

## GRANITOIDS OF NORTHERN VICTORIA LAND, ANTARCTICA: IMPLICATIONS OF CHEMICAL AND ISOTOPIC VARIATIONS TO REGIONAL CRUSTAL STRUCTURE AND TECTONICS

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**ABSTRACT.** The pre-Devonian basement of northern Victoria Land (NVL), Antarctica, may be divided into three geological terranes separated by north-northwest-trending high-angle faults. The Wilson Terrane (WT) in the west is characterized by amphibolite-grade, continentally-derived metasediments of late Precambrian(?) age. The Bowers Terrane (BT) in central NVL has been interpreted as a Cambrian volcanic arc assemblage. The Robertson Bay Terrane (RBT) in the east is underlain by a folded lower greenschist facies graywacke-shale (turbidite) sequence of early Paleozoic age.

Two spatially and temporally different groups of granitoids are present, and each displays distinct and different compositional polarity. The Cambro-Ordovician Granite Harbour Intrusives (GHI) are confined to the WT and consist of various lithologies which are exclusively I-type in the east and predominantly S-type in the west. First order trend surface analysis of major and trace elements is compatible with increasing involvement of peraluminous metasedimentary (old continental crustal) material in production of GHI from east to west and supports an interpretation of GHI as a plutonic belt on the margin of the East Antarctic Craton (EAC). Nd and Sr isotopic data corroborate involvement of old material. The Devonian Admiralty Intrusives (AI) are found only in BT and RBT and consist predominantly of I-type tonalites, granodiorites, and monzogranites. Pronounced compositional polarity (major and trace elements) indicate increasing involvement of old crustal material from south to north. Regular variations of initial  $\epsilon_{Nd}$  and  $\epsilon_{Sr}$  corroborate this interpretation. These data do not support a model of emplacement of AI in their present setting on the EAC margin.

The isotopic compositions as well as the major and trace element character of the two groups of granites indicate that a major discontinuity in the lower crust coincides with the boundary between WT and BT + RBT. The compositional polarity in AI may be interpreted as evidence that BT and RBT are allochthonous terranes. Details of the juxtaposing of the three terranes are not clear, but assembly of BT + RBT with WT is inferred to have occurred after

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**Admiralty plutonism and is constrained to have occurred before deposition of the Beacon Supergroup in NVL (basal units are presumed to be Permian).**

## INTRODUCTION

This paper summarizes the results of a comprehensive regional reconnaissance investigation of granitoids of northern Victoria Land, Antarctica. The petrographic and chemical data discussed here are the result of studies by Wyborn (1981; unpub. data), Borg, Stump, and Holloway (1986), and Stump, Borg, and Armstrong (unpublished) which include samples of granitoids collected from outcrops scattered over the entire 78,000 km<sup>2</sup> area of northern Victoria Land. In addition, new Sm-Nd and Rb-Sr isotopic data for some of these granitoids are presented and discussed. This paper is a direct result of a Ph.D. dissertation by Borg (ms, 1984), and its goal is to synthesize the granitoid data into a coherent regional picture in order to address questions relating to their origin and tectonic setting.

Modern geologic investigations in the Transantarctic Mountains began in the late 1950's during activities associated with the IGY. From that time through the late 1970's, work on the granitoids was generally restricted to reconnaissance geologic mapping and petrographic descriptions. In northern Victoria Land, mainly under the auspices of the United States Antarctic Research Program (USARP) and the New Zealand Antarctic Research Programme (NZARP), many field parties contributed information on the location and petrography of the granitoids. This work was reported by Harrington and others (1964, 1967), LeCouteur and Leitch (1964), Gair (1964, 1967), Nathan and Schulte (1968), Riddoils and Hancox (1968), Skinner and Ricker (1968), Crowder (1968), Sturm and Carryer (1970), and Laird, Andrews, and Kyle (1974), among others, and was summarized by Gair and others (1969) in the first geologic map of northern Victoria Land. Aside from this basic mapping, only a few chemical analyses and several isotopic ages had been produced. Nevertheless, the limited age data provided the basis for the distinction of two groups of granitoids in the region. These were the lower Paleozoic Granite Harbour Intrusives of Gunn and Warren (1962) and the middle Paleozoic Admiralty Intrusives of Harrington (1958), as redefined by Grindley and Warren (1964).

In the early 1980's, more comprehensive studies of granites were begun, first under the auspices of the German Antarctic North Victoria Land Expedition (GANOVEX I: Wyborn, 1981) and then under USARP (Stump and others, 1982; Borg, ms, 1984; Borg, Stump, and Holloway, 1986). These studies have provided a wealth of new information on the granitoids allowing consideration on a regional scale.

The study area, shown in figures 1 and 2, occupies the northernmost part of the Transantarctic Mountains in the Ross Sea sector. The central and eastern parts are the remains of a broad upland which has been severely dissected by alpine and large valley glaciers which drain north into the southern Pacific Ocean and east and southeast into the Ross Sea. Although

