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Thermal regimes in cratered terrain with emphasis on the role of impact melt

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Abstract

Heavily cratered terrain is characteristic of the older surfaces of the terrestrial planets; this type of terrain is older than 3.9AE on the moon. Lunar highland rocks, the only samples other than meteorites from such terrain, consist of about 10 percent primitive crust lithologies, 60 percent impact-produced fragmental breccias, and about 30 percent impact-melt rocks with abundant clasts or xenoliths. Both the impact-melt breccias and the fragmental breccias consist of intimate mixtures of superheated shock melt derived from near the point of impact (a small fraction of the crater volume excavated) and less shocked, colder clastic debris from farther out but mostly within the crater. This initial bimodal temperature distribution is due to the extremely rapid attenuation of the shock wave away from the point of impact, and the fact that rock can be crushed and excavated although it may have been shock-heated to < 200°C. The distinction between the melt rocks and fragmental breccias is the fraction of melt in the mixture, the former resulting from mixtures with over 50 percent melt component. There is a complete spectrum of melt-clast mixtures, but lithologies with between 1/4 and 2/3 melt seem to be relatively rare in the lunar highland collection. Sheets of impact melt typically occur as a lining on the floor of craters and pools or tongues that spill out a short distance over the rim; the fragmental breccias tend to overly the melt sheets and form most of the deposits outside the crater; however, glass fragments and bombs of melt are mixed into many of the fragmental breccias.

The shock wave accelerates the melt to velocities of several km/sec downward and outward, allowing the melt to overtake the slower moving fragmental debris. The mixing must be extraordinarily complete, because melts commonly have clasts within every 1 mm^2 area of thin sections. Once the hot and cold components are mixed, thermal equilibrium is achieved in less than 100 sec due to the sub mm scale of mixing. In the fragmental breccias small particles of melt sintered to act as a binder for the fragmental material; in some mixtures the melt quenched so rapidly that glass remains in the matrix. In other cases the melt was sufficiently abundant or the clastic material sufficiently warm that the matrix melt particles cooled more slowly, crystallized, and reacted with the rims of small mineral clasts. In the crystalline impact-melt rocks the mixtures initially contained over 2/3 melt, a substantial fraction of the clastic debris was digested, and the liquid quenched into the interval between liquidus and solidus, initiating nucleation and accounting for the fine grain size of most impact melts. Because heat represents 23–35 percent of the impacting projectiles' kinetic energy, and melting takes up a substantial fraction of the heat, the heat transfer and phase transformations driven by melt-clast interactions are a significant fraction of all the reactions which can take place in the anhydrous, refractory materials that made up the lunar highlands during the period of intense meteorite bombardment.

Introduction

Heavily cratered terrains are known to exist on Mercury from Mariner 10 imagery (Murray *et al.*, 1974); Venus by radar mapping (Rumsey *et al.*, 1974); the moon; Mars from photographs taken by Mariners 6, 7, and 9; and Phobos and Deimos by Mariner 9 imagery. In addition, shock effects are common in some classes of meteorites (McCall, 1973), but the planets from which these objects are derived are largely unknown. Age determinations on breccias from the heavily cratered lunar highlands virtually all fall in the interval from 4.1–3.85AE, with most falling around 3.95AE (Tera *et al.*, 1974). These ages suggest that the major bombardment of the moon was confined to the first 7×10^8 years of lunar history. If the bombarding objects were in the more likely classes of orbits, then all of the inner planets, including the earth, were subjected to a bombardment similar in duration to the lunar bombardment and differing by no more than a factor of four in intensity (Wetherill, 1975). During this period of bombardment, the projectiles' kinetic energy must have been a significant energy input to the crust of all of the terrestrial planets. The question to be addressed in this paper is how this energy is distributed in the crust, and, specifically, what types of phase transformations result from this energy input. It is our contention that the impact melts produced near the point of impact, and deposited as sheets, dikes, bombs, and a major constituent of fragmental matrix breccias, play a major role in the energy transfer.

Lunar highlands lithologies

For purposes of this discussion the samples from the lunar highlands collected at the Apollo 14, 15, 16, and 17 landing sites may be divided into three categories: (1) primitive plutonic rocks, including a variety of troctolites, norites, dunites, and anorthosites, making up about 10 percent of the highlands suite, (2) fragmental-matrix polymict breccias making up about 60 percent, and (3) impact-melt polymict breccias making up about 30 percent. The proportions of these types at the different sites vary, for reasons that will be explored below.

