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VULCANIAN ERUPTION MECHANISMS

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First application of newly developed theory to volcanological observations of explosive eruptions shows that previous estimates of pre-explosion gas pressures may be overestimated by an order of magnitude.

Introduction

The andesite stratovolcano Ngauruhoe, in North Island New Zealand, erupted explosively during the afternoon of 19 February 1975. The eruption was closely observed and filmed. There were two main phases. A 1.5 hour gas-streaming phase[1] produced an 11-13 km high eruption column which was continually fed by a large number of closely spaced explosions. This phase was followed by a series of discrete cannon-like explosions at 15 to 50 minute intervals over a period of five hours[2]. The latter style of activity is common on many andesite and basaltic andesite volcanoes, for example Asama[3] and Arenal[4], and is referred to as vulcanian type activity[5,6].

Vulcanian explosions have been studied from several recent eruptions[7,8] and display common characteristics: the rock mass ejected per explosion is usually 10^5 to 10^6 tonnes[3,6] and often contains a high proportion ($\gtrsim$50%) of non-juvenile material; during active periods, intervals between explosions vary from less than one minute, e.g. Anak Krakatoa[6], to about one day, e.g. Asama[3], Sakurazima[9]; pyroclastic avalanches (nuées ardentes) are often produced[8,10,11].

Nairn and Self[2] recently described the February 1975 eruption of Ngauruhoe. Here we use newly developed theory to analyse the largest of the cannon-like explosions (at 18.10 hours on February 19) and discuss the mechanisms of vulcanian explosions. McBirney[12] recently reviewed controls on explosive andesitic eruptions and criticised the use of the Bernouilli equation to derive pre-explosion pressures. However, use of the 'gun-barrel' equation, recommended by McBirney, is also open to criticism. This paper corrects some earlier computations[1,2] of pre-explosion pressures at Ngauruhoe and demonstrates that gas pressures required to generate vulcanian explosions are probably much lower than hitherto thought.

Discrete vulcanian explosions

1. Direct observations

The best documented discrete explosion at 18.10 hours consisted of the expulsion of a cloud of gas containing fragments with a wide range of sizes. The initial velocity was supersonic, resulting in a shock wave[2]. The position and extent of the cloud was recorded on a series of photographs timed with sufficient accuracy to permit estimates to be made of the average velocity between each pair of photographs. Fig. 1 shows the resulting variation of velocity with height; an estimate of errors has been included.

It is known that the velocity of a cloud of material ejected into the atmosphere at high speed must decrease approximately exponentially with height[13] and so a minimum initial velocity can be obtained by fitting a straight line to the data in Fig. 1. Clearly the initial velocity was at least 400 m/s and may have been as high as 500 m/s. The fact that a shock wave accompanied the explosion demonstrates that the velocity was greater than about 300 m/s. A best estimate of 400 m/s is adopted, since this value was also obtained from the measured ranges of 1 m diameter blocks ejected by the same explosion[2].

2. Theory of vulcanian explosions

Discrete, intermittent explosions must be the result of the sudden release of pressure in a gas by the failure of some form of retaining medium. In the vulcanian case the gas may be magmatic or meteoric. It seems improbable that a layer of unconsolidated clasts at the top of the conduit can substantially retain the build-up of an appreciable gas pressure. We assume, therefore, that magma is always involved in such events. New magma rises in a conduit after a previous explosion and cools at its upper surface, forming a "cap".

The compressional strength of dolerite is known to remain nearly constant[14] with temperature up to 950°C; in view of the lack of contrary evidence, we assume that tensile strengths of rocks, commonly quoted to be of order 10% of compressional strengths, also remain constant up to this temperature. Tensile strengths (at low pressures) of 100-200 bars are deduced for rocks of andesitic type from the limited data available[14,15]. In order to obtain an estimate of the thickness of crust sufficiently cool to provide a strength of this order, standard treatments on heat flow can be used[16]. Cooling from magmatic temperature (say 1000°C) during the 50 minute interval before the 18.10 hr explosion could have produced a layer, cooler than 950°C, which was up to 15 cm thick, the distance a thermal wave can travel in rock in this time. Clearly, cool fragments of rock debris smaller than 30 cm in diameter would be efficient heat sinks on this time scale. Indeed, the addition of 10% by weight of such debris, derived from the conduit walls or the fall-back in the vent area from earlier explosions, would cool a layer of any desired thickness to 950°C.

