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.

(Received January 4, 1971; revised March 17, 1971.)

VOL. 76, NO. 23 JOURNAL OF GEOPHYSICAL RESEARCH AUGUST 10, 1971

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

K. L. CURRIE

Geological Survey of Canada
Ottawa, Ontario

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.

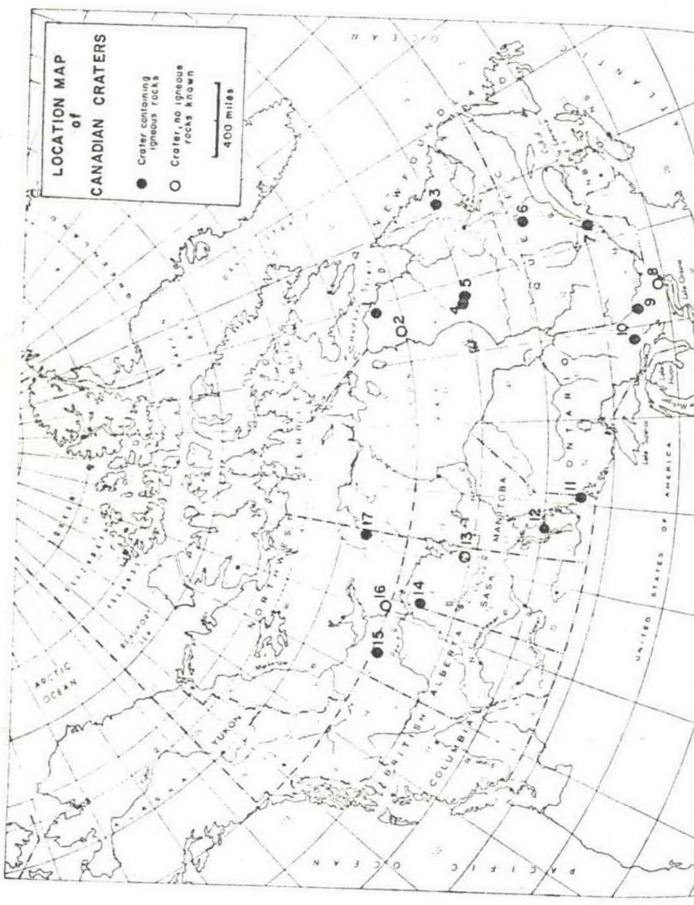
Igneous rocks, that is, rocks crystallized from a melt, coexist with shock-metamorphosed rocks in at least 13 of the 17 known Canadian craters (Figure 1). The igneous rocks may be divided into four types, namely (1) massive, (2) igneous breccia, (3) pseudotachylite, and (4) cognate inclusions.

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.



using these areas to weight the appropriate chemical analyses. Since this procedure is obviously inaccurate, in the most cases estimates of limiting compositions are also given.

GEOCHEMISTRY OF INDIVIDUAL CRATERS

Although some information on the chemistry of the igneous rocks is available from 11 of the 13 craters, information on the chemistry and petrography of the accompanying breccias and country rocks is available for only 7 craters. All data are summarized in Table 1. Remarks on individual craters follow.

Brent is a bowl some 2900 meters in diameter and 960 meters deep, filled by some 650 meters of brecciated Precambrian rocks, overlain by Ordovician sedimentary crater fill [*Millman et al.*, 1960]. The Precambrian granite gneisses surrounding the crater are quite uniform in composition, permitting unusually accurate determination of the rock composition previously filling the crater. Table 2 shows the data used in estimating this composition.

Much of the breccia filling consists of almost unmetamorphosed fragments of the country rocks. Thin shock-metamorphosed zones [*Dence*, 1968] display a characteristic greenish cast, which is also found in breccia screens around the crater out to a distance of 800 feet. Analyses of these rocks (Table 2) show that they depart progressively from the composition of the Precambrian rocks toward that of the igneous rocks (Figure 2). Strongly metasomatized rocks contain anorthoclase and chloritized riebeckite and aegirine.

Fine-grained, red, vesicular trachyte occurs below the center of the Brent crater at depths of 1100 feet, and 2716–2850 feet, and on the northeast edge of the crater [*Currie*, 1969*a*], forming an arcuate dikelike mass. Chemically the rocks are olivine-normative alkaline trachytes (Table 2) similar to the altered breccias. Ocellar monchiquite dikes typical of the Nippising alkaline province [*Currie and Ferguson*, 1970] occur within and around the Brent crater. Their radiometric ages of 558 and 576 m.y. (M. Shafiqullah, unpublished data, and *Shafiqullah et al.* [1968]) agree with radiometric dates on other Nippising alkiline dikes. The carbonate matrix of breccias from the west side of the Brent crater yields $^{18}O/^{16}O$ ratios characteristic of carbonatite.

Brent lies on the Ottawa-Bonnechere graben system, which localized Nippising alkaline magmatism [*Currie*, 1970*a*]. With the exception of shock metamorphism, the similarity in size, shape, and petrochemistry of Brent to characteristics of the Callander Bay alkaline complex, 42 miles to the west, is very striking. The Newman Island alkaline complex, 12 miles west of Callander Bay, contains within its crater Ordovician sedimentary rocks correlative to those at Brent. In the absence of shock metamorphism, Brent would certainly be classified as an alkaline igneous complex within the Nippising alkaline igneous province.

Mistastin Lake is an elliptical crater roughly 13 by 20 km, cut mainly into homogeneous augen granodiorite [*Currie*, 1968]. A lens of anorthosite with marginal mangerite crosses the crater itself causing uncertainty in the composition of rocks within the crater. The available data and best estimate are shown in Table 3. Concentric ring dikes of igneous rocks cut shocked Precambrian on the shore of the lake and on a central island. Analyses of an older homogeneous fine-grained rock and a younger vesicular rock are shown in Table 3, together with analyses of younger igneous breccias that cross cut and include them. The igneous rocks are significantly depleted in silicon, potassium, and rubidium relative to average country rocks and are enriched in calcium and magnesium. Although proportions of country rocks could be adjusted to match the igneous composition (Table 3, column 7), it seems very improbable on field-mapping evidence that these proportions represent the original rocks within the crater.

Fig. 1. (*Opposite*) Known sites of shock metamorphism in Canada. In the following number key, a reference documenting the occurrence of igneous rocks is given where such rocks are known. (1) New Quebec crater [*Currie*, 1966], (2) Lac Couture, (3) Mistastin Lake [*Currie*, 1968*a*], (4) West Clearwater Lake crater [*Bostock*, 1969], (5) East Clearwater Lake crater [*Currie and Shafiqullah*, 1968], (6) Manicouagan [*Currie*, 1970*c*], (7) Charlevoix [*Rondot* 1968; *Currie* 1969*b*], (8) Holleford, (9) Brent [*Currie and Shafiqullah* 1967], (10) Sudbury [*Collins* 1934; *Speers*, 1957], (11) West Hawk Lake crater [*Short*, 1970], (12) Lake St. Martin [*Currie* 1970*b*], (13) Deep Bay, (14) Carswell [*Currie* 1969c], (15) Steen River [*Carrigy*, 1968], (16) Pilot Lake, (17) Nicholson Lake [*Dence et al.*, 1968].

TABLE 1. Summary of Chemical Composition of Rocks from Canadian Craters
(Major element content in per cent; minor elements in ppm.)

