NA
1/18/05

MOL.20050414.0140

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Submitted to: Geology

Scoria Cone Construction Mechanisms, Lathrop Wells Volcano, Southern Nevada

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Abstract

Scoria cones are commonly assumed to have been constructed by the accumulation of ballistically-ejected clasts from discrete and relatively coarse-grained Strombolian bursts and subsequent avalanching such that the cone slopes are at or near the angle of repose for loose scoria. The cone at the hawaiitic Lathrop Wells volcano, southern Nevada, contains deposits that are consistent with the above processes during early cone-building phases; these early deposits are composed mainly of coarse lapilli and fluidal bombs and are partially welded, indicating relatively little cooling during flight. However, the bulk of the cone is comprised of relatively fine-grained (ash and lapilli), planar beds with no welding, even within a few tens of meters of the vent. This facies is consistent with deposition by direct fallout from sustained eruption columns of relatively well-fragmented material, primarily mantling cone slopes and with a lesser degree of avalanching than is commonly assumed. A laterally extensive fallout deposit (up to 20 km from the vent) is inferred to have formed contemporaneously with these later cone deposits. This additional mechanism for construction of scoria cones may also be important at other locations, particularly where the magmas are relatively high in volatile

content and where conditions promote the formation of abundant microlites in the rising mafic magma.

Introduction

Scoria cones, one of the most abundant volcanic landforms on Earth, are commonly inferred to have been constructed from the deposits of Strombolian eruptions, which are characterized by intermittent bursts of gas and mainly coarse-grained pyroclasts (e.g., large lapilli, blocks, and bombs) as large gas bubbles rise to the top of a slow-moving (or stationary) magma column, typical of activity at Stromboli volcano in Italy (see reviews of scoria cone features by Wood, 1981; Head and Wilson, 1989; and Riedel, 2003). A much-cited (e.g., Fisher and Schmincke, 1984; Vespermann and Schmincke, 2000) model for this type of activity and resulting cone construction was developed by McGetchin et al. (1974), based upon their observations of cone-building at one of the vents of Mount Etna in Sicily. In the McGetchin et al. model, pyroclasts are ejected during bursts from a vent at a range of angles from vertical to about 25° off vertical. Each clast follows a ballistic trajectory, depositing a ring around the vent with a rounded rim representing the distance of maximum deposition. As the ring builds with successive bursts it forms a sharp-rimmed cone that becomes oversteepened with respect to the angle of repose of the loose deposits (assuming they are non-welded), resulting in grain avalanching both on the outer cone slopes and the inner slopes of the crater. The cone continues to grow upward and outward through a combination of ballistic emplacement and grain avalanching, until eruptions cease. During this growth phase, the vent is commonly blocked by avalanched pyroclasts such that subsequent bursts partly re-eject previously-erupted material.

The McGetchin et al. model predicts deposits comprised of mainly bombs and lapilli. Bombs will be commonly fluidal in shape and surface texture. Lapilli-sized pyroclasts (scoria) will range from fluidal to angular (the latter representing pieces of previously-erupted larger clasts that were broken upon impact or during grain avalanching and recycling in the vent) to, in some cases, rounded (reflecting ball milling-like processes of recycled, brittle clasts in the vent). Bedding structures will be dominated (except in deposits from the earliest phase of cone-building) by features associated with grain avalanching – for example, irregular bedding contacts and lenses of coarse, inversely-graded clasts. Bursts that are particularly rich in magma clots, such that the accumulation rate of material on the cone slopes is rapid enough that clasts are able to weld, will produce some zones of welded bombs or spatter (a.k.a. agglutinate) particularly in areas close to the vent (such as the inner crater slopes or the rim and upper part of the outer cone slopes); this also reflects a short, ballistic "flight time" that limits cooling and solidification of clasts prior to deposition (e.g., see Head and Wilson, 1989). Coarse bombs might roll down the cone slopes to deposit in a ring or coarse apron around the base. Deposits beyond a cone formed by the McGetchin et al. model would be limited to thin, highly localized beds of ash and fine lapilli due to the paucity of fine material associated with true Strombolian activity and the lack of a sustained eruption column (e.g., Vergniolle and Mangan, 2000, state that the mass of material in the convective part of Strombolian eruptive columns typically accounts for less than 0.17% of the total mass erupted).

