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SHOCK METAMORPHISM OF BASALT

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Exploration of the Moon's surface by the Orbiters and Surveyors has led to new support for the hypothesis that many lunar craters are generated by impact. However, these probes have also produced evidence for volcanism as a crater-forming process. Criteria for differentiating primary circular structures of impact and volcanic origins based on morphology and exterior deposits, as seen by the probes, have been advanced by many workers (Reference 1). Other investigators contend that many of these criteria are ambiguous, imprecise, or of multiple application. We must conclude therefore that the question of origin and distinction of lunar craters will not be solved solely on external appearance or comparison with terrestrial analogs.

Analyses of terrestrial craters of diverse origin have disclosed that those formed by meteorite impact are unique in that they always contain rock materials shock-metamorphosed by transient pressure waves whose amplitudes can exceed a half megabar. In contrast, no features attributed to shock action (e.g., shatter cones, coesite-stishovite, planar features, thetomorphs) have been reported from any recognized volcanic structures, such as calderas, maars, or diatremes, in which some gas explosive activity has operated.

The current interpretation of Surveyor data from chemical analyses of the surface veneer at the lunar touch-down sites indicates the presence of materials of basalt-like composition (Reference 2). If this is confirmed by results from future Apollo landings, then the ability to distinguish shocked from unshocked basalts will be of paramount importance in determining the origin and history of specimens returned to Earth and, ultimately, in establishing the relative roles of impact and volcanism in the development of lunar craters. As the time of the first landing approaches, unequivocal criteria for recognizing shock effects in basalt need to be determined and specified.

An obvious approach would be to compare basalts from terrestrial volcanic and impact structures. Unfortunately, of the 50 or more structures on Earth at which evidence of impact has been found (Reference 3), none are actually formed in pre-existing volcanic terranes although at some, "volcanic" rocks derived from shock-melting were emplaced during or after impact (Reference 4). Lonar Lake, a 1.8 km wide crater in basalt of the Deccan flows in India, has been considered as impact in origin (Reference 5) but, so far, none of the rocks from its rim show any direct signs of shock.

However, most of the distinctive features developed in rocks by shock pressures during meteorite impacts are also duplicated by underground nuclear explosions (Reference 6). Several crater-forming nuclear explosions in volcanic rocks, including basalts, at the Nevada Test Site (Reference 7) have produced effects which may also be typical of lunar surface materials subjected to high shock pressures generated by crater-forming meteorites (Reference 8). Study of shock-induced changes in basalt from one such explosion thus provides criteria for recognition of shock metamorphism in any fine-grained basic volcanic rocks obtained from Apollo missions.

THE DANNY BOY CRATER

The DANNY BOY event (March, 1962) involved detonation of a 0.42 kiloton nuclear device at a depth of 33.5 m in a volcanic flow series capping Buckboard Mesa, Nevada Test Site (Reference 9). The explosion produced a crater of 66.5 m diameter and 19 m apparent depth (Figure 1). Ejecta ranged from fine pebble fragments to blocks up to 6 m. Most ejecta show no outward signs of change but about 1% exhibit intense shock damage. Visibly shocked ejecta appear as (1) less dense, lighter-colored crushed pieces, (2) blebs of dense, dark-green radioactive glass, coating fracture surfaces, and (3) low density masses of vesiculated rock in which feldspar crystals are destroyed (Figures 2, 3, and 4).

The rock material at shot depth, termed basalt for engineering purposes, is actually an andesitic basalt composed of 60-70% andesine-labradorite (An_{47-59}), 10-25% olivine (Fa_{27-30}), 1-2% augite, 5-10% interstitial glass (altered), 2-5% titaniferous magnetite, and 1-2% calcite (Reference 10). The plagioclase occurs mainly as laths 0.05 to 0.3 mm in length that exhibit trachytic texture (Figure 5a). Chemical zoning in the plagioclase, although not evident in the microscope, is disclosed by electron microprobe analysis which indicates moderate variation in the Ca/Na ratio across crystals and a marked increase in potassium near their boundaries. Some of the plagioclase and most of the interstitial glass have been strongly altered to montmorillonite. The olivine grains are actually multiphase systems (Figure 5b). Olivine initially crystallized from the lavas has a clear light yellow-green color and occurs as single larger grains and clusters of smaller grains. The outer regions of some olivine grains grade into a paler yellow-green phase, showing a decrease in Fe and Mg content and a few percent of Ca, which appears to be a pyroxene of uncertain identity presumably formed by reaction between the olivine and melt prior to plagioclase crystallization. Many olivine grains contain inclusions of euhedral magnetite. Most olivine individuals were altered to red-brown iddingsite along cracks and in patches with well-defined boundaries. An iron-rich montmorillonoid (nontronite or celadonite) develops preferentially near contacts with plagioclase. A very dark, subopaque phase, distributed in diffuse patches mainly around magnetite, has an index of refraction close to 1.49 and may be saponite.

FIRST STAGES OF SHOCK DAMAGE

The first indications of shock-induced changes in DANNY BOY basalt appear as irregular fractures and/or cleavage in plagioclase laths (Reference 11) (Figure 5c). Microscope examination of ejecta which display no visible signs of internal shock damage (Reference 12) confirms that most fragments that experienced pressures below 300 kb are not significantly different from unshocked basalt. Fragments having a gray-green color lighter than unshocked basalt of similar texture are more likely to contain numerous tiny fractures (Reference 13). A few plagioclase laths in many of these samples contain thin, criss-crossing (or parallel to the short dimension) planar markings (Figure 5d) which superficially resemble the planar features observed in shocked quartz and feldspars. These markings are present, however, in laths in unshocked Danny Boy samples and apparently are a growth feature produced during crystallization.

Postshot drilling at DANNY BOY demonstrated that rock immediately adjacent to the wall of the lower half of the expansion cavity, although ruptured, experienced only moderate microfracturing of plagioclase and olivine (Reference 14). Glass and vesiculated rock are absent along this wall. Apparently, intensely shocked rock and melt, which should line the cavity as it grows, were ejected from the cavity when it vented during cratering. The rock remaining in place behind the wall represents shock damage below 300 kb.

Thus, for lower shock pressures (50-300 kb) the only useful criterion for shock damage seems to be an unusual increase in microfracturing but, unless comparison can be made with unshocked equivalents from the same rock units to determine the pre-existing degree of microfracturing, it may be impossible to verify any abnormality.

Plagioclase should convert to isotropic feldspar or maskelynite while retaining its original crystal outlines (thetomorphs) within the pressure interval between 335-470 kb (Reference 15). Such thetomorphs have not been observed in ejecta samples collected at DANNY BOY, even though they were probably formed in a small fraction of the ejecta. Maskelynite has been produced experimentally in basalt taken from the DANNY BOY site (Figures 6a and 6b) by the implosion tube method (Reference 16) (see Appendix I); the associated olivine is strongly fractured and displays both the undulatory extinction and mosaic structure of disoriented domains observed by Carter et al. (Reference 17) in experimentally shocked olivine. Thus, extrapolating from the implosion tube experiments, thetomorphic feldspar and deformed ferromagnesian minerals may be expected to characterize intermediate levels (300-500 kb) of shock damage in basalt samples from lunar impact craters.

EFFECTS FROM INTENSE SHOCKS

Above an estimated 500 kb (Reference 18), the basalt undergoes drastic alterations of physical and mineralogical properties which greatly change its megascopic appearance. Ejecta fragments are noticeably lighter in weight owing to development of numerous vesicles which show considerable systematic variations in diameter even in small hand specimens. Typical vesicle diameters measured in several samples range from 0.1-0.3 mm to 0.5-1.0 cm over distances of 10 cm. The positions of the original plagioclase laths are now occupied by irregular-shaped blebs of yellowish-gray material and darker granular masses apparently represent olivine crystals. The overall fabric of the basalt thus remains intact: even though the feldspars and some olivines have experienced changes in shape, they preserve their relative spatial positions.

The extent to which physical properties are modified by intense shock pressures and associated heat effects is indicated by comparison of measurements on an unshocked basalt and an equivalent sample shocked above 500 kb (Table 1). The range quoted for the U.S. Geological Survey measurements encompasses a variety of flow units at Buckboard Mesa, ranging in character from dense through vesicular to vuggy or cindery materials. Some of the values for the unshocked basalt fall outside the U.S.G.S. limits because of differences in measurement procedures.

In all vesiculated samples, plagioclase is more or less completely melted (Figures 6c and 6d), destroying all crystal boundaries. Some clear glassy areas contain minute blotches of a birefringent material recognized as a micaceous phase derived from the montmorillonite alteration product. This layer lattice mineral thus is more resistant to isotropization or melting than the feldspar (Reference 19).

In the first stages of melting and vesiculation, many olivine grains shatter along regular (Figure 7a) to irregular fractures (Figure 7b), producing fragments which disperse mechanically into the fluidized feldspar. Other grains become darker reddish-brown, generally inward from their boundaries, suggesting incipient decomposition (Figure 7c). This figure also shows close-spaced, linear features which resemble shock-induced planar features. It is believed however that these are an especially well-developed example of the lamellar growth features observed in unshocked olivines (see Figure 5b), along which alteration to

Table 1

Physical Properties of DANNY BOY Basalts

Property*	Shocked Basalt	Unshocked Basalt	U.S.G.S. Values†
Porosity (percent):	55	0 ± 0.4	0.7 - 18.5
Permeability (darcies):	2.15	0	—
Matrix Density (g/cc):	2.754	2.874	2.79 - 2.84
Bulk Density (g/cc):	1.03	2.72	2.47 - 2.70
Hardness (Mohs):	3.4	5.6	—
Dilatational Velocity (m/sec):	3,730	5,340	4,130 - 5,830
Shear Velocity (m/sec):	—	3,170	2,530 - 3,130
Young's Modulus (kg/cm^2):	2.46×10^5	7.61×10^6	$9.45 - 25.0 \times 10^6$
Crushing Strength (kg/cm^2):	1,025	46,500	35,000 - 81,000
Tensile Strength (kg/cm^2):	—	—	4,940 - 5,530

*Measurements of shocked and unshocked basalt samples from the explosion environment made under supervision of Dr. Harold Overton, Dept. of Chemical Engineering, University of Houston, Houston, Texas.

† Unpublished measurements made by personnel of the U.S. Geological Survey, Denver, Colorado; includes samples from several flow units.

iddingsite occurs preferentially. Rarely, shocked olivine grains display distinct planar fractures and other lamellar structures (Figure 7d) which presumably were produced by the transient pressure waves. Distinct mosaic structure develops in some larger olivine grains but most grains still show only uniform extinction in cross-polarized light.

At this shock level there was little interaction between melted plagioclase and the crystalline olivine fragments. Quenching apparently was rapid (seconds to minutes) and flow was confined to the immediate region of each feldspar mass, with only minor mixing of adjacent masses. Flow lines visible within individual masses are of lengths consistent with pre-shock crystal dimensions. Concentric flow rings are particularly common around vesicles.

Electron microprobe scanning photos provide a graphic display of melting, flow, mixing, and chemical reactions in the vesiculated basalts. Calcium in the anorthite molecule sharply delineates the plagioclase laths of unshocked basalt (Figure 8a). As a consequence of melting, glassy grains of plagioclase appear as shapeless masses which display some variation in Ca concentration (Figure 8b). Microprobe traverses across these masses show erratic variations in Ca, Al, and Si, which can be explained by intimate contortion of the zoned plagioclases during highly localized flow and by possible minor mixing at boundaries. Microprobe analysis confirms this irregular pattern but also reveals that potassium becomes more uniformly distributed throughout the clear glass in contrast to its tendency to concentrate within outer zones of the unshocked feldspars. Concentrations of K_2O as high as 6.5% have been measured in some glassy masses. Microprobe scanning for Ca, Mg, and Fe at olivine sites indicates a thin calcic rim to form around some fragments; probe traverses confirm this but show the interiors to still be relatively constant in Fe and Mg.

With increasing shock damage, olivine crystals comminute further and disperse in the feldspar melt, which itself continues to spread out in formless patches having variable Ca content (Figure 8c). The number of individual olivine fragments becomes at least 10 times greater than normal for unshocked basalt. Olivine becomes increasingly darker red-brown and less translucent, and the bright second order birefringence colors characteristic of unshocked larger grains are replaced by a dull orange-brown. Most small fragments are still recognized as olivine (Reference 20) but a few appear to have interacted with the melt to produce poorly crystalline material marked by a very weak birefringence (Figure 9a). Microprobe analysis of areas containing this material show wide variations in Na, K, and Ca from the feldspars and Fe and Mg from olivine. Although not resolved visually in the microprobe optical system, some masses within such areas are a brownish, granular feldspar glass, others are degraded olivine, and still others are apparently reaction products containing varying amounts of Na, K, and Ca in association with Fe and Mg. Magnetite, noticed as opaques and readily distinguishable with the microprobe, remains stable except for some peripheral decomposition into phases such as hematite.

MAXIMUM SHOCK DAMAGE

In the highest stages of shock before melting of the ferromagnesian minerals, the olivine grains break into myriads of tiny fragments that spread throughout the plagioclase melt (Figure 9b). Judging from the areas of clear patches exposed in thin sections, unmixed plagioclase glass now occupies only about 10-20% by volume of rock, in contrast to the 60-70% occupied by feldspars in unshocked basalt.

