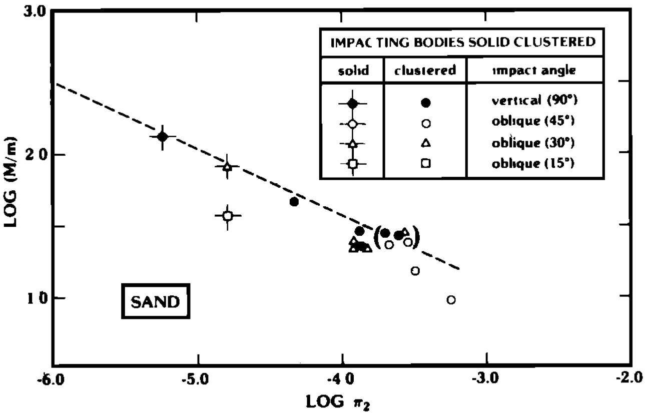

Fig. 5. The effect of oblique impact angles on the cratering efficiency of clustered impacts (aluminum and steel shot) into sand. The general trends observed in Figure 4 for higher impact velocities into pumice is also observed here. Data in parentheses indicate higher-density steel shot and long ejecta clouds. The dashed line represents the best fit to the data shown in Figure 3.

and impact velocity, as discussed by *Schmidt and Holsapple* [1980]. First, we establish such relations for the targets used in clustered-impact experiments. Second, we examine the effects of different target and projectile densities on cratering efficiency.

Schmidt and Holsapple [1980] and *Holsapple and Schmidt* [1982] suggested that a set of dimensionless parameters defines dependent and independent variables controlling impact cratering. Of interest here is the relation between the dependent variables of cratering efficiency defined as the ratio between displaced mass M and projectile mass m and the independent variable π_2 called the gravity-scaled size defined as

$$\pi_2 = 3.22\, gr/v^2$$

where g is the gravitational acceleration, r is the projectile radius, and v is velocity. The displaced mass is defined by the product of bulk target density and the measured volume of the crater referenced to the preimpact surface. *Gault and Wedekind* [1977] pointed out that a single functional relation may not be correct over an extended velocity range, but it is used here for convenience. Also of interest is the ratio between target δ_T and projectile density δ_P.

Figure 1 shows the π_2 efficiency relation for two different targets of no. 140-200 sand (i.e., sand grains with sizes between 105 μm and 149 μm that will pass through a no. 140 sieve mesh but will be retained in a no. 120 sieve mesh), and compacted pumice (finer than 105 μm) from Mono Craters, California. The slightly different slopes for these materials probably reflect the different angles of internal friction and cohesion. These differences are of no further application here except to provide a qualitative effect of different strength targets. Appendix Tables B1–B3 provide the detailed impact conditions for the data shown in Figure 1.

Figure 2 confirms the preliminary conclusions of *Schmidt et al.* [1979] and *Schmidt* [1980] that projectile or target density has little, if any, effect on cratering efficiency. Projectiles with densities ranging from 0.087 to 6.9 g/cm^3 impacted into pumice showed no consistent or significant departure from projectiles of a single density impacted into the same target. Likewise, impacts by projectiles of one density into targets with densities ranging from 0.47 to 0.8 g/cm^3 showed no significant departures from Al projectiles impacting sand. Figures 1 and 2 together demonstrate that marked departures of cratering efficiency for clustered impacts relative to single events must be viewed in terms of fundamental differences in the impact process and/or the effect of projectile configuration (e.g., diameter to length ratio of projectile cluster).

3.2. *Clustered Impacts and Cratering Efficiency*

For purposes of discussion, clustered impacts are arbitrarily grouped according to the maximum lateral dimension r_c of the ensemble of projectiles relative to the radius r_s of a single projectile of the same mass and density. "Tight" clusters are defined here for clusters where $r_c/r_s < 3$, "open" clusters for $3 < r_c/r_s < 10$, and "dispersed" clusters for $r_c/r_s > 10$. Appendix A summarizes how r_c is determined. Figure 3 shows that vertical impacts by an open cluster of pyrex fragments into sand consistently displace about a factor of 5 less mass than a single-body impact of the same mass. Because the independent variable π_2 includes the projectile radius, the appropriate π_2 for a clustered impact should include the observed radius r_c of the ensemble of fragments. Such an approach views the impacting clusters as a single but low-density projectile, an assumption frequently used in theoretical simulations of the same problem [e.g., *O'Keefe and Ahrens*, 1982]. This approach also illustrates that very early time complexities associated with individual fragments impacting nearly simultaneously are lost at late times in crater growth, for sufficiently closely spaced fragments. Figure 3 shows that using the overall cluster radius brings the data for clustered impacts close to the nominal π_2 efficiency line for single-body impacts of the same mass. It should be noted

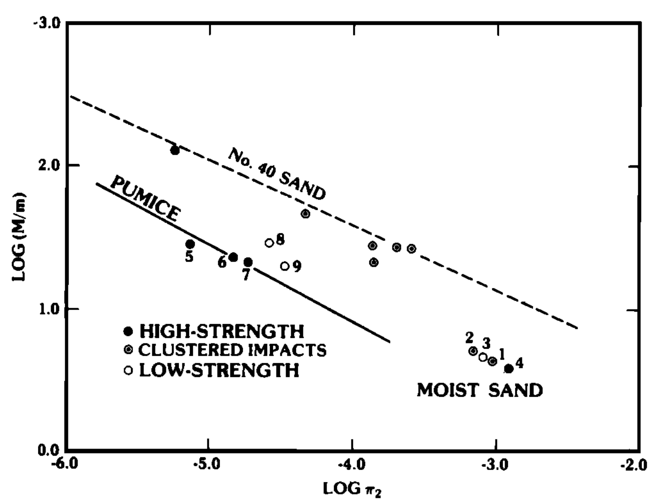

Fig. 6. Comparison of cratering efficiencies for clustered and weak bodies impacting vertically into no. 40 sand, moist sand, and compacted pumice at low velocities (20–200 m/s). The π_2 term for clustered impacts includes the cluster radius rather than the equivalent solid body radius of the same mass. Numbered data correspond to projectiles with different strengths. Data points 1 (3031) and 2 (4445) represent thin-walled oblate spheroids with low and high viscosity, respectively. Point 3 (5152) indicates tightly clustered sand and 4 (3940) represents a solid, competent impactor of the same size. At very low velocities (<20 m/s), impacts into moist sand show no change in cratering efficiency. Point 5 (830546) represents a solid nylon impactor, whereas 6 (830548) and 7 (830549) indicate hollow nylon spheres impacting compacted pumice. Data points 8 (830602) and 9 (830601) correspond to sand-embedded plaster and a puttylike plastic impacting the same target. Projectiles that were deformed at impact tend to have slightly higher cratering efficiencies relative to the undeformed nylon impactors.