Numerous attempts have been made to relate the ejection velocity of fragments f volcanic e osions, pa icularly those of vulcanian type, to the initial pressure of compressed gas driving the explosion[6,8, 12, 17,18]. All of these treatments are essentially based on a modified form of the Bernouilli equation. We are not satisfied that this equation adequately represents the conditions in any actual volcanic explosion.

The simplest treatment of an explosion driven by expanding gas is one in which it is assumed that complete decompression to atmospheric pressure occurs, and that all of the internal energy released by the expansion is used to accelerate the explosion products, both released gas and clasts, to the same velocity. The energy equation[19] is then:

$$- \int \frac{dP}{\rho} = \int g \, dh + \int u \, du \qquad (1)$$

in which ρ is the bulk density of the eruption products, P is the pressure, g is the acceleration due to gravity, h is the vertical co-ordinate and u the velocity. ρ must be defined in terms of n, the weight fraction of released gas in the exploding mixture, σ, the gas density, and σ_r, the clast density:

$$\frac{1}{\rho} = \frac{n}{\sigma} + \frac{1-n}{\sigma_r} \qquad (2).$$

σ is in turn dictated by the temperature, pressure and composition of the gas; in the present circumstances it is adequate to assume that the perfect gas law applies. It is necessary, before integrating (1), to decide whether the gas expansion will be more nearly isothermal or adiabatic; the deciding factor is the efficiency with which heat can be transferred from clasts to gas and depends on the clast size distribution[20]. In the case of strombolian explosions, in which the time scale is very short, an adiabatic approximation is valid[13]. For vulcanian explosions, the best solution probably lies between the isothermal and adiabatic cases. The results of integrating (1) using (2) are:

$$nRT_i \ln(P_i/P_f) + \frac{(1-n)}{\sigma_r}(P_i-P_f) = g\Delta h + \tfrac{1}{2}u_f^2 \qquad (3)$$

in the isothermal case and, in the adiabatic case:

$$nRT_i \frac{\gamma}{(\gamma-1)}\left[1-\left(\frac{P_f}{P_i}\right)^{\left(\frac{\gamma-1}{\gamma}\right)}\right] + \frac{(1-n)}{\sigma_r}(P_i-P_f) = g\Delta h + \tfrac{1}{2}u_f^2 \qquad (4)$$

where P_i is the initial pressure driving the explosion, P_f is the final pressure, assumed equal to atmospheric, Δh is the vertical distance over which the gas decompression occurs, γ is the ratio of the specific heats of the gas, R is the gas constant and u_f is the final velocity. If numerical values are inserted, it is generally found that the term $g\Delta h$ can be neglected for explosions in which the expansion of gas occurs over a vertical distance of less than a few hundred metres.

The modified version of the Bernouilli equation is usually written:

$$P_i - P_f = \tfrac{1}{2}\sigma_r u_f^2 \qquad (5)$$

in terms of the variables already defined. There has been some discussion[12] as to what density should appear in this equation: σ_r (as written here) or ρ. Comparison of equations (5) and (3) reveals the essential problem with the modified Bernouilli equation:

it only approximates the correct expression if n is sufficiently small (and if Δh is also small). The values of n encountered in real volcanic explosions (say 0.1 to 30 weight % if plinian, vulcanian and strombolian events are included) are always too large for this approximation to be true.

We have argued above that the build up of pressure beneath a restraining cap may be the source of vulcanian explosions. In such a case the mixing of gas and clasts from the disrupted cap and the surrounding rocks may not be great in the early part of the motion; a physical model based on the motion of a solid block of coherent (or shattered) rock overlying a gas body of similar cross sectional area may be more applicable. If the vertical extent of the cap is L and its density is σ_r, and if the gas body beneath the cap has vertical extent X, initial temperature T_i, pressure P_i and gas constant R, then simple geometry shows that

$$\frac{X}{L} = \left(\frac{n}{1-n}\right)\left(\frac{\sigma_r R T_i}{P_i}\right) \qquad (6)$$

so that the solutions may again be expressed in terms of n, the gas weight fraction in the explosion products. The equation of motion for the cap in the vertical h direction is

