Evidence for Continental Crustal Assimilation in the Hemlock Formation Flood Basalts of the Early Proterozoic Penokean Orogen, Lake Superior Region

U.S. GEOLOGICAL SURVEY BULLETIN 1904-I

AVAILABILITY OF BOOKS AND MAPS OF THE U.S. GEOLOGICAL SURVEY

Instructions on ordering publications of the U.S. Geological Survey, along with the last offerings, are given in the current-year issues of the monthly catalog "New Publications of the U.S. Geological Survey." Prices of available U.S. Geological Survey publications released prior to the current year are listed in the most recent annual "Price and Availability List." Publications that are listed in various U.S. Geological Survey catalogs (**see back inside cover**) but not listed in the most recent annual "Price and Availability List" are no longer available.

Prices of reports released to the open files are given in the listing "U.S. Geological Survey Open-File Reports," updated monthly, which is for sale in microfiche from the U.S. Geological Survey, Books and Open-File Reports Section, Federal Center, Box 25425, Denver, CO 80225. Reports released through the NTIS may be obtained by writing to the National Technical Information Service, U.S. Department of Commerce, Springfield, VA 22161; please include NTIS report number with inquiry.

Order U.S. Geological Survey publications **by mail** or **over the counter** from the offices given below.

BY MAIL

Books

Professional Papers, Bulletins, Water-Supply Papers, Techniques of Water-Resources Investigations, Circulars, publications of general interest (such as leaflets, pamphlets, booklets), single copies of periodicals (Earthquakes & Volcanoes, Preliminary Determination of Epicenters), and some miscellaneous reports, including some of the foregoing series that have gone out of print at the Superintendent of Documents, are obtainable by mail from

U.S. Geological Survey, Books and Open-File Reports Section
Federal Center, Box 25425
Denver, CO 80225

Subscriptions to periodicals (Earthquakes & Volcanoes and Preliminary Determination of Epicenters) can be obtained ONLY from

Superintendent of Documents
U.S. Government Printing Office
Washington, DC 20402

(Check or money order must be payable to Superintendent of Documents.)

Maps

For maps, address mail orders to

U.S. Geological Survey, Map Distribution
Federal Center, Box 25286
Denver, CO 80225

Residents of Alaska may order maps from

U.S. Geological Survey, Map Distribution
New Federal Building - Box 12
101 Twelfth Ave., Fairbanks, AK 99701

OVER THE COUNTER

Books

Books of the U.S. Geological Survey are available over the counter at the following U.S. Geological Survey offices, all of which are authorized agents of the Superintendent of Documents:

- **ANCHORAGE, Alaska**—4230 University Dr., Rm. 101
- **ANCHORAGE, Alaska**—605 West 4th Ave., Rm. G-84
- **DENVER, Colorado**—Federal Bldg., Rm. 169, 1961 Stout St.
- **LOS ANGELES, California**—Federal Bldg., Rm. 7638, 300 North Los Angeles St.
- **MENLO PARK, California**—Bldg. 3, Rm. 3128, 345 Middlefield Rd.
- **RESTON, Virginia**—National Center, Rm. 1C402, 12201 Sunrise Valley Dr.
- **SALT LAKE CITY, Utah**—Federal Bldg., Rm. 8105, 125 South State St.
- **SAN FRANCISCO, California**—Customhouse, Rm. 504, 555 Battery St.
- **SPOKANE, Washington**—U.S. Courthouse, Rm. 678, West 920 Riverside Ave.
- **WASHINGTON, DC**—U.S. Department of the Interior Bldg., Rm. 2650, 1849 C St., NW.

Maps

Maps may be purchased over the counter at the U.S. Geological Survey offices where books are sold (all addresses in above list) and at the following U.S. Geological Survey offices:

- **ROLLA, Missouri**—1400 Independence Rd.
- **FAIRBANKS, Alaska**—New Federal Bldg., 101 Twelfth Ave.

Chapter I

Evidence for Continental Crustal Assimilation in the Hemlock Formation Flood Basalts of the Early Proterozoic Penokean Orogen, Lake Superior Region

By WARREN BECK and V. RAMA MURTHY

U.S. GEOLOGICAL SURVEY BULLETIN 1904

CONTRIBUTIONS TO PRECAMBRIAN GEOLOGY OF LAKE SUPERIOR REGION

P.K. SIMS and L.M.H. CARTER, Editors

U.S. DEPARTMENT OF THE INTERIOR
MANUEL LUJAN, JR., Secretary

U.S. GEOLOGICAL SURVEY
Dallas L. Peck, Director

UNITED STATES GOVERNMENT PRINTING OFFICE: 1991

For sale by the
Books and Open-File Reports Section
U.S. Geological Survey
Federal Center
Box 25425
Denver, CO 80225

Library of Congress Cataloging-in-Publication Data

Beck, J. Warren.
Evidence for continental crustal assimilation in the hemlock formation flood basalts of the Early Proterozoic Penokean orogen, Lake Superior region / by Warren Beck and V. Rama Murthy.
p. cm.—(Contributions to Precambrian geology of Lake Superior region ; ch. I) (U.S. Geological Survey bulletin ; 1904–I)
Includes bibliographical references.
1. Rock deformation—Superior, Lake, Region. 2. Geology—Stratigraphic—Proterozoic. 3. Basalt—Superior, Lake, Region. 4. Geology, Structural—Superior, Lake, Region. I. Murthy, V. Rama. II. Title . III. Series. IV. Series: U.S. Geological Survey bulletin ; 1904–I.
QE75.B9 no. 1904–I.
[QE604]
557.3 s—dc20
[551.7'15'097749] 91–9934
CIP

CONTENTS

FIGURES

TABLES

Evidence for Continental Crustal Assimilation in the Hemlock Formation Flood Basalts of the Early Proterozoic Penokean Orogen, Lake Superior Region

By Warren Beck[1] *and* V. Rama Murthy[1]

Abstract

Two major suites of mafic volcanic and intrusive rocks are juxtaposed across the Niagara fault zone within the central part of the Early Proterozoic Penokean orogen, in the Lake Superior region. North of the fault zone, the volcanic rocks overlie Archean crust, and possibly were erupted during a major Early Proterozoic (rifting) event ≈2.0 Ga. The volcanic and intrusive rocks south of the fault zone, however, are largely juvenile crust emplaced during the Early Proterozoic. This area of crust comprises the Wisconsin magmatic terranes, and taken together it resembles a modern volcanic arc.

Neodymium isotopic systematics from Quinnesec Formation tholeiites in the northern part of the Wisconsin magmatic terranes yield an isochron age of 1.87±0.05 Ga, and an ε_{Nd}=+4.2. Such a large positive ε_{Nd} is indicative of derivation from a mantle with long-term depletion in light rare earth elements, and is similar to values predicted by some models for the source regions for mid-ocean ridge basalts at 1.9 Ga. This characteristic, combined with the general geochemical characteristics and tectonic setting of these magmatic terrane tholeiites, suggests that these rocks may have been erupted onto oceanic crust and derived from an Early Proterozoic depleted mantle reservoir. The overall tectonic affinity of the Wisconsin magmatic terranes, however, appears to be arc related.

In contrast, the neodymium isotopic data of Hemlock Formation continental tholeiites from the continental margin terrane (north of the fault zone) do not form an isochron; rather, they indicate mixing of a juvenile basaltic component with a continental-crustal light rare earth element-enriched reservoir. Two-component assimilation-fractional crystallization models suggest that the source of the basaltic end-member of this mixing suite was the same as that which generated the light rare earth element-depleted basalts of the large magmatic belt south of the fault zone, for example, an Early Proterozoic depleted mantle mid-ocean ridge basalt reservoir. The continental crustal component of these basalts appears to have been enriched in many incompatible elements, and thus probably was not a lower crustal granulite, but rather may have been higher crustal level granite or sediments.

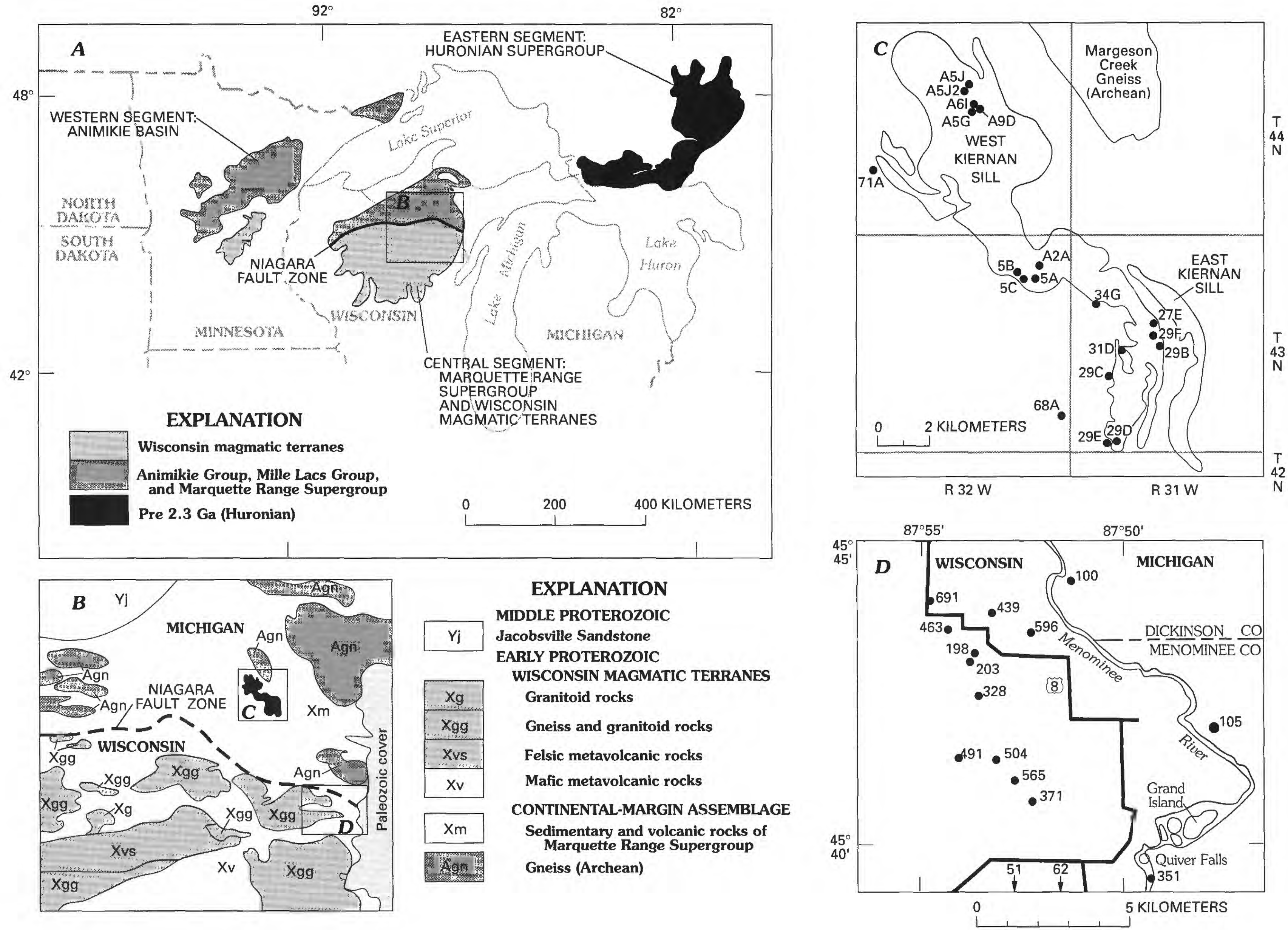
Manuscript approved for publication January 28, 1991.

[1]Department of Geology and Geophysics, University of Minnesota, Minneapolis, MN 55455.

INTRODUCTION

The Penokean orogen in the Lake Superior region contains several major sequences of Early Proterozoic rocks. These include the Marquette Range Supergroup, the Animikie basin strata, and the Penokean magmatic terranes of Wisconsin and Minnesota (fig. 1). The Marquette Range Supergroup and Animikie basin rocks are temporally and stratigraphically similar, and are typified by southward-thickening packages of sedimentary rocks, interfingered with locally extensive continental flood basalt sequences. Although age control on the deposition of the three packages of rocks is poor, all were apparently deposited on or near the south margin of the Superior craton between 2.5 and 1.86 Ga (Van Schmus, 1976; Beck, 1988).

Recent tectonic models of the Early Proterozoic evolution of the Lake Superior region have been posed in terms of one of the following processes: (1) plate margin sedimentation at and near the south margin of the Superior province, followed by the development of an active subduction zone and arc-related magmatism along this boundary (Van Schmus, 1976); or (2) either one period of continental


A
92°
82°
48°
42°
EASTERN SEGMENT: HURONIAN SUPERGROUP
WESTERN SEGMENT: ANIMIKIE BASIN
NORTH DAKOTA
SOUTH DAKOTA
MINNESOTA
WISCONSIN
MICHIGAN
Lake Superior
Lake Michigan
Lake Huron
NIAGARA FAULT ZONE
CENTRAL SEGMENT: MARQUETTE RANGE SUPERGROUP AND WISCONSIN MAGMATIC TERRANES
EXPLANATION
Wisconsin magmatic terranes
Animikie Group, Mille Lacs Group, and Marquette Range Supergroup
Pre 2.3 Ga (Huronian)
0
200
400 KILOMETERS
B
Yj
MICHIGAN
Agn
NIAGARA FAULT ZONE
WISCONSIN
Xm
Xgg
Xg
Xvs
Xv
Paleozoic cover
EXPLANATION
MIDDLE PROTEROZOIC
Yj Jacobsville Sandstone
EARLY PROTEROZOIC
WISCONSIN MAGMATIC TERRANES
Xg Granitoid rocks
Xgg Gneiss and granitoid rocks
Xvs Felsic metavolcanic rocks
Xv Mafic metavolcanic rocks
CONTINENTAL-MARGIN ASSEMBLAGE
Xm Sedimentary and volcanic rocks of Marquette Range Supergroup
Agn Gneiss (Archean)
C
Margeson Creek Gneiss (Archean)
A5J
A5J2
A6I
A5G
A9D
WEST KIERNAN SILL
71A
5B
A2A
5A
5C
34G
EAST KIERNAN SILL
27E
29F
29B
31D
29C
68A
29E
29D
0
2 KILOMETERS
T 44 N
T 43 N
T 42 N
R 32 W
R 31 W
D
87°55'
87°50'
45° 45'
45° 40'
WISCONSIN
MICHIGAN
100
691
439
463
596
198
203
328
DICKINSON CO
MENOMINEE CO
Menominee
River
8
105
491
504
565
371
Grand Island
Quiver Falls
351
51
62
0
5 KILOMETERS

rifting (Cambray, 1977, 1978) or several (Larue, 1983; Larue and Sloss, 1980; Ueng and others, 1988; LaBerge and others, 1984; Schulz and others, in press), leading to the development of a passive margin and an oceanic basin, followed by ocean closure and the collision of island arc complexes with the Superior province during the Penokean orogeny. Other recent models interpret the Animikie basin strata and the upper strata of the Marquette Range Supergroup as having been deposited in a migrating foredeep basin related to the late-stage docking of the Penokean arc complex at the south margin of the Superior province (Hoffman, 1987; Southwick and others, 1988; Barovich and others, 1989).

The central part of the Lake Superior region can be divided into two distinctive Early Proterozoic terranes (fig. 1*B*), separated by a major east-trending boundary—the Niagara fault zone. This fault zone was a major crustal boundary during the Early Proterozoic (Larue, 1983; Greenberg and Brown, 1983; LaBerge and others, 1984; Larue and Ueng, 1985; Sims and others, 1985; Ueng and Larue, 1988), and was the principal axis of deformation during the Penokean orogeny, representing the proposed frontal overthrust zone of the Penokean magmatic terranes (Sims and others, 1989; Klasner, 1984; LaBerge and others, 1984; Klasner and others, 1988).

North of the Niagara fault zone, in Michigan and Wisconsin, the Marquette Range Supergroup was deposited on Archean crust near the south margin of the Superior province and consists of supracrustal sedimentary rocks and continental flood basalts. A second, 250-km-wide terrane—the Wisconsin magmatic terranes—lies to the south of the Niagara fault zone; these magmatic terranes consist principally of submarine tholeiites, rhyolites, and calc-alkaline volcanic rocks, together with extensive tonalitic, trondhjemitic, and granitic intrusive rocks (Van Schmus, 1976; Sims and others, 1989). A few sedimentary rocks are also present in this southern terrane, but they appear to represent a minor component. The southern terrane strongly resembles a modern volcanic arc complex (Van Schmus, 1976, 1980; Cudzillo, 1978; LaBerge and others, 1984; Sims and others, 1989), whereas the northern terrane resembles a continental rift, subsiding margin, and foredeep basin assemblage.

Figure 1 (facing page). Views of the Early Proterozoic Penokean orogen, Lake Superior region. *A*, Simplified geologic map showing locations of the Animikie and Mille Lacs Groups of Animikie basin (western segment of orogen), Marquette Range Supergroup (central segment), and Wisconsin magmatic terranes. Modified from Morey and others (1982). Also shown is the Huronian Supergroup (eastern segment). *B*, Enlarged view of central segment; boxes indicate locations of views *C* and *D*. *C*, Location of West Kiernan sill and adjacent rocks, showing sample localities of the Hemlock Formation. *D*, Sample localities for the Quinnesec Formation. Data for numbered sample localities are in tables 1 and 2.

Significant mafic volcanism in the central segment of the Lake Superior region began to develop about 1.90 Ga (Banks and Rebello, 1969; Banks and Van Schmus, 1971; Van Schmus, 1976; Beck, 1984). Major flood basalt sequences were erupted in the Marquette Range Supergroup during the Menominee Group period of deposition (Cannon, 1986), but the most extensive volcanic sequences developed in the Wisconsin magmatic terranes south of the Niagara fault zone.