The larger olivine grains are now a deep reddish-brown where still translucent (Figure 9c). Their outer areas particularly become very dark and subopaque. In bright transmitted light, these areas appear blotchy as the opacity varies. In reflected light, parts of the dark areas can be identified as the magnetite grains observed in unshocked olivines. The rest of the areas presumably correspond to iddingsite and other alteration products, without however the sharp boundaries noted in unshocked equivalents. Microprobe analyses show Fe and Mg to be more uniformly distributed throughout these grains than was the case for unshocked olivines. The measured FeO content in many small dark olivine grains surrounded by feldspar glass often drops to values as low as 10% compared with values of 25-30% found in unshocked basalts. Analysis of the adjacent melt indicates a relative enrichment in iron.

The progressive darkening of olivine results from decomposition in which the iron is released as a discrete phase to form clots up to colloidal sizes. Sometimes these clots grow into spots visible in the microscope (Figure 9d). A similar effect has been described by Chao (Reference 21) in other shocked ferromagnesian minerals and is also found in biotites and amphiboles in volcanic rocks or xenoliths (Reterence 22). This process involves oxidation leading to magnetite or hematite. Sclar (Reference 23) reports that metallic iron developed in experimentally shocked olivine and in meteoritic olivine by incongruent, shock-induced melting under reducing conditions. For DANNY BOY samples, isolation of individual grains and rapid quenching favor reduction so that free iron could be a possible product (Reference 24).

In one sample in which vesicles reach 1 cm in diameter and constitute over 60% of the bulk volume, the walls between vesicles consist of stretched and flowed clear plagioclase glass containing blackish, opaque grains (Figure 10a). These grains occasionally show traces of recognizable olivine but now are largely converted to iron oxide (magnetite?) plus a residue of unknown identity. Locally, iron from the grains has stained the immediate regions of the surrounding plagioclase glass.

In sharp contrast, in several samples some fragmental olivine grains remain free of darkening decomposition products. Many still retain near normal high birefringence. Others show notable reductions in birefringence so that interference colors are approaching 1st order yellows. A few grains are nearly isotropic.

Rarely, individual olivine grains are seen to undergo complete isotropization without loss of shape (Figure 10b). The resulting grains show no birefringence or interference figures. The grain illustrated contains bubbles and cooling cracks that suggest it was momentarily fluid before quenching to a glass. The dark band on the left in Figure 10b represents a zone of iddingsite also transformed to glass.

The section of a square crystal (Figure 10c) in the corner of a larger disrupted square enclosed and penetrated by a glassy phase shows up in uncrossed nicols as a dark, translucent, reddish-brown mass which is devoid of birefringence. From its appearance, I tentatively identified it as a magnetite grain. However, microprobe analysis proves it to be almost free of iron but rich in silver. Owing to absence of detectable sulphur, this crystal may have been native silver present as a minor constituent in the basalt. More likely, it was a crystal of argentite shocked during the explosion and intruded by melt without itself being dissolved (with loss of shape). The globular markings within this square phase may represent regions of decomposition in which the sulphur volatilized or "boiled off" prior to quenching of the crystal and its surroundings. This interpretation admittedly is speculative.

Carter et al. (Reference 25) state that recrystallization characterizes olivines shocked above 450-500 kb. Good examples of this are rare in most DANNY BOY samples but recrystallization is well-developed (Figure 10d) in the most heavily shocked ejecta in which residual temperatures were high enough to promote this process.

The poorly crystalline, low birefringent to isotropic material previously mentioned now constitutes 40-60% of the dark substances. Microprobe scanning of this material shows it to contain Fe and Mg in co-association with K, Na, Ca and Al (Figures 8e and 8h) but the composition is highly variable. Most of the material can be identified by microprobe analysis as granular, translucent feldspar glass, generally enriched in K_2O and containing small, variable amounts of FeO and MgO. However, much of the remainder consists of 2-5% FeO plus variable amounts of CaO, MgO, Al_2O_3, SiO_2 and alkalies in which the Na_2O/K_2O ratio varies between 0.60-0.70, compared with 0.90-1.90 in alteration products of unshocked basalt.

X-ray diffraction analysis of clots of granular material from one sample shows a single weak principal line of plagioclase, two weak lines assigned to olivine, and the following group of lines: 3.198 A; 2.973 A; 2.125 A; and 1.410 A. These lines closely fit the dA pattern of the pyroxene omphacite [(Ca, Na) (Mg, Fe^{+2}, Fe^{+3}, Al) Si_2O_6] (Reference 26). This identification could not be verified by index of refraction measurements owing to the extremely fine sizes of this slightly birefringent material and its dispersion within the plagioclase glass.

Inspection at high magnification (1000x) shows, in addition to specks assumed to be this pyroxene, outlines of larger granular masses with higher birefringence which appear to be broken olivine fragments in process of reacting with the feldspar (Figure 11a).

I interpret the crystalline phase to be a chemical reaction product between olivine and plagioclase melt leading to a pyroxene-like substance which did not organize into a well-crystallized state in the brief period of high temperature activity. Temperature within a plagioclase melt formed by shock pressures above 500 kb would exceed 1600°C (Reference 27) but rapid cooling of small ejecta fragments would quickly suspend incipient reactions. Such a product would be expected from reaction between the Ca-Na feldspar and the Mg-Fe olivine. Because of the brief time interval before quenching, insufficient for diffusion to remove one or more elements and for equilibrium to be attained, abnormal amounts of potassium may be incorporated in the phase and atypical Ca/Na ratios would indicate departures from normal omphacite compositions. The fact that omphacite is the stable pyroxene at the high pressures of the upper mantle (Reference 28) does not prove that it is the expected dense form produced by shock (Reference 29). Its occurrence in the most strongly shocked basalts, if real, is probably more a matter of chemical composition than of thermodynamics or kinetics.

Chao (Reference 30) notes that general melting and mixing of shocked quartz-bearing granitic rocks begins above about 500 kb. The threshold pressure for melting of the feldspars in basalt may be somewhat higher (Reference 31). Small patches of quenched melt (Figure 11b) occasionally are encountered in the vesiculated samples. This brownish glass shows swirls and colored streamlines marked by variations in tints attributed to iron. Microprobe scans indicate Ca and Al to be distributed throughout the glass, which implies considerable mixing of fluidized plagioclase masses. The Fe and Mg, however, are concentrated in certain areas within the glass and Si is even more variably distributed. This pattern suggests that olivine dissolves in the feldspar melt but its released elements fail to disperse uniformly before quenching. Sometimes, ribbons of Fe-rich material can be seen extending from patches of brown-tinted glass as the molten olivine is carried into the feldspar melt.

The distribution of elemental components is more uniform in the glass than in the dark, poorly crystalline material. This material is characterized by both chemical and mechanical disequilibrium to a degree seldom observed in natural rocks and glasses. Broad, erratic variations in element distribution, lacking obvious correlation with phases visible in the microscope, appears to be another criterion for shock damage.

Chao states that shock vaporization of silica-rich rocks takes place above 600 kb (Reference 32); this value is probably higher (perhaps 800 kb) for basalt. The mechanism of silicate vaporization by shock has not yet been established. Most terrestrial impactites contained water which, when shock-heated, flashes into H_2O vapor that forms expanding bubbles within any melt or fluidized grains (Reference 33). At higher pressures, silicates themselves may dissociate and vaporize, first at localized "hot spots" and then throughout the molten mass (Reference 34).

In DANNY BOY samples there is a close correlation between size of vesicles and degree of shock damage. Bubbles increase in diameter as plagioclase melts more completely and olivine breaks down and disperses. However, no petrographic evidence was found for silicate vaporization as the chief cause of vesiculation, even though this basalt, like most basic volcanic rocks, is low in water of crystallization. DANNY BOY core samples obtained prior to the explosion contained 0.42 - 0.78% H_2O, probably introduced into microfractures as groundwater. Additional water may have accumulated around the shot point during emplacement hole drilling or from dehydration of sealing grout.

If silicate vaporization were the primary cause of vesiculation, then comparison of the chemical compositions of unshocked and vesiculated basalts should expose significant differences in the more volatile components. Results of analyses for major element content in several unshocked and shocked samples are recorded in Table 2. The differences are well within the limits of variation noted in Buckboard Mesa basalts. Although all samples came from the same flow unit at shot depth, the changes were too small to substantiate any real volatilization of the alkalies. It is concluded that vesiculation of DANNY BOY basalt results principally from outgassing of adsorbed water and silicate vaporization plays only a minor role as general melting commences. If water is scarce in near-surface lunar materials, rocks vesiculated by impact-related shocks may be rare to absent, whereas rocks vesiculated by volcanic degassing processes may be commonplace.

MEASUREMENTS OF SHOCK DAMAGE IN MINERALS

Index of Refraction

Changes in refractive indices of constituent minerals provide one quantitative assessment of shock metamorphism of the DANNY BOY basalts. Measurements of maximum and minimum indices of selected mineral phases, made by oil immersion in sodium vapor light, are summarized in Table 3. Precise values were difficult to obtain for alteration products in unshocked minerals and especially

Table 2

Chemical Analyses of DANNY BOY Basalts

	Unshocked		Shocked			
Element As Oxide (%)	DB 2-2*	DB 2-3†	DB 5-A*	DB 5-C†	DB-5-C† Glassy	DB 5-L†
SiO_2	53.9	56.4	54.6	55.0	56.0	55.2
Al_2O_3	18.2	18.35	17.9	17.84	17.97	17.82
$FeO + Fe_2O_3$	7.9	7.72	8.2	7.98	7.98	8.50
MgO	5.1	4.89	5.3	4.33	4.56	4.60
CaO	6.7	7.04	7.1	7.04	6.79	7.07
K_2O	2.3	2.63	2.0	2.51	2.55	2.53
Na_2O	—	3.54	—	3.54	3.59	3.64
TiO_2	1.2	—	1.2	—	—	—
		100.53%		98.24%	99.44%	99.36%

*Analysis by X-ray Fluorescence

† Analysis by Atomic Absorption

for dispersed, mixed, and variably decomposed phases from shocked samples. Where no limits of error are given, the values are considered accurate only to the third significant figure.

The lowest α and γ values obtained from unshocked plagioclase correspond to an andesine with An_{37} molecule. This composition is too sodium-rich when compared with analyses obtained by electron microprobe. The enrichment of Na and particularly of K in the outer parts of most of the plagioclase laths is responsible for the anomalously albite-rich content determined by the optical method. The lowest values obtained from plagioclase glass grains correspond to a composition of An_{42} to An_{46} for synthetic plagioclase glass (Reference 35). As shown

Table 3

Index of Refraction Measurements

	Category	α	γ	Remarks
I.	Plagioclase (Unshocked)	1.545*	1.554*	Lowest value; some grains as high as 1.551
II.	Plagioclase Alteration Product	1.51	1.53	Montmorillonite
III.	Olivine (Unshocked)			
	Clear	1.688*	1.725*	Composition of Fa_{30}
	Iddingsite	1.695†	1.740†	Variable
IV.	Olivine: Granular Alteration Product	1.62		Variable: Celadonite or Nontronite
V.	Olivine: Dark Alteration Product	1.48-1.49		Saponite?
VI.	Clear Plagioclase Glass	1.521-1.535*		Sometimes shows very weak birefringence
VII.	Blackish feldspar Glass	1.524-1.539*		In strong transmitted light, appears variable brownish-yellow
VIII.	Light Brown Granular Glass	1.56		May be equivalent to poorly crystalline chemical reaction product but index hard to fix; some may be feldspar glass with impurities.
	Dark Brown Granular Glass	1.62		
IX.	Shocked Olivine: Clear with High Birefringence	1.68-1.71		Uncommon
X.	Shocked Olivine: Asterism Grain #2	1.66-1.69		Near normal birefringence
XI.	Shocked Olivine: Asterism Grain #3	1.60-1.63		Dark, with inclusions
XII.	Shocked Olivine: Asterism Grain #4	1.528†		Inclusions; weak birefringence
XIII.	Shocked Augite	1.535†	1.555†	Pleochroic

*Precision to ±0.001 †Precision to ±0.002

by microprobe analysis, there can be sufficient homogenization of the feldspar melt in some samples to produce an average composition in this range.

Although clear, unshocked olivine has nearly constant index values, the associated granular and dusky materials showed somewhat variable indices indicative of differing degrees of alteration. Index variations measured in shocked olivine grains and in products derived by reaction and/or mixing between feldspar melt and olivine were even greater than those noted in unshocked olivine assemblages. Only greenish-yellow, clear olivine fragments retained indices near the values for unshocked materials. The indices obtained from large, hand-picked olivine grains from intensely shocked samples show a wide spread of values; birefringence in these grains is also reduced. The values for grain groups XI and XII, in particular, are well below the lowest ($\eta\alpha$) value of 1.636 characteristic of iron-free olivine (forsterite). Olivine glass of Fa_{30} composition should have a refractive index of 1.595 (Reference 36). The differences from grain to grain may result in part from variable shock damage. However, values below the limit for olivine glass Fa_{30} are believed to reflect even more the effects of initial impurities and alteration products which tend to redistribute chemically in the shocked grains. Note that the $\eta\alpha$ value obtained from one shocked augite grain is considerably lower than the lowest $\eta\alpha$ value determined from any normal augite (Reference 37).