Fragmental-matrix polymict breccias

Fragmental-matrix polymict breccias consist of angular to subrounded glass, mineral, and lithic fragments in a seriate grain distribution. A substantial amount of matrix (arbitrarily defined as fragments $< 20\ \mu m$) is present, as well as numerous clasts > 0.5 m seen in photographs taken on the lunar surface. The matrices range in porosity from 0 to 30 percent with the bulk of the pores being less than 20 μm across. In one subgroup of these rocks, vitric-matrix breccias, a significant amount of the matrix fragments are glass particles that are sintered together. Other classes of fragmental-matrix breccias contain holocrystalline matrices which appear to have contained glass that has crystallized and begun to equilibrate with the smaller clasts. In general, small mineral clasts show evidence of equilibration with the matrix glass by forming rims or overgrowths with the same compositions as the crystallized glass (Warner, 1972).

Impact-melt polymict breccias

Impact-melt polymict breccias consist of mineral and lithic fragments set in a matrix which has behaved as a liquid. The proportion of matrix is higher than in the fragmental-matrix polymict breccias, ranging from 60 percent to essentially 100 percent of some rocks. Matrix textures range from flow-banded glass through devitrified glass to subophitic and poikilitic textures similar to many terrestrial volcanic rocks. Warner *et al.* (1973) have shown that the textures are a function of bulk composition and cooling history. Age determinations on this group of rocks make up the bulk of the nonmare ages falling in the 3.85–4.05AE intervals.

Evidence that impact-melt polymict breccias are indeed impact-generated and not endogenic volcanic rocks with a high xenolith content includes: (1) siderophile trace-element abundances ascribed to surficial contamination by meteoritic debris because siderophile abundances are 10^{2-8} times higher than levels believed indigenous to the moon (Morgan *et al.*, 1974), (2) the wide and even dispersion of lithic and mineral debris such that no 1 mm^2 area in a thin section is free of clasts, (3) Rb–Sr isotopic systematics suggesting Rb enrichment prior to 4.25AE and not near the time of crystallization (Nyquist *et al.*, 1974), and (4) extensive evidence that the melts had sufficient superheat to fuse a substantial portion of the clasts (Simonds, 1975 and below). The possibility of impact-triggered volcanism can be ruled out for most of the lunar highland rocks by the same arguments that rule out conventional volcanism. French (1972) has pointed out that impact-triggered volcanism at the 125 km Sudbury structure (the Nickel Irruptive) was the result of an unusually high geothermal gradient at the time of impact, and should not be a common phenomenon.

Review of cratering mechanics and terrestrial crater studies

The process of impact-fusion and cratering has been explored using numerical and experimental simulation of: the impact of hypervelocity projectiles, the passage of the shock waves through the projectile and target, the excavation and secondary impact of excavated material, and the gravitational collapse of the crater. Impact of a hypervelocity projectile into silicates has been most recently explored by O'Keefe and Ahrens (1975 and 1976). Similar calculations were performed by Bjork (1961) for Meteor Crater, Arizona. The O'Keefe and Ahrens (1975 and 1976) calculations indicate that melting (in part to superheated temperatures), is confined to a small fraction of the crater volume; most of the material excavated is heated to temperatures of less than 200°C. In effect, the rapid attenuation of shock-heating results in a bimodal temperature in the material excavated. The calculations also suggest that the melt is accelerated to velocities of several km/sec, while the less shocked material is accelerated to lower velocities (some in excess of 1 km/sec). The target material is initially accelerated downward, but it is deflected to the side and then upward and outward (Gault *et al.*, 1968). The ejecta eventually become an outward moving curtain of material (Oberbeck *et al.*, 1975a, b). The papers by Oberbeck *et al.* (1975a, b) and Morrison and Oberbeck (1975) emphasize the significance of the reworking of both ejecta and material farther out from the crater by secondary impacts. The final morphology of the crater is substantially altered by gravitational collapse of the initial transient cavity (Dence, 1968). With increasing size, crater morphology changes from simply bowl-shaped depressions, to terraced depressions with flat floors, to craters with central peaks, which grade into craters with central rings and ringed basin structures. Gault *et al.* (1975) emphasize the role of gravity in determining the size and geometry of craters. They point out that an impact with a given energy will produce a larger crater on a planet with lower gravity (the size scales as $g^{-.25}$); thus a lunar crater will be 1.5 times as large as the same energy impact would produce on earth. However the crater radius at which the changes in morphology occur scale as g^1, thus ringed basins characterize much smaller structures on the earth than on the moon.

