

Impact jetting of geological materials

W. Yang, T. J. Ahrens

Lindhurst Laboratory of Experimental Geophysics, Seismological Laboratory
California Institute of Technology, Pasadena, California 91125 USA

Abstract: To understand jetting of earth materials, gabbro slabs were accelerated to 1.5 - 2 km/s and impacted gabbro, novaculite, and porous sandstone targets at inclination angles of 30° - 60°. The ejecta were collected using a catcher box filled with styrofoam and the particles extracted using chloroform. Jetting angles and ejecta masses are determined. The mass of the ejected particles per unit area ($\sim 50 \text{ mg/cm}^2$) of the impactor remains almost independent of the impact velocity, inclination angle, thickness of the target, sample mineralogy, and density. Hydrodynamic models are used to calculate the jetting mass, angle, and velocity. The metallic jetting model predicts ~ 6 times more ejecta than experimentally measured as the inclination angle increases. X-ray diffraction of the recovered ejecta shows that it is still in crystalline form, which agrees with thermodynamic calculations. Because the theoretical jetting model for thin metal plates provides a poor description of the experiments, the application of metal plate theory to planet-sized objects appears to be questionable.

Key words: Impact, Jetting, Ejecta

1. Introduction

When two objects collide over a range of angles and impact velocities, high-velocity material is released from the contact zone between the two objects. This phenomena is called jetting. Jetting has been extensively studied in the case of symmetric and asymmetric collisions of thin metal plates both theoretically and experimentally (Birkhoff et al. 1948, Wang 1989, Pack and Curtis 1990). Kieffer (1977) applied the symmetric collision theory to the impact of geologic materials and predicted that molten silicate jets would be produced upon impact at velocities as low as 1 - 2 km/s. Melosh and Sonett (1984), applying the theory of symmetric collisions to the collision of two unequal spheres, suggested that a mega-impact event on the proto-Earth may have ejected enough mass in a solid, liquid, and vapor plume to form the Moon. More recently, Vickery (1993), using Melosh and Sonett's model, calculated the jetting velocity, ejecta mass, and composition in the case of an asteroid impact on Earth. She concluded that for such events, the initially molten, now glassy objects that are recognized as tektites, which in several cases have strewn fields of $10^3 - 10^4$ km, did not originate from the jetting process. As most of the tektites strewn

fields can either be related to specific craters, or a terrestrial origin (Cohen 1963, Taylor and Epstein 1962, Blum et al. 1992), it appears that tektites are associated with the high-speed ejecta, which is lofted at large angles $> 45^\circ$ to the local horizontal. Although there have been several studies and applications of the jetting theory to geologic materials, virtually no experimental constraints are available for the jetting sources involving geological materials. This work summarizes our laboratory results and compares these to theoretical results.

2. Experiments

Experiments were conducted using a 40-mm propellant gun to accelerate 5-mm thick gabbro discs to 1.5 – 2 km/s. Upon impact with inclined (30° – 60°) rectangular target slabs (5- to 12-mm thick gabbro, novaculite, and porous sandstone), ejecta were collected in a catch box filled with styrofoam (32 kg/m^3 , 0.1-m thick). Figure 1 and Table 1 give the experimental configuration and conditions. As a result of the impacts, a series of elliptically shaped craters, ~ 5 cm long and ~ 2 cm wide, were formed. By careful measurement of the relative

Table 1. Experimental parameters.

Shot #	Flyer Plate		Target		Impact Angle	Impact v (km/s)	
	ρ (g/cm ³)	t (mm)	m	ρ (g/cm ³)			t (mm)
846	2.89	5.04	gabbro	2.89	4.98	30°	1.51
852	2.90	4.99	gabbro	2.90	4.79	30°	1.52
855	2.90	4.99	gabbro	2.90	4.87	30°	1.51
905	2.88	5.16	novaculite	2.24	10.2	30°	1.95
906	2.87	5.13	novaculite	2.24	10.2	45°	1.95
907	2.88	5.16	novaculite	2.24	10.0	30°	1.52
927	2.89	5.35	sss	1.80	11.9	45°	1.49
928	2.90	4.57	sss	1.83	11.8	45°	1.83
940	2.90	4.89	gabbro	2.98	10.2	60°	1.52
941	2.90	5.42	gabbro	2.88	10.1	60°	2.02

Here v = velocity; m = material; t = thickness; ρ = density; gabbro = San Marcos Gabbro, Escondido, CA; novaculite = Norton, Black Hard Arkansas sharpening stone, AK; sss = Saltwash South Sandstone, UT.