X-Ray Diffraction Analysis

X-ray diffraction powder patterns made from both unshocked and shocked basalts provide a quick means of distinguishing the two states. All strong peaks characteristic of plagioclase appear in diffractograms from unshocked samples but the major olivine peaks fail to develop. These olivine peaks show up when heavy mineral concentrates from these samples are x-rayed, as does the strongest peak at a d spacing of 3.003 - 3.008 A for augite. The value of d_{130} can be used to fix the fayalite content of olivine (Reference 38). Olivine in the heavy mineral fraction gives an average d_{130} spacing of 2.791 corresponding to Fa_{39} in comparison with the Fa_{27-30} obtained by oil immersion. In diffractograms made from shocked samples, only the strongest plagioclase peak at d = 3.21 A survives and its intensity is reduced to about 10-20% of the unshocked equivalent. Weak olivine peaks for d = 2.53, 2.28, and 1.76 A are recorded in diffractograms from all but the most heavily shocked samples, in which that at 1.76 A disappears. A very broad "hump" develops in diffractograms from shocked basalts over the 2θ (Cu Kα radiation) interval between 16 and 34°; this is characteristic of most silicate glasses.

Asterism

This technique measures the distortion or break-up of the crystal structure of a single grain into variably disoriented micro-crystals and is a sensitive indicator of the degree of shock damage within an individual phase (Reference 39). Films showing the spots, streaks, or rings obtained by x-ray diffraction analysis of randomly oriented, rotated single grains of unshocked and shocked olivines appear in Figure 12. The three shocked grains show a progressive spread and coalescence of spots from left to right in direct correlation with their selection from parts of shocked samples that display increasing shock damage. The degree of asterism evidenced by these olivine individuals from the heavily shocked DANNY BOY samples is far greater than the maximum known from any mineral species from unshocked rocks stressed by volcanic or tectonic processes.

Lines from the d_{130} plane of olivine, although weak, could be measured on the x-ray asterism films. The values obtained for the olivine grain sequence, left to right, shown in Figure 12 are, respectively: 2.80 A (Fa_{50}), 2.79 A (Fa_{38}), 2.77 A (Fa_5), and 2.76 A. The last value falls below the value for pure forsterite. This systematic shift in d_{130} with increasing shock is interpreted to result from one or both of these factors: (1) distortion and/or breakdown of the crystal structure and (2) separation of an iron-rich phase (see Figure 9d) from the olivine lattice leaving a residue of magnesium-rich material. The anomalous value of 2.76 A, below that appropriate to pure forsterite, is consistent with the very low values of refractive indices measured on some of the most strongly shocked olivine grains.

Results of the measurements just described suggest a general test or scheme of analysis suited to recognition of shock damage in discrete particles present in lunar rocks or the lunar soil. The procedure would consist first of determining the indices of refraction of a grain, then x-raying it for degree of asterism, and finally obtaining its chemical analysis by electron microprobe. Once the mineral species and its composition are known, the presence of anomalous refractive indices for that composition will point towards possible shock damage. A pronounced degree of asterism should confirm the action of shock. Certain characteristic microfeatures, visible in the microscope, should add to the proof.

COMPARISONS WITH VOLCANIC GLASSES

Natural volcanic glasses, such as pumice and quenched basalt, will produce x-ray diffraction patterns similar in most respects to those derived from the intensely shocked basalts. Crystalline phases, including devitrification products, may give distinct peaks if present in sufficient quantity. However, these phases when extracted will show almost no asterism, in definitive contrast to such phases in shocked rocks.

Basaltic glasses (e.g., those formed from surface cooling of lava lakes) invariably contain Fe dissolved throughout the glassy phase, tinting it various shades of brown (Figure 11c). Except in the completely melted material, this coloration is absent in the feldspar glass formed in shocked DANNY BOY basalt. I have observed textures in pumice (Figure 11d) which resemble those in the early stages of shock melting of this basalt. However, pumices are silicic in composition and thus are chemically distinguishable from shocked basalt. Furthermore, flow lines in the clear glass of most pumices tend to be long and continuous (often extending well beyond the field of view at low microscope magnifications), in contrast to the localized flow confined to the region occupied by single melted crystals in the shocked basalt.

APPLICATIONS TO LUNAR CRATERING

If hypervelocity impacts are the major cause of the lunar circular structures, we can expect to find evidence of shock in some of the samples returned from Apollo landings. However, the proportion with clearcut, unequivocal signs of shock damage is likely to be very small. Examination of the pressure gradient around both impact zones and nuclear explosion centers indicates that less than 10 percent of the total volume of excavated plus ruptured rock will be subjected to pressures above 300 kb. Based on energy partition, the fraction melted will be even less (Reference 40). For basalt, completely melted rock comprises 1% or less and partly melted, vesiculated rock would make up only 2-3% (Reference 41). Well over 50% of the ejecta from an impact crater experiences only elastic waves, so that no damage other than large-scale tension fractures will be inflicted on the fragments. The remaining percentage of impacted rocks will show weak to moderately strong shock damage, recognizable only in those minerals which fail in diagnostic ways.

The above model applies to single impacts. If any part of the lunar surface builds up over time by accumulation of ejecta from many neighboring and distant impacts, the proportion of intensely shocked rocks in these deposits gradually will rise slightly. Subsequent impacts on this accreting surface will convert still more rock to strongly shocked states. Unless some of the previous shock effects are erased by these later impacts (Reference 42), the net result of multiple impacts over time on the lunar surface will be to increase the relative proportion and actual number of rock bodies containing diagnostic evidence of varying degrees of shock metamorphism. However, impact is primarily a comminuting process. Individual large blocks strongly shocked during one event may break up during ejection or fallback or can be further comminuted by subsequent impacts. If comminution tends to be more efficient near the line of impact penetration, the relative number of smaller individuals available for sampling on the lunar surface will be biased towards concentration of strong shock effects. These factors must be considered before any attempt is made to interpret lunar cratering history from statistical analysis of distribution of shock effects in the limited number of Apollo samples returned in the next few years.

SUMMARY

Drawing upon the DANNY BOY results, I conclude that the best evidence for intense shock metamorphism in lunar basalts will be pronounced asterism and anomalously low refractive indices in ferromagnesian minerals. Petrographic features resulting from rapid strain within constituent minerals may or may not be present. Compositional inhomogeneities, low Fe content, and lack of extended flow in melted tectosilicates also suggest a shock history. Unusual textures, typified by varying dispersal of tiny pieces of fragmented mineral grains, are still another criterion.

Basalts shocked at intermediate levels (300-500 kb) will record some shock damage such as mosaicism and undulatory extinction in ferromagnesian minerals. Planar features in plagioclase would be particularly diagnostic of shock. Some samples may contain thetomorphic feldspar or maskelynite. Basalts subjected to shock pressures below 300 kb will show mainly irregular fracturing of constituent minerals as the prevailing effect.

Some of these criteria apply also to other rock types proposed as possible lunar materials. Thus, if the lunar surface is predominantly chondritic or ultrabasic, shock effects in the ferromagnesian minerals (and any associated metal particles) will be conspicuous. If more silicic rocks occur in the Moon's crust, chances for recognizing shock deformation covering a wider range of pressures will improve if quartz, probably the most versatile indicator of shock damage, is present as discrete grains. Shock effects in the lunar "soil", which may be largely comprised of finer-size ejecta from impacts further comminuted by micrometeorites, can be detected if crystalline grains of 10 microns or larger are present. Only if the lunar crustal layers were primarily glass during the major periods of impact, would difficulty be encountered in deciphering a shock history in either vitreous or devitrified samples because a systematic study of shock effects in glasses has not yet been made.

Vesicular or glassy fragments, readily apparent to an astronaut's practiced eye, are among the most significant samples to be sought as evidence for the origin of lunar craters. If these samples consistently contain crystalline phases free of shock effects, it will be difficult to uphold impact as the main crater-forming process. The problem of origin of circular structures on the Moon must then be fully reconsidered in favor of some other, probably volcanic, process. If, instead, crystalline phases such as olivine and the pyroxenes frequently display conclusive evidence of shock damage in these samples, impact as a major lunar process can be considered established beyond question. Only its relative importance would remain to be determined.

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20. These commonly show low second order interference colors owing to thicknesses less than that of the thin section; such grains are usually the only birefringent, bright materials remaining in the otherwise isotropic section.

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33. I have observed alignment of vesicles in quartz grains from a quartzite shocked during the SEDAN nuclear cratering event in which the patterns produced are precisely those followed by fluid inclusions in grains within unshocked quartzite.

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rocks are held to be shock-induced melts by some investigators. Bubbles within them are generally absent or infrequent and small. This may mean that silicate vaporization did not take place or that continual flow and mixing destroyed those bubbles that formed.

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APPENDIX I

IMPLOSION TUBE SAMPLES

Experiments with the implosion tube method can conveniently shock small samples of rock or rock powders to peak compressive stresses from 300 to 500+ kb. for load periods up to 10 - 20 μ sec. Although reflected shock waves are produced as these waves encounter free surfaces, the resulting oscillations only unload the general state of compression without subjecting the samples to strong tensile stresses. The resulting shock damage in minerals or rocks is remarkably similar to damage experienced by these materials when affected by intense pressures from meteorite impacts or nuclear explosions.

I have given the details of the development and applications of the implosion tube method in my paper on Experimental Microdeformation of Rock Materials by Shock Pressures from Laboratory-Scale Impacts and Explosions (in Shock Metamorphism of Natural Materials, French and Short, Eds., Mono Press, Baltimore, 1968). To synopsize the essentials of the method as described in the paper: Steel or brass tubes, approximately 50 cm. in length and 3 cm. in diameter are drilled out to produce hollow centers 1 cm. wide. Rock or mineral cores or loose powders are packed into the tube center and the tube is tightly sealed. For each implosion, the sample tube is positioned axially within a large, thin-walled cylinder of about 10 cm. diameter. Either solid or liquid (usually nitromethane) explosive is placed into the cylinder and detonated. While this cylinder is exploded outward, the detonation waves can only push inward or implode upon the sample tube along the axis. The tube thus survives the rupturing effect of the explosion and remains intact at the explosion site. The samples can be cut out of the tube and examined by a variety of methods, including a petrographic analysis of thin sections.

Typical of the shock-induced damage in quartz, feldspar, micas, carbonates, etc. loaded as grains or core in the implosion tube are multiple sets of planar features, kink and deformation bands, patchy extinction, granulation or shock-lithification, formation of thetomorphs, and actual melting. These effects are described in my paper but this appendix includes new observations on changes imparted to olivine, pyroxene, and albite present in several sample forms in the implosion tubes. These will be discussed primarily by direct reference to the photomicrographs reproduced on the following pages.

Figure 13a shows a shock-lithified mixture of albite and olivine grains packed into a steel tube. The effect of implosion (attaining a peak pressure of approximately 450 kb) was to squeeze and compact the loose grains into a tight, coherent mass. During this process, the grains fractured and fragmented so that smaller pieces were shoved into closing interstices. Cohesion was achieved largely by interlocking and localized interpenetration of adjacent grains. The olivine shows shock-induced fractures and some mosaic structure but the albite appears largely unchanged.

A single set of close-spaced lamellae (NE-SW) developed from shock-induced stresses acting on many of the loose enstatite grains packed into a brass implosion tube subjected to about 350 kb peak pressure (Figure 13b). These lamellae may be analogous to the planar features produced in quartz by shock-loading.

A solid core of peridotite, placed in a steel implosion tube, shows mainly fractures imposed on the large olivine grains that appear to be undergoing incipient fragmentation (Figure 13c). Strain bands are formed in a few grains but mosaic structure is absent. Incipient melting (see irregular clear area in center) occurs within a few grains. Strain bands were produced in olivine within peridotite loaded in a brass implosion tube (Figure 13d). Some of the other grains show wavy to patchy extinction but mosaic structure is poorly developed in this sample. Most grains display a notable increase in microfractures compared with unshocked peridotite.

Well-developed mosaic structure (Figure 14a; crossed nicols) appears in olivine grains loaded loose into a steel implosion tube and shock-lithified into a coherent mass. Fractures break up the grain shown into slightly displaced segments but strain effects extend beyond crack boundaries, indicating continuing deformation after the compacted state was reached.

Loose olivine grains in a brass implosion tube underwent incipient melting in and around individuals (Figure 14b). The resulting glass occupies fractures produced in the grains as they were broken during compression and closing of the interstices.

A large melt zone was produced in the inner part of the shock-lithified olivine grains packed in a steel implosion tube. The "waste heat" resulting from inward compression of the grains into a coherent mass, at peak pressures exceeding 400 kb (and post-compression temperatures probably well above 1000°C), led to general melting of the olivine in the central region. In Figure 14c, the dark mass on the left is quenched olivine melt (containing a few crystalline olivine grains (light)). The grain on the right is a very strongly shocked olivine which shows a somewhat lowered birefringence in crossed nicols; further to the right (not shown) and extending to the contact between sample and wall of the tube center, the olivine grains are all still crystalline and show decreasing shock damage from the melted region outward. The elongate crystals in the middle of the photomicrograph (Figure 14d) are composed of olivine which had time to grow from the melt as a quench phase.

