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Shocked basalt from Lonar Impact Crater, India, and experimental analogues

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Abstract—Exposed rocks at Lonar Impact Crater, Maharashtra, India are typical Deccan Trap tholeiitic flood basalts. Major minerals in the basalt are labradorite, augite, pigeonite, ulvospinel, and devitrified palagonite. The shock-metamorphosed basalts can be divided into five progressively more-shocked classes whose distinctive features are: *Class 1*, grains are fractured. *Class 2*, labradorite is partially to totally converted to isotropic maskelynite, the shock produced feldspar glass; pyroxene and devitrified palagonite show undulatory extinction. *Class 3*, labradorite is converted to glass that shows some evidence of flow; pyroxene grains are granulated and appear to contain sparse dendritic titaniferous magnetite crystals possibly along glass lamellae; the devitrified palagonite is partially to totally isotropic. *Class 4*, labradorite has melted to a clear, vesiculated glass that has flowed so extensively that the original lathlike shape of the grains is no longer recognizable; pyroxene grains are visibly melted on their edges and contain skeletal titaniferous magnetite crystals; the devitrified palagonite has become isotropic, implying that it was revitrified by the shock. *Class 5*, labradorite and pyroxene grains have melted, and the melts are thoroughly mixed into brown glass; innumerable dendritic crystals of titaniferous magnetite are dispersed throughout the remaining pyroxene fragments and the melt; in places the glass has devitrified into spherulites. Samples of the Lonar basalts were experimentally shocked in a vacuum to pressures between 200 and 650 kbar by a 20 mm, high-velocity gun. Plagioclase and palagonite in experimentally shocked samples show deformation similar to that in the naturally shocked rocks, but pyroxene does not show optically resolvable edge melting in the experimentally shocked samples. Comparison of the plagioclase textures in the two sets of rocks gives the following pressures for the naturally shock-metamorphosed Lonar basalts: *Class 1*, $P < 200$ kbar; *Class 2*, $200 < P < 400$ kbar; *Class 3*, $400 < P < 600$ kbar; *Class 4*, $P > 600$ kbar. We estimate that pressures in excess of 800–1000 kbar are required for the formation of totally shock-melted rocks from nonporous basalt.

1. INTRODUCTION

LONAR IMPACT CRATER IN MAHARASHTRA, INDIA (19°58′N, 76°31′E), is an almost circular depression in the basalt flows of the Deccan traps (Fredriksson *et al.*, 1973). The crater is 1830 m in diameter at the rim and is nearly 150 m deep. A shallow saline lake occupies part of the floor of the crater and covers 100 m of sedimentary fill.

Ejecta from the crater are found in two distinct debris units. The lower unit, which contains most of the ejecta, is crudely stratified with individual fragments showing no evidence of shock. This unit corresponds roughly to the "throwout" unit at Meteor Crater, Arizona (Shoemaker, 1963). The overlying debris unit is thoroughly mixed and contains fragments of all degrees of shock metamorphism and from all stratigraphic units penetrated by the crater. This unit corresponds roughly to the "fallout" unit at Meteor Crater.

Lonar is the only known impact site on earth in basalt, and accordingly provides a valuable analog to the cratered lunar maria. We report here on shock metamorphism of fragments from the mixed debris unit and of samples from one of the basalt flows which we shocked in laboratory experiments. In comparing the two sets of samples, it is important to keep in mind that the duration of the impact event at Lonar was about 1 sec while the duration of laboratory shock events is typically about 1 μsec. James (1969) and Short (1969) have described basalt shocked by a nuclear blast, which would have had an intermediate shock duration.

2. UNSHOCKED BASALT

The basalt at Lonar is typical of the Deccan Trap tholeiitic flood basalt of Cretaceous-Eocene age. The crater walls and drill cores reveal a series of flow units, ranging from 5 to 30 m in thickness. There are minor petrographic differences between flows, particularly in the abundance of phenocrysts, but on the whole compositions are very uniform (Table 1). Within each flow, however, there is typically a gradation upward from a massive dense interior to a flow top which is vesicular with the vugs largely filled with secondary minerals. Commonly the flow top is brecciated and oxidized, and on some flows it was deeply weathered contemporaneously. Flow top material is well represented in the mixed debris unit, but the shocked samples described below are believed to derive from dense flow interiors.

Basalt from an unweathered flow interior at a depth of 81 m in a drill core taken 700 m north of the rim of Lonar Crater was selected as the material for the experiments described below and is typical of unshocked basalt. It is a light grey porphyritic to microporphyritic rock, with groundmass crystals of 0.2 mm diameter or less (Fig. 1). The primary minerals are plagioclase feldspar, two clinopyroxenes, opaque iron-titanium oxides, and devitrified basaltic glass. The feldspar crystals are lath shaped; typically 5–15% of the rock is feldspar phenocrysts of up to 1.5 mm diameter and 1 cm in length. The feldspar crystals generally show twinning and many, but not all, show undulatory extinction. The pyroxenes are irregular in shape and generally show fractures and cleavages. Opaque minerals and devitrified basaltic glass occur interstitially. Individual mineral compositions are shown in Table 2. The plagioclase is labradorite with phenocrysts having compositions close to An_{68-69} and groundmass laths having compositions from An_{55} to An_{68}. The two clinopyroxenes are augite and pigeonite; the latter is

Table 1. Compositions of whole rock samples and of shock glasses in Deccan basalts.

	1[a]	2[a]	3[a]	4[b]	5[b]	6[c]	7[c]	8[c]	9[c]
SiO_2	49.01	49.33	49.22	51.77	51.6	50.56	51.94	50.57	50.7
	(1.07)*	(1.07)		(3.27)		(0.46)			
TiO_2	2.29	1.96	2.00	1.99	2.9	2.78	1.96	2.39	2.0
	(0.16)	(0.06)		(0.60)		(0.82)			
Al_2O_3	15.96	13.79	15.48	13.46	13.7	12.79	13.94	13.33	14.4
	(2.11)	(0.16)		(0.79)		(1.15)			
FeO	—	—	—	12.54	13.8	11.28	10.18	10.61	9.8
				(1.28)		(1.07)			
Fe_2O_3	14.72	13.58	13.44	—	—	3.23	3.27	4.04	3.2
	(0.17)	(0.84)				(0.65)			
MgO	5.34	6.54	6.09	5.30	5.4	5.40	5.60	5.83	6.2
	(0.34)	(0.97)		(0.50)		(0.34)			
CaO	9.61	12.55	11.47	9.88	9.7	10.29	9.70	10.40	9.4
	(1.66)	(1.42)		(1.33)		(0.38)			
Na_2O	2.32	1.81	1.84	2.25	2.2	2.55	2.67	2.30	2.6
	(0.13)	(0.18)		(0.28)		(0.24)			
K_2O	0.74	0.44	0.47	0.59	0.6	0.59	0.74	0.52	1.0
	(0.61)	(0.07)		(0.35)		(0.14)			
Total	99.99	100.00	100.01	97.78	99.9	99.47	100.00	99.99	99.3
	(2.98)	(2.21)		(3.94)		(2.03)			
H_2O†	2.22	3.79	2.73	—	—	—	2.13	2.31	—
	(0.57)	(2.85)							

1. Unshocked Lonar basalt, mean of 3 samples.
2. Shocked Lonar basalt, Class 3, mean of 2 samples.
3. Shocked Lonar basalt, Class 5, single sample.
4. Brown shock glass, Class 5, mean of 24 spots.
5. Brown shock glass, Class 5, mean of 5 spots (defocused), Fredriksson *et al.* (1973, p. 863).
6. Deccan basalt, mean of 10 samples, Sukheswala and Poldervaart (1958, p. 1487).
7. Deccan basalt, mean of 11 samples, Turner and Verhoogen (1960, p. 208).
8. Deccan basalt, mean of 4 samples low in formation, *Ibid.*
9. Continental tholeiites, mean of 144 samples, Hyndman (1972, p. 171).

[a]XRF whole rock analyses, normalized to 100% giving anhydrous totals.
[b]Electron microprobe analyses, H_2O not detected.
[c]Analytical technique not described in reference.
*Standard deviations of data between samples; totals derived by root of sum of squares.
†Determined by ignition loss.

generally altered to serpentine. The opaque minerals are anhedral ulvospinels, which generally contain amorphous siliceous inclusions and less abundant ilmenite. Palagonite occurs in angular interstices between mineral grains. It is generally birefringent and has devitrified to radiating fibrous crystals. The major cations in the palagonite are silicon and iron, with smaller amounts of calcium, aluminum, magnesium, and potassium; it typically contains more than 20 wt.% water. Some compositional zonation is present.

