by a sheet of igneous breccia (Onaping tuff) that displays shock-metamorphosed fragments [*French*, 1968]. The Onaping tuff is a highly varied, and possibly composite, unit, but analyses of its more massive and uniform parts are quite similar to those of the irruptive (Table 1), and Sr-isotope data [*Fairbairn et al.*, 1968] also suggest the same source. Many highly silicic analyses of the Onaping tuff have been reported, but they appear to be contaminated by inclusions of quartzite [*Speers*, 1957]. The igneous rocks of the Sudbury structure are much lower in potash than igneous rocks from other Canadian craters, but the matrix of the common Sudbury breccias is enriched in potassium and heavy metals compared to the country-rock inclusions, according to the data of Speers and the data shown in Table 1.

Manicouagan crater, an octagonal depression 61 km across, is cut into Precambrian metamorphics and partially filled with sheets of igneous rocks, through which projects a rectangular, off-center block of shock-metamorphosed anorthosite [*Currie*, 1970c]. For an object as large as Manicouagan, the difficulties in arriving at an average composition of country rocks are obvious. However, convergence of two limiting estimates (Table 5) suggests that errors are compensating, and the computed average is reasonably accurate. Chemical data on the composition of pseudotachylite (Table 5) fall into two groups. One group could result from melting of wall rocks by frictional heat [*Philpotts*, 1964]. The other group is much more ferromagnesian and evidently contains an admixture of foreign material. Chemical balance

TABLE 5. Chemical Composition of Country Rocks and Igneous Rocks from the Manicouagan Crater

	1	2	3	4		5	6	7	8	9
	wt %	wt %	wt %	wt %	s.d.	wt %	wt %	wt %	wt %	wt %
SiO_2	57.91	58.11	58.03	57.47	1.71	49.11	48.43	47.77	48.92	37.43
TiO_2	0.61	0.59	0.60	0.74	0.08	1.01	0.24	0.23	1.16	0.25
Al_2O_3	20.77	20.08	20.36	18.33	1.32	17.59	25.67	28.36	17.57	4.06
Fe_2O_3	2.36	2.15	2.18	3.42	0.39	5.90	1.41	1.33	4.21	9.51
FeO	2.72	2.80	2.73	2.63	0.29	3.94	0.08	0.14	5.10	5.34
MgO	2.63	2.53	2.53	3.61	0.65	7.53	4.71	2.80	5.38	31.86
CaO	6.15	5.58	5.91	5.71	0.82	9.76	9.54	8.94	8.01	1.70
MnO	0.09	0.09	0.09	0.11	0.02	0.21	0.02	0.04	0.18	0.27
Na_2O	4.38	4.38	4.38	4.08	0.22	3.02	5.76	5.02	3.91	0.43
K_2O	2.70	2.83	2.77	3.02	0.38	2.33	0.51	1.15	1.38	0.28
H_2O	0.42	0.69	0.87	1.01	0.10	2.97	3.38	3.86	1.53	10.48
P_2O_5	0.23	0.30	0.27	0.29	0.05	0.19	0.03	0.03	0.26	0.04
Selected Trace-Element Data (in ppm)										
Ni	24	23	23	38		50	43	nil	85	846
Co	7	6	6	1		24	nil	nil	25	120
Cr	42	36	38	71		320	5	nil	365	3500
V	99	90	95	146		340	85	40	nil	450
Ba	1250	1110	1200	1510		1150	1100	950	1450	140
Zr	370	520	450	930		750	320	300	115	45
Sr	460	440	450	480		580	650	600	825	45
Rb	30	46	40	59					60	nil

1. Average country rock in crater (assuming 25% anorthosite, 20% gabbro and mafic gneiss, 5% granite, 35% charnockite, and 15% gneiss complex).
2. Average country rock in crater (assuming 20% anorthosite, 15% gabbro and mafic gneiss, 8% granite, 25% charnockite, and 33% gneiss complex).
3. Preferred average of country rocks in crater (38 analyses).
4. Average doreitic igneous rock in crater, with standard deviation (37 analyses).
5. Average mafic, potassic pseudotachylite (6 analyses).
6. Average country rock of pseudotachylite (8 analyses).
7. Average aluminous, sodic pseudotachylite (2 analyses).
8. Average alkali basalt from crater (4 analyses).
9. Average ultramafic inclusion in alkali basalt from crater (9 analyses).

calculations suggest 20–80% addition of picritic alkali basalt. *Willemse* [1938] concluded that norite had been added to Vredefort pseudotachylite.