Sequences of related mafic volcanic and intrusive rocks of the northern terrane include the Hemlock Formation, Clarksburg Volcanics Member of the Michigamme Formation, Badwater Greenstone, and the Emperor Volcanic Complex, all of the Marquette Range Supergroup. Although the original extent of these metavolcanic complexes is difficult to estimate from the sketchy geologic record, taken together they probably formed a major Early Proterozoic continental flood basalt province. Each of these rock bodies is locally as much as 5–10 km thick, but they lack great lateral extent. Whether these metavolcanic rocks are the erosional remnants of a much greater expanse of flood basalts or were deposited as local accumulations is not clear. Numerous large layered mafic intrusions occur within the Hemlock Formation, which are thought to be genetically related to the volcanic rocks (Ueng and others, 1988; Gair and Wier, 1956; Bayley, 1959). One of the largest of these—the West Kiernan sill (fig. 1*C*)—has well-developed igneous layering (Gair and Wier, 1956; Wier, 1967) throughout its approximately 2 km thickness. For this report, the West Kiernan sill, together with the Hemlock metabasalt, was sampled for geochemical analyses representative of the northern terrane.

The Early Proterozoic metavolcanic rocks south of the Niagara fault zone underlie a large area of northern Wisconsin (Bayley and others, 1966; Jenkins, 1973; Greenberg and Brown, 1983; Sims and others, 1989). These rocks form the southern magmatic belt, comprising the Wisconsin magmatic terranes. A widespread volcanic body, the Quinnesec Formation in eastern Florence and northern Marinette Counties, Wisconsin (fig. 1*D*), consists primarily of metamorphosed pillowed basalt flows with minor pyroclastic rocks; it spans a broad compositional range from tholeiitic through calc-alkaline to rhyolitic. Rare occurrences of metasedimentary rocks occur within the Quinnesec Formation, generally as thin lenses of graphitic slate, iron-formation, marble, quartzite, and metagraywacke (Dutton, 1971; Cummings, 1978; Greenberg and Brown, 1983; Sims, 1990). Overall thicknesses of these rocks, though difficult to estimate, probably exceed 3 km (Bayley and others, 1966). Structural thickening of these units, however, undoubtedly occurred during the Penokean orogeny.

The rocks of the Quinnesec Formation have been metamorphosed to greenschist facies, except adjacent to the Penokean plutons, where metamorphic grade may exceed hornblende-oligoclase or hornblende-andesine amphibolite (Bayley and others, 1966). Large areas of the northern continental-margin terrane have also been metamorphosed to lower or middle greenschist facies; however, rocks in the cores of the several large metamorphic nodes, such as the Republic or Watersmeet nodes, may reach sillimanite or kyanite grade (James, 1955).

Based on their chemical and isotopic compositions, most of the igneous rocks in the Wisconsin magmatic terranes appear to be juvenile crust erupted during the Early Proterozoic, although evidence exists for interaction with older Archean basement in the southernmost of these terranes, in central Wisconsin (Anderson and Cullers, 1987; Van Schmus and Anderson, 1977). The Quinnesec is the southern terrane formation sampled in this study to determine the nature and source of volcanic rocks in the Wisconsin magmatic terranes. Neodymium and strontium isotopic evidence from both mafic and felsic igneous rocks of the magmatic terranes supports these general conclusions; the data show depleted-mantle source signatures near the Niagara fault zone (Beck, 1984; Barovich, Patchett, and Peterman, 1987; Barovich and others, 1989) and a progressive southward decrease in ε_{Nd} values along a north-south trend (Barovich and others, 1989).

In contrast, substantial chemical and isotopic evidence indicates involvement between the Early Proterozoic igneous rocks of the northern continental-margin terrane and older Archean crust. Initial Nd isotopic data from continental tholeiites of this terrane are indicative of mixing with Archean continental crust, whereas two-component AFC (assimilation–fractional crystallization) models (modified from Nielson, 1985, 1988; and DePaolo, 1981) suggest that the source of the basaltic end-member of this mixing suite was the same as that which generated the LREE-depleted basalts of the southern magmatic belt, for example, an Early Proterozoic depleted mantle (MORB) reservoir. The continental crustal component of these basalts appears to have been enriched in many incompatible elements, and thus was probably not a lower crustal granulite; instead, it may have been higher level granitic crust or sediments. The observation that these continental tholeiites appear to have been generated via crustal contamination of magmas derived from the depleted mantle is similar to that observed in several modern flood basalt provinces (for example, Carter and others, 1978; Carlson and others, 1981a, b; Dickin, 1981; Mahoney and others, 1984), and thus indicates some long-term uniformity in the processes generating this type of igneous activity. The main objective of this report is to compare the geochemical signatures of the mafic volcanic and intrusive igneous rocks found in these two Early Proterozoic terranes, and to evaluate the differences in their genesis and history, emphasizing the Hemlock Formation.

ACKNOWLEDGMENTS

Financial support derived from the National Science Foundation grant # NSF EAR 7919590, the Minnesota Geological Survey, the University of Minnesota Department of Geology and Geophysics, and the Stanford University Department of Geology is all gratefully acknowledged. Special thanks go to David Southwick and G.B. Morey of the Minnesota Geological Survey; David Larue and Charles Ueng of Stanford University; Paul Sims, Klaus Schulz, Zell Peterman, and Sam Goldich of the U.S. Geological Survey; and Tom Fox and John Wilban of Michigan State University.

ANALYTICAL METHODS

Major element analyses for the Hemlock tholeiites and West Kiernan sill intrusive rocks were obtained by induced couple plasma (ICP) at Barringer Magenta Company Ltd., Toronto, Ontario; REE, Th, Ta, and Hf analyses were obtained by neutron activation at Michigan State University (Fox, 1983). Other trace elements, including Ba, Zr, Y, V, Cr, and Ni, were measured using X-ray fluorescence at Stanford University (Ueng and others, 1988). Samples of the Quinnesec volcanic rocks and some trace element analyses were provided by K.J. Schulz, U.S. Geological Survey.

Neodymium and strontium isotopic measurements were made at the University of Minnesota Department of Geology and Geophysics, using a 10-cm double-focusing Mattuch-Hertzog design MINMASS solid source mass spectrometer (Nier and Schlutter, 1985; Nier and others, 1983), and on a 12-in. NBS design Nier-type single-focusing mass spectrometer. Elemental concentrations were determined by isotope dilution using ^{87}Rb, ^{84}Sr, and a combined ^{145}Nd–^{149}Sm spike tracers. All Sm and Nd measurements were obtained as a metal ion emission using a double Ta-Re filament geometry, with Nd and Sm loaded as a chloride on the Ta side filament. Both Sr and Rb were run as chlorides on single Re filaments, with the Sr filaments first being coated with a layer of Ta_2O_5 powder. Strontium isotopic composition analyses were corrected for in-run mass fractionation assuming a ^{86}Sr/^{88}Sr ratio of 0.1194, whereas Nd isotopic composition analyses were corrected utilizing a ^{146}Nd/^{144}Nd ratio of 0.7219. Strontium analyses were normalized against NBS987 assuming a ^{87}Sr/^{86}Sr ratio=0.71020, whereas Nd analyses were normalized against LJNd standard, assuming a ^{143}Nd/^{144}Nd ratio=0.511860. Mean 2σ errors are reported at $\pm$ 0.000050 for the Sr isotopic composition analyses and at $\pm$ 0.000030 for the Nd isotopic analyses. All errors are reported with a 2σ confidence level. Decay constants of λ=1.42×10^{-11}y^{-1} and 6.54×10^{-12}y^{-1} were used as for ^{87}Rb and ^{147}Sm, respectively.

Sample locations for rocks of the Hemlock and Quinnesec Formations are shown in figure *1C* and *1D*, respectively. More detailed descriptions have been given by Beck (1988), Fox (1983), and Ueng and others (1988).

GEOCHEMISTRY OF THE HEMLOCK AND QUINNESEC FORMATIONS

The major and trace element characteristics of the volcanic rocks on opposite sides of the Niagara fault zone have been described by Bayley (1959), Cudzillo (1978), Greenberg and Brown (1983), Fox (1983), Schulz (1984), and Ueng and others (1988). The Hemlock volcanic rocks are almost exclusively bimodal basalts and rhyolites that contain several large consanguineous gabbroic intrusive bodies. In general, these volcanic rocks have tholeiitic to subalkaline AFM trends and relatively high concentrations of the LIL (large ion lithophile) elements. Compositionally, the Hemlock volcanics appear to be indistinguishable from other volcanic suites in the Marquette Range Supergroup, such as the Badwater Greenstone or Clarksburg Volcanics Member of the Michigamme Formation (Cudzillo, 1978).

The volcanic rocks of the southern magmatic terrane, in contrast, span a large compositional range from basaltic through andesite to rhyolite, but are dominantly calc-alkaline in composition. The Quinnesec Formation is distinctive in this regard in that it is predominantly tholeiitic in composition and is strongly depleted in the LIL elements and HFS (high field strength) elements. These characteristics distinguish the Quinnesec volcanic rocks from the Hemlock Formation, and are consistent with the general findings of Cudzillo (1978), who demonstrated that overall, the basalts in the northern terrane show significantly higher concentrations of TiO_2 and Zr as compared to those south of the Niagara fault zone. In Cenozoic basalts, these elements, together with the other HFS elements (Nb, Hf, and Ta), have proved to be useful geochemical discriminates for determining basalt tectonic provenance, particularly for discriminating between basalts erupted in convergent plate environments versus those found in divergent settings (Pearce and Cann, 1973; Pearce and Norry, 1979; Pearce, 1982; Arculus, 1987). Using this modern analog, basalts erupted along convergent plate margins characteristically have lower TiO_2 and Zr concentrations than basalts from divergent and intraplate settings (Pearce and Cann, 1973). In general, the concentrations of these elements in the Hemlock volcanic rocks are consistent with an intraplate origin, whereas the concentrations found in the Quinnesec volcanic rocks are consistent with a convergent margin origin (Cudzillo, 1978).

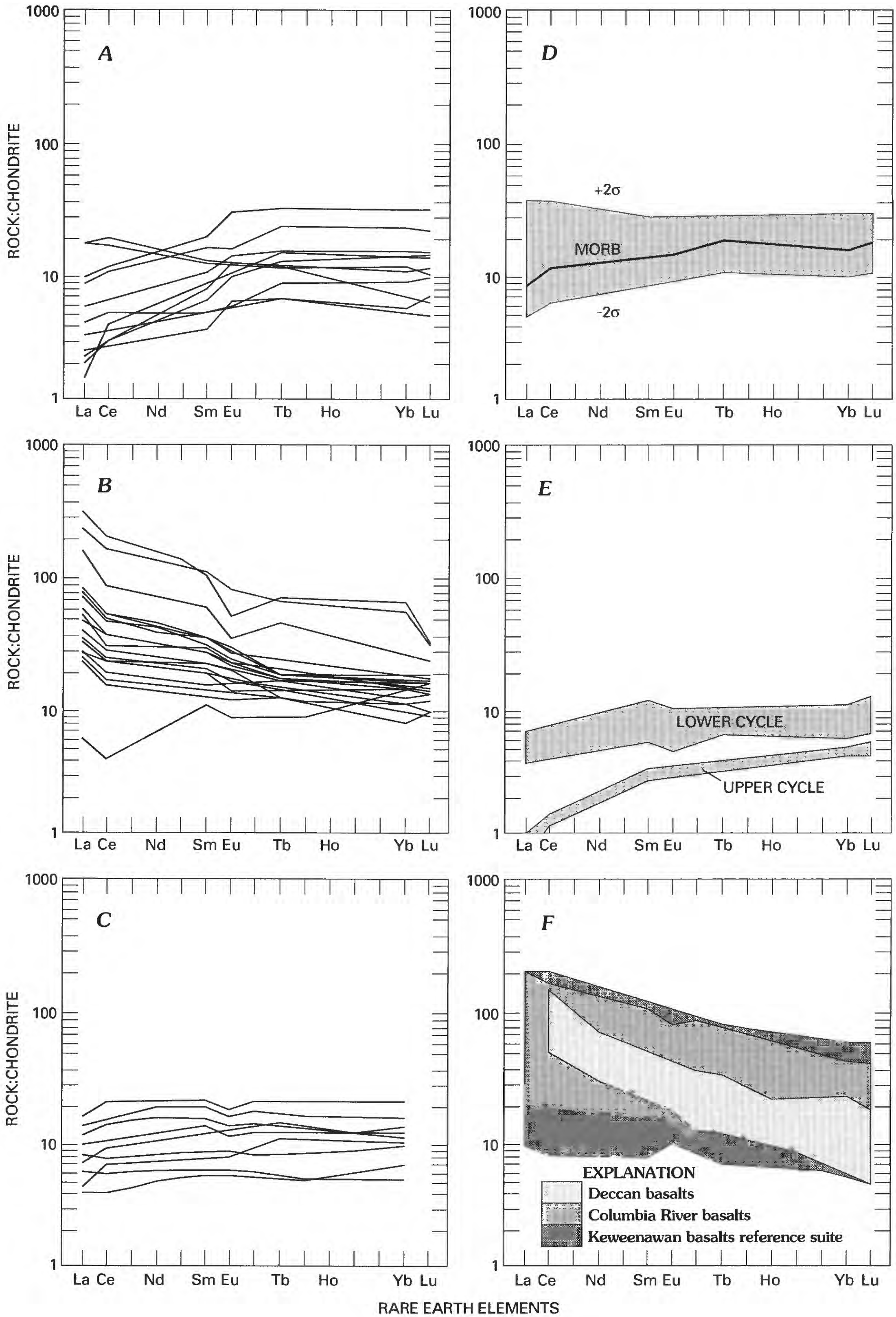
Among the most revealing tectonic discriminates between the two contrasting suites of volcanic rocks is their REE (rare earth element) patterns (fig. 2). The REE data from the Quinnesec basalts (Sims and others, 1989) have average rock:chondrite abundances of about 10, flat heavy REE patterns, and no appreciable Eu anomalies; and they reveal depletion in the light REE. A comparison with REE patterns from various modern and ancient tectonic environments shows that the Quinnesec volcanics have patterns similar to modern island arc tholeiites or modern MORB, and patterns similar as well to those of some Archean basaltic komatiites and Archean magnesian basalts of Munro Township, Ontario. They are probably most similar to the average modern MORB pattern, or to those of abyssal shield tholeiites generated during the early stages of island arc genesis, which are known to have REE patterns strongly resembling MORB (Kay and Senechal, 1976; Pallister and Knight, 1981). The Quinnesec REE patterns are, however, distinctly *dissimilar* to those of any continental flood basalt suite, modern or ancient (fig. 2).

In contrast to the Quinnesec basalts, the Hemlock volcanic rocks have high average rock:chondrite REE abundances (20–50) and are typically light REE enriched. Their REE patterns are strikingly similar to those of intraplate volcanic rocks, particularly those of typical continental flood basalts, such as the Keweenawan basalts or the Deccan flood basalts (fig. 2). Thus, these REE profiles serve to distinguish between the Quinnesec and Hemlock Formations, as well as to characterize the Hemlock as being probably of continental flood basalt affinity.

ISOTOPIC AND TRACE ELEMENT DATA

Many studies have utilized Sr and Nd isotopic tracers in concert to help determine the petrogenesis of continental volcanic rocks (for example, Mahoney, 1984; Mahoney and others, 1981; Hawkesworth and Vollmer, 1979; Dosso, 1984; Carlson and others, 1981a, b; Dickin, 1981; Carter and others, 1978; Moorbath and Thompson, 1980; Thompson and others, 1982; McDougall, 1976). For young volcanic rocks, such covariations often yield information about the nature of the source regions or about magma contamination processes. Unfortunately in our study, as is the case in many ancient terranes, the volcanic rocks of the northern continental-margin terrane have been subjected to postemplacement regional metamorphism. The bulk of the rocks in this belt have been metamorphosed to at least greenschist facies, and some parts have been metamorphosed to sillimanite or kyanite grade. As a result, the Sr whole-rock isotopic systematics have been disturbed or reset, and are probably useful only in a general way for determining petrogenesis.

The whole-rock Sr isotopic data from the Hemlock and Quinnesec Formations (figs. 3, 4; table 1) define trends which might be considered errorchrons, yielding ages of about 1.5–1.6 Ga. Other geologic and geochronologic evidence from this region clearly indicates that these cannot be true crystallization ages; however, such ages are in the


A
B
C
D
E
F
ROCK:CHONDRITE
1000
100
10
1
La Ce Nd Sm Eu Tb Ho Yb Lu
+2σ
MORB
-2σ
LOWER CYCLE
UPPER CYCLE
EXPLANATION
Deccan basalts
Columbia River basalts
Keweenawan basalts reference suite
RARE EARTH ELEMENTS

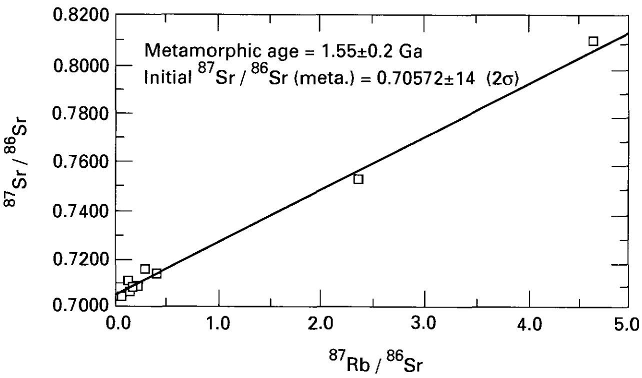


Figure 3. Rb/Sr errorchron for the Hemlock Formation volcanic rocks, showing metamorphic age for these rocks.