Dence (1971) has pointed out that impact melt occurs in four types of setting in terrestrial craters, namely (1) glass bombs, (2) glassy and recrystallized masses in fragmental breccias, (3) sub-horizontal sheets lining crater floors and spilling out over the rim, and (4) dikes intruding basement rocks. An additional type of melt deposit may be the surface flows described by Howard and Wilshire (1975) in and near lunar craters 15–300 km in diameter; such deposits would be eroded off any of the larger terrestrial craters. With the exception of the surficial lunar flows, the thick masses of impact melt are confined to the top of the basement, although studies of Canadian structures (Dence, 1971) suggest that some fragmental breccia may occur between the melt sheets and the basement. Thick units of fragmental breccias may occur in the interior as well as the exterior of a structure; for example, fragmental breccias occur within both Sudbury (Onaping Formation which overlies a potential melt sheet), and the Ries structures (von Engelhardt, 1971). Fragmental breccias are also known to overly the melt sheets in the West Clearwater Lake structure (Dence, 1964) and Papagai (Masaitis *et al.*, 1975). The lack of melt sheets in the smaller terrestrial craters suggests that the fraction of melt going into a sheet increases as the size of the crater increases (Dence, 1971).

Studies of terrestrial impact-melt sheets, glass bombs, and glass fragments in melt matrices suggest that the melts are extremely well-mixed, consistent with their high speed of travel and presumably very turbulent flow. Studies of glass bombs at the Ries (von Engelhardt, 1967) suggest a very limited composition range for the melt, and this observation is supported by the study of Stähle (1972) of both the bombs and smaller glass fragments. The 230 m thick sheet at Manicouagan has a SiO_2 composition of 57.3 ± 1.1 (1σ), in spite of a range of 49 to 72 percent SiO_2 in the target rocks (Currie, 1972; Floran *et al.*, 1976). Broad-beam microprobe analyses of dikes immediately adjacent to the floor of the Mistastin structure (Grieve, 1975) suggest that the basal part may not be well homogenized, although the upper mass of the eroded sheet shows only a limited compositional range. The melt sheet at the largest terrestrial crater with one preserved, Papagai in Siberia (Masaitis *et al.*, 1975), shows $SiO_2 = 63.13 \pm 1.2$ (1σ).

Soil breccias

While the impact-melt polymict breccias make up most of the dated rocks in the 4.05–3.85AE interval, many of the vitric-matrix breccias can be demonstrated to have formed after the period of intense bombardment, that is after 3.8AE. Most of the vitric-matrix breccias contain an abundance of solar wind derived gasses, suggesting that the material now in the breccias was once on the lunar surface and thus does not come from large events excavating material mostly from depth. These samples have major and trace element compositions similar to the locally collected soils. Vitric-matrix breccias from mare regions (Apollo's 11, 12, 15, and 17) contain lithic fragments of mare basalts similar to samples dated as young as 3.2AE; thus the breccias formed after that time. The vitric breccias from Apollo 17 contain an abundance of a distinctive orange glass, which is shown both by study of soil samples (Rhodes *et al.*, 1974 and Heiken and McKay, 1974) and infrared remote sensing techniques (Adams *et al.*, 1974) to be abundant in the vicinity of Apollo 17 only on the mare surfaces which lack craters over a kilometer across and yield rocks dating less than 3.7AE. Surely vitric-matrix breccias formed prior to 3.8AE, but a lack of a suitable radiometric dating technique for these solar-wind-rich, poorly equilibrated glass-bearing breccias has frustrated attempts to identify old breccias. One possible suite of old vitric breccias are those samples from Apollo 14 (*e.g.* 14301 and 14318) which contain decay products produced by the fission of Pu^{244} (Crozaz *et al.*, 1973), but this evidence does not definitively require that they be old.

