ammonia which in combination with chlorine forms chloramines. Chloramines can prolong the stability of residual disinfectant during distribution and can eliminate certain organic byproducts resulting from chlorination[11]. Residual amounts of ammonia and nitrite may be neutralized by final chlorination. Ammonia is oxidized to nitrogen gas[12] and nitrite to nitrate[13].

Chemical analyses on the final effluent from the process (pH adjusted to 6.2) demonstrate total aluminium to be $<0.03\ \mathrm{mg\ l^{-1}}$. This is below the levels of aluminium in drinking water considered to be safe in the United States[4].

If it is assumed that only ammonia is produced (maximum $\mathrm{Al/NO_3^-}$ required) and that the aluminium wasted in water decomposition can be ignored because hydrogen formed from reaction (4) represents <2% of the total aluminium used, then the three-electron change for aluminium oxidation ($\mathrm{Al \rightarrow Al^{3+} + 3e^-}$) and the eight-electron change for nitrate to ammonia reduction mean that 1.16 g of aluminium are required to reduce 1 g of nitrate. □

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Dimensions and dynamics of co-ignimbrite eruption columns

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VERY powerful volcanic eruptions cannot always form classical Plinian eruption columns[1–4]. Instead, collapsing fountains may develop above the vent and shed pyroclastic flows which spread laterally along the ground[5]. The upper part of these hot, dense pyroclastic flows may become buoyant through the entrainment, heating and expansion of ambient air, coupled with the sedimentation of larger clasts suspended in the flow. The buoyant material may rise, in a co-ignimbrite eruption column, carrying massive quantities of fine dust and volatiles into the stratosphere[6,7]. Here we present a model of this process, and show that the co-ignimbrite columns associated with the eruptions of Toba[8,9] 75,000 years ago and Tambora[10] in 1815 may have ascended only about 32 and 23 km; the latter is comparable with the less powerful 1982 Plinian eruption column of El Chichón[11]. This corroborates arguments that the mass of sulphuric acid aerosols injected into the stratosphere and not the eruptive power determines the climatic impact of an eruption[12,13].

The classical Plinian eruption column is formed when very hot, dense material is ejected upwards from the volcanic vent at high speed ($\sim 300\ \mathrm{m\ s^{-1}}$)[4,14–16]. This column entrains ambient air, which rapidly heats up and expands; the resulting buoyant plume may then rise tens of kilometres into the atmosphere (Fig. 1*a*). But if the mass eruption rate or vent radius is too large or the eruption velocity too small, the material rising in the lower column will not become buoyant, and a collapsing fountain, only a few kilometres high, forms[1–4,16,17] (Fig. 1*b*). Dense, hot pyroclastic flows may spread laterally from this fountain[1,5]. As these develop, pyroclasts sediment out and entrained overlying air expands, lowering the density of the mixture. If sufficient air is entrained, material peels off the top of the current and may develop into a coherent, buoyant plume (Fig. 1*c*). In this way the thermal energy of a collapsing fountain may be transferred into a vast buoyant plume, and massive quantities of erupted material may penetrate high into the atmosphere. This phenomenon has been simulated in both analogue laboratory experiments[20] and numerical modelling[15].

Co-ignimbrite columns developed during many of the most powerful historical eruptions[21], including Tambora (1815)[10,18], Krakatau (1883)[19] and Katmai (1912). In the Tambora eruption, the pyroclastic flows entered the sea ~20 km from the vent and the explosive interaction with evaporating surface water contributed to the development of the co-ignimbrite column[10,18]. Co-ignimbrite columns are also believed to have formed in several immense pre-historic eruptions[7] including the Aira caldera eruption in southern Kyushu, 21,000 y BP (before present)[22,7], the Minoan eruption in Santorini, 3,500 y BP[8,23] and the Toba eruption in Sumatra, 75,000 y BP[8,9].