positions of the target and the crater created by the ejecta, the jetting angle was determined. Then the styrofoam which contained the ejecta was dissolved in chloroform and the ejecta were recovered. Table 2 summarizes the results. The design of the present planar experiment has several advantages over the traditional sphere impacting a half-space target. The ejecta are totally separated from other debris, the jetting angle is determined easily by geometrical measurement, and the experimental results can be compared with theoretical predictions. By changing the impact angle, we can simulate the different regimes of a sphere impacting a half-space target. Figure 2 shows typical X-ray diffraction patterns of recovered ejecta. The results show that no amorphous phase

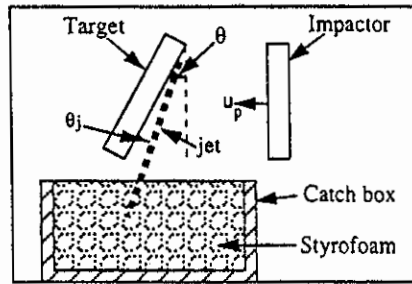


Figure 1. Configuration of oblique impact experiments: u_p - impact velocity, θ - impact angle, and θ_j - jetting angle.

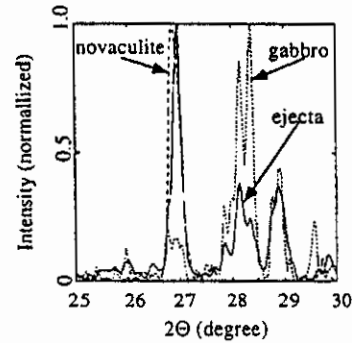


Figure 2. X-ray diffraction patterns (35 kV, Cu anode) of the ejecta from shot 906 (Table 1).

is present, thus the ejecta are still in crystalline form. Comparison of X-ray diffraction patterns of ejecta and ground-up unshocked materials (Fig. 2) shows that their patterns match. Thus the ejecta are, unlike tektites, composed of both the target and impactor materials. Tektites are largely glass which have major element compositions similar only to target materials. They contain, in some cases, only minute traces of the projectile materials. Scanning electron microscope (SEM) images of the ejecta from the present experiments show that the particles are less than a few microns in diameter despite the fact that grain sizes of the impactor and target are as large as 3 mm.

Table 2. Theoretical results and experimental values (in parentheses).

Shot No.	846	852	855	905	906	907	927	928	940	941
Jet mass (mg/cm^2)	53 (66)	52 (53)	52 (-)	64 (30)	153 (62)	64 (30)	155 (42)	140 (54)	299 (45)	323 (52)
Jetting angle (degree)	6.7	6.8	6.8	5.1	6.1	5.2	6.6	5.8	3.8	4.3
			(6.5 \pm 0.5)	(4.7 \pm 0.5)	(5.5 \pm 1)	(8.1 \pm 0.5)	(9.0 \pm 1)	(10 \pm 1.5)	(3.2 \pm 0.6)	(10 \pm 1.5)
Jet velocity (km/s)	5.78	5.82	5.86	7.43	4.92	5.79	3.80	4.61	2.76	3.70

3. Theoretical model

Analytical asymmetric collision models are described by Wang (1989) and Pack and Curtis (1990). In our treatment we take the collision point o as the origin of a moving coordinate system (referenced to the laboratory coordinate system). The flow pattern of the impactor and target plates is shown in Fig. 3. We assume that the flow depicted in Fig. 3 is incompressible and the surface between the

impactor and the target remains planar. Then Bernoulli's theorem yields equal flow velocities of the jet, u_j , slug, u_s , and incoming flow, u_1 , and u_2 . If we further assume that the jet and slug move along one straight line, using the conservation of mass and momentum and geometric relations, we get the jet mass m_j , the average jet velocity in the moving coordinates u_j , the jet velocity v_j , and jetting angle θ_j in laboratory coordinates as:

$$\theta_2 = \arctan(m_1 u_p / (m_1 + m_2) / \tan \theta) \quad (1)$$

$$m_j = m_{1j} + m_{2j} = [m_1(1 - \cos(\theta - \theta_2)) + m_2(1 - \cos \theta_2)]/2 \quad (2)$$

$$u_j = (m_{1j} u_p / \tan \theta + m_{2j} u_p / \sin \theta) / m_j \quad (3)$$

$$v_j^2 = u_j^2 + (u_p / \sin \theta)^2 + 2u_j u_p \cos \theta_2 / \sin \theta \quad (4)$$

$$\theta_j = \arcsin(\sin(\theta_2) u_j / v_j) \quad (5)$$

Calculated values for m_j , θ_j , and v_j are given in Table 2. In order to estimate the pressure and temperature that the materials have experienced, Bernoulli's equation is used again and the flow is assumed now to be compressible

$$e + pv + u^2/2 = e_o + p_o v_o + u_o^2/2 \quad (6)$$

Substituting e and p with the Hugoniot relations $e = p(v_o - v)/2$ and $p = c_o^2(v_o - v)/[(1 - s)v_o + sv]^2$, we can solve (6) for p and v at the stagnation point. With other thermodynamic parameters, the shock temperature and post-shock temperature the materials have experienced can be calculated (Yang et al. 1992). The parameters used are listed in Table 3.