The most common secondary minerals are hematite, calcite, zeolites (in flow

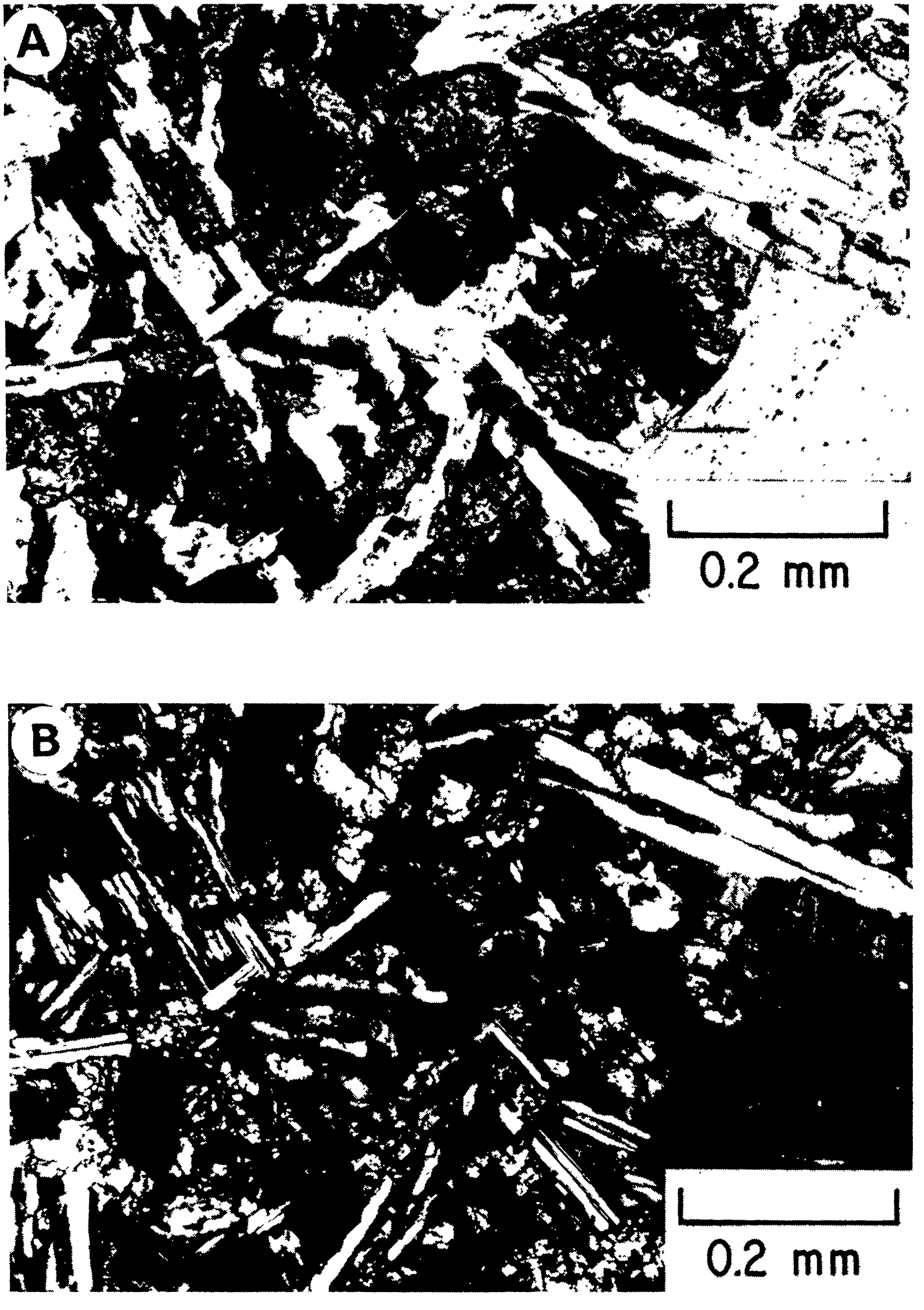

Fig. 1. Lonar basalt, unshocked, from a flow at 81 m depth. (a) Plane polarized light. (b) With polarizers crossed at 80°. Note microporphyritic texture, plagioclase laths and phenocryst, birefringent pyroxene grains, and opaque minerals.

top material), chlorite (in augite and pigeonite), and serpentine (in pigeonite). Except near flow tops, these secondary minerals comprise less than 10% of the rock.

3. Shock-Metamorphosed Basalts from Lonar

The naturally shock-metamorphosed basalts can be divided into five classes. The least shocked samples, Class 1, resemble unshocked basalt in hand-specimen appearance. Samples from Classes 2, 3, and 4 appear to be lighter grey than the unshocked basalts and are somewhat less dense. The density decreases through Classes 2, 3, and 4, but it is not easy to differentiate these classes, particularly Classes 2 and 3, in the field. They differ markedly in thin section, however, and the classification scheme is therefore based on thin section textures and mineralogy. The distinctive features of each class are the following:

- Class 1. Fracturing and comminution are the most obvious evidence of damage.
- Class 2. Labradorite laths are partially to totally isotropic but retain their original crystal shape (i.e., maskelynite has been formed).
- Class 3. Labradorite is isotropic and shows evidence of slight flow (and/or vesiculation) forming lath-shaped patches of clear glass with plagioclase composition.
- Class 4. Labradorite is melted and vesiculation and flow are so extensively developed that the lath-like form of the original grains generally is not recognizable; glass is mostly of plagioclase composition and is colorless. Pyroxene grains are fractured, subrounded, and altered on grain boundaries.
- Class 5. Most of the rock is melted and the shock-melted glass is brown due to mixing of plagioclase, pyroxene, and opaque oxide components.

These criteria are nearly identical to those proposed by James (1969) for olivine trachy-basalt shocked by a nuclear explosion at the Nevada Test Site. The rock properties are gradational and in some samples textures of two classes may be mixed.

In the following sections we describe the shocked basalts. In most respects laboratory samples are very similar to the naturally shocked samples. Microprobe data on the naturally shocked basalts are given in Tables 1 and 2. Petrographic data on individual laboratory samples are summarized in Table 3. Important differences are discussed in Section 4. Characteristic textures in the naturally shocked rocks and the laboratory analogs are shown in Figs. 2–8.

Class 1 (Fig. 2A,B; Fig. 3A,B). In hand specimens, Class 1 samples are fractured, but otherwise indistinguishable from unshocked basalts. The general volcanic porphyritic or microporphyritic texture is preserved in Class 1 rocks. Well-developed irregular fracturing is the most obvious shock effect and is particularly pronounced in plagioclase phenocrysts. Grain boundaries may be faulted and offset by the irregular fractures. Undulatory extinction is apparent in

Table 2. Electron microprobe analyses of minerals and glasses in basalt from Lonar Crater, India.

Sample	1 Plag.	2 Mask.	3 Plagioclase Glass	4	5	6 Pigeon.	7	8 Augite	9	10 Augite	11	12 Ulvöspinel	13	14	15	16	17 Ilmenite
	UNSHK	CL. 2	CL. 3	CL. 4	CL. 5	Unshocked		CL. 2	CL. 3	CL. 4	CL. 5	UNSHK	CL. 2	CL. 3	CL. 4	CL. 5	CL. 5
SiO_2	50.65	51.71	52.32	53.02	53.90	50.06	51.24	51.23	52.69	50.43	50.58	1.00	0.62	0.17	2.44	3.47	0.79
	(0.40)*	(0.49)	(1.06)	(1.88)	(3.29)	(0.42)	(0.71)	(0.93)	(0.51)	(0.71)	(0.86)	(0.20)	(0.37)		(3.84)	(1.36)	
TiO_2	—	0.07	0.05	0.32	0.32	0.16	0.88	0.89	0.80	0.83	0.88	29.27	27.63	27.96	29.29	31.45	46.79
		(0.01)	(0.01)	(0.04)	(0.35)	(0.04)	(0.16)	(0.33)	(0.08)	(0.13)	(0.16)	(0.80)	(0.61)		(2.41)	(4.57)	
Al_2O_3	29.90	30.05	28.85	29.51	24.10	6.70	2.03	2.47	2.19	1.51	2.12	1.68	1.76	1.52	1.28	1.65	0.69
	(0.55)	(0.46)	(0.90)	(1.20)	(3.96)	(0.06)	(0.25)	(0.18)	(0.18)	(0.52)	(0.76)	(0.09)	(0.11)		(0.40)	(0.78)	
FeO	0.63	0.57	0.58	0.68	3.93	26.09	11.10	12.13	11.15	14.59	12.40	62.85	64.20	63.19	63.67	55.46	41.74
	(0.03)	(0.03)	(0.06)	(0.07)	(3.05)	(0.29)	(0.97)	(2.31)	(0.69)	(3.41)	(1.42)	(0.84)	(2.49)		(5.28)	(0.63)	
MgO	—	0.21	0.20	0.13	1.36	13.34	15.41	15.44	16.19	14.61	15.47	—	0.06	0.50	0.35	2.26	1.61
		(0.01)	(0.01)	(0.03)	(1.25)	(0.40)	(0.74)	(1.68)	(0.30)	(0.86)	(1.03)		(0.02)		(0.22)	(0.31)	
CaO	13.82	13.90	14.03	12.91	10.60	3.65	17.76	16.92	17.68	16.67	17.43	0.38	0.07	0.19	0.39	0.84	1.68
	(0.25)	(0.31)	(0.59)	(1.51)	(2.12)	(0.29)	(0.34)	(0.89)	(0.61)	(1.25)	(1.38)	(0.10)	(0.05)		(0.48)	(0.55)	
Na_2O	3.36	3.54	3.32	2.71	3.37	—	—	0.26	0.23	—	0.24	—	0.04	0.15	0.15	0.40	1.33
	(0.14)	(0.19)	(0.17)	(0.44)	(0.67)			(0.02)	(0.02)		(0.04)		(0.02)		(0.25)	(0.13)	