There has been growing recognition in recent years that the classical Strombolian mechanism for cone construction, as elucidated by McGetchin et al. (1974), does not explain many features of scoria cones that are observed during detailed field studies. For example, many scoria cones are associated with appreciable fallout deposits that might be several meters thick near the cone and gradually thin over distances of many kilometers (e.g., Segerstrom, 1950; Self, 1976; Heiken, 1978; Luhr and Simkin, 1993; Hooten et al., 2001) and/or have been historically observed to include periods of sustained, ash-rich eruption columns that reach kilometers into the atmosphere (see review by Riedel et al., 2003). The occurrence of sustained eruption columns indicates an additional process, not accounted for by McGetchin et al., which might influence scoria cone construction – namely, deposition of material by fallout from a sustained column instead of (or in addition to) deposition by direct ballistic emplacement. In this paper we describe deposits within the scoria cone of the Lathrop Wells volcano, southern Nevada, that record both construction mechanisms.

Lathrop Wells volcano

The Lathrop Wells volcano (Figure 1) is the youngest (75-80 ka; Heizler et al., 1999) volcano in the Crater Flat Volcanic Zone, southern Nevada (see Crowe and Perry, 1989; Vaniman et al., 1982; Crowe et al., 1982, 1983; BSC 2004a). The volcano is composed of evolved alkali basalt (hawaiite, or trachybasalt; Vaniman et al., 1982; Perry and Straub, 1996) and recent experimental studies suggest that the initial dissolved water content of the magma might have been as high as 4.6 wt% (Nicholis and Rutherford, 2004). It consists of: (1) a small (~140 m high) scoria cone, (2) two aa lava flow fields that extend ~1 km from the cone – one of these vented from the early cone and flowed south-southeastward (south lava field, Figure 1), while the later one flowed initially northeastward from the cone and then wrapped towards the south (north-east lava field, Figure 1), and (3) a scoria lapilli and ash fallout deposit that might have extended as far as 20 km to the north of the cone (BSC, 2004b), where it has been found as a thin reworked ash preserved in fault-related fractures. D. Krier and G. Heiken determined the total volume of eruptive products to be ~0.09 km^3 (cone – 0.02 km^3, lavas – 0.03 km^3, fallout – 0.04 km^3; BSC, 2004b). Physical volcanological aspects of the volcano have been touched upon by several authors (e.g., Crowe et al., 1983; Crowe, 1986; Wohletz, 1986; Valentine et al., 1992; Doubik and Hill, 1999; BSC, 2004b). The most recent comprehensive studies will be reported elsewhere; in this paper we focus only on the cone itself.

Scoria cone facies

Commercial quarrying of the cone's southeastern flank has provided excellent exposures of the interior facies and stratigraphy of the cone. The cone surface and most of quarry exposures are dominated by loose, highly vesicular lapilli- and small block-sized scoria clasts deposited in the later (upper) phases of cone-building. However, quarry operations between 1999-2002 exposed underlying deposits of coarse, partly welded agglutinate that record an earlier cone-building phase; subsequent quarry work has re-buried most of these deposits at the time of this writing.

