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Proto-Atlantic Oceanic Crust and Mantle: Appalachian/Caledonian Ophiolites

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Details of the history of the so-called Proto-Atlantic Ocean can be elucidated from a study of the occurrence of ophiolite suites in the Appalachian/Caledonian system.

SEVERAL models have been proposed for the evolution of the Appalachian/Caledonian Orogen involving oceans, continental margins and island arcs[1-6]. Most of these invoke contraction of a Proto-Atlantic Ocean during Lower Palaeozoic times. In three models[4-6] the significance of the ophiolite suite to the pre-orogenic existence of oceanic crust and mantle is emphasized. Fully developed ophiolite suites[7-10] consist chiefly of dunite and harzburgite below passing into gabbro, often a complex transition[9] involving a large clinopyroxene component, with gabbroic[8] and ultrabasic dykes. The gabbro changes upward into massive and pillowed basic lavas, sometimes through a classic "sheeted diabase complex" involving, in its central parts, 100% dykes. The basic lavas are commonly conformably overlain by deep-water marine sediments[9]. Our present knowledge of the structure and composition of oceanic crust and mantle[11,12] strongly suggests that ophiolite occurrences represent oceanic crust and mantle generated by

Most of these ophiolites are either dated as, or suspected to be, Early Ordovician with the exception of two Newfoundland occurrences (Nos. 19 and 20 in Fig. 1) which are demonstrably older and probably of Cambrian age. We consider their time of emplacement and deformation, and their significance in terms of axial plate accretion versus a possible origin in marginal oceanic basins. The tectonic subdivisions that are used in Fig. 1 in terms of the Palaeozoic continental shelf, belts of Early Ordovician deformation, and Palaeozoic island arcs and