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
K_2O	0.17	0.20	0.17	0.18	0.74	—	—	0.08	0.05	—	0.04	—	0.13	0.03	0.20	0.25	2.03
	(0.02)	(0.02)	(0.02)	(0.03)	(0.24)			(0.01)	(0.01)		(0.02)		(0.02)		(0.02)	(0.02)	
MnO	—	0.00	0.01	—	—	—	—	0.24	0.24	—	—	1.06	1.42	1.40	—	—	—
		(0.00)	(0.01)					(0.03)	(0.02)			(0.28)	(0.10)				
Total†	98.53	100.25	99.53	99.46	98.32	100.00	98.42	99.66	101.22	98.64	99.16	96.24	95.93	95.11	97.77	95.78	96.66
	(0.94)	(0.76)	(1.52)	(2.73)	(6.52)	(0.71)	(1.48)	(3.15)	(1.11)	(3.84)	(2.51)	(1.22)	(2.59)		(6.99)	(4.91)	

1. Plagioclase phenocrysts, unshocked, mean of 7 grains.
2. Maskelynite, Class 2, mean of 18 grains.
3. Colorless plagioclase glass, Class 3, mean of 8 grains.
4. Colorless plagioclase glass, Class 4, mean of 10 grains.
5. Colorless plagioclase glass, Class 5, mean of 11 grains.
6. Pigeonite, unshocked, mean of 3 grains normalized to 100% in anhydrous calculation, 12.69% H_2O (2.00).
7. Augite, unshocked, mean of 10 grains.
8. Augite, Class 2, mean of 4 grains.
9. Augite, Class 3, mean of 9 grains.
10. Augite, Class 4, mean of 5 grains.
11. Augite, Class 5, mean of 15 grains.
12. Ulvöspinel, unshocked, mean of 12 grains.
13. Ulvöspinel, Class 2, mean of 5 grains.
14. Ulvöspinel, Class 3, single grain, iron-rich zones may reach 71.75% FeO.
15. Ulvöspinel, Class 4, mean of 3 grains.
16. Ulvöspinel, Class 5, mean of 2 grains.
17. Ilmenite, Class 5, single grain.

*Numbers in parentheses are standard deviations of data between individual grains; totals calculated by the root of the sum of the squares of the standard deviations in the column.

†Anhydrous totals; H_2O not detected.

LONAR BASALT - NATURALLY SHOCKED - CLASS 1

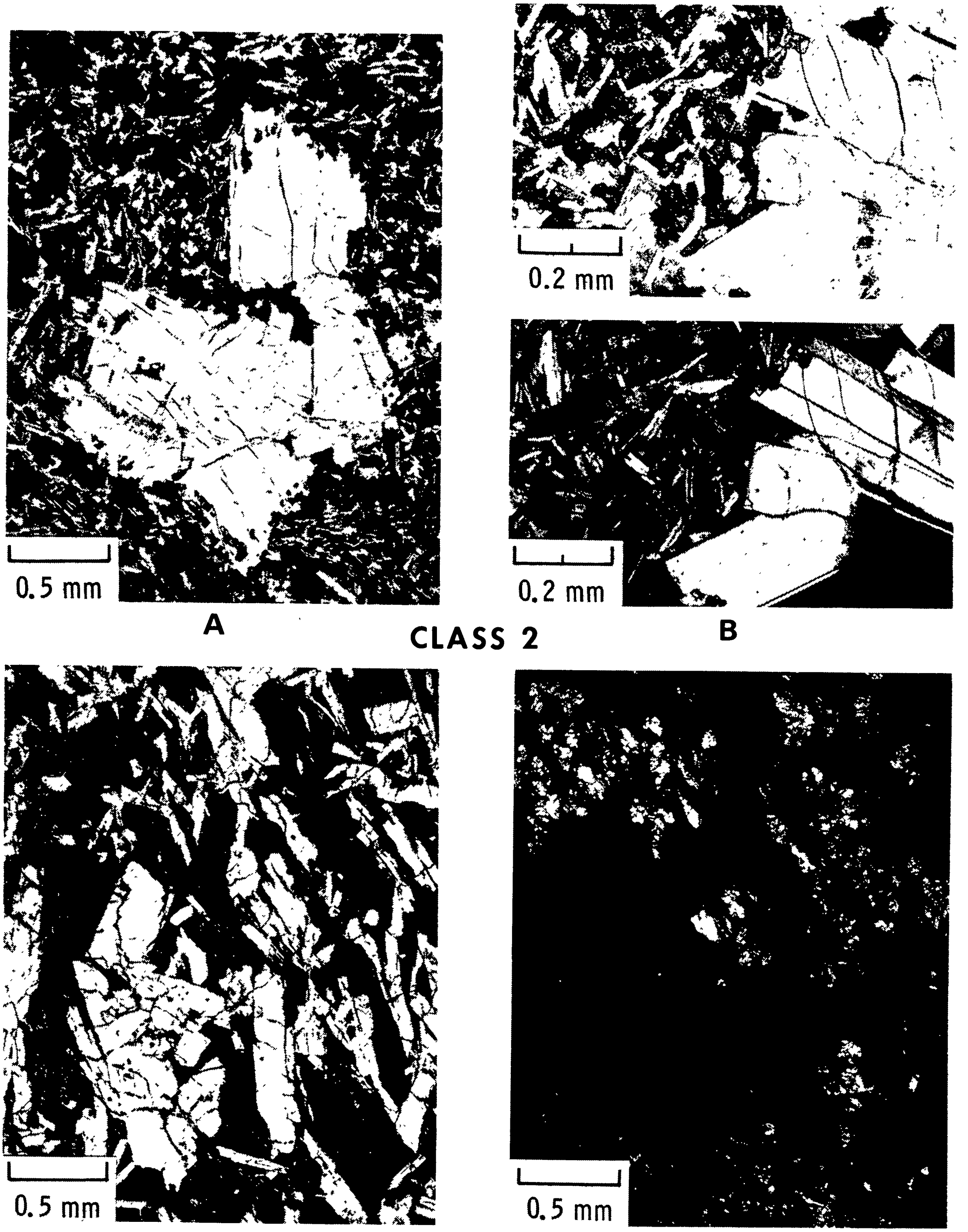

Fig. 2. Lonar basalt, naturally shocked. Upper plates, Class 1. Lower plates, Class 2. (A) Typical texture of a Class 1 rock, with fracturing more prominent in the phenocrysts than in the surrounding fine-grained groundmass. Initial rock texture is preserved. Plane polarized light. (B) Irregular fractures in labradorite phenocryst. Top, plane polarized light. Bottom, polarizers crossed at 80°. (C) Typical texture of a Class 2 rock with prominent fracturing and some granulation of the plagioclase. Initial rock texture is preserved. Plane polarized light. (D) Same region with polarizers crossed at 80°. Isotropic plagioclase is maskelynite, birefringent grains are pyroxene, and opaque grains are opaque minerals.