$$P - P_f = L\sigma_r \ddot{h} - L\sigma_r g - \tfrac{1}{2}\rho_a C_D \dot{h}^2 \qquad (7)$$

where P is the general value of the pressure during the expansion, P is given by

$$P = P_i \left(\frac{X}{X+h}\right)^{\gamma} \qquad (8)$$

initially, since the expansion is adiabatic until some small clasts begin to mix with, and supply heat to, the gas. The final term in equation (7) represents atmospheric drag acting on the rising cap: C_D is a drag coefficient with value close to unity and ρ_a is the atmospheric density. Equation (7) is readily integrated numerically using (6) and (8) to yield the maximum velocity, u_f, of the products during the explosion process. The results of such calculations, and also of the use of the simpler equations (3) and (4), are summarized in Fig. 2, in which u_f is shown as a function of P_i for a range of values of n in each case.

The fact that at least 60-65 weight % of the fragments ejected during the 18.10 hr explosion were smaller than 10 mm[1] and able, therefore, to maintain thermal equilibrium with the gas during most of the explosion[20], implies that the velocities corresponding to equation (3) (isothermal case) may be more appropriate for vulcanian explosions than those derived from equation (4); the solutions to equation (7) certainly represent the lowest possible velocity that corresponds to any particular pair of values of n and P, since they give the greatest weight to energy losses. The speeds given by equation (4) are very close to those from equation (3) at low pressures and fall to about 70% of the equation (3) speeds as the pressure approaches 1000 bars. The n and P values given below are means of equations (3) and (7) biased towards equation (3) on the basis of this argument.

The following combinations of initial gas pressure and released gas weight % are implied by the observed maximum velocity of 400 m/s: for n = 30%, P_i = 2 to 5 bars; for n = 10%, P_i = 10 to 30 bars; for n = 5%, P_i = 40 to 100 bars; for n = 3%, P_i = 100 to 300 bars. We argued earlier that the likely range of values of tensile strength of andesite at sub-solidus temperatures is 100 to 200 bars[14,15]. Then the above permutations of pressure and gas content would imply that the explosion products of the 18.10 hr event contained 2 to 5 weight % water. It was estimated[2] that equal proportion of juvenile and non-juvenile material were expelled in the explosion, and so if it is assumed that all of the water were juvenile, 4 to 10 weight % would be required in the magma. The lower end of this range is comparable to the measured primary water contents[21,22] of andesite magmas, but it is probably implied that some meteoric water was also involved.

3. Magma volume and conduit shape considerations.

The total volume of rock expelled in the 18.10 hr explosion and four other similar outbursts on the same day was about 5×10^5 m^3 dense rock, approximately half of which was juvenile. We may assume that juvenile material was re-emplaced in the upper parts of the volcano between explosions, so that a total of about 2.5×10^5 m^3 of pre-existing cone material was excavated.

This volume cannot have been removed from a localised region near the vent since we know[1] that there were no significant changes in the geometry of this region during the explosive activity: if 2.5×10^5 m^3 is taken to occupy a vertical cylinder with length equal to diameter, the required dimension is 68 m, which is greater than the crater bottom diameter. There is an added reason why such a geometry is unlikely. Heating of groundwater near the magma body is only possible if heat can penetrate the required distance in the time available; the repose period before the 18.10 hr explosion was some 50 minutes, and thermal waves can only travel distances of the order of a few tens of centimetres in rock in this time[16].

A long, cylindrical conduit feeding the vent is the geometry which maximises the chances of groundwater being involved in the explosions. Ngauruhoe stands some 950 m high above the surrounding topography; if a vertical length of, say, 500 m were involved, the excavated cylinder needed to provide both the juvenile and non-juvenile debris for all five major explosions would have has a diameter of 32 m. Fig. 3 shows the situation envisaged: a long, cylindrical conduit about 20 m in diameter containing magma, cooled at the surface and chilled at its contact with the cone material, contains clasts which have fallen into the conduit from earlier activity. Water in these clasts and in the cone material immediately surrounding the magma is heated to near-magmatic temperatures and, together with exsolved juvenile magmatic water, drives the explosion when the cap over the vent fails. It is not possible to estimate accurately the relative contributions from magmatic and juvenile water. The 18.10 hr explosion must have removed a rock layer some 5 m thick from the conduit walls to satisfy the observed mass. Only a small fraction of this rock and its pore water could have been heated by conduction in the 50 minutes prior to the explosion, though water and steam in inter-connected fissures may have been heated by convection. If all the available water in the wall rock layer were involved in the explosion, a water content of 2 to 3 % in this rock would be consistent with the expected water contribution from the magma, as noted above.