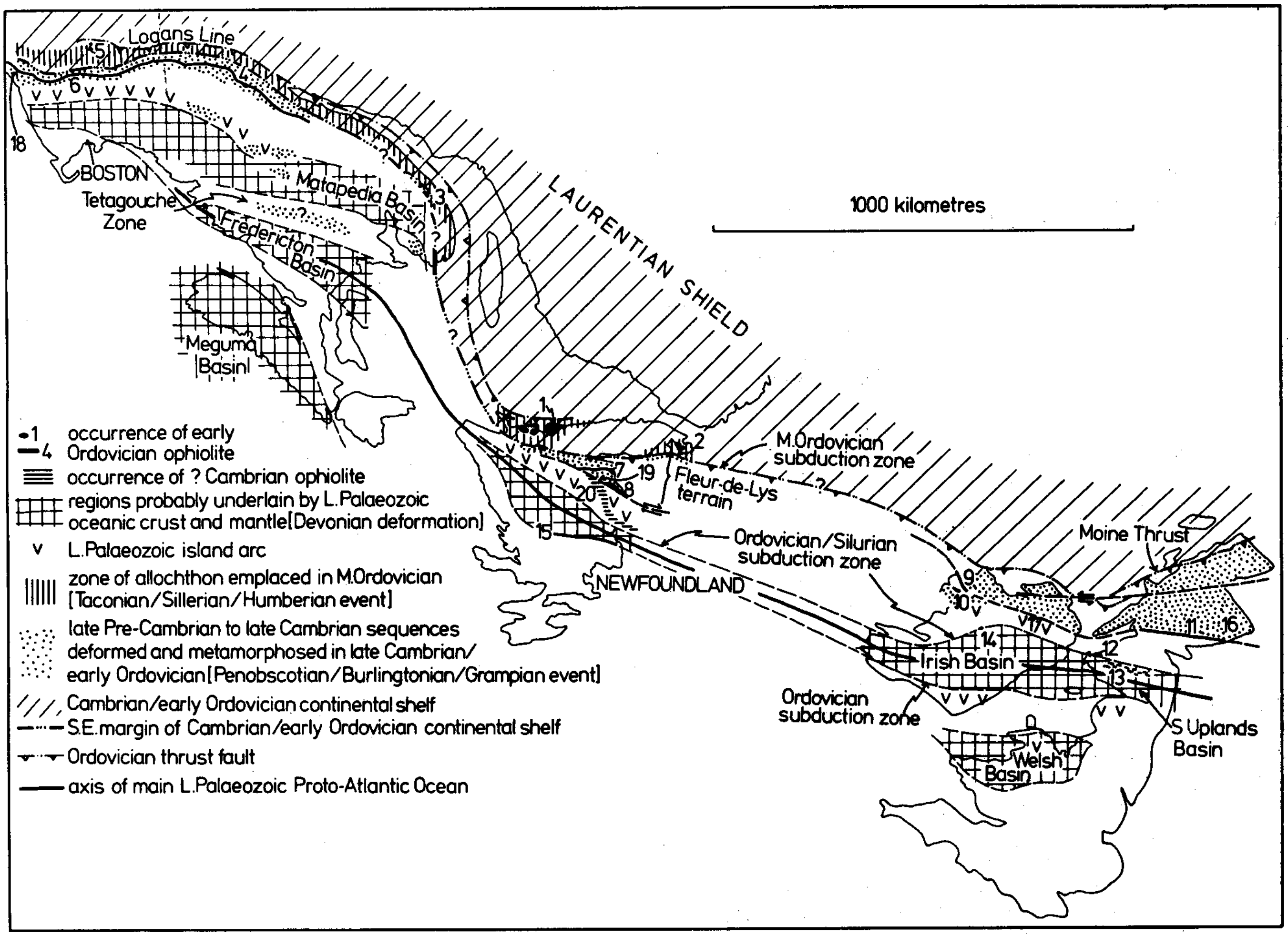

Fig. 1 Occurrence of ophiolites and some other ultrabasic/basic rock suites in the Appalachian/Caledonian Orogenic Belt between New York and Scotland. (1) Bay of Islands Complex; (2) Hare Bay Peridotites; (3) Mt Albert Peridotite; (4) Quebec Serpentinite Belt; (5) Starks Knob; (6) Vermont Serpentinite Belt; (7) Baie Verte Ophiolite Complex; (8) Betts Cove/Tilt Cove Ophiolite Complex; (9) Clew Bay Serpentinite Belt; (10) Lough Nafooey Group; (11) Highland Boundary Fault Zone; (12) Ballantrae Ophiolite Complex; (13) Arenigian pillow lavas in anticlinal cores in the Leadhills region; (14) Early Ordovician pillow lavas at Strokestown; (15) Gander River Belt; (16) Aberdeenshire gabbros; (17) Tyrone Igneous Complex; (18) Cortland Complex; (19) Nippers Harbour and Beaver Cove Groups; (20) Little Bay Head Group.

plate accretion at oceanic ridges[13] and in marginal oceanic basins[14], that have subsequently been emplaced during orogeny at consuming plate margins[13,15]. The dunite and harzburgite probably represent depleted upper mantle residue from which basalt has been withdrawn to form oceanic crust[16]. In this article we list occurrences of ultrabasic and basic rocks in the Appalachian/Caledonian system, from New York to Scotland, that we believe belong to the ophiolite suite and represent Lower Palaeozoic oceanic crust and mantle.

ocean basins, are simplified from those established in earlier articles[3,5]. We use the term Proto-Atlantic Ocean in the sense initiated by Wilson[1] to describe a former ocean within the site of the present Appalachian/Caledonian Orogen. This ocean was not the embryonic stage of the present Atlantic but an entirely older ocean which had essentially closed, by plate consumption, in Middle to Late Devonian times[5]. The present Atlantic Ocean has opened in a series of complex stages, beginning in Late Triassic or Early Jurassic times. The justification for continued usage of the term Proto-Atlantic for the Lower Palaeozoic ocean is that it very roughly followed the line of opening of the present central and north Atlantic. The term Appalachian Atlantic Ocean[5] may be appropriate for the entire orogen.