LONAR BASALT - EXPERIMENTALLY SHOCKED

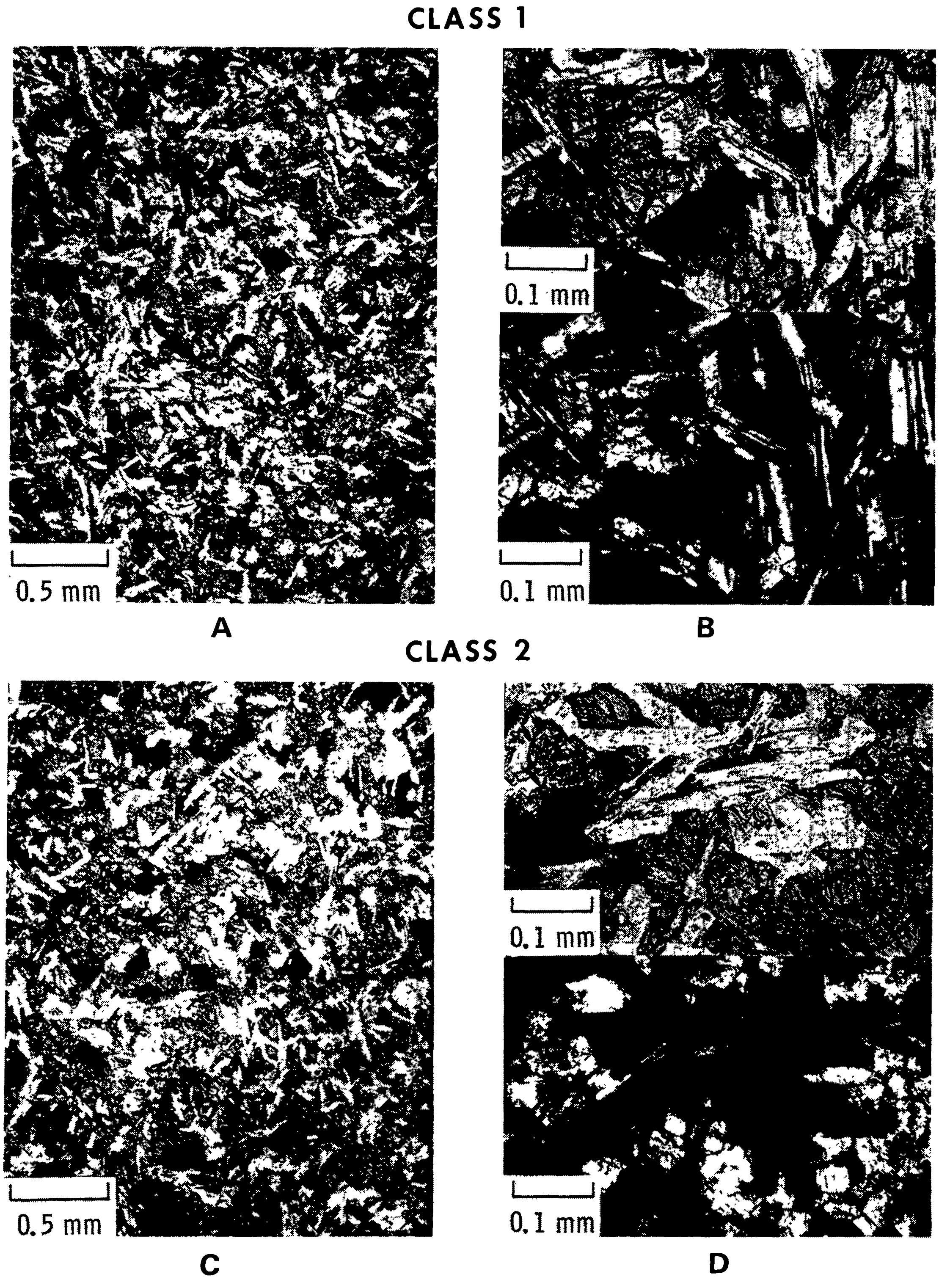

Fig. 3. Lonar basalt, laboratory shocked. Upper plates, Class 1. Lower plates, Class 2. (A) Texture of sample shocked to 202 kbar, Class 1, basically unchanged from initial texture (Fig. 1). Plane polarized light. (B) Sample did not include a large phenocryst, as shown in the naturally shocked Class 1 sample, Fig. 2, but some fracturing is visible in the fine-grained groundmass shown here. Top, plane polarized light. Bottom, polarizers crossed at 80°. Note slight undulatory extinction in plagioclase in groundmass. (C) Texture of sample shocked to 270 kbar, Class 2, showing similarity to initial texture (Fig. 1). (D) Plagioclase laths are undeformed, but are converted to maskelynite. Top, plane polarized light. Bottom, polarizers crossed at 80°.

labradorite and pyroxene. The birefringence of the devitrified palagonite is variable. A few percent of the plagioclase phenocrysts are partially isotropic. Grains of ulvospinel appear unaltered in transmitted light.

Class 2 (Fig. 2C,D; Fig. 3C,D). The most obvious shock effect of Class 2 rocks is the partial to complete vitrification of the plagioclase laths to maskelynite. The general volcanic porphyritic or microporphyritic texture is preserved. Fine-scale fracturing is evident in the pyroxene but is not obvious in the groundmass plagioclase; plagioclase phenocrysts, however, are generally fractured. Pyroxenes show undulatory extinction; palagonite is partially isotropic. In transmitted light opaque minerals appear unaltered.

Class 3 (Fig. 4A,B; Fig. 5A,B). The distinctive characteristic of Class 3 rocks is that plagioclase laths have been converted to plagioclase glass which has flowed locally. This plagioclase glass should not be called maskelynite because it shows evidence of flow. The glass is clear and contains small vesicles in places. In most places relict microporphyritic texture is apparent in these rocks, but the original texture has been modified by flow and deformation in the regions of plagioclase glass. Pyroxene grains are highly fractured and, where near regions of plagioclase glass which has flowed, may be disrupted into small fragments. Opaque skeletal crystals, a few microns in diameter, occur within some pyroxene grains, possibly within submicroscopic glass lamellae. Similar crystals within a pyroxene grain in a Class 5 rock are shown in Fig. 7. These crystals are presumably magnetite or titaniferous magnetite, but are too small for microprobe analysis; we will refer to them as titaniferous magnetite (see Class 5). The brown palagonite generally retains its color in thin section, but in places appears darkened; it is partially to totally isotropic under crossed polarizers. Therefore, we conclude that the devitrified palagonite has been revitrified by the shock. In transmitted light opaque minerals show some alteration on grain boundaries, but are not severely changed.

Class 4 (Fig. 4C,D; Fig. 5C,D). In Class 4 samples all plagioclase has been converted to colorless glass, which is recognizable in hand specimen by its turbid appearance. The microporphyritic texture of the original basalt has been destroyed in these rocks by flow of the plagioclase glass. Very few of the original laths are recognizable. Vesiculation is well developed in the plagioclase glass and vesicles range up to several millimeters in diameter. Some pyroxene grains are subrounded and fragments are dispersed in the plagioclase glass. Fragments of pyroxene are locally melted to brown glass on their edges, but generally this brown glass is not mixed into the plagioclase glass. Small magnetite crystals occur in the crystalline pyroxene (possibly in submicroscopic glass lamellae) and in the edge melt, but they are not abundant. Palagonite is largely converted to opaque material and is isotropic. Opaque minerals are broken and deformed.

Class 5 (Figs. 6, 7, 8). In hand specimen these samples are easily recognizable as coarsely vesicular, black obsidian-like glass. In thin section they are characterized by a predominance of light to dark brown glass which surrounds a variety of inclusions. The glass shows schlieren and flow textures, commonly accented by aligned bands of small skeletal or dendritic crystals. Vesicles are abundant and may be either spherical or elongate. Recrystallized plagioclase occurs sparsely in the glass. Relict pyroxene grains in the glass are rounded and generally contain innumerable skeletal crystals.

The great bulk of the glass has a composition corresponding to the whole rock composition (Table 1). Some of the colorless glass corresponds to plagioclase composition. As is best illustrated on a triangular diagram (Fig. 9), glasses show a mixing trend between these two compositions, with a distinct light brown color apparent as the iron oxide content, expressed as FeO, reaches 10%. Relict pyroxene grains have been rounded and reduced by fracturing and edge melting, from a mean diameter of 130 μm in unshocked basalts to 30 μ in Class 5 specimens. Magnetite dendrites are abundant in association with relict pyroxenes and in trains swirled through the glass. These have the form of a toy jack with six mutually perpendicular limbs of equal length radiating from a nucleus and range from less than 1 to 32 μ across. The small size prohibited quantitative analysis but qualitative microprobe analysis indicates that only iron and titanium metals are present and are in proportions approximately 19 to 1 (Schaal, 1976). This ratio approximates that observed in augite, in contrast to the 3 to 1 ratio in ulvospinel, suggesting that they grew in glass derived from pyroxene without necessary involvement of material from primary opaque minerals. This is supported by the association of the dendrites with pyroxene remnants not only in Class 5 samples but more sparsely in Class 3 and 4 samples where melting of the pyroxene is not as well exhibited.

In many regions the brown glass has devitrified into fibrous spherulites. The width of the individual crystals in the spherulites is generally less than 1 μm; the length may be as great as 100 μm. The spherulites have nucleated on and grown outward from relict pyroxene grains, recrystallized plagioclase, magnetite dendrites, or vesicle walls. In some places, where they presumably nucleated on submicroscopic seeds, they occur isolated in the glass and have the shape of a wheat sheaf. Although quantitative microprobe analyses of the glass and spherulite were difficult to obtain, qualitative probe analyses demonstrate that the spherulites have the same composition as the glass; both contain silicon, aluminum, iron, calcium, magnesium, titanium, sodium, and potassium. They have less magnesium and calcium and more aluminum than the pyroxene grains. The structure of the spherulites is independent of the schlieren structure in the rocks, indicating that they grew after cessation of flow. However, a cell-like impingement structure frequently is observed, suggesting simultaneous nucleation and growth of the spherulites, probably while the glass was still relatively hot.