Here we extend the eruption column model of Woods[14], using the conservation of mass, momentum and enthalpy and the entrainment assumption for a well mixed, buoyant plume[25] to simulate a steady-state co-ignimbrite eruption column. We assume the mixture of fine, hot ash and entrained air that rises

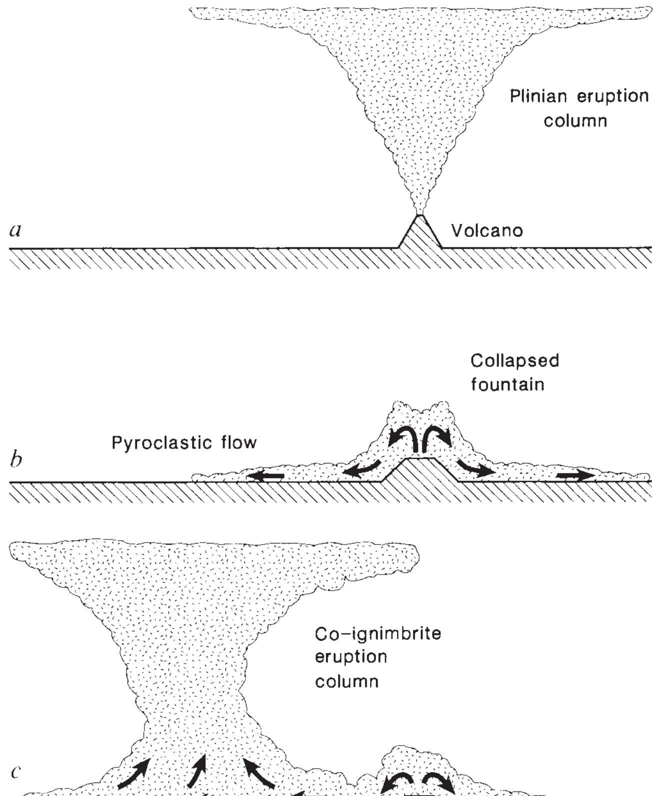

FIG. 1 Schematic of *a*, Plinian eruption column; *b*, fountain shedding lateral pyroclastic flows soon after the collapse of a Plinian column; *c*, development of a co-ignimbrite column formed as the buoyant elutriated mixture of fine ash and volatiles rises off the pyroclastic flow. The centre of the co-ignimbrite column may be displaced laterally from the vent[24] because of asymmetries in the pyroclastic flows, resulting perhaps from the topography of the volcano or the presence of a body of water.

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TABLE 1 Predicted and reported eruption column statistics

Eruption	Total volume erupted (km^3 dense rock equivalent)	Volume of ash elutriated† (km^3 dense rock equivalent)	Duration of co-ignimbrite column‡	Mass eruption rate from vent (10^9 kg s^{-1})	Column height§ (km)	Mass of sulphuric acid aerosols‖ (10^{10} kg)
Toba[8,9] 75,000 yr BP	2,840	840	9–14 days	7.1	32 ± 5*	—
Tambora[10,12,27] 1815	50	20	2–3 days	0.5	23 ± 3*	15–20
Mount St. Helens[24] 18 May 1980 lateral blast¶	0.13	0.03	30–80 s*	7 ± 3*	25 ± 1	—
El Chichón[11,12] 1982 (Plinian)#	1.1	1.1	—	0.05	22 ± 4	1–2

* Calculated herein.

† From the pyroclastic flows into the co-ignimbrite column.

‡ Estimated from deep-sea cores for Toba[8] and historical evidence for Tambora[10,27].

§ Toba and Tambora co-ignimbrite column heights are estimated from the model (error margins include uncertainties in initial conditions); the prediction for Toba is much lower than that of Ninkovich *et al.*[8], consistent with the field data of Rose and Chesner[9].

‖ Injected into stratosphere.

¶ In the text we describe the ash cloud as an instantaneous co-ignimbrite thermal, rather than a maintained co-ignimbrite column; it had an observed ascent time of 6–8 minutes.

Average of the A, B and C eruptions[11].

off the pyroclastic flow to feed the column is well mixed, is in thermal equilibrium and is just buoyant relative to the ambient. The hot, elutriated material continues mixing with air, which expands, decreasing the bulk density of the mixture below that of the ambient (Fig. 2*a*). This buoyancy causes an upward acceleration of material (Fig. 2*b*), which initially causes the mass flux per unit area to increase with height faster than the rate of addition of mass through entrainment of ambient. The column radius therefore decreases to conserve mass (Fig. 2*c*) and the column approaches the natural shape of a buoyant plume.

