EXPLOSIVE ERUPTIONS ON ASTEROIDS: THE MISSING BASALTS ON THE AUBRITE PARENT BODY;

Lionel Wilson[1,2] and Klaus Keil[1]; [1] Planetary Geosciences Div., School of Ocean & Earth Science & Technology, University of Hawaii, Honolulu, Hawaii 96822, U.S.A. [2] Environmental Science Div., Institute of Environmental & Biological Sciences, Lancaster University, Lancaster LA1 4YQ, U. K.

Background: If aubrites formed by melting/fractionation of enstatite chondrite-like material, as implied by chemical, mineralogical and isotopic similarities [1], then plagioclase-rich, basaltic complements to the aubrites (enstatite-plagioclase basalts) should exist [2-6]. Such rocks are not found as individual meteorites, suggesting are that either (i) plagioclase-rich rocks crystallized from early partial melts, migrated to the surface of the aubrite parent body, and were removed and destroyed by ancient impacts, so that no such meteorites fall today [1]; or (ii) the source materials of the aubrites were poorer in plagioclase than known enstatite chondrites so that extensive volumes of plagioclase-rich rocks did not form on the aubrite parent body [1], and oldhamite [6, 7] or other sulfides [8], instead of plagioclase, produced the negative Eu anomalies of many aubrites. We propose a third mechanism: the missing basalts were expelled volcanically from the parent body. Expansion of even tiny amounts of volatiles in a melt nearing the surface of a small, low-gravity body will disrupt the melt into a spray of droplets moving faster than the local escape velocity.

Analysis: Partial melts rise through planetary interiors mainly under buoyancy [9] and, at shallow depths, propagate as dikes [10]. Dikes are systematically wider [11, 12] on low gravity bodies, leading to a greater total volume flux and less chance of melt stalling as an intrusion. Steady explosive eruptions can occur as long as the exsolved volatile content, n, of the melt is enough to ensure that disruption into a spray of gas and pyroclastic droplets takes place on decompression to the planetary atmospheric pressure, P_a, [13]; this requires $P_a < [(Q\ T\ \rho_l)/(3\ M)]\ [(n/(1-n)]$, where Q is the universal gas constant, M the volatile molecular weight, and T the magma temperature. Inserting typical values ($T \sim 1200$ K, $M \sim 30$, $\rho_l \sim 2500$) implies that explosive eruptions will occur if n exceeds a few wt.% on Venus, a few hundred ppm on Earth and a few ppm on Mars [13]; clearly, explosive eruptions on asteroids, where the external pressure is essentially zero apart from the presence of the gases released from the eruption itself [14], can take place for *extremely* small n.

Thermodynamic and fluid mechanical analyses of explosive eruptions [13-16] show that thorough disruption of a magma erupting into a vacuum produces an optically dense gas/pyroclast mixture [13], the clast ejection velocity, U, being given by $U^2 = [(2\ n\ Q\ T)/M]\ \log_e(P_d/P_f)$, where P_f is the atmospheric pressure into which the erupting mixture discharges and γ is the specific heat ratio of the magmatic volatile. At large gas expansions this equation must be replaced by one in which the gas expands isentropically; this is equivalent to imposing an upper limit to the value of (P_d/P_f), and numerical studies show that a value $\sim 10^4$ is appropriate [13]. The eruption velocity U must then be compared with the escape velocity, V, from the surface of a uniform, spherical body of radius R and density σ, which is $V = [(8/3)\ \pi\ G\ \sigma]^{1/2}\ R$, where G is the universal gravitation constant.

Results: The table shows values of V for asteroids of various radii using $\sigma = 3500$ kg/m^3, and also the values of n, n_{crit}, (for $\gamma = 4/3$ and $M = 30$, values typical of a wide range of low molecular wt. volatiles) at which U equals V; for values of n greater than those listed, most ejecta from an eruption will escape from the parent body. The table shows why magmatic explosive eruptions cannot eject pyroclasts with escape velocity from any terrestrial planet. However, for asteroids of < ~100 km radius, ejection of pyroclastic mixtures is possible for relatively low values of n_{crit}.

Discussion: Are the minimum n_{crit} values shown in the table reasonable? This question can only be addressed qualitatively, as common volatiles possibly important in the history of the aubrite parent body do not leave readily detectable signatures in the aubrite meteorites [17]. Although aubrites do not appear to have originated on the H and L enstatite chondrite (EH, EL) parent bodies, chemical, mineralogic and isotopic similarities suggest that they formed from similarly highly-reduced enstatite chondrite-like precursor material [1]. Thus, concentrations of volatile elements in EH and EL chondrites give at least a qualitative measure of possible abundances of volatiles in aubrite precursors. Carbon, nitrogen, fluorine, sulfur and chlorine are the more abundant volatiles that have left signatures in enstatite chondrites. Sulfur ranges from ~ 2.6-6.1 wt. % and carbon averages ~0.4 wt. % [18]. Fluorine ranges from 100-250 ppm, and chlorine from 570-750 ppm in EH4, averages 210 ppm in EH5, and ranges from 160-250 ppm in EL6 chondrites [18]. Nitrogen averages 330 ppm in 3 EH4s, 200 ppm in 2 EH5s, and 220-ppm in 4 EL6s without and 700 ppm in 3 EL6s with sinoite [19]. It is hard to assess how much vapor these elements contribute to plagioclase-rich partial melts: little is known about melt/vapor partition coefficients of volatiles at very low oxygen fugacities and relevant temperatures [20]. We know of no experiments to find the nature and amount of vapor phase released by melting of enstatite chondrites, but vaporization experiments have been made on the L6 chondrite Holbrook [21], the carbonaceous chondrite Allende [22], and the ureilite Kenna [23]. Although not perfect analogs to aubrite precursor materials, these meteorites release substantial amounts of vapor, including CO-N_2, CO_2, S_2, SO_2 and others, which can result in appreciable vesiculation of the residue [21]. We conclude that it is likely that ample volatiles would be generated during partial melting of enstatite chondrite-like precursor materials of the aubrites to result in explosive pyroclastic volcanism.

