the diversity of inclusions in various stages of shock metamorphism, recrystallization or assimilation; and (2) the variation from crater to crater in their bulk composition. The first factor is readily apparent in rocks that have been chilled so that their matrices are glassy or aphanitic; the second is more apparent in rocks that have cooled more slowly, allowing homogenization, assimilation and recrystallization to proceed. The glassy rocks are representative of initial magma conditions, as indicated by craters such as West Clearwater Lake, where the textural evolution from glassy to the most coarsely crystalline igneous rocks can be traced in rocks that show little variation in bulk composition (see section below).

The glassy to fine-grained igneous rocks commonly contain fragments of the country rocks in such abundance that they may be called breccias with igneous matrices [e.g. *Bostock*, 1969]. Detailed studies of fresh glasses [*Chao*, 1967; *von Engelhardt*, 1967; *von Engelhardt and Dence*, 1971] have shown that the inclusions exhibit all grades of shock metamorphism [*Chao*, 1968; *von Engelhardt and Stöffler*, 1968]. Such shocked fragments are associated with contorted inclusions and schlieren of lechatelierite, fused feldspars, and other phases, all of which testify to temperatures well above those of normal magmas [*French*, 1968*a*; *Hörz*, 1965]. Furthermore, the complete absence of phenocrysts in the glasses indicates that cooling and, in the aphanitic rocks, crystallization did not begin until the magmas were virtually at rest. Flow banding, where seen, is developed as trains of small inclusions or glassy schlieren, in some cases emphasized by oriented vesicles.

Little reaction is evident between inclusions and matrix in the glassy and aphanitic igneous rocks [*French et al.*, 1970], but in more slowly cooled rocks reaction aureoles commonly develop, notably around silica fragments [*Taylor and Dence*, 1969], and inclusions are partially or completely melted, assimilated, or recrystallized. The most strongly shocked inclusions are most vulnerable to assimilation, so that in rocks in which the matrix grain size averages 0.1 mm or coarser only the largest or most weakly shocked inclusions are preserved. However, such rocks generally exhibit a distinct irregularly mottled texture produced by variations in grain size and by clustering of mineral species, forming the 'ghosts' of completely resorbed inclusions. The great effectiveness of the resorption process is due to the original superheated state of the melt, and to the high internal energy of the inclusions, which in varying degree are heated as well as disordered by the shock process [*Chao*, 1968].

It should be emphasized that the larger igneous bodies have not been formed by amalgamation and welding of discrete fragments and shards, as in welded ignimbrites, but have been emplaced as compact sheets or pools of magma. Placid, near surface conditions of crystallization allow grain sizes to reach 0.2 to 0.5 mm in the larger bodies. The mineralogy is normal and, where the bulk composition is appropriate, follows Bowen's classic reaction series. Feldspars show simple normal zoning, in which cores of plagioclase are rimmed with alkali feldspars. In some cases where the melt has high normative feldspar and feldspar inclusions are common, overgrowths on the inclusions may give the rock a microporphyritic appearance. However, there is generally little difficulty in distinguishing such overgrowths from normal phenocrysts.

## COMPOSITIONS

From the analyses and sources listed in Table 2 the compositions of igneous rocks from fifteen craters have been calculated in terms of the ternary ratios, normative quartz (Q) : normative plagioclase (Ab + An) : normative potash feldspar (Or) and total alkalis (A) : iron (F) : magnesium (M). Similar calculations were carried out for country rocks adjoining seven of the craters.

Quartz and feldspar compose 75% to 92% of the normative constituents (with the exception of 68% for Ries sample DB1), so that ternary plots of Q–Or–(Ab + An) show the main features of these rocks (Figure 1). The AFM diagram (Figure 2) provides additional information on variations in the analyses. The main conclusions from a consideration of these analyses are:

1. There is considerable scatter in the compositions of the melted rocks from the fifteen craters (Figure 1). Normative quartz and plagioclase show, in general, inverse correlation, but potash feldspar varies less regularly.

2. The country and melt rocks for some craters are closely similar in composition, whereas at other craters they differ considerably (Figure 1). Three variations occur: (a) the melt rocks are lower in normative quartz than the country rocks (Henbury and East Clearwater); (b) the melt rocks are richer in potash feldspar than the country rocks (West Clearwater and Manicouagan); or (c) both conditions hold (Carswell, Brent, and some analyses from the Ries crater).

