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Impact Melts

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Almost forty terrestrial structures are known in which igneous rocks or glasses are associated with rocks showing shock deformation. In Quaternary craters, glasses containing Ni-Fe particles are undoubtedly impact melted. At older, larger craters, igneous materials occur as (1) fresh, recrystallized or altered glass in mixed breccias; (2) subhorizontal layers tens to hundreds of meters thick, depending on crater size; and (3) dikelike intrusions into basement rocks beneath the crater floor. These igneous rocks are distinguished from normal volcanic rocks by their heterogeneity, abundant inclusions of shocked country rocks, and lack of phenocrysts. In general they agree closely in composition with adjacent country rocks, but they commonly are relatively enriched in K and Mg and depleted in Si and Na. These chemical differences are attributed to reaction with vapors and solutions under conditions of near-surface crystallization with access to atmospheric oxygen. In some melts Ni and Fe are enriched, suggesting meteorite contamination. No contributions from deep magmatic sources are required to explain the chemistry of the melts. The theory of cratering by hypervelocity impact as applied to natural terrestrial events satisfactorily accounts for the form and distribution of the igneous rocks. The large volumes of impact melt in terrestrial craters >20 km across suggests (1) that the strength of target materials must be considered in extrapolating cratering theory to impacts of such dimensions; (2) the floors of large lunar craters. For example, Tycho, if of impact origin, should be underlain by several hundred meters of impact melt.

'The chemical composition shown by the two analyses quoted is one little in accordance with all that petrographers are accustomed to regard as normal for igneous rocks. . . . The lava-rock of Jänisjärvi has the composition of an argillaceous sediment [*Eskola*, 1921, p. 8].'

Eskola's thoughtful study of the geological curiosity at Jänisjärvi (Yänisyärvi) and of the problem of accounting for the igneous rocks there is representative of early investigations of structures that later became known as 'cryptovolcanic' [*Bucher*, 1936] or 'cryptoexplosion' [*Dietz*, 1959].

Jänisjärvi itself, north of Lake Ladoga, is now within the USSR and has not been the subject of recent study. However, despite its absence from current lists of possible impact sites [*Short and Bunch*, 1968; *Freeberg*, 1969; *Zotkin and Tsvetkov*, 1970], there can be little doubt that Jänisjärvi belongs to the select group of structures in which igneous rocks are found in characteristic association with shock-metamorphosed rocks. Such an association has been recognized at the Scandinavian localities of Lakes Lappajärvi [*Lehtinen*, 1970], Dellen [*Svensson*, 1968] and Mien [*Svensson*, 1969; *Stanfors*, 1969], all of which Eskola compared closely with Jänisjärvi on structural and textural grounds. However, there are distinct chemical differences between the igneous rocks at the four sites. As Eskola recognized, to account for these differences, any volcanic theory of origin requires the massive assimilation of adjacent country rocks (Precambrian mica schists in the case of Jänisjärvi) by any postulated primary magma.

In the last decade hypervelocity impact of cosmic bodies has been established as a viable hypothesis for the origin of structures such as those discussed by Eskola, and of the igneous rocks they contain [*French*, 1968*a*]. The applicability of hypervelocity impact theory to the problem of interpreting such large, ancient craters has been conclusively demonstrated by the analysis of Quaternary craters at which the association of meteorites with shocked and

melted rocks is well documented [*Spencer*, 1933; *Nininger*, 1954; *Shoemaker*, 1960]. On the other hand in ancient, shock-metamorphosed craters the presence of igneous rocks, in some cases in large quantities, has led some to continue to advocate a volcanic origin and to deny the value of shock metamorphism as a specific criterion of natural hypervelocity impact. In particular those holding the volcanic viewpoint have argued that certain geochemical data indicate an internal origin for the igneous rocks at several shock-metamorphosed structures [*Currie and Shafiqullah*, 1967, 1968; *Bostock*, 1969]. Others have suggested combinations of impact and volcanism. However, with the exception of the compound structure at Sudbury [*French*, 1968*b*] the consistency of the relationships observed at various craters over a wide range of sizes indicates that a single process has produced both craters and their associated igneous rocks. Debate therefore has focussed on the requirement that the impact hypothesis account for the forms and disposition of melt rocks in shock-metamorphosed structures: their textures; their composition, which, although generally similar to adjacent country rocks, shows significant differences in detail; and their apparent volume relative to crater dimensions.

OCCURRENCES

On the basis of structure and the presence of shock metamorphism, some sixty terrestrial localities are now included in the prime list of hypervelocity impact sites. Almost forty of these are known to contain glasses or igneous rocks, and in all cases these structures are emplaced in predominantly quartzo-feldspathic country rocks (plutonic or sedimentary). The apparent lack of melted materials at the remaining sites can be attributed in some instances to depth of erosion or lack of detailed investigation. In many cases, however, the absence of melt probably arises from the carbonate-rich character of the country rocks. At high shock pressures such rocks may be expected to dissociate with evolution of CO_2 instead of producing significant quantities of melt.

The craters that have associated melts are listed in Table 1, arranged according to size and relative depth of erosion. Depth of erosion generally increases with increasing age. It has been shown that crater structure also changes with size and with the character of the country rock. In the case of craters formed in predominantly crystalline silicate rocks, as are most of the craters in Table 1, those smaller than about 5 km have a simple bowl form, as exemplified by the Barringer and Brent craters. Larger craters are complex, having a central uplift that becomes more prominent with increased crater size, and the largest craters (>25 km) have a distinct ring structure, with or without a prominent central peak [*Dence*, 1965, 1968].

FORM AND DISTRIBUTION OF MELT ROCKS

Variations in crater structure, as outlined above, are accompanied by variations in the distribution of melt rocks, which can be illustrated by reference to the better known craters in Table 1. Melt rocks occur in four main forms at the different craters: (1) as isolated glassy 'bombs,' (Table 1, column 1); (2) as glassy or recrystallized masses in mixed breccias (Table 1, columns 2–6); (3) as thick sheets of igneous rock (Table 1, columns 4–6); (4) as minor dikes and irregular intrusions into the basement of the crater (Table 1, columns 6 and 7).

1. *Glassy bombs.* Isolated glassy bombs or impactite slags [*Spencer*, 1933; *Nininger*, 1954] form part of the unconsolidated ejecta found in and around the larger meteorite craters of Recent age. Individual bombs may be 20 cm or more across, are generally highly vesicular, and commonly show contamination with meteoritic materials [*Taylor and Kolbe*, 1965; *Brett*, 1967], as well as inclusions of shocked country rocks.

2. *Glassy or recrystallized masses in mixed breccias.* The unconsolidated deposits and their associated meteorite fragments are stripped off by even slight erosion. In the somewhat more deeply eroded craters (Table 1, column 2) melt materials are preserved on the crater rim in patches of more or less consolidated rock, in which the melt occurs as glassy or aphanitic masses associated with shock-metamorphosed rock and mineral fragments to form mixed breccias.

Breccia associations of this type are probably the most distinctive lithologic unit in shock-metamorphosed structures and have generally been called 'suevite.' Suevite at the type location of the Ries crater [*von Engelhardt*