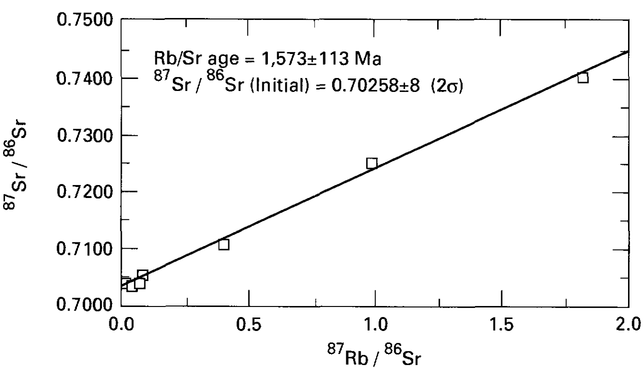


Figure 4. Rb/Sr errorchron for the Quinnesec Formation basalts, showing metamorphic age for these rocks.

range of other Sr metamorphic ages reported from northern Wisconsin and upper Michigan (1.65–1.55 Ga; Sims and Peterman, 1980), and therefore may record true metamorphic ages. Such an interpretation of these data would, however, require large-scale reequilibration of the Sr isotopic composition. As no igneous intrusives of this age have yet been found in this region, the nature of such Middle Proterozoic metamorphic events remains poorly understood. Because of the metamorphic overprinting on the whole-rock Sr isotopic systematics, the primary initial $^{87}Sr/^{86}Sr$ isotopic compositions cannot be calculated unambiguously, and thus they probably yield no useful information about the source regions of these two suites of rocks.

Figure 2 (facing page). Chondrite-normalized REE patterns for *A*, the Quinnesec and *B*, the Hemlock Formations, compared with *C*, island arc tholeiites (Gill, 1981); *D*, MORB (mid-ocean ridge basalts; Basaltic Volcanism Study Project, 1981); *E*, Archean magnesian basalts and basaltic komatiites of the Abitibi Group (Basaltic Volcanism Study Project, 1981); and *F*, continental flood basalts of the Deccan (Mahoney, 1984), Keweenawan, and Columbia River basalt provinces (Basaltic Volcanism Study Project, 1981). Quinnesec data are from K.J. Schulz, U.S. Geological Survey; Hemlock data are from Ueng and others (1988).

Table 1. Rb-Sr data for the Hemlock and Quinnesec Formations

[Sample numbers refer to locations given in figure 1*C–D*; only first two- or three-digit number for Quinnesec samples appears in fig. 1*D*]

Sample No.	Rb (ppm)	Sr (ppm)	$^{87}Sr/^{86}Sr$	$^{87}Rb/^{86}Sr$
Hemlock Formation				
5A	15.178	350.4	0.70695±26	0.1259
29F	10.06	537.1	.70533±13	.0541
29D	23.51	318.8	.708657±65	.2132
5B	55.24	68.42	.75114±7	2.3285
5C	55.46	34.76	.80808±8	4.6604
71A	35.08	256.2	.714058±80	.3959
29E	5.88	177.8	.70994±13	.1443
34G	9.45	167.1	.708237±94	.1634
Quinnesec Formation				
62–1	1.767	63.1	0.70482±9	0.0810
203–31–1	52.8	153.66	.72442±9	.9934
463–86–1	69.79	119.2	.74038±12	1.6926
491–90–1	11.79	85.06	.712050±50	.4007
565–101–1	1.810	82.91	.70365±7	.0631
105–4–1	1.115	78.45	.703499±64	.0411

Unlike the Sr isotopic compositions, the Nd isotopes do not appear to have been disturbed by metamorphism subsequent to emplacement of the rocks. The Quinnesec data form an isochron that yields an age of 1.870± 0.056 Ga, and an initial ε_{Nd} of +4.2 (fig. 5; table 2). This age is interpreted as a crystallization age, and is coeval with the 1.87 (+0.030–0.010) Ga Pb/Pb concordia intercept age obtained for several felsic intrusive rocks in the southern magmatic terrane (Banks and Rebello, 1969; Banks and Van Schmus, 1971). The initial ε_{Nd} is that of a very LREE-depleted reservoir, and indicates that a mantle reservoir with long-term LIL element depletion had existed for at least several hundred million years prior to the eruption of the Quinnesec basalts. This initial ε_{Nd} falls along the trajectory for the MORB mantle reservoir on a Nd isotopic evolution model (fig. 6), suggesting that the Quinnesec basalts may have been derived from the Proterozoic precursor of the modern MORB mantle reservoir.

In contrast to the coherent nature of the Quinnesec Nd data, the Hemlock data do not define a Nd isochron. A linear regression through the Hemlock data produces a line that could be interpreted as an errorchron, with an age of 2.7±0.5 Ga (fig. 7; table 2). Although this is the age of large parts of the Superior granite-greenstone terrane, which underlies parts of the region, an Archean age for the Hemlock is unlikely, inasmuch as other geochronologic evidence suggests that the Hemlock cannot be older than 2.1 Ga and probably is ≈1.9 Ga (Banks and Van Schmus,

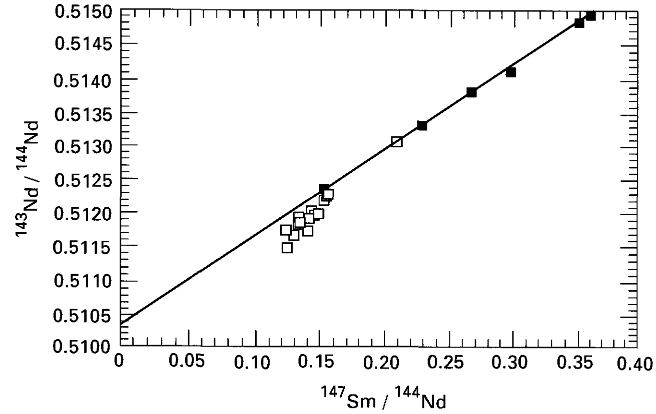


Figure 5. Present-day Sm/Nd isotopic systematics for the Quinnesec (solid squares) and Hemlock (open squares) volcanic rocks. Quinnesec Formation has an age of 1.870±0.056 Ga and an initial ε_{Nd} of +4.2. Hemlock data do not define a Nd isochron.

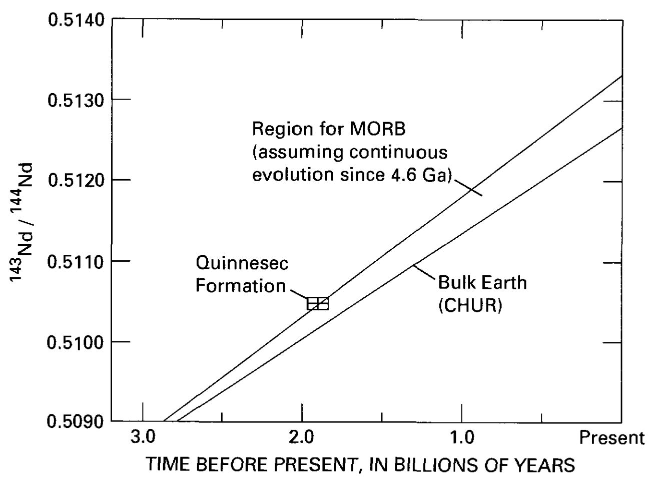


Figure 6. $^{143}Nd/^{144}Nd$ isotopic evolution diagram, showing location of Quinnesec initial ratio and age (with 2σ errors) relative to the trajectories for MORB and Bulk Earth (CHUR).

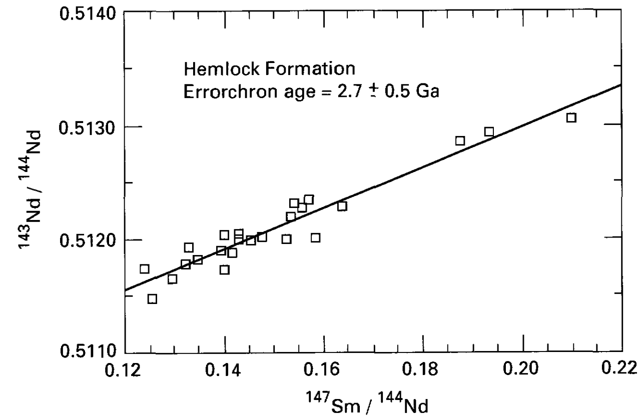


Figure 7. Plot of present-day $^{143}Nd/^{144}Nd$ versus $^{147}Sm/^{144}Nd$ for the Hemlock volcanic rocks. If interpreted as an errorchron, these data suggest an age of 2.7±0.5 Ga (2σ). The preferred interpretation, however, is that this array represents a two-component mixing line.

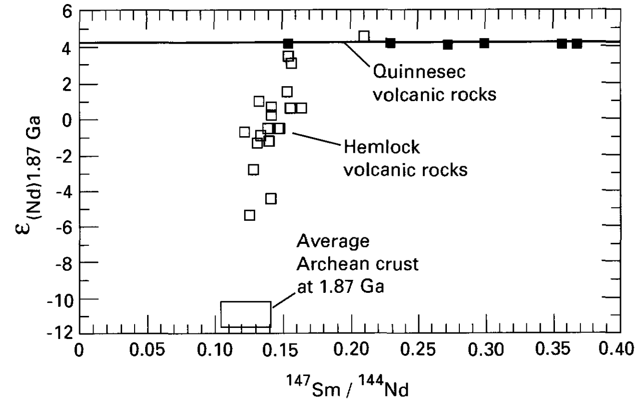


Figure 8. Sm/Nd isotopic data for the Quinnesec (solid squares) and Hemlock (open squares) volcanic rocks, calculated for approximately 1.87 Ga. Also shown is a box for ε_{Nd} of average Archean crust, specifically Amitsoq gneiss of southwestern Greenland at 1.87 Ga (from Baadsgaard and others, 1986), relative to the average $^{147}Sm/^{144}Nd$ of crustal granitoids (from Othman and others, 1984).

1971; Banks and Rebello, 1969; Aldrich and others, 1965; Hoffman, 1987). Several other explanations of the quasi-linear nature of the Hemlock data are possible, however. For example, they might be interpreted as a so-called "mantle isochron," or alternatively, they could represent some sort of mixing array. The possibility that this array represents a mantle isochron will be considered briefly following, but because of other relationships within the isotopic, trace element, and major element systematics, it is considered most likely that the Hemlock array represents a mixing array. Evidence for this assertion may be derived from a plot of the initial Nd isotopic compositions for both the Hemlock and Quinnesec Formations (fig. 8).

Calculation of initial isotopic ratios requires that some estimate be made of the age of deposition of the Hemlock tholeiites. The best estimate of this age comes from the 1,950 Ma Pb/Pb concordia intercept age obtained from a rhyolite of the Hemlock Formation (Banks and Van Schmus, 1971; Van Schmus, 1976 (old constants)). Using the new constants (Steiger and Jäger, 1977), this age would be approximately 1.90 Ga. Other geologic and geochronologic evidence supports this as a geologically reasonable age (Van Schmus, 1976, 1980; Bickford and others, 1986). Such an age is slightly older than that of the Quinnesec Formation, which certainly fits with the overall tectonics of the region. If a depleted-mantle model age is calculated for the least contaminated (most LREE depleted) Hemlock basalt, we obtain an age of about 1.87 Ga, which again corroborates the assertion that the Hemlock volcanics are approximately the same age as the Quinnesec volcanics. If we accept this as the crystallization age for the volcanics of the Hemlock Formation, then we can plot their initial Nd isotopic ratios together with those of the Quinnesec basalts

Table 2. Sm-Nd data for the Hemlock and Quinnesec Formations

[Sample numbers refer to locations given in fig. 1*C–D*; only first two- or three-digit number for Quinnesec samples appears in fig. 1*D*]

Sample No.	Sm (ppm)	Nd (ppm)	$^{143}Nd/^{144}Nd$	$^{147}Sm/^{144}Nd$	$(^{143}Nd/^{144}Nd)_i$
Hemlock Formation isotopic data					
A6I	3.8853	16.42	0.511992±17	0.1431	0.510231
5J–2	3.075	13.334	.511903±20	.1395	.510190
A27F	3.635	15.1313	.511973±54	.1453	.510194
5A	2.48	10.16	.512011±27	.1476	.510195
29F	.893	4.016	.511823±43	.1345	.510168
29D	6.012	27.3	.511911±17	.1332	.510271
5B	17.64	76.00	.511722±41	.1403	.509996
5C	18.5	88.76	.511495±51	.1261	.509943
71A	8.897	41.426	.511671±24	.1299	.510072
29B	1.862	5.3716	.513028±31	.2097	.510448
29E	5.894	26.84	.511786±27	.1328	.510152
34G	3.438	13.236	.512312±14	.1571	.510379
A2A	5.837	25.02	.511886±21	.1411	.510159
31D	4.25	20.696	.511713±31	.1242	.510185
A5J	.9724	3.826	.512185±88	.1537	.510294
A9D	1.1216	4.3871	.512302±50	.1546	.510399
29C	2.774	11.722	.512017±46	.1431	.510256
68A	2.560	9.470	.512263±23	.1635	.510251
A5G	1.25	4.844	.512273±25	.1561	.510249
Quinnesec Formation isotopic data					
62–1	1.905	7.423	0.512337±40	0.1552	0.510432
198–28–1	1.935	4.323	.513766±51	.2707	.510432
203–31–1	2.654	5.381	.514068±17	.2983	.510432
463–86–1	1.664	2.748	.514941±30	.3662	.510432
491–90–1	.976	1.656	.514855±50	.3560	.510432
105–4–1	.766	2.024	.513273±38	.2289	.510432
100–2	.3637	.8462	.513668±26	.2600	.510432

relative to their corresponding initial $^{147}Sm/^{144}Nd$ ratios (fig. 8). As seen in this illustration, the most radiogenic representatives of the Hemlock Formation have initial ε_{Nd} values equivalent to those of the Quinnesec Formation, whereas the remainder of the values define an array pointing towards the region of the box identified as Archean continental crust. This box spans the range in $^{147}Sm/^{144}Nd$ ratios for both average crustal granulites and average granitoids worldwide (Othman and others, 1984), whereas the ε_{Nd} range for this box represents the Archean Amitsoq gneisses of southwestern Greenland recalculated for 1.87 Ga (modified from Baadsgaard and others, 1986). Such data are often associated with some type of mixing process, and suggest that the Hemlock volcanics may have been derived from a LREE-depleted source with an ε_{Nd} value similar to that of the Quinnesec volcanics, but were subsequently contaminated by older continental crust. Alternatively, the Hemlock volcanic rocks could potentially have been derived from two distinct mantle sources, or from a mantle source with variable Nd isotopic composition, some portions of which experienced a long-term LIL enrichment whereas others experienced a long-term LIL depletion. This second alternative would give rise to a so-called mantle isochron, and necessitates that the magma giving rise to the Hemlock volcanics remained unhomogenized during magma genesis. In either case, the isotopic data seem to imply mixing between two discrete sources that have distinctive Nd isotopic compositions. This in turn implies long-term differences in the REE compositions for these respective reservoirs.

MIXING RELATIONSHIPS

It is difficult to determine whether the Hemlock Formation was derived from a mixed mantle source or experienced continental crustal contamination during passage through or emplacement in the crust. One way to address this question is to look for sympathetic variations between the initial Nd isotopic compositions and the major and trace element compositions of the Hemlock basalts and associated rocks. If sufficiently good data correlations can be defined, then end-member compositions can sometimes be characterized, which then can be compared with compositions of known crustal and mantle potential source rocks. Pure two-component mixing should lead to hyperbolic mixing relationships on some types of variation diagrams, and to linear plots on other variation diagrams (Langmuir, Bender, and others, 1977; Langmuir, Vocke, and others, 1977; Vollmer, 1976). Most commonly, however, when mixing occurs, it occurs in combination with fractional crystallization. This more complicated case may lead to more complex curve geometries with lines and hyperbolas as end-member cases, as discussed by DePaolo (1981). In such cases, the rock compositions may need to be compared with the results of more complex magma genesis models to determine whether magma mixing or contamination has occurred.

When the data of the Hemlock volcanic rocks are plotted on discriminate diagrams, data correlations indicative of both mixing and fractional crystallization are found. Many of the major and trace elements indeed correlate with the initial Nd isotopic compositions of these basalts. These include Th, Ta, REE, Zr, Nb, Hf, and Y, as well as a number of the major elements and oxides, including K_2O, MgO, and Mg*. Because of space constraints, only a few of these are shown here (fig. 9), but they include representatives from the Hemlock basalts as well as gabbros, ultramafics, and granophyres from the related West Kiernan sill. On each of these plots, the data from the basalts and granophyres form an arcuate trend with the samples always appearing in the same relative order. The ultramafics and gabbros of the West Kiernan sill, however, form their own distinct trend on some plots, indicating that a second process may have operated in the West Kiernan sill magma chamber.

