CONTROLLED RELEASE OF AVALANCHES

BY EXPLOSIVES

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ABSTRACT

The effects of explosives and blasting agents on snow are discussed from the viewpoint of rock-blasting technology. Air-blast, crater formation, and ground motion are considered, and the characteristics of various types of explosives are outlined. Recent developments in the commercial manufacture of liquid and slurried explosives and blasting agents are described, and the possibilities for application of these materials in avalanche control are explored.

Introduction

Explosives have long been used for deliberate controlled release of avalanches, using charge emplacement techniques that evolved to suit prevailing conditions. The principal methods of charge emplacement have been: i) hand delivery, in which solid charges are laid on the snow surface or thrust into the snowpack for immediate firing, and ii) projectile delivery, in which fuzed charges are fired into the target zone by guns. Consideration has been given to emplacement of explosive charges prior to winter for firing on demand, but this technique is probably unacceptable in areas where there is unrestricted public access.

Established methods appear to be reasonably effective, although from a technical standpoint there are some questionable aspects and quantitative information is very limited. From a safety standpoint, the record for avalanche blasting is very good, but safe application of traditional methods seems to depend heavily on the skill and integrity of control personnel; by contrast, industrial applications of explosives demand inherently safe procedures.

The following notes are intended to review the behavior of explosives and blasting agents, the response of snow to explosives, and recent developments that might be applicable to avalanche blasting. One objective of this review is to bring out the great difference in response characteristics between snow and the materials for which typical blasting technology has been developed.

Action of Explosives

An explosion involves very rapid generation of energy in limited space, with sudden development of great pressure, usually accompanied by violent gas expansion. It is commonly created by direct chemical reaction, but other thermal, mechanical, electrical, or nuclear processes can give rise to explosions when energy is released at rates greatly exceeding the local dissipation rate. In a chemical explosive a great amount of energy – approximately 1 kcal/g – is released in a very short time (microsecond reaction time), so that the power level is enormous (about 50 billion kilowatts per square meter at the detonation front).

Chemical explosives undergo exothermic reaction, propagating a reaction wave from the point of initiation. If the velocity of this wave is higher than the acoustic velocity of the unreacted material, as in "high" explosives, the process is called *detonation*; if it is lower than the acoustic velocity of the unreacted material, as in "low" explosives or propellants, it is called *deflagration*. Ideal detonation velocities of some explosives exceed 8000 m/sec. Detonation pressure (which can exceed 300,000 atmospheres in some explosives) is approximately proportional to the square of detonation velocity, and therefore explosives with high detonation velocity can be expected to produce intense shock waves and to have great shattering power, or brisance. By contrast, deflagrating explosives such as black powder are unlikely to transmit a true shock wave to surrounding material, and they depend almost entirely on gas expansion for their blasting effectiveness.

Gas blasting can also be accomplished with devices other than conventional chemical explosives. Air-blasting systems release high pressure air (typically around 12,000 lbf/in.^{2}) from containers charged by multi-stage compressors. Carbon dioxide systems vaporize liquid CO_2 by a heater element and discharge it from a shell at high pressure. Fuel/oxidant devices explode gas or vapor mixtures (e.g. propane and compressed air) in a combustion chamber and discharge through a venting port.

When fired inside a solid or fluid medium, a high explosive creates a severe stress wave, or shock wave, which initially propagates radially outward from the charge at a speed higher than the acoustic velocity of the medium. Geometrical spreading and losses in the medium cause the wave to attenuate rapidly, reducing both amplitude and velocity until it eventually becomes an elastic wave traveling at the sonic velocity of the medium. The initial amplitude of the shock wave from a typical high explosive far exceeds the yield strength of any solid material, and material in the immediate vicinity of the charge undergoes intense compression that is essentially hydrodynamic and adiabatic; brittle material such as rock is completely pulverized in this zone. As distance from the charge increases, plastic or inelastic compression becomes progressively less severe, and shear resistance of the confining material becomes increasingly important. At greater ranges, where wave amplitude drops below the elastic limit of the medium, tensile hoop stresses (tangential stresses) associated with the radial pressure pulse cause radial cracking. When the radial stress wave meets free boundaries (rock/air interfaces) at normal incidence it reflects as a tensile wave, and surface spalling will occur if the amplitude is great enough.

In many materials only a minor proportion of the total explosive energy is transmitted in the shock wave – typically less than 20% in common rocks, and sometimes only a few percent. For a given type of explosive, the initial shock intensity in a solid medium is governed largely by the efficiency of coupling between the explosive and the medium. Good coupling calls for intimate contact between the charge and the medium (as with a liquid or slurry explosive), and for "impedance matching," i.e. for the product of detonation velocity and density for the explosive to be approximately equal to the product of acoustic velocity and density for the medium. Once the shock has been transmitted to the medium, a great deal of its energy is absorbed immediately in the hydrodynamic compression zone. The effectiveness of a given material in transmitting or absorbing shock energy in the hydrodynamic zone is characterized largely by the Rankine-Hugoniot equation of state, or by a graphical "Hugoniot" characteristic giving the pressure/volume relationship for very rapid loading and unloading. In broad terms, a material that is highly compressible over the applicable pressure range can be expected to be effective in attenuating shock pressure.

The spherical wave propagating from a point charge in an isotropic infinite medium attenuates geometrically, with wave amplitude inversely proportional to radius and wave energy inversely proportional to radius squared. The wave also attenuates because of internal energy dissipation in the medium, with amplitude decreasing exponentially with distance traveled. The combined attenuation is best described by a function with an inverse proportionality factor and an exponential decay factor, but in practice it is usual to plot shock pressure against scaled radius on logarithmic scales and express the result approximately as a simple power relation, with amplitude inversely proportional to radius raised to a power of roughly 2 to 3, depending on the material type and the radius (the power decreases with increasing scaled radius).

So far the discussion has been confined to the stress wave, which actually accounts for only a minor portion of the explosive energy. It is next necessary to consider the expanding gases which follow the stress wave and contain most of the available energy.