4. Experimental Analogs

In an attempt to accurately assign pressure ranges to shock effects observed in basalts from Lonar, we have shock-loaded a number of samples of an unshocked basalt obtained from the core at 81 m depth (Fig. 1). Discs (8 mm diameter × 0.5 mm) were encapsulated in stainless steel 304 and shocked at various pressures

LONAR BASALT - NATURALLY SHOCKED - CLASS 3

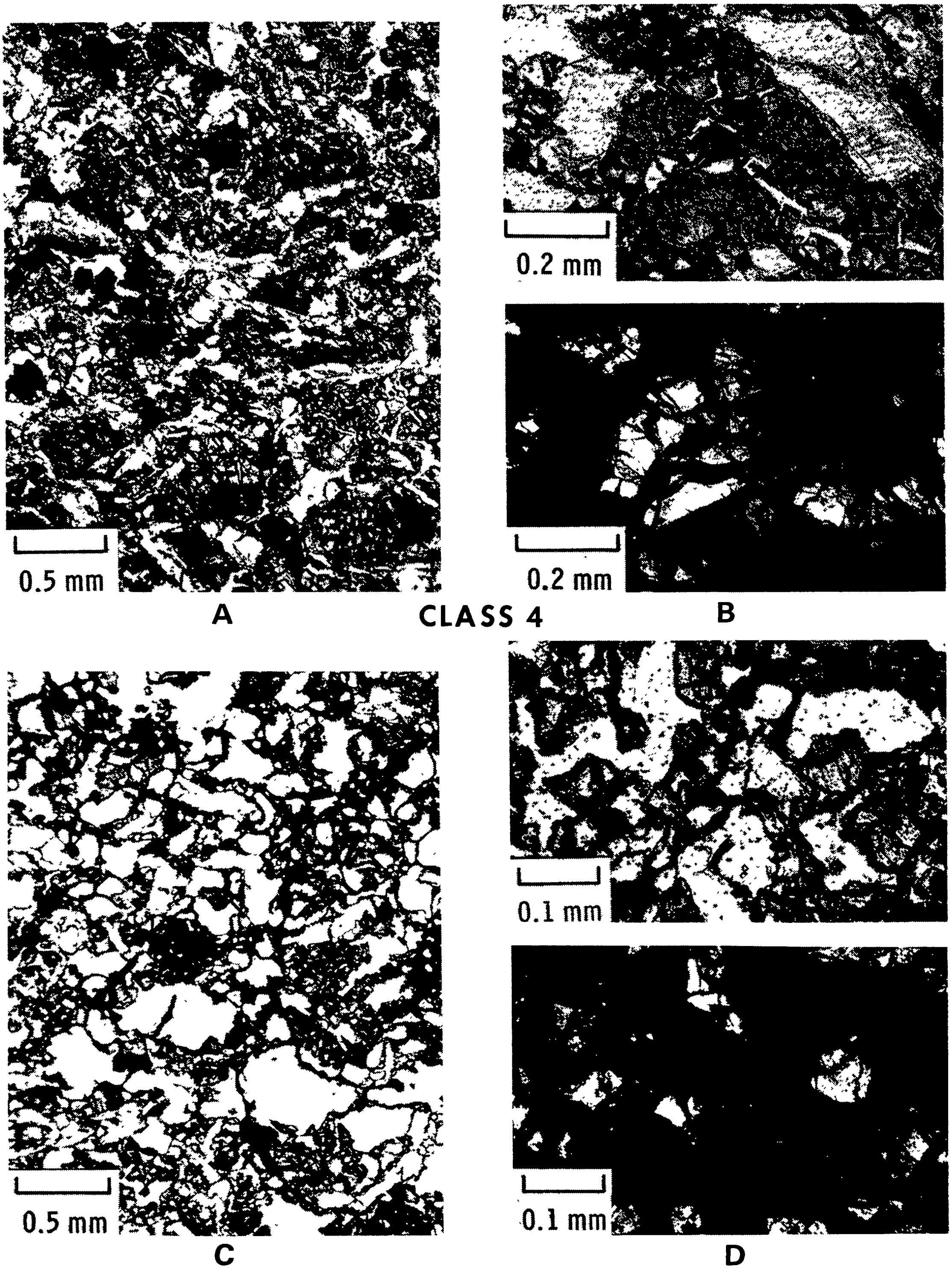

Fig. 4. Lonar basalt, naturally shocked, Upper plates, Class 3. Lower plates Class 4. (A) Typical texture of Class 3 rock with labradorite laths showing some flow but preserving relict microporphyritic texture. Plane polarized light. (B) Isotropic plagioclase and granulated pyroxene. Top, plane polarized light. Bottom, polarizers crossed at 80°. (C) Typical texture of Class 4 rock with vesiculated plagioclase grains. Original microporphyritic texture has been destroyed. Plane polarized light. (D) Melted plagioclase grains and relict pyroxene fragments. Top, plane polarized light. Bottom, polarizers crossed at 80°.

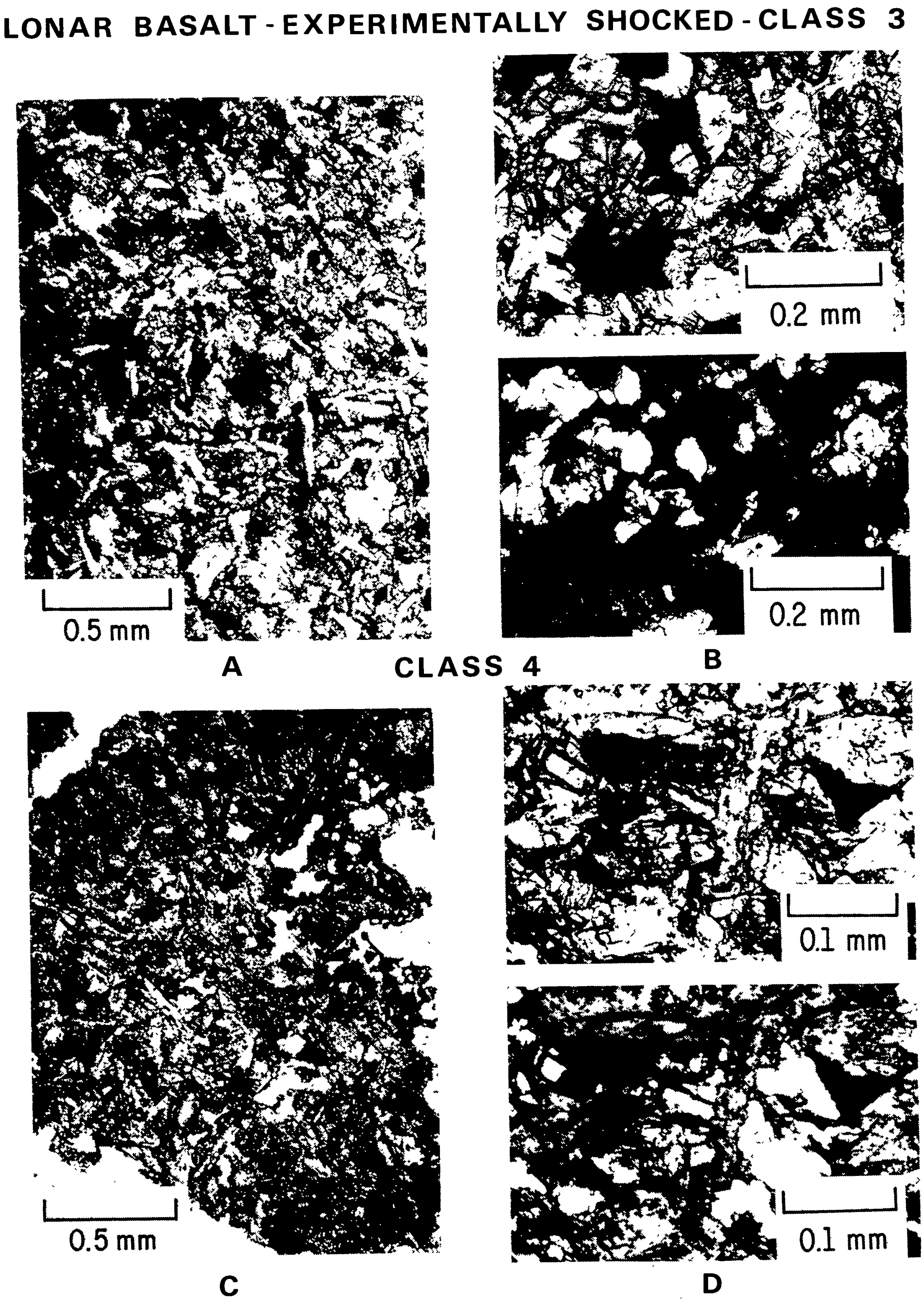

Fig. 5. Lonar basalt, laboratory shocked. Upper plates, Class 3. Lower plates, Class 4. (A) Texture of sample shocked to 510 kbar, Class 3, showing some loss of initial microporphyritic texture. Plane polarized light. (B) Sample showing slight vesiculation in isotropic feldspars (light grains in top photo). Top, plane polarized light. Bottom, polarizers crossed at 80°. Pyroxenes are fractured. (C) Texture of sample shocked to 640 kbar, Class 4, showing some loss of initial microporphyritic texture. Loss of texture is not as complete as in naturally shocked Class 4 rocks. (D) Melted feldspars showing some flow, and granulated pyroxenes. Top, plane polarized light. Bottom, polarizers crossed at 80°.