In another patch of melted olivine in this tube, the light areas now are clear, iron-poor olivine glass whereas the darker areas, which tend to form a reticulate pattern, are iron-rich zones which may be magnetite (Figure 15a). The initial composition of the olivine was approximately $Fo_{85} Fa_{15}$.

The central region of shock-lithified loose albite grains imploded in a steel tube appears in Figure 15b. The light areas on the left are clear, glass-like thetomorphs after albite whereas the mass shown on the right consists of compacted crystalline albite containing numerous tiny microfractures. The dark patches on the left are brown-tinted zones of melted feldspar. When the same area is examined with nicols crossed (Figure 15c), the lack of birefringence in the grain outlined on the left confirms that these have been more or less completely isotropized to form thetomorphs. The transitional stage in this isotropization process is evident in some grains in the center and right.

Figure 15d provides a detailed view of a single grain of albite involved in the shock-lithification of loose grains in a brass implosion tube. The peak pressures attained in this experiment were about 100 kb less than in the implosion of albite in the steel tube experiment described in the preceding paragraph. Hence, post-compression temperatures were many hundreds of degrees °C less and melting of the central region did not occ. Thetomorphs also fail to form. Most albite grains experienced some fracturing but, in a very few individuals, well-developed planar features were produced, as shown in Figure 15d. Albite mixed 1 to 1 by volume with olivine, after shock-loading in both brass and steel tubes, failed to develop any planar features whatsoever; the presence of the less compressible olivine may have prevented the effective compression of the feldspar by acting as a more rigid framework. However, albite within a fine-crystalline granite core sample, when shock-loaded in a brass implosion tube, developed numerous planar features indicating that, in the absence of more "shock-resistant" minerals such as pyroxenes or olivine and in low porosity (tight) material, these features are more likely to form in quantity, probably during the earlier stages of compression.

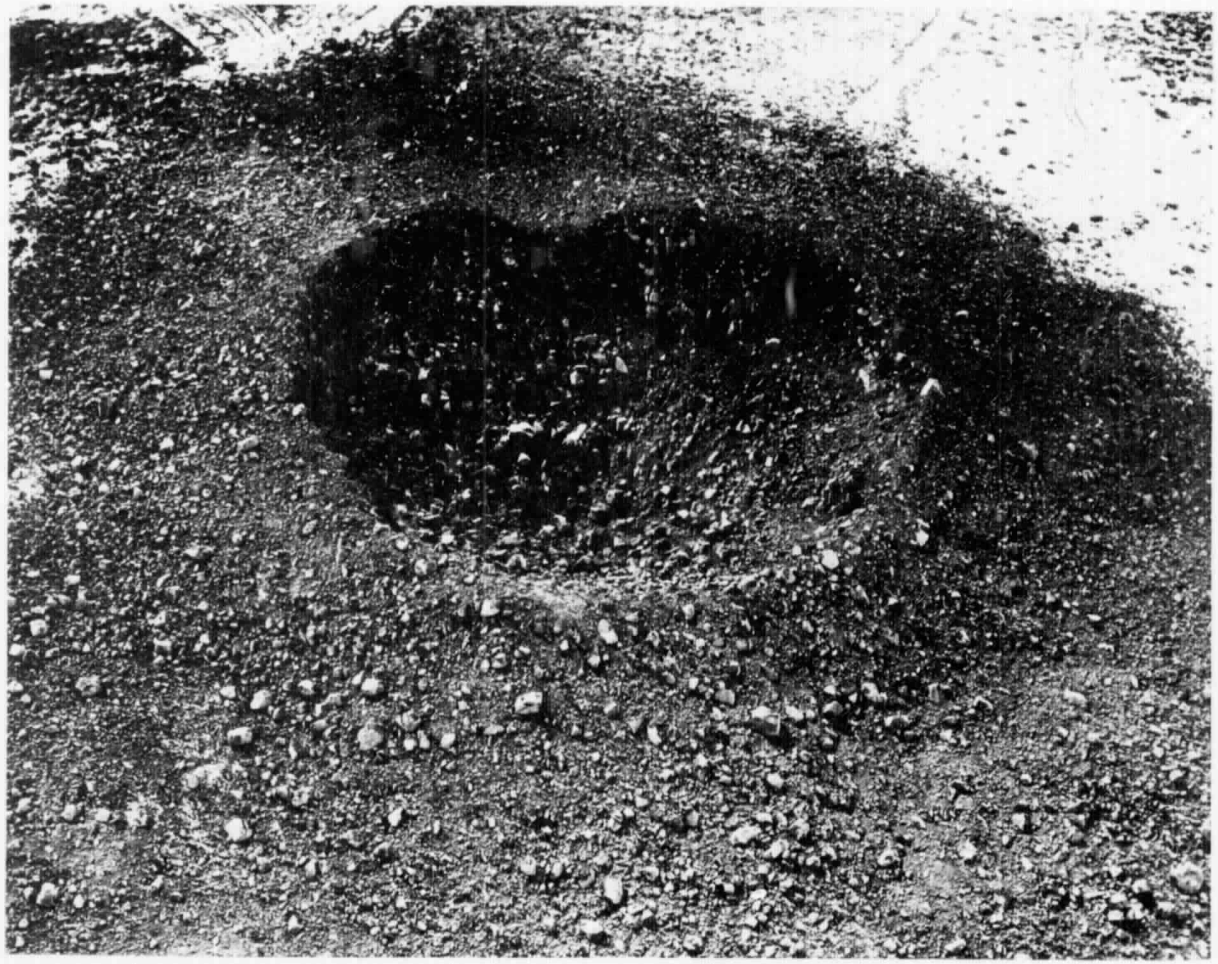

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Figure 1. Aerial oblique view of the DANNY BOY nuclear crater formed from a 0.42 kiloton explosion in a basalt flow at the Nevada Test Site. The crater is 66.5 m in diameter and has an apparent depth of 19 m. Some of the ejecta blocks are larger than 2 m on a side. There is a slightly upraised rim owing to upheaval of the jointed basalt and deposition of fallback. In places the rim is now 6 or more meters above the original surface.

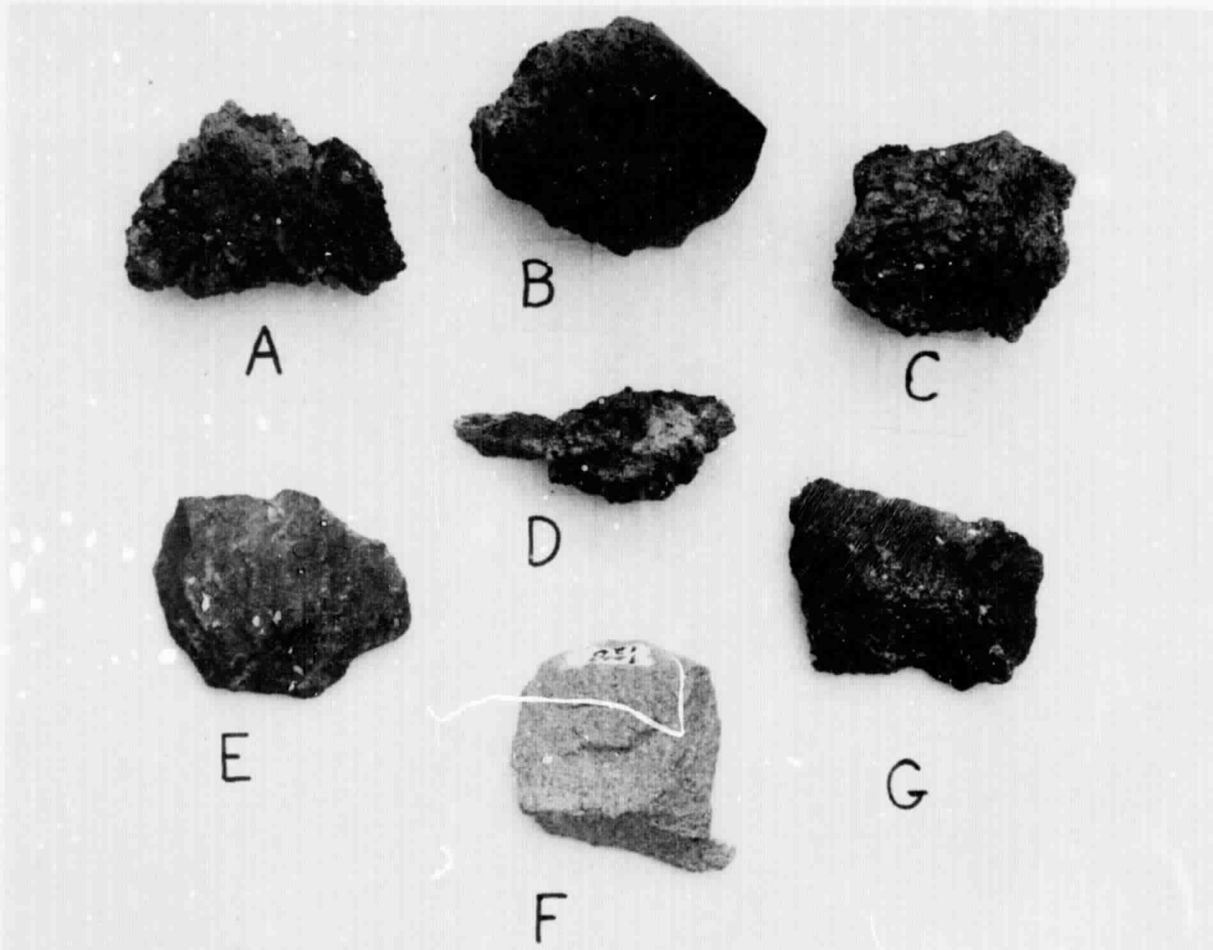

Figure 2. Samples of unshocked and shocked basalt from the DANNY BOY nuclear crater site. For scale, maximum horizontal dimension of B is 8 cm. Samples A through D are intensely shocked and may contain vesicles up to 0.5 cm in diameter; the original pre-shock texture of each is still recognizable. Samples E and G are, respectively, dense and slightly vesicular unshocked basalt fragments. Sample F is notably lighter in color than E and G; because it shows an abnormally high density of microfractures when examined in the microscope, it is considered to be moderately shocked.

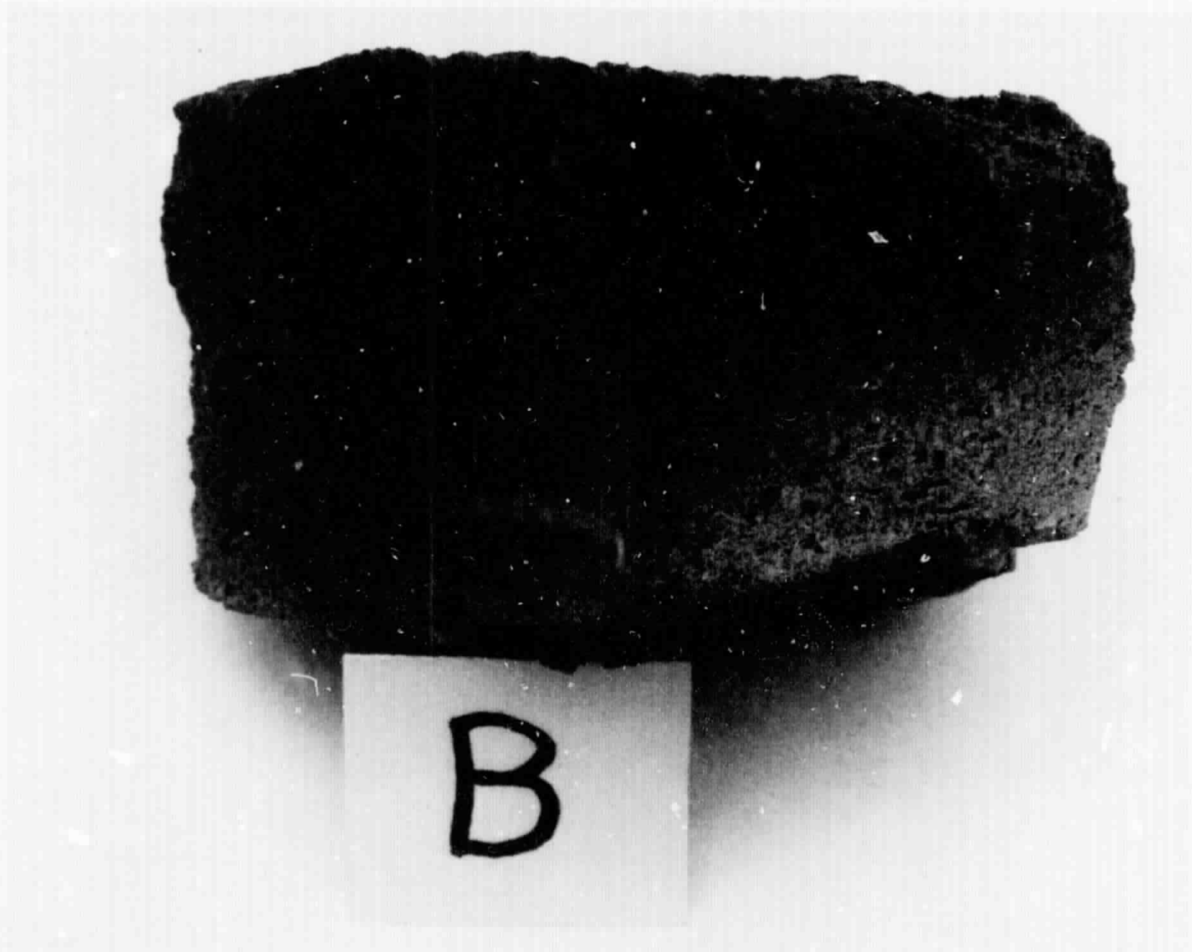

Figure 3. Detailed view of sample B shown in Figure 2. Note the gradient of increasingly large vesicles from lower right to upper left. Faint traces of the original basalt texture can be seen in the lower right. The degree of melting and mixing of feldspar, and decomposition of olivine, increases from lower right to upper left.