Early (lower) cone facies

The early cone facies is massive to weakly bedded, dipping northward at ~20°, where exposed by quarrying on the cone's southeast flank; some of the bedding is vaguely lenticular over scales of meters and shows some inverse grading, typical of grain avalanche beds. Grain size includes minor coarse ash, but is dominated by lapilli and bombs in the centimeter to decimeter size range (Figure 2a). Some fluidal ribbon and spindle bombs reach a meter in length. Individual clasts have shapes ranging from elongate (e.g., ribbons) to irregular to roughly equant, and are generally moderately to highly vesicular with most vesicles being several mm in size. The deposits are moderately to poorly sorted (based upon visual inspection in the field) and are mainly clast supported. In addition, the deposits are partly welded, particularly in coarser-grained horizons dominated by small bombs, such that the early cone facies forms a strongly indurated horizon. However, the welding is not sufficiently strong in the *in situ* deposits exposed in the quarry to have resulted in significant flattening of clasts or coalescence into densely welded zones.

Numerous mounds of pyroclastic material on the top of the south lava field all contain abundant fluidal bombs. Most of these mounds are comprised of loose material, but a few (e.g., where exposed by quarry operations or along the edge of the lava flows) are comprised of weakly to completely welded agglutinate that preserves original bedding. The abundance of fluidal bombs and various degrees of welding is consistent with rafting of material from the early cone by contemporaneous lava effusion from the base of the cone, although a few of these mounds might be remnants of spatter-rich tumuli formed by local lava degassing.

Later (upper) cone facies

Stratigraphically higher parts of the quarry provide excellent exposure of the dominant cone-building deposits in the later cone facies; limited exposures of the contact between early and late cone facies is sharp, indicating a rapid change in emplacement and eruption mechanisms. The later cone facies deposits form beds typically ~10 cm to ~1 m in thickness that dip outward from the rim (southeastward) at angles of 30-32° in lower exposures, but shallowing with height to angles of approximately 20° near the rim and then dipping inward inside the crater (BSC, 2004b). Some beds have geometries and features indicative of emplacement by grain avalanching; for example, they are lenticular over meters of distance (with local evidence for erosion into underlying deposits) and/or have clear reverse grading and clast-supported, coarse lenses typical of granular flows.

Other beds have characteristics that seem to be more typical of direct deposition by fallout. These characteristics include: planar top and bottom contacts, good sorting, massive to planar-stratified internal structure, continuity of beds and their grain size and structure both upward toward the crater rim and horizontally along quarry faces over distances of at least tens of meters (limited by exposure). The coarse lapilli and small block bed in the lower half of Figure 2b is laterally continuous over at least 50 m along the full length of a quarry face, before being covered by talus, with continuous internal stratification of zones of slightly coarser or finer grained clasts consistent with deposition by fallout; some local lenses of coarse clasts indicating some concurrent avalanching of large fragments. The beds that overlie it (which are composed of ash to fine scoria lapilli) are quite continuous and planar, even in detailed internal stratification, as they extend up slope (Figure 2c). Formation of these beds is consistent with fallout from eruption columns of well-fragmented magma that were sustained for some period(s) of time.

Most clasts in the later cone facies are highly vesicular and blocky to elongate in shape with angular edges. Many of them are likely fragments of "recycled" coarser clasts that avalanched into the vent and were re-ejected. Compared to the early cone deposits, fluidal bomb shapes are rare in the later cone facies, comprising less than 10% of those beds that contain them. Grain size characteristics of individual beds vary from coarse lapilli and bombs (up to 0.75 m long in one bed), to beds that are dominated by small lapilli and ash. Coarser-grained beds have open frameworks. In addition to being well sorted compared to the early cone facies agglutinate and having a significant portion that appears to have been deposited by fallout from sustained eruption columns, the later cone facies exhibits no evidence of welding, regardless of proximity to vent.