LONAR BASALT — CLASS 5

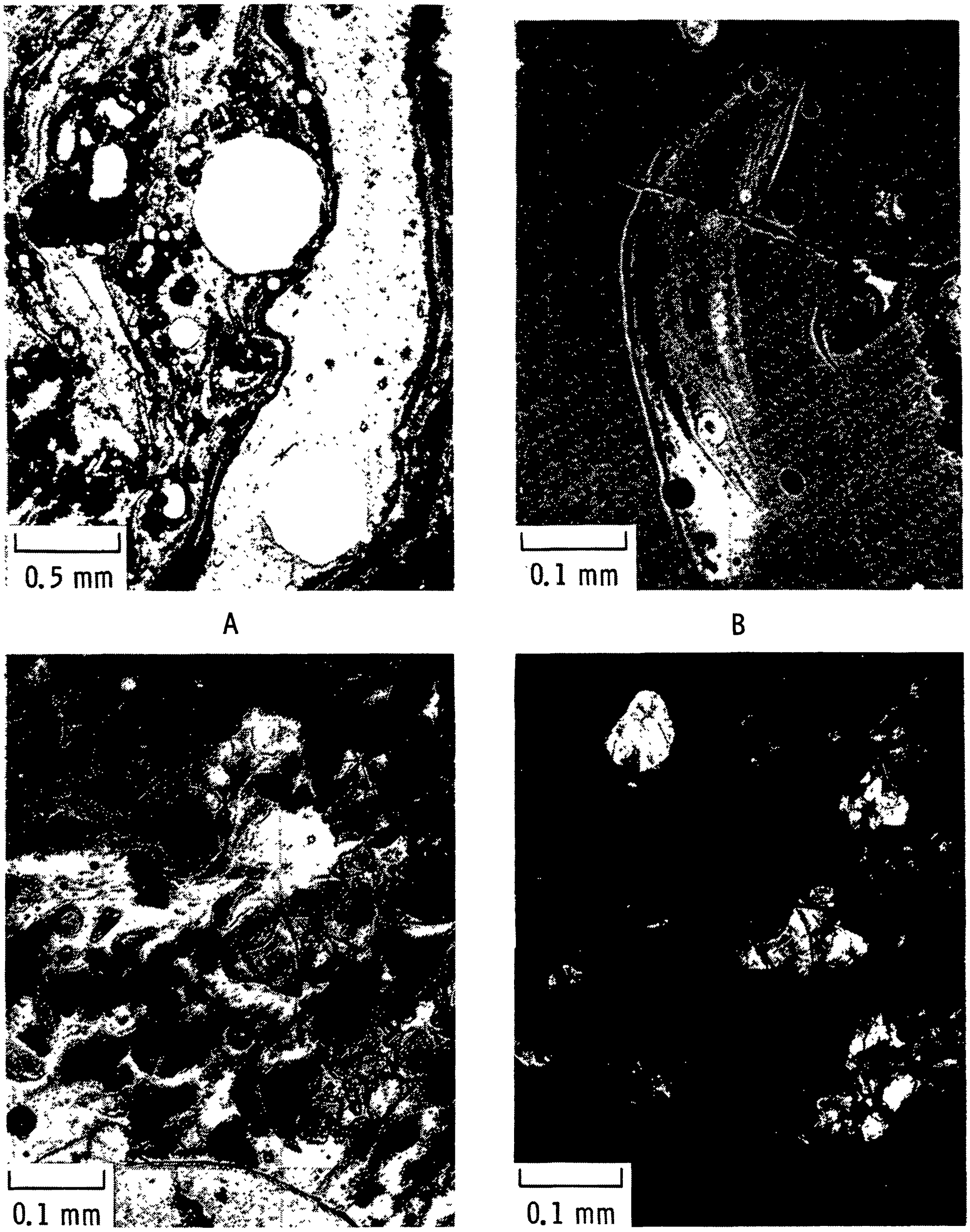

Fig. 6. Lonar basalt, naturally shocked, Class 5. (A) Typical vesiculated glass of Class 5 rocks. In thin section the glass is usually light brown in color (light grey on photo) with dark brown flow bands (black on photo). Note vesicles, relict pyroxene fragments, and schlieren enhanced by dendritic titaniferous magnetite crystals. Plane polarized light. (B) A region in which mixing of the melted mineral components is incomplete. The central light area is a zone of melted plagioclase. It is surrounded by brown glass. Flow of the plagioclase parallels that of aligned opaque grains to the right. Plane polarized light. (C) A region in which melting of the mineral components is incomplete. All plagioclase in this region has melted; a patch of colorless plagioclase glass is visible just above the

between 200 and 650 kbar by a 20 mm caliber flat plate accelerator in a vacuum of 50 μm of Hg. Details of the experimental shock-loading procedures are described by Hörz (1970). Samples were recovered intact and were made into polished thin sections for microscope and microprobe analysis.

Peak shock pressures reported are pressures induced in the metal sample assemblies by impact of the flat plates; pressures are determined by graphical impedance-matching techniques (for example, Duvall and Fowles, 1963) using the Hugoniot data reported in McQueen *et al.* (1970) and Jones *et al.* (1965). The samples were all enclosed in stainless steel 304 containers (68% Fe, 21% Cr, 9% Ni); all flyer plates were made of Fansteel 77 (89% W, 7% Ni, 4% Cu), except for the lowest pressure shot, for which the flyer plate was stainless steel 304. The pressures attained and the velocities of the projectiles fired were: 202 kbar (0.96 km/sec, stainless steel projectile); 250 kbar (0.96 km/sec); 270 kbar (1.02 km/sec); 281 kbar (1.05 km/sec); 334 kbar (1.22 km/sec); 428 kbar (1.49 km/sec); 442 kbar (1.53 km/sec); 445 kbar (1.54 km/sec); 510 kbar (1.72 km/sec); 594 kbar (1.94 km/sec); 642 kbar (2.06 km/sec). Pressures are accurate to approximately ±3%, with the main uncertainty due to inaccuracies of approximately 1% in measuring the projectile velocities and of approximately 2% in the Hugoniot data. The duration of the shock pulse in a typical experiment is ~ 1 μsec. Pertinent experimental information is tabulated in Table 3 and summarized below.

Class 1 (Fig. 3A,B). The most obvious shock feature of naturally shocked Class 1 rocks is irregular fracturing which is particularly well developed in the plagioclase. Similar fracturing was reproduced in the sample experimentally shocked to 202 kbar (Fig. 3A). In this sample undulatory extinction is apparent in some of the labradorite and pyroxene, but it is not pronounced.

Class 2 (Fig. 3C,D). The most evident shock effect of naturally shocked Class 2 rocks is partial to complete vitrification of the plagioclase laths to maskelynite. Partial vitrification of plagioclase is observed in the samples experimentally shocked to 250, 270, and 281 kbar. Nearly total vitrification without significant evidence of flow or vesiculation is observed in the sample shocked to 334 kbar. In all four of these samples pyroxenes exhibit extreme undulatory extinction and some mosaicism and in all four of these samples the devitrified palagonite retains its color, but with increasing pressure the birefringence is reduced. The opaque minerals appear unchanged.

Class 3 (Fig. 5A,B). The characteristic effect of Class 3 rocks is vesiculation and flow of the plagioclase. Plagioclase in experimentally shocked samples does

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center of the photo. Some pyroxene has melted; the darker glass in the upper left is derived from melted pyroxene. It contains numerous skeletal magnetite crystallites. There are, however, many unmelted pyroxene grains embedded within the glass. In some places thin bands of brown glass can be traced directly to rounded pyroxene grains and edge-melting of these grains can be seen. (D) Same view, crossed polarizers. Birefringent grains are pyroxenes.