On each plot in figure 9 a best-fit right-rectangular hyperbola has been fitted to the basalt-granophyre data using a nonlinear least-squares regression technique (Beck, 1988). As mentioned, this type of hyperbolic relationship is in some cases taken as evidence of simple two-component mixing. Proceeding on this assumption, compositional information about the end-members may at times be derived from the hyperbolic approach of the data to asymptotic values. In this case, additional constraints on the Nd isotopic composition of the end-members may be obtained from figure 8, which can then be used in figure 9 to infer something about other compositional parameters of the end-members. Figure 8 indicates that the mantle which generated the Quinnesec volcanics had an ε_{Nd} of about +4.2. This range of ε_{Nd} has been plotted in figure 10*A* for comparison with the Hemlock volcanics. One end of the basalt-granophyre trend is located in the range of highly depleted ε_{Nd}-high Mg* values typical of basalts derived from the source regions for MORB at approximately 2.0 Ga, whereas the other end falls at the low Mg*-low ε_{Nd} end of this diagram, corresponding to compositions typical of Archean continental crust at approximately 2.0 Ga. For

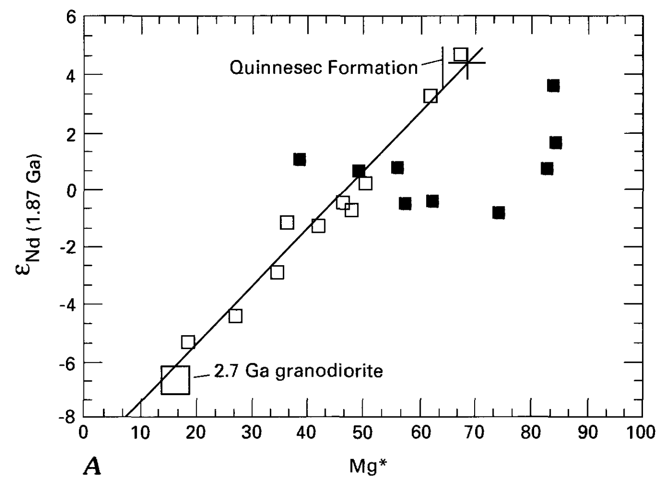
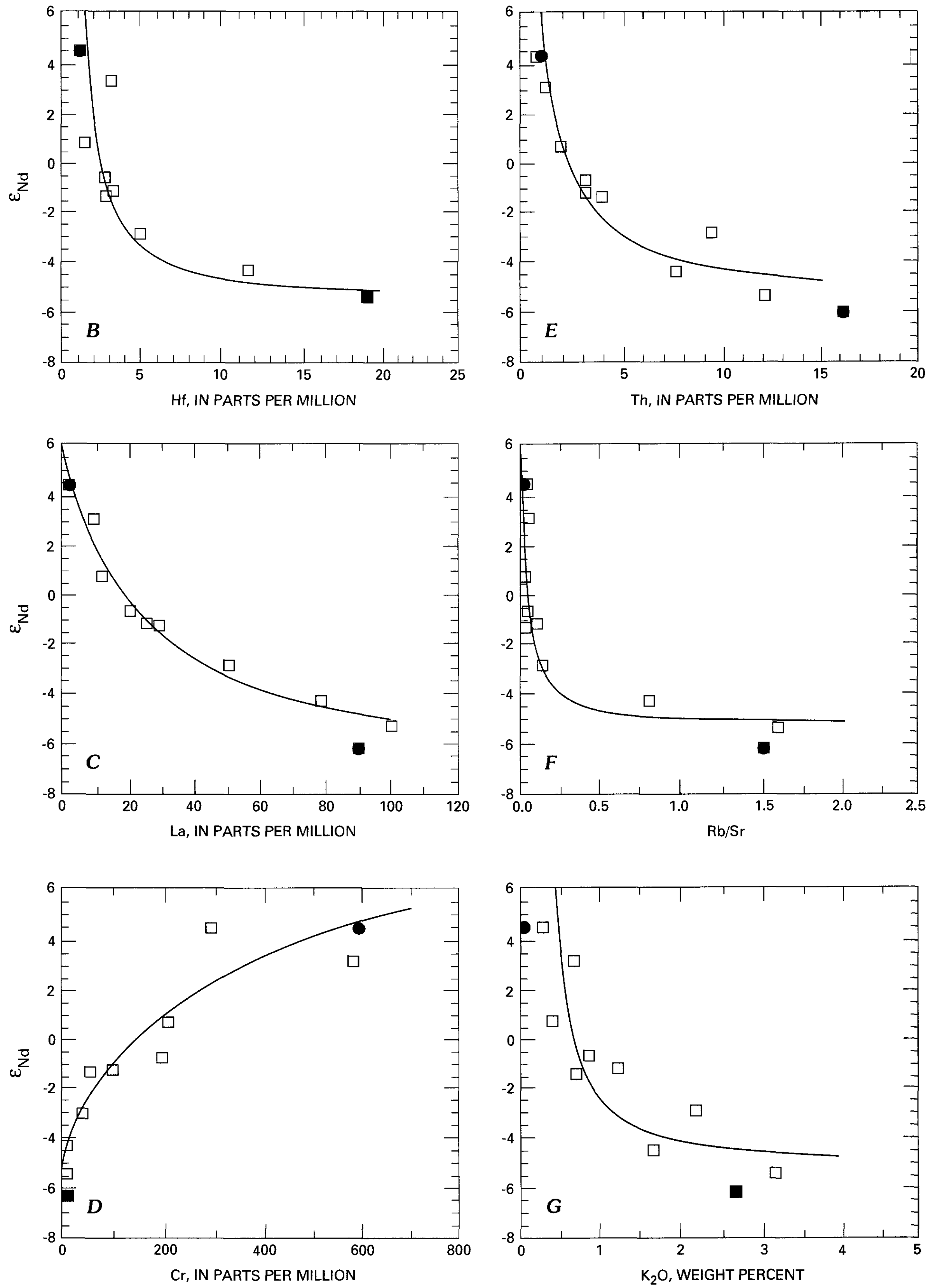


Figure 9 (above and facing page). Plots of initial ε_{Nd} (approximately 1.87 Ga) versus *A*, Mg*; *B*, Hf; *C*, La; *D*, Cr; *E*, Th; *F*, Rb/Sr; *G*, K_2O for the basalt-granophyre trend of the Hemlock data. A best-fit right-rectangular nonlinear least-squares hyperbola is shown on each plot. On any plot, solid circle, average of most depleted MORB basalts (Basaltic Volcanism Study Project, 1981); solid square, representative granodiorite from the Rainy Lake district, northwestern Minnesota (from Shirey and Hanson, 1987). In *A*, vertical line, range of initial ε_{Nd} for Quinnesec Formation; cross, range of initial ε_{Nd} corresponding to Mg* numbers in the range 68–72 typical of basalts derived from the source regions for MORB (Frey and Prinz, 1978; Frey and others, 1978). Basalt-granophyre trend implies mixing between Archean crust and MORB.

modern MORB, most primitive basaltic melts have Mg* numbers in the range 68–72 (Frey and Prinz, 1978; Frey and others, 1978; Basaltic Volcanism Study Project, 1981). An error bar in figure 9*A* shows the range in ε_{Nd} that corresponds to this range in Mg* numbers for the Hemlock volcanics. If the Hemlock volcanics were derived from the convecting mantle (which is also the source region for MORB), then the most primitive Hemlock magmas should also fall in this range of Mg* numbers. This is indeed the case, and as shown on this plot (fig. 9*A*), the ε_{Nd} value corresponding to this range of Mg* numbers for the Hemlock volcanics is for all intents and purposes identical to the ε_{Nd} initial value for the Quinnesec volcanics. The implication of this equivalence is that the Hemlock continental flood basalts were apparently derived from the same highly depleted mantle region from which the Quinnesec volcanics were derived, which as already noted corresponds to the range in isotopic characteristics expected from the Early Proterozoic precursor of the MORB reservoir. That is, both the Quinnesec and Hemlock volcanics appear to have been derived from the Early Proterozoic convecting mantle (MORB) reservoir.

The other end of the Hemlock basalt-granophyre trend shown in figure 9*A* falls at the low Mg*-low ε_{Nd} of the diagram, corresponding to compositions typical of Archean continental crust at ≈2.0 Ga. This coincidence


B
E
C
F
D
G
εNd
Hf, IN PARTS PER MILLION
Th, IN PARTS PER MILLION
La, IN PARTS PER MILLION
Rb/Sr
Cr, IN PARTS PER MILLION
K2O, WEIGHT PERCENT

supports the contention that the Hemlock magma was contaminated by Archean continental crust. We know that the Hemlock volcanics were erupted through and onto 2.7–3.6 Ga Archean crust (Van Schmus, 1976; Futa, 1981). Because granodiorite is among the most common rock compositions of upper crustal plutonic rocks throughout the Canadian Shield (Taylor and McLennan, 1985), granodiorite seems an appropriate composition to select as a crustal contaminant. The square box in figure 9*A* depicts an average Mg* value for six representative 2.7 Ga Archean granodiorites from the Superior province, together with their corresponding mean ε_{Nd} values calculated for 1.87 Ga (from Shirey and Hanson, 1987). This data area fits satisfactorily on the mixing trajectory for the basalt-granophyre data trend, plotting as an extreme point at the low ε_{Nd} end of this curve. Thus, figure 9*A* seems to provide us two suitable and quite reasonable end-members for a two-component mixing array. If we use these compositional data as a priori known values for the ε_{Nd} of our two end-members of the mixing array, then we can approximate other compositional parameters for the end-members. We can then compare these bulk compositions with those of known actual rock compositions, as a test of the mixing hypothesis.

Each view of figure 9*B–F* shows the basalt-granophyre trend for the Hemlock volcanic rocks, as well as data points representing compositions for an average of most depleted MORB, and of representative granodiorites from the Rainy Lake area, modified from Shirey and Hanson (1987). The composition of the hypothetical basaltic end-member can be determined from these plots by noting the compositions of the points of intersection between the mixing hyperbolas and the line defined by ε_{Nd}=+4.2. Table 3 summarizes these results and compares the data with compositional data representative of mid-ocean ridge tholeiites, island arc tholeiites, and ocean island tholeiites from Hawaii, as well as representative Keweenawan rift olivine tholeiites. Although the results are not absolutely conclusive, the basaltic end-member determined from this analysis seems to bear the strongest similarity to that of type I MORB. This similarity is perhaps most strongly revealed by a comparison of the REE patterns for the hypothetical basaltic component plotted relative to average patterns for MORB (fig. 10), which clearly shows that the Hemlock hypothetical basaltic component is similar in REE concentrations and REE pattern to that of MORB. Thus, the composition of the Hemlock basaltic component is consistent with its derivation from a mantle reservoir with a long-term LREE depletion.

In like manner, a footprint of the crustal component of the Hemlock volcanic rocks can be defined, as presented in table 4 and figures 11 and 12. Table 4 shows a compilation of mixing curve data for the hypothetical Hemlock crustal contaminant, together with compositional data from average felsic upper crust (Taylor and McLennan, 1985), Archean

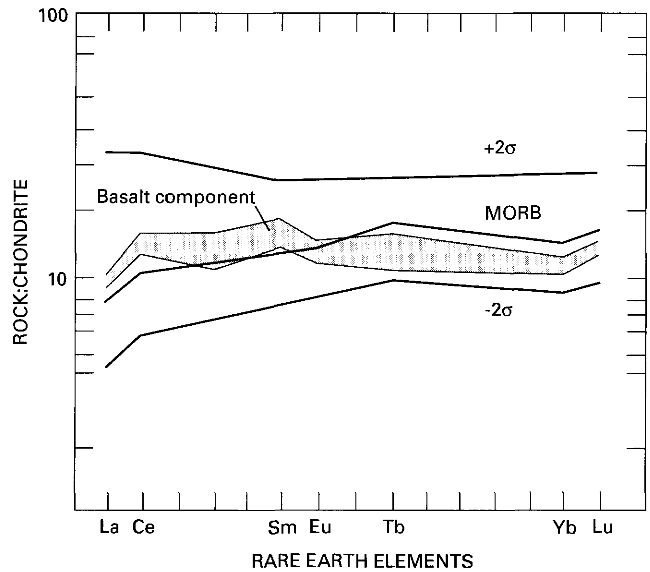


Figure 10. Chondrite-normalized REE patterns showing a comparison between the Hemlock basaltic component and that of MORB (from Basaltic Volcanism Study Project, 1981).

granodiorite (Shirey and Hanson, 1987), quartz-rich graywacke (Taylor and McLennan, 1985; Bhatia, 1981), and average Huronian mudstone (Taylor and McLennan, 1985; McLennan, 1979). A fairly good match can be made between the Hemlock crustal component and the Archean granodiorite, except that the hypothetical crustal contaminant appears to be preferentially enriched in the LIL elements and HFS elements (fig. 11). All patterns except the average lower continental crust show elevated K_2O and Th contents, whereas all exhibit negative Nb anomalies characteristic of continental crust, as well as LREE enrichment, and high overall concentrations of the REE and HFS elements. Although the overall elemental patterns among these composite rock types are similar, the hypothetical crustal component is clearly much more enriched in many of these elements than the average crustal sources. Nevertheless, the hypothetical crustal component is not unreasonably enriched in these elements, and could potentially represent a small percentage partial melt of a crustal source already enriched in these elements. For example, figure 12 shows the REE pattern of the crustal contaminant plotted relative to the granites of the Isle of Skye (Thorp and others, 1977; Thompson, 1982; Thompson and others, 1982). The pattern of LREE enrichment and the overall elevated REE concentrations exhibited by the crustal component are similar to those of the granites of the Isle of Skye, but are typically enriched in these elements by about a factor of two. Although such enrichments are uncommon, Hanson (1980) has shown that factor of 2–3 enrichments of the REE can be obtained by small percentages (3–5 percent) of batch partial melting of a granitic source at 800 °C and 4 kb (fig. 12). Partial melts of a granite into a basaltic melt at

Table 3. Geochemical comparison among the theoretical basaltic end-member, MORB, Keweenawan tholeiites, island arc basalts, and ocean island basalts

[All major elements in weight percent; all trace elements in parts per million. Data from type I MORB, island arc tholeiites, ocean island tholeiites, and Keweenawan olivine tholeiites from Basaltic Volcanism Study Project (1981). Range in ε_{Nd} values for Keweenawan tholeiites from Dosso, 1984. Estimated ε_{Nd} for island arc tholeiites from Albarede and Brouxel, 1987. Leaders (---), no data]

Element, oxide, ratio	Basaltic end-member (1.87 Ga)	Type I MORB (1.87 Ga)	Keweenawan Rift olivine tholeiites	Island arc tholeiites	Ocean island tholeiites
SiO_2	48	48–49	46–50	50–54	48–52
TiO_2	1.0	0.6–0.62	1.2–1.8	0.5–1.1	1.4–2.6
Al_2O_3	13.5	12.1–16.5	14.5–17.5	15.7–19	9.0–13.8
FeO_t	---	8.8–9.0	---	6.3–8.5	---
MnO	0.18	0.12–0.15	0.15–0.22	0.14–0.24	0.16–0.17
MgO	10	10.3–17.81	6.2–8.4	5.7–9.0	7.2–14
CaO	10	11.2–12.4	6.3–10.5	10.5–12.9	7–11.2
Na_2O	---	1.3–1.92	2.4–3.8	1.5–3.0	1.5–2.3
K_2O	0.5	0.03–0.07	0.3–1.3	0.18–0.50	0.27–0.5
P_2O_5	0.06	0.06	0.14–0.20	0.07–0.19	0.17–0.3
Hf	1.7	1–8	2.3	2.0	3–7
Ta	0.5	0.2–1.0	0.5	---	---
Zr	70	32	40–140	45–130	120–250
Nb	13	1–5	6	1–6	13–24
Y	20	---	20–76	20–30	17–24
Th	1.2	0.2–2.3	0.9	0.5–6.5	1.0–1.65
Yb	2.5	---	3–7	2.0	2.0
Cr	600	270–700	40–270	40–110	300–700
Ni	200	300	35–200	10–40	---
La	3.5	1.2	10	4	15
Ce	10	6.4	20	10	38
Nd	7	4.7	12	8.5	---
Sm	2.5	1.54	3	2.1	6.8
Eu	0.1	0.6	1.1	0.8	2.0
Lu	0.4	0.3	0.3	0.3	0.3
Mg*	70	68–72	43–60	51–71	57–78
Rb/Sr	0.01	0.01	0.03	0.015	0.03
ε_{Nd}	+4.2	+4.2	–2.6 to +3.2 (at 1.1 Ga)	4.0?	---

≈1,100 °C could potentially result in even greater enrichments of the melt in the REE and HFS elements, although such an assertion is speculative because of the notably poor constraints on distribution coefficients between granitic mineral phases and high-temperature basaltic melts. Alternatively, additional enrichments of these elements could have occurred as a result of differentiation subsequent to the incorporation of the crustal component into the basaltic melt. Thus, REE patterns similar to that of the Hemlock crustal component do not appear out of line if the crustal component represents a small percentage partial melt of a granite similar in composition to the granites of the Isle of Skye.