Early Ordovician Ophiolites

In this section we briefly describe the ophiolite occurrences that are marked by numbers in Fig. 1. The Bay of Islands Complex[17] (No. 1 in Fig. 1) consists of a fully developed ophiolite suite[4] of probable Tremadocian age. The complex lies in a large thrust sheet forming the highest slice[4] of a transported assemblage emplaced, onto the Ordovician continental shelf, from a provenance site to the south-east[18]. The Hare Bay Peridotites[19] (No. 2), like the Bay of Islands Complex, form part of the highest slice of a transported assemblage. This slice carries rocks which were metamorphosed and deformed before emplacement (personal communication from R. Smyth) and which probably formed part of the Fleur de Lys terrain (Fig. 1). Pillow lavas at Cape Onion have yielded Tremadocian graptolites[20], and this is the only direct evidence for the age of the Hare Bay, and probably, by analogy, the Bay of Islands, ophiolites. The Mount Albert Peridotite[21] (No. 3) is probably of Early Ordovician age and intrudes the Shickshock metamorphic terrain that is lying, like the Hare Bay Peridotites, in a thrust sheet emplaced from the south-east in Middle Ordovician times. Much of the Shickshock terrain consists of basic volcanics and may represent a slice of oceanic crust carrying a hot mantle diapir. Early Ordovician ophiolites[22,23] are included in the serpentinite belt of Quebec (No. 4). These ophiolites are associated with, and post-date, metamorphic rocks (Caldwell) deformed in Late Cambrian or Early Ordovician times. Both the Caldwell metamorphics and the ophiolites may lie entirely within a Middle Ordovician thrust sheet, similar to that of Hare Bay, because the ophiolites lie on a chaotic mélange (wildflysch) terrain. Starks Knob (No. 5), in north-eastern New York State, is the only known occurrence of volcanic rocks in the Middle Ordovician wildflysch terrain of the Taconic region[5]. The Starks Knob pillow basalt and interstitial carbonate is possibly a detached block of Ordovician oceanic crust. Detrital chromite and ultrabasic detritus in the Middle Ordovician Normanskill flysch of the Taconic region indicates the former presence of ultrabasic source rocks to the east. The serpentinite belt of western New England (No. 6) is made up mostly of screens and pods of ultramafic rocks[24] lying mainly in Ordovician slates and basic volcanic rocks in a zone believed to represent the root zone or provenance site of the Middle Ordovician thrust sheets lying to the west[5]. Possibly these ultramafic rocks represent slices of oceanic mantle emplaced during the westward translation of the Taconic thrust sheets.

The Baie Verte Ophiolite Complex (No. 7) post-dates the metamorphism and deformation of the Fleur de Lys metamorphic terrain and forms a steeply dipping sheet lying in a narrow zone between Fleur de Lys metamorphic rocks and Lower Devonian clastics and volcanics. These ophiolites have entirely tectonic external contacts and underwent their first major deformation during Middle Devonian emplacement. Nearby, the Betts Cove/Tilt Cove Ophiolite Complex[15,25] (No. 8) forms the conformable base of the Arenigian Snooks Arm Group, has steep tectonic contacts against rocks of the Fleur de Lys terrain, and underwent its first major deformation in Middle Devonian times.

In Ireland, the Clew Bay Serpentinite Belt[26] (No. 9) is a possible westward extension[27] of the Highland Boundary Fault Zone of Scotland. It has a complex history of repeated movement and serpentinite mobilization (unpublished work of W. E. A. Phillips and J. F. Dewey) during the Lower Palaeozoic and may have formed a northern bounding lineament of the South Mayo Trough[28] during Ordovician times. The Lough Nafooey Group (chiefly pillowed basalt and jasper, No. 10) forms the lowest member[29] of the Ordovician succession of the South Mayo Trough and seems to be of early Arenigian age. The South Mayo Trough was, during Ordovician times, a deeply subsiding graben with uplifted Dalradian Highlands to the north and south[28,29]. In tectonic position and relationships, there is a strong analogy between the ophiolite-bearing Baie Verte Suture of Newfoundland and the South Mayo Trough; the Lough Nafooey Group may represent the upper oceanic crust of a narrow oceanic foundation to the South Mayo Trough. The Clew Bay serpentinites underwent a major mobilization and injection during Late Silurian times[26], and may be remobilized mantle ultrabasic rocks from an oceanic foundation.