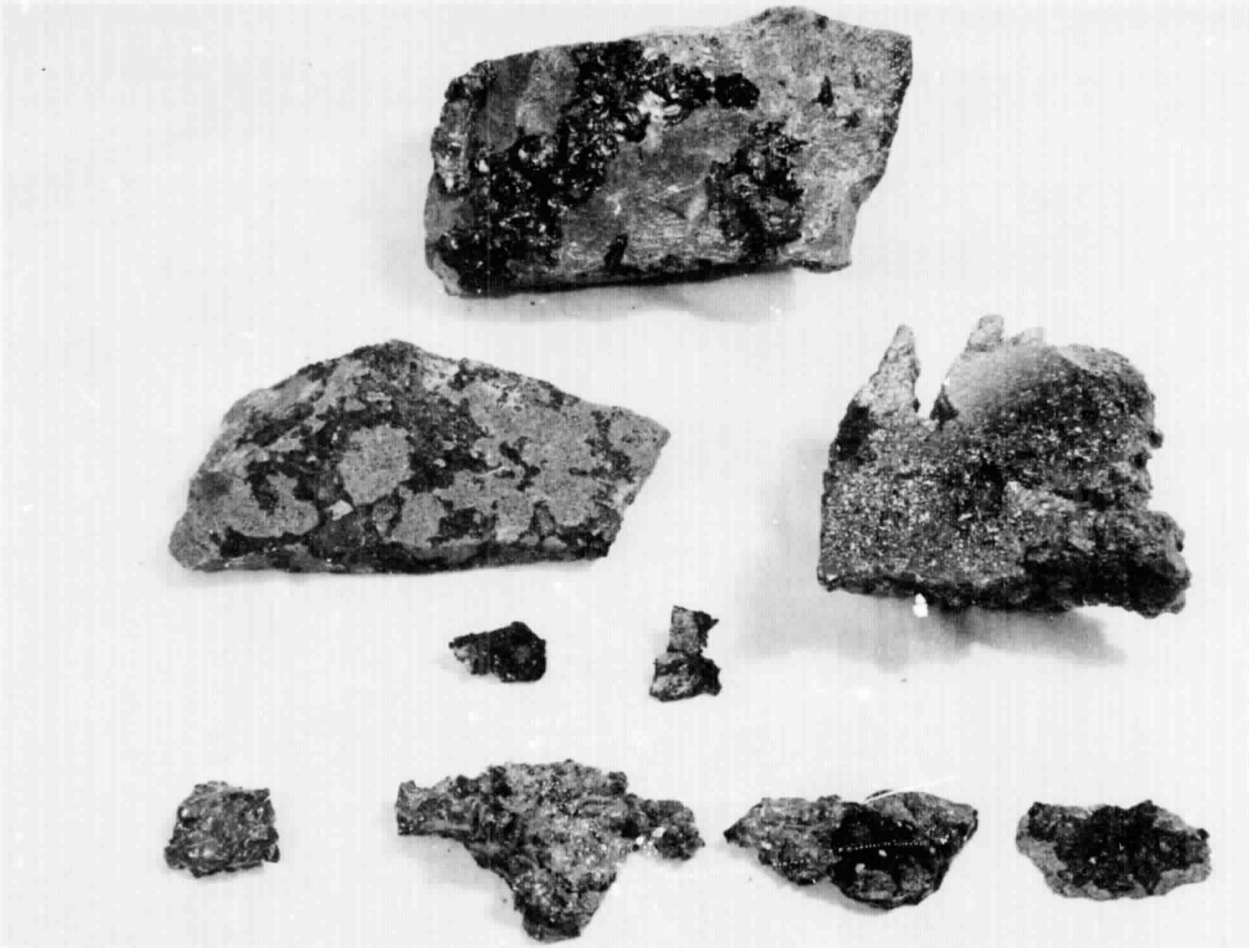

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Figure 4. Two principal types of glass associated with ejecta produced by the DANNY BOY nuclear explosion. Globular coatings of radioactive melt, deposited on fracture surfaces, are shown on samples at the top, center left, and lower right. This melt was derived mainly from the effects of very high temperatures associated with detonation of the nuclear device. Samples in center right and lower left are vesiculated, low-radioactivity glass-like material (similar to samples shown in Figures 2 and 3) formed directly by shock wave action, without the basalt having passed into a completely fluid state, at greater distances from the explosion center. Largest specimen is about 15 cm in long dimension.

(a) (b)

(c) (d)

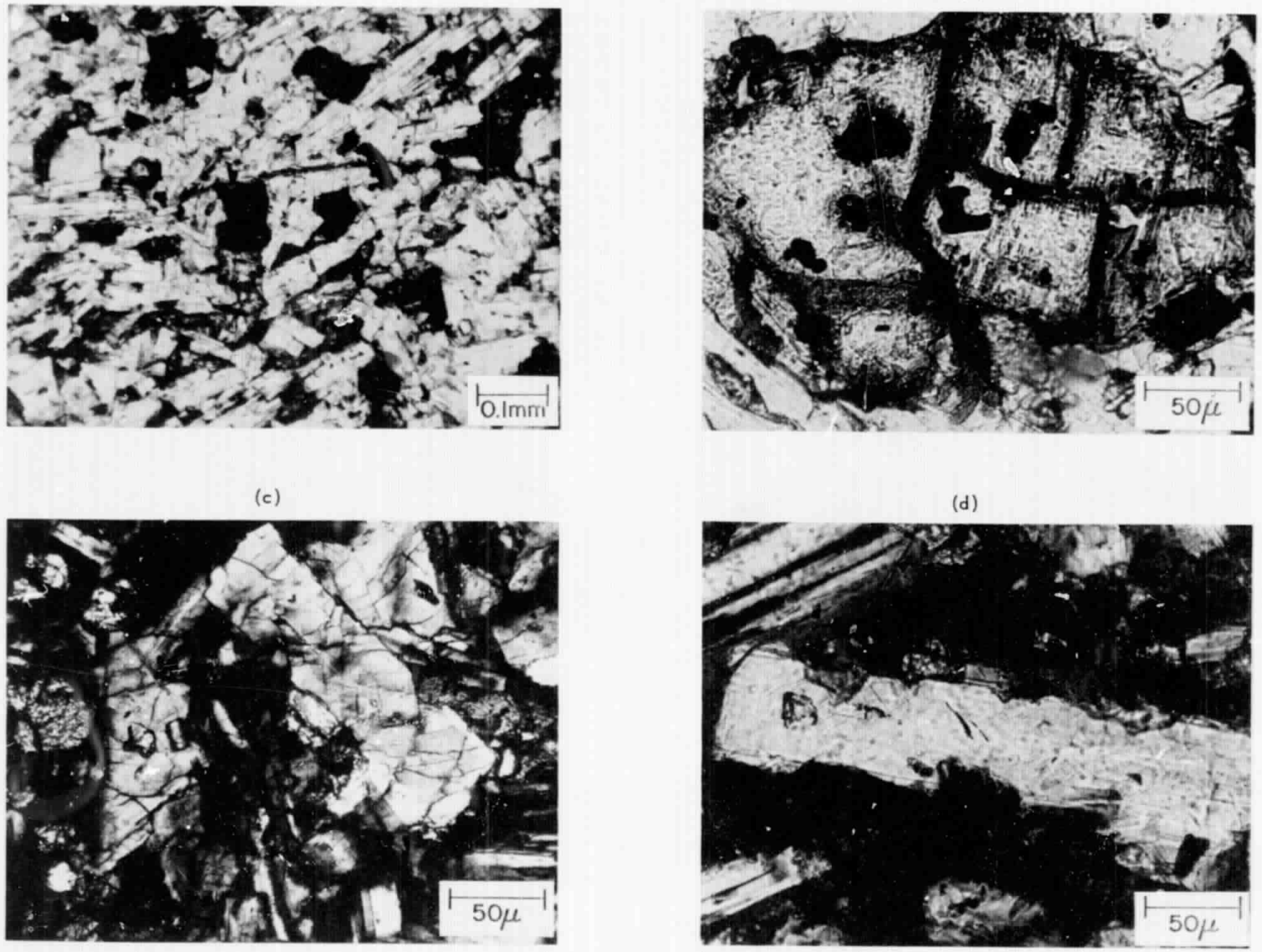


Figure 5. (a) Typical texture of unshocked basalt: light crystals are plagioclase laths; dark ones are olivine grains (fresh to altered) or magnetite. (b) Single grain of unshocked olivine: darker translucent areas along cracks and in patches are iddingsite; very dark opaque grains are magnetite. Note lamellar structures emanating from cracks; these are zones of alteration now occupied by iddingsite. (c) Shock-induced microfractures developed in plagioclase laths. (d) Lath of plagioclase containing unusual markings of uncertain origin. Those parallel to lath boundaries apper: to be traces of growth surfaces; those which crisscross the unshocked grain may be stress-induced lamellae.

(a) (b) (c) (d)

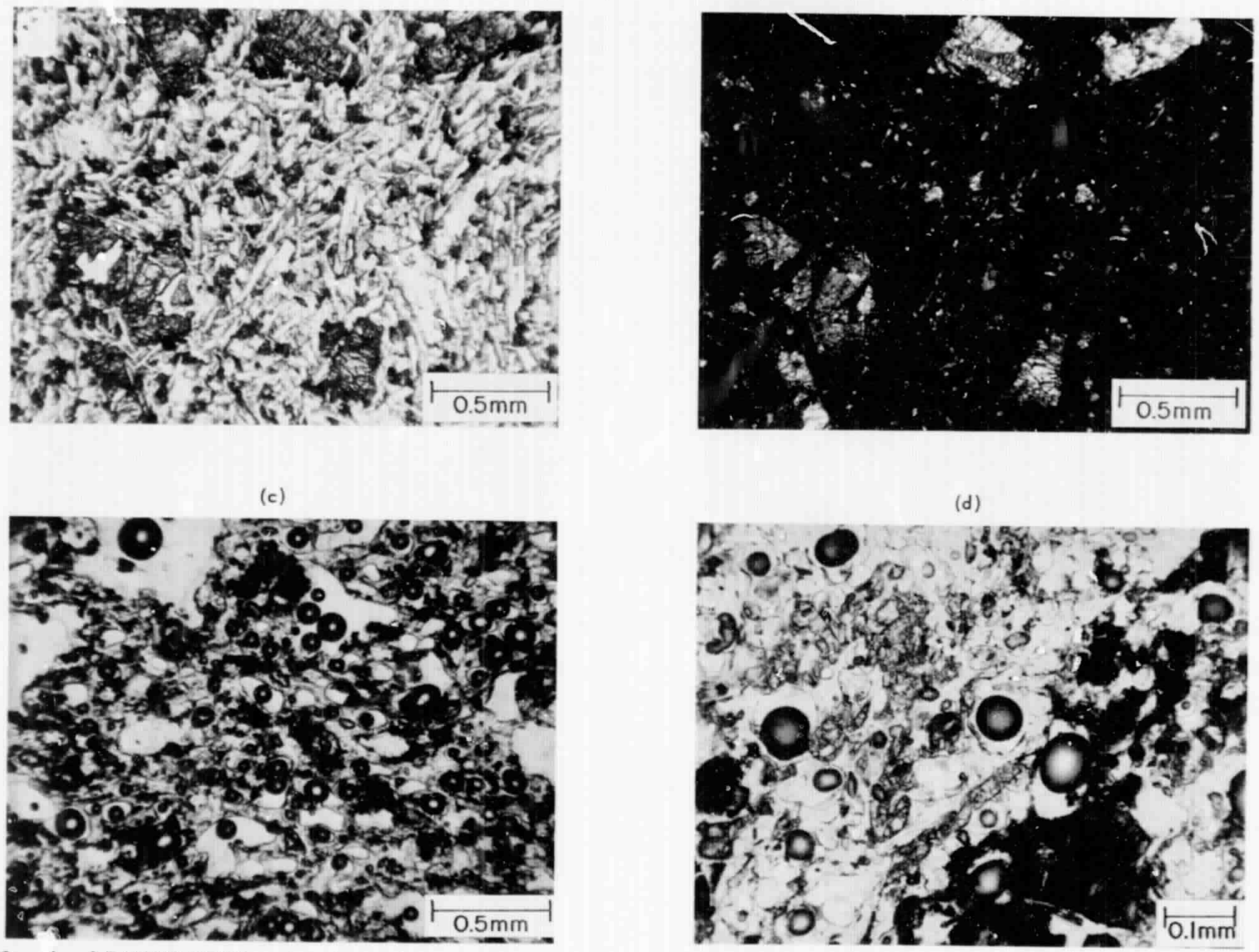


Figure 6. (a) Sample of DANNY BOY basalt subjected to shock pressures of 350-400 kb by the implosion tube method; the individual feldspar crystals appear normal although the olivine grains are strongly fractured. (b) Same area as shown in a, photographed here with crossed nicols; the feldspar crystals are almost completely isotropic and the olivine grains show mosaic structure. (c) Texture characteristic of early stage of feldspar melting within an intensely shocked basalt sample. Note numerous large vesicles (smaller circular ones are bubbles in mounting medium). (d) Sample similar to c; clear, glassy plagioclase lacks definite shapes and contains numerous tiny vesicles; large olivine grains on right are reddish-brown and dusky translucent whereas smaller olivine fragments on left are still clear and yellowish-green, with normal birefringence.