	No. of Analyses	Unit*	SiO_2	TiO_2	Al_2O_3	Fe_2O_3	MgO	CaO	MnO	Na_2O	K_2O	H_2O	P_2O_5	Cu	Zn	Ni	Cr	Sr	Rb
Brent	18	a	68.4	0.51	15.0	4.34	1.05	1.45	0.05	3.52	4.33	1.29	0.08	11	70	5	15	1500	78
	11	b	63.1	0.81	14.7	6.60	2.17	0.73	0.09	2.69	7.70	1.22	0.09	...	...	...	...	...	...
	6	c_1	58.8	0.64	17.1	6.24	2.28	1.03	0.09	3.47	9.13	0.93	0.31	13	25	95	40	360	146
	4	c_2	32.3	4.34	7.6	14.8	8.3	15.9	0.17	0.86	3.74	2.2	0.27	...	...	...	...	...	...
New Quebec	1	a	63.6	0.47	16.1	4.3	2.3	4.3	0.08	4.7	1.9	0.8	0.09	...	...	...	...	...	...
		b	68.6	0.42	15.8	6.1	1.8	3.2	0.06	3.7	0.08	0.1	nil	...	...	...	...	...	...
Mistastin	10	a	65.5	0.59	15.8	4.2	0.8	3.0	0.05	4.1	5.0	0.6	0.17	...	...	...	...	...	131
	4	b	56.5	1.20	17.8	7.7	1.7	5.7	0.09	4.2	1.3	1.8	0.33	...	...	...	...	...	nil
	6	c_1	55.9	0.97	19.5	6.3	1.7	6.5	0.08	4.6	2.0	1.2	0.31	...	...	...	...	...	20
Lake St. Martin	3	c	61.4	0.36	15.2	5.5	3.7	1.8	0.05	4.54	4.25	...	0.19	...	...	...	...	...	...
East Clearwater		a	63.2	0.51	15.6	4.8	3.1	3.3	0.08	3.8	3.1	0.9	0.21	20	50	12	10	...	...
	2	b	63.5	0.89	21.0	5.0	1.5	2.1	0.14	1.65	6.40	4.21	0.41	3	40	90	10	...	...
	12	c_1	62.8	0.50	15.8	4.6	2.9	3.8	0.10	3.0	5.7	2.3	0.32	30	235	780	200	...	...
West Clearwater	16	a	60.8	0.71	16.7	5.25	2.38	4.82	0.09	4.31	2.38	0.76	0.25	20	75	20	5	510	72
	8	b	57.2	0.89	16.2	5.0	2.90	4.60	0.08	3.91	3.41	2.06	0.30	67	205	<5	<5	500	80
	12	c_1	60.4	0.73	15.9	5.30	2.67	4.48	0.05	3.78	3.60	1.33	0.30	19	70	20	30	560	110
		c_2	38.7	0.54	11.9	17.0	15.7	3.2	0.64	1.12	0.11	10.9	0.30	...	...	...	...	...	...
Carswell	14	a	66.7	0.32	17.0	5.8	1.1	1.2	0.11	2.17	5.17	0.3	0.11	25	80	30	35	...	...
	4	b	57.2	0.89	16.2	6.0	2.90	4.60	0.08	3.4	3.9	4.2	0.31	40	60	80	40		
	7	c_1	60.8	0.13	18.9	3.72	2.25	0.02	1.25	8.88	0.1	0.33	75	210	...	120	115	...	...
Steen River	3	a	66.70	0.42	15.30	4.30	1.23	2.76	nd	3.79	2.74	1.76	0.16	...	...	...	...	...	...
	1	c_1	55.67	0.74	18.30	6.19	2.54	5.98	nd	2.47	2.61	6.41	0.27	...	...	...	...	...	...
	3	b	64.76	0.42	14.49	3.74	1.71	2.44	nd	2.82	5.27	3.48	0.12	...	...	...	...	...	...
Sudbury	34	c_1	55.2	0.8	16.9	8.4	5.2	7.4	0.1	2.9	1.4	1.3	0.2	...	...	...	...	...	...
	6	a	70.0	0.46	13.21	5.1	2.2	2.8	0.03	2.2	2.6	1.1	0.09	...	...	...	...	...	...
	6	c_3	66.9	0.57	13.73	6.2	2.3	2.9	0.03	2.2	3.3	0.9	0.10	...	...	...	...	...	...
	1	b	58.9	0.46	15.56	8.7	4.8	5.5	0.28	2.3	1.5	2.2	0.09	...	...	...	...	...	...
Manicouagan	38	a	58.0	0.60	20.4	4.9	2.6	5.9	0.09	4.7	2.7	1.4	0.27	...	...	23	39	450	38
	18	b	55.1	0.74	19.0	6.4	3.7	4.8	0.14	3.5	3.4	1.2	0.25	...	...	7	70	430	56
	37	c_1	57.5	0.74	18.3	6.0	3.6	5.7	0.11	4.1	3.0	1.0	0.29	...	...	38	71	480	59
	4	c_2	48.9	1.16	17.6	9.3	5.4	8.0	0.18	3.9	1.4	1.5	0.26	...	...	85	365	825	60
		c_3	37.4	0.25	4.1	14.8	31.9	1.7	0.27	0.43	0.28	10.5	0.02	...	...	800	3000	45	nil
Charlevoix	3	c	61.7	0.99	16.0	6.3	2.0	2.4	0.08	2.5	5.1	2.7	0.20	...	...	...	...	...	...
Average country rock			64.1	0.50	16.5	4.67	1.82	3.34	0.081	3.89	3.42	0.89	0.17	20	70	20	20	370	80
Average salic igneous rock			59.05	0.66	17.2	5.85	3.03	4.13	0.068	3.26	4.22	1.72	0.28	35	155	200	90	450	85
Average Precambrian†			66.4	0.6	15.5	4.6	2.0	3.8	0.1	3.5	3.3	...	0.2	...	...	...	...	...	...

* a, country rock; b, igneous breccia; c_1, salic igneous rock; c_2, basic igneous rock; c_3, pseudotachylite.
† After *Eade et al.* [1966].

TABLE 2. Chemical Composition of Country Rocks and Igneous Rocks from the Brent Crater

	1		2		3		4		5		6	7	8
	wt %	s.d.	wt %	s.d.	wt %	s.d.	wt %	s.d.	wt %	s.d.	wt %	wt %	wt %
SiO_2	66.20	2.97	68.72	2.93	68.77	4.70	68.38	3.53	58.83	1.63	32.3	66.50	63.1
TiO_2	0.54	0.16	0.50	0.09	0.49	0.16	0.51	0.14	0.64	0.24	4.34	0.58	0.81
Al_2O_3	15.68	0.55	14.80	1.15	14.87	2.27	15.00	0.93	17.10	1.90	7.6	14.08	14.8
Fe_2O_3	1.95	0.79	2.29	0.97	1.44	0.85	1.85	0.87	5.69	2.49	5.3	2.26	4.01
FeO	3.05	1.13	2.10	1.19	2.63	1.31	2.49	1.21	0.55	0.41	9.5	3.52	2.59
MgO	1.95	1.10	1.02	0.45	0.63	0.24	1.05	0.96	2.28	0.24	8.3	2.16	2.17
CaO	2.25	1.62	1.31	0.89	1.62	0.69	1.45	1.07	1.03	0.55	15.9	1.44	0.73
MnO	0.85	0.03	0.035	0.02	0.07	0.02	0.05	0.03	0.09	0.08	0.17	0.07	0.09
Na_2O	3.08	0.48	3.65	0.57	3.61	1.91	3.52	0.68	3.47	0.76	0.86	3.43	2.69
K_2O	3.92	1.85	4.02	0.65	4.84	0.36	4.33	0.94	9.13	1.51	3.74	4.04	7.70
H_2O	0.72	0.11	1.74	0.36	1.12	0.11	1.29	0.46	0.93	0.12	2.21	1.10	1.24
P_2O_5	0.11		0.11		0.03		0.08		0.31	0.08	0.27	0.05	0.09
CO_2	0.47		nil		0.75		0.33		nil		9.61	0.86	nil
Selected Trace-Element Data (in ppm)													
Zn	100		40		80		70		25		1200		127
Cu	10		11		15		11		13		7		11
Ni	3		5		5		5		95		330		47
Co	5		5		5		5		8		67		16
Cr	15		5		25		15		40		500		28
V	15		15		15		15		15		300		25
Ba	900		1100		1100		1050		570		500		512
Zr	380		400		700		500		700		300		650
Sr	270		250		100		210		35		1100		350

1. Average leucocratic garnet gneiss (4 analyses).
2. Average granite gneiss (8 analyses).
3. Average granite (6 analyses).
4. Average Precambrian rock in the crater (18 analyses).
5. Average trachyte (6 analyses).
6. Average monchiquite (4 analyses).
7. Average non-metasomatized breccia (6 analyses).
8. Average metasomatized breccia (11 analyses).