The Cr and Ni concentrations of the crustal and basaltic end-members are both plotted in figure 13 together with the average compositions for oceanic crust, upper continental crust, lower continental crust, total continental crust, orogenic andesites, and primitive mantle (from Taylor and McLennan, 1985). The composition of the Hemlock basaltic component is close to that of modern oceanic crust, whereas the Hemlock crustal component is similar to the composition of average upper crust, and considerably different from that of the lower crust. Whereas the depleted nature of Cr and Ni in the Hemlock crustal component may well result from fractionation occurring subsequent to its incorporation into the basaltic melt, its composition may also be related to the source composition of this component. Thus the Cr/Ni relations of the crustal and basaltic components are consistent with their apparent derivation from the upper continental crust and MORB reservoirs,

Table 4. Geochemical comparison between the theoretical end-member and several representative crustal compositions

[Chemical compositions of the hypothetical Hemlock crustal contaminant, together with comparisons with compositions of average felsic upper crust (Taylor and McLennan, 1985), Archean granodiorite (Shirey and Hanson, 1987), quartz-rich graywacke (Taylor and McLennan, 1985; Bhatia, 1981), and average Huronian mudstone (Taylor and McLennan, 1985; McLennan, 1979). Major elements in weight percent; trace elements in parts per million. Leaders (---), no data]

Element, oxide, ratio	Average felsic upper crust	Archean granodiorite	Crustal end-member	Quartz-rich graywacke	Average Huronian mudstone
SiO_2	69.7	74.8	80	81.1	71.69
TiO_2	.5	.22	---	.62	.41
Al_2O_3	15.8	15.0	10.5	10.1	15.96
FeO*	---	---	---	2.76	3.36
MnO	.15	.06	---	.03	.02
MgO	1.4	.21	.2	1.44	1.67
CaO	2.9	1.46	---	.26	.26
Na_2O	4.3	4.07	---	1.69	1.35
K_2O	2.2	2.94	3.5–4.5	1.93	5.51
P_2O_5	---	.04	---	.14	.12
Hf	4	---	20–25	10.1	---
Ta	---	---	4.5–5	---	---
Zr	200	76–665	800–900	384	---
Nb	---	6–27	50	11	---
Y	14	---	150–200	32	52
Th	.22	---	16–20	16.4	---
Yb	---	1–15	16	2.9	3.8
Cr	30	1–17	5	51	56
Ni	5	4–12	10	19	14
La	37	10–40	100–120	43	49
Ce	75	20–130	175–225	83	115
Nd	33	10–75	100	42	51
Sm	5.7	1.5–18	25–40	7.1	9.3
Eu	1.6	0.4–3.5	5–8	1.1	1.8
Lu	.22	---	1.2	2.9	---
Mg*	---	11–30	10	---	---
Rb/Sr	.21	---	2–2.5	2.0	8.04

respectively. Hence the assertion that the geochemical signatures of the Hemlock volcanic rocks may have been generated by crustal contamination of a basaltic melt from the depleted mantle appears to be corroborated by the isotopic, trace element, and major element signatures of these rocks.

ASSIMILATION–FRACTIONAL CRYSTALLIZATION MODEL CALCULATIONS COMPARED WITH OBSERVED CHEMISTRIES

The preceding discussion of element composition and possible sources and processes in the Hemlock Formation may be compared with the results of combined AFC (assimilation–fractional crystallization) models, as a further test of the assertion that the Hemlock basalts resulted from mixing between a MORB-like basaltic source and a continental crustal contaminant. Two such AFC models were coupled together for this purpose. One of these models, TRACE.FOR (Nielson, 1985; 1988), is an incremental crystallization model used to determine the major and trace element concentrations during differentiation of a mafic magma. The model Nd isotopic compositions, on the other hand, were determined using the output from TRACE.FOR in combination with a second AFC model, based principally upon one developed by DePaolo (1981). DePaolo's AFC model was not used directly to predict the isotopic compositions of melt fractions resulting from TRACE.FOR, because DePaolo's model calculates melt isotopic compositions assuming a constant bulk distribution

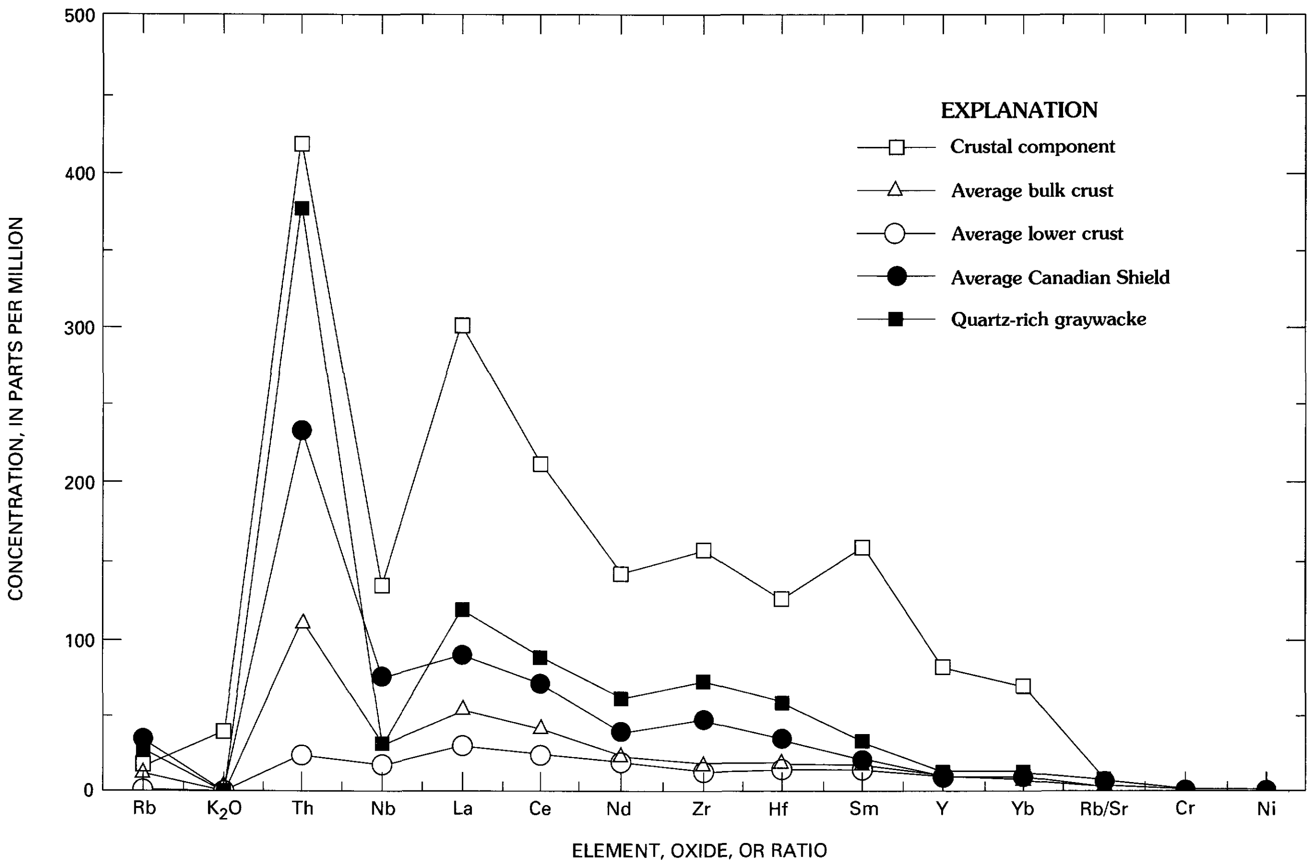


Figure 11. Spider diagram showing chondrite-normalized concentrations of the HFS elements, some REE, and several incompatible elements for the Hemlock crustal component, average bulk crust, average lower continental crust (modified from Taylor and McLennan, 1985), average Canadian Shield, and average quartz-rich graywacke.

coefficient for the fractionating phases. In nature (and in TRACE.FOR), the modal proportions of the crystallizing phases often change as crystallization progresses, whereas individual mineral/melt distribution coefficients may also change during the fractionation process owing to variations in temperature. Since such effects generally result in variations of the bulk distribution coefficient, DePaolo's model had to be adjusted to allow for such conditions. Another difficulty with the DePaolo model is that it does not have a provision allowing for periodic recharge and (or) eruption to occur concurrently with assimilation or fractional crystallization. TRACE.FOR, on the other hand, does have provisions which allow for periodic recharge and (or) eruption. As such, DePaolo's model has been modified to utilize the output of TRACE.FOR to calculate the Nd elemental and isotopic composition of the melt, as discussed by Beck (1988).

An average MORB parental melt (table 3, from Basaltic Volcanism Study Project, 1981) was used as a starting composition for the basaltic melt input into TRACE.FOR. For those runs utilizing a crustal contaminant, the average granite composition from Taylor and McLennan (1985, tables 9.2, 3.1) was used (see table 4). TRACE.FOR was run in a variety of configurations utilizing fractional crystallization ±magma recharge±assimilation of granitic crust±simultaneous eruption. The amount of recharge, assimilation, and eruption occurring during each program run can be represented in a shorthand form (*X*/*Y*/*Z*); *X*, *Y*, and *Z* can be any non-negative numbers, generally less than 1, where *X* represents the amount of recharge, *Y* the amount of assimilation, and *Z* the amount of eruptive material. A value of 1 would represent an amount of recharge, assimilation, or eruption equivalent to the amount removed from the melt system by crystallization; 0.5 would represent an amount of recharge, assimilation, or eruption equivalent to one-half of the mass removed from the magma chamber by crystallization, and so on. For example, (*X*/*Y*/*Z*)=(1.0/0.3/1.0) represents a run in which for every increment of melt removed from the magma by crystallization, an equivalent increment of melt is added to magma chamber by recharge, 0.3× such increment is added to the magma from a crustal assimilant, and 1.0 equivalent increment is removed from the system by eruption. Obviously, this case represents a non-steady-state case in which the total volume of magma will decrease with time, with 2.0 magma masses leaving the system for every 1.3 masses added.

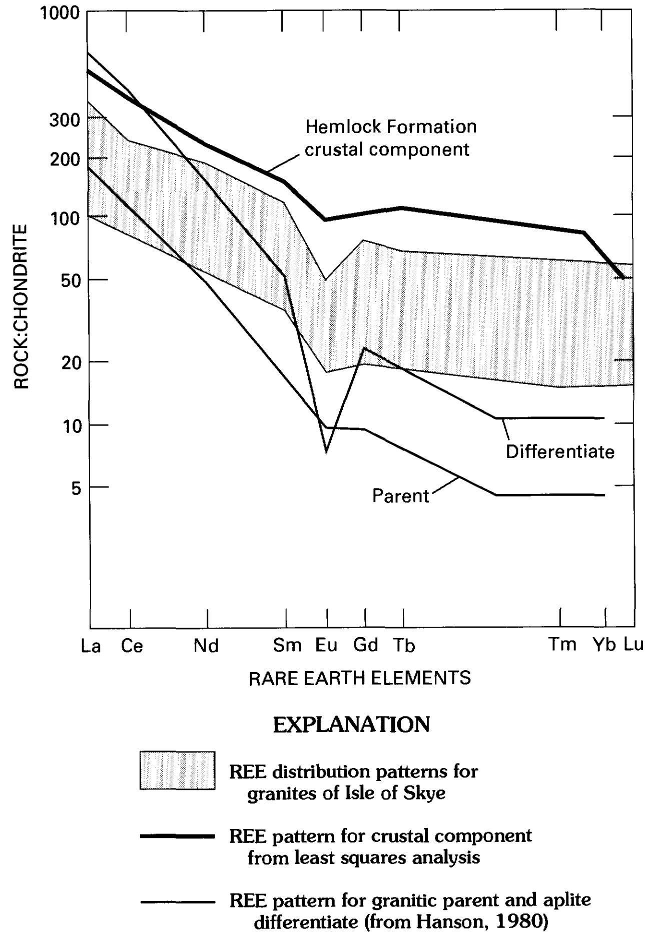


Figure 12. Comparison of chondrite-normalized REE patterns of the Hemlock crustal component, granites of the Isle of Skye (from Thompson and others, 1982; Thorp and others, 1977), as well as granitic parent and theoretical small-percentage (1–2 percent) partial melt of this parent (differentiate) (from Hanson, 1980).

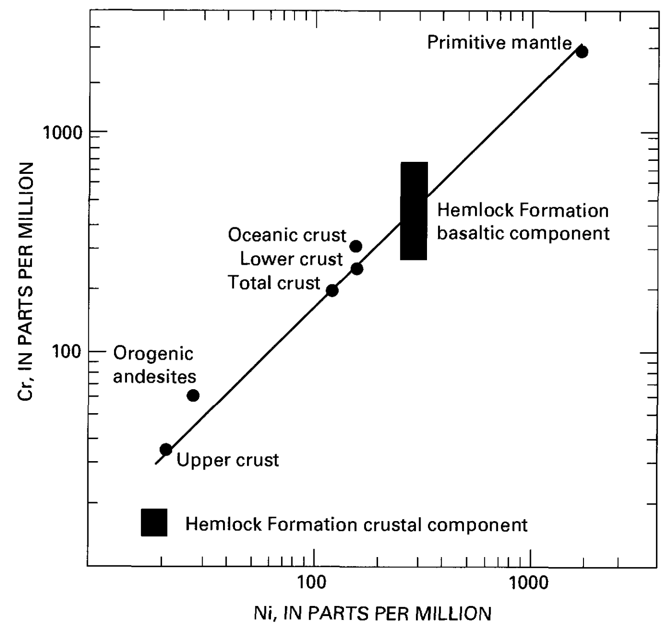


Figure 13. Plot of Cr and Ni showing composition of the Hemlock Formation basaltic and crustal components relative to composition of upper continental crust, orogenic andesites, total continental crust, lower continental crust, oceanic crust, and primitive mantle (modified from Taylor and McLennan, 1985).

Some of the results of these AFC models are presented in figures 14–20. Six different configurations of recharge, assimilation, and eruption are shown in these figures, including (0.0/0.3/0.0), (0.0/0.3/0.5), (0.5/0.3/0.5), (1.0/0.3/0.0), as well as (0.5/0.0/0.5), and (1.0/0.0/0.5). The first four options include a term for assimilation of continental crust, whereas the last two do not. All runs included fractional crystallization.

Figures 14–16 show several major and trace elements plotted relative to the fractionation index Mg*, whereas the remaining figures (17–20) show several major and trace element concentrations plotted relative to their initial ε_{Nd}. Each graph shows the results of the TRACE.FOR/ISOTOPE model compared with compositions of the basalts and granophyres of the Hemlock Formation.

Plots of REE versus Mg* (not shown) reveal that all permutations of the model provide a reasonable match to the Hemlock data, and in general do not discriminate among the various potential processes. Likewise, the same may be said for the plots of Zr versus Mg* (not shown), except perhaps for the model (0.0/0.3/0.5), whose poor match for low Mg* values may indicate that magma recharge±assimilation may be required to enrich the melt in the HFS elements such as Zr.

Plots of Ni (not shown) and V (fig. 14) versus Mg* likewise generally reflect fairly good matches within the scatter of the data between the Hemlock volcanic rocks and the results of the models, indicating that olivine and clinopyroxene fractionations probably were indeed important controls on melt chemistry during genesis of the Hemlock volcanics. As was shown for the REE, these Ni and V trends do not discriminate among the various potential processes, except that the models involving assimilation may provide a slightly better fit to the Hemlock data for V plotted against Mg* than those models without assimilation.

The plots of K_2O (weight percent) versus Mg* (fig. 15) reveal excellent matches for the four cases involving crustal assimilation, but only poor correlations between the Hemlock volcanics and the model data for the two cases not involving crustal assimilation [(1.0/0.0/0.5) and (0.5/0.0/0.5)]. If this potassic enrichment is not a product of subsequent regional metamorphism (which is unlikely to have occurred on this scale), then the Hemlock magmas must have tapped some source of potassium enrichment during the genesis of its melts. These models show that crustal assimilation is a suitable potential source of such an enrichment. Alternatively, this type of potassic

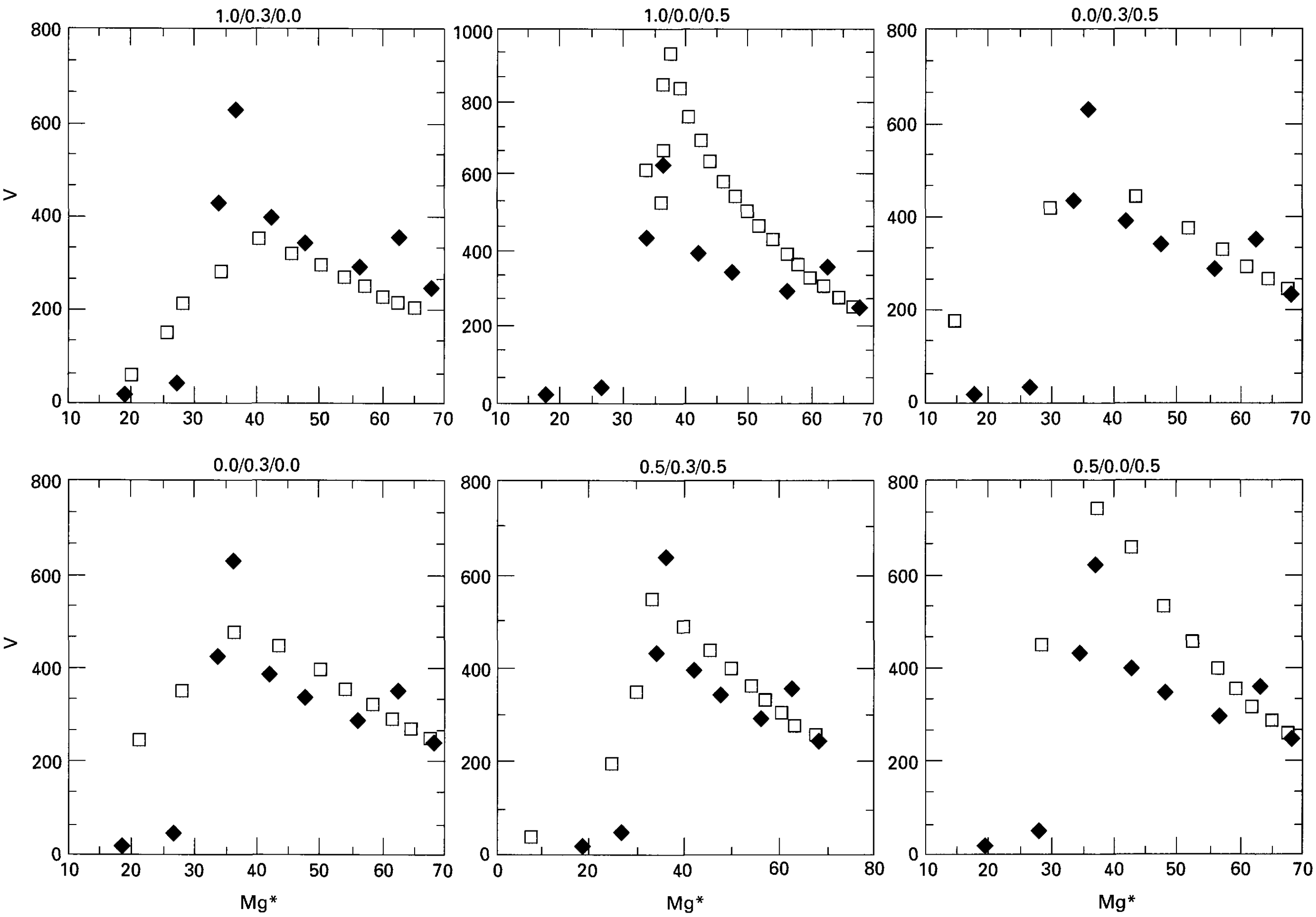


Figure 14. Plots of V (ppm) versus Mg* for the results of six different configurations of the assimilation–fractional crystallization model TRACE.FOR (open squares, from Nielson, 1988), compared with compositions of the Hemlock Formation (filled diamonds).

enrichment could equally well have been caused by mantle metasomatism just prior to the eruption of the Hemlock magmas.