Figure 3 shows how the total height of our model co-ignimbrite eruption column depends upon the total mass flux and temperature of the material erupted at the vent. Using field data, Sparks and Walker[7] argued that a fraction, $\lambda > 0.35$, of the total erupted juvenile material will be elutriated from the pyroclastic flow and rise in the co-ignimbrite column. Recent data from Toba[9] and Tambora[10] also suggest that $\lambda \approx 0.35 \pm 0.05$ (Table 1), and we used this value for the typical calculations shown in Fig. 3. The development of the co-ignimbrite column may restrict the entrainment of air into the pyroclastic flows subsequently erupted, causing their areas to increase[26]; however, the presence of water may limit the lateral extent of these flows, as occurred in Tambora[10]. An important result of our numerical investigations is that for a given mass eruption rate the total height of a co-ignimbrite eruption column is relatively insensitive to the initial elutriation velocity (0.1–10 m s^{-1}) or equivalently the area of the pyroclastic flows. Also, the column height increases with eruption temperature and, to a lesser extent, with the altitude of the tropopause so that co-ignimbrite columns nearer the equator tend to be higher.

Figure 3 shows for comparison the total height of a mid-latitude Plinian column with an eruption velocity of 300 m s^{-1} and eruption temperature of 1,100 K. For a given erupted mass

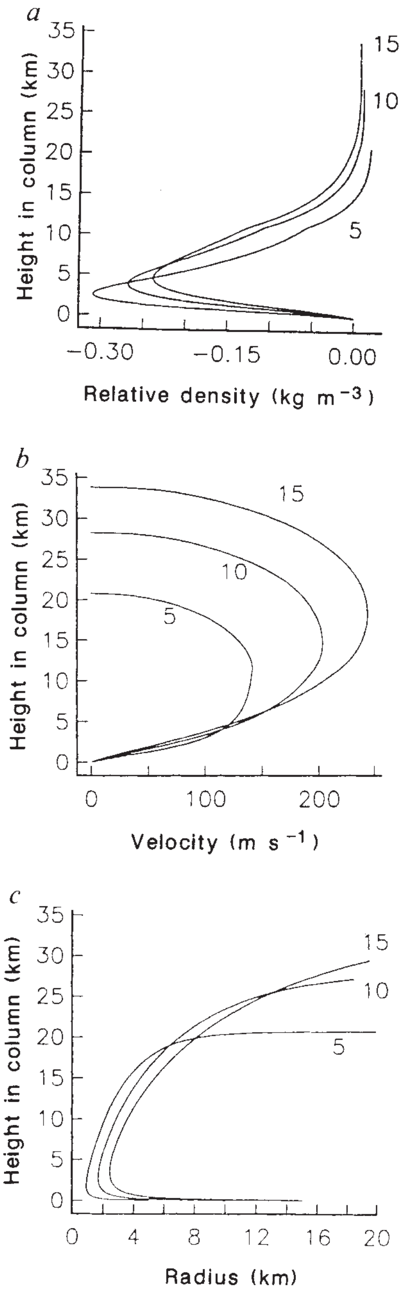

FIG. 2 Calculations showing the variation with height in a co-ignimbrite eruption column of *a*, average density of material relative to ambient density at that height, *b*, average vertical velocity and *c*, radius, assuming axisymmetry. Numbers on the curves represent the radius (km) of the pyroclastic flow that supplies material to the co-ignimbrite column. The temperature of the material erupting at the vent is 1,000 K and the initial velocity of elutriation from the pyroclastic flow is 1 m s^{-1}; other values are as in Woods[14]. The mixture of fine ash and entrained air rising from the pyroclastic flow into the co-ignimbrite column is just buoyant and has cooled to 832 K. The very rapid acceleration in the lower part of the column (*b*) extends above the height at which the cloud has its minimum radius (*c*). As the hot, dusty material rises off the ground, it entrains air which heats up, expands and increases the buoyancy of the cloud (*a*). Higher in the column, the density difference decreases as the thermal energy available to generate buoyancy in the cloud is diminished.