East Clearwater Lake crater is crudely quadrilateral, roughly 22 km on a side, cut into Archean granulitic rocks ranging from gabbroic to granitic composition. Beneath the lake, a central core of shocked Precambrian rocks [*Dence*, 1968] is surrounded by a ring of igneous rocks grading downward from igneous breccia into massive, green dacite with radiometric age 265 m.y. (Shafiqullah, unpublished data). In Table 4 the average composition of the basement rocks as computed by *Eade et al.* [1966] and by *Bostock* [1969] is compared with the average composition of the central core of Precambrian, and with the igneous rocks. Although the compositions are all very similar, the igneous rocks contain more potassium, much more zinc nickel and chromium, and less sodium than the country rocks. The rocks of the central uplift show a significant increase in K/Na ratio relative to the surrounding country rocks.

West Clearwater Lake crater, about 32 km in diameter, contains a circular chain of islands about 13 km in diameter. The lower parts are composed of altered and fractured Archean metamorphic rocks, shock metamorphosed along fractures. Igneous breccia occurs as pods and veins within the complex, and as a thin sheet overlying the basement and grading rapidly up into homogeneous red dacite (K/Ar age 292 m.y.) that appears to be attached to vertical dikelike mass following the outside of the island chain. The composition of the basement complex has been studied by *Bostock* [1969], whose results are shown in Table 4, together with analytical results on igneous rocks from surface, and from veins and dikes of igneous

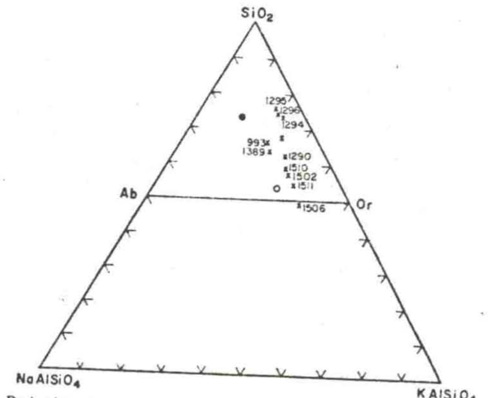


Fig. 2. Projection of chemical analyses of altered breccias from the Brent crater into the system SiO_2-$NaAlSiO_4$-$KAlSiO_4$. Crosses show the position of each of the 11 individual analyses averaged in Table 2, with the identification number of each analysis. The solid circle shows the average composition of the country rocks; the open circle shows average composition of the potassic trachyte. Note the strong linear trend of the analyses away from the SiO_2 corner toward the average composition of potassic trachyte.

TABLE 3. Chemical Composition of Country Rocks and Igneous Rocks from the Mistastin Lake Crater

	1 wt %	2 wt %	3 wt %	4 wt %	5 wt %	6 wt %	7 wt %
SiO_2	68.3	52.0	60.9	65.5	55.9	56.6	56.9
TiO_2	0.52	0.42	1.34	0.59	0.97	1.20	0.80
Al_2O_3	14.5	27.2	14.5	15.8	19.5	17.8	20.9
Fe_2O_3	7.1	1.0	4.3	1.3	4.1	7.3	2.3
FeO	2.5	2.6	5.6	2.9	2.2	0.4	3.9
MgO	0.6	1.5	0.9	0.8	1.7	1.7	1.2
CaO	1.9	8.9	4.5	3.0	6.5	5.7	6.5
MnO	0.05	0.04	0.12	0.05	0.08	0.09	0.07
Na_2O	4.0	5.3	4.0	4.1	4.6	4.2	4.6
K_2O	5.7	0.9	4.2	5.0	2.0	1.3	2.7
H_2O	0.4	0.6	1.2	0.6	1.2	1.8	0.8
P_2O_5	0.15	0.16	0.34	0.17	0.31	0.33	0.23
Rb (ppm)	162	0	63	131	20	nil	41

1. Average augen granodiorite (4 analyses).
2. Average anorthosite (3 analyses).
3. Average mangerite (3 analyses).
4. Estimated average Precambrian rock in crater (77% analysis 1 + 12% analysis 2 + 11% analysis 3; 10 analyses).
5. Average massive igneous rock (6 analyses).
6. Average igneous breccia (4 analyses).
7. Mix of Precambrian rocks closest in composition to igneous rocks (9% analysis 1 + 51% analysis 2 + 40% analysis 3).

TABLE 4. Chemical Composition of Country Rocks and Igneous Rocks from the Clearwater Lake Craters

	1	2		3		4		5	6	7		8
	wt %	wt %	s.d.	wt %	s.d.	wt %	s.d.	wt %	wt %	wt %	s.d.	wt %
SiO_2	63.2	60.84	6.95	65.3	7.61	62.8	1.54	63.5	57.2	60.37	1.88	38.7
TiO_2	0.51	0.71	0.41	0.43	0.39	0.50	0.01	0.89	0.89	0.73	0.13	0.54
Al_2O_3	15.6	16.68	1.19	17.4	2.32	15.8	1.37	21.0	16.2	15.90	0.58	11.9
Fe_2O_3	2.0	1.99	1.01	2.1	1.76	2.7	0.54	3.1	5.1	4.12	1.23	4.3
FeO	2.8	3.26	1.57	2.6	1.58	1.9	0.55	1.9	0.9	1.18	0.80	2.7
MgO	3.1	2.38	1.85	1.5	1.34	2.9	0.65	1.5	2.9	2.67	0.57	15.7
CaO	3.3	4.82	1.69	3.0	1.95	3.8	0.61	2.1	4.6	4.48	0.51	3.2
MnO	0.08	0.09	0.08	0.04	—	0.10	0.03	0.14	0.05	0.05	0.01	0.12
Na_2O	3.8	4.31	0.53	3.38	1.04	3.05	0.31	1.65	3.91	3.78	0.40	1.12
K_2O	3.1	2.38	0.82	3.36	0.83	3.69	0.14	6.40	3.41	3.60	0.45	0.11
H_2O	0.9	0.76	0.27	0.41	0.31	2.30	0.75	4.21	2.06	1.33	0.87	10.9
P_2O_5	0.21	0.25	0.18	0.27	0.07	0.32	0.04	0.41	0.30	0.30	0.08	0.3
Selected Trace-Element Data (in ppm)												
Zn		25		50		235		40	75	205		70
Cu		10		20		30		3	20	67		19
Ni		35		12		780		90	20	5		20
Co		30		5		35		7	50	30		30
Cr		10		20		200		10	5	5		5
V		120		65		65		70	180	110		100
Ba		850		770		550		2000	720	1000		1020
Zr		95		130		150		300				

1. Average country rock, from *Eade et al.* [1966].
2. Average country rock, from *Bostock* [1969] (16 analyses).
3. Average country rock, central uplift of east lake (20 analyses).
4. Average massive igneous rock from east lake (12 analyses).
5. Average igneous breccia, east lake (6 analyses).
6. Average igneous breccia, west lake (8 analyses).
7. Average massive igneous rock from west lake (12 analyses).
8. Average analysis of gypsiferous ultramafic veinlets from drill cores beneath west lake (4 analyses).

breccia penetrated in bore holes, including gypsiferous serpentine seams. Although not analyzed, mineralization in the form of millerite-tetrahedrite seams is also found in these cores. The chemical results show significant enrichment of potassium and impoverishment in soda in igneous rocks relative to country rocks. The igneous rocks in West Clearwater Lake crater are enriched in alkalies and impoverished in magnesium, nickel, and chromium compared with those in East Clearwater Lake crater, which, according to conventional petrologic theory, would indicate a somewhat higher degree of differentiation.

