lithostatic overburden term (equation (5*b*)). The characteristic depth for explosion craters is typically assigned to the depth of burial [e.g., *Vortman*, 1968; *Johnson et al.*, 1969; *Herr*, 1971]. For impact craters, h has several possibilities. *Schmidt* [1980] implies that the penetration depth of the projectile for impacts is proportional to the depth of burial for explosions. If impactor penetration depth scaled to projectile radius is constant (independent of velocity, etc.), then h simply becomes r_p.

The second atmospheric scaling parameter also draws on the concept of the added atmospheric overburden except that the value of h in equation (5) for an impact becomes the maximum depth of the transient crater had it formed in a vacuum. Such a view is based on observations that craters rapidly achieve a maximum depth largely through compression and then grow laterally through excavation [see *Orphal et al.*, 1980; *Schultz et al.*, 1981]. Hence the earliest stages of crater growth should not be sensitive to lithostatic or atmospheric overburden. If it is further assumed that crater scaling is proportional (i.e., geometric similarity at all scales), then crater depth should be a given fraction of the crater radius, R_v, had it formed in a vacuum. In this case, R_v can be given in terms of the independent dimensionless parameter, π_2 (equation (3)), i.e., $\pi_2^{\alpha/3}(\delta_p/\delta_t)^{1/3}$.

The third scaling parameter is derived from dimensional analysis. *Chabai* [1965, 1977] proposed the following scaling rule for explosion cratering:

$$(R_v/h) \sim (P_o + \delta_t gh)^{1/3}(h)/E^{1/3} \quad (6a)$$

where the explosive charge of energy E is buried at the depth h. If this rule is applied to impact cratering where h is assumed to be directly proportional to r, then

$$(R_v/r)^3 \sim (P_o + \delta_t gr)/\delta_t v^2 \quad (6b)$$

$$(R_v/r)^3 \sim P_o/\delta_t Q \quad \text{for } P_o >> \delta gr \quad (6c)$$

where Q is defined as the specific energy (energy/mass), or $1/2v_i^2$. Equation (6*c*) is essentially the form of the dimensionless pressure parameter proposed by *Holsapple* [1980]. *Holsapple* [1980] noted that this parameter is actually the same as equation (5) by combining equations (6) and (4):

$$M/m \sim (2P_o/\delta_t v_i^2)^{-\beta}(\pi_2)^{-\alpha} \sim (P_o/\delta_t g r_p)^{-\beta}(\pi_2)^{-(\alpha+\beta)} \quad (7a)$$

$$M/m \sim (P_o/\delta_t v_i^2)^{-\beta}(\pi_2)^{(-\alpha+\beta)} \sim (P_o/\delta_t g r_p)^{-\beta}\pi_2^{-\alpha} \quad (7b)$$

where β is derived empirically. Equation (7*a*) presumes that equation (6) applies without a change in the exponent α. *Holsapple* [1980], however, suggested that the added atmospheric pressure changes the cratering efficiency exponent α, analogous to a change in the effective depth of burst, as explicitly included in equation (7*b*). If h is proportional to r_p, then equation (7*b*) becomes identical to equation (5*b*).

More recent analysis of crater scaling using the assumption of a point source, coupling parameter by *Holsapple and Schmidt* [1987] suggests a more self-consistent and complete expression for atmospheric effects involving two dimensionless pressure factors. The first is the applied dynamic pressure created at impact ($\delta_t v^2$) scaled to the lithostatic pressure ($\delta_t g r_p$); the second is the static atmospheric pressure ratioed to the lithostatic pressure. This approach implicitly assumes that no other stress scales apply (e.g., drag acting on individual particles or the effect of projectile wake blast); hence, the following additional expression has been suggested by K.A. Holsapple (personal communication, 1991):

$$M/m \sim [(P_o/\delta_t v^2)\pi_2^{\alpha/3}]^{-\beta}\,\pi_2^{-\alpha} = \pi_p^{-\beta}\pi_2^{-\alpha} \quad (8)$$

For completeness, a fifth scaling relation incorporates the possibility that strength, rather than gravity, controls late stage crater growth. *Holsapple and Schmidt* [1987] provide the following scaling relation for strength-controlled growth:

No atmosphere $\quad \pi_v(Y/\delta_t v_i^2)^{\beta'} = \text{const} \quad$ (9a)

With atmosphere $\quad \pi_v(Y/\delta_t v_i^2)^{\beta'} = F(P/Y) \quad$ (9b)

where Y represents target strength (i.e., cohesion); $F(P/Y)$ depicts the functional dependence between atmospheric pressure (P) and strength; and the exponent β' is given by a coupling parameter, μ, with $\beta' = 3\mu/2$. For particulate (porous) targets, the value of μ ranges from 0.37 to 0.40 [*Holsapple and Schmidt*, 1987]; hence β' would range from 0.56 to 0.6. If atmospheric pressure were to completely dominate strength (and other processes) in reducing cratering efficiency, then it might be expected that β' should be the appropoate scaling exponent for $F(P/Y)$ as well. Note that equation (9) predicts that projectile size should have no effect unless both gravity and strength play a role.

In summary, five alternative relations for the effects of atmospheric pressure can be envisioned: four involving gravity-controlled growth and one considering the possible effect of strength. If the observed cratering efficiencies under atmospheric pressure are referenced to efficiencies in a vacuum (equation (4)), then one of the following relations should accommodate the data for a given target:

$$k\pi_2^{\alpha}\pi_v \sim [P_o/\delta_t gh]^{-\beta} \sim [P_o/\delta_t r_p]^{-\beta} \quad (10a)$$

from equation (5) for given gravity and $h \sim r_p$;

$$k\pi_2^{\alpha}\pi_v \sim [P_o/\delta_t gh]^{-\beta} \sim [(P_o/\delta_t R_v)(\pi_2^{\alpha/3})(\delta_t/\delta_p)^{1/3}]^{-\beta} \quad (10b)$$

from equation (5) for given gravity and $h \sim$ (crater depth) $\sim R$;

$$k\pi_2^{\alpha}\pi_v \sim [P_o/\delta_t Q]^{-\beta} \sim [P_o/\delta_t v^2]^{-\beta} \quad (10c)$$