A picritic alkali basalt is exposed at Manicouagan in the form of brecciated plugs and small lensoid sheets intruding and including suevitic breccias. The basaltic matrix (Table 5) carries numerous blocks of an unusual ultrabasic rock consisting of enstatite, phlogopite, and minor olivine and diopside. The chemistry is reminscent of some alkaline ultrabasic dike swarms. These inclusions appear to be xenoliths of an early crystallizing fraction of the alkaline basalt [*Currie*, 1970c].

Roughly 90% of the igneous rocks at Manicouagan consist of two sheets of granular to trachytoid brownish rocks, differing in grain size and mineralogy of pyroxene. The uniformity of chemical composition (Table 5) is very striking. High K_2O content classifies the rocks as doreite, not andesite [*Nockolds*, 1954], and the alkaline character of the rock is shown also by the *MacDonald and Katsura* [1964] classification. When corrected for deuteric oxidation, most analyses show normative olivine. Comparison of this rock with the average Precambrian rock (Table 5) shows statistically significant differences for 9 of the 14 analyzed elements. An addition of 16% of picritic alkali basalt would bring the average country rock into coincidence with the average igneous.

DISCUSSION

The close association of igneous and shock-metamorphosed rocks suggests three possible origins for the igneous rocks: (1) crystallization from impact melted country rocks, (2) crystallization from endogenic magma whose emplacement is mechanically or thermally controlled by an impact structure, or (3) crystallization from an endogenic melt with whose emplacement is associated shock metamorphic phenomena. Each hypothesis implies specific geochemical and physical consequenees. In addition to the data summarized in Table 1, we may note physical factors common to all, or most of, the occurrences: (1) the igneous rocks occur at the base of the crater (of Brent, Sudbury, Lake St. Martin); (2) massive igneous rocks are generally fresh and unaltered, and the igneous breccias are moderately to severely altered; (3) significant amounts of igneous rocks are present in the form of dikes, some hundreds of yards long, and tens of yards deep.

Impact melting should produce a magma identical in chemistry to the country rocks, except for differential volatilization [*Taylor*, 1966], which would be emplaced mainly at the top of the fallback breccia [*Roberts*, 1968]. In large craters, differential volatilization should lead to depletion of volatile elements such as Rb, P, and K. None of these elements are depleted in any of the reported igneous rocks except those from Mistastin Lake, and K is enriched in most. After consolidation of an impact melt, alteration and metasomatism may take place by circulation of ground water through the breccia zone [*Milton*, 1970]. Even assuming that the slight observed alteration is sufficient to alter the composition, experimental data [*Ermanovics et al.*, 1967; *Burnham*, 1967] show that near surface hydrothermal alteration, which consists mainly of leaching of alkalies and enrichment in silica with increase in Na/K ratio, does not cause the observed increase in K, Mg, and heavy metals. The only near-surface metasomatic process leading to similar chemical changes is fenitization, which is invariably connected with alkaline magmatism. Impact melting does not explain either the variety of igneous rocks found in some craters (carbonatite, monchiquite, trachyte at Brent; meimechite, basalt, doreite at Manicouagan) or the homogeneity of other igneous units over large areas. Can impact form homogeneous melt over square mile areas, yet leave pools of aberrant composition?

The location of igneous rocks in well-preserved craters suggests that the rocks all lie at the base of the crater, a position quite compatible with intrusion of igneous rocks into the base of a structurally weakened zone. Impact creates long-lived disturbances in pressure and temperature owing to crater excavation and insulation by the breccia blanket, but calculations suggest that magma generation by this mechanism would take millions of years, whereas field evidence and isotopic age dating suggest almost identical ages for the igneous rocks and breccia blanket in Canadian craters. Mechanical stresses associated with an impact could tap preexisting magma by cracking the cover rocks, or could create magma by sudden release of