All chemical explosives produce large volumes of high pressure gas, and in typical blasting situations most of the explosive energy is utilized in expanding this gas. In an underwater explosion the expanding gas produces a bubble which displaces water radially outward, continuing to grow until its internal pressure drops below the ambient hydrostatic pressure and flow reverses. (In deep water, the bubble pulsates in size, and it rises and deforms by buoyancy effects.) When an explosion occurs deep inside a solid medium, the gas can only expand into the cavity formed by shock wave crushing, into cracks formed by the shock wave, into pre-existing cracks or pores, or into cracks that are formed by the gas pressure itself. The usual objective in blasting practice is to create a situation where the expanding gas can form and exploit cracks so as to displace material to a free boundary.

Low explosives and gas blasting devices set deep into strong impermeable material are often incapable of initiating cracks; they have to rely on existing flaws such as cracks, pores, planes of weakness, etc. However, they are particularly effective in situations where shock damage is either unnecessary or detrimental. For example, in blasting hard coal there is no necessity for stress wave shattering, and in "heaving" surface slabs, such as concrete pavements or floating ice, shock damage can produce premature venting of the gas, with consequent reduction of flexural breakage. For blasting strong uncracked rock in large masses it is usually more economical to use a high explosive, using the shock wave to initiate cracks that can be exploited and extended by the gases. For any type of explosive an air space between the charge and the solid medium can greatly reduce the initial gas pressure as well as shock wave amplitude, and an unstemmed shothole can similarly reduce the gas pressure that is applied to the blasted material.

In order to characterize the properties of explosives and the blast response of materials, it is convenient to scale shock and blast effects to remove the effect of charge size. In ordinary blasting practice, where body forces in the blasted medium are negligible, dynamic and geometric similitude permits linear dimensions such as charge depth, burden, hole spacing, crater radius, etc. to be normalized with respect to charge radius for a given type of explosive. For a given charge density the charge volume is proportional to charge weight, and thus it has become usual to scale linear dimensions with respect to the cube root of charge weight, i.e. a length measured in feet is divided by the cube root of charge weight measured in pounds to give a scaled length expressed in units of $ft/lb^{1/3}$.

Response of Snow to Explosives

Snow is very different from materials that are usually blasted by explosives; it is very weak, and can be excavated and handled with ease. However, the low strength and low density of snow do not lead to any great increase in blasting effectiveness, since snow is an energy-absorbing medium.

The coupling between a high explosive charge and snow is generally poor, and theoretically the impedance matching is far from ideal. The snow lying in avalanche starting zones is not likely to have acoustic velocities much above 1000 m/sec, and low density snow may have acoustic velocities of only a few hundred meters per second. Thus the product of acoustic velocity and snow density is likely to be an order of magnitude lower than the product of detonation velocity and density for explosives and blasting agents. By contrast, the impedance matching ratio for frozen soil is close to unity for typical explosives. In snow the hydrodynamic zone, in which energy is absorbed by inelastic compression of the material, is relatively large, as snow is readily compressible and a significant amount of compression is irreversible. Adiabatic compressibility curves (Hugoniot curves) show that snow of about 0.4 g/cm^3 density can be compressed to about 50% of its unstrained volume by pressures of only 20 bars or so.

Direct experimental evidence shows that dense snow, of the type found in the surface layers of the Greenland Ice Sheet, is tremendously effective in attenuating stress waves (Fig. 1). At close range, such as 1 ft from a 1-lb charge, the peak pressure in snow is much smaller than the

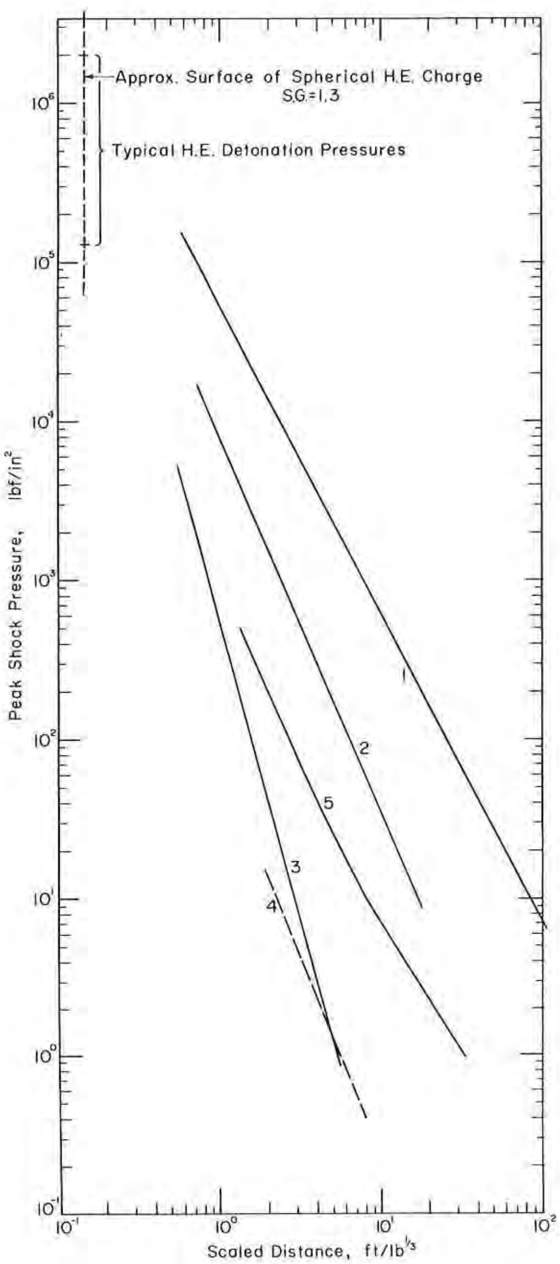


Figure 1. Stress wave attenuation in various materials. 1) Granite, 2) glacier ice, 3) ice cap snow, 4) seasonal snow, 5) air. (See Mellor 1968 and 1972 for details of data sources.)

corresponding pressure in granite – about 100 times smaller. Looking at the attenuation in relative terms, the scaled distance from the charge at which shock pressure drops below the uniaxial compressive strength of the material is shorter for snow than for granite.

