Wagner, G. H., Kleintektonische Untersuchungen im Gebiet des Nördlinger Rieses, *Geol. Jahrb., 81*, 519, 1964.

Waters, A. C., R. V. Fisher, R. E. Garrison, and D. Wax, Matrix characteristics and origin of lunar breccia samples Nos. 12034 and 12073, Apollo 12, in *Proceedings of the Apollo 12 Lunar Science Conference, Houston, Texas, January 1971*, edited by A. A. Levinson, Pergamon, New York, in press, 1971.

Wood, J. A., U. Marvin, J. B. Reid, G. J. Taylor, J. F. Bower, B. N. Powell, and J. S. Dickey, Relative proportions of rock types, and nature of the light-colored lithic fragments in Apollo 12 soil samples, in *Proceedings of the Apollo 12 Lunar Science Conference, Houston, Texas, January 1971*, edited by A. A. Levinson, Pergamon, New York, in press, 1971.

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Origin of Igneous Rocks Associated with Shock Metamorphism as Suggested by Geochemical Investigations of Canadian Craters[1]

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Chemical analyses of igneous and country rocks from Canadian craters show that the igneous rocks are consistently richer in potassium, magnesium, and heavy metals, and poorer in sodium and silicon than their associated country rocks. Geochemical balance calculations suggest that 20–80 per cent of the igneous rocks are composed of material not found in the country rocks, commonly a potassic basic to ultrabasic rock, such as those exposed in the craters Brent, Manicouagan, and Clearwater. Low-grade fenitization occurs at Brent. These data are not compatible with origin of the igneous rocks by either shock melting, or impact-induced volcanism. The data suggest explosive alkaline volcanism for the origin of at least some of the rocks.

Igneous rocks, that is, rocks crystallized from a melt, coexist with shock-metamorphosed rocks in at least 13 of the 17 known Canadian craters (Figure 1). The igneous rocks may be divided into four types, namely (1) massive, (2) igneous breccia, (3) pseudotachylite, and (4) cognate inclusions.

Massive igneous rocks form sheet and vein systems, apparently emplaced beneath a breccia cover. Country rocks in contact with them are hornfelsed. Igneous breccias, comprised of country-rock fragments and rare igneous fragments in a matrix similar to the massive igneous rocks, form flow-textured veins and lenses in altered and brecciated country rocks. Rarely, they form small sheets, or steeply-plunging pipelike masses. Pseudotachylite, a glassy or aphanitic matrix charged with rounded, abraded fragments of country rocks, occurs in complexly anastamosing dikes, rootless pods, and other unusual forms, commonly displaying strong flow banding and compositional layering. Inclusions or dikes of unusual ultrabasic rocks of alkaline affinity are found within the massive igneous rocks and the breccias of the craters Brent, Manicouagan, and Clearwater. The relations between the igneous rocks and the breccias displaying shock metamorphism are very close. Commonly there is gradation from one to the other, suggesting that they formed virtually contemporaneously, but in a few cases, where exposures are favourable, (e.g. Manicouagan, Mistastin, and West Clearwater), the igneous rocks can be seen to intrude and cross cut the breccia.

The igneous rocks have been sampled during detailed mapping of the craters and were chemically analyzed by rapid methods in the Geological Survey of Canada laboratories under the direction of S. Courville. Maximum percentage errors for an individual analysis by these methods are discussed by *Eade et al.* [1966] but in general do not exceed 2% of the amount present for major elements, and 10% of the amount present for minor elements.

In comparing groups of analyses, a Student's *t* test, corrected for small sample size, has been used where more than 5 analyses in each group are available, and differences are termed significant if they would occur randomly less than 1% of the time. Where fewer than 5 analyses are available, the standard deviation of the larger group is computed, and compositions are termed significantly different if the difference exceeds three times the standard deviation. Where the average composition of country rocks in a crater is referred to, the average has been computed by measuring the areas underlain by various formations on the geological map, extended where necessary by extrapolation, and

[1] Lunar Science Institute Contribution 37.