Carswell crater forms an almost perfect circle 39 km in diameter, cut through Proterozoic sandstone into crystalline rocks [*Currie*, 1969c]. A rim syncline overturned away from the center is bounded on both sides by faults. The central core of crystalline rocks, shock metamorphosed along its margin, is separated from the rim sandstone by lenses of aphanitic, flow-banded, fragment-charged rocks, sheathed by igneous breccia. These igneous rocks are significantly richer in potassium and magnesium, and poorer in silicon and sodium than the crystalline rocks. If the sedimentary rocks are included, the differences are even larger. Shock metamorphism is not found in the sedimentary rocks, even where they overlie shock-metamorphosed basement rocks [*Currie*, 1967].

The *Sudbury structure*, 58 km long by 22 km wide, poses some of the difficult problems in Canadian geology. The geology is highly complex and controversial, and chemical data are not particularly abundant. The Sudbury irruptive has the form of a lopolithic sheet, 1.72 b.y. old, whose mean composition (Table 1) as computed by *Collins* [1934] is somewhat similar to that of igneous rocks found in other Canadian craters, but rather different from that of large gabbroic lopoliths. The irruptive is overlain 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 calculations suggest 20–80% addition of picritic alkali basalt. *Willemse* [1938] concluded that norite had been added to Vredefort pseudotachylite.

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

	1	2	3	4	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).

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 reminiscent 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 consequences. 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 pressure. Comparison of computed geotherms shows melting of crustal rocks due to release of pressure is very unlikely, [cf. *Lachenbruch*, 1970]. Melting by pressure release 100–200 km below surface is quite plausible, but an assumption that an impact sufficient to excavate the Brent crater, for example, could promptly summon up igneous rocks from 100 km down seems fantastic.

The geometry and composition of the igneous rocks can be explained by explosive endogenic volcanism if it is assumed that the magma has unusually high assimilative powers. Since explosives of high brisance (e.g. H_2) are present in volcanic gases, it seems unreasonable to suppose that volcanic explosions cannot at least locally and rarely produce shock phenomena.

The igneous rocks in Canadian craters cannot be completely explained by any theory so far advanced. A theory of explosive endogenic volcanism satisfies the geochemical data, but appeals to geological processes as yet unobserved. Impact hypotheses appear unlikely to explain the data.

Acknowledgments. M. R. Dence, Dominion Observatory, J. G. Murtaugh and J. Rondot, Quebec Department of Mines, and H. R. McCabe, Manitoba Department of Mines and Natural Resources, donated specimens for analysis. M. Shafiquallah very kindly allowed me to use unpublished material collected by us. H. H. Bostock not only contributed specimens, but contributed to the methodology of the study.

Publication was, in part, supported by NASA contract NSR 09-051-001.

References

Bostock, H. H., The Clearwater complex, *Geol. Surv. Can. Bull., 178*, 1969.

Burnham, C. W., Hydrothermal fluids at the magmatic stage, in *Geochemistry of Hydrothermal Ore Deposits*, edited by H. L. Barnes, p. 34, Holt, Rinehart and Winston, New York, 1967.

Carrigy, M. A., Evidence of shock metamorphism in rocks from the Steen River structure, Alberta, in *Shock Metamorphism of Natural Materials*, edited by B. M. French and N. K. Short, pp. 367–378, Mono, Baltimore, Md., 1968.

Collins, W. H., Life history of the Sudbury nickel eruptive, 1. Petrogenesis, *Trans. Roy. Soc. Can., 30*, sec. 4, 123, 1934.

Currie, K. L., Some analogues of lunar craters on the Canadian shield, *Annals N.Y. Acad. Sci., 123*, 915, 1965.

Currie, K. L., Geology of the New Quebec crater, *Geol. Surv. Can. Bull., 150*, 36 pp., 1966.

Currie, K. L., Shock metamorphism in the Carswell circular structure, Saskatchewan, Canada, *Nature, 213*, 56, 1967.

Currie, K. L., Mistastin Lake, Labrador: A new Canadian crater, *Nature, 220*, 776, 1968.

Currie, K. L., Alkaline rocks: Callander Bay and Brent, Ontario, *Geol. Surv. Can. Pap., 69-1A*, 136, 1969*a*.

Currie, K. L., Charlevoix structure, Quebec, *Geol. Surv. Can. Pap., 69-1A*, 138, 1969*b*.

Currie, K. L., Geological notes on the Carswell circular structure, *Geol. Surv. Can. Pap., 67-32*, 1969c.

Currie, K. L., A hypothesis on the origin of alkaline rocks suggested by the tectonic setting of the Monteregian Hills, *Can. Mineral., 10*, 411, 1970*a*.

Currie, K. L., New Canadian cryptoexplosion crater at Lake St. Martin, Manitoba, *Nature, 226*, 839, 1970*b*.

Currie, K. L., The geology and petrology of the Manicouagan resurgent caldera, *Geol. Surv. Can. Bull., 198*, 1970*c*.

Currie, K. L., and J. Ferguson, The mechanism of intrusion of lamprophyre dikes indicated by 'offsetting' of dikes, *Tectonophysics, 9*, 525, 1970.

Currie, K. L., and M. Shafiqullah, Carbonatite and alkaline igneous rocks in the Brent crater, Ontario, *Nature, 215*, 725, 1967.

Currie, K. L., and M. Shafiqullah, The geochemistry of some large Canadian craters, *Nature, 218*, 457, 1968.

Dence, M. R., Shock zoning at Canadian craters: Petrography and structural implications, in *Shock Metamorphism of Natural Materials*, edited by B. M. French and N. M. Short, p. 169, Mono, Baltimore, Md., 1968.

Dence, M. R., M. J. S. Innes, and P. B. Robertson, Recent geological and geophysical studies of Canadian craters, in *Shock Metamorphism of Natural Materials*, edited by B. M. French and N. M. Short, p. 339, Mono, Baltimore, Md., 1968.

Eade, K. E., W. F. Fahrig, and J. A. Maxwell, Composition of crystalline shield rocks and fractionating effects of regional metamorphism, *Nature, 211*, 1249, 1966.

Ermanovics, I. F., A. D. Edgar, and K. L. Currie, Evidence bearing on the origin of the Belleoram stock, southern Newfoundland, *Can. J. Earth. Sci., 4*, 413, 1967.

Fairbairn, H. W., G. Faure, W. H. Pinson, and P. M. Hurley, Rb-Sr whole-rock age of the Sudbury lopolith, *Can. J. Earth Sci., 5*, 707, 1968.

French, B. M., Sudbury structure, Ontario: Some petrographic evidence for an origin by meteorite impact, in *Shock Metamorphism of Natural Materials*, edited by B. M. French and N. M. Short, p. 383, Mono, Baltimore, Md., 1968.

Lachenbruch, A. H., Crustal temperature and heat production: Implications of the linear heat-flow relation, *J. Geophys. Res., 75*, 3291, 1970.

MacDonald, G. A. and K. Katsura, Chemical composition of Hawaiian lavas, *J. Petrol., 5*, 82, 1964.

Millman, P. M., B. A. Liberty, J. F. Clark, P. L. Willmore, and M. J. S. Innes, The Brent crater, *Publ. Dominion Astrophys. Observ., 24*(1), 1960.

Milton, D. J., Gosses Bluff impact structure, *Astrogeologic Studies, Annual Progress Report, 1968–1969* p. 34, U.S. Geological Survey, Washington, D.C., 1970.

Nockolds, S. R., Average chemical composition of some igneous rocks, *Bull. Geol. Soc. Amer., 65*, 1007, 1954.

Philpotts, A. R., Origin of pseudotachylites, *Amer. J. Sci., 262*, 1008, 1964.