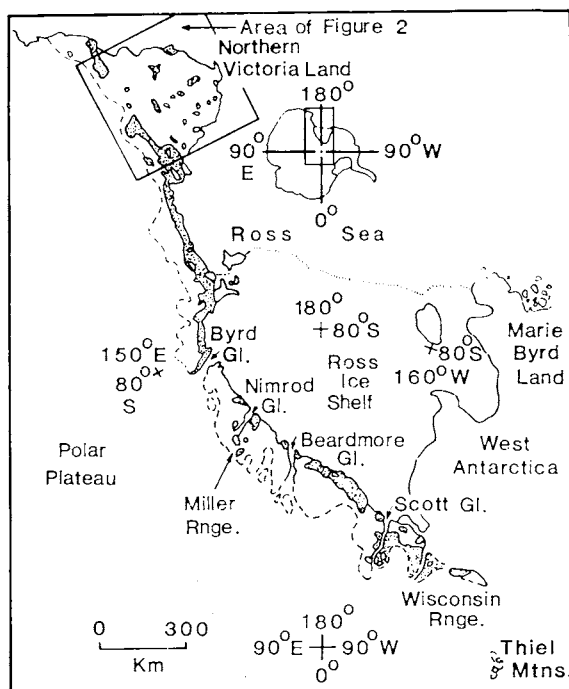
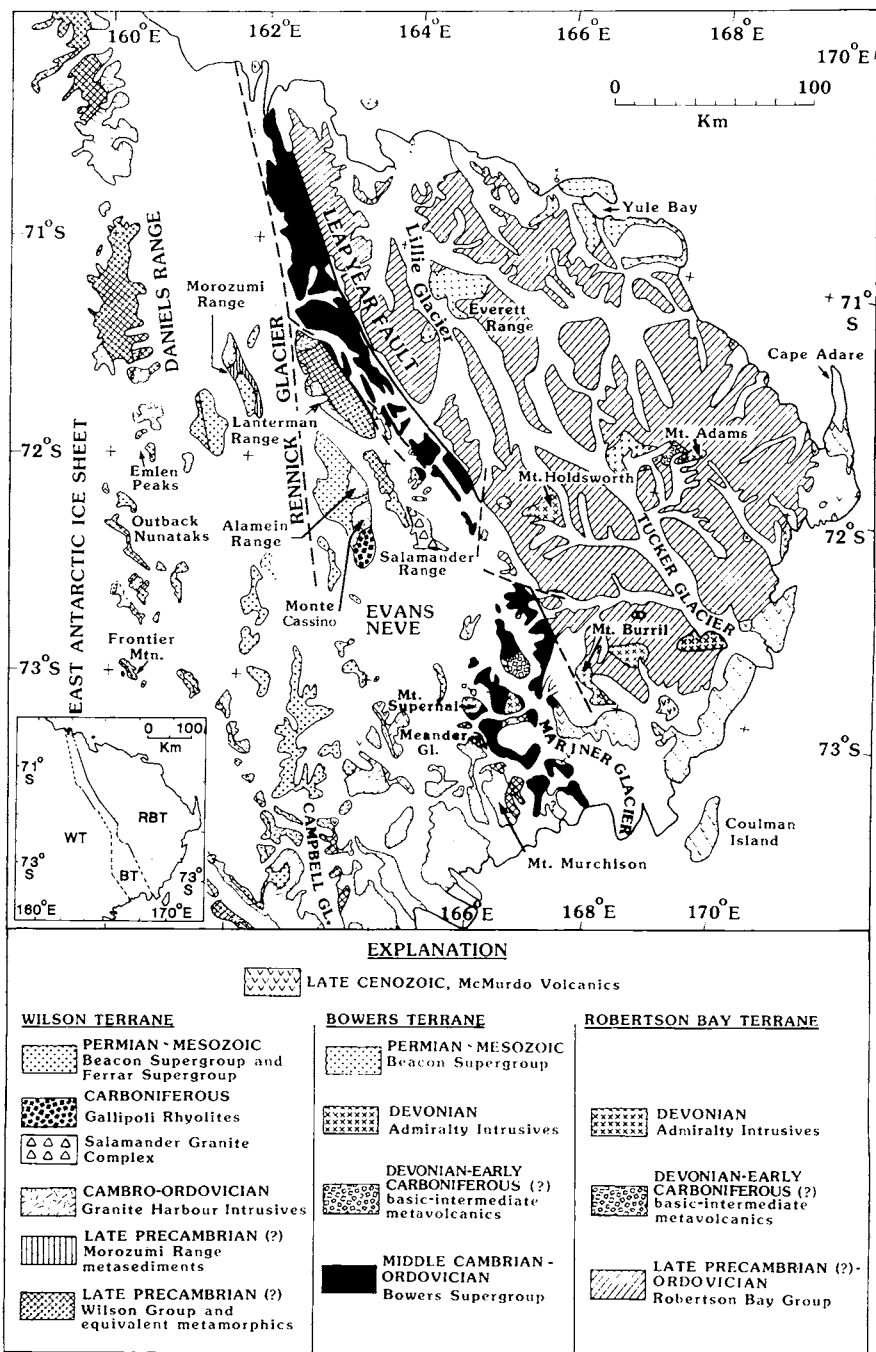


Fig. 1. Location map of the Transantarctic Mountains. Areas of granitoid outcrop are stippled.

this area may have supported a more extensive ice plateau in the past, only a small ice sheet, the Evans Névé, remains today. The western margin, which borders the Polar Plateau, has been dissected by relatively small plateau outlet glaciers which coalesce and move north (to the southern Pacific) via the Rennick Glacier or south (to the Ross Sea) via the Campbell Glacier. The vast majority of the area is covered by ice and snow with less than 5 percent being exposed bedrock. Outcrops exist primarily as ridge lines and cliff faces, and fresh (unweathered) rock is easily obtained.

#### REGIONAL GEOLOGY

Northern Victoria Land (NVL) occupies an important position with respect to Gondwana geology, because it lies at the former juncture between southeastern Australia and the Transantarctic Mountains. Thus, a proper understanding of the geology of this area is imperative to regional interpretations. NVL is conveniently divided into three distinct geologic regions or terranes (Stump and others, 1983b; Weaver, Bradshaw, and Laird, 1984; Tessensohn, 1984) which are referred to here as the Wilson, Bowers, and Robertson Bay Terranes. These regions are defined by different groups of pre-late Paleozoic metasedimentary basement rocks and are shown in figure 2.



In the west, toward the East Antarctic Craton (EAC), is the Wilson Terrane (WT). This region is characterized by amphibolite grade schists, gneisses, and minor marble. Clastic lithologies, ranging from siltstones to conglomerates, are dominant. The rocks have been complexly deformed during two and perhaps three folding events (Wodzicki, Bradshaw, and Laird, 1982; Kleinschmidt and Skinner, 1981). These rocks are referred to as the Wilson Group (WG) as defined by Dow and Neall (1972, 1974) and include the Rennick Schist of Gair (1964). The precise age of these rocks has been elusive but is constrained to be older than about 500 to 550 Ma (Gair and others, 1969; Adams and others, 1982). Grindley and Warren (1964) suggested that these rocks are correlative with the Precambrian Nimrod Group, a possibly cratonic assemblage in the central Transantarctic Mountains, but the possibility exists that they are correlatives of the Beardmore Group (Ross Supergroup) of the central Transantarctic Mountains (see Stump, ms and 1982, and Grindley, 1981, for definition and description of the Beardmore Group). The question of precise correlation remains unresolved; however, an important interpretation, which seems to be held by all parties, is that WG represents a phase of geosynclinal sedimentation on the margin of the Antarctic Craton during late(?) Precambrian or Early Cambrian time.

Also present in the Morozumi Range of WT are greenschist facies meta-turbidites. These rocks had been correlated with the Robertson Bay Group of the Robertson Bay Terrane (see below) in previous studies (for example, Gair and others, 1969; Tessensohn and others, 1981). However, recent work has shown that there is no evidence to support this correlation (Bradshaw and Laird, 1983). Indeed, the fact that Wyborn (1983) found that chromites, possibly derived from volcanics within the Bowers Supergroup of the Bowers Terrane, are a significant component of the Robertson Bay Group, but are absent from the turbidites in the Morozumi Range, provides further evidence against correlation. Finally, Cambro-Ordovician fossils described by Wright, Ross, and Repetski (1984) from the Robertson Bay Group indicate that it was being deposited about the same time that the Morozumi Range turbidites were being intruded by a Granite Harbour pluton (see below). Thus, WT metamorphic rocks comprise a lithologic province distinct from Bowers and Robertson Bay Terranes.

The WT experienced extensive plutonism in Cambrian to early Ordovician time. Granitoids, along with associated migmatites and pegmatites, were emplaced in WT during this time and are referred to as the Granite Harbour Intrusives (GHI) (Gunn and Warren, 1962; Grindley and Warren, 1964; Gair, 1964, 1967; Nathan and Schulte, 1968; Sturm and Carryer, 1970; Nathan, 1971a, b; Tessensohn and others, 1981). Sys-

← Fig. 2. Geologic sketch map of northern Victoria Land. Compiled from maps in Gair and others (1969), Stump and others (1983b), Borg (ms, 1984), Borg, Stump, and Holloway (1986), Kleinschmidt, Roland, and Schubert (1984), Tessensohn (1984), and Weaver, Bradshaw, and Laird (1984). Inset map shows the relationship of the Wilson Terrane (WT), Bowers Terrane (BT), and Robertson Bay Terrane (RBT).

tematic descriptions are given by Borg (ms, 1984), Borg, Stump, and Holloway (1986), and Wyborn (1981). Rock types include metaluminous, often hornblende-bearing, tonalites and granodiorites as well as peraluminous, 2-mica  $\pm$  garnet-bearing, granodiorites and granites (rock nomenclature follows Streckheisen, 1976). Borg (ms, 1984) and Borg, Stump, and Holloway (1986) summarized isotopic data and concluded that the best maximum estimate for the age of magma generation of GHI is  $\approx$ 550 Ma. Furthermore, they conclude that emplacement and final cooling occurred by  $\approx$ 500 to  $\approx$ 480 Ma. These are part of a belt of Cambro-Ordovician granitoids which intrude Ross Supergroup (and older rocks) throughout the Transantarctic Mountains. The magmatism occurred as syn- to post-tectonic intrusions associated with the Ross Orogeny (Faure and others, 1979; Adams, Gabites, and Grindley, 1982; Borg, ms, 1980; 1983; Grindley, 1981; Tessensohn, 1981). K-Ar systems in the WG were reset during this time (Adams and others, 1982).