Apollo 14 and Apollo 16

The non-mare landing site with the greatest abundance of fragmental breccia types with both vitric and holocrystalline matrices is Apollo 14. Head and Hawke (1975) have shown that the Apollo 14 site lies within the continuous ejecta blankets thrown out by two large craters, Fra Mauro (90 km in diameter) and an unnamed crater (175 km in diameter) to the northwest of the landing site. According to this model, the alignment of hills radial to Mare Imbrium is due to reworking of the terrain by secondary projectiles from Imbrium, in accordance with the models of Oberbeck *et al.* (1975b) and Morrison and Oberbeck (1975). In contrast, the landing site with the greater abundance of impact-melt polymict breccias, Apollo 16, has been suggested by Head (1975) to lie within a 90 km diameter crater and a younger 25 km crater, with the terrain extensively modified by later smaller primary and secondary craters. Potentially, the difference in abundance of rock types between the landing sites is due to the position of the landing sites relative to the larger local craters.

Because the melts produced in a single event appear to be homogeneous, geochemical data should allow grouping of impact-melt breccias, particularly at the Apollo 16 site, where the melt-rock breccias are abundant. Such a preliminary grouping suggests that a minimum of four events are sampled at Apollo 16, one producing a KREEP or noritic melt typically with a poikilitic texture, a second producing largely intersertal melts with a more aluminous composition (the VHA basalts of Hubbard *et al.,* 1973), a third still more aluminous composition represented by 68415, and a fourth, the more mafic composition of sample 62295, which lies at the most magnesian extreme of the VHA grouping, outside of the main cluster of analyses. Such a multiple series of melt sheets is compatible with the series of overlapping craters at the Apollo 16 site identified by Head (1975).

A partial section through a lunar impact melt sheet—Apollo 17, Station 6 boulder

The suite of five matrix samples from the Apollo 17, Station 6 boulder provides one of the best sets of lunar samples in which to examine textural variations within a single sheet (Simonds, 1975). The boulder, like most samples of lunar impact melts, is characterized by a very fine-grained matrix with subhedral to euhedral feldspars, mineral clasts so evenly distributed that no 1 mm^2 area is free of them, siderophile abundances above those believed indigenous to the moon (Higuchi and Morgan, 1975), a relatively high abundance of metallic iron, and an initial Sr^{87}/Sr^{86} indicating that the 3.98AE crystallization age postdates any major Rb enrichment by over 200 m.y. (Nyquist *et al.*, 1974). Furthermore, the boulder's noritic composition falls in the 15–22 percent Al_2O_3 range characteristic of most lunar impact melts. The restricted composition range in major (Al_2O_3 = 17.77–18.73) lithophile (Sm = 12.3–16.9 ppm), and siderophile (Au = 0.526–3.93 ppb) elements suggests that the boulder is all part of a single melt sheet. The boulder is inferred to be a 17 m thick section through the sheet, potentially most of the sheet's total thickness, because the boulder is nearly equal in size to the largest of the blocks in the 1 km long line of blocks 1/3 of the way up the North Massif, from which it is derived. The sheet may have been (1) at the base, within, or near a small pre-Serenitatis crater, (2) a surficial flow from a pre-Serentiatis crater, or (3) a flow deposited with a thick mass of ejecta from the Serenitatis event. Samples from the boulder reveal a textural sequence from fine to coarse grained, suggesting a variation in cooling history across the boulder.

The KREEP-like composition falls near the plagioclase–olivine–orthopyroxene peritectic of Walker *et* *al.* (1972). In accordance with that liquidus diagram, crystallization begins with plagioclase (An_{84-92}), followed by olivine (Fo_{63-73}), pyroxene (mostly pigeonite *mg#* = 71–81 and minor augite *mg#* = 71–81), ilmenite, and finally a variety of residual phases including metal and troilite. The variation in cooling rate due to the proximity of the margin of the sheet, and possibly the initial abundance of clastic debris has produced correlated changes in grain size, texture, clast abundance, and the relative abundance of different clast types. The best-foliated, most vesicular part of the sheet (samples 76015 and 76215) has a poikilitic texture consisting of 15 μm feldspar tablets in pyroxene oikocrysts up to 3 mm long, and 9–14 percent mineral clasts (0.05 to 1 mm) and less than 1 percent lithic clasts over 5 cm (seen in lunar surface photography). Small patches within 76215 have an ophitic texture consisting of 600 μm euhedral feldspar, 300 μm pigeonite, and less than 2 percent mineral clasts. The opposite end of the boulder (76275 and 76295) is massive, relatively free of vesicles, contains many clasts over 5 cm, and petrographically is seen to have a subophitic matrix with 10–15 μm plagioclase, 15–30 μm pyroxene, and over 17 percent mineral clasts. Sample 76315, collected between the two pairs, is intermediate in most parameters.