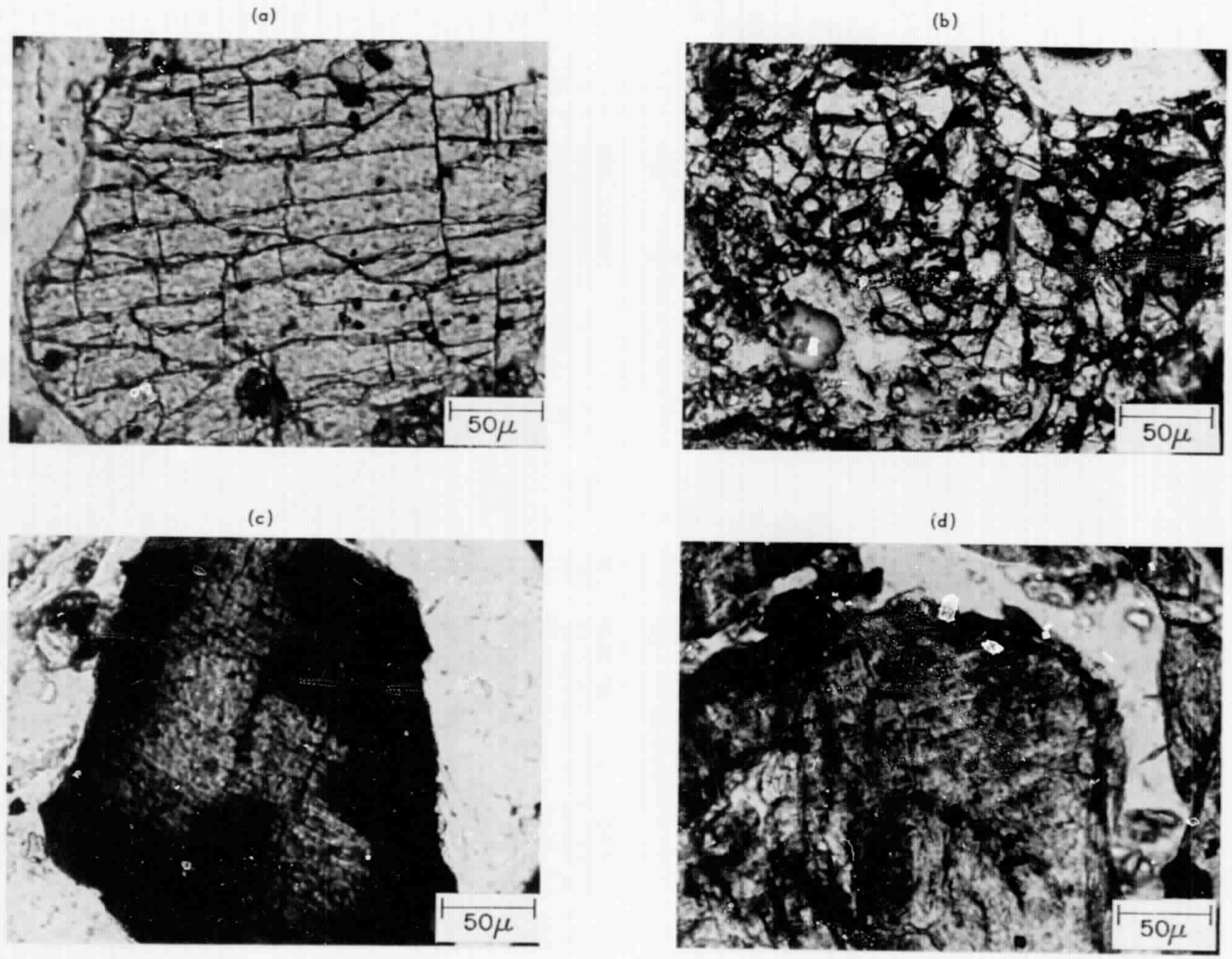


Figure 7. (a) Subparallel fragments bounded by shock-induced fractures in olivine grain. (b) Irregular fractures in shocked olivine grain; the resulting fragments have not yet been dispersed into the feldspar melt. (c) Single olivine grain held in shock-melted feldspar; the outer part of the grain appears dark and subopaque in uncrossed nicols. The regular lamellar-like markings in the translucent central region are pre-shock in origin. (d) Shock-produced regular, close spaced fractures and other planar lamellae in olivine.

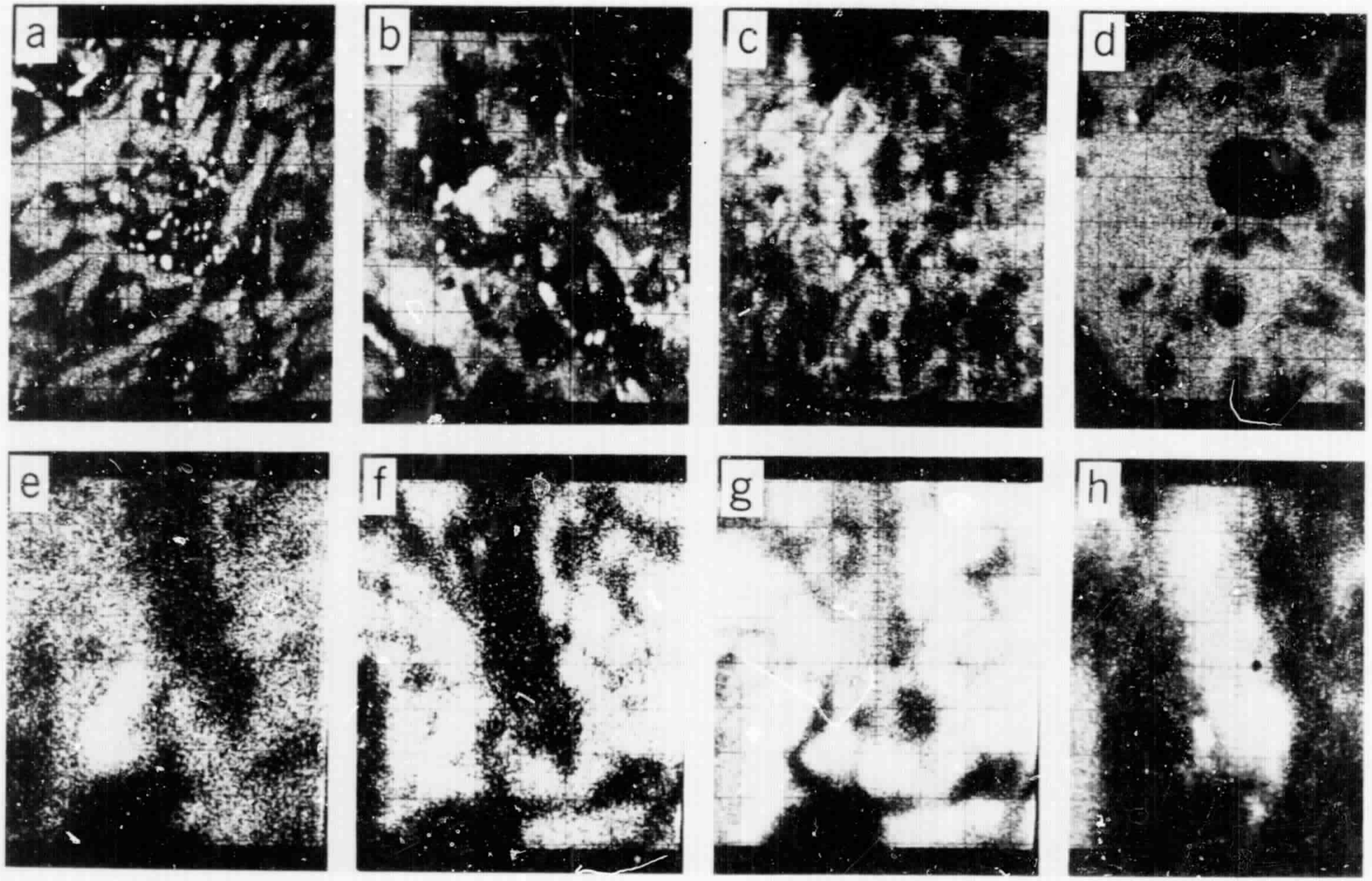


Figure 8. Electron microprobe scanning photographs covering selected areas of shocked basalt. (a through d; scale: one square = 350 μ): Distribution of calcium in unshocked sample (a) outlining mainly feldspar laths; early stage meltin in intensely shocked sample (b) (brightest white spots are calcite); more completely mixed feldspar melt in sample equivalent to that shown in Figure 9a (c); and glassy area from patch shown in Figure 11b (d). (e through h; scale: one square = 88 μ): Area of poorly crystalline material similar to that shown in Figure 11a, indicating distribution of magnesium (e), iron (f), calcium (g) and aluminum (h).

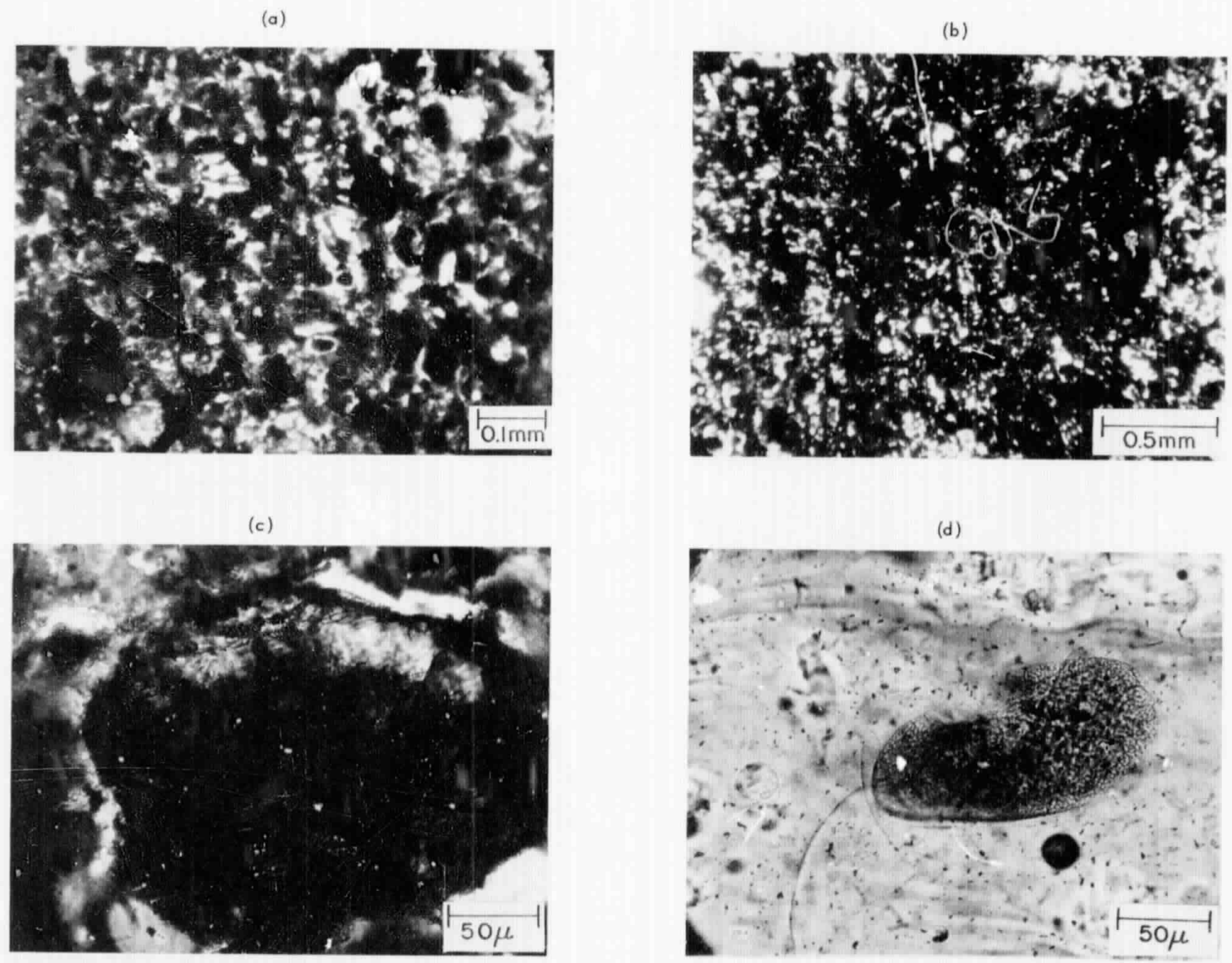


Figure 9. (a) Texture formed in intensely shocked sample in which olivine grains break up and disperse throughout mixed feldspar melt. Light areas are clear plagioclase glass. Very dark areas are decomposed olivine and magnetite. Medium dark areas are, in part, reaction products between feldspar and olivine. (b) Similar to a; dispersal even greater, so that only a small fraction of feldspar melt remains unmixed. (c) Single shocked olivine grain now largely subopaque owing to general decomposition or alteration involving chemical release of iron to form minute, colloidalsized clots of one or more unidentified phases. (d) Single olivine grain, enclosed in mixed melt, showing decomposition into enlarged clots of iron oxide (magnetite?)