The Bowers Terrane (BT) is a northwest-trending, fault-bounded region in the central part of NVL. The Bowers Supergroup (BSG), exposed in this terrane, contains a variety of lithologies divided into three groups, a lower volcanic and volcanoclastic unit, a middle unit of Middle to Late Cambrian marine sediments, and an upper unit of clastic fluvial sediments, mainly quartzite and conglomerate (Laird, Cooper, and Jago, 1977; Laird and others, 1972; Laird, Bradshaw, and Wodzicki, 1982; Laird and Bradshaw, 1983; Laird, 1981; Cooper and others, 1976, 1983). Recent syntheses of fossil data and stratigraphic relations by Cooper and others (1983) and Mortimer, Schmidt-Thome, and Tessensohn (1984) indicate deposition of the latter group of rocks during Late Cambrian to Early Ordovician time. The BSG has been isoclinally folded about northwest-trending axes (approximately parallel to the elongation of the terrane). This terrane has been interpreted as representing a Cambrian island arc complex (Weaver, Bradshaw, and Laird, 1984), but its relationship to the other rock groups (and terranes) in NVL has been somewhat speculative.

Robertson Bay Terrane (RBT) is defined by the presence of an extensive graywacke-shale sequence known as the Robertson Bay Group (RBG), which crops out in the eastern part of NVL (Rastall and Priestly, 1921; Harrington and others, 1964; LeCouteur and Leitch, 1964). These rocks have been interpreted as turbidites deposited in a marine fan complex (Crowder, 1968; Wright, 1981; Field and Findlay, 1983), and studies of chromites by Wyborn (1981) suggest these rocks may have developed in association with the Bowers Supergroup. Recent fossil discoveries indicate a latest Cambrian or earliest Ordovician time of deposition for at least part of this sequence (Wright, Ross, and Repetski, 1984; Burrett and Findlay, 1984). These rocks have been tightly folded about northwest-trending axes (Crowder, 1968; Bradshaw, Laird, and Wodzicki, 1982; Findlay and Field, 1983). There are no known correlatives of RBG farther south in the Transantarctic Mountains. Wade and Couch (1982) and Bradshaw, Andrews, and Field (1983) considered correlation with the Swanson Formation of Marie Byrd Land, but they concluded that, while

there are many similarities between the units and they may both be portions of a continuous geologic province, precise correlation is unwarranted. Based on K-Ar geochronology, Adams and others (1982) inferred that metamorphism and folding(?) of RBG occurred between 400 and 500 Ma.

In addition to distinct lithologies in the terranes, some structural differences exist as well. While WT shows evidence of complex, multiple deformation and high-grade (amphibolite) metamorphism (Kleinschmidt and Skinner, 1981), BT and RBT regionally show only lower greenschist facies metamorphism and relatively simple folding (Bradshaw, Laird, and Wodzicki, 1982; Laird and Bradshaw, 1983; Findlay and Field, 1983).

All three terranes contain evidence for mid- to late-Paleozoic magmatism (Grindley and Oliver, 1983). Within BT and RBT, a group of mid-Paleozoic, granitoid plutons called Admiralty Intrusives (AI) intrude the metamorphic rocks of BSG and RBG (Harrington, 1958; Grindley and Warren, 1964; LeCouteur and Leitch, 1964; Gair and others, 1969; Tessensohn and others, 1981; and many others). Field relations suggest that the granitoids were emplaced as strongly discordant, epizonal plutons (Borg, ms, 1984). Furthermore, they appear to be presently exposed at a similar structural level throughout the region. Recent work on AI (Wyborn, 1981; Borg, ms, 1984; Borg, Stump, and Holloway, 1986) shows this group to consist of a rather restricted variety of rock types including metaluminous (often hornblende-bearing) tonalites, granodiorites, and monzogranites, with only four samples mildly peraluminous (CIPW normative corundum = 1-1.2 wt. percent). Borg (ms, 1984) and Borg, Stump, and Holloway (1986) have summarized radiometric data and conclude that emplacement and cooling of AI probably occurred between  $\approx 390$  and  $\approx 360$  Ma, with granitoid generation ages slightly older. For present purposes, an age of 400 Ma is taken as the best estimate of the time of magma generation of AI.

Some authors believe that AI are also found in WT (Stump and others, 1983b; Tessensohn, 1984; Weaver, Bradshaw, and Laird, 1984; Bradshaw, Weaver, and Laird, 1985), but there is no evidence that requires this view. The most recent arguments favoring AI in WT have been reviewed by Tessensohn (1984) and pertain to exposures of granite in three areas: southern Salamander Range, Mt. Camelot in the Alamein Range, and Mt. Supernal (fig. 2). Because of the important ramifications of whether or not AI occur in WT, a careful review of relevant data is warranted. The Salamander Granite Complex (Borg, Stump and Holloway, 1986; formerly the Salamander Granodiorite of Laird, Andrews and Kyle, 1974) is a hypabyssal granite pluton of Carboniferous age exposed in the southern Salamander Range, near the WT-BT boundary. Tessensohn (1984) infers that it is emplaced into both terranes, crosscutting the fault boundary. Two points are important with regard to this interpretation. First, no contacts with country rock are exposed, and so there is no hard evidence for the geologic setting of this pluton. However, the presence of a Ferrar sill in the granite suggests an affinity with WT. Second, this granitoid is considered to be distinct from AI on the basis of petro-

graphic and chemical characteristics as well as being somewhat younger (Borg, Stump and Holloway, 1986), and so its geologic setting is probably irrelevant to a regional discussion of AI. Clearly, the geologic setting of the Salamander Granite Complex is important to the regional evolution of NVL, as discussed later, but it is not evidence that AI are terrane "stitching" granites. The granitoid at Mt. Camelot has been inferred to be of Admiralty age on the basis of one K-Ar biotite date reported by Dow and Neall (1974). However, the granitoids in this area have subsequently yielded Rb-Sr mineral isochrons and a 3-point whole-rock isochron consistent with a Granite Harbour age (Borg, ms, 1984; Stump, Borg, and Armstrong, unpublished). Also, the K-Ar dated sample is from an outcrop not far from an exposed Jurassic Ferrar sill, and the base of the sill projects to a position about 20 m above the sample location. Thus, the K-Ar date would appear to be a product of partial Ar loss during the Jurassic. The granodiorite at Mt. Supernal lies near the WT-BT boundary (compare fig. 2 with the geologic map in Tessensohn, 1984), and Tessensohn (1984) infers that it resides at least partly within WG rocks, because the terrane boundary trends toward the pluton. However, at its southwest margin, where WG rocks should occur if Tessensohn (1984) is correct, it intrudes lower greenschist facies metavolcanics of mafic to intermediate composition (Borg, ms, 1984). These volcanics may be part of the BSG, or they may be correlative with similar volcanics at Lawrence Peaks and Mt. Black Prince. Based on interpretations made by Findlay and Jordan (1984), the former correlation is preferred. The important point, however, is that the metavolcanic lithologies intruded by the Supernal Granodiorite are not known from WG, and so there is no geologic basis for placing this granitoid in WT. The fact that the WT-BT boundary to the south of Mt. Supernal trends in a very general way toward this granitoid is insufficient evidence on which to claim that the pluton is in WT. In summary, then, we conclude that AI are a feature unique to BT and RBT.