Table 3. Parameters used in pressure and temperature calculations.

	γ_0	θ_0 (K)	c_0 (km/s)	s	P (GPa)	T_{hmax} (K)	T_{pmax} (K)
Gabbro	5.2 ^a	1022 ^b	5.6	0.15	18	815	304
sss	0.7 ^c	999 ^c	2.90	0.72	7	454	364
Novaculite	0.7 ^c	999 ^c	2.35	1.1	21	1196	411

Here γ_0 - Grüneisen constant; θ_0 - Debye temperature; a - calculated from the formula $\gamma_0 = \alpha c_0^2 / c_p$, where α - thermal expansion coefficient, c_p - heat capacity (Touloukian et al. 1989); b - obtained by fitting c_p to Debay's formula; c_0 and s are obtained by fitting the shock-wave data (Marsh 1980); T_{hmax} and T_{pmax} are maximum shock and post-shock temperatures, respectively; sss - Saltwash South sandstone; d - from Swegle (1990).

4. Discussion and conclusions

From Table 2 we can see that the calculated masses of ejecta are significantly greater than those of the experiments, except for shot 846 and 852 (Table 1). By plotting the ejecta masses versus inclination angle on Fig. 4, we immediately see that while the theory predicts an increase of ejecta mass as the inclination

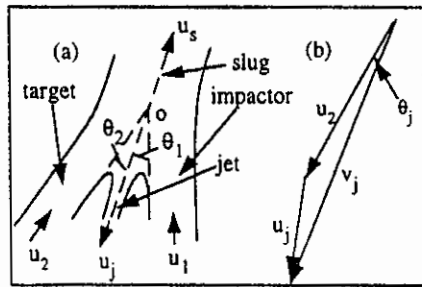


Figure 3. (a) Flow pattern of the impactor and target in a moving frame, o - collision point; (b) velocity vectors are given in laboratory coordinates; v_j - jet velocity, θ_j - jetting angle.

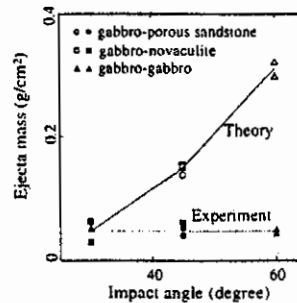


Figure 4. Ejecta mass per unit area versus impact angle.

angle and plate thickness increase, the experiments show an approximately constant amount of ejecta mass ($\sim 50 \text{ mg/cm}^2$) despite the fact that the impact velocity, material, and plate thickness were varied considerably. Since increasing the thickness of the target does not appear to increase the mass of ejecta, we conclude that only part of the total thickness of the impactor and target contribute to the formation of a jet. This thickness is about 5 mm (shots 846 and 852) with our experimental conditions. In Melosh and Sonett's model, and also in Vickery's calculations, the thickness which is assumed to contribute to jetting is chosen as the radius of the impacting sphere. In light of the present experiments the above assumption appears to be unsupported. Obviously different jet ejecta masses can be inferred by assuming different thicknesses. It seems that the present jetting theory does not obviously apply to geological materials. Although our experiments were conducted at relatively low velocities, the impactor and target materials both experienced shock pressures far in excess of their strengths, hence they should behave like fluids. In addition, the theoretical model predicts little ejecta mass change when impact velocity changes. Thus we believe that the discrepancy between experiments and theory will not disappear at high impact velocities (e.g., 10 km/s). From the X-ray diffraction patterns (Fig. 2), we find that the ejecta contain significant amounts of impactor and target materials. Since most tektites do not contain significant amounts of an extraterrestrial component (Koeberl and Shirey 1993), by analogy we do not believe they are produced by the jetting process upon asteroid impact. However, the tektites may be produced by other processes after jetting occurs during impact events. The jetting angles (Table 2) are all less than 10° . This suggests that oblique (or asymmetric) impact is very different from symmetric impact. Thus applying symmetric impact theory (as was used

by Melosh and Sonett, and Vickery), does not appear to be appropriate for asymmetric impacts. The calculated shock and post-shock temperatures are all below the melting points of the materials used. This agrees closely with the X-ray diffraction and SEM results in which no melting was detected. We also conclude, in contrast to Kieffer (1977), that impact velocities greater than 2 km/s are required to produce molten jets for the silicate materials used in our experiments.

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