The craters and rims of many scoria cones are characterized by coarse material and abundant welded spatter or agglutinate (e.g., Wood, 1980, and the authors' own observations). In contrast, the deposits at the top and in the crater of the cone at Lathrop Wells volcano are comprised entirely of loose scoria ash, lapilli and small blocks/bombs characteristic of the late cone facies (Valentine et al., 1992). About 6 m below the summit there is a 40-cm thick stratified and cross-stratified ash and coarse ash deposit that is sandwiched conformably between massive scoria beds such as those described above and that pinches out laterally over a distance of ~40 m. The bedding structures within the ash deposit are indicative of deposition from a weak density current such as a pyroclastic surge (e.g., Valentine and Fisher, 2000). Scanning electron microscopy reveals that the ash particles are dominatly tachylitic (microcrystalline basalt) with less abundant sideromelane (basaltic glass) (BSC, 2004b). The western rim of the cone and the ground at the base of this sector of the cone is littered with a some decimeter-sized blocks that record the final explosive event from the main cone. These blocks are mainly composed of welded fragments of relatively dense, angular basalt breccia and agglutinate, and probably resulted from a late-stage steam explosion that disrupted and ejected part of a solidified conduit plug.

Tephra deposits beyond the cone

Details of the Lathrop Wells fallout deposit (thickest measured section is slightly over 3 m, located 1 km directly west of the crater on flat terrain) will be reported elsewhere, but a few observations are mentioned here as they pertain to the construction of the cone itself. In the immediate vicinity of the cone (within ~1km) the deposit consists of numerous centimeter- to decimeter- thick, planar, well-sorted beds of highly vesicular lapilli and ash. D. Krier and G. Heiken (BSC, 2004b) report relative abundances of sideromelane and tachylite in fine ash components of these beds. Tachylite abundance (22-77%) is within the same range as reported recently for products of the 2001 eruptions of Mount Etna (Taddeucci et al., 2004). In a sector to the northwest of the cone, and within ~500 m of its base, there is an area of about 24,000 m^2 that exposes a ~1 m-thick section of laminated and cross-laminated, and slightly palagonitized ash. This section, likely deposited by pyroclastic surges from hydrovolcanic explosions, is sandwiched between scoria ash and lapilli beds of the main fallout sequence, implying that it does not represent the initial explosive activity at the vent (e.g., Crowe et al., 1983;

Wohletz, 1986), and pinches out laterally such that its volume is less than 0.03% of the total erupted products of the volcano. The explosive activity that produced this apparently did not affect the opposite side of the cone where the quarry exposures are located. Finally, the north-east lava flow field is overlain by fallout deposits near the cone, but is underlain by several centimeters of planar-bedded ash and small lapilli at its easternmost margin. Scoriaceous mounds on the top of this lava flow field are dominated by loose scoria lapilli such as found in the later cone facies and the fallout deposits, consistent with rafting of later cone material and proximal fallout deposits along the top of the flow(s). We infer that this lava flow was at least partly contemporaneous with formation of the fallout tephra deposits.

Interpretation and Summary

The lower, early cone facies exhibits characteristics that are relatively consistent with the McGetchin et al. (1973) model and with emplacement by Strombolian eruptions in the classical sense. It is relatively coarse grained (coarse lapilli and bombs) and contains abundant fluidal bombs (e.g., spindle and ribbon bombs) that took their shape by following individual ballistic paths. The clasts did not experience large flight times and were therefore sufficiently hot to weld with each other upon deposition. There is some evidence for grain avalanching in these deposits, but, as described above, the dips we measured on crude bedding interfaces are on the order of 20°, substantially less than the ~30-32° value that is associated with grain avalanche-maintained angle of repose for loose scoria. It is possible that the deposits we observed were produced during the earliest phase of cone building in the McGetchin et al. model (Stage 1 in their Figure 14;

McGetchin et al., 1974). South-flowing blocky aa lava flow(s) were likely contemporaneous with early cone building as recorded in the early cone facies; parts of the early cone were rafted atop this flow(s). Figures 3a and 3b represent our interpretation of early cone building at Lathrop Wells volcano.