Mid- to late-Paleozoic volcanism in BT is represented by andesite, rhyolite, and pyroclastics of the Lawrence Peak Volcanics (Grindley and Oliver, 1983) and in RBT by basaltic-andesites, andesites, and dacites of the Black Prince Volcanics (Borg, unpub. data; Grindley and Oliver, 1983; Findlay and Field, 1982). Findlay and Jordan (1984) have described these rocks as being similar to Andean volcanics and have interpreted fossils and K-Ar data as indicative of a latest Devonian to Carboniferous age.

In WT, Carboniferous magmatic activity is represented by the Gallipoli Rhyolites, which rest unconformably on Granite Harbour granitoids (Stump and others, 1982; Grindley and Oliver, 1983), and by the Salamander Granite Complex (SGC). The Gallipoli Rhyolites are composed primarily of silicic, ash-flow tuffs with a minor, intermediate composition component. The SGC represents hypabyssal magmatism, perhaps related to volcanism, but it cannot be co-magmatic with the Gallipoli Rhyolites specifically as had been suggested by Laird, Andrews, and Kyle (1974), because the Rb and Sr values of the Gallipoli Rhyolites do not lie on or near the Rb-Sr fractionation trend observed in the SGC (Borg, ms, 1984;

Borg, Stump, and Holloway, 1986). Thus, these two units represent distinct occurrences of Carboniferous magmatism in WT.

Relationships between the three groups of volcanics and the SGC are largely speculative. Despite the similar (but ill-defined) time frame occupied by these rock groups, there is no requirement that any or all are genetically related or part of a continuous magmatic province. The two main groups of Paleozoic plutonic rocks are the subject of this paper; however, the nature and geologic setting of the volcanics, as well as the tectonic setting of the SGC, remain important aspects of the geology of NVL which warrant further research.

A period of erosion during the late Paleozoic produced the sub-Beacon peneplain which is extensively exposed in WT but is not widely known from BT or RBT. During Permian and Triassic time, glaciogenic, fluvial, and lacustrine sediments of the Beacon Supergroup were deposited (Barrett, Grindley, and Webb, 1972). These rocks are found throughout WT, but they are not found in RBT. Beacon rocks have, however, been described as depositionally overlying the BSG at one locality on the western side of the Leitch Massif (fig. 2; 71°55'S, 164°30'E) (Tessensohn and others, 1981).

Basaltic sills and flows of the Ferrar Group were emplaced during the Jurassic (Hamilton, 1965). These rocks are widespread in WT but have not been clearly identified in either BT or RBT.

Late Cenozoic alkaline volcanics (primarily phonolitic lavas and breccias) of the Hallett Volcanic province are exposed in a belt that runs along the eastern coast and bends into the southeastern portion of NVL, crossing the three older terranes (Hamilton, 1972; Armstrong, 1978). Recently, a 9 Ma hypabyssal alkali-granite pluton was discovered in the volcanic province at the mouth of the Meander Glacier (Stump and others, 1983a; Borg, Stump, and Holloway, 1986).

Although the existence and general character of the three Precambrian(?) to Paleozoic basement groups have been known since the 1960's (LeCouteur and Leitch, 1964; Gair, 1964; Crowder, 1968; Riddols and Hancox, 1968; Nathan and Skinner, 1971), it was not until the 1981-82 austral summer that these groups were found to occupy three spatially distinct terranes separated by fault boundaries (Stump and others, 1983b). The terrane boundaries shown in figure 2 are the same as shown by Stump and others (1983b) and Weaver, Bradshaw, and Laird (1984), except that the southwestern boundary of BT (south of the Evans Névé) has been shifted  $\approx 10$  km to the west. This placement is based on new data for the granitoids (presented here), which constrain the boundary to pass east of Mt. Murchison and west of Mt. Supernal, as well as on new mapping in the area done during GANOVEX III (Tessensohn, 1984; Kleinschmidt, Roland, and Schubert, 1984). Though the position of this boundary is still subject to some interpretation, it is gratifying to note that the recent GANOVEX III field work located it in outcrop very close to the position inferred by Borg (ms, 1984) in an earlier phase of this study.

Previously, these geologic terranes had been interpreted as the products of two successive orogenic belts which developed along, and were accreted to, the EAC (Hamilton, 1964, 1967; Oliver, 1964; Craddock, 1972; Stump, 1973; Elliot, 1975; Laird, 1981; Laird and Bradshaw, 1982). The WG was thought to represent a continuation of the Ross Orogen (from the Transantarctic Mountains to the south), with folding and emplacement of the GHI during the early Paleozoic Ross Orogeny. The BSG and the RBG were believed to represent sedimentation somewhat younger than WG, but it was assumed that these rocks were folded during the Ross Orogeny (Laird and others, 1972; Craddock, 1972; Elliot, 1975). A second orogenic belt, termed the Borschgrevink Orogen, was defined by the presence of AI and two mid-Paleozoic K-Ar ages on metasediments of RBG (Craddock, 1972). Later, Adams and others (1982) interpreted mid-Paleozoic K-Ar ages for rocks of BSG as further evidence of thermal metamorphism during the Borschgrevink Orogeny. Because BSG and RBG were assumed to be part of the Ross Orogen, the amount of deformation associated with the Borschgrevink Orogeny was unclear (Craddock, 1972).

Subsequently, several workers have speculated on the origin of these terranes and the nature of their faulted boundaries. These speculations range from a model in which the boundary faults have merely juxtaposed different crustal levels of a continuous terrane (Tessensohn and others, 1981) to more complex models of allochthonous terranes juxtaposed by major transform faults (Bradshaw, Weaver, and Laird, 1985; Weaver, Bradshaw, and Laird, 1984; Burrett and Findlay, 1984). Also, the results of recent work on the Leap Year Fault, between BT and RBT, and on the Lanterman Fault, between WT and BT, suggest they may be major thrust systems (Wright and Findlay, 1984; Kleinschmidt, 1985; Tessensohn, 1985; Wright, 1985) on which the terranes have been assembled (Gibson and Wright, 1985). The concept of allochthonous terranes has particular appeal because of the complete distinction between metamorphic rocks of the three terranes which has been emphasized in recent reviews of the regional geology (Stump and others, 1983b; Laird and Bradshaw, 1983).

Despite the considerable effort made to address the regional tectonic problem, the topic has remained highly speculative, because many arguments have been based on inconclusive data such as gross lithologic similarities or dissimilarities, structural style, and metamorphic grade. The paucity of fossil evidence that bears on the problem and the poor exposure of critical areas allow considerable poetic license in models put forward. The diversity of tectonic models in even the most recent papers attests to the continuing controversy. This situation has arisen because logistic difficulties in Antarctica severely limit classical geologic techniques. In these circumstances a regional sampling program to address tectonic problems using chemical and isotopic data may be a fruitful alternative approach.