Roberts, W. A., Shock crater ejecta characteristics, in *Shock Metamorphism of Natural Materials*, edited by B. M. French and N. M. Short, p. 101, Mono, Baltimore, Md., 1968.

Rondot., J., Nouvel impact meteoritique? Le structure semi-circulaire de Charlevoix, *Can. J. Earth Sci., 5*, 1305, 1968.

Shafiqullah, M., W. M. Tupper, and T. J. S. Cole, K-Ar ages of rocks from the crater at Brent, Ontario, *Earth Planet. Sci. Lett., 5*, 148, 1968.

Short, N. M., Anatomy of a meteorite crater, West Hawk Lake, Manitoba, Canada, *Bull. Geol. Soc. Amer., 81*, 148, 1970.

Speers, E. C., The age relations and origin of common Sudbury breccia, *J. Geol., 65*, 497, 1957.

Taylor, S. R., Australites, Henbury impact glass, and subgreywacke, *Geochim. Cosmochim. Acta, 30*, 1121, 1966.

Willemse, J., On the old granite of the Vredefort region and related rocks, *Trans. Geol. Soc. South Africa, 40*, 43, 1938.

(Received December 21, 1970;
revised March 4, 1971.)

VOL. 76, NO. 23 JOURNAL OF GEOPHYSICAL RESEARCH AUGUST 10, 19[illegible]

Impact Melts

MICHAEL R. DENCE

Gravity Division, Earth Physics Branch
Department of Energy, Mines and Resources, Ottawa, Ontario, Canada

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*, 1968a]. 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*, 1968b] 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*

TABLE 1. Craters with Shock Effects and Melt Rocks

Crater Diameter	Classification by Relative Erosion Depth 1	2	3	4	5	6	7
100 meters	Wabar Henbury Aouelloul Monteraqui	(Wolf Creek)					
1 km	Barringer						
		Tenoumer Köfels	(Lonar L.) New Quebec*	Holleford† W. Hawk L.† Brent†			
5 km							
		Bosumtwi					
					L. Wanapitei*	Pilot L.* L. Mien*†	
10 km			Deep Bay†			Lac Couture*	
			Steen River†	E. Clearwater† Strangway		Nicholson L. L. Dellen Rochechouart Lappajärvi (Jänisjärvi) L. Mistastin Gosses Bluff	
20 km			Manson†				
30 km		Ries					
				L. St. Martin†	W. Clearwater		
50 km							Carswell Siljan Charlevoix
100 km					Manicouagan	Sudbury	Vredefort

Parentheses indicate craters at which shock effects have yet to be identified.
* Melt rocks known mainly or only from glacial float.
† Melt rocks known mainly or only from diamond drilling.

et al., 1969] forms surficial deposits up to tens of meters thick and is distributed both inside and outside the crater rim. There is abundant evidence that the glassy masses ('bombs' or 'Fladen') in the great majority of Ries melt deposits were aerodynamically shaped and chilled before deposition in the ejecta blanket [*Hörz*, 1965].

Mixed breccias in which glasses are associated with shocked fragments are also developed in the interior of craters among the rocks underlying the crater floor, and so are only exposed in more deeply eroded craters, such as West Clearwater Lake [*von Engelhardt and Dence*, 1971]. In these breccias the fresh or recrystallized glasses show intricate intrusive relationships with the enclosing fragmental rocks, indicating that the masses of melt were incorporated into the breccia while still hot and mobile. In some cases breccia fragments are entrained between layers of glass to give a banded fabric. Such breccias have also been called 'suevites,' but the term is more properly applied only to rocks like the Ries material, in which the glassy masses are of the Fladen type. In craters of small to intermediate size (up to 10 km), the relationships of breccias within the crater rims are generally complicated by slumping.

3. *Subhorizontal sheets of igneous rock.* In large craters the melt occurs predominantly as large sheets of igneous rock. The sheets are distributed within the craters as an annulus around one or more peaks of the central uplift, as seen at the West Clearwater Lake and Manicouagan occurrences. Mappable variations in the igneous rocks in both structures are mainly based on differences in grain size and in the content of inclusions that produce differences in patterns of jointing.

At West Clearwater Lake, for example, the following succession has been recognized on the ring of islands [*Dence*, 1964; *Bostock*, 1969]: (a) fractured and weakly shocked basement gneisses overlain by (b) up to 40 meters of mixed breccias with glassy fragments, overlain in turn, generally with sharp contact, by (c) a unit, averaging 30 meters in thickness, of fine-grained igneous rock with abundant shocked inclusions (coherent breccia of Bostock). The latter unit has a well-developed vertical jointing similar to jointing developed in welded ignimbrites, with which the Clearwater rocks have been compared [*Kranck and Sinclair*, 1963]. The fine-grained rocks grade upward into (d) a coarser-grained, massive, weakly jointed phase in which inclusions are generally inconspicuous (quartz latite of Bostock).

Similar variations on a larger scale have been mapped at Manicouagan [*Murtaugh and Currie*, 1969], where, nonetheless, paleomagnetic measurements show that the igneous rocks behaved as a single cooling unit after their formation in the Triassic [*Robertson*, 1967; *Larochelle and Currie*, 1967]. The preserved igneous section at West Clearwater is as much as 130 meters thick; at Manicouagan it is twice as thick. At both craters an estimated 50 meters or more of section has been removed by erosion, the missing material probably being similar to the fine-grained, vesicular, inclusion-rich igneous rocks recovered by drilling below sedimentary fill in East Clearwater Lake [*Dence et al.*, 1965].

The full lateral extent of the igneous rock sheets can only be surmised from the preserved record. A comparison of the more completely preserved craters suggests that with increasing crater size, the thick igneous sheets are more extensively spread over the crater floor and in the largest craters may even overlap the rim of the primary crater [as defined in *Dence*, 1968]. Thus at West Clearwater [*Dence*, 1965] and Lake St. Martin [*McCabe and Bannatyne*, 1970] craters the thick igneous sheets are concentrated on the inner side of a ring uplift of crystalline basement rocks 20 km in diameter. At Manicouagan, on the other hand, the ring structure has a diameter of about 45 km and is completely covered by the 200-meter-thick sheet of igneous rocks. They extend radially for a further 5 to 10 km well into the peripheral trough that marks the down-dropped crater rim.

Massive igneous rocks have not been recorded at the Ries, where the ring uplift is 12 km in diameter, but strong magnetic anomalies within the crystalline ring [*Pohl and Angenheister*, 1969] may indicate concentrations of melt comparable to those at the Canadian craters. The exposures of crystalline vesicular igneous rocks at Polsingen and Amerbach on the east side of the crater [*von Engelhardt et al.*, 1969] are probably outlying tongues of the inferred igneous sheet.

4. *Dikes of melt and breccia in basement rocks.* The fourth form in which igneous rocks occur at shocked structures is also observed at Manicouagan in deep gullies that dissect the crater rim. There small dikes of glass and breccia cut the fractured basement rocks. The dikes are similar in composition, texture, and age to the overlying sheets of igneous rocks and breccias and are apparently derived from them as fracture fillings during the later stages of crater formation. At the most deeply eroded structures, such as those listed in column 7 of Table 1, minor intrusions of this type are the only manifestations of the more extreme conditions of strain and temperature that were attendant on their formation. Representative occurrences include the melt rocks and breccias from Charlevoix [*Rondot*, 1968] and Carswell [*Currie*, 1969] craters and the enstatite granophyre dikes at Vredefort [*Willemse*, 1937]. Pseudotachylite veins found at a number of these craters are not considered to be a form of the melt rocks but are interpreted as resulting from frictional melting of mobilized basement rocks, particularly those involved in the central uplift.

TEXTURES

The considerable textural variety exhibited by the igneous rocks of shock-metamorphosed structures is attributable to two factors: (1 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).