The strong attenuating properties of snow become evident when explosive cratering capabilities are considered. In Figure 2 the dimensions of craters in dense snow are plotted against charge depth, all linear dimensions being scaled with respect to the cube root of charge weight. Comparative data for solid ice and frozen ground are given in Appendix A. In spite of the low density and low strength of snow, crater dimensions are very similar to corresponding dimensions for solid ice, and crater radius in snow is about the same as crater radius in frozen soils.

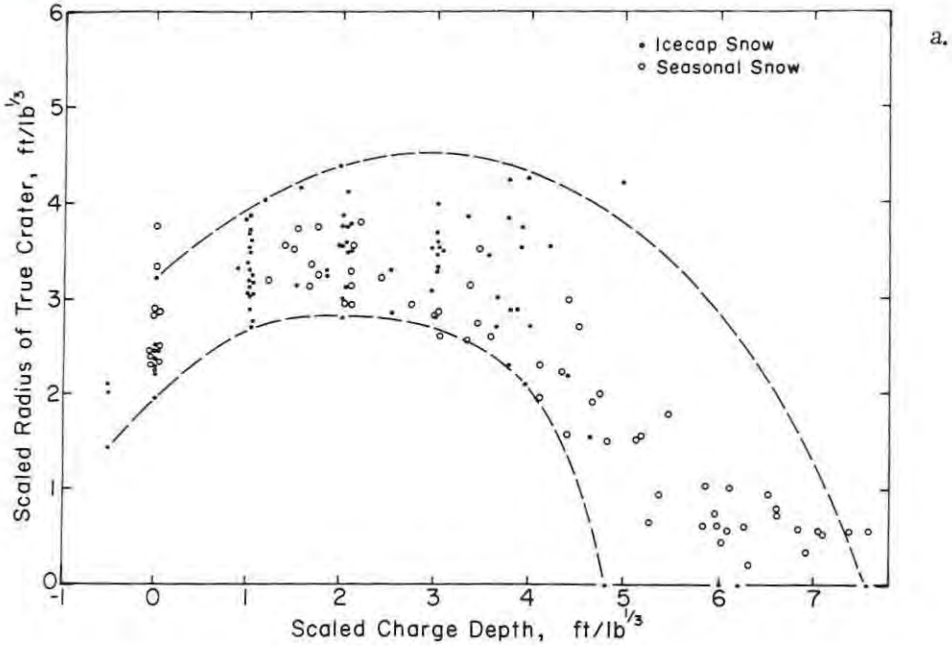
When a concentrated explosive charge is detonated in air above a snow surface a pressure wave propagates spherically, eventually making contact with the surface and reflecting from the surface. Reflection reinforces the pressure wave, but a snow surface is less effective than a rigid surface in producing this reinforcement. Figure 3 gives relationships between incident pressure and reflected pressure at normal incidence for a snow surface and a rigid surface. The reflected wave travels through air that has been compressed adiabatically by the incident wave, and since this allows it to travel faster than the incident wave it can overtake and fuse with the incident wave for a certain range of incidence angles, as illustrated in Figure 4. This effect causes the airblast pressure at the snow surface to vary with distance and with height of burst as shown in Figure 5.

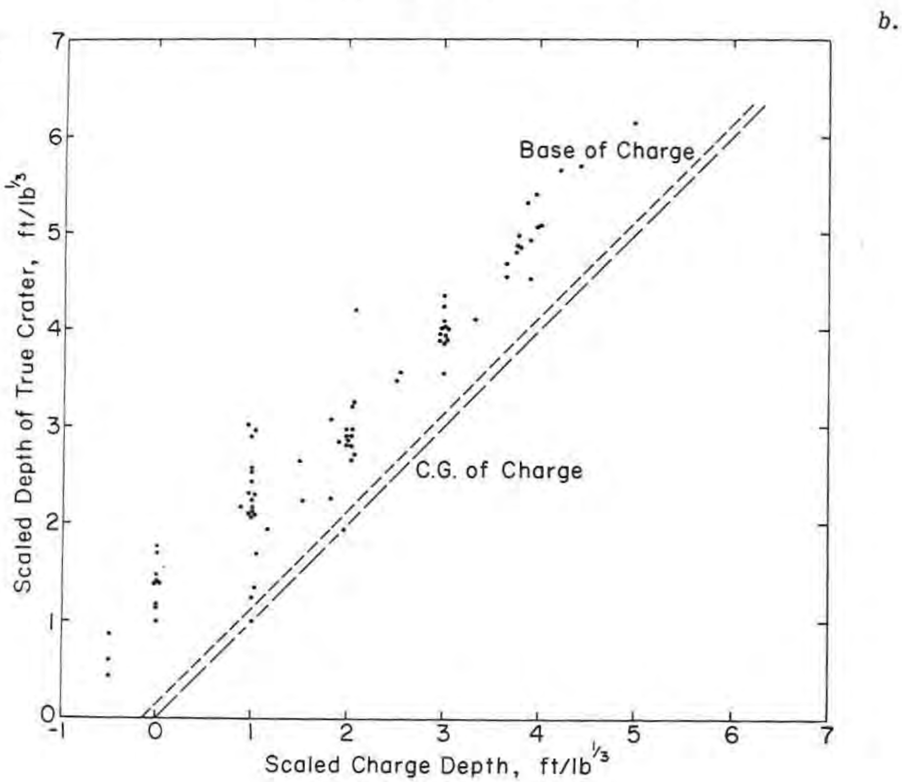
Release of Avalanches by Explosives

The exact mechanism by which explosions release avalanches is not known, but some relevant factors can be identified.

First of all, an explosion propagates a stress wave that can travel through the air above the snow, through the snow itself, or through the ground beneath the snow. The stress wave abruptly displaces particles in the material it traverses, producing strains and accelerations. Secondly, the explosion generates a bubble of rapidly expanding gas that can thrust against confining material and can pressurize cracks and pores.