Mineral clasts, 0.05–1 mm throughout the boulder, are dominantly An_{95-97} plagioclase and Fo_{65-85} olivine, but the ratio of plagioclase to olivine clasts increases with increasing grain size, and minor pyroxene clasts occur in the finest samples. Feldspar clasts occasionally have rims of An_{84-92} which are thicker and better formed in the coarser samples. Only a few percent of small feldspar clasts display such potential shock features as undulous extinction, lamellae, or the flame texture characteristic of recrystallized feldspar glass. These features are more abundant in the larger lithic clasts, but too few large clasts are sampled for any precise abundance estimates. The largest lithic clasts sampled range from granulitic textured anorthositic troctolites to vuggy norites. No samples of fragmental breccia have been identified as clasts within the boulder. The correlated variation in clast abundance and major and trace element abundances (admittedly a small range) suggests that the clasts initially had a noritic composition slightly less aluminous than the melt component. If this is the case, a sizable fraction of the initial mineral clast population has been digested to eliminate the pyroxene and the An_{65-90} plagioclase characteristic of lunar norites. A precise estimate is impossible, but about 25 percent clasts in the initial mix is compatible with most observations. This large abundance of clasts, most of which were not shock-heated, judging from the preserved population, can extract a great deal of heat from the melt, and this implies a thermal history for the boulder's melt sheet which appears to be compatible with terrestrial melt sheets and hence is quite general.

Thermal model

Studies of the Station 6 boulder, the numerical and experimental investigations of cratering mechanics, and previous studies of terrestrial craters suggest that major textural and mineralogical features are the result of a sequence of processes: (1) formation of a superheated liquid well mixed on the scale of one gram samples taken meters apart, (2) rapid mixing of the superheated silicate liquid with fine, broken-up, cold clastic debris, (3) rapid thermal equilibration between clasts and melt with digestion of the more easily fused clasts, (4) crystallization of the matrix and loss of heat to the surroundings. If the inference that the clasts had approximately the same composition as the melt is valid, then both had a liquidus of about 1310°C and a solidus of about 1100°C (Walker *et al.*, 1972). Estimates of the initial temperatures of the melt and clasts must be inferred, but the preservation of some clasts suggests that the clast plus melt mixture equilibrated below the liquidus. Conformity of the texturally recognized paragenetic sequence to the experimentally predicted one suggests that the mixture was not quenched to sub-solidus temperatures, and probably was not quenched below the highest temperature for the occurrence of pyroxene (about 1200°C) (Simonds *et al.*, 1974).

The melt does not appear to be quenched sufficiently far below the liquidus to produce spherulitic or other textures characteristic of greatly supercooled melts (Lofgren, 1974). The small grain size of the subhedral feldspar suggests that a flood of feldspar nuclei forms as the melt is being quenched. The feldspar crystallization presumably releases sufficient latent heat to heat the clasts. This latent heat of fusion buffers the temperature of the equilibrated melt and clast mixtures to the range between the liquidus and the solidus. The initial temperature of the clasts is inferred from the lack of shock features in feldspar clasts, which do not appear to have been shocked to pressures of over 100 kbar. Maximum post-shock temperatures associated with such pressures are about 200–300° (Ahrens and O'Keefe, 1972). Simply heating the 25 percent clasts to the liquidus can extract about 250° from the melt, and each 1 percent clasts fused can extract an additional 4°. As a consequence of the small size and even dissemination of the mineral clasts, thermal equilibration takes place in less than 100 seconds (Onorato *et al.*, 1976).

Once the melt and clasts have equilibrated and crystallization has begun, the dominant control on heat transfer will be the loss of heat to the region surrounding the melt. Because the dimensions involved are orders of magnitude greater than those for clasts-melt interaction, this loss of heat is a much slower process. Evidence indicating that the clast-quenching mechanism is terminated by the start of crystallization suggests that the viscosity of the melt must increase very rapidly. The increase is sufficiently rapid for flow-foliated vesicles over 10 cm long in the melt to preserve their elongated shape. Convection within the melt is apparently prevented by the rapid viscosity increase, and is consistent with the lack of chemical differentiation by crystal settling even in thick sheets of impact melt.