As with K_2O, the plots of Nb versus Mg* (fig. 16) indicate that models without assimilation cannot generate a Nb trend similar to that of the Hemlock volcanics. In fact, those models with both assimilation and magma recharge seem to provide the best fits to the Hemlock data. These plots suggest that both magma recharge and assimilation result in Nb enrichments of the melt, but that crustal assimilation is the more important of the two processes.

Figures 17–20 show some of the Nd isotopic results of the TRACE.FOR/ISOTOPE models together with the data from the Hemlock volcanics. As noted before, and as shown by each of these plots, the large spread in ε_{Nd} values in the Hemlock data either necessitates assimilation of old continental crust or requires the Hemlock lavas to have been generated from a mixed mantle source—one source with a highly depleted Nd isotopic composition and another highly enriched in Nd. All these plots show that those models lacking a term for crustal assimilation [such as (1.0/0.0/0.5) and (0.5/0.0/0.5)] *cannot* generate a range of ε_{Nd} values such as seen in the Hemlock data. The remaining four models in each figure all contain a term for crustal assimilation, and (as shown) some of these do generate appropriate ranges of ε_{Nd} approximating that seen in the Hemlock data.

In the plot of La versus ε_{Nd} (fig. 17), all models containing an assimilation term generate patterns similar to that of the Hemlock data, except for model (1.0/0.3/0.0), which has terms for recharge, assimilation, and fractional crystallization, but no term for volcanism. For this model, the ε_{Nd} values plateau out at a level above that for the most evolved members of the Hemlock volcanic rocks, suggesting that for this model, the ε_{Nd} values are buffered (1) by the large influx of Nd with depleted-mantle signature from the magma recharge term, and (2) by enrichment of Nd in the residual melt because it is an incompatible element. All other models containing an assimilation term generate suitable ranges of ε_{Nd}, but do not discriminate among themselves enough to allow selection of a preferred model. This same pattern is repeated in plots of all the REE versus ε_{Nd} (not shown).

Virtually the same results are shown by the plots of ε_{Nd} versus Zr, Ni, Mg* (fig. 18), SiO_2 (fig. 19), and K_2O (fig. 20), all of which show reasonable matches for the

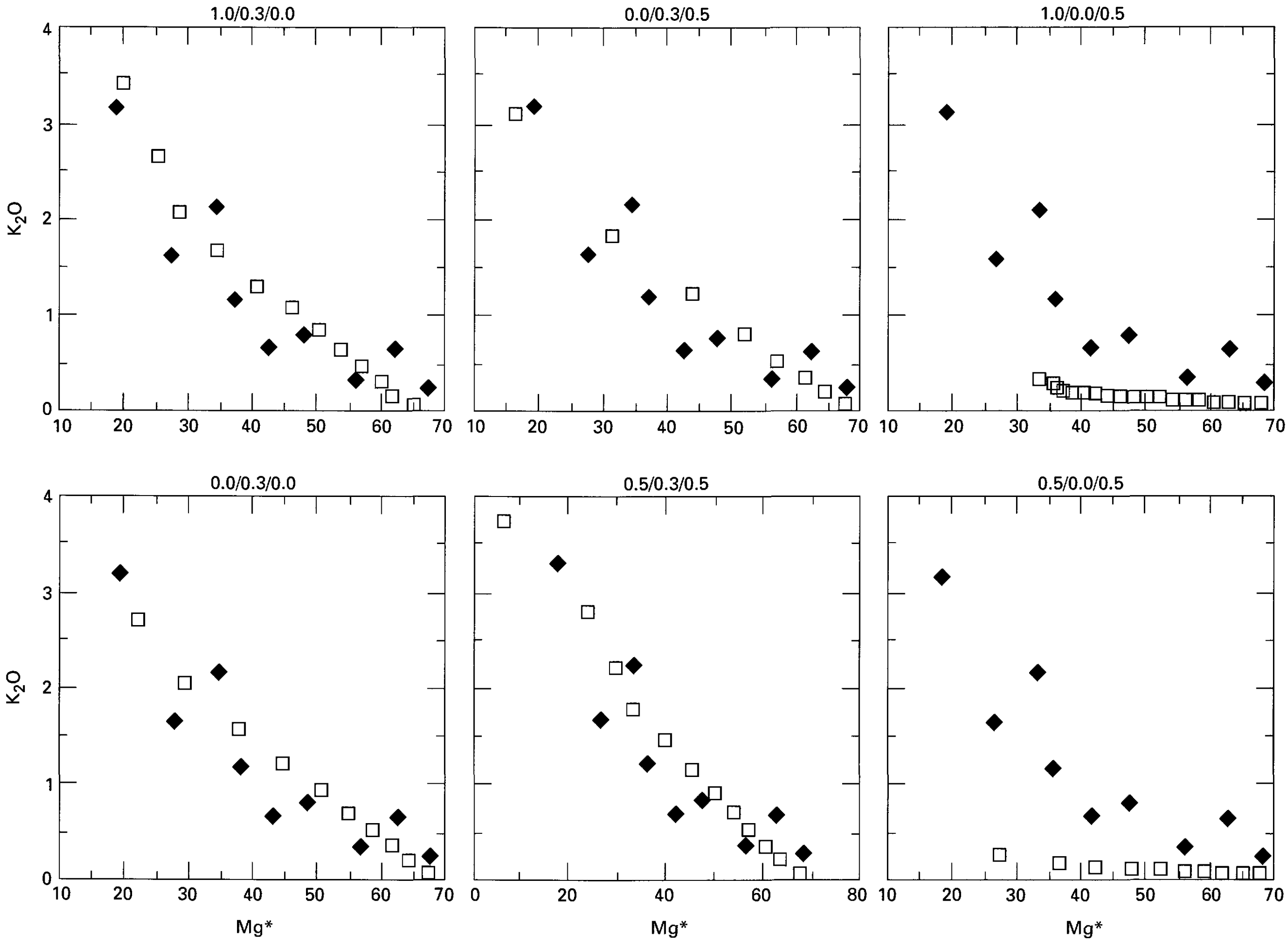


Figure 15. Plots of K_2O (weight percent) versus Mg* for the results of six different configurations of the assimilation–fractional crystallization model TRACE.FOR (open squares, from Nielson, 1988), compared with compositions of the Hemlock Formation (filled diamonds).

models containing an assimilation term, except for model (1.0/0.3/0.0), which again does not provide sufficiently negative ε_{Nd} values for the most evolved magmas.

The general conclusion that may be drawn from these mixing and AFC calculations is that some combination of fractional crystallization, magma recharge, and assimilation of Archean upper crust adequately explains the data observed in the Hemlock volcanic rocks, and that the data are fit best by a model that involves all three of these processes. Although it is possible that these chemical and isotopic systematics could have been generated by mixing of two mantle sources, this is considered an unlikely explanation because the low ε_{Nd} component appears to have had a highly evolved rock composition, unlike any potential mantle source, LIL enriched or otherwise.

CONCLUSIONS

We conclude that the Niagara fault zone is a major crustal boundary that juxtaposes two Early Proterozoic terranes of different character. This dichotomy is quite clear cut with respect to the contrasting composition of volcanic rocks on either side of the fault zone. The Hemlock volcanic and related intrusive rocks to the north of the shear zone have many of the compositional characteristics of continental flood basalts, whereas the Quinnesec volcanic and related intrusive rocks to the south have compositions indicating a tectonic affinity with island arc or ocean floor volcanic regimes. Other geologic evidence, however, suggests that the Quinnesec and associated volcanics are most probably of island arc or back arc basin affinity (Sims and others, 1989).

The Nd and Sr isotopic compositions of the Quinnesec volcanic rocks suggest that they were derived from a mantle source with a long-term LREE depletion, and a ε_{Nd} similar to that anticipated for the source region for MORB at ≈1.9 Ga. The Nd and Sr isotopic compositions of the Hemlock volcanics are typical of those in continental flood basalt provinces. These compositions, when coupled with their trace and major element compositions, suggest that the Hemlock volcanics may have been generated by a

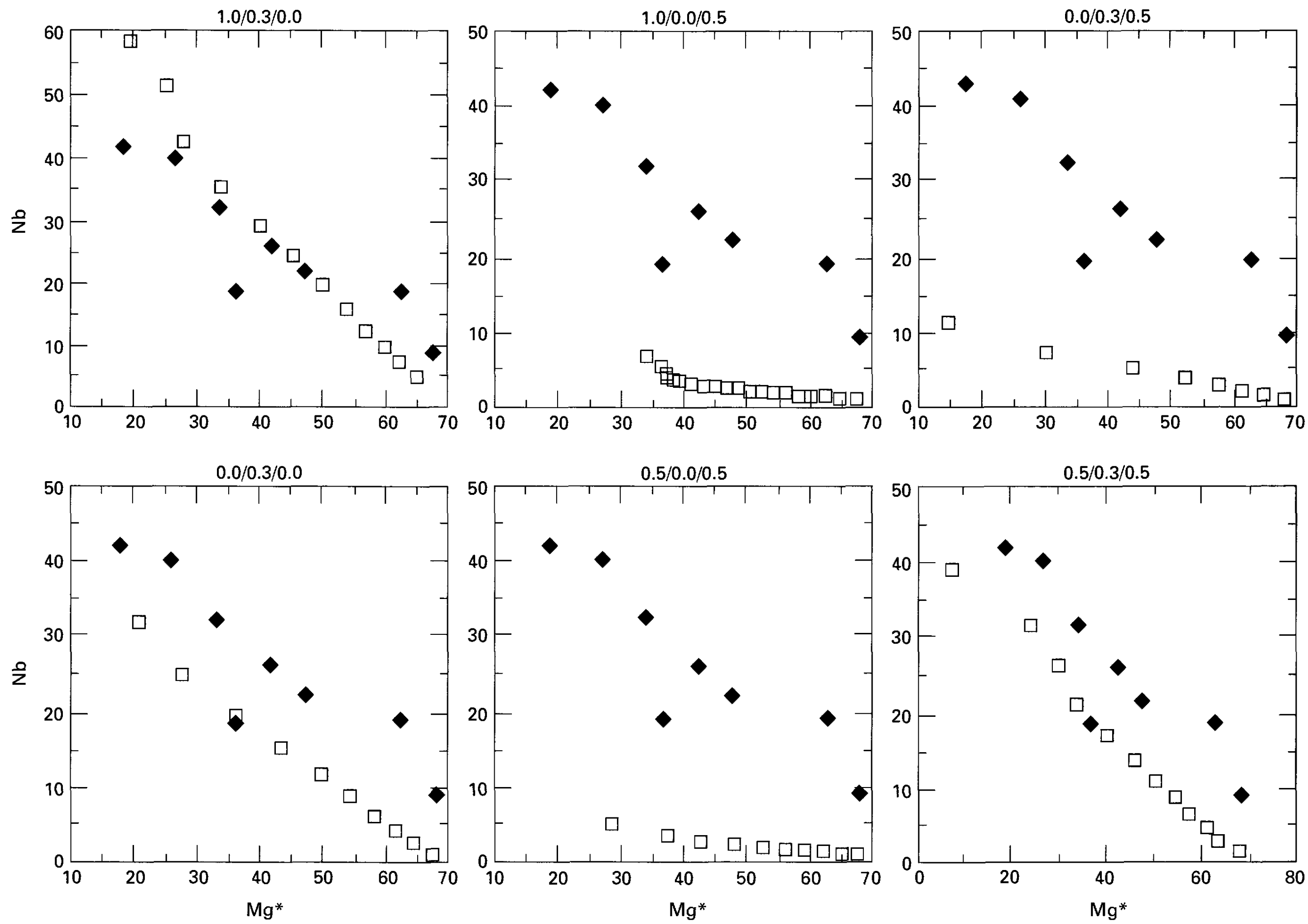


Figure 16. Plots of Nb (ppm) versus Mg* for the results of six different configurations for the assimilation–fractional crystallization model TRACE.FOR (open squares, from Nielson, 1988), compared with compositions of the Hemlock Formation (filled diamonds).

two-component mixing process between a mantle component similar in composition to the source regions for the Quinnesec volcanics and a second LIL-element-enriched component which was either Archean upper continental crust or an old "metasomatized" mantle component. The results of combined mixing–fractional crystallization models suggest that the most likely candidate for this second component was Archean granodioritic crust or sediments derived from this source.

REFERENCES CITED

Albarede, F., and Brouxel, M., 1987, The Sm/Nd secular evolution of the continental crust and the depleted mantle: Earth and Planetary Science Letters, v. 82, p. 25–35.

Aldrich, L.T., Davis, G.L., and James, H.L., 1965, Ages of minerals from metamorphic and igneous rocks near Iron Mountain, Michigan: Journal of Petrology, v. 6, p. 445–472.

Anderson, J.L., and Cullers, R.L., 1987, Crust-enriched mantle-derived tonalites in the Early Proterozoic Penokean orogen of Wisconsin: Journal of Geology, v. 95, p. 139–154.

Arculus, R.J., 1987, The significance of source versus process in the tectonic controls of magma genesis: Journal of Volcanology and Geothermal Research, v. 32, p. 1–12.

Baadsgaard, H., Nutman, A.P., and Bridgwater, D., 1986, Geochronology and isotopic variation of the early Archean Amitsoq gneisses of the Isukasia area, southern West Greenland: Geochemica et Cosmochimica Acta, v. 50, p. 2173–2183.

Banks, P.O., and Rebello, D.P., 1969, Zircon age of a Precambrian rhyolite, north-eastern Wisconsin: Geological Society of America Bulletin, v. 80, p. 907–910.

Banks, P.O., and Van Schmus, W.R., 1971, Chronology of Precambrian rocks of Iron and Dickinson counties, Michigan: 17th Annual Institute on Lake Superior Geology, Duluth, Minnesota, Abstracts and Field Guides, p. 9–10.

Barovich, K.M., Patchett, P.J., and Peterman, Z.E., 1987, Origin of the 1.9–1.7 Ga Penokean continental crust of the Lake Superior region [abs.]: Eos, v. 68, p. 1547.

Barovich, K.M., Patchett, P.J., Peterman, Z.E., and Sims, P.K., 1989, Nd isotopes and the origin of 1.9–1.7 Ga Penokean continental crust of the Lake Superior region: Geological Society of America Bulletin, v. 101, p. 333–338.

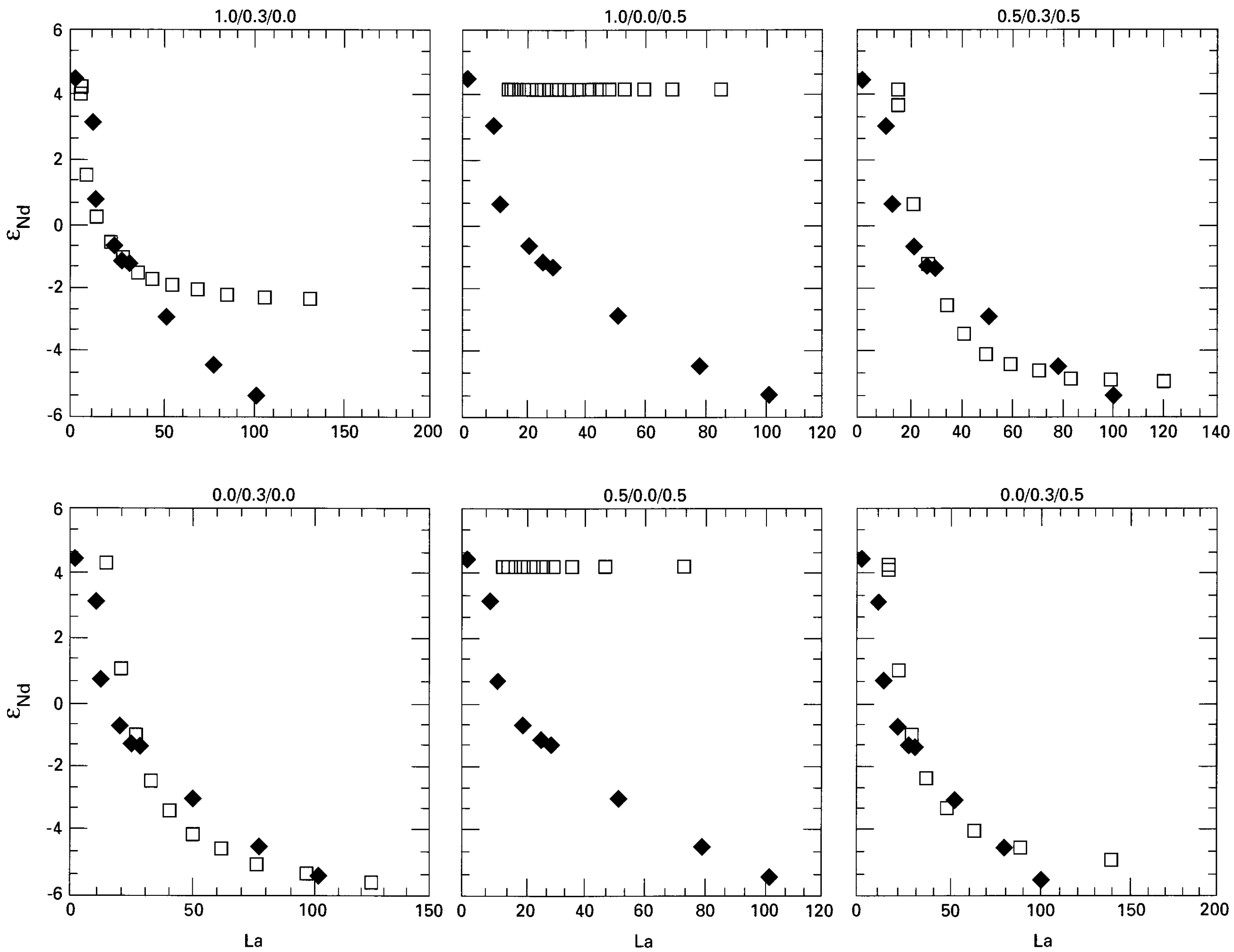


Figure 17. Plots of La (ppm) versus ε_{Nd} (1.87 Ga) for the results of six different configurations of the assimilation–fractional crystallization model TRACE.FOR/ISOTOPE (Beck, 1988; modified from Nielson, 1988, and DePaolo, 1981) (open squares), compared with compositions of the Hemlock volcanic rocks (filled diamonds).