The general aim is to destroy the stability of an inclined layer of snow by increasing stress, by decreasing strength, or by a combination of the two.





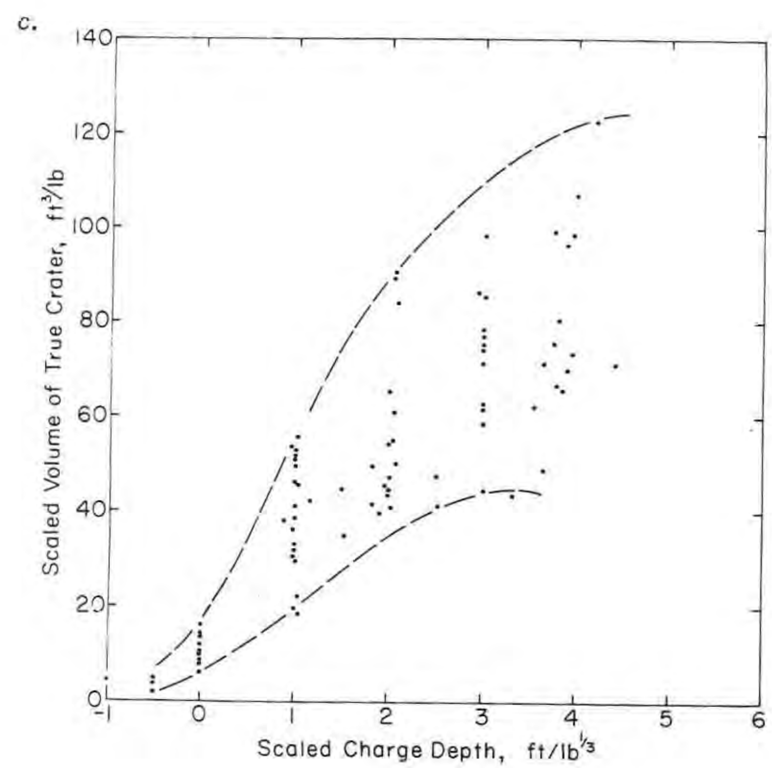


Figure 2. Scaled crater data for snow. (Basic data from Livingston 1968 and Fuchs 1957.)

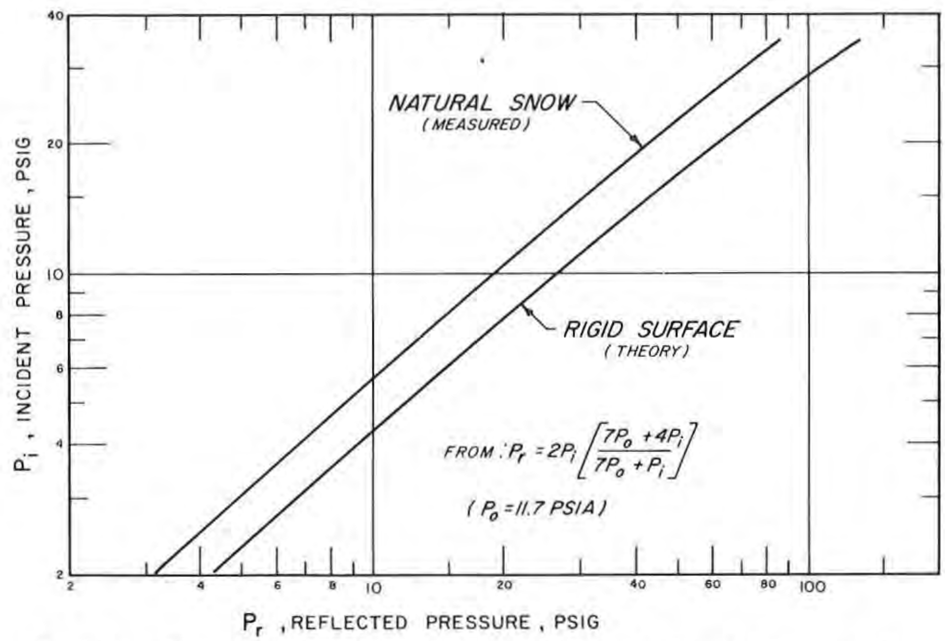


Figure 3. Relations between incident pressure and reflected pressure for normal reflection of airblast from a rigid surface and a snow surface. (From Ingram 1962.)

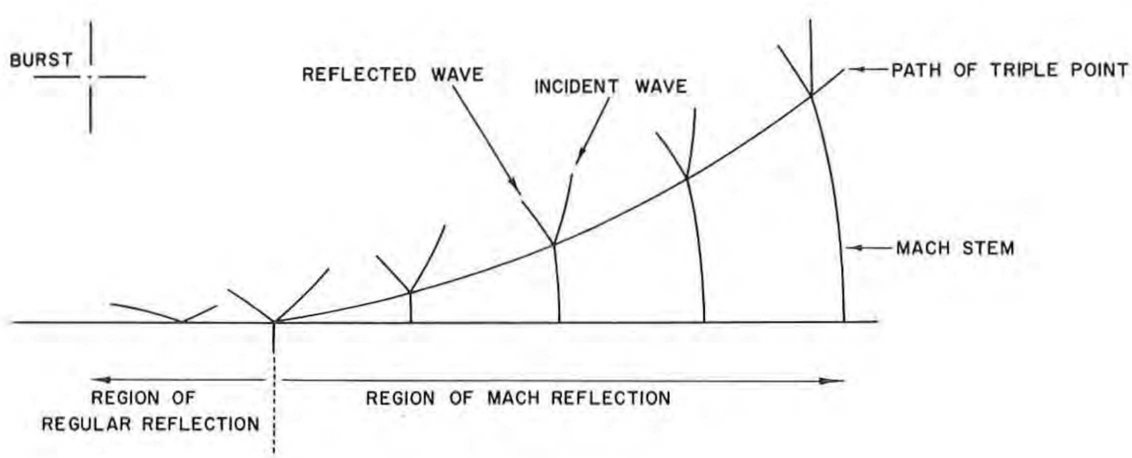


Figure 4. Wave fusion and mach front progression for airblast over a reflecting surface.