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

Chemical Component	Brent BC	Brent BF	Brent B952	West Clearwater Lake WC-F	West Clearwater Lake WC-C	West Clearwater Lake WC-B	Lake Wanapitei 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.

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 2b. Descriptions of Rocks Analyzed and Data Sources

Crater	Sample Designation	Description and Data Source
Brent	BC	Coarsest-grained phase of Brent melt. Analysis by R. Wirthlin.
	BF	Fine-grained phase of Brent melt. Mean of analyses by R. Wirthlin and *Currie and Shafiqullah* [1967].
	B952	Mixed breccia with melted matrix in central hole 1-59 of Brent crater, 952 ft below collar of hole. Analysis from *Currie and Shafiqullah* [1967].
West Clearwater Lake	WC-F	Average of 5 analyses of fine-grained, inclusion-rich melt ('coherent breccia,' from *Bostock* [1969]).
	WC-C	Analysis of fresh black glass with small inclusions, from *von Engelhardt and Dence* [1971].
	WC-B	Average of 5 analyses of mixed breccias with shocked fragments. Analyses of *Bostock* [1969] −3; *von Engelhardt and Dence* [1971] −2.
Lake Wanapitei	W	Electron microprobe analysis of fresh glass matrix from mixed breccia. Analysis by P. B. Robertson, from *Dence and Popelar* [1971].
		Sources for Other Data (in Figures 2 and 3)
Ries	301, 303	Garnet-biotite-gneiss of Maihingen and Appetshofen. Possible source rocks for Ries glasses [*von Engelhardt et al.*, 1969, Tables 10 and 11].
	T1, T2, T3	Average compositions of fresh, partially recrystallized and recrystallized Ries glasses [*von Engelhardt*, 1967, Table 6].
	T3W	Average composition of recrystallized glasses from Wörnitzostheim drill hole [*von Engelhardt*, 1967, Table 6].
	153, 155	Crystalline suevite of Amerbach [*von Engelhardt*, 1967, Table 5].
	DB1.	Altered suevite glasses, Deiningen drill hole 330–350 meters [*Förstner*, 1967, Table 4].
Henbury	H-S	Average subgreywacke [*Taylor*, 1967, Table 3].
	27	Throw-out subgreywacke [*Taylor*, 1967, Table 3].
	G	Average glass [*Taylor*, 1967, Table 1].
Carswell	CAR	Average country rock and melt [*Currie and Shafiqullah*, 1967, Table 1 (*c* and *a*)].
East Clearwater Lake	EC	Average country rock and melt [*Currie and Shafiqullah*, 1968, Table 1 (c_1 and *a*)].
Manicouagan	MAN	Average country rock and melt ('doreite') [*Currie and Shafiqullah*, 1968, Table 1 (*c* and a_1)].
Brent	B	Average country rock, [*Currie and Shafiqullah*, 1967, Table 1 ($d_1 + d_2$)].
West Clearwater Lake	WC	Average country rock, [*Bostock*, 1969, Table 1].
	WC-M	Average igneous rock ('quartz latite') [*Bostock*, 1969, Table 5].
Charlevoix	C	Average melt rock ('impactite') [*Rondot*, 1968].
Dellen	D	Igneous rock ('andesite') [*Eskola*, 1921].
Jänisjärvi	J	Igneous rock ('dacite') [*Eskola*, 1921].
Lake Mien	M	Igneous rock ('rhyolite') [*Eskola*, 1921].
New Quebec	NQ	Igneous rock [*Currie*, 1966].
Vredefort	V	Average enstatite granophyre, [*Willemse*, 1937].

IMPACT MODEL

The theory of hypervelocity impact [*Bjork*, 1961; *Gault and Heitowit*, 1963], supported by experiment [*Shoemaker et al.*, 1963], shows that for typical terrestrial impact velocities of 15–20 km/sec significant quantities of both the target materials and the projectile will be vaporized or fused. In Figure 3 a model, modified from *Gault et al.* [1968] and *Dence* [1968], for the excavation stage of such a cratering event is presented. Attenuation of the shock wave is based on an initial impact pressure of about 5 Mb and an indicated shock pressure of about 200 kb immediately below the region of deepest excavation. The theory indicates that, for a low porosity, polymineralic material such as basalt or granite, most of the target shocked above about 2 Mb will be vaporized, and most shocked to between 0.5 and 2 Mb will be fused or partially fused. The shock-melted materials will be given particle velocities in the directions indicated by the arrows in Figure 3 and will engulf less strongly shocked and accelerated materials in the outer parts of the growing crater. The impacting body will undergo a similar sequence of shock events and will in part be mixed with the melted target materials, probably remaining concentrated in the upper parts of such a melt. A portion of the melt will be ejected as indicated, leaving the remainder as a lining of the cavity when growth ceases. The relatively thin lining will then consist of melt overlying mixed breccia, with the proportion of breccia to melt increasing toward the crater margin.

The crater at this stage has been called the *primary crater* [*Dence*, 1968] but may as aptly be termed the *transient cavity* to emphasize the interpretation that a rapid readjustment takes place to give the final crater form. The general sequence of events, as presented by *Dence* [1968], is illustrated in Figure 4. Small, simple craters are formed by slumping of the crater walls (Figure 4*a*). In this case the melted and brecciated materials lining the transient cavity are swept into the center of the crater with large amounts of weakly shocked material from the crater walls to form a lens of complexly mixed breccias. Melt and breccia at the bottom of the transient cavity are over-ridden

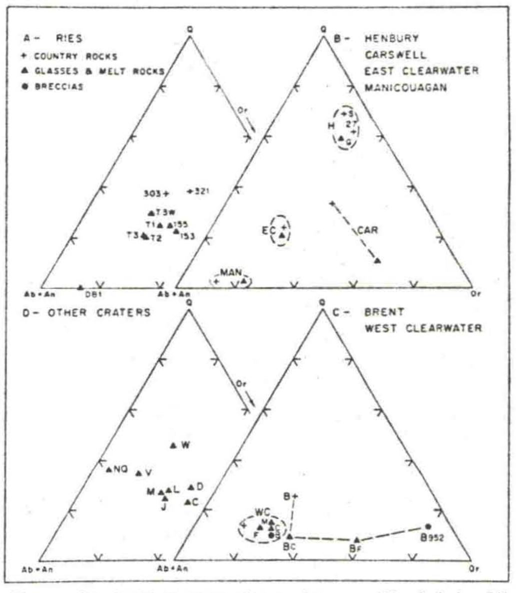


Fig. 1. Ternary plots, for fifteen craters, of normative quartz (Q) : plagioclase (Ab + An) : potash feldspar (Or), calculated as Barth catanorms [*Barth*, 1962]. Sources and descriptions of analyses given in Table 2.

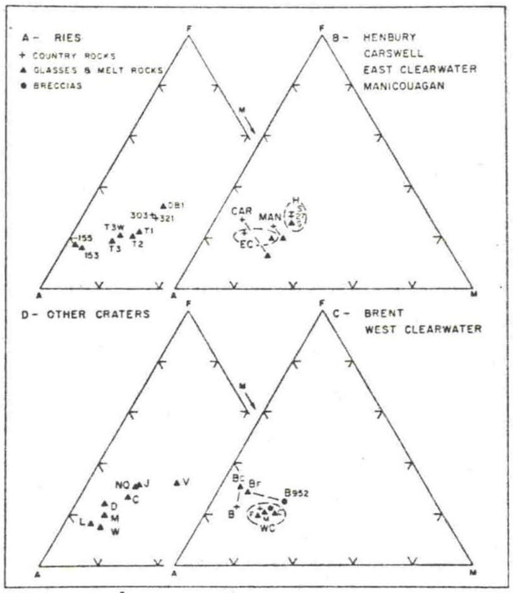


Fig. 2. Ternary plots, for fifteen craters, of the ratio iron (F) : magnesium (M) : alkalis (A). Sources and description of analyses given in Table 2.

and remain relatively undisturbed. In large craters collapse of the uplifted rim materials initiates deep sliding, which results in uplift of the crater floor in the center and down drop of the crater rim (Figure 4*b*). The crater lining has a passive role in these events and largely retains its original relationships, except in the center where it is pierced by peaks of the central prominence. Melt and breccia will, however, fill fractures that may open up in the underlying basement rocks in the final stages of adjustment.