The upper cone facies seems to record cone-building processes significantly different from the McGetchin et al. model. While there is some evidence for local grain avalanching of coarser clasts, the dominant bedding characteristics include planar top and bottom contacts, massive to crudely (but planar) stratified bed interiors, and lateral continuity both parallel to cone slopes and horizontally within quarry exposures. The clasts within these beds are well to moderately sorted and are, in most cases, dominated by highly vesicular ash to lapilli sizes and they show no sign of welding. This is true even in very proximal deposits that were once in the crater (inward dipping), within only a few tens of meters of the vent area. All of these characteristics are most consistent with deposition by fallout from sustained (probably on the order of tens of minutes to hours) eruption columns of well-fragmented magma. Rather than cone construction during the upper cone phase being dominated by ballistic emplacement and subsequent avalanching, construction was dominated by the accumulation of fallout deposits that, consistent with one of the fundamental characteristics of fallout, mantled the cone slopes. On occasion the slopes would become oversteepened and there would be minor avalanching to maintain the angle of repose, but most of the deposits are essentially *in situ* fallout beds. The shallowing of bedding dips upward in the cone is consistent with fallout mantling a cone rim. Localized deposits of weak pyroclastic surges are consistent with very local, partial collapse of ash-rich portions of an eruption column such as observed in the 2001 explosive activity at Mount Etna (Taddeucci et al., 2004). Our interpretation of the later cone-building processes is illustrated in Figures 3c,d.

The important role of fallout from sustained, finer-grained eruption columns for construction of scoria cones, in addition to the processes described in the McGetchin et al. (1974) model, has been discussed in detail by Riedel et al. (2003); the Lathrop Wells cone provides an excellent example where deposit facies and field observations support this broader view of cone construction. We infer that the tephra fallout blanket that covers some of the terrain around the volcano resulted from the same eruptions as the later cone-building facies. The abundance of tachylitic material (compared to sideromelane) in these deposits provides a mechanism by which the effective viscosity of the magma is increased by the presence of abundant microlites, relative to pure melt (see, for example, Heiken, 1978). This increased viscosity would cause the basaltic magma to behave in a manner akin to silicic magmas with respect to bubble dynamics in that the higher viscosity prevents the rise of bubbles with respect to magma as well as coalescence to form larger bubbles as in pure Strombolian behavior. Instead, the microlite-rich magma results in an abundance of small bubbles (possibly enhanced if the microlites act as bubble nucleation sites) that produce a highly-fragmented eruption column. The resulting finer particle sizes are able to effectively transfer heat with entrained air in the eruption column, promoting a high-standing (on the order of a few kilometers) column from which clasts deposit by fallout after a long flight time that allows for extensive cooling (and hence the absence of welded deposits; we note that recycling of pieces of previously-erupted bombs, which we view as minor but which has not been quantified, would also provide a source of solidified, cooled clasts that would not weld when re-deposited). Microlite growth might reflect cooling of the magma column when the vent is choked by grain avalanches (e.g., Heiken, 1978) and/or by a decrease in magma flow rate (e.g., Taddeucci et al., 2004). Care needs to be exercised in assuming whether a given scoria cone is produced by "classical" Strombolian mechanisms. In detail, each cone has its own characteristics that record unique sequences of eruption processes, and we suspect that many basaltic cones have important components of fallout from relatively sustained eruption columns rather than Strombolian bursts.

There is some ambiguity in terminology for mafic scoria cone-forming eruptions and this might partly be due to application of the term *Strombolian* to include explosions "separated by periods of less than 0.1 seconds to several hours" (Blackburn et al., 1976). From a fluid dynamics perspective, explosions separated by less time than a characteristic roll-over time for large eddies near the base of an eruption column will have their individual "signals" or impulses swamped out by turbulence such that above some height (perhaps equivalent to a few times the vent diameter) the column will behave as if it had a steady source. Analyses are under way to test potential threshold parameters for determining whether explosions with a given time spacing would produce an effectively steady eruption column as opposed to being purely discrete bursts. Parfitt (2004) has argued that the transition towards effectively steady eruption column behavior in scoria cone-producing eruptions reflects a transition from pure Strombolian towards Hawaiian eruption dynamics, while Riedel et al. (2003) argue that it is a transition towards sub-Plinian dynamics. The degree of fragmentation (related to vesicle size distribution and/or to magma-water interaction), which in turn relates to clast dispersal and in-flight cooling (read, welding or lack thereof; Head and Wilson, 1989), must also be taken into account, as in Walker's (1973) original classification scheme for fallout deposits. Grain size characteristics at Lathrop Wells indicate that it is less appropriate to link it to transitional behavior towards Hawaiian style eruptions, which are normally considered to produce very little fine material. The term "violent Strombolian" has been used by some authors in reference to these eruptions, which correctly implies a smaller scale (eruptive volume and eruption column height) than is associated with sub-Plinian eruptions (e.g., Sparks et al., 1997; Arrighi et al., 2001).