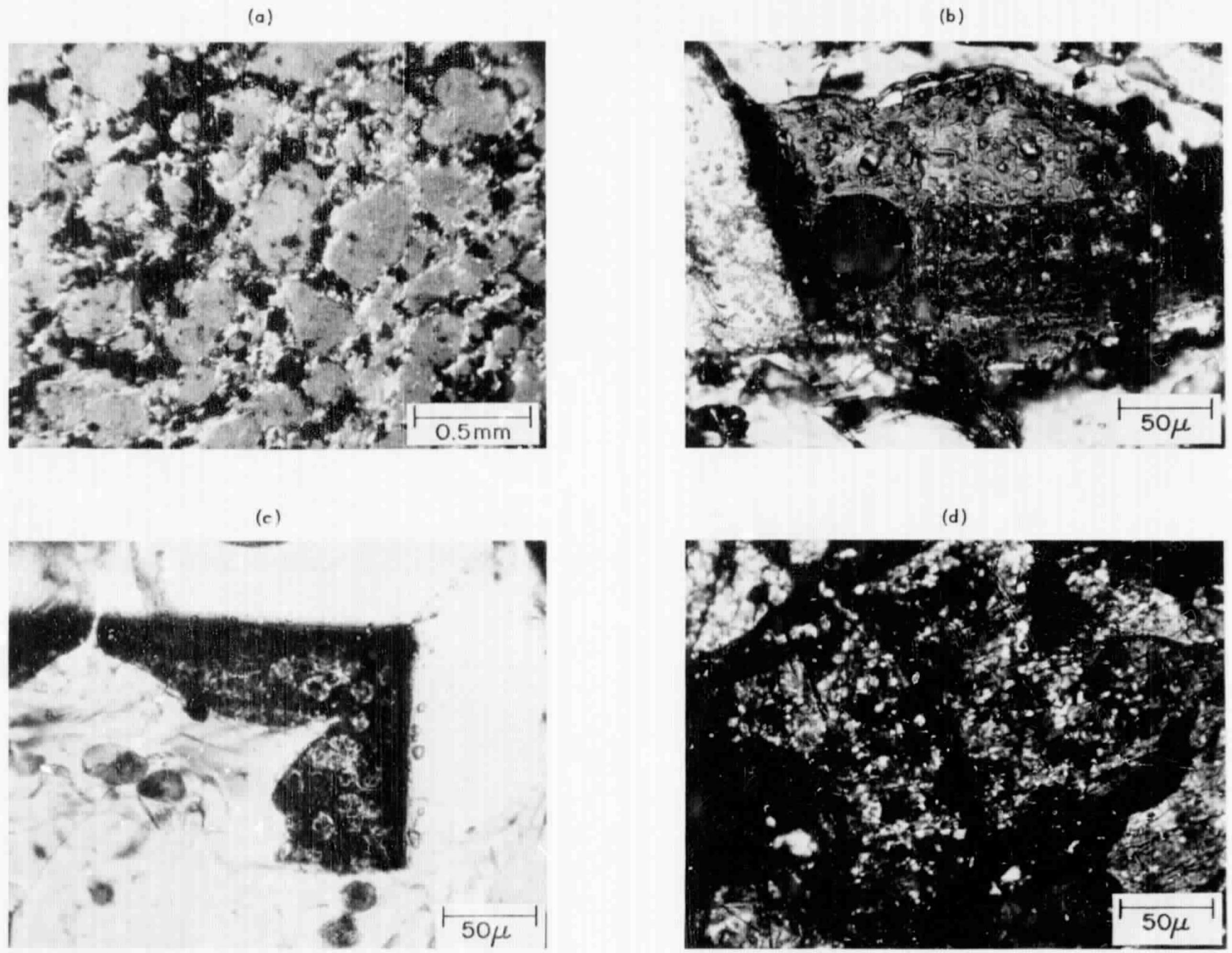
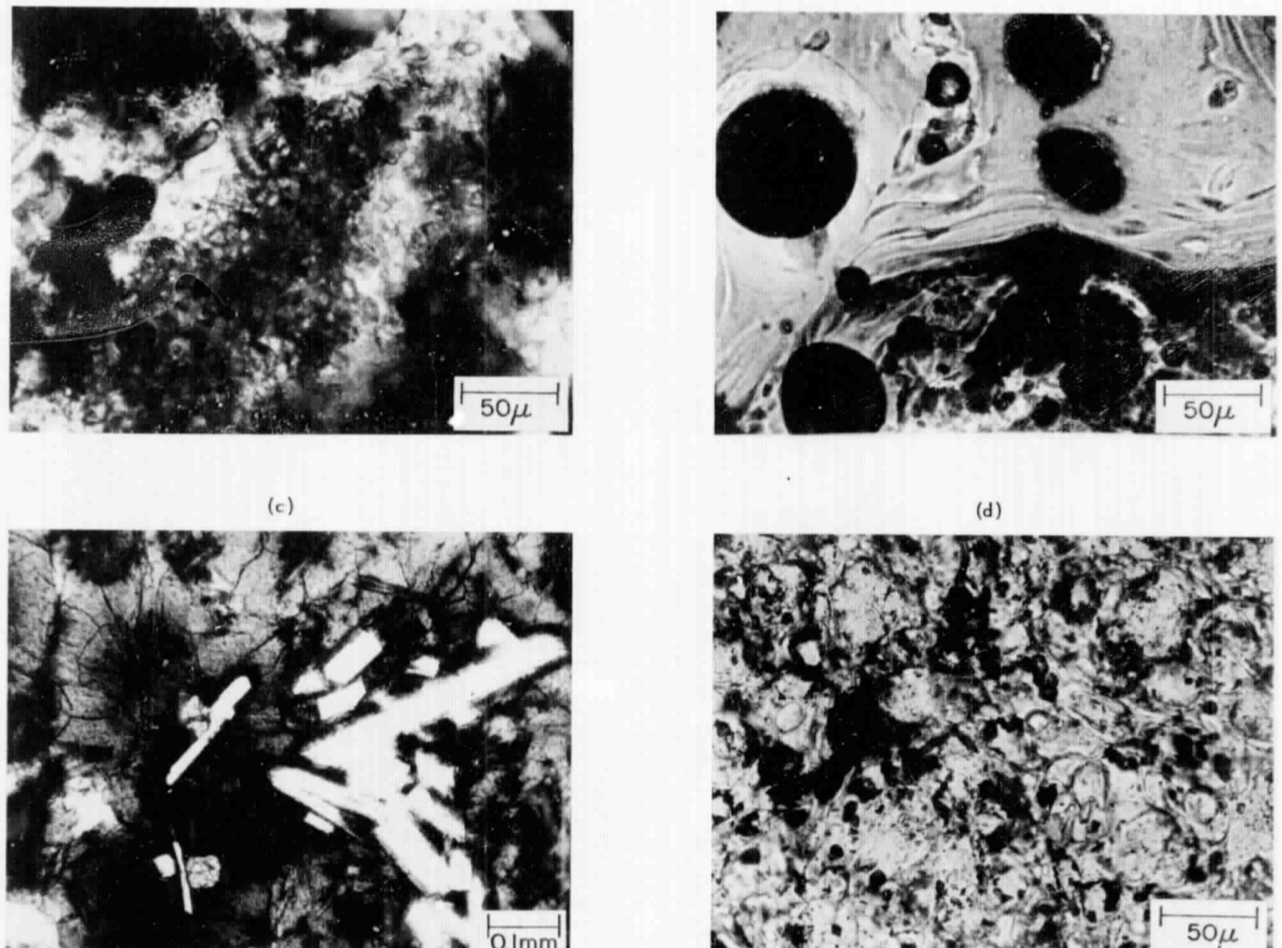


Figure 10. (a) Thin, septa-like walls of plagioclase melt and olivine and magnetite grains surrounding vesicles in a sample showing extreme vesiculation. (b) Single grain of isotropic olivine surrounded by plagioclase glass; vesicles and bands of iron oxide appear in the grain which may have been momentarily fluid. (c) Remnant of a square-outlined crystal of silver-rich mineral which was shocked and then mixed with melt; globular areas may be sites of degassing. (d) Example of recrystallization texture formed in intensely shocked and heated olivine grain.

(a) (b)



(c) (d)

Figure 11. (a) Detail of appearance of poorly crystalline material (center) consisting of light and dark olivine fragments reacting with feldspar melt to form chemically variable products (medium shades) including omphacite. (b) Part of a patch of mixed quenched glass containing elements contributed by melted plagioclase and olivine; lines of flow are evident; dark circular objects are vesicles. (c) Glassy basalt collected from a lava lake in Hawaii. Note well-formed crystals of plagioclase. The light to dark areas (containing cracks) are the quenched melt; these areas are yellowish-brown, indicating more or less uniform dispersal of Fe. (d) Texture typical of pumice: light areas are silica-rich glass containing numerous vesicles; dark areas are amphiboles and other phases. Flow lines in the glass noted in other thin sections from this sample commonly extend beyond the length of the photo shown here. Compare texture with Figure 6c.

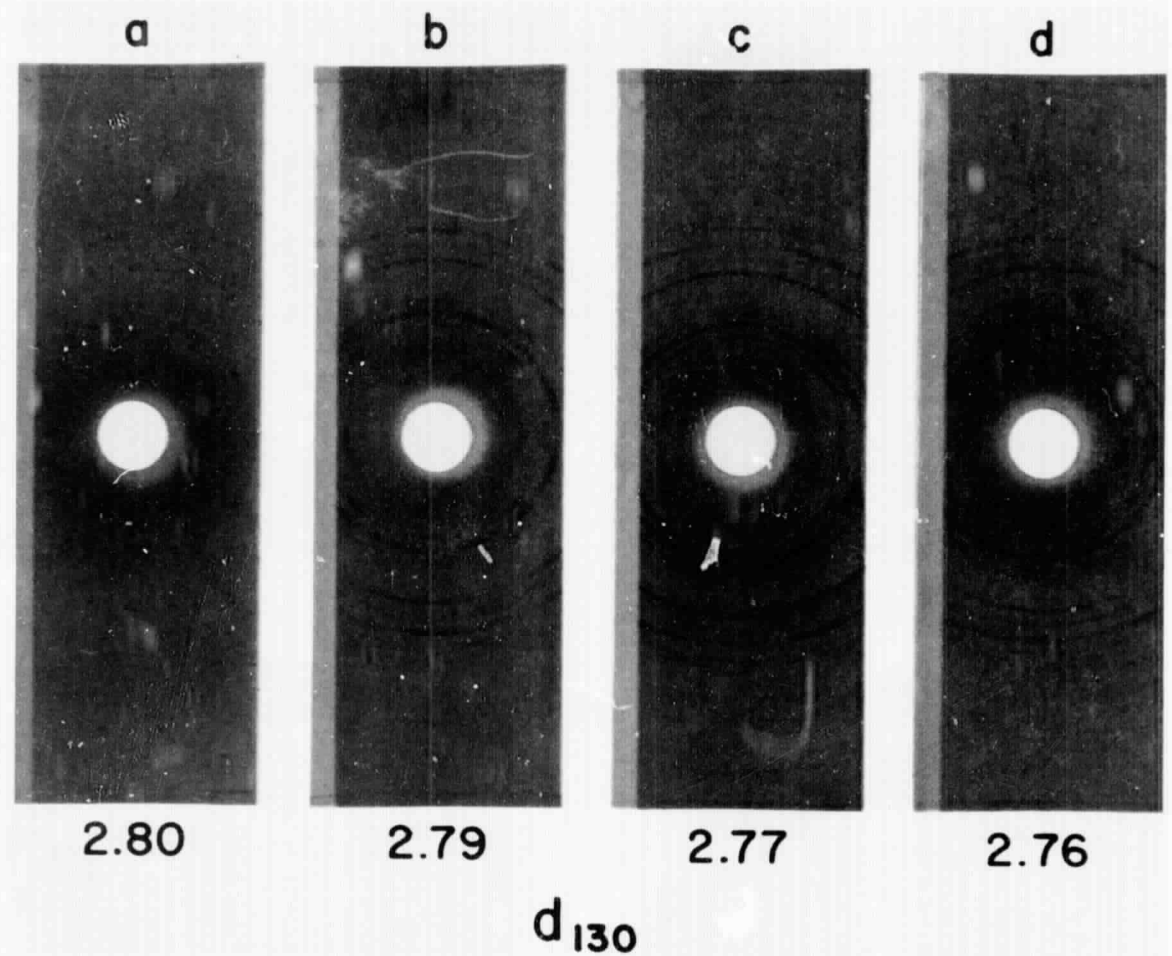


Figure 12. Film strips showing asterism patterns obtained from unshocked and shocked single grains of olivine by slow rotation in an x-ray beam of Cu K radiations for 6 hours. (a) Spot pattern characteristic of unshocked olivine; (b) streak-ring pattern typical of grain from sample shown in Figure 6c; (c and d) patterns produced by grains from samples similar to that shown in Figure 9a. Numbers below strips refer to d_{130} values measured on film; see text.