Did the aubrites form on a small parent body, which is the other requirement for ejection of pyroclastic mixtures into space? Although many of the smaller current asteroids are probably fragments of larger parent bodies, it is unlikely that the initial population contained many more asteroids a few 100 km in size than are observed today [24, 25], otherwise many more would have survived. Since today's asteroids with the taxonomic properties of the aubrites are very small, it is not likely that once a large (several 100 km radius) aubrite parent body existed. The largest of the E asteroids, thought to have surface compositions similar to aubrites, is 44 Nysa, 36·7 km in radius [26]. Recent spectral reflectance measurements of this asteroid show a band due to FeO-bearing pyroxene unknown from other E asteroids [27]. Since aubrites contain only FeO-free pyroxene, 44 Nysa may not be the parent body of known aubrites, thus eliminating the largest E asteroid as an aubrite source object [24, 25]. The next largest E asteroid, 64 Angelina, is ~ 30 km in radius, and the E asteroids of the Hungaria family are smaller yet (434 Hungaria, the largest, is< ~ 6 km in radius [1]). It therefore seems safe to assume that the aubrite parent was relatively small and so had a low enough escape velocity to allow pyroclastics to escape into space.

Finally, we comment on the eucrites, the only known asteroidal basalts, which are rather "normal" pigeonite-plagioclase basalts except that, by terrestrial standards, they are low in volatiles and formed under very "dry" conditions. Eucrites, together with related howardites and diogenites [28], have similar spectral reflectances to the asteroid 4 Vesta [29], which is 250 km in radius [26]. If it is indeed their parent body, then an n_{crit} of ~ 3·1 wt % would be need for the eruption velocity to exceed its escape velocity (Table 3). No such basaltic magmas are known on Earth, let alone are likely to have existed in the "dry" environment in which the eucrites formed. Thus, the existence of eucritic and lack of aubritic basalts is totally consistent with our model. If eucrites do not come from the asteroid 4 Vesta, then our model suggests that they should have formed on a relatively large asteroid, probably larger than 100 km in radius.

<u>Table</u>: The escape speed V (eq. 2) for an asteroid of radius R and density 3500 kg/m^3, and the critical magma gas content n_{crit} (for $\gamma = 4/3$ and M = 30) at which the eruption velocity U (eq. 1) equals V.

R/km	1	10	25	50	100	250	500	1000	1500
V/(m/s)	1·4	14	35	70	140	350	700	1400	2100
n_{crit}	0·49ppm	49ppm	0·031%	0·12%	0·49%	3·1%	12%	49%	>100%!

<u>References</u>: [1] K. Keil, Meteoritics 23, 195, 1989. [2] T.R. Watters and M. Prinz, Proc. LPSC 10th, 1073, 1979. [3] R. Wolf, M. Ebihara, G.R. Richter and E. Anders, GCA 47, 2257, 1983. [4] H. Newsom, K. Keil and E.R.D. Scott, Meteoritics 21, 469, 1986. [5] R. Brett and K. Keil, EPSL 81, 1, 1987. [6] M.M. Wheelock, C.F. Heavilon and K. Keil, LPSC XXI, 1327, 1990. [7] M.M. Wheelock, C.F. Heavilon, K. Keil, G.J. Taylor and G. Crozaz, Meteoritics 24, 340, 1989. [8] K. Lodders and H. Palme, LPSC XXI, 710, 1990. [9] D. McKenzie, EPSL 74, 81, 1985. [10] N.H. Sleep, JGR 93, 10255, 1988. [11] L. Wilson and J.W. Head, LPSC XIX, 1283, 1988. [12] L. Wilson and E.A. Parfitt, LPSC XX, 1213, 1989. [13] L. Wilson and J.W. Head, JGR 86, 2971, 1981. [14] S.W. Kieffer, p. 647 in: Satellites of Jupiter, U. Ariz. Press, 1982. [15] L. Wilson, JVGR 8, 297, 1980. [16] L. Wilson, R.S.J. Sparks and G.P.L. Walker, G. J. Roy. Astr. Soc. 63, 117, 1980. [17] D.W. Sears, Icarus 43, 184, 1980. [18] B. Mason, Chapter B, Part 1, Geolog. Surv. Prof. Pap. 440-B-1, 1979. [19] C.B. Moore, E.K. Gibson and K. Keil, EPSL 6, 457, 1969. [20] R.A. Fogel, P.C. Hess and M.J. Rutherford, LPSC XIX, 342, 1988. [21] J.L. Gooding and D.W. Muenow, Meteoritics 12, 401,1977. [22] J.L. Gooding and D.W. Muenow, GCA 40, 675, 1976. [23] E.K. Gibson, GCA 40, 1459, 1976. [24] D.R. Davis, C.R. Chapman, S.J. Weidenschilling and R. Greenberg, Icarus 62, 30, 1985. [25] D.R. Davis, S.J. Weidenschilling, P. Farinella, P. Paolicchi and R.P. Binzel, p. 805 in: Asteroids II, U. Ariz. Press, 1989. [26] E.F. Tedesco, p. 1090 in: Asteroids II, ibid. [27] M.J. Gaffey, J.F. Bell and D.P. Cruikshank, p. 98 in: Asteroids II, ibid. [28] R.H. Hewins and H.E. Newsom, p.73 in: Meteorites and the Early Solar System, U. Ariz. Press, 1988. [29] G.J. Consolmagno and M.J. Drake, GCA 41, 1271, 1977.