In the above treatment we have not found it necessary to invoke the rapid mixing of juvenile material with groundwater that might lead to flash boiling[23]. This mechanism has been proposed as a means of creating pressures of the order of 3-5 kilobars, similar to the pressures deduced for high velocity explosions[17] by applying the Bernouilli equation. Our analysis does not require such high pressures; indeed, we doubt that they are ever required .

4. Eruption column behaviour

The rise height, h, of the convective plume from the 18.10 hr explosion can be computed from a formula for convective rise from an instantaneous source and compared with the observed height: h, in metres, is given[24] by

$$h = 1.87\ Q^{\frac{1}{4}} \qquad (9)$$

where Q is the released heat energy in joules. The 18.10 hr event emitted[1] 2×10^{8} kgm of rock, of which about half was juvenile (i.e. hot and able to contribute to driving convection). However, about half of the material injected into the plume was lost almost immediately (after 12-15 seconds) by the partial collapse of the column to form pyroclastic avalanches[1]. Thus, the heat available to drive convection is estimated to have been a maximum of 4×10^{13} J, leading to a predicted column height, h, of 4700 m. The observed value[1] was at least 4000 m, the discrepancy implying an efficiency of heat utilisation of about 50 %.

This may be compared to values much closer to 100 % found for maintained plumes produced by other eruptions[25] and also to the value found for a maintained plume at Ngauruhoe. During part of the gas-streaming eruptive phase, lasting from 13.25 to 13.45 hr, prior to the series of discrete explosions, a 12 km high convecting column existed[1] over Ngauruhoe. The equivalent of equation (9) for continuous column convection is[24,25]

$$h = 8.2\ \dot{Q}^{\frac{1}{4}} \qquad (10)$$

where h is the column height in metres as before and $\dot{Q}$ is the rate of release of heat energy in watts. A 12 km column height implies a mass eruption rate of 3.2×10^6 kg/s[25]. The measured volume[2] erupted in this cloud was 1.6×10^6 m^3 dense rock which, averaged over 20 minutes and using the density of andesite equal to 2550 kg/m^3, corresponds to 3.4×10^6 kg/s, in good agreement with the above value, suggesting that the efficiency of conversion of heat to work was close to 100% in this case.

Summary

Vulcanian explosions are very common at the many active andesitic strato-volcanoes clustered along subducting plate margins. Some of these eruptions are more violent than those described from Ngauruhoe[8,26]. However, previous estimates of pre-explosion over-pressures have generally been too large, and this paper demonstrates that relatively small pressures are needed to produce the observed behaviour during this type of eruption. Basaltic andesite magmas have water contents which are comparable to those deduced for the explosions[21], and the involvement of groundwater is possibly a significant feature of the events, but not an essential feature as proposed by Schminke[27]. It is not necessary to invoke violent mixing of juvenile material and ground water to explain the explosions. Eruption cloud heights can be related to the rate of release of juvenile material during steady gas-streaming activity, and to the amount of released material in discrete explosions, using the formulae found to apply to larger-scale eruptions[25].

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Figure captions

Figure 1.

Deceleration of 18.10 hr plume from analysis of still photographs. Errors shown as bars. Straight line fitted between maximum and minimum values; curved line approximates exponential deceleration. S is speed of sound in air for reference. Steep portion of curve (A) represents deceleration in gas thrust phase[7]; flat portion (B) represents slow, stable velocity condition while mixing with air and column collapse takes place; (C) is slight increase in velocity at beginning of convective thrust phase. Downward pointing arrow indicates onset of column collapse.

Figure 2.

Maximum velocity of explosion products as a function of initial pressure driving the gas expansion for various types of volcanic explosions. The dotted line MBE is the modified Bernouilli equation (equation 5). The dashed lines are calculations using equation 3 and are labelled by the weight percent gas (taken to be steam) used in the calculations. For these curves perfect thermal contact between gas and clasts is assumed. The solid curves, also labelled by weight percent gas in the exploding mixture, represent solutions to equation 7; the gas cools adiabatically during its expansion from an initial temperature of 1220 K; in the case of the curve for 1 % gas, the effect of reducing the initial temperature by 250 degrees is shown. The dashed and continuous curve for each gas content bracket the upper and lower limits of velocity for a given driving pressure in vulcanian explosions. When the ejecta are predominantly less than 10 mm in diameter, velocity values correspond more closely to the dashed curves.