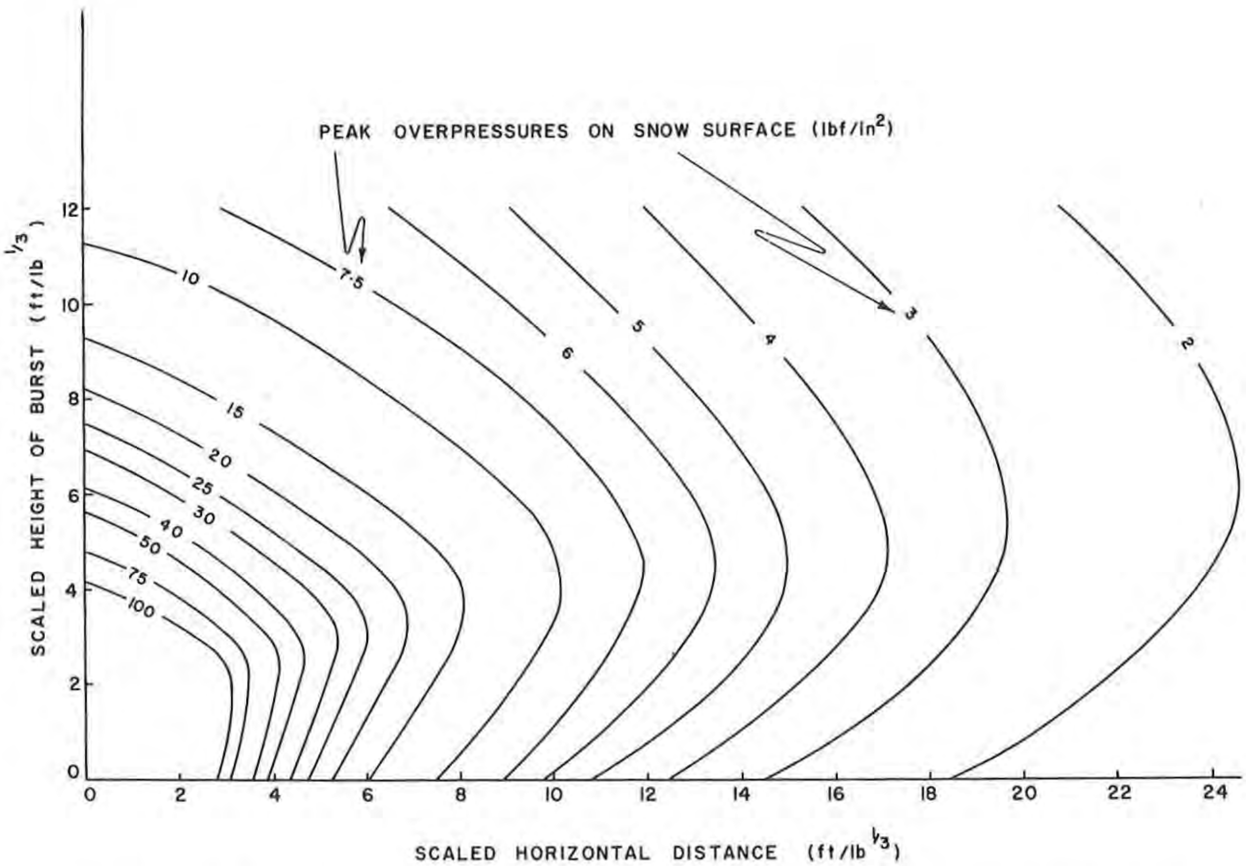


Figure 5. Peak overpressures related to height of burst and distance from ground zero for airblast over snow. (After Ingram 1962.)

One very positive method of attacking the snow slope, especially when it consists of a coherent slab, is to cut a swath in a direction normal to the fall line, thereby interrupting the continuity and at the same time applying downslope thrust, airblast, ground shock, and ejecta impact. This approach calls for either a line of point charges or a continuous linear charge, and there is no doubt that the charges should be set at optimum depth, which for practical purposes can be taken conservatively as 3 $ft/lb^{1/3}$ (striking a balance between maxima for crater radius and crater volume and allowing for variation of snow type). In practice, charges would probably be set within about 1 ft of the base of the snowpack, and optimum charge weight W_{opt} (lb) would be calculated for the actual overburden depth H (ft) using the relationship $W_{opt} = (H/3)^3$. A simple rule for estimating spacing of point charges would be to take spacing equal to twice the charge depth. This method is positive, but it is not economical and in many cases would amount to overkill.

A very different method is to apply airblast to the snow surface, thereby creating a brief (~ 10 msec) increase of normal stress and downslope shear stress. With this method much of the explosive energy is dissipated in air, but the loading is relatively widespread. A quantitative approach to airblast loading is difficult, since the release mechanism is not fully understood and the required overpressure varies considerably with the type of snow and its inherent stability. A simple way of looking at the problem is to consider the airblast as a transient normal pressure which at distant range translates to an increase of downslope shear stress and an increase of intergranular friction, the latter effect being partly offset by pressure rise in the pores of the snow (pressure rise in the pores lags and attenuates with increasing distance from the surface). Some indication of a lower limit of useful airblast overpressure is provided by sonic booms from aircraft, which sometimes release unstable snow with widespread overpressures of approximately 2 lbf/ft^2 (1.4×10^{-2} $lbf/in.^2$).