In Scotland, the Highland Boundary Fault Zone (No. 11) formed a southern bounding fault complex to a rising Highland metamorphic terrain from Middle Ordovician to Devonian times[30]. In this zone the Jasper and Green Series[31], consisting of spilitic pillow lavas, cherts, and black shales of probable Arenigian age[32], occur as discontinuous fault-bounded slices. These rocks, with associated serpentinite, gabbro, diabase, ophitic dolerite, and hornblende and chlorite schist, may form part of an Early Ordovician ophiolite complex post-dating the deformation and metamorphism of the Dalradian. The Ballantrae Complex[33,34] (No. 12) consists of a fully developed, though strongly deformed and disjunctive, ophiolite complex including serpentinite, ariégite[35,36], gabbro, trondjemite, pillow lava, chert, and argillite. The complex is, at least partly, of Arenigian age[37] and is unconformably overlain by Ordovician sediments[38]. Blueschist metamorphism affects part of the complex[35], and this may indicate emplacement and deformation of the ophiolites at, or near, a zone of lithosphere plate destruction[13]. In the Southern Uplands the oldest rocks are a series of Arenigian pillow lavas, cherts, and argillites lying beneath the thick Ordovician/Silurian turbidite sequences[39] (No. 13). These rocks probably form the upper part of a Palaeozoic oceanic crust[40] which may underlie much of the Southern Uplands and Irish Basins (Fig. 1). Early Ordovician pillow lavas at Strokestown (No. 14) may also form part of this Palaeozoic oceanic crust.

In Newfoundland, the Gander River Belt[41,42] (No. 15) consists of a zone of ultrabasic and gabbroic rocks, Ordovician pillow lava, argillite, greywacke and limestone. The discontinuous and lenticular bodies of pyroxenite, serpentinite, and gabbro have uncertain relationships with the volcanics and sediments. The gabbros seem to cut small biotite-granites similar to Early Devonian granite plutons. Whether or not the gabbros and ultrabasic rocks form an integral part of an Ordovician ophiolite suite with the pillow lavas thus depends on the age of the small granite bodies.

As well as the fairly clear evidence of Early Ordovician sea-floor spreading, producing the ophiolite suites described here, there is evidence of Early Ordovician basic magmatism within or near the zone of the Late Cambrian/Early Ordovician metamorphic belt (Fig. 1). The gabbro suites of Aberdeenshire[43] (No. 16, Fig. 1) were intruded during the metamorphic climax in the Dalradian[30], the Tyrone Igneous Complex in Northern Ireland (No. 17) was intruded just after the Dalradian deformation and metamorphism[44], and the Cortland Complex[45] in southern New York State (No. 18) was intruded during the polyphase structural and metamorphic history of the Manhattan Schists.

Significance of the Ophiolite Suite

The preponderance of Early Ordovician ophiolites might suggest that the Proto-Atlantic Ocean was initiated in Early Ordovician times, immediately after the Late Cambrian/Early Ordovician orogeny. It has been suggested[4] that this Ordovician oceanic phase was short-lived in Newfoundland, and that the ocean was closed by Middle Ordovician times, with the emplacement of the Bay of Islands Complex. We find this view unacceptable for the following reasons: (1) The existence of a sequence of continental shelf carbonates, showing a rapid south-eastward facies change (the shelf edge in Fig. 1) from carbonate boulder slides into a thin continental rise argillite sequence[4,5,46], throughout the western part of the Appalachians, seems to us to demand the existence of an ocean throughout Cambrian times. (2) It is difficult to account for the Late Cambrian/Early Ordovician Grampian orogeny by deformation and metamorphism of a thick marine sequence in a narrow, intracontinental belt. Mesozoic and Tertiary orogeny is clearly related to continental margins and continental collision in zones of lithosphere plate destruction[13] (subduction zones)[47]. The early orogeny of the Appalachian/Caledonian system can be similarly accounted for by the deformation and metamorphism of a continental margin sedimentary assemblage[5]. Also, evidence from the Atlantic Ocean shows that continental separation is not immediately preceded by an intracontinental orogeny. (3) Although inliers of Pre-Cambrian basement rocks occur in the early metamorphic terrain (the Lewisian inliers of north-west Scotland, for example), much of Central Newfoundland, including the eastern part of the Fleur de Lys terrain, is underlain at shallow depths by a high velocity (7.0 km s^{-1}) crust[48]. We suggest that this basement represents Palaeozoic, Proto-Atlantic oceanic crust and mantle. (4) An older ophiolite suite (Nippers Harbour and Beaver Cove Groups, No. 19 in Fig. 1) forms the foundation of the eastern part of the Fleur de Lys terrain. The Little Bay Head Group[49] in eastern Notre Dame Bay is an assemblage of pillow lavas, gabbros, and sheeted dyke complexes with occasional peridotite diapirs, older than Early Ordovician age[5,15]. These rocks may belong to an ophiolite suite generated during a Cambrian phase of Proto-Atlantic sea-floor spreading.

