Quaternary sites [*Spencer*, 1933; *Taylor*, 1967] and have been clearly related to the associated meteorites. Among the older craters distinct nickel enrichment has been reported for the melt rocks at East Clearwater Lake [*Currie and Shafiqullah*, 1968] and from Lappajärvi [*Lehtinen*, 1970] and Strangways [*Brett et al.*, 1970]. At Clearwater Lake the analyses of the adjoining and apparently contemporaneous east and west craters show large differences in the nickel content of their respective melt rocks. This effect may reflect different levels of sampling. At East Clearwater Lake crater, drilling sampled the upper levels of the melt rock where meteoritic contamination could be expected to be concentrated. At the west crater the equivalent levels have been removed by erosion, and the remainder contains no apparent concentration of nickel.

2. *Selective melting.* Even after correction for meteoritic contamination the average composition of glass from the Henbury craters shows distinctly less normative quartz than do the subgreywackes ejected from the main crater. *Compston and Taylor* [1969] have offered two possible solutions: (1) that the bias results from preferential melting of the chlorite-clay matrix of the parental rocks, or (2) that the specific parent rock was richer in matrix minerals than were any of the subgreywacke samples analyzed. The first suggestion receives support from the study of fresh Ries glasses (Type T1 of Table 2), which are found to contain a much higher proportion of inclusions of silica phases, at various stages of shock metamorphism, than of other minerals [*von Engelhardt*, 1967, 1971]. In such cases analyses made on glasses from which inclusions have, as far as possible, been removed will tend to be biased in the direction of lower content of silica than the parent material. This effect is unlikely to be apparent in larger, more slowly cooled igneous masses in which most inclusions will have been assimilated.

3. *Composition of target rocks actually melted.* The difficult task of determining the composition of the parental rocks is, of course, common to all craters and is rarely amenable to direct solution. The data for Clearwater Lake and Manicouagan suggest that, where a precise reconstruction of rock distributions prior to cratering is not possible, the method of averaging a large number of fresh samples of country rocks gives a surprisingly satisfactory result, at least for large craters. For example, the two adjoining Clearwater Lake craters are underlain by the same gneiss complex. However, basic rocks appear to be more abundant under the west crater than under the east, and this is reflected not only in the average composition of the country rocks but also in the compositions of the igneous rocks in the respective craters (Figure 1*b* and 1*c*).

On the other hand, at Brent the distinct differences between the mean composition of the gneissic country rocks and of the freshest part of the melt-zone rocks (BC, Figures 1*c* and 2*c*) may have a multiple explanation. Ultramafic alnöite dikes of Cambrian age cut the Precambrian gneisses in the vicinity of the crater and occur as inclusions in the breccias and the melt rocks. The dikes are at least 100 m.y. older than the crater [*Hartung et al.*, 1971] and are only incidently involved in the cratering process. The analyses of *Currie and Shafiqullah* [1967] indicate that up to 5% alnöite may be incorporated into the melt, the proportion being controlled by the data for TiO_2, CaO, Cr, and V in particular, all of which are much more abundant in the alnöite than in the gneisses. However such a mixture of gneiss and alnöite leaves a distinct Ni enrichment and a slight Fe enrichment in the melt rocks, suggesting that the melt rocks have also been contaminated by meteoritic material.

The group of Brent analyses also provides data on potash enrichment (Figure 1*c*). The replacement of Na by K is evident, not only in the fine-grained parts of the melt zone (BF) and in the igneous components of the breccias (B952), but also in inclusions in which shocked perthitic feldspars retain their original texture. The textures show that the potassic character of the rocks results largely from replacement of plagioclase by potash feldspar [*Hartung et al.*, 1971], through the action of solutions heated by the residual heat in the crater. The effect may be compared with hydrothermal alteration of rhyolitic glasses described by *Fenner* [1936]. The milder potash enrichment of apparently fresh igneous rocks at other craters is of a similar character. Again, the relative enrichment in magnesium shown by many of the same

igneous rocks is comparable to magnesium enrichment in quartz normative rocks of the Ben Nevis complex described by *Haslam* [1968]. The AFM variation diagram of the latter rocks compares closely to that of the Ries rocks plotted in Figure 2*a*. Haslam attributes the trend to crystallization of water-saturated magma under constant partial pressure of oxygen, as would occur if the cooling magma were in contact with the atmosphere. Similar conditions during the crystallization of the Ries rocks were suggested by *von Engelhardt* [1967]. The strongly oxidized nature of the crystalline igneous rocks from most craters, together with their structural position, leaves little doubt that atmospheric oxygen was available to provide conditions of crystallization similar to those described by Haslam. It follows that no emanations from depth are required to explain their compositional variations.

VOLUMETRIC CONSIDERATIONS

The volume of igneous rocks in shock-metamorphosed structures has been considered by *Beals* [1965], *Short* [1965], and *Dence* [1965], who all concluded that most if not all of the igneous rocks observed at craters such as Brent, Clearwater, and Manicouagan could be accounted for by shock melting. *French* [1968*b*], on the other hand, concluded that impact melting alone was insufficient to generate the much larger volumes of igneous rocks at Sudbury.

The partitioning of original kinetic energy of the projectile has been studied for impact velocities of 6.25 to 6.36 km/sec by *Gault and Heitowit* [1963] and *Braslau* [1970], who calculated that 19 to 26% of the original energy was retained in the target as waste heat from attenuation of the shock wave. The application of these results to large natural craters is difficult because of the uncertainties of extrapolating to impact velocities of 15–20 km/sec or more and to crater dimensions five orders of magnitude larger than the dimensions of craters formed in the laboratory.

On the other hand, there is a notable difference between the position and relative proportions of the melt rocks at Brent and at the two larger craters. At Brent only about 1% of the observed 5×10^{10} cm^3 of igneous rock (based on drilling results) is concentrated in the melt zone [*Dence*, 1968], the rest being dispersed in the upper mixed breccias. At West Clearwater and Manicouagan the greater proportion of the melted rocks at each crater occurs in the subhorizontal sheets that cover the crater floor around the central peak. The volume of melt so distributed at Manicouagan is calculated, allowing for erosion, to be 400 km^3.

It appears that a greater proportion of the impact energy is expended as heat and that more of the resulting melt remains lining the crater floor in the larger craters than in the smaller. That large craters are less efficiently excavated is also suggested by the extensive distribution of shock metamorphism in the basement rocks in the Charlevoix [*Robertson*, 1968] and Manicouagan [*Murtaugh and Currie*, 1969] craters.

CONCLUSION

The position has been presented that the distinctive igneous rocks found in shock-metamorphosed structures are the product of impact melting. The theory of hypervelocity impact accounts for the distribution and bulk composition of the rocks and, with the exception of Sudbury, is in reasonable agreement with their observed volumes. The most distinctive features of the rocks, heterogeneity, abundant inclusions of shocked fragments of country rocks, and lack of phenocrysts, are relatively independent of composition. They are most completely preserved in fresh, glassy rocks but can commonly be observed even in the more coarsely crystalline rocks in which assimilation and crystallization have obliterated many features. Although the theory suggests that the melted rocks may differ in composition from their parental rocks by the addition of a meteoritic contamination and by selective fusion of components with relatively low melting points, secondary effects introduced during cooling and crystallization by circulating vapors and solutions may lead to significant changes in composition. The effects are similar to those observed in volcanic rocks crystallized under near-surface conditions of water saturation and high partial pressure of oxygen due to access to the atmosphere.

Further investigations will be concerned with elucidating the crystallization history of the melt rocks, the assimilation and recrystalliza-