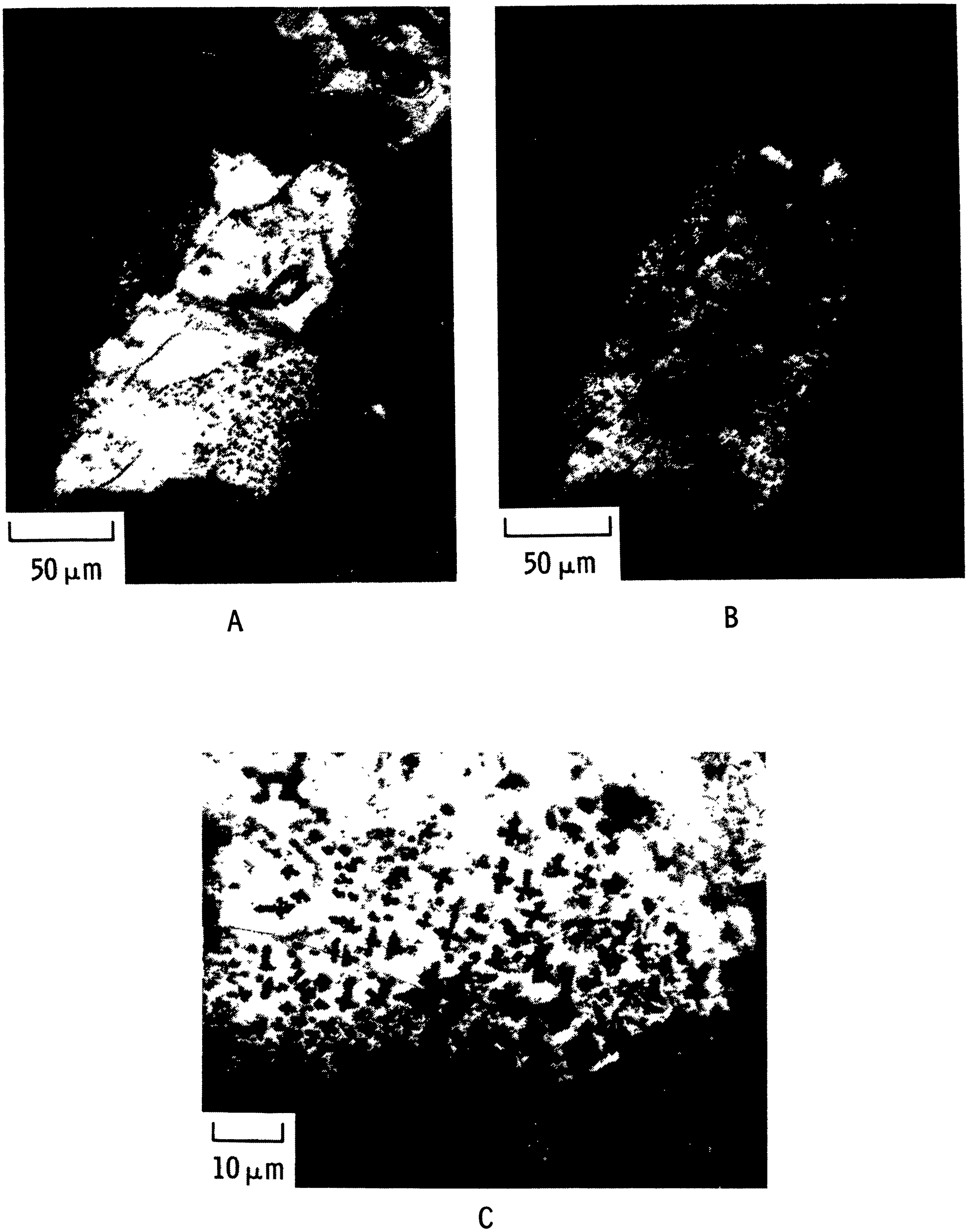

Fig. 7. Lonar basalt, naturally shocked, Class 5. Pyroxene grain inclusions. (A) Pyroxene grain containing opaque dendritic inclusions; surrounded by glass. (B) Same view, crossed polarizers. (C) Enlargement taken with plane polarized light with oil immersion. Shows detail of ornamentation of opaque dendrites.

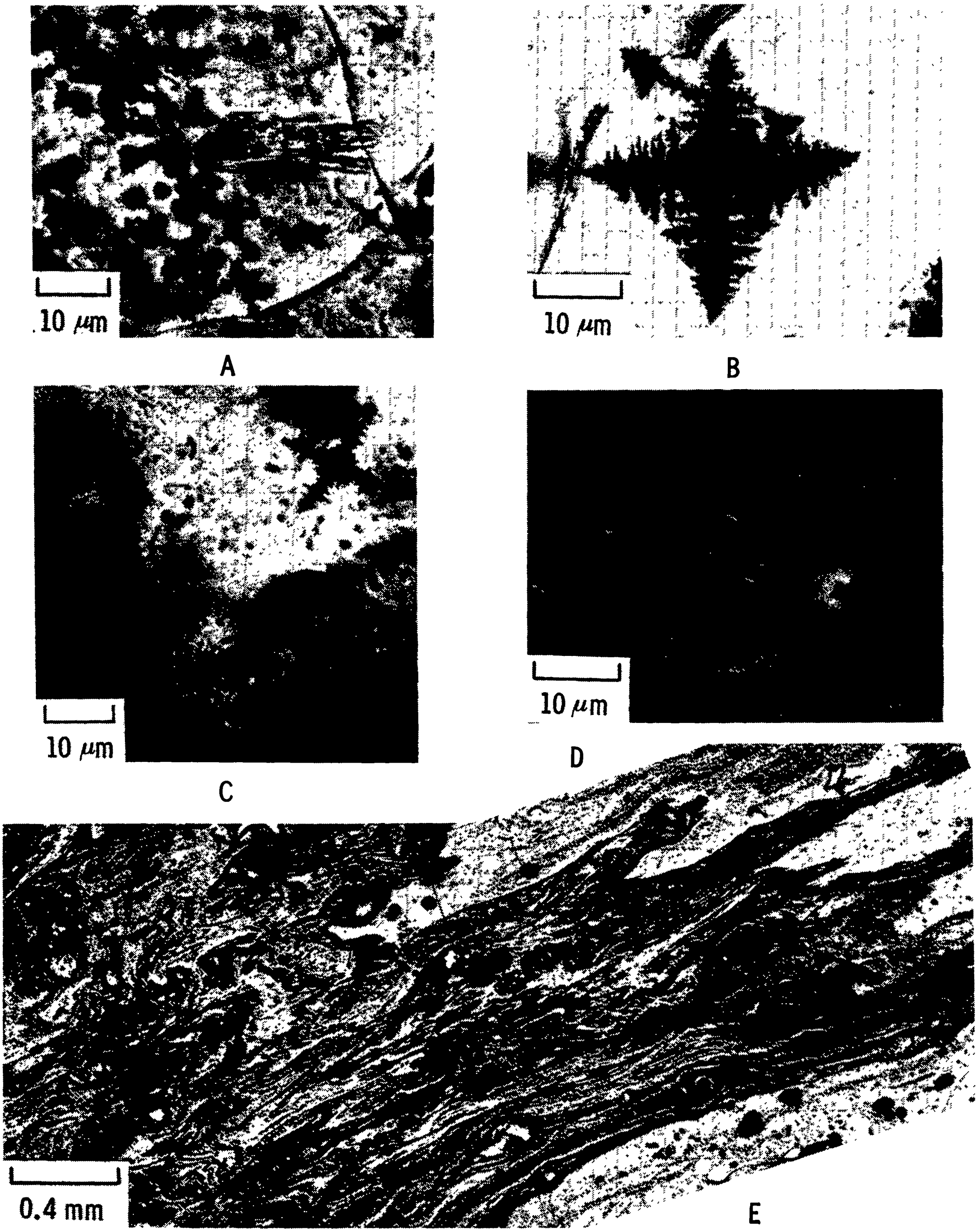

Fig. 8. Lonar basalt, naturally shocked, Class 5. Dendrites and spherulites in shock-melted glass. (A) Dendritic titaniferous magnetite crystals and a bow-tie spherulite within brown glass. Plane polarized light; oil immersion. (B) The largest dendritic titaniferous magnetite crystal found in the shock-melted glass. Plane polarized light; oil immersion. (C) An opaque dendrite, fan spherulites with scalloped edges (lower right and left margin), and a plumose spherulite with feathery edges (bottom center). Plane polarized light; oil immersion. (D) Titaniferous magnetite crystals aligned in flow bands in brown glass. Enlargement of region in (E). Plane polarized light; oil immersion. (E) Flow banding in shock-melted glass. This degree of heterogeneity is characteristic of the shock-melted glasses from Lonar. Plane polarized light.