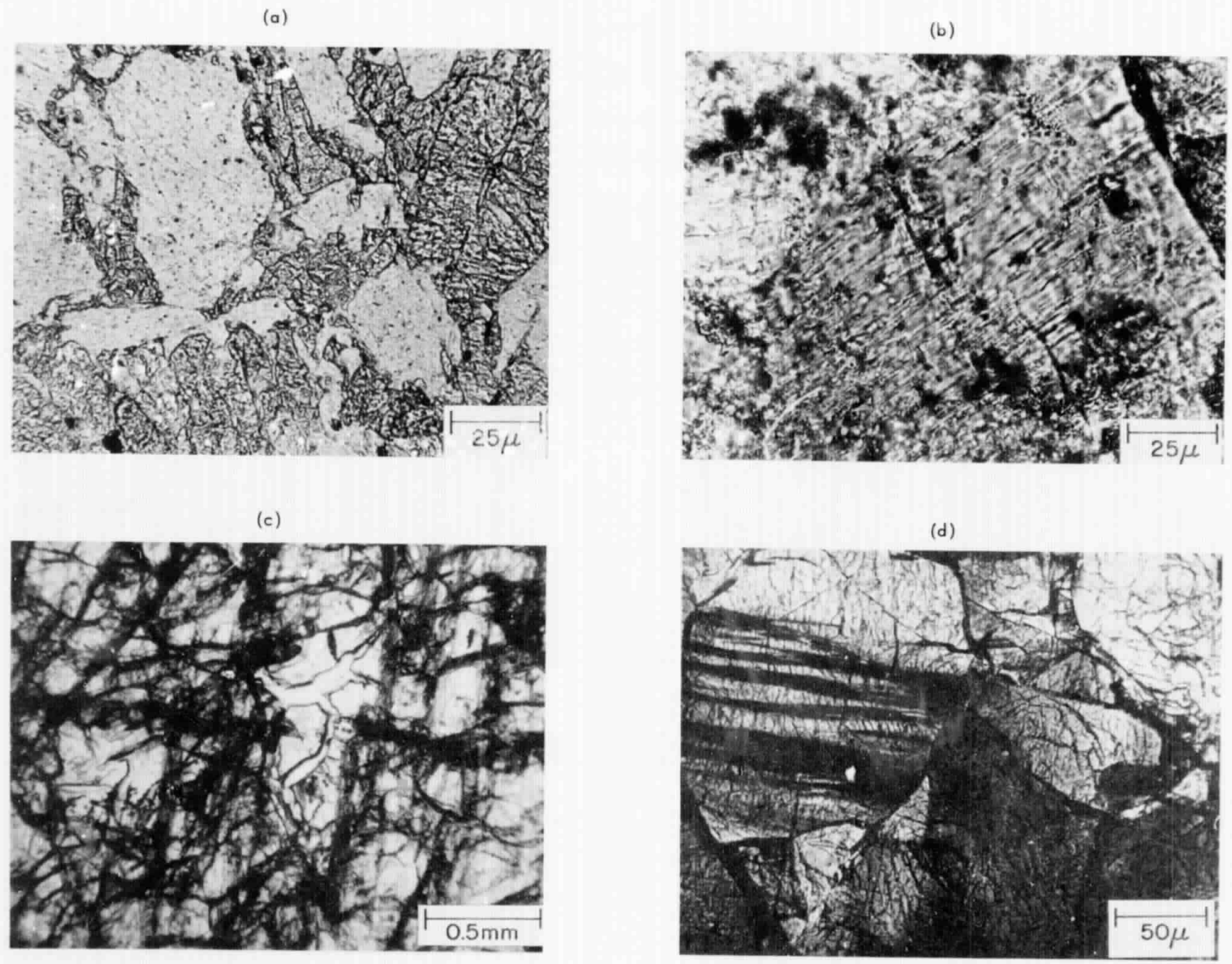


Figure 13. (a) Shock-lithified mixture of albite and olivine (steel tube implosion). (b) Shock-produced (?) lamellae in enstatite (brass tube implosion). (c) Fractures and incipient melting in olivine grains (steel tube implosion). (d) Strain bands within olivine grains in peridotite (steel tube implosion).

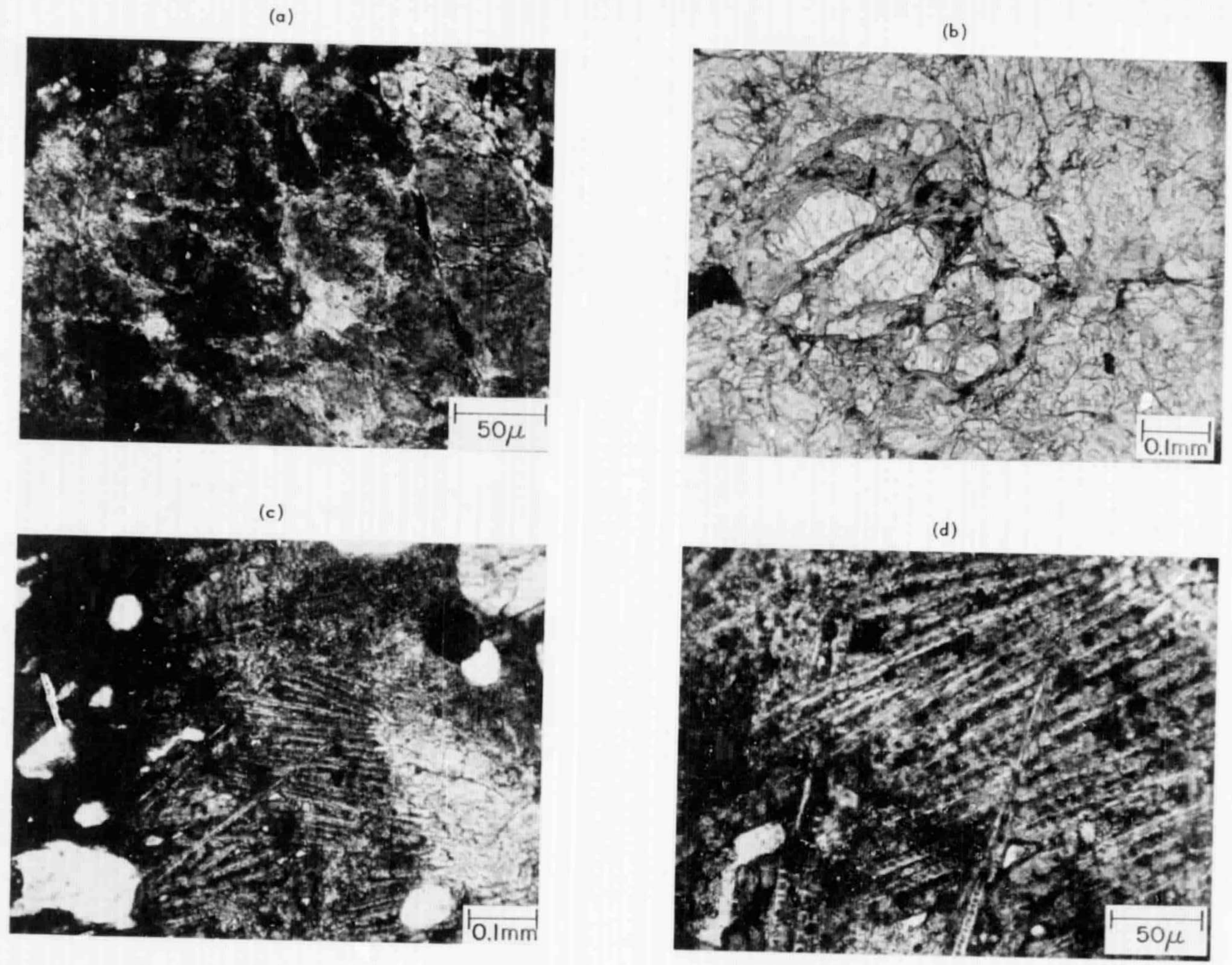


Figure 14. (a) Mosaic structure produced in shock-lithified olivine grains (steel tube implosion). (b) Incipient melting along cracks in shock-lithified olivine (brass tube implosion). (c) Region of general melting and quench crystal formation in shock-lithified olivine grains (steel implosion tube). (d) Details of elongate quench crystals of olivine formed from olivine melt.

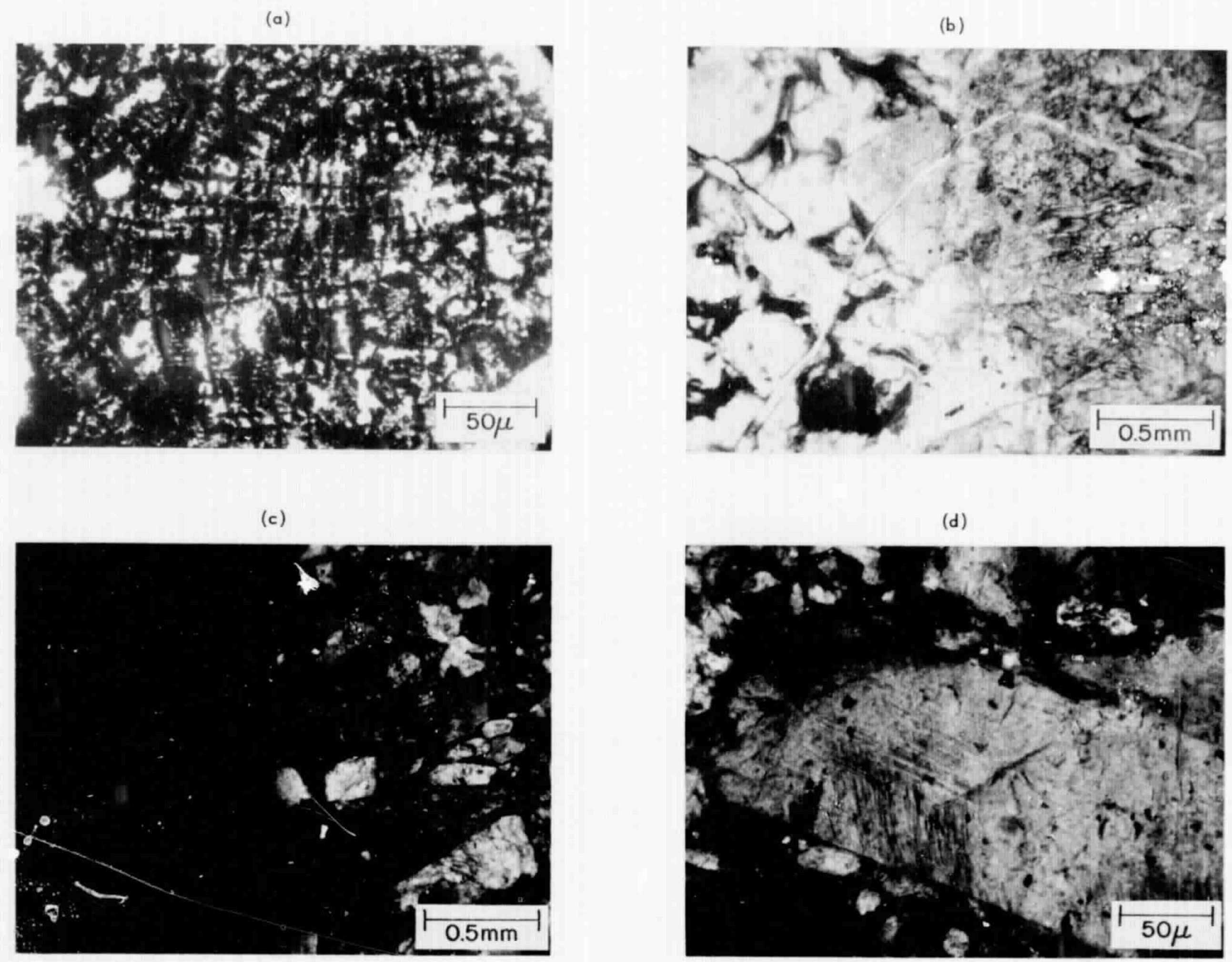


Figure 15. (a) Reticulate pattern of iron-rich phase separated from iron-poor olivine melt (clear glassy areas) (brass tube implosion). (b) Development of albite thetomorphs (left) in shock-lithified loose grains, observed in bright-field illumination with nicols uncrossed (steel tube implosion). (c) Same area as shown in (b) with nicols now crossed. (d) Single albite grain with shock-induced planar features (brass tube implosion).