PALEOZOIC GRANITIC ROCKS OF NORTHERN VICTORIA LAND

*Introduction.*—Geologists have long recognized the existence of different types of granitoids and have expended much effort in attempts to categorize them and to explain their origin. Considering that granitoids occupy a significant portion of the Earth's crust, and that they must be representative of substantial volumes of material in the deeper crust, these efforts are well justified. Despite the attention over many years, however, some aspects of the origin of granitoids have remained controversial. With the advent of modern plate tectonic theory, many granite petrologists began to study granitoids in relation to their tectonic setting. Regional studies of granitoid rocks in the past two decades are numerous (Bateman and Dodge, 1970; Presnall and Bateman, 1973; Kistler and Peterman, 1973, 1978; Chappell and White, 1974; Ishihara, 1977; Strong and Dickson, 1978; Pitcher, 1979, 1982; White, 1979; Atherton and Tarney, 1979; Wones, 1980; DePaolo, 1980; Barker, 1981, and other papers in *Granites and Rhyolites*, Jour. Geophys. Research, v. 86, B11; Farmer and DePaolo, 1983; Roddick, 1983; to name a few). It is abundantly evident from these studies that granitic rocks may form in a variety of ways from a variety of materials. However, a pervading theme is that granites compositionally reflect their source materials and that granite types can be correlated, to a certain degree, with tectonic setting. Broad associations of granitic rocks with tectonic setting have been recognized for some time. For example, the calc-alkaline, tonalite-quartz-diorite-granodiorite-monzogranite series and the peraluminous, 2-mica, granites are associated, respectively, with the ocean side and continent side of continental margin mobile belts (Kistler and Peterman, 1973, 1978; Miller and Bradfish, 1980; Kistler, Ghent, and O'Neil, 1981; Pitcher, 1982; Farmer and DePaolo, 1983), whereas peralkaline granites, often rich in fluorine, have been associated with intracratonic, anorogenic, or perhaps continental rifting environments (Loiselle and Wones, 1979).

The geographic distribution of granitoid types is important to regional geologic interpretations. In terms of the I- and S-type classification of granitoids of Chappell and White (1974), several authors have noted that I-type granitoids are found on the ocean side and S-types are found on the continent side of continental margin mobile belts (White, Williams, and Chappell, 1976; Pitcher, 1982; White and Chappell, 1983). Furthermore, studies of Mesozoic and younger calc-alkaline (dominantly I-type) granitic batholiths (Sierra Nevada, western United States and western Mexico; Moore, 1959; Bateman and Dodge, 1970; Baird, Baird, and Welay, 1974; DePaolo, 1981a; Farmer and DePaolo, 1983; Bateman, 1983; Gastil, 1983; Baird and Miesch, 1984; Andes and Antarctic Peninsula; Atherton and others, 1979; Saunders, Tarney, and Weaver, 1980; Stern and Stroup, 1982) have demonstrated that major and trace elements, as well as isotopic compositions, vary in a fairly regular way from the ocean side to the continent side and have proved valuable in unravelling the tectonic evolution of some regions (Silver, Early, and Anderson, 1975; Reed, Miesch, and Lanphere, 1983). Among the most significant of these

variations are the continentward increase in  $K_2O$  (and  $K_2O$  at fixed  $SiO_2$ ), initial  $^{87}Sr/^{86}Sr$ ,  $\delta^{18}O$ , and decrease in initial  $^{143}Nd/^{144}Nd$ . Other, less consistent parameters include continentward decrease in specific gravity,  $CaO$ ,  $MgO$ , total  $Fe$ ,  $Al_2O_3$ ,  $TiO_2$ , and  $Na_2O$ , and increase in  $SiO_2$  (Bateman and Dodge, 1970; Baird, Baird, and Welday, 1974).

The cause of these variations in granitic batholiths is somewhat controversial. They are rather similar to chemical variation in subduction related volcanic arcs (Dickinson, 1975; Condie, 1976), but there is no unequivocal basis for suggesting they are due directly to the same processes. Rather, variations in plutonic rocks correlate better with crustal thickness and with variations in country rock compositions than with depth to seismic zones as postulated from subduction related volcanic arcs (Kistler and Peterman, 1973, 1978; Condie, 1976). Several papers including Chappell and White (1974), White (1979), White, Williams, and Chappell (1977), Compston and Chappell (1979), and White and Chappell (1977) have postulated that regional variations are due largely to regional differences in crustal lithologies which became involved in partial melting. They require no direct association with subduction related magmatism and argue against involvement of mantle derived magmas (McCulloch and Chappell, 1982). On the other hand, DePaolo and Wasserburg (1976, 1979), DePaolo (1981c), and Farmer and DePaolo (1983) argue that regular chemical and isotopic variations in continental margin granitoids (specifically, the Sierra Nevada and southern California batholiths and the northern Great Basin granites) are due to different degrees of mixing of mantle derived magmas with various crustal components. They suggest that these mantle derived magmas may be related to subduction processes. To the east of these marginal batholiths, in the central Great Basin, Farmer and DePaolo (1983) have emphasized the importance of nearly coincident discontinuities in the regional geology and the regional variation of initial Sr and Nd isotopic compositions of the granitoids. They interpret this as marking the western boundary of Precambrian craton and note that regular variations in chemistry and isotopic compositions do not occur east (on the craton side) of this boundary.

It is quite evident from the preceding discussion that many problems remain to be addressed before the origin of continental margin batholiths is fully understood. Nevertheless, the chemical and isotopic variations are an extremely important observation regardless of specific processes involved in producing them. The salient point to be realized is that there is a real chemical asymmetry associated with continental margin granitoids and that the variations can, quite logically, be viewed as reflecting greater involvement of old crustal, metasedimentary (chemically weathered) material in the granitoids from the margin inboard toward the continent. This point is particularly important to this study, which is aimed at regional tectonic problems.

*Isotopic results.*—Data representation ( $\epsilon_{Nd}$  and  $\epsilon_{Sr}$  notation) follows that of DePaolo (1981a) and Farmer and DePaolo (1983). Low  $\epsilon_{Sr}$  values (near zero) are indicative of mantle derivation, whereas higher  $\epsilon_{Sr}$  values are

found in magmas derived from old crustal materials. For  $\epsilon_{Nd}$ , values of about + 8 during the early to middle Paleozoic indicate mantle derivation (Nelson and DePaolo, 1984), whereas lesser values indicate increasing involvement of isotopically evolved (old, crustal) material.

Isotopic data collected on the GHI for this study are summarized in table 1. Initial Nd and Sr isotopic compositions have been calculated for these samples by using an assumed granite generation age of 550 Ma. The initial  $^{87}Sr/^{86}Sr$  ratios range from 0.7091 to 0.7148, and the  $^{143}Nd/^{144}Nd$  ratios range from 0.51083 to 0.51068, indicating that the origin of these granitoids has substantially involved old crustal material. In figure 3, these values have been put into  $\epsilon$ -notation.