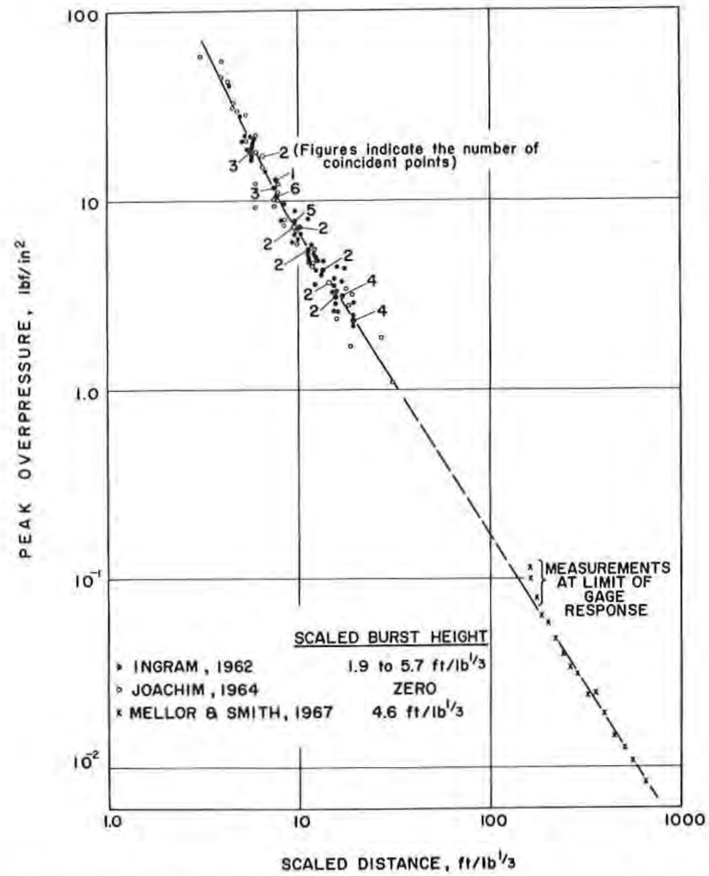


Figure 6. Airblast overpressure above a level snow surface (all data adjusted to 6000 ft altitude).

This pressure level is equivalent to rapid addition and removal of 4 to 5 in. of low density (0.1 g/cm^3) snow at typical release zone slope angles. For more positive results from airblast it might be better to plan on covering the target zone with at least 0.5 $lbf/in.^2$, which is rather higher than the nominal ground pressure of a man on skis. With a burst height of about 5 $ft/lb^{1/3}$, pressures exceeding 0.5 $lbf/in.^2$ would spread to a radius of almost 50 $ft/lb^{1/3}$ (Fig. 6), i.e. a 1-lb charge fired about 5 ft above the snow surface would cover a target zone 100 ft in diameter, or an 8-lb charge fired at a height of about 10 ft would cover a 200-ft-diameter zone. With a charge fired at the snow surface, the coverage radius might be about 25% lower than the values given, but the charge will also form an appreciable crater (Fig. 2).

A third possibility is to fire charges at the base of the snowpack, using the underlying ground to spread the shock and limiting charge size so as to suppress venting and thereby utilize gas expansion within the snow cover. One potential advantage of this technique is that shock attenuation in rock is much less than in snow or air (Fig. 1), so that ground disturbance ought to be significant over a relatively wide area. The other feature is that gas expansion can be used to exploit planes of weakness and to pressurize the pores of the snow, the aim being to "heave" the snowpack and to lower the shear strength by increasing pore pressure. With this method, charges would be laid in contact with the ground and charge size would be scaled to give critical weight W_{crit} (lb) for the prevailing overburden H (ft) using the relationship $W_{crit} = (H/7)^3$.

Possibilities for Technical Developments

There are a number of possibilities for innovation in avalanche blasting, but it would be desirable to first make a systematic study of the relative effectiveness of airblast, hydrodynamic disruption, undersnow shock, undersnow gas expansion, and ground shock. Without such information, it is difficult to assess various types of explosives and blasting devices, or to select optimum methods of charge emplacement or projectile fuzing. However, it may be worth mentioning some techniques that do not seem to have been tested for avalanche blasting.

Over the past decade there have been considerable developments in the production and use of explosives and blasting agents based on ammonium nitrate, particularly in slurry form, and there has been renewed interest in liquid explosives, especially those based on nitroparaffins and hydrazines. Some of these materials are blasting agents that contain no high explosive ingredients and are not cap-sensitive, while other materials consist of two separate non-explosive components that are blended into an explosive immediately before use. These characteristics permit the materials to be transported, handled and stored under more relaxed regulations than those that cover Class A explosives.

The availability of cheap and safe fluid explosives opens up some prospects for novel applications and emplacement techniques in avalanche work. For example, plastic pipes could be laid from a safe and sheltered standpoint to an avalance release zone before the first snowfall, and fluid explosive could be loaded hydraulically as required during the winter, using gravity flow or pumping. The blasting cap for each pipeline could be either pre-placed or in the charge chamber introduced with the hydraulic load. The charge chamber could be designed to give a concentrated charge, a linear charge, or a dispersed charge, and it could be set either at ground level or at the top of a post rising above snow level.

At places where frequent repetitive avalanche blasting is required in a limited area, such as at a mine site in the mountains, a permanent installation of compressed air blasting equipment might have operational and economic advantages. With this type of system reusable airblasting shells would be set at ground level in avalanche release zones, with high pressure lines running to a centrally located multi-stage compressor. The shells would fire automatically by remote control when a pre-set pressure level (around 12,000 $lbf/in.^2$) was imposed by the compressor. The blasting elements installed on the snow slopes would be completely inert until activated by the controller. Initial cost of such a system would be relatively high, but operating costs would be low.

The technical effectiveness of gas blasting could be tested easily and cheaply by using carbon dioxide shells, which themselves could be used as a substitute for explosives in a pre-placement system. These shells contain liquid carbon dioxide, which is vaporized and discharged when an electrically actuated heater element is fired.

There are possibilities for development of a cheaper system of repetitive blasting using direct combustion of gaseous fuel/oxidant mixtures such as propane and ordinary compressed air. A system of this type would probably have a combustion chamber permanently installed at the blasting site, with rechargeable storage tanks for fuel and oxidant nearby. The chamber would be charged for each firing by remotely operated valves, and would be fired electrically with a "spark plug."

Permanent installations for avalanche blasting can probably not be justified in most areas under present conditions, but it seems quite likely that increasing recreational and industrial activity in the mountains could change the situation in the future. Pushbutton systems would be less entertaining than hand-charging or artillery fire, but they might be safer and more positive.