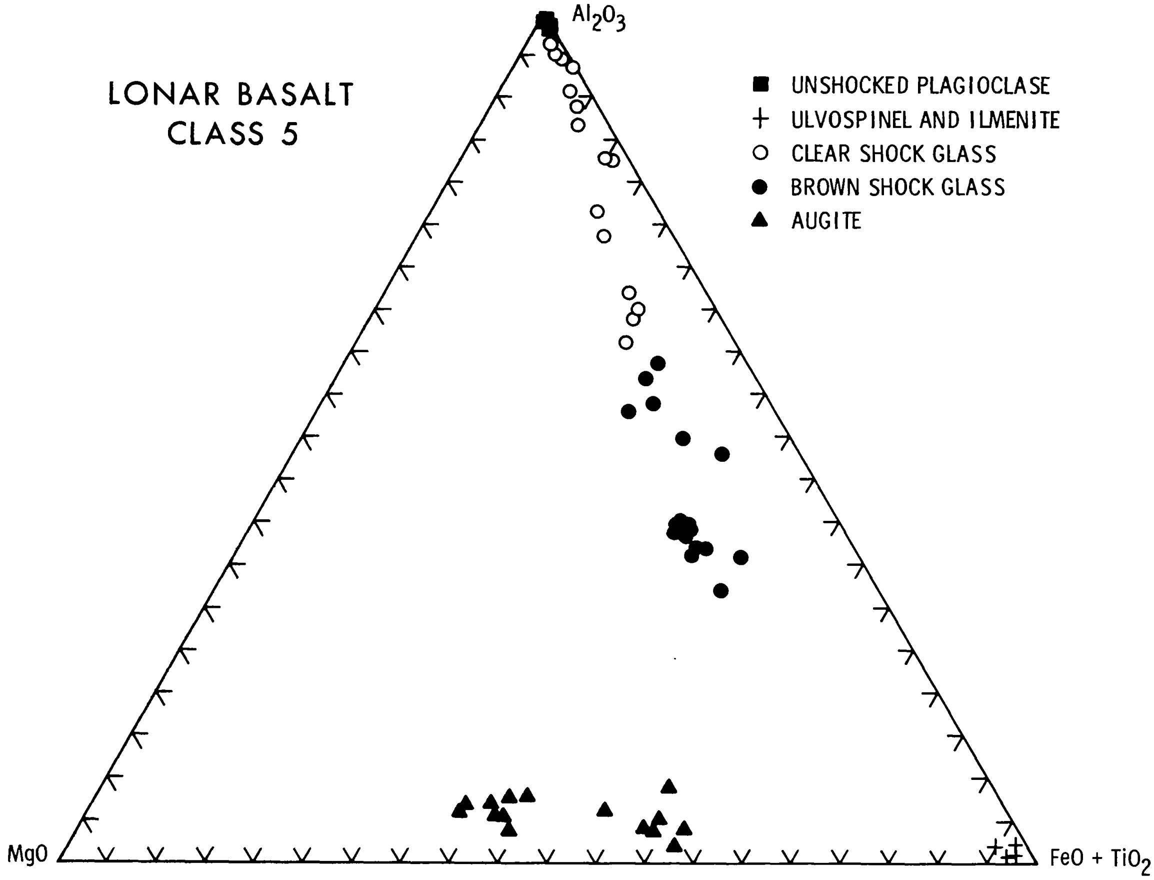

Fig. 9. Ternary diagram showing composition variation of colorless and brown shock glasses with respect to the major minerals in Class 5 samples of naturally shocked Lonar basalt.

not develop flow features as extensively as plagioclase in naturally shocked rocks, but it does display the characteristic vesiculation of plagioclase shown by naturally shocked Class 3 samples. Minor amounts of vesiculation occur in the sample shocked to 428 kbar, increasing amounts in samples shocked to 442, 445, 510, and 594 kbar. Incipient flow of plagioclase is observed in the samples shocked to 428, 442, and 510 kbar. Flow is well developed in samples shocked to 445 and 594 kbar. Pyroxenes in these samples are granulated and show extreme undulatory extinction and mosaicism. Palagonite generally retains its color but some is darkened. It is generally isotropic under crossed polarizers. The opaque minerals are unchanged, with the exception of minor fragmentation.

Class 4 (Fig. 5C,D). The characteristic texture of the naturally shocked Class 4 rocks is extensive flow of the plagioclase, resulting in loss of the original microporphyritic texture, and edge-melting of pyroxene grains. We observe such extensive flow and vesiculation only in the sample experimentally shocked to 642 kbar and assign it to Class 4. (This sample is dark and difficult to study, so our conclusions about its texture are somewhat tentative. We are at present conducting more experiments in the 500–1000 kbar range, but find it challenging to recover and section samples. This work will be reported at a later date.)

Systematic trends are recognizable in both the naturally shocked and experimentally shocked rocks: the sequence of plagioclase destruction and the changes of appearance of the palagonite are similar in both suites of rocks. Flow of plagioclase melt does not appear to develop as extensively in experimentally shocked samples as in naturally shocked samples, presumably because experimentally shocked samples are quenched in a much shorter time than naturally shocked samples. Schaal (1976) considers this problem in comparing shock-melted basalt in lunar microcraters with shock-melted basalt from Lonar.

The main difference between the two suites of samples appears to be in the appearance of the pyroxene. At low pressures a comparable degree of granulation of pyroxene occurs in the two suites. At high pressures, however, pyroxenes from Lonar show edge-melting (Class 4) and formation of some skeletal magnetite crystals (Classes 3, 4, and 5; Figs. 4 and 7). Neither of these effects has been observed in experimentally shocked samples, although they would be expected to occur at pressures above 400 kbar if the experimentally shocked samples were exact analogs of the naturally shocked basalts.

5. Summary

For nonporous basalts, a careful comparison of textures produced under laboratory and natural shock conditions can yield pressure calibrations for the naturally shocked rocks *if* the shock indicators selected form by processes which are rapid compared to the duration of the laboratory event. However, if the processes involve flow, cation-diffusion, or sluggish phase changes, the experimentally shocked samples will not provide an accurate basis for pressure estimates for samples from big impact events. We conclude that the response of *plagioclase* to experimental shock events is nearly identical to its response in much longer natural shock events, although flow is less extensively developed at the higher shock pressures, and therefore, base our pressure calibrations primarily on a comparison of plagioclase textures. The following pressure assignments are made:

Class 1: $P < 200$ kbar
Class 2: $200 < P < 400$ kbar
Class 3: $400 < P < 600$ kbar
Class 4: $600 < P < \sim 800$ kbar
(Class 5 estimate: $P > 800$–1000 kbar)

The upper pressure limit set for Class 1 is considerably higher than previously estimated for fracturing and crushing in nonporous rocks (e.g., Stöffler, 1971; Short, 1969). The upper limit of Class 2 is consistent with previous estimates of upper limits for partial to total vitrification of plagioclase in nonporous rocks (Stöffler, 1971, p. 5547, 5548; Short, 1969, p. 83). Pressures for Classes 3, 4, and 5

Table 3. Description of

	Class 1	Class 2			
					Shock
Property	202 kbar	250 kbar	270 kbar	281 kbar	334 kbar
Texture	Nearly same as unshocked; rich in palagonite	Micropor-phyritic texture preserved	Micropor-phyritic texture preserved	Micropor-phyritic texture preserved	Micropor-phyritic texture preserved
Plagio-clase	Minor undula-tory extinction. Minor frac-turing	Index and birefring-ence reduced and variable. Partially isotropic. Extreme undulatory extinction	Index re-duced. Bire-fringence reduced. Over 90% isotropic	Index re-duced. Bire-fringence re-duced. (Less isotropic feldspar than 270 kbar sample!)	Index re-duced. Most is isotropic. Locally traces of melt
Pyroxene	Fractured (but so is pyx. in unshocked)	Fractured and crushed. Some undula-tory extinc-tion and mosaicism	Fractured. Undulatory extinction and mosaicism	Granulated. Severe mosaicism and undula-tory extinc-tion	Granulated. Severe mosaicism and undula-tory extinc-tion
Opaque minerals	Unaltered	Unaltered	Unaltered	Basically unaltered. Possibly slight fracturing	Unaltered
Pala-gonite	Unaltered (original palagonite is generally bright rust colored)	Slightly reduced birefring-ence. Color preserved	Variable birefring-ence. Color preserved	Variable and gener-ally reduc-ed birefring-ence. Color preserved	Variable birefring-ence. Mosaic-ism. Color preserved
General com-ments	Sample shocked uniformly. No absolute diag-nostic differ-ence from un-shocked	Sample shocked uniformly. ~10% of feld-spars totally transformed to maskely-nite	Sample shocked uniformly	Sample shocked uniformly. Not much palagonite in section, but abundant opaque minerals	Sample shocked uniformly

experimentally shocked Lonar basalt.

Class 3					Class 4
pressure					
428 kbar	442 kbar	445 kbar	510 kbar	594 kbar	642 kbar
Micropor-phyritic texture preserved	Micropor-phyritic texture recognizable	Micropor-phyritic texture difficult to recognize	Micropor-phyritic texture recognizable	Micropor-phyritic texture destroyed	Micropor-phyritic texture destroyed. Vesiculated
Isotropic. Minor flow and vesicu-lation	Isotropic Minor flow and vesicu-lation	Isotropic. Over 90% highly vesicu-lated and flowed	Isotropic. Minor flow and vesicu-lation	Isotropic. Flow and vesiculation well developed	Isotropic. Highly vesiculated
Severely fractured. Extreme mosaicism and undula-tory extinc-tion	Severely fractured. Birefringence reduced (?). Mosaicism and undulatory extinction	Fractured; granulated. Mosaicism and undula-tory extinc-tion	Fractured. Mosaicism and undula-tory extinc-tion	Granulated; fragments dispersed by flow of plagioclase. Undulatory extinction	Fragmented; dispersed by flow of plagioclase
Basically unaltered. Some fragmentation	Unaltered	Unaltered	Unaltered	Fragmented. Oxidized on margins	Possibly partially melted. Ox-idation on margins in a few places, but not as prominent as in 594 kbar sample
Most color lost. Has transformed to fine-grained black material	Birefringence reduced. Some iso-tropic. Color preserved	Largely isotropic. Color preserved	Most, but not all, is dark and isotropic	Not recog-nizable	Not recog-nizable
Some ir-regularities in shock in-tensity, par-ticularly around edges. Palagonite difficult to recognize	Much of sample lost	Some ir-regularities in shock in-tensity. Edges less highly shocked than center	Uniformly shocked. Sample rich in opaque minerals, poor in palagon-ite. In several places pyroxene is recrystallized. Not observed in other samples so is considered anomalous	Most of sample lost	About $\frac{1}{4}$ of sample lost

are considerably higher than previous estimates for basalt (Short, 1969; Fredriksson *et al.*, 1973) and for crystalline quartzofeldspathic rocks from the Ries Crater (Chao, 1968, p. 138; Engelhardt and Stöffler, 1968, p. 160).

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