A number of lines of evidence suggest that the melt is initially superheated. First is the inference made above that the initial fraction of clasts was initially cold, at a temperature of less than 300°, that the clasts amounted to an average of about 25 percent of the mixture, and that the matrix began to crystallize between the liquidus temperature of 1310°C and the temperature for initial occurrence of pyroxene at 1200°C. A simple lever rule calculation indicates a minimum initial melt temperature of 1450° to 1560°C. Larger degrees of superheating are suggested by the nature of clast digestion. The digestion appears to follow faithfully the equilibrium phase relations, leaving plagioclase clasts equal or greater than matrix plagioclase in anorthite content and olivine clasts equal or greater in forsterite content. In addition virtually all the pyroxene, probably about 30 percent of the original noritic clast mixture, has been digested, except in the samples which are inferred to have the highest initial clast content. A simple thermal equilibrium argument appears to explain the progressive nature of the clast digestion with decreasing clast content. Less energy will be available to fuse clasts in clast-rich mixtures because more heat will have been required to heat clasts to near-liquidus temperatures. An alternative explanation for the selective removal of phases would be that different phases have different mechanical crushing properties and that the removal of pyroxene was due to more extensive crushing of that phase than plagioclase or olivine. However, it is unlikely that plagioclase of a 5 mole percent greater An content is significantly stronger than its more albite-rich counterpart. Yet the preserved plagioclase has distinctly higher An content than the matrix or typical plagioclase associated with norites. Further arguments that impact melts are initially superheated come from the numerical calculations of O'Keefe and Ahrens (1975 and 1976), and the observations of Hörz (1965) and El Goresy (1965) for Ries melts and Carstens (1975) for Fennoscandian craters.

Because there is a textural progression from the impact-melt breccias with a continuous matrix of melt to the fragmental breccias with abundant glass fragments, it is logical to extend the model for quenching the melt's matrix by the enclosed clasts to the fragmental breccias. The principal difference between impact-melt breccias and fragmental breccias may be thought of as the much smaller ratio of hot matrix to cold clasts in fragmental breccias. Both theoretical and experimental studies suggest that the minimum time necessary to lithify debris laden with 10 μm particles of hot glass is only a few seconds (Simonds, 1973). Preservation of the glass in matrix of the sintered samples suggests that the glass was chilled too quickly to crystallize, a matter of seconds to minutes (Uhlmann *et al.*, 1975). Such times are shorter than the time necessary for heat transfer from a mass the size of the hand specimens returned by the Apollo program. Quite probably the significant heat transfer responsible for the preservation of the glass and other textures of the fragmental breccias is between the matrix and the enclosed cold clastic material, and not on the scale of an ejecta blanket, thus explaining the anomalously small thicknesses of cooling units of fragmental breccias estimated by Brett (1975), as pointed out in his footnote.

Manicouagan impact melt sheet

Study of the melt sheet at Manicouagan is significantly different from study of lunar samples, because the sheet has not been disaggregated by later impacts, and the mineralogy and composition of the target rocks can be determined directly. The 230 m thick sheet forms a ring around the central uplift, with an outer diameter of 65 km and an inner eroded margin with a diameter of about 24 km (Floran *et al.*, 1976). The melt sheet had a pre-erosion volume of 200–600 km^3, requiring 1–3 $\times$ 10^{28} ergs for fusion alone.

Melt also occurs as isolated masses throughout an intensely shocked anorthositic central uplift. The outer 10 km of the sheet sits on *in-situ* basement with only isolated patches of fragmental breccia less than 5 m thick between melt and basement; whereas nearer the center, melt occurs between basement blocks over 100 m across. The melt has the composition of a monzonite and, like the Apollo 17, Station 6 boulder, it has a restricted range in composition (SiO_2 = 57.3 ± 2.3), in spite of the great range in country-rock compositions (SiO_2 ranges from 49 to 72 percent). The chemical composition of the country rocks has been estimated by Currie (1972), and contrary to his statements, a simple and geologically defensible mixture of those compositions can duplicate the composition of the melt. The melt has an age of 214 ± 5 m.y. and an initial Sr^{87}/Sr^{86} ratio of .70991, indicative of formation from Precambrian rocks (B.-M. Jahn, personal communication).