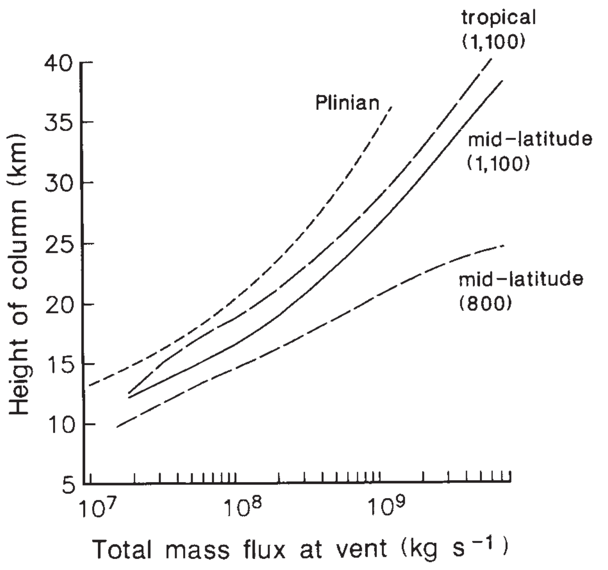

FIG. 3 A typical calculation of the total height of the co-ignimbrite eruption column as a function of the mass eruption rate at the vent. The ash cloud is assumed to have an initial velocity of 1 m s^{-1}. The numbers in brackets are two typical eruption temperatures[5] (1,100 K and 800 K). The co-ignimbrite columns are assumed to convect 35% of the erupted material into the atmosphere[7,9,10]. Other eruption properties are taken from lateral blast data[24] for Mount St. Helens. Two types of atmosphere, a mid-latitude atmosphere with the tropopause at 11 km and a tropical atmosphere with the tropopause at 15 km. Also shown is a Plinian column which is erupted into the mid-latitude environment with an initial velocity of 300 m s^{-1} and an initial temperature of 1,100 K.

flux, a Plinian column rises much higher than a co-ignimbrite column, primarily because nearly all the hot erupted pyroclasts convect upwards in a Plinian column (Fig. 1*a*). Furthermore, material which erupts to form a Plinian column contains a gas mass fraction of only 1-5% at the vent[1,2]; large volumes of air are only entrained at higher altitudes, where the air is less dense. In contrast, material in the pyroclastic flow entrains a very large mass of the relatively dense, cool air just above the ground. This air is convected up into the co-ignimbrite column, lowering the temperature of the mixture a few hundred degrees below eruption temperature and contributing 30-60% of the total mass rising from the flow; for large mass eruption rates ($\geq 10^9$ kg s^{-1}) or low eruption temperatures this further decreases the height of the co-ignimbrite column relative to that of the Plinian column. But in very powerful eruptions, Plinian columns only develop if the eruption velocity is very large; vent erosion rapidly lowers this velocity for a fixed mass eruption rate and a collapsing fountain forms[1-4,17]. In this case, the only means of injecting material high into the atmosphere is a co-ignimbrite column; for example, over 92% of air-fall from the 1815 Tambora eruption was co-ignimbrite ash[10].

Table 1 shows the predicted mass eruption rate at the vent that would have been required to maintain the 25-km cloud observed during the Mount St Helens lateral blast on 18 May 1980, assuming 23% (ref. 24) of the erupted material is entrained into the cloud; this calculation implies the column only lasted 1-2 minutes, whereas the reported ascent time of the cloud was 6-8 min[24]. This cloud may be better described as a 'co-ignimbrite thermal' rising off the pyroclastic flow almost instantaneously[25] rather than continuously; such a blast cloud could ascend to 25 km (ref. 24). It may be that only the much larger eruptions, for example 1815 Tambora, can generate sufficient material over a sufficiently long time to maintain a co-ignimbrite column.

Table 1 also compares our estimates of the heights of two co-ignimbrite columns (Toba and 1815 Tambora) with the Phinian eruption column of El Chichón (1982). Although the 1815 Tambora eruption produced 50 times as much material as the El Chichon eruption and had 10 times the power, the column only reached a height similar to the El Chichón Plinian column, injecting 20 times as much ash into the stratosphere. This is a particularly important result, because it supports the argument[12] that eruptive power does not determine the climatological impact of a volcanic eruption; very powerful eruptions forming co-ignimbrite columns cannot inject material significantly higher than much weaker Plinian eruptions. Our low estimates for the injection height of co-ignimbrite ash also support arguments that much of the volcanic ash falls out of the atmosphere too rapidly to have a long-term impact upon climate[13,27].

We reiterate[12] that it is the mass of sulphur gas injected into the stratosphere, where it forms sulphuric acid aerosols, which has the most important long-term effect upon climate. This mass is a function of the magma chemistry as well as of total mass erupted. Per unit mass of erupted material, Tambora injected one-fifth as much sulphur into the stratosphere as El Chichón. This is because El Chichón (1) was particularly sulphur rich[12] and (2) produced a Plinian rather than co-ignimbrite column.

Perhaps our most significant result is that the most powerful eruptions can inject massive quantities of ash 20-35 km into the atmosphere even if a Plinian column cannot develop. Simple estimates suggest that this ash, which mainly consists of small glassy shards[6,7] with high drag coefficients[9], is dispersed by atmospheric winds[27] to form a blanket of airfall several centimetres thick, over an area of 10^5-10^7 km^2. This is consistent with field data[7-10]. ☐

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