Acknowledgements

The work reported here was funded by the U.S. Department of Energy's Yucca Mountain Project, via Bechtel-SAIC LLC (BSC). We thank Gordon Keating for reviewing the manuscript prior to submission to *Geology*.

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Figure Captions

Figure 1 – Geologic map showing main features of the Lathrop Wells volcano.

Figure 2 – (a) Early cone facies, consisting mainly of lapilli and bombs, partly welded, with crude bedding dipping towards the right (north). Backpack is c. 40 cm high. Photo by Frank Perry. (b) Upper cone facies, showing coarse-lapilli bed that is overlain by finer-grained lapilli beds; the latter are well sorted and continuous both laterally and up the quarry slope (parallel to original cone surface). Photo by Gordon Keating.

Figure 3 - Inferred sequence of events at Lathrop Wells volcano.

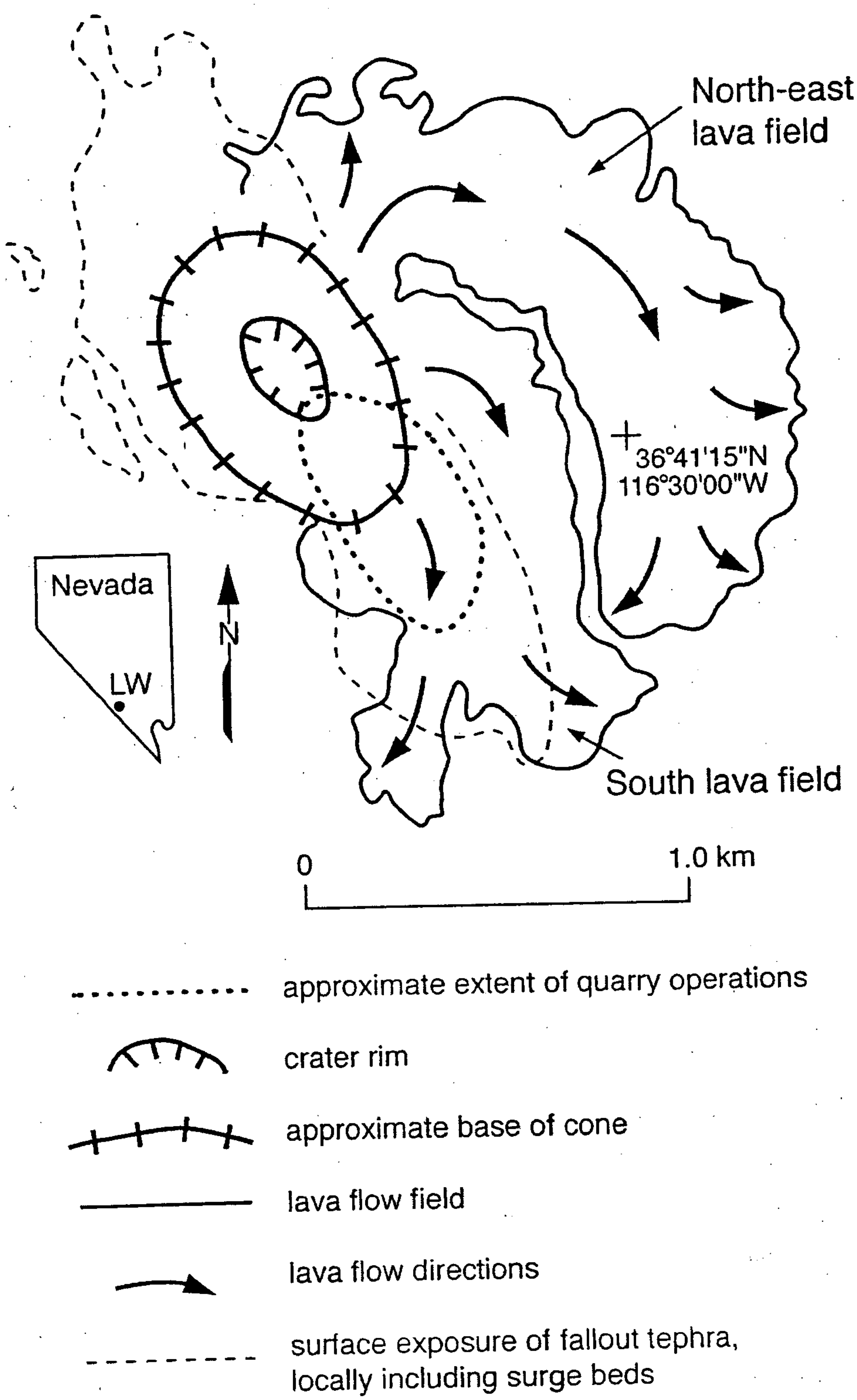
North-east
lava field
36°41'15"N
116°30'00"W
Nevada
LW
N
South lava field
0
1.0 km
approximate extent of quarry operations
crater rim
approximate base of cone
lava flow field
lava flow directions
surface exposure of fallout tephra,
locally including surge beds