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Appendix A. Crater Data for Ice and Frozen Ground

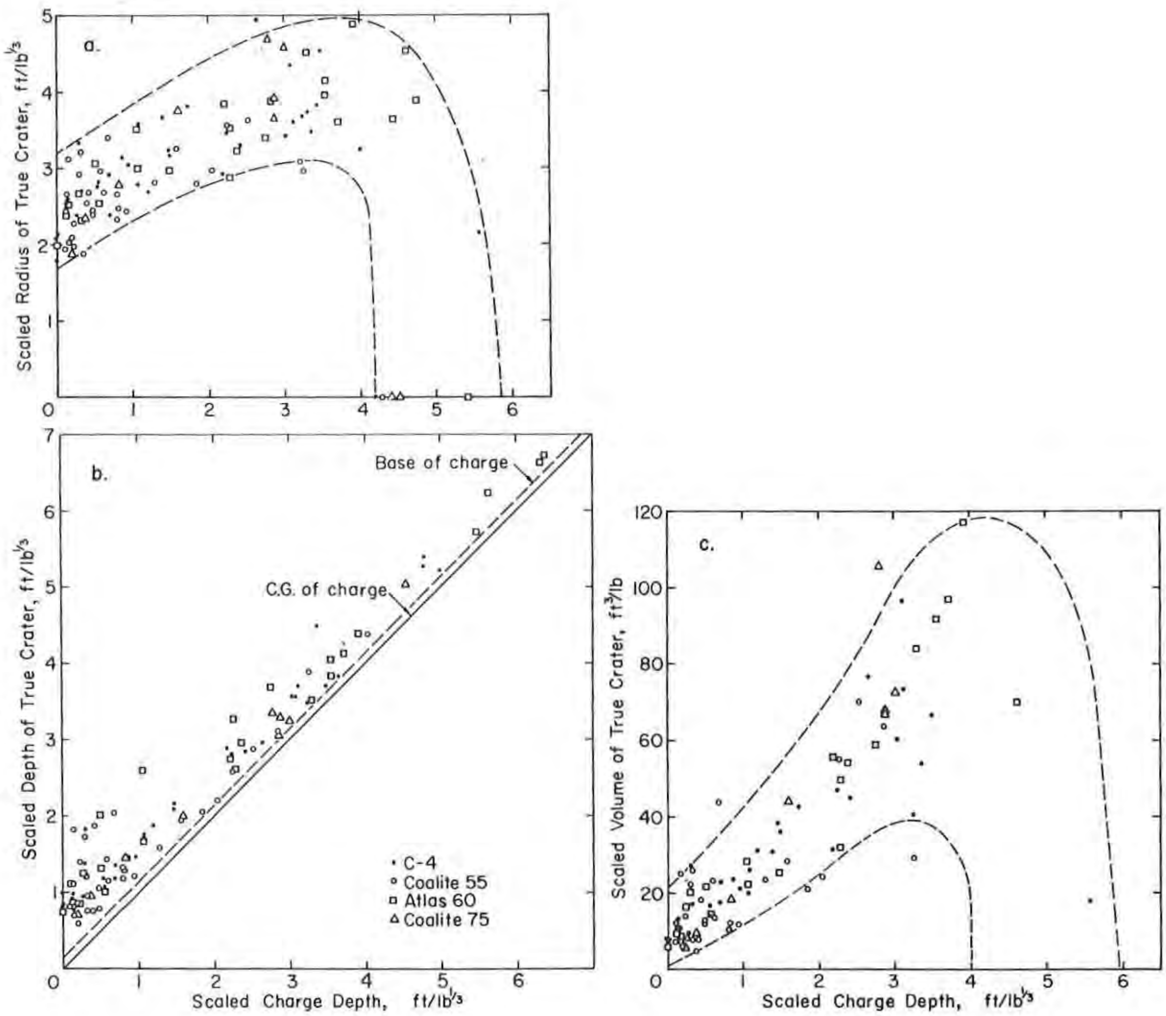

Figure A1. Scaled data for cratering blasts in massive glacier ice. (Scaled from test results by Livingston 1960.)