The model provides four mechanisms by which the composition of the consolidated melt rocks may differ from that of the adjacent country rocks: (1) addition of meteoritic material to the melt; (2) selective melting of low-melting-point components of country rock; (3) differences between the composition of the target rock actually melted and the mean or calculated composition of the adjacent country rocks; (4) alteration during the following consolidation.

Differential vaporization close to the point of impact has also been suggested, but such vaporized materials are likely to be widely dispersed and need not be considered in this discussion.

1. *Contamination by meteoritic material.* This process leads to enrichment of the melt rocks in nickel, cobalt, iron, and, in the case of chondrites, magnesium, as well as in certain trace elements. Of these nickel, being two or three orders of magnitude more abundant in meteorites than in average crustal rocks, is potentially the most useful indicator of meteoritic contamination. Nickel-iron anomalies are well known in glasses from Henbury and other

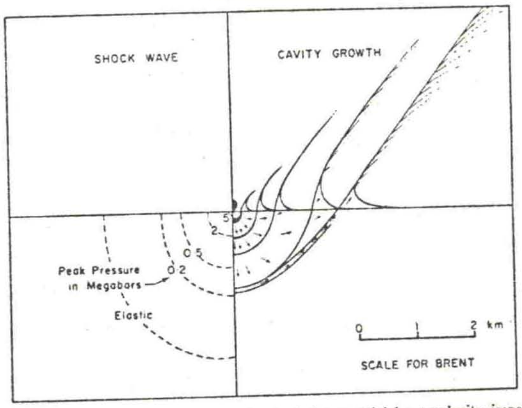


Fig. 3. Model of the excavation stage of a typical terrestrial hypervelocity impact crater based mainly on analysis of data from Brent crater. On the right, stages in the excavation are depicted with vectors of particle motion after *Gault et al.* [1968]. On the left are shown the corresponding positions of the attenuating shock wave.

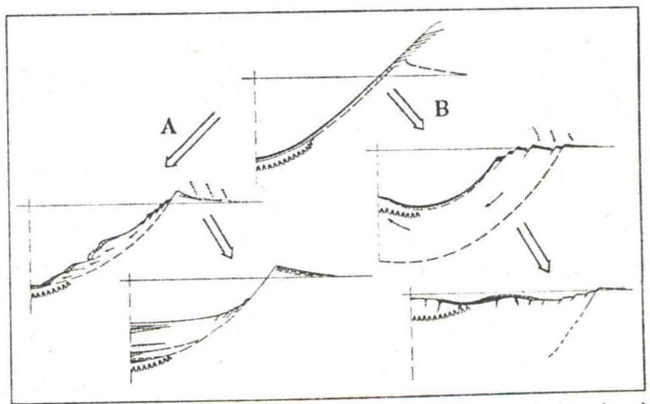


Fig. 4. Two alternative post-excavation histories of an impact crater. (*a*) Slumping of the crater walls to give a simple crater of the Barringer-Brent type. Melt and breccias lining the excavated cavity are disrupted and incorporated into a central bowl-shaped body of breccias. (*b*) Deep-seated sliding of the crater walls to give a central uplift, ring uplift, and depressed rim, as in a complex crater of the Clearwater-Manicouagan type. The crater lining remains largely intact but fills fractures in the underlying basement rocks. Limits of shock deformation of the basement rocks shown by inverted V's.

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 compositions 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^{13} 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 recrystallization of shocked inclusions, and the processes of chemical variation. Isotopic studies have already made a contribution. The study of argon distribution in shocked rocks shows a distinct correlation with grade of shock metamorphism and with the degree of secondary alteration [*Hartung et al.*, 1971]. The ratio of strontium isotopes has been determined at several craters, for example, Henbury [*Compston and Taylor*, 1969] and Tenoumer [*French et al.*, 1970] and has been shown to be similar in melt and country rocks, as expected under the impact hypothesis.

Further theoretical studies are needed in which the scaling of the strength of target materials is more fully considered. The indication that large craters contain more melt, relative to crater dimensions, than small craters implies a decrease of excavation efficiency with increasing crater size. Also a larger proportion of the melt is not ejected but remains in the crater as a continuous lining of the crater floor and walls. If similar relationships hold on the moon, large lunar craters such as Tycho, if formed by impact, should be floored by a sheet of shock-melted rock several hundred meters thick, which initially would have extended up to or even over the crater rim. Rapid, deep sliding to form the central uplift and terracing of the rim would disrupt the sheet and possibly lead to flow and ponding of still fluid impact melt.

REFERENCES

Barth, T. F. W., *Theoretical Petrology*, John Wiley, New York, 1962.

Beals, C. S., The identification of ancient craters, *Ann. N.Y. Acad. Sci.*, *123*, 904–914, 1965.

Bostock, H. H., The Clearwater complex, New Quebec, *Geol. Surv. Can. Bull.*, *178*, 63 pp., 1969.

Bjork, R. L., Analysis of the formation of Meteor Crater, Arizona, *J. Geophys. Res.*, *66*, 3379–3387, 1961.

Braslau, D., Partitioning of energy in hypervelocity impact against loose sand targets, *J. Geophys. Res.*, *75*, 3987–3999, 1970.

Brett, R., Metallic spherules in impactite and tektite glasses, *Amer. Mineral.*, *52*, 721–733, 1967.

Brett, R., D. J. Guppy, and D. J. Milton, Two circular structures of impact origin in Northern Territory, Australia (abstract), *33rd Ann. Meet. Meteorit. Soc.*, 1970.

Bucher, W. H., Cryptovolcanic structures in the United States, *16th Int. Geol. Congr., U.S.A., Rep. Session, 2*, 1055–1064, 1936.

Chao, E. C. T., Impact metamorphism, in *Researches in Geochemistry*, vol. 2, edited by P. H. Abelson, pp. 204–233, John Wiley, New York, 1967.

Chao, E. C. T., Pressure and temperature histories of impact metamorphosed rocks—based on petrographic observations, in *Shock Metamorphism of Natural Materials*, edited by B. M. French and N. M. Short, pp. 135–158, Mono, Baltimore, Md., 1968.

Compston, W., and S. R. Taylor, Rb-Sr study of impact glass and country rocks from the Henbury meteorite crater field, *Geochim. Cosmochim. Acta*, *33*, 1037–1043, 1969.

Currie, K. L., Geology of the New Quebec Crater, *Geol. Surv. Can. Bull.*, *150*, 36 pp., 1966.

Currie, K. L., Geological notes on the Carswell circular structure, Saskatchewan (74K), *Geol. Surv. Can. Pap. 67-32*, 60 pp., 1969.

Currie, K. L., and M. Shafiqullah, Carbonatite and alkaline igneous rocks in the Brent crater, Ontario, *Nature*, *215*, 725–726, 1967.

Currie, K. L., and M. Shafiqullah, Geochemistry of some large Canadian craters, *Nature*, *218*, 457–459, 1968.

Dence, M. R., A comparative structural and petrographic study of probable Canadian meteorite craters, *Meteoritics*, *2*, 249–270, 1964.

Dence, M. R., The extraterrestrial origin of Canadian craters, *Ann. N.Y. Acad. Sci.*, *123*, 941–969, 1965.

Dence, M. R., Shock zoning at Canadian craters: Petrography and structural implications, in *Shock Metamorphism of Natural Materials*, edited by B. M. French and N. M. Short, pp. 169–184, Mono, Baltimore, Md., 1968.