We suggest that the initial phase of Proto-Atlantic growth began in latest Pre-Cambrian times, following the accumulation of sediments and volcanics in an intracontinental graben system[5]. Support for this concept of a Late Pre-Cambrian/Earliest Cambrian continental distension comes from the remarkable development of an alkaline rock province in the continents bordering the Central and North Atlantic[50]. This province includes carbonatite, syenite, and kimberlite yielding radiometric ages from 585 to 560 m.y. These rocks are associated with a network of Late Pre-Cambrian/Early Cambrian graben[50] which may be an analogue of the East African Rift alkaline province. In western Newfoundland, Late Pre-Cambrian or Earliest Cambrian flood basalts and dyke swarms[51] probably mark this initial continental rupture. These basalts are, perhaps, analogous to the Palaeocene flood basalts of east Greenland and north-west Scotland which mark the beginning of separation of Greenland from Europe. We suggest that, following the establishment of a Proto-Atlantic Ocean during Cambrian times, the Late Cambrian/Early Ordovician orogeny resulted from the deformation and metamorphism of the early graben and continental rise sediments and volcanics above a descending plate, west of a zone of lithosphere plate destruction[3,5] (Fig. 1).

In the western Pacific the marginal basins behind, and between, island arc complexes are fairly certainly the result of a sea-floor spreading process by which island arcs move slowly away from continental margins[14]. We suggest that the Early Ordovician Appalachian/Caledonian ophiolites resulted from a similar process during the establishment of marginal basins within, and north-west of, the Early Ordovician metamorphic terrain. The westward emplacement of the transported ophiolites (the Bay of Islands Complex, for example), during the Middle Ordovician movement phase, was probably achieved by closing of the westernmost marginal basins by subduction on their south-eastern margins, and the resultant thrusting of wedges of oceanic crust and mantle onto the continental margin. Ophiolite suites such as those of Baie Verte and Betts Cove probably originated in separate marginal basins and were emplaced by Middle Devonian deformation during a major continent/continent collision[5]. The Matapedia Basin (Fig. 1) includes a distinctive argillite/ribbon limestone facies and may have developed as an Early Ordovician marginal basin by the separation of the Tetagouche volcanic/granitic/metamorphic zone from the continental margin.