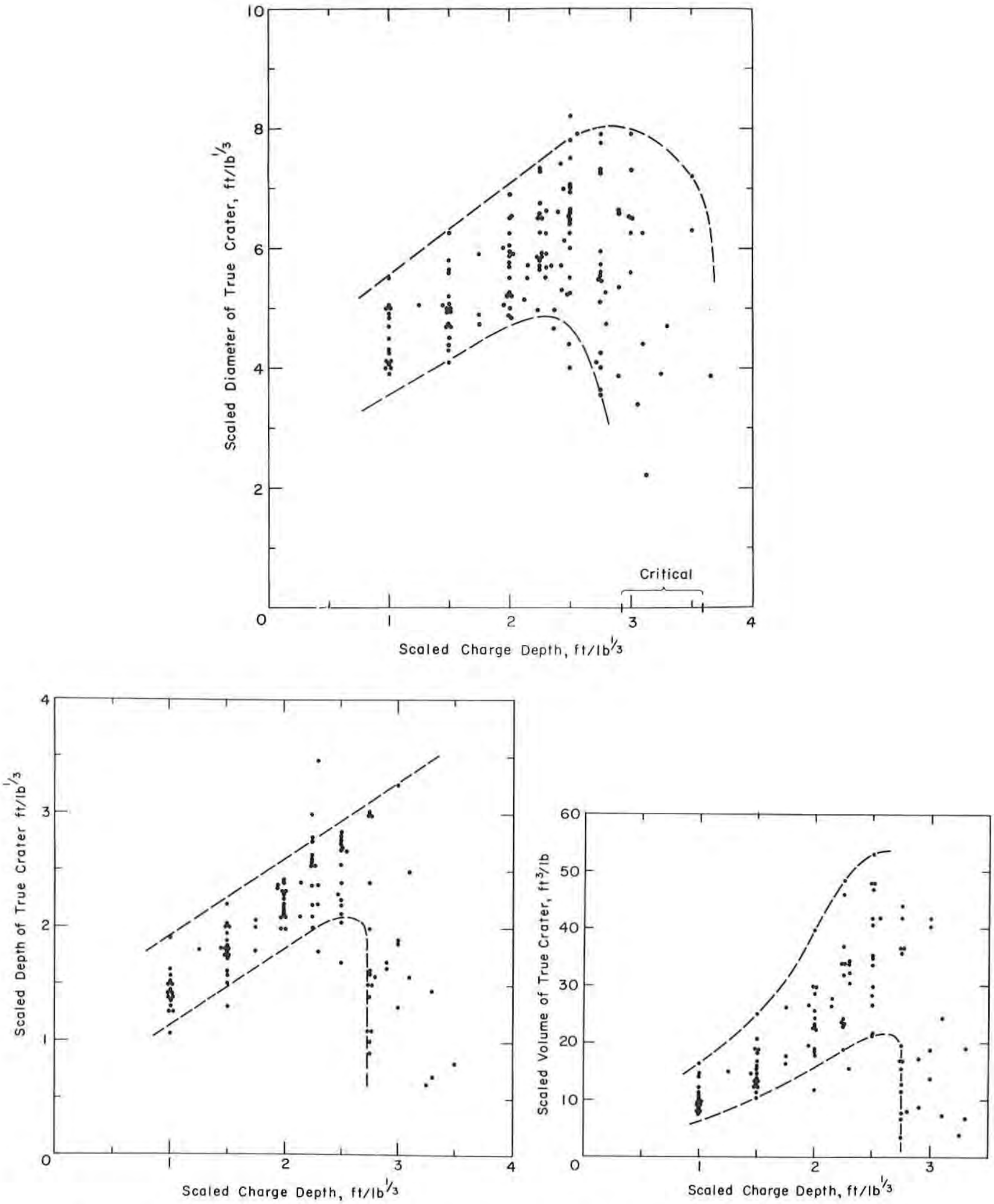

Figure A2. Scaled crater data for frozen silt. (Basic data from McCoy 1965, Mellor and Sellmann 1970, Mellor 1971.)

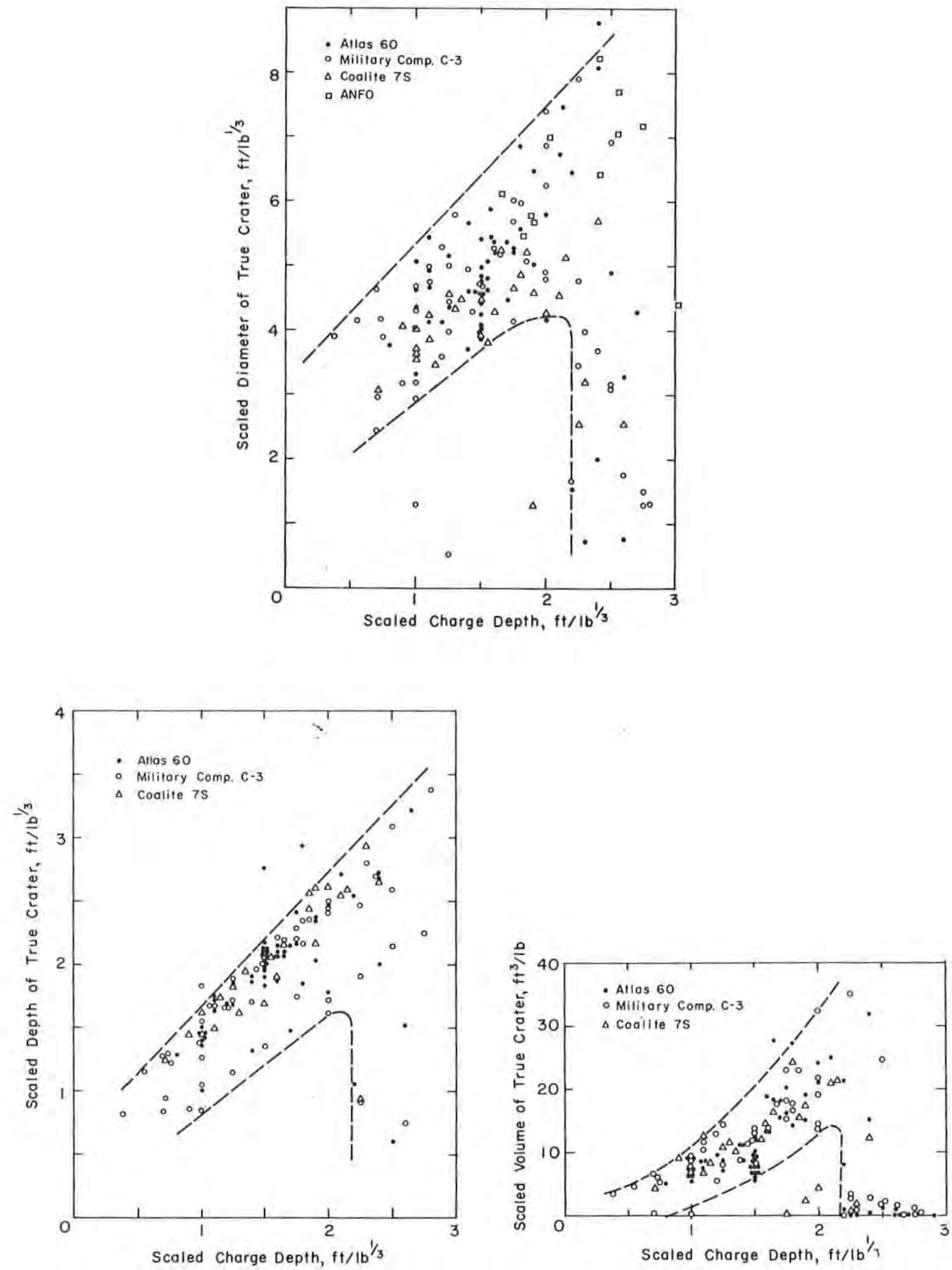

Figure A3. Scaled crater data for a frozen mixture of gravel and silt. (Basic data from Livingston and Murphy 1959, Mellor and Sellmann 1970.)