3. The AFM plots (Figure 2) show considerably less scatter than the normative plots (Figure 1). Much of the variation shown is encompassed by the analyses of the Ries crater rocks (Figure 2*a*), which show a distinct trend toward enrichment in alkalis relative to iron and magnesium from glassy rocks (T1) to crystallized rocks (T3). The trend is reversed, however, in the strongly altered glass from the deep Deiningen drill hole (DB1), which shows distinct enrichment in iron and magnesium relative to alkalis, associated with depletion in silica (Figure 1*a*).

4. For other craters the AFM plots show only slight differences between country rocks and igneous rocks. Most common is a relative enrichment in magnesium in the igneous rocks with, in some cases, a decrease in alkalis. The greatest magnesium enrichment is shown by the analyses for Carswell and Brent, which also show the strongest potash enrichment (Figure 1*b* and *c*). However, as there is no enrichment apparent in total alkalis, sodium is depleted.

5. Iron enrichment is indicated only in the case of Brent analyses, though the Henbury glass would show a similar trend if the analyses had not been adjusted for meteoritic contamination [*Taylor*, 1967].

In summary, the melt rocks and glasses in shock-metamorphosed structures show greater similarity to the composition of adjacent country rocks than to each other. In a number of cases, however, the igneous materials are enriched in magnesia and potash and depleted in silica and soda relative to their respective country rocks. Those who advocate an endogenic origin for these structures have minimized the difficulties of shocking and fusing large quantities of country rocks by the explosion of gases [*Bostock*, 1969] emanating, they maintain, from alkalic ultrabasic materials [*Currie and Shafiqullah*, 1968]; instead they have focused on the differences between country and igneous rocks. These differences they consider incompatible with an impact origin and therefore a clear indication of a deep-seated terrestrial origin. This claim requires closer examination in the light of the sequence of events in an impact event.



TABLE 2*a*. Chemical Analyses of Crater Rocks
(New analyses or averaged analyses.)

| Chemical Component | Brent | | | West Clearwater Lake | | | Lake Wanapitei |
|---|---|---|---|---|---|---|---|
| | BC | BF | B952 | WC-F | WC-C | WC-B | W |
| $SiO_2$ | 59.6 | 58.4 | 57.5 | 59.6 | 57.90 | 57.22 | 75.10 |
| $TiO_2$ | 0.7 | 0.84 | 0.8 | 0.85 | 0.56 | 0.79 | ... |
| $Al_2O_3$ | 15.8 | 15.5 | 17.4 | 16.2 | 15.33 | 15.87 | 9.33 |
| $Fe_2O_3$ | 5.0 | 5.0 | 6.5 | 3.7 | 2.94 | 5.56 | ... |
| FeO | 4.0 | 3.8 | 2.0 | 1.3 | 2.31 | 0.64 | 2.27* |
| MgO | 1.2 | 1.8 | 4.4 | 2.5 | 3.14 | 3.20 | 1.19 |
| CaO | 2.5 | 1.7 | 0.4 | 4.6 | 4.55 | 4.45 | 1.12 |
| $Na_2O$ | 4.3 | 2.4 | 0.4 | 4.2 | 3.51 | 3.79 | 2.54 |
| $K_2O$ | 5.0 | 8.1 | 9.7 | 3.2 | 3.56 | 3.76 | 3.21 |
| MnO | 0.15 | 0.16 | 0.06 | 0.07 | 0.07 | 0.08 | ... |
| $P_2O_5$ | 0.29 | 0.24 | ... | 0.29 | 0.27 | 0.42 | ... |
| $H_2O+$ | 1.64 | 2.12 | 2.0 | 1.40 | 4.63 | 2.65 | ... |
| $H_2O-$ | ... | ... | ... | ... | 1.16 | ... | ... |
| $CO_2$ | ... | ... | ... | ... | ... | ... | ... |
| Total | 100.18 | 100.06 | 101.16 | 97.91 | 99.93 | 98.43 | 94.76 |

* Total Fe as FeO.