Abundant plagioclase, olivine, pyroxene, quartz, alkali feldspar, garnet, biotite, and scapolite in the high-metamorphic grade Grenville rocks of the target allow a wider range of interactions between the melt and country rock than the plagioclase, low-calcium pyroxene, olivine mineralogy of the lunar highlands. As with the Apollo 17, Station 6 boulder there is a correlated variation between clast abundance and grain size. Grain size increases monotonically upwards in all 27 sections sampled through the sheet; the top of the sheet has been removed by erosion. The melt's crystallization follows the sequence expected for its bulk composition. Crystallization begins with plagioclase ($An_{38-55}Ab_{44-58}Or_{1-4}$) and possibly olivine (all of which is altered); augite ($Wo_{35-45}En_{34-48}Fs_{14-25}$) comes in about half way through plagioclase crystallization; pigeonite ($Wo_{6-14}En_{45-54}Fs_{40-48}$), or more rarely hypersthene follows the augite, and is followed in turn by alkali feldspar ($An_{1-5}Ab_{22-40}Or_{55-77}$), tridymite, quartz, apatite, titanomagnetite, and ilmenite. Millimeter patches of coarse alkali feldspar and quartz occur in rocks of all grain sizes, possibly due to a buildup of fluid in the later stages of crystallization. Thin siliceous veins that cut some samples, and extensive deuteric alteration of ferromagnesian minerals in nearly all samples are inferred to result from this late-stage fluid. Lithic clasts up to tens of meters across occur in the lower 30 m of the melt, and their abundance is estimated at <10 percent, but lichens obscure virtually all natural rock surfaces. Although the mineral clast content decreases upward in all sections sampled throughout the melt, the thickness of the zone with >2 percent mineral clasts ranges from less than 15 m to over 40 m. The thickness may differ by 20 m in sections only a km apart. The mineral clast abundance rarely exceeds 12 percent even in samples within a meter of the basement. As with the Apollo 17, Station 6 boulder, the clast population is quite different from that in the country rocks; the clasts are about 3/4 plagioclase and 1/4 quartz, with rare grains of magnetite and olivine. The ratio of plagioclase to quartz clasts increases upward in the sheet. As in the lunar samples, only a few percent of the clasts show potential shock effects. Rectangular patches of magnetite and as yet unidentified silicates appear to be pseudomorphs after biotite or amphibole, but no hint remains of the original garnet, scapolite, or alkali feldspar present in the basement. The preserved mineral clasts have reacted extensively with the melt. Quartz clasts are surrounded by rims of small augite grains in the finest, most clast-rich samples, and in the coarser samples of the augite is in turn rimmed by alkali feldspar and quartz. The plagioclase clasts are filled with micron-size patches of alkali feldspar. However, at the base of the sheet a few grains show replacement only at their margins. Similar features have been noted in the Mistastin Crater melt (Grieve, 1975).

The Manicouagan melt is distinctive from lunar impact melts in that most of the section is free of readily identified clasts. Only samples 14310, 68415, and possibly 15382 and 15386 represent essentially clast-free impact melts from the moon. The narrow compositional range of the Manicouagan melt (Floran *et al.*, 1976; Currie, 1972) suggests that clasts similar to those near the basement were present throughout the section. The more extensive clast digestion at Manicouagan may be due to the higher water and alkali content which effectively fluxed the system. Also biotite, garnet, amphibole, and scapolite clasts are missing at Manicouagan because they break down at igneous temperatures, and the alkali feldspar clasts melt at temperatures well below the melt's liquidus.

Discussion

The major significance of impact melts in the period of intense cratering of the terrestrial planets is that they transfer most of the high-temperature heat following cratering and thus take part in many of the phase transformations on planetary surfaces. Energy partitioning studies by Gault and Heitowit (1963), Braslau (1970), and O'Keefe and Ahrens (1975) suggest that of the projectiles' total kinetic energy, 23–35 percent is converted into heat by the passage of the shock fronts, 43–53 percent transports ejecta and then is dissipated as modest temperature increases over a broad area, 8–24 percent is consumed comminuting country rock, and <1 percent becomes seismic and radiant energy. All three sets of calculations suggest that a major portion of the thermal energy goes into a small volume, due to the rapid attenuation of the shock front away from the point of impact. Most of the heat goes into a zone of partially molten to partially vaporized rock. The large degree of superheating proposed for the melt is compatible with these calculations. Subsequent to its formation, this melt is violently mixed with much colder debris to form the sheets of impact melt and the breccias. The rapid attenuation of the shock fronts results in the melt being the only significant mass of material raised to temperatures of over a few hundred degrees. Thus the material able to undergo phase transformations is primarily the melt itself and the material which comes in contact with the melt.

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