In figure 3A ( $\epsilon_{Nd}$  versus time), the GHI fall within an envelope of Nd-evolution for continental crust which was generated at  $\approx 1.8$  Ga. The peraluminous or S-type granitoids certainly represent crustal melts, and so their initial Nd compositions reflect the Nd composition of the continental crustal material underlying the WT at 550 Ma. Thus, the lower-to mid-crustal material in the WT is not older than  $\approx 1.8$  to 2.0 Ga and appears to be similar in age to the crustal material that produced S-type granites of the Lachlan Fold Belt of southeastern Australia. Another important feature displayed in figure 3B, is that the array of five data points extends to the right in  $\epsilon_{Nd}$  versus  $\epsilon_{Sr}$  space with moderate to high initial  $\epsilon_{Sr}$  values and with no initial  $\epsilon_{Nd}$  values  $< -9$ . Thus, there is no indication of involvement of old Rb-depleted lower crustal material similar to the North American Craton (Farmer and DePaolo, 1983, fig. 7) or of Archean material ( $\epsilon_{Nd} < -25$ ). An important implication of this is that the continental areas from which WG sediments were derived (presumably the EAC) have an average age of  $\approx 1.8$  to 2.0 Ga. Thus, one may infer that the EAC adjacent to NVL is Proterozoic with little or no Archean material.

Both Rb-Sr and Sm-Nd isotopic measurements were made on seven whole-rock samples of AI granitoids (table 2). Initial isotopic compositions have been calculated using an assumed age of 400 Ma. Initial ratios range from  $\approx 0.7051$  to  $\approx 0.7169$  for  $^{87}Sr/^{86}Sr$  and from  $\approx 0.51128$  to  $\approx 0.51096$  for  $^{143}Nd/^{144}Nd$ . These compositions indicate substantial contribution of old crustal material to some of the granitoids and less contribution to others.

In figure 3A, the data form an array that lies above "typical" continental crustal compositions and extends toward compositions expected from a depleted mantle source. This array is similar to arrays of Phanerozoic, metaluminous, continental margin batholithic rocks exposed elsewhere in the world (Liew and McCulloch, 1985, fig. 11) indicating that AI has an origin similar to other continental margin granitoids. The array of data for metaluminous (I-type) granitoids of the Lachlan Fold Belt reported by McCulloch and Chappell (1982) has been included on figure 3A for comparison. The low end of the array of AI approaches the Nd-evolution envelope of  $\approx 1.8$  Ga crustal material. Because there are no strongly peraluminous (S-type) compositions that would indicate derivation solely from old continental crustal rocks, it is possible that a mantle

TABLE 1  
Sm-Nd and Rb-Sr isotopic data\*; Granite Harbour Intrusives

Locality	Sample	Age**	Sm -- ppm --	Nd --	$^{147}\text{Sm}/^{144}\text{Nd}$	$^{143}\text{Nd}/^{144}\text{Nd}$	$^{143}\text{Nd}/^{144}\text{Nd}_{(550)}$	Rb -- ppm --	Sr	$^{87}\text{Rb}/^{86}\text{Sr}$	$^{87}\text{Sr}/^{86}\text{Sr}$	$^{87}\text{Sr}/^{86}\text{Sr}_{(550)}$
Aviator Glacier	ELR	490	6.8	36.6	0.1127	$0.511144 \pm 20$	0.51074	135.6	274.8	1.4271	$0.72338 \pm 9$	0.7122
Mount Murchison	EOG	527	8.0	35.5	0.1355	$0.511318 \pm 21$	0.51083	93.9	254.4	1.0672	$0.71747 \pm 6$	0.7091
Alamein Range	ETC	535	6.1	32.0	0.1153	$0.511125 \pm 30$	0.51071	136.5	242.1	1.6306	$0.72315 \pm 5$	0.7104
Daniels Range	ANG25	510	5.81	28.31	0.1242	$0.511152 \pm 24$	0.51070	176.2	136.2	3.7481	$0.74417 \pm 9$	0.7148
Daniels Range	ANG27	510	9.94	51.37	0.1171	$0.511107 \pm 22$	0.51068	213.1	185.0	3.3346	$0.73569 \pm 7$	0.7095

\* Isotopic measurements were made at the Research School of Earth Sciences, the Australian National University, Canberra. Uncertainties are 2-sigma errors. Analytical procedures for isotopic measurements as well as ratios used to normalize the data are found in McCulloch and Chappell (1982).

\*\* Age estimates: Ages of ELR and EOG are estimates of the cooling age of these rocks as represented by Rb-Sr mineral isochrones based on biotite and whole-rock pairs (Borg, ms, 1984; Stump, Borg, and Armstrong, unpublished). The age of ETC is an estimate of the cooling age based on a three point whole-rock Rb-Sr isochron using this sample and two others from the Alamein Range (Borg, ms, 1984; Stump, Borg, and Armstrong, unpublished). The age of samples ANG25 and ANG27 is based on a Rb-Sr whole-rock isochron age estimate for granitoids of the southern Daniels Range reported by Keuzer and others (1981).

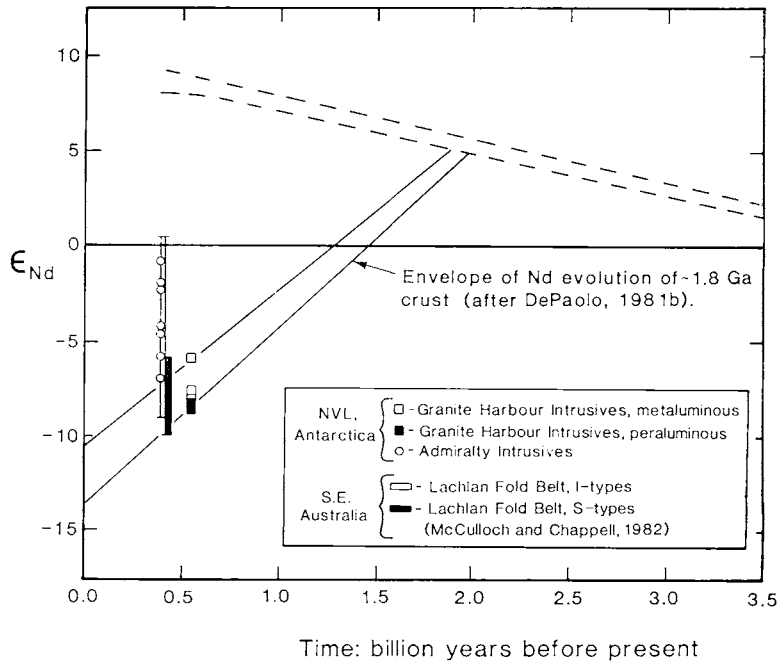
TABLE 2  
Sm-Nd and Rb-Sr isotopic data\*: Admiralty Intrusives