Basaltic Volcanism Study Project, 1981, Basaltic volcanism on the terrestrial planets: New York, Pergamon Press, 1286 p.

Bayley, R.W., 1959, Geology of the Lake Mary quadrangle, Iron County, Michigan: U.S. Geological Survey Bulletin 1077, 112 p.

Bayley, R.W., Dutton, C.E., Lamey, C.A., and Treves, S.B., 1966, Geology of the Menominee iron-bearing district, Dickinson County, Michigan and Florence and Marinette Counties, Wisconsin: U.S. Geological Survey Professional Paper 513, 96 p.

Beck, J.W., 1984, Nd and Sr isotopic studies of the Quinnesec and Hemlock Formations in northeastern Wisconsin and adjacent Michigan: 30th Annual Institute on Lake Superior Geology, Wausau, Wisconsin, Abstracts, v. 30, p. 1–2.

______ 1988, Implications for early Proterozoic tectonics and the origin of continental flood basalts, based on combined trace element and neodymium/strontium isotopic studies of mafic igneous rocks of the Penokean Lake Superior belt, Minnesota, Wisconsin and Michigan: Minneapolis, Minn., University of Minnesota Ph. D. thesis, 262 p.

Bhatia, M.R., 1981, Petrology, geochemistry and tectonic setting of some flysch deposits: Canberra, Australia, Australian National University Ph. D. thesis, 211 p.

Bickford, M.E., Van Schmus, W.R., Macdonald, R., Lewry, J.F., and Pearson, J.G., 1986, U-Pb zircon geochronology project for the Trans-Hudson orogen: Saskatchewan Geological Survey Investigation 86–4, p. 101–107.

Cambray, F.W., 1977, The geology of the Marquette District—A field guide: Michigan Basin Geological Society, 61 p.

______ 1978, Plate tectonics as a model for the environment of deposition and deformation of the early Proterozoic of northern Michigan: Geological Society of America Abstracts with Programs, v. 10, p. 376.

Cannon, W.F., 1986, Bedrock geologic map of the Iron River 1°×2° quadrangle, Michigan and Wisconsin: U.S. Geological Survey Miscellaneous Investigations Series Map I–1360–B.

Carlson, R.W., Lugmair, G.W., and Macdougall, J.D., 1981a, Crustal influence in the generation of continental flood basalts: Nature, v. 289, p. 160–162.

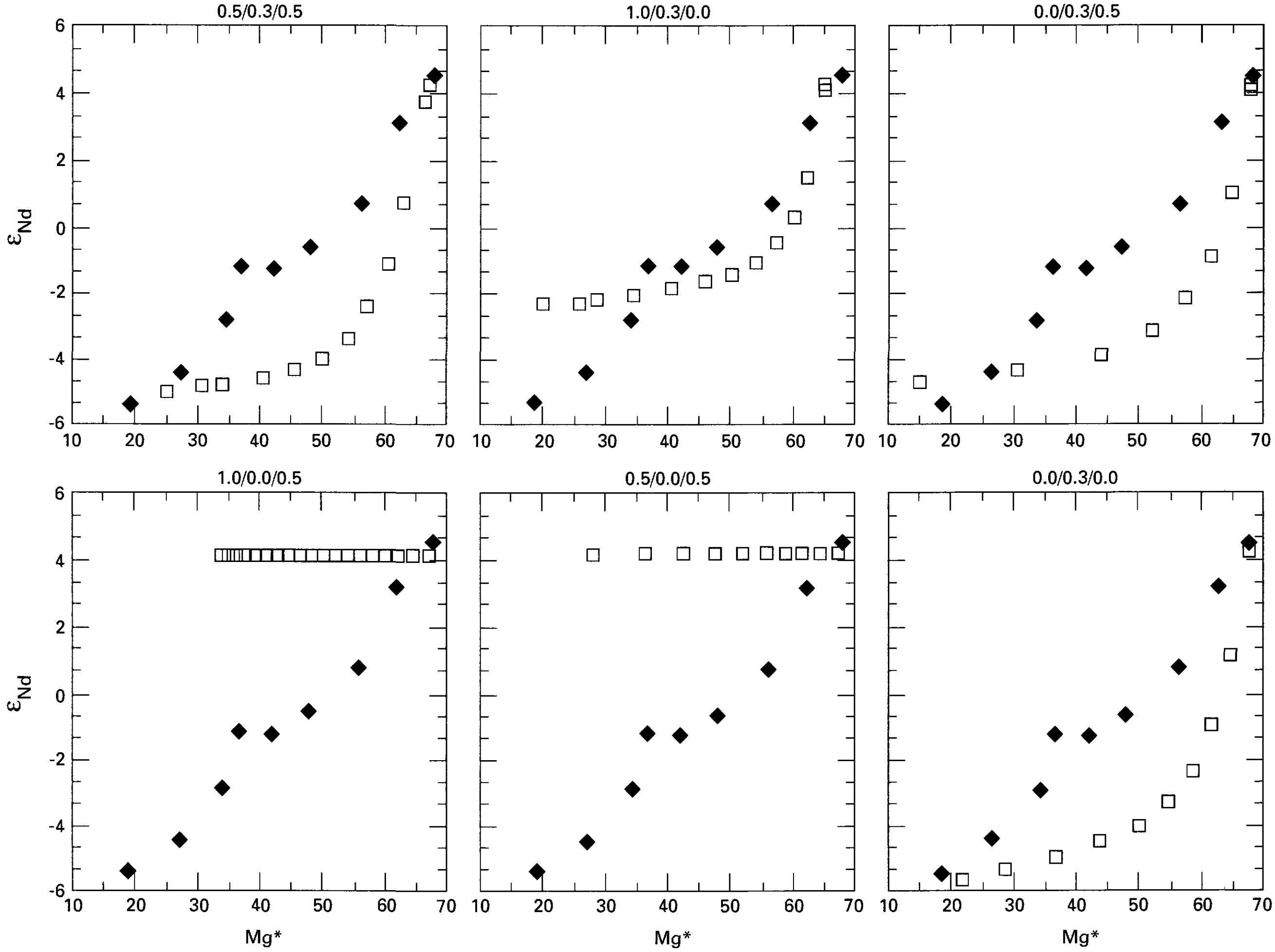


Figure 18. Plots of Mg* versus ε_{Nd} (1.87 Ga) for the results of six different configurations of the assimilation–fractional crystallization model TRACE.FOR/ISOTOPE (Beck, 1988; modified from Nielson, 1988, and DePaolo, 1981) (open squares), compared with compositions of the Hemlock volcanic rocks (filled diamonds).

______ 1981b, Columbia River volcanism—The question of mantle heterogeneity or crustal contamination: Geochimica et Cosmochimica Acta, v. 45, p. 2483–2500.

Carter, S.R., Evenson, N.M., Hamilton, P.J., and O'Nions, R.K., 1978, Neodymium and strontium isotopic evidence for crustal contamination of continental volcanics: Science, v. 202, p. 743–747.

Cudzillo, T.F., 1978, Geochemistry of early Proterozoic igneous rocks, Northern Wisconsin and Upper Michigan: Lawrence, Kans., University of Kansas Ph. D. thesis, 202 p.

Cummings, M.L., 1978, Metamorphism and mineralization of the Quinnesec Formation, northeastern Wisconsin: Madison, Wis., University of Wisconsin Ph. D. thesis, 190 p.

DePaolo, D.J., 1981, Trace element and isotopic effects of combined wallrock assimilation and fractional crystallization: Earth and Planetary Science Letters, v. 53, p. 189–202.

Dickin, A.P., 1981, Isotopic geochemistry of Tertiary rocks from the Isle of Skye, N.W. Scotland: Journal of Petrology, v. 22:2, p. 155–189.

Dosso, L., 1984, The nature of Precambrian subcontinental mantle—Isotopic study (Sr,Pb,Nd) of the Keweenawan volcanism of the north shore of Lake Superior: Minneapolis, Minn., University of Minnesota Ph. D. thesis, 221 p.

Dutton, C.E., 1971, Geology of the Florence area, Wisconsin and Michigan: U.S. Geological Survey Professional Paper 633, 54 p.

Fox, T.P., 1983, Geochemistry of the Hemlock Metabasalt and Kiernan Sills, Iron County, Michigan: Lansing, Mich., Michigan State University M.S. thesis, 81 p.

Frey, F.A., Green, D.H., and Roy, S.D., 1978, Integrated models of basalt petrogenesis—A study of quartz tholeiite to olivine melilites from southeastern Australia utilizing geochemical and experimental petrological data: Journal of Geology, v. 19, p. 463–513.

Frey, F.A., and Prinz, M., 1978, Ultramafic inclusions from San Carlos, Arizona—Petrologic and geochemical data bearing upon their petrogenesis: Earth and Planetary Science Letters, v. 38, p. 129–176.

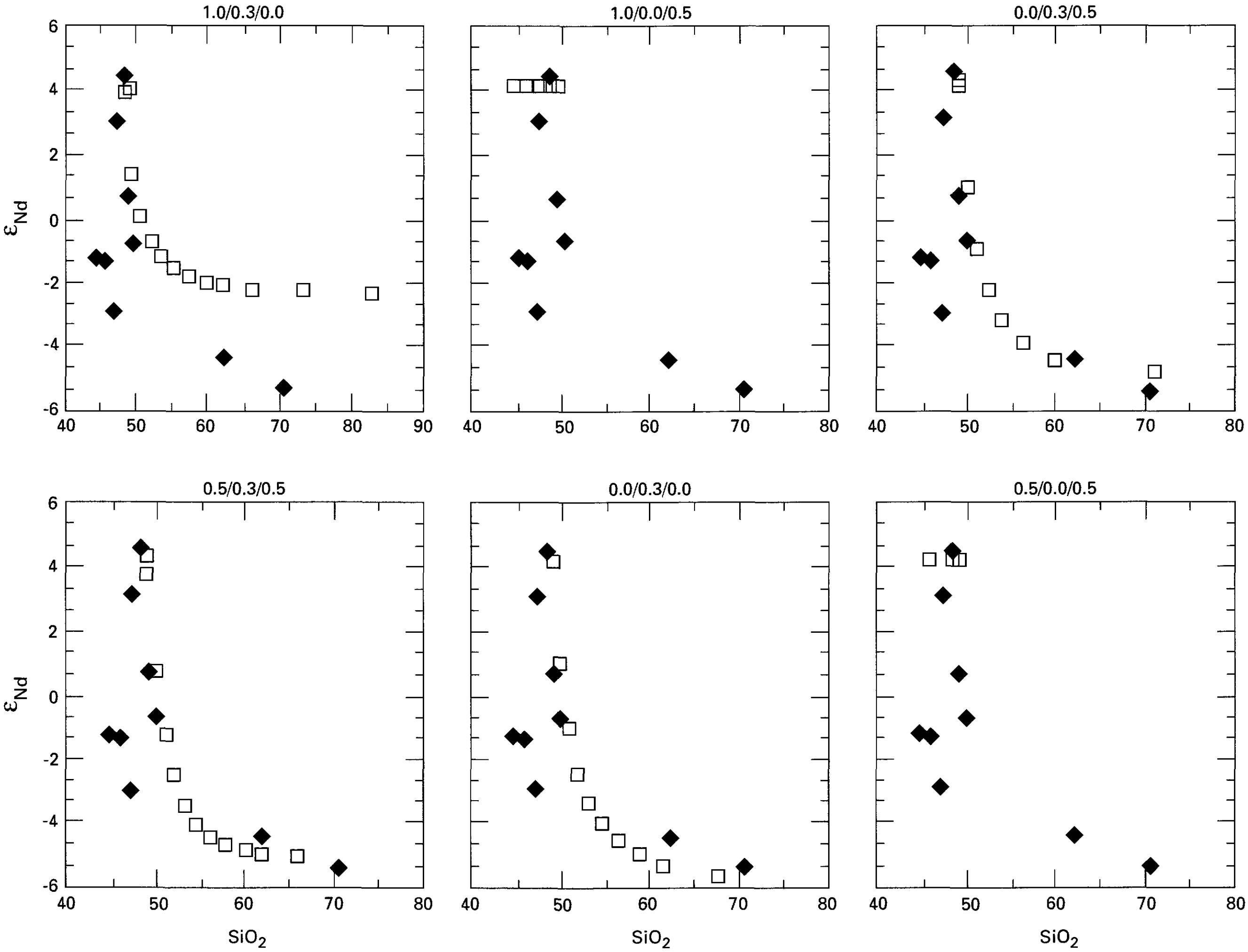


Figure 19. Plots of SiO_2 (weight percent) versus ε_{Nd} (1.87 Ga) for the results of six different configurations of the assimilation–fractional crystallization model TRACE.FOR/ISOTOPE (Beck, 1988; modified from Nielson, 1988, and DePaolo, 1981) (open squares), compared with compositions of the Hemlock volcanic rocks (filled diamonds).

Futa, Kiyoto, 1981, Sm-Nd systematics of a tonalitic augen gneiss and its constituent minerals from northern Michigan: Geochimica et Cosmochimica Acta, v. 45, p. 1245–1249.

Gair, J.E., and Wier, K.L., 1956, Geology of the Kiernan quadrangle, Iron County, Michigan: U.S. Geological Survey Bulletin 1044, 88 p.

Gill, J., 1981, Orogenic andesites and plate tectonics: Berlin-Heidelberg, West Germany, Springer-Verlag, 390 p.

Greenberg, J.K., and Brown, B.A., 1983, Lower Proterozoic volcanic rocks and their setting in the southern Lake Superior district, *in* Medaris, L.G., Jr., ed., Early Proterozoic geology of the Lake Superior region: Geological Society of America Memoir 160, p. 67–84.

Hanson, G.N., 1980, Rare earth elements in petrogenetic studies of igneous systems: Annual Reviews of Earth and Planetary Science, v. 8, p. 371–406.

Hawkesworth, C.J., and Vollmer, R., 1979, Crustal contamination versus enriched mantle—$^{143}Nd/^{144}Nd$ and $^{87}Sr/^{86}Sr$ evidence from the Italian volcanics: Contributions to Mineralogy and Petrology, v. 69, p. 151–165.

Hoffman, P.F., 1987, Early Proterozoic foredeeps, foredeep magmatism, and Superior type iron formations of the Canadian shield, *in* Kroner, A., ed., Proterozoic lithospheric evolution: American Geophysical Union Geodynamics Series, v. 17, p. 85–98.

James, H.L., 1955, Zones of regional metamorphism in the Precambrian of northern Michigan: Geological Society of America Bulletin, v. 66, p. 1455–1487.

Jenkins, R.A., 1973, The geology of Beecher and Pemine Townships, Marinette County, Wisconsin: 19th Annual Institute on Lake Superior Geology, Madison, Wisconsin, Abstracts, p. 15–16.

Kay, R.W., and Senechal, R.G., 1976, The rare earth geochemistry of the Troodos ophiolite complex: Journal of Geophysical Research, v. 81, p. 964–970.

Klasner, J.S., 1984, Gravity models of gneiss domes and a granite pluton in northeastern Wisconsin: 30th Annual Institute on Lake Superior Geology, Wausau, Wisconsin, Abstracts, p. 24.