Figure 3.

Schematic of proposed cross-section through crater region of Ngauruhoe prior to the 18.10 hr explosion.

Fig. 1

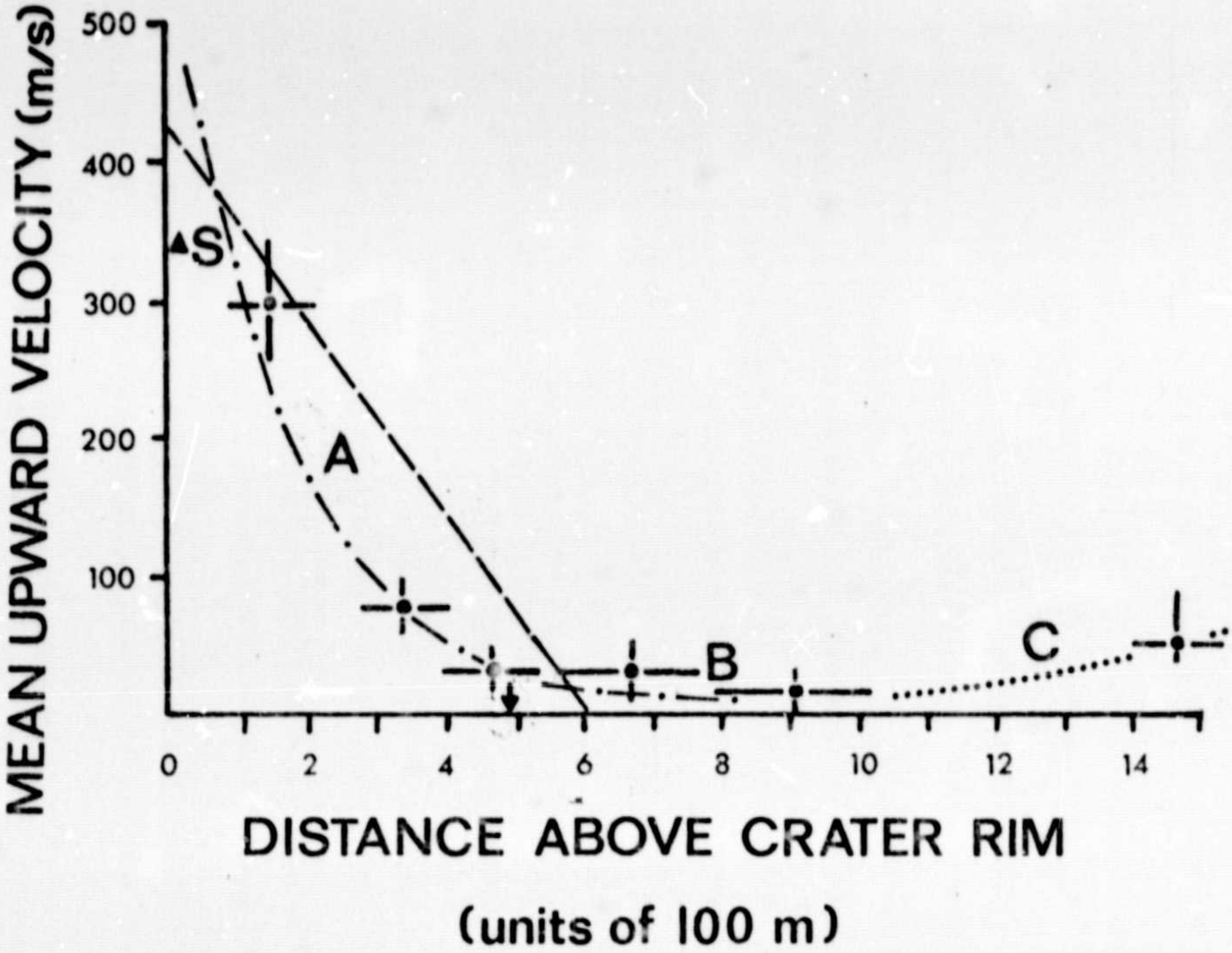
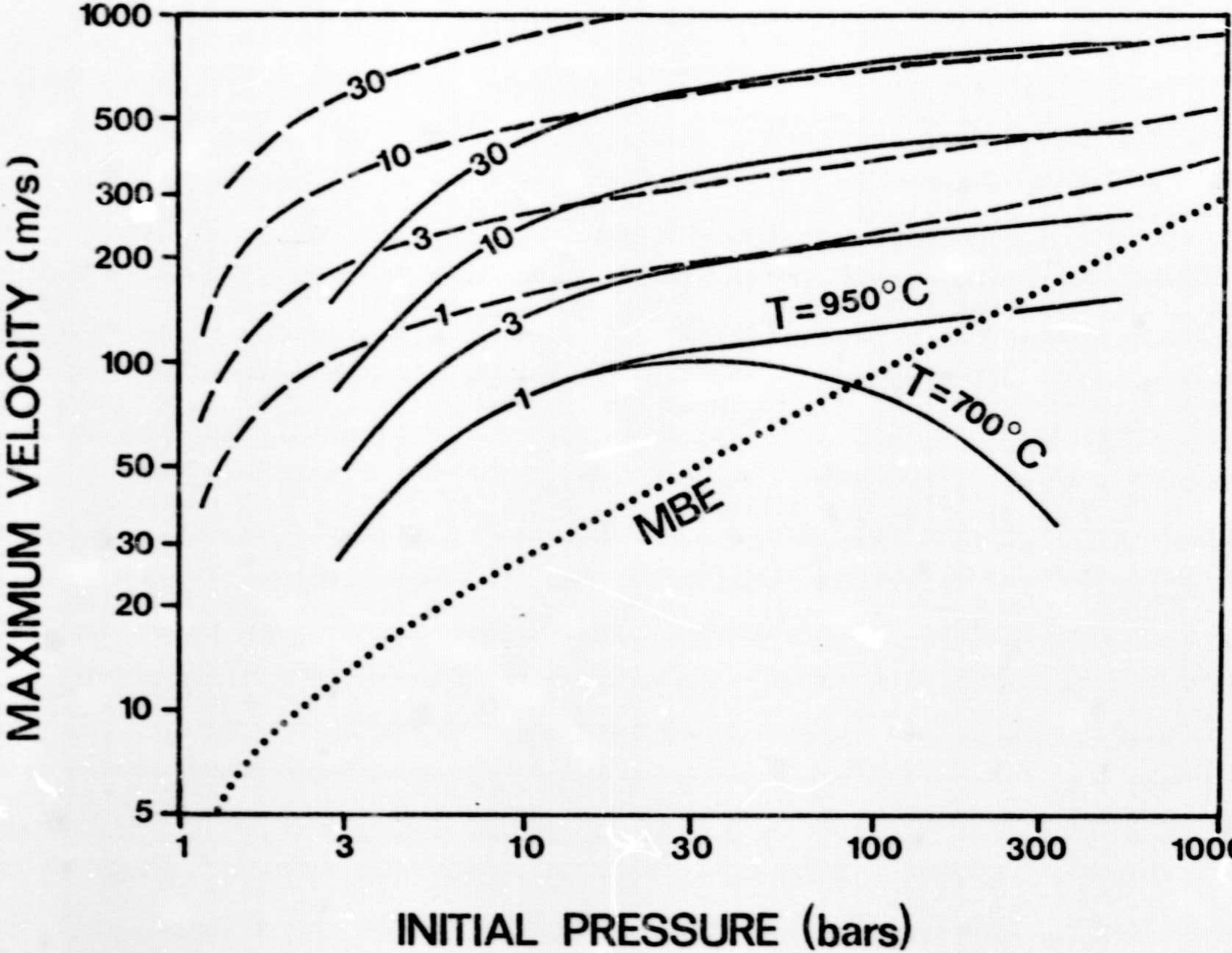