Locality	Sample	Age**	Sm	Nd	$^{147}\text{Sm}/^{143}\text{Nd}$	$^{143}\text{Nd}/^{144}\text{Nd}$	$^{143}\text{Nd}/^{144}\text{Nd}_{(100)}$	Rb	Sr	$^{87}\text{Rb}/^{86}\text{Sr}$	$^{87}\text{Sr}/^{86}\text{Sr}$	$^{87}\text{Sr}/^{86}\text{Sr}_{(100)}$
			-- ppm --	--				-- ppm --				
Lower Tucker Glacier	ANG3	~380	8.28	31.78	0.1575	$0.511611 \pm 14$	0.511198	139.0	197.6	2.033	$0.71818 \pm 6$	0.7066
Yule Bay	ANG10	~393	8.17	39.81	0.1241	$0.511432 \pm 20$	0.511107	196.0	136.8	4.1472	$0.73873 \pm 7$	0.7151
Yule Bay	ANG11	~393	5.44	27.49	0.1196	$0.511344 \pm 10$	0.511031	188.4	131.8	4.1394	$0.73007 \pm 8$	0.7125
Yule Bay	ANG14	~393	7.67	40.27	0.1153	$0.511258 \pm 24$	0.510956	256.2	127.9	5.8091	$0.74995 \pm 8$	0.7169
Mount Adams	EMN	380	4.3	21.6	0.1207	$0.511395 \pm 21$	0.511079	91.1	240.2	1.0962	$0.71520 \pm 9$	0.7090
Mount Burril	ENS	385	3.2	17.1	0.1126	$0.511519 \pm 18$	0.511224	85.8	256.0	0.9679	$0.71123 \pm 8$	0.7057
Mount Supernal	FAS	364	4.3	21.7	0.1200	$0.511593 \pm 14$	0.511279	117.6	181.8	1.8694	$0.71604 \pm 8$	0.7054

\* Isotopic measurements were made at the Research School of Earth Sciences, the Australian National University, Canberra. Uncertainties are 2-sigma errors. Analytical procedures for isotopic measurements as well as ratios used to normalize the data are found in McCulloch and Chappell (1982).

\*\* Age estimates: Ages of ENS and FAS are estimates of the cooling age of these rocks as represented by Rb-Sr mineral isochrons based on biotite and whole-rock pairs (Borg, ms, 1984; Stump, Borg, and Armstrong, unpublished). The age of EMN is an estimate of the cooling age based on a Rb-Sr mineral isochron using whole-rock, quartz + plag, K-feldspar, and biotite (Borg, ms, 1984; Stump, Borg, and Armstrong, unpublished). The age of samples ANG10, ANG11, and ANG14 are based on a whole-rock Rb-Sr isochron age of the Yule Batholith reported by Kreuzer and others, (1981). The age of samples ANG3 is based on its proximity to EMN.

Fig. 3.

Diagrams of initial  $\epsilon_{Nd}$  versus time and  $\epsilon_{Nd}$  versus  $\epsilon_{Sr}$ 

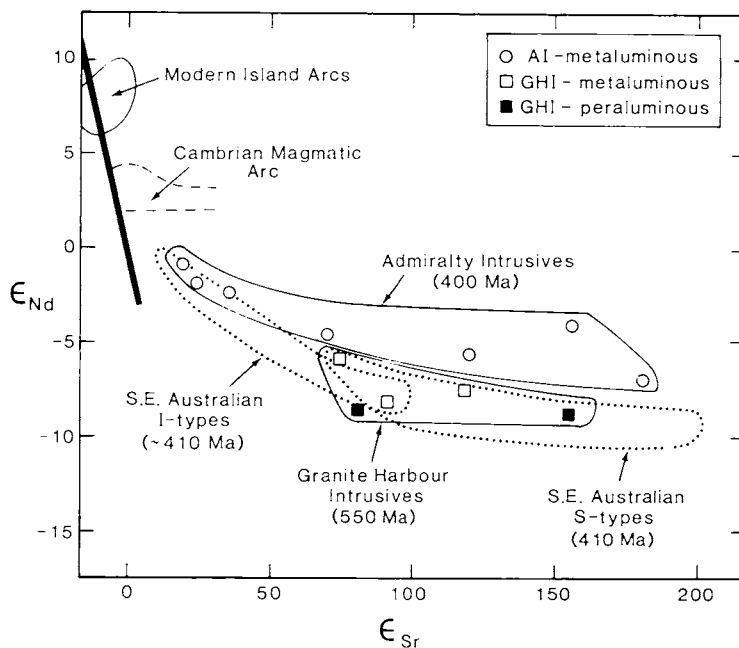
A. Initial  $\epsilon_{Nd}$  is plotted against time in this Nd-evolution diagram. For reference, an envelope enclosing compositions of  $\approx 1.8$  Ga crustal material is shown which was taken from DePaolo (1981b), and an envelope of compositions representing a depleting mantle has been sketched using data from Nelson and DePaolo (1984). Fields for south-eastern Australian granitoids are taken from McCulloch and Chappell (1982).

The Granite Harbour Intrusives fall within the envelope of  $\approx 1.8$  Ga crustal material and, because two of these samples are strongly peraluminous rocks representing wholly crustal melts, it is unlikely that material older than 1.8 to 2.0 Ga was involved. The Admiralty Intrusives lie in an array above the  $\approx 1.8$  Ga crustal envelope, extending toward the depleted mantle envelope. Because there are no peraluminous samples, the Nd composition of the crustal material involved in the Admiralty Intrusives cannot be clearly constrained. It is possible that  $\approx 1.8$  Ga or older materials were involved.

component is involved in these granites. Thus, it is possible that crustal material of at least this age, and perhaps older, was involved in production of AI. At present, therefore, we cannot rule out the possibility that the crustal material involved in production of the two groups of granitoids in NVL may have a similar age of  $\approx 1.8$  to  $\approx 2.0$  Ga.

Despite the possible similarity in age of crustal materials involved in genesis of AI and GHI, a comparison of both Nd and Sr isotopic compositions indicates that the crustal sources were distinct. As is evident on figure 3B, a plot of initial  $\epsilon_{Nd}$  versus  $\epsilon_{Sr}$ , AI forms a curved array with the more crust-like values to the right and the least crust-like values to the upper left. Samples with the least crust-like signature fall in the field of southeast Australian I-types, and samples with more crust-like signature

Fig. 3 (continued)



B. Initial  $\epsilon_{Nd}$  versus  $\epsilon_{Sr}$  for the Granite Harbour Intrusives and the Admiralty Intrusives. Fields for island arcs and Cambrian magmatic arcs are from Farmer and DePaolo (1983), and fields for southeastern Australian granitoids are from McCulloch and Chappell (1982).

Values for the Granite Harbour Intrusives indicate significant involvement of old crustal material to all granitoids. These samples form an array that extends to high  $\epsilon_{Sr}$  while leveling out at  $\epsilon_{Nd}$  of  $-8$  to  $-9$ , similar to fields of southeastern Australian S-types.

The Admiralty Intrusives form a curved array which extends to high  $\epsilon_{Sr}$  with  $\epsilon_{Nd}$  significantly higher than the arrays for the Granite Harbour Intrusives or the southeastern Australian S-types. In view of the fact that all the Admiralty Intrusives are metaluminous granitoids, this array indicates that the crustal source materials of the Admiralty Intrusives are different from the crustal rocks involved in the Granite Harbour Intrusives or the southeastern Australian granitoids. See text for further discussion.

define an array to the right which is significantly above the fields for GHI and the southeastern Australian S-types. Curved, convex-up arrays such as this are typical of continental margin batholithic rocks and have been interpreted by DePaolo and Wasserburg (1979), DePaolo (1981a), and Farmer and DePaolo (1983) to be the product of mixing via fractional crystallization and assimilation between a depleted mantle component and a Rb-enriched crustal component. Alternatively, this covariance of initial  $\epsilon_{Nd}$  and  $\epsilon_{Sr}$  may be interpreted as evidence of an isotopically variable source region (McCulloch and Chappell, 1982). Whatever the reason, however, at high  $\epsilon_{Sr}$  values the arrays flatten out at an  $\epsilon_{Nd}$  composition reflecting the age of the local continental crustal materials. With this in mind,

the arrays of data for AI and GHI are seen to be significantly different in the following way. The crustal source involved in GHI must have  $\epsilon_{Nd} \approx -9$  at 550 Ma. These materials would evolve to  $\epsilon_{Nd} \approx -10$  to  $-11$  by 400 Ma. However, the array of AI appears to flatten out at high  $\epsilon_{Sr}$  and may not go below  $\epsilon_{Nd} \approx -8$  at 400 Ma. Furthermore, the materials melted to form the GHI produced strongly peraluminous granites with initial  $\epsilon_{Sr} < +100$  whereas the materials from which AI were formed did not produce strongly peraluminous granitoids even though they had  $\epsilon_{Sr} = +155$  at 400 Ma. Thus, although the source materials of GHI appear to be similar to the source materials of the Lachlan Fold Belt granitoids of southeast Australia, they are clearly distinct from the source materials involved in the origin of AI.

