anorthositic rock fragments and such of different stages of shock metamorphism including light colored fused glasses. The north–northeast trending ray may have furnished dark glasses of basaltic composition.

Another possibility is that anorthositic rocks and glass came from pre-mare rocks of highland type underlying the basaltic mare material. The mare material is assumed to form a relatively thin layer in the area of the Apollo 11 landing site. In this case the anorthositic rocks and glasses may have been ejected from larger mare craters such as Sabine E, D and Moltke (SHOEMAKER *et al.*, 1969).

Table 5. Comparison of Surveyor analytical results (PATTERSON *et al.*, 1969) with the composition of dark and light colored glasses (wt. %)

	Surveyor 5 (Mare Tranquillitatis)	Dark colored glasses Average	Surveyor 7 (Tycho)	Light colored glasses Average
SiO_2	46	39	50	45
TiO_2	8	8	—	0·7
Al_2O_3	14	11	21	24
FeO	12	18	7	7
MgO	4	9	7	8
CaO	14	10	15	14
Na_2O	0·6	0·4	—	0·3

Coatings of brown, vesicular glass on pieces of breccia or crystalline rocks, and fragments of the same glass occur in the soil and breccias. This glass is more vesicular and richer in mineral inclusions and schlieren than the other glasses described above.

Three such glasses adhering to two basaltic rocks and one breccia have been analyzed. The results, given in Table 6 and in Figs. 9–11, show that these glasses belong to the group of dark colored glasses of basaltic composition. The basaltic rocks, No. 2 and 3 of Table 6 show indications of shock metamorphism at the contact of the glass coating: pyroxene grains contain deformation lamellae and in the rock No. 3 plagioclase is transformed into diaplectic glass (see next section). We assume, therefore, that the glass coatings were produced by the impact of small rock fragments or splashes of melt, ejected from meteorite craters. The brown glass of coating No. 3 contains 0·07 wt. % Cr_2O_3, the pyroxene of the underlying basalt 0·4 wt. % Cr_2O_3.

Table 6. Chemical composition of vesicular glass coatings (microprobe analysis, wt. %)

	Sample	No.	SiO_2	TiO_2	Al_2O_3	FeO	MnO	MgO	CaO	Na_2O	K_2O	Total
Brown glass coating breccie	10085-26	M58A	39·86	8·03	12·62	16·13	0·16	7·32	11·49	0·24	0·85	95·93
Brown glass coating basaltic rock	10060-34	—	39·69	8·68	9·95	19·45	0·18	7·19	10·85	0·28	0·08	96·36
Brown glass coating basaltic rock	10085-25	M61	41·09	8·58	9·68	20·83	0·21	4·77	10·56	0·38	0·11	96·20
Inclusion of gray glass in the brown glass	10085-25	M61	45·91	3·40	4·59	13·85	0·20	12·67	15·77	0·08	0·00	96·47
Pyroxene in the basaltic rock	10085-25	M61–41	46·84	3·11	4·07	9·11	0·12	13·65	17·32	0·11	0·03	94·36

It is therefore unlikely that this glass was formed by fusion of the impacted basalt. It probably represents mainly the material of the impacting projectile. However, some individual components of the impacted rock were fused without being dissolved in the melt. This is shown by an inclusion of a gray glass of pyroxene composition in the brown glass. The composition of the gray glass is nearly identical with that of the pyroxene in the basalt (see Table 6).

Conclusions

During the formation and excavation of an impact crater a large amount of rock will be subjected to stress waves with peak pressures below the dynamic elastic limit of the minerals affected. This material will be fractured, deformed and ejected. However, it will not contain shock effects *sensu stricto* as defined in the introduction, i.e. deformation structures, solid state transformations and fusion products which can be formed only by pressures above the dynamic elastic limit.

According to the geometry of dissipation of the energy set free by the impact of a meteorite the amount of rock affected by stresses below the dynamic elastic limit represents by far the greatest portion of all material ejected from the crater.

From the observed shock effects in Apollo 11 samples we establish the following simplified classification of 5 stages of progressive shock metamorphism in lunar rocks.

(1) The lowest degree of shock metamorphism is represented by rocks the pyroxenes and plagioclases of which contain deformation structures. The plagioclase has a normal or reduced birefringence and refraction index. Apparently, deformation structures in pyroxene begin to develop at lower peak pressures than those in plagioclase. The pressure range in which deformation lamellae are formed in lunar plagioclase seems to be rather narrow.

(2) The next stage of shock metamorphism is characterized by rocks containing diaplectic plagioclase glasses together with pyroxene and olivine both exhibiting deformation structures. We estimate the pressure range of this stage to be from $\simeq$300 to $\simeq$550 kbar.

(3) We have not yet observed selectively fused plagioclase in any lunar rocks; a stage of shock metamorphism frequently found in terrestrial impact craters (e.g. Ries Basin, Germany). This may be due to the similar values of the melting temperatures of lunar plagioclase and pyroxene, resulting in simultaneous melting of both minerals.

(4) A still higher stage of shock metamorphism is represented by complete melting of rocks resulting in the various glasses described above. Melting is achieved by shock pressures producing residual temperatures which exceed the liquidus temperature of the rocks. We assume the pressure range of this stage to be from $\simeq$600 kbar to the Megabar region.

(5) The highest stage of shock metamorphism leads to vaporization of rocks. The very homogeneous glass bodies may be condensation products of silicate vapor. Vaporized meteoritical material may be incorporated.

Three of these stages have been observed, on a small scale, in one single fragment ($1 \times 0{\cdot}4 \times 0{\cdot}6$ cm) of a basaltic rock, shown in Fig. 12. The surface of this fragment is covered with a brown glass (No. 3, Table 6), representative of stage 4. Beneath the glass follows a zone in which all plagioclase is converted into diaplectic glass. The