Figure 1

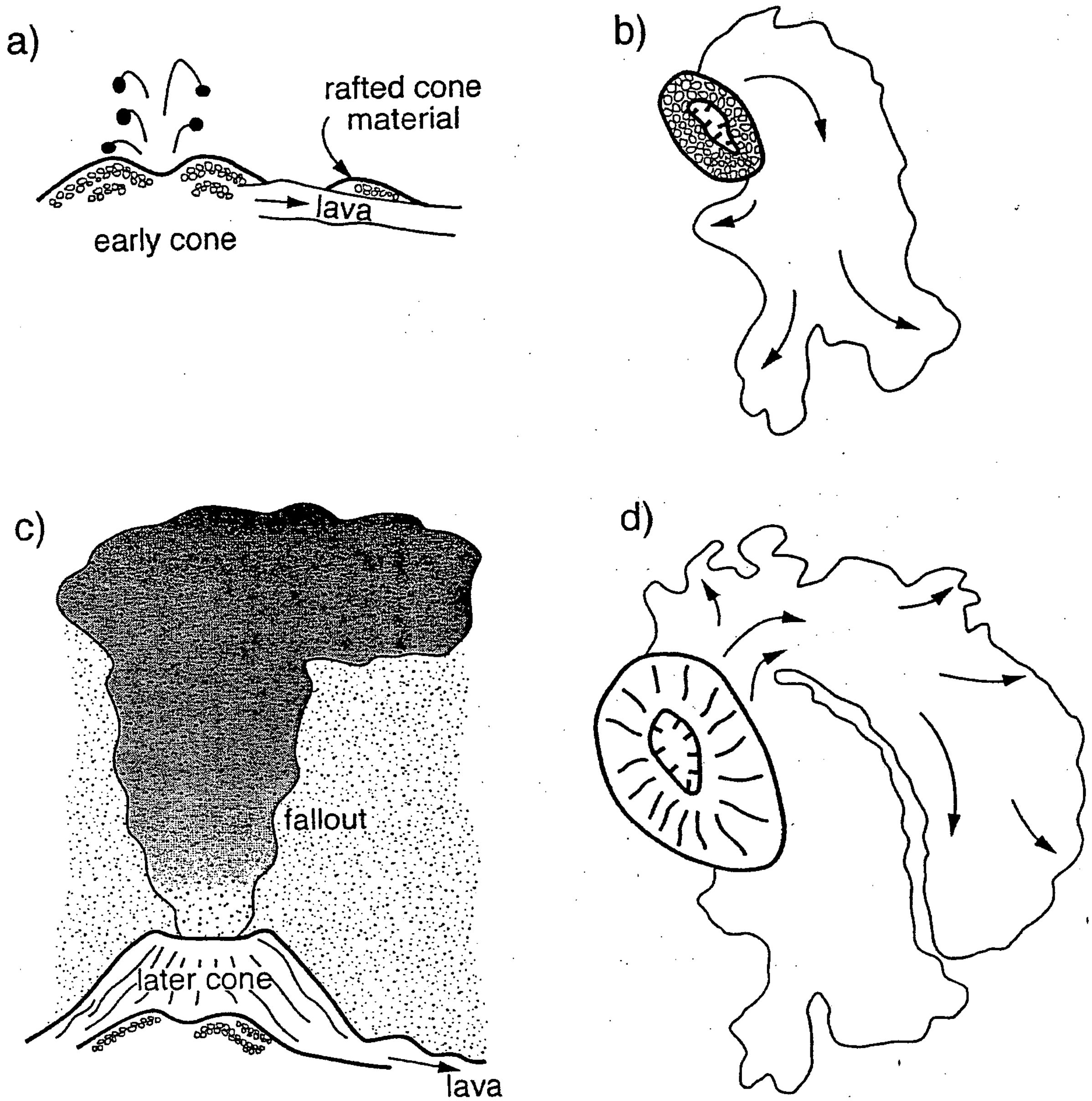
a)
rafted cone
material
lava
early cone
b)
c)
fallout
later cone
lava
d)