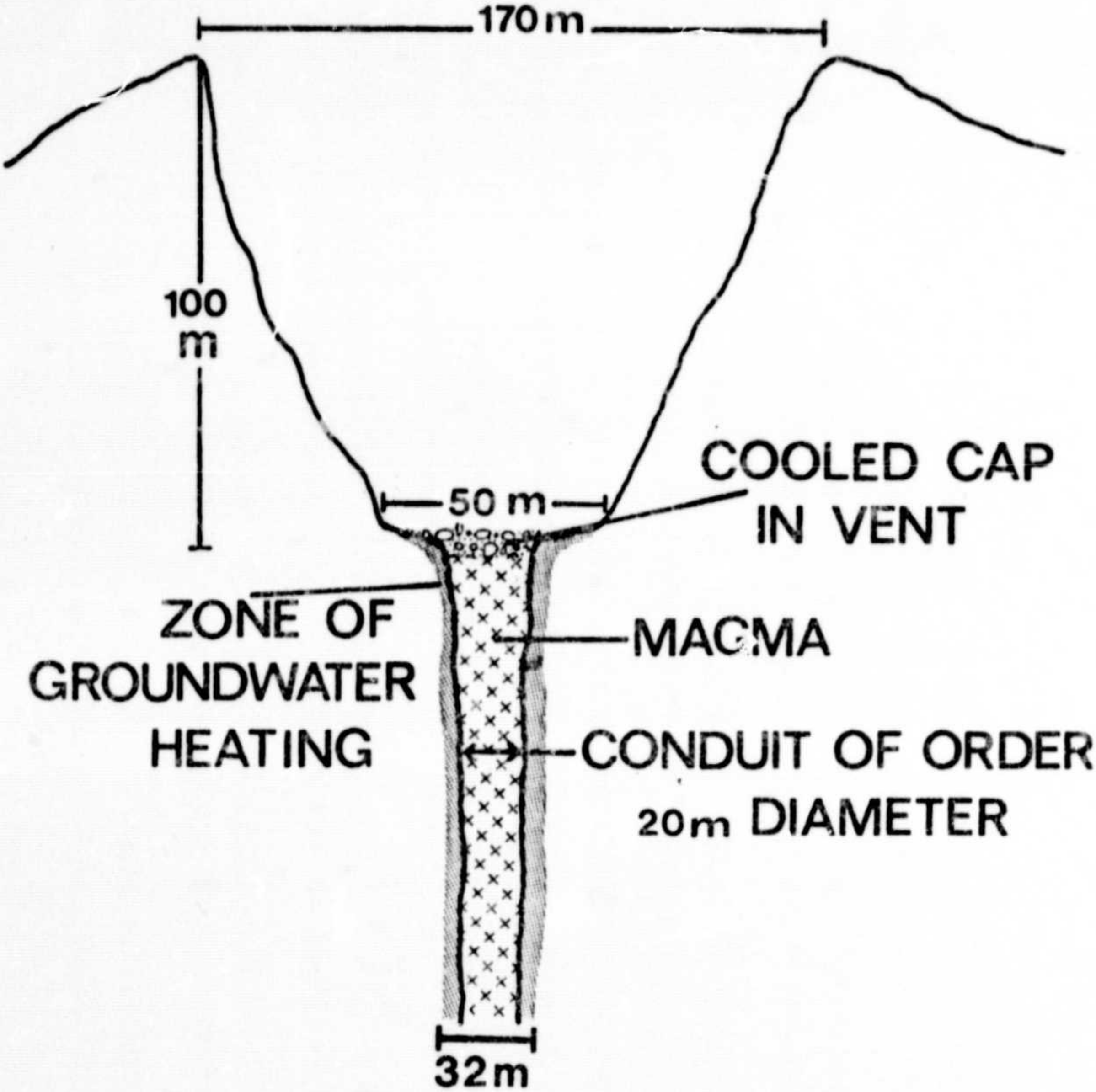

MEAN UPWARD VELOCITY (m/s)
500
400
300
200
100
S
A
B
C
0
2
4
6
8
10
12
14
DISTANCE ABOVE CRATER RIM
(units of 100 m)

Fig. 2


1000
500
300
200
100
50
30
20
10
5
MAXIMUM VELOCITY (m/s)
30
10
30
3
10
1
3
1
T=950°C
T=700°C
MBE
1
3
10
30
100
300
1000
INITIAL PRESSURE (bars)


170 m
100 m
50 m
COOLED CAP IN VENT
ZONE OF GROUNDWATER HEATING
MAGMA
CONDUIT OF ORDER 20m DIAMETER
32m