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1 Wilson, J. T., *Nature*, **211**, 676 (1966).
2 Williams, H., *Amer. J. Sci.*, **262**, 1137 (1964).
3 Dewey, J. F., *Nature*, **222**, 124 (1969).
4 Stevens, R. K., *Spec. Paper Geol. Assoc. Canada*, **7**, 165 (1970).
5 Bird, J. M., and Dewey, J. F., *Bull. Geol. Soc. Amer.*, **81**, 1031 (1970).
6 Fitton, J. G., and Hughes, D. J., *Earth Planet. Sci. Lett.*, **8**, 223 (1970).
7 Pantazis, T. M., *Cyprus Geol. Surv. Mem.*, **8** (1967).
8 Reinhardt, B. M., *Schweiz. Miner. Petrogr. Mitt.*, **49**, 1 (1969).
9 Moores, E. M., *Spec. Paper Geol. Soc. Amer.*, *119* (1969).
10 Davies, H. L., *Twenty-third Internat. Geol. Congr.*, **1**, 209 (1968).
11 Le Pichon, X., *Tectonophys.*, **7**, 385 (1969).
12 Vogt, P. R., Schneider, E. D., and Johnson, A. L., *Monog. Amer. Geophys. Un.*, **13**, 556 (1969).
13 Dewey, J. F., and Bird, J. M., *J. Geophys. Res.*, **75**, 2625 (1970).
14 Karig, D. E., *J. Geophys. Res.*, **75**, 239 (1970).
15 Dewey, J. F., and Bird, J. M., *J. Geophys. Res.* (in the press).
16 Kay, R., Hubbard, N. J., and Gast, P. W., *J. Geophys. Res.*, **75**, 1585 (1970).
17 Smith, C. H., *Mem. Geol. Surv. Canada*, **290** (1958).
18 Rodgers, J., and Neale, E. R. W., *Amer. J. Sci.*, **261**, 713 (1963).
19 Tuke, M. F., *Canad. J. Earth Sci.*, **5**, 501 (1968).
20 Kay, M., *Mem. Amer. Assoc. Petroleum Geol.*, **12**, 665 (1969).
21 Smith, C. H., and MacGregor, I. D., *Bull. Geol. Soc. Amer.*, **71**, 1978 (1960).
22 Stevens, R. K., Church, W. R., and St Julien, P., *Abstr. Geol. Soc. Amer.*, **7**, 215 (1969).
23 Lamarche, R. Y., *Abstr. Geol. Assoc. Canada* (*Montreal Meeting*), 26 (1969).
24 Chidester, A. H., *Prof. Paper US Geol. Surv.*, **345** (1962).
25 Upadhyay, H., Dewey, J. F., and Neale, E. R. W., *Proc. Geol. Assoc. Canada* (in the press).
26 Dewey, J. F., and Phillips, W. E. A., *Geol. J.*, **3**, 237 (1963).
27 Anderson, J. G. C., *Geol. Mag.*, **97**, 265 (1960).
28 Dewey, J. F., *Quart. J. Geol. Soc. Lond.*, **119**, 313 (1963).
29 Dewey, J. F., McKerrow, W. S., and Moorbath, S., *Scott. J. Geol.*, **6**, 133 (1970).
30 Dewey, J. F., and Pankhurst, R., *Trans. Roy. Soc. Edinb.*, **68**, 361 (1970).
31 Jehu, T. J., and Campbell, R., *Trans. Roy. Soc. Edinb.*, **52**, 175 (1917).
32 Anderson, J. G. C., *Trans. Roy. Soc. Edinb.*, **61**, 497 (1947).
33 Balsillie, D., *Geol. Mag.*, **69**, 107 (1932).
34 Bailey, E. B., and McCallien, W. J., *Trans. Geol. Soc. Edinb.*, **17**, 33 (1957).
35 Bloxam, T. W., and Allen, J. B., *Trans. Roy. Soc. Edinb.*, **64**, 1 (1959).
36 O'Hara, M. J., in *Ultramafic and Related Rocks*, 167 (Wiley, New York, 1967).
37 Dewey, J. F., Rickards, R. B., and Skevington, D., *Norsk. Geol. Tiddskr.*, **50**, 19 (1970).
38 Williams, A., *Mem. Geol. Soc. Lond.*, **3** (1962).
39 Walton, E. K., *Geol. Rundsch.*, **50**, 63 (1961).
40 Dewey, J. F., *Scott. J. Geol.* (in the press).
41 Jenness, S. E., *Rept. Newfoundland Dept. Mines and Resources*, **11** (1958).
42 Jenness, S. E., *Mem. Canada Geol. Surv.*, **327** (1963).
43 Read, H. H., *Lpool Manchr. Geol. J.*, **2**, 653 (1961).
44 Cobbing, E. J., Manning, P. I., and Griffith, A. E., *Nature*, **206**, 1132 (1965).
45 Ratcliffe, N. M., *Bull. Geol. Soc. Amer.*, **79**, 777 (1968).
46 Rodgers, J., in *Studies of Appalachian Geology, Northern and Maritime* (Interscience, New York).
47 White, D. A., Roeder, D. H., Nelson, T. H., and Crowell, J. C., *Bull. Geol. Soc. Amer.*, **81**, 3431 (1970).
48 Sheridan, R. E., and Drake, C. L., *Canad. J. Earth Sci.*, **5**, 337 (1968).
49 McClean, H. S., *Bull. Geol. Surv. Newfoundland*, **22** (1947).
50 Doig, R., *Canad. J. Earth Sci.*, **7**, 22 (1970).
51 Williams, H., and Stevens, R. K., *Canad. J. Earth Sci.*, **6**, 1145 (1969).

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