Figure 3

Figure 2a

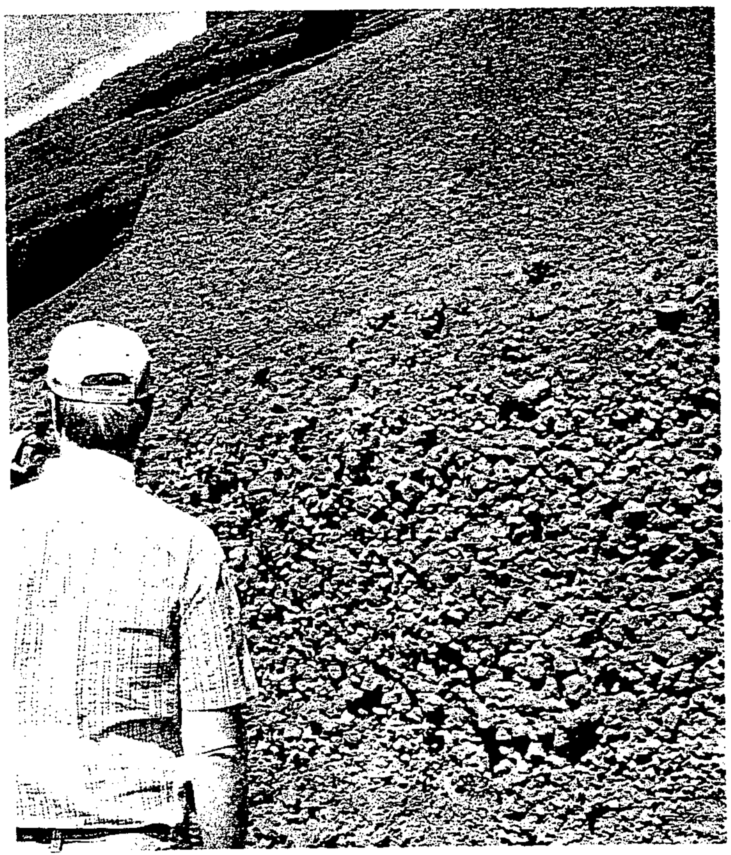

Figure 2b