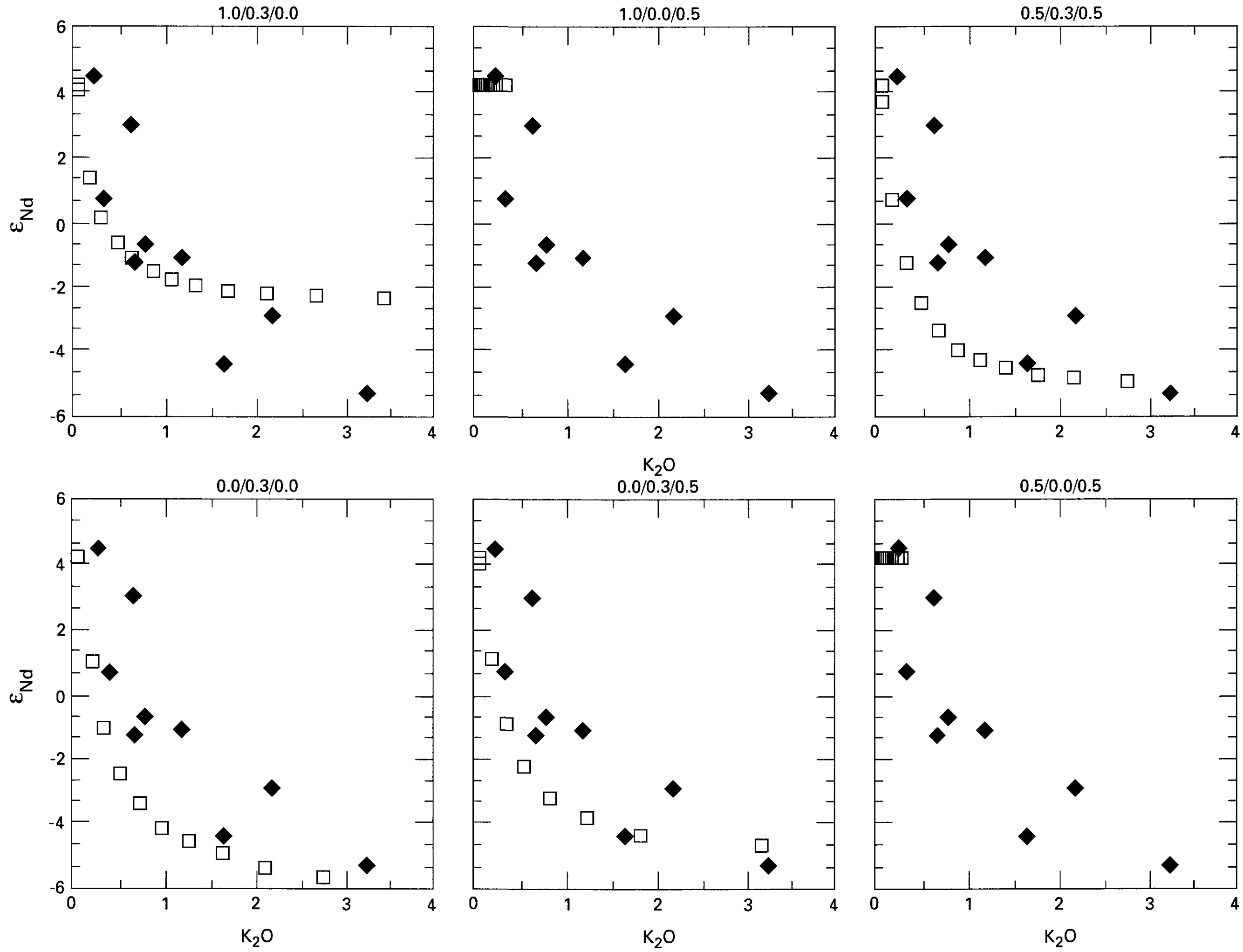


Figure 20. Plots of K_2O (weight percent) versus ε_{Nd} (1.87 Ga) for the results of six different configurations of the assimilation–fractional crystallization model TRACE.FOR/ISOTOPE (Beck, 1988; modified from Nielson, 1988, and DePaolo, 1981) (open squares), compared with compositions of the Hemlock volcanic rocks (filled diamonds).

Klasner, J.S., Ojakangas, R.W., Schulz, K.J., and LaBerge, G.L., 1988, Evidence for development of an early Proterozoic overthrust-nappe system in the Penokean orogen of Northern Michigan: 34th Annual Institute on Lake Superior Geology, Marquette, Michigan, Proceedings and Abstracts, p. 56–57.

LaBerge, G.L., Schulz, K.J., and Myers, P.E., 1984, The plate tectonic history of north central Wisconsin: 30th Annual Institute on Lake Superior Geology, Wausau, Wisconsin, Abstracts, p. 25–26.

Langmuir, C.H., Bender, J.F., Bence, A.E., Hanson, G.N., and Taylor, S.R., 1977, Petrogenesis of basalts from the FAMOUS area—Mid-Atlantic ridge: Earth and Planetary Science Letters, v. 36, p. 133.

Langmuir, C.H., Vocke, R.D., Hanson, G.N., and Hart, S.R., 1977, A general mixing equation with applications to Icelandic basalts: Earth and Planetary Science Letters, v. 37, p. 380–392.

Larue, D.K., 1983, Early Proterozoic tectonics of the Lake Superior region—Tectonostratigraphic terranes near the purported collision zone, *in* Medaris, L.G., Jr., Early Proterozoic geology of the Lake Superior region: Geological Society of America Memoir 160, p. 33–47.

Larue, D.K., and Sloss, L.L., 1980, Early Proterozoic sedimentary basins of the Lake Superior Region: Geological Society of America Bulletin, pt. II, v. 91, p. 1836–1874.

Larue, D.K., and Ueng, W.L., 1985, Florence-Niagara terrane—An early Proterozoic accretionary complex, Lake Superior region: Geological Society of America Bulletin, v. 96, p. 1179–1187.

Mahoney, J.J., 1984, Isotopic and chemical studies of the Deccan and Rajmahal traps, India—Mantle sources and petrogenesis: San Diego, Calif., University of California Ph. D. thesis, 189 p.

Mahoney, J.J., Macdougall, J.D., and Lugmair, G.W., 1984, Origin of contemporaneous tholeiitic and K-rich alkalic lavas—A case study from the northern Deccan Plateau, India: Earth and Planetary Science Letters, v. 63, 305 p.

Mahoney, J.J., Macdougall, J.D., Lugmair, G.W., Murali, A.V., Sankar Das, M., and Gopalan, K., 1981, Origin of the

Deccan Trap flows at Mahabaleshwar inferred from Nd and Sr isotopic and chemical evidence: Earth and Planetary Science Letters, v. 60, p. 47–60.

McDougall, I., 1976, Geochemistry and origin of basalts of the Columbia River Group, Oregon and Washington: Geological Society of America Bulletin, v. 87, p. 777–792.

McLennan, S.M., 1979, Rare earth elements in Huronian (Lower Proterozoic) sedimentary rocks—Composition and evolution of the post-Kenoran upper crust: Geochimica et Cosmochimica Acta, v. 43, p. 375.

Moorbath, S., and Thompson, R.N., 1980, Strontium isotope geochemistry and petrogenesis of the early Tertiary lava pile of the Isle of Skye, Scotland, and other basic rocks of the British Tertiary province—An example of magma crust interaction: Journal of Petrology, v. 21, p. 295–321.

Morey, G.B., Sims, P.K., Cannon, W.F., Mudrey, M.G., Jr., and Southwick, D.L., 1982, Geologic map of the Lake Superior region—Minnesota, Wisconsin, and northern Michigan: Minnesota Geological Survey State Map Series S–13, scale 1:1,000,000.

Nielson, R.L., 1985, EQUIL.FOR—A program for modelling low pressure differentiation processes in natural mafic magma bodies: Computers and Geosciences, v. 11, p. 531–546.

______ 1988, TRACE.FOR—A program for the calculation of combined major and trace-element liquid lines of descent for natural magmatic systems: Computers and Geosciences, v. 14, p. 15–35.

Nier, A.O., Murthy, V.R., and Dosso, L., 1983, Minmass—A small double-focusing mass spectrometer for geochemical research [abs.]: Eos, v. 64, no. 18, p. 334.

Nier, A.O., and Schlutter, D.J., 1985, High performance double focusing mass spectrometer: Reviews of Scientific Instruments, v. 56, p. 214–219.

Othman, B.D., Polve, M., and Allegre, C.J., 1984, Nd-Sr isotopic composition of granulites and constraints on the evolution of the lower continental crust: Nature, v. 307, p. 510–515.

Pallister, J.S., and Knight, R.J., 1981, Rare earth element geochemistry of the Samail Ophiolite near Ibra, Oman: Journal of Geophysical Research, v. 86, p. 2673–2697.

Pearce, J.A., 1982, Trace element characteristics of lavas from destructive plate boundaries, *in* Thorp, R.S., ed., Andesites and related rocks: New York, John Wiley, 724 p.

Pearce, J.A., and Cann, J.R., 1973, Tectonic setting of basic volcanics determined using trace element analyses: Earth and Planetary Science Letters, v. 19, p. 290–300.

Pearce, J.A., and Norry, M.J., 1979, Petrogenetic implications of Ti, Zr, Y, and Nb variations in volcanic rocks: Contributions to Mineralogy and Petrology, v. 69, p. 33–47.

Schulz, K.J., 1984, Early Proterozoic Penokean igneous rocks of the Lake Superior region—Geochemistry and tectonic implications: 30th Annual Institute on Lake Superior Geology, Wausau, Wisconsin, Abstracts, p. 65–66.

Schulz, K.J., Sims, P.K., and Morey, G.B., in press, Tectonic synthesis of the Penokean orogen, *in* Reed, J.C., Jr., and others, eds., The geology of North America, volume C.

Shirey, S.B., and Hanson, G.N., 1987, Mantle heterogeneity and crustal recycling in Archean granite-greenstone belts—Evidence from Nd isotopes and trace elements in the Rainy Lake area, Superior Province, Ontario, Canada: Geochimica et Cosmochimica Acta, v. 50, p. 2631–2651.

Sims, P.K., 1990, Geologic map of Precambrian rocks of Iron Mountain and Escanaba 1°×2° quadrangles, northeastern Wisconsin and northwestern Michigan: U.S. Geological Survey Miscellaneous Investigations Series Map I–2056, scale 1:250,000.

Sims, P.K., and Peterman, Z.E., 1980, Geology and Rb-Sr ages of lower Proterozoic granitic rocks, northern Wisconsin, *in* Morey, G.B., and Hanson, G.N., eds., Selected studies of Archean gneisses and lower Proterozoic rocks, southern Canadian Shield: Geological Society of America Bulletin Special Paper 182, p. 139–146.

Sims, P.K., Peterman, Z.E., and Schulz, K.J., 1985, The Dunbar gneiss-granitoid dome—Implications for early Proterozoic evolution of northern Wisconsin: Geological Society of America Bulletin, v. 96, p. 1101–1112.

Sims, P.K., Van Schmus, W.R., Schulz, K.J., and Peterman, Z.E., 1989, Tectono-stratigraphic evolution of the Early Proterozoic Wisconsin magmatic terranes of the Penokean orogen: Canadian Journal of Earth Sciences, v. 26, p. 2145–2158.

Southwick, D.L., Morey, G.B., and McSwiggen, P.L., 1988, Geologic map (scale 1:250,000) of the Penokean orogen, central and eastern Minnesota, and accompanying text: Minnesota Geological Survey Report of Investigations 37, 25 p.

Steiger, R.H., and Jäger, Emile, 1977, Subcomission on geochronology—Convention on the use of decay constants in geo- and cosmochronology: Earth and Planetary Science Letters, v. 36, p. 359–371.

Taylor, R., and McLennan, S., 1985, The continental crust—Its composition and evolution: Oxford, England, Blackwell Scientific Publications, 312 p.

Thompson, R.N., 1982, Geochemistry and magma genesis of rocks of the British Tertiary Province, *in* Sutherland, D.S., ed., Igneous rocks of the British Isles: New York, John Wiley, 645 p.

Thompson, R.N., Dickin, A.P., Gibson, I.L., and Morrison, M.A., 1982, Elemental fingerprints of isotopic contamination of Hebridean Paleocene mantle-derived magmas by Archean sial: Contributions to Mineralogy and Petrology, v. 79, p. 159–168.

Thorp, R.S., Potts, P.J., and Sarre, M.B., 1977, Rare earth evidence concerning the origin of granites of the Isle of Skye, Northwest Scotland: Earth and Planetary Science Letters, v. 36, p. 111–120.

Ueng, W.L., Fox, T.P., Larue, D.K., and Wilband, J.T., 1988, Geochemistry and petrogenesis of the early Proterozoic Hemlock volcanic rocks and the Kiernan sills, southern Lake Superior region: Canadian Journal of Earth Sciences, v. 25, p. 528–546.

Ueng, W.L., and Larue, D.K., 1988, The early Proterozoic structural and tectonic history of the southcentral Lake Superior region: Tectonics, v. 7, p. 369–388.

Van Schmus, W.R., 1976, Early and middle Proterozoic history of the Great Lakes area, North America: Philosophical

Transactions of the Royal Society of London Series A, v. 280A, p. 605–628.

——— 1980, Chronology of igneous rocks associated with the Penokean Orogeny in Wisconsin, *in* Morey, G.B., and Hanson, G.N., eds., Selected studies of Archean gneisses and lower Proterozoic rocks, Southern Canadian Shield: Geological Society of America Special Paper 182, p. 159–168.

Van Schmus, W.R., and Anderson, J.L., 1977, Gneiss and migmatite of Archean age in the Precambrian basement of central Wisconsin, U.S.A.: Geology, v. 5, p. 45–48.

Vollmer, R., 1976, Rb-Sr and U-Th-Pb systematics of alkaline rocks—The alkaline rocks of Italy: Geochimica et Cosmochimica Acta, v. 40, p. 283–295.

Wier, K.L., 1967, Geology of the Kelso Junction quadrangle, Iron County Michigan: U.S. Geological Survey Bulletin 1226, 47 p.

☆U.S. GOVERNMENT PRINTING OFFICE: 1991-673-049/46014

SELECTED SERIES OF U.S. GEOLOGICAL SURVEY PUBLICATIONS

Periodicals

Earthquakes & Volcanoes (issued bimonthly).
Preliminary Determination of Epicenters (issued monthly).

Technical Books and Reports

Professional Papers are mainly comprehensive scientific reports of wide and lasting interest and importance to professional scientists and engineers. Included are reports on the results of resource studies and of topographic, hydrologic, and geologic investigations. They also include collections of related papers addressing different aspects of a single scientific topic.

Bulletins contain significant data and interpretations that are of lasting scientific interest but are generally more limited in scope or geographic coverage than Professional Papers. They include the results of resource studies and of geologic and topographic investigations; as well as collections of short papers related to a specific topic.

Water-Supply Papers are comprehensive reports that present significant interpretive results of hydrologic investigations of wide interest to professional geologists, hydrologists, and engineers. The series covers investigations in all phases of hydrology, including hydrogeology, availability of water, quality of water, and use of water.

Circulars present administrative information or important scientific information of wide popular interest in a format designed for distribution at no cost to the public. Information is usually of short-term interest.

Water-Resources Investigations Reports are papers of an interpretive nature made available to the public outside the formal USGS publications series. Copies are reproduced on request unlike formal USGS publications, and they are also available for public inspection at depositories indicated in USGS catalogs.

Open-File Reports include unpublished manuscript reports, maps, and other material that are made available for public consultation at depositories. They are a nonpermanent form of publication that may be cited in other publications as sources of information.

Maps

Geologic Quadrangle Maps are multicolor geologic maps on topographic bases in 7 1/2- or 15-minute quadrangle formats (scales mainly 1:24,000 or 1:62,500) showing bedrock, surficial, or engineering geology. Maps generally include brief texts; some maps include structure and columnar sections only.

Geophysical Investigations Maps are on topographic or planimetric bases at various scales; they show results of surveys using geophysical techniques, such as gravity, magnetic, seismic, or radioactivity, which reflect subsurface structures that are of economic or geologic significance. Many maps include correlations with the geology.

Miscellaneous Investigations Series Maps are on planimetric or topographic bases of regular and irregular areas at various scales; they present a wide variety of format and subject matter. The series also includes 7 1/2-minute quadrangle photogeologic maps on planimetric bases which show geology as interpreted from aerial photographs. Series also includes maps of Mars and the Moon.

Coal Investigations Maps are geologic maps on topographic or planimetric bases at various scales showing bedrock or surficial geology, stratigraphy, and structural relations in certain coal-resource areas.

Oil and Gas Investigations Charts show stratigraphic information for certain oil and gas fields and other areas having petroleum potential.

Miscellaneous Field Studies Maps are multicolor or black-and-white maps on topographic or planimetric bases on quadrangle or irregular areas at various scales. Pre-1971 maps show bedrock geology in relation to specific mining or mineral-deposit problems; post-1971 maps are primarily black-and-white maps on various subjects such as environmental studies or wilderness mineral investigations.

Hydrologic Investigations Atlases are multicolored or black-and-white maps on topographic or planimetric bases presenting a wide range of geohydrologic data of both regular and irregular areas; principal scale is 1:24,000 and regional studies are at 1:250,000 scale or smaller.

Catalogs

Permanent catalogs, as well as some others, giving comprehensive listings of U.S. Geological Survey publications are available under the conditions indicated below from the U.S. Geological Survey, Books and Open-File Reports Section, Federal Center, Box 25425, Denver, CO 80225. (See latest Price and Availability List.)

"Publications of the Geological Survey, 1879- 1961" may be purchased by mail and over the counter in paperback book form and as a set of microfiche.

"Publications of the Geological Survey, 1962- 1970" may be purchased by mail and over the counter in paperback book form and as a set of microfiche.

"Publications of the U.S. Geological Survey, 1971- 1981" may be purchased by mail and over the counter in paperback book form (two volumes, publications listing and index) and as a set of microfiche.

Supplements for 1982, 1983, 1984, 1985, 1986, and for subsequent years since the last permanent catalog may be purchased by mail and over the counter in paperback book form.

State catalogs, "List of U.S. Geological Survey Geologic and Water-Supply Reports and Maps For (State)," may be purchased by mail and over the counter in paperback booklet form only

"Price and Availability List of U.S. Geological Survey Publications," issued annually, is available free of charge in paperback booklet form only.

Selected copies of a monthly catalog "New Publications of the U.S. Geological Survey" available free of charge by mail or may be obtained over the counter in paperback booklet form only. Those wishing a free subscription to the monthly catalog "New Publications of the U.S. Geological Survey" should write to the U.S. Geological Survey, 582 National Center, Reston, VA 22092.

Note.--Prices of Government publications listed in older catalogs, announcements, and publications may be incorrect. Therefore, the prices charged may differ from the prices in catalogs, announcements, and publications.