Dence, M. R., and J. Popelar, Evidence for an impact origin for Lake Wanapitei, Ontario, *Can. J. Earth Sci.*, in press, 1971.

Dence, M. R., M. J. S. Innes, and C. S. Beals, On the probable meteorite origin of Clearwater Lakes, Quebec, *J. Roy. Astron. Soc. Canada*, *59*, 13–22, 1965.

Dietz, R. S., Shatter cones in cryptoexplosion structures (meteorite impact?), *J. Geol.*, *67*, 496–505, 1959.

Eskola, P., On volcanic necks in Lake Jänisjärvi in eastern Finland, *Bull. Comm. Geol. Finlande*, *55*, 3–13, 1921.

Fenner, C. N., Bore-hole investigations in Yellowstone Park, *J. Geol.*, *44*, 225–315, 1936.

Förstner, U., Petrographische Untersuchungen des Suevit aus den Bohrungen Deiningen und Wörnitzostheim im Ries von Nördlingen, *Contrib. Mineral. Petrol.*, *15*, 281–308, 1967.

Freeberg, J. H., Terrestrial impact structures—a bibliography, 1965–68, *U.S. Geol. Surv. Bull. 1320*, 1969.

French, B. M., Shock metamorphism as a geological process, in *Shock Metamorphism of Natural Materials*, edited by B. M. French and N. M. Short, pp. 1-17, Mono, Baltimore, Md., 1968a.

French, B. M., Sudbury structure, Ontario: Some petrographic evidence for an origin by meteorite impact, in *Shock Metamorphism of Natural Materials*, edited by B. M. French and N. M. Short, pp. 383–412, Mono, Baltimore, Md., 1968b.

French, B. M., J. B. Hartung, N. M. Short, and R. S. Dietz, Tenoumer crater, Mauritania: Age and petrologic evidence for origin by meteorite impact, *J. Geophys. Res.*, *75*, 4396–4406, 1970.

Gault, D. E., and E. D. Heitowit, The partition of energy for hypervelocity impact craters formed in rock, *Proc. 6th Hypervelocity Impact Symp.*, *2*, 419–456, 1963.

Gault, D. E., W. L. Quaide, and V. R. Oberbeck, Impact cratering mechanics and structures, in *Shock Metamorphism of Natural Materials*, edited by B. M. French and N. M. Short, pp. 87–99, Mono, Baltimore, Md., 1968.

Hartung, J. B., M. R. Dence, and J. A. S. Adams, Potassium-argon dating of shock-metamorphosed rocks from the Brent impact crater, Ontario, Canada, *J. Geophys. Res.*, *76*, this issue, 1971.

Haslam, H. W., The crystallization of intermediate and acid magmas at Ben Nevis, Scotland, *J. Petrol.*, *9*, 84–104, 1968.

Hörz, F., Untersuchungen an Riesgläsern, *Beitr. Mineral. Petrogr.*, *11*, 621–661, 1965.

Kranck, S. H., and G. W. Sinclair, Clearwater Lake, New Quebec, *Geol. Surv. Can. Bull.*, *100*, 25 pp., 1963.

Larochelle, A., and K. L. Currie, Paleomagnetic study of igneous rocks from the Manicouagan structure, Quebec, *J. Geophys. Res.*, *72*, 4163–4169, 1967.

Lehtinen, M., New evidence for an impact origin of Lake Lappajärvi, western Finland, *Bull. Geol. Soc. Finland*, *42*, 89–93, 1970.

McCabe, H. R., and B. B. Bannatyne, Lake St. Martin crypto-explosion crater and geology of the surrounding area, *Geol. Surv. Manitoba, Geol. Pap. 3/70*, 1970.

Murtaugh, J. C., and K. L. Currie, Preliminary study of Manicouagan structure, *Dep. Natur. Resour., Quebec, P.R. 583*, 1969.

Nininger, H. H., Impactite slag at Barringer crater, *Amer. J. Sci.*, *252*, 277–290, 1954.

Pohl, J., and G. Angenheister, Anomalien des Erdmagnetfeldes und Magnetisierung der Gesteine im Nördlinger Ries, *Geol. Bavarica*, *61*, 327–336, 1969.

Robertson, P. B., La Malbaie structure, Quebec—a Palaeozoic meteorite impact site, *Meteoritics*, *4*, 89–112, 1968.

Robertson, W. A., Manicouagan, P. Q., paleomagnetic results, *Can. J. Earth Sci.*, *4*, 641-649, 1967.

Rondot, J., Nouvel impact météoritique fossile? La structure semicirculaire de Charlevoix, *Can. J. Earth Sci.*, *5*, 1305–1317, 1968.

Shoemaker, E. M., Penetration mechanics of high velocity meteorites, illustrated by Meteor Crater, Arizona, *21st Int. Geol. Congr., Norden, Rep. Session, 18*, 418–434, 1960.

Shoemaker, E. M., D. E. Gault, H. J. Moore, and R. V. Lugn, Hypervelocity impact of steel into Coconino sandstone, *Amer. J. Sci.*, *261*, 668–682, 1963.

Short, N. M., A comparison of features characteristic of nuclear explosion craters and astroblemes, *Ann. N.Y. Acad. Sci.*, *123*, 573–616, 1965.

Short, N. M., and T. E. Bunch, A worldwide inventory of features characteristic of rocks associated with presumed meteorite impact craters, in *Shock Metamorphism of Natural Materials*, edited by B. M. French and N. M. Short, pp. 255-266, Mono, Baltimore, Md., 1968.

Spencer, L. J., Meteoric iron and silica-glass from the meteorite craters of Henbury (Central Australia) and Wabar (Arabia), *Mineral. Mag.*, *23*, 387–404, 1933.

Stanfors, R., Lake Mien—an astrobleme or a volcano—tectonic structure, *Geol. Fören. Stockholm Förh.*, *91*, 73–86, 1969.

Svensson, N.-B., The Dellen Lakes, a probable meteorite impact in central Sweden, *Geol. Fören. Stockholm Förh.*, *90*, 309–316, 1968.

Svensson, N.-B., Lake Mien, southern Sweden—a possible astrobleme, *Geol. Fören. Stockholm Förh.*, *91*, 101–110, 1969.

Taylor, F. C., and M. R. Dence, A probable meteorite origin for Mistastin Lake, Labrador, *Can. J. Earth Sci.*, *6*, 39–45, 1969.

Taylor, S. R., Composition of meteorite impact glass across the Henbury strewnfield, *Geochim. Cosmochim. Acta*, *31*, 961–968, 1967.

Taylor, S. R., and P. Kolbe, Geochemistry of Henbury impact glass, *Geochim. Cosmochim. Acta*, *29*, 741–745, 1965.

von Engelhardt, W., Chemical composition of Ries glass bombs, *Geochim. Cosmochim. Acta*, *31*, 1677–1689, 1967.

von Engelhardt, W., Detrital impact formations, *J. Geophys. Res.*, *76*, this issue, 1971.

von Engelhardt, W., and M. R. Dence, Petrological investigations of glasses from the West Clearwater Lake crater, Quebec, *Pub. Earth Phys. Br., Ottawa*, in press, 1971.

von Engelhardt, W., and D. Stöffler, Stages of shock metamorphism in crystalline rocks of the Ries basin, Germany, in *Shock Metamorphism of Natural Materials*, edited by B. M. French and N. M. Short, pp. 159–168, Mono, Baltimore, Md., 1968.

von Engelhardt, W., D. Stöffler, and W. Schneider, Petrologische Untersuchungen im Ries, *Geol. Bavarica*, *61*, 229–295, 1969.

Willemse, J., On the old granite of the Vredefort region and some of its associated rocks, *Trans. Geol. Soc. S. Africa*, 43–119, 1937.

Zotkin, I. T., and V. I. Tsvetkov, Searches for meteorite craters on the earth, *Astron. Vestnik*, *4*, 55–65, 1970.

(Received February 3, 1971;
revised March 10, 1971.)