COMPOSITIONAL POLARITY OF THE GRANITE HARBOUR INTRUSIVES  
AND THE ADMIRALTY INTRUSIVES

*General.*—With respect to regional geologic problems, an important finding of this study is that significant compositional variation with geographic position exists within each of the major groups of Paleozoic granitoids. Regional variation of chemical parameters has been examined using trend-surface calculations following the approach of Baird, Baird, and Welday (1974) and Reed, Miesch, and Lanphere (1983). First-order trend surfaces have been calculated by the least squares method which is particularly useful because compositional variation can be quantified and the direction of maximum increase or decrease can be estimated without making assumptions about the orientation of an ancient continental margin as was commonly done in earlier studies (Bateman and Dodge, 1970; Kistler and Peterman, 1973).

*Granite Harbour Intrusives.*—In terms of mineralogical and major element criteria of the I- and S-type classification of Chappell and White (1974) and White and Chappell (1977), the eastern and northeastern margin of WT contains exclusively I-types, whereas S-types are the dominant granitoid in the southern and western portion (fig. 4). Following arguments of White and Chappell (1977), White (1979), and Pitcher (1982), this spatial association can be interpreted as a reflection of different crustal source rocks. Specifically, a predominantly mafic dioritic lower crust is inferred beneath I-types in the north and east, and a metasedimentary crustal source is inferred in the west and south. This transition from I-types to dominantly S-types is clearly important and may be an expression of the early Paleozoic edge of the Antarctic continent.

Trend surfaces were calculated for major elements, five trace elements, and a few elemental ratios and sums. Chemical data of GHI used for these calculations are from Wyborn (unpub. data, 8 rock analyses), Borg (ms, 1984), and Borg, Stump, and Holloway (1986). While wanting to maximize the number of samples included in this analysis, it is undesirable to have an extremely uneven sample distribution. Because of the high sample density in the Monte Cassino region, five representative samples were chosen from the twelve available to avoid prejudicing the cal-

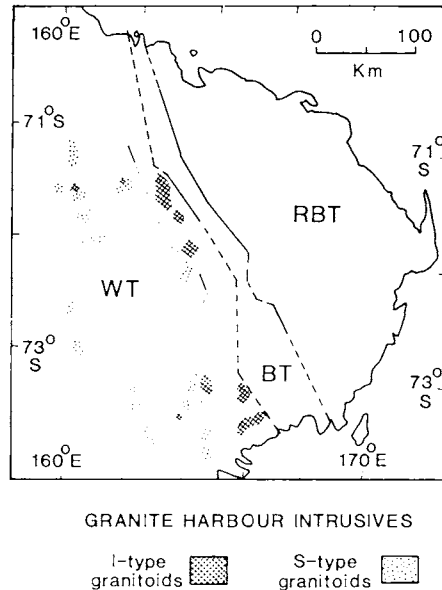


Fig. 4. Distribution of I-type and S-type Granite Harbour Intrusives. These early Paleozoic granitoids are only found within the Wilson Terrane (WT). I-types exclusively are found along the east-northeastern margin of the WT. S-types dominate to the south and west. The dash-dot line is the eastern limit of known S-types. Characterization as I-type or S-type is based on both chemical and mineralogical criteria.

culations. Thus, the 62 rock analyses used in these calculations represent the largest possible set with the most even (random) distribution possible. It should be noted, however, that trend-surfaces calculated using all 69 available analyses of GHI do not differ in any meaningful way from the results reported here.

The results of these calculations are presented in table 3 and shown graphically in figure 5. This analysis indicates that, in NVL, GHI vary significantly in composition with geographic position. The statistics relating to the significance or strength and to the magnitude of the trends indicate a comparable or stronger correlation of chemistry with geographic position for GHI than reported for the Sierra Nevada (Baird, Baird, and Welday, 1974) or for plutonics in the Aleutian Range, Alaska (Reed, Miesch, and Lanphere, 1983). The chemical variation is fairly regular and indicates a pronounced compositional polarity which fits well with the distribution of I- and S-type granitoids. The arrows on figure 5 indicate the direction of maximum increase (+ slope) of the chemical parameter in question. Arrows are also annotated with the rate of change (slope) of the trend-surface and the percentage of the total variation explained by the first-order model.

As is evident from figure 5A, the slope directions for all parameters considered are remarkably similar. The slope azimuths (irrespective of + or - slope) range from N45E to N74E (relative to grid directions where

TABLE 3  
Summary of trend surface calculations for the  
Granite Harbour Intrusives\*

Chemical Parameter	Significance level of the linear model	Percent of variance explained by the model	Grid azimuth of maximum increase	Slope
SiO <sub>2</sub>	99.99	30.25	238°	5.66 wt%/100km
TiO <sub>2</sub>	99.74	18.31	60°	0.23 wt%/100km
Al <sub>2</sub> O <sub>3</sub>	99.22	15.17	56°	1.27 wt%/100km
Fe <sub>2</sub> O <sub>3</sub>	99.99	30.19	63°	2.25 wt%/100km
MnO	99.97	24.47	61°	0.03 wt%/100km
MgO	99.99	26.68	57°	1.53 wt%/100km
CaO	99.99	33.45	58°	2.22 wt%/100km
Na <sub>2</sub> O	18.90	0.71	ND**	ND
K <sub>2</sub> O	99.99	33.03	245°	1.64 wt%/100km
K <sub>2</sub> O/Na <sub>2</sub> O	99.81	19.13	242°	0.65 /100km
Al number†	99.91	21.29	235°	0.08 /100km
K <sub>2</sub> O Index‡	99.87	20.12	254°	30.83 /100km
Rb	99.99	26.53	253°	87.2 ppm/100km
Sr	99.37	15.77	60°	100.4 ppm/100km
Y	99.93	21.97	67°	10.5 ppm/100km
Zr	91.38	7.97	45°	69.8 ppm/100km
Ba	81.51	5.56	84°	90.6 ppm/100km
Rb/Sr	99.99	28.42	253°	1.8 /100km

\* Data for 62 samples were used in these calculations. Data are from Wyborn (unpublished data, 8 samples) and from Borg, Stump, and Holloway (1986; see also Borg, ms, 1984). Analyses of splits of the same rock powders at the two labs at which these data were produced demonstrate that interlab variations are small for all elements, and so the data from the two labs can be directly compared with a high degree of confidence (Borg, ms, 1984). Seven samples from the Monte Cassino area (EKH, EKI, EPD, EYC, ERH, EZS, and FAF from Borg, Stump, and Holloway, 1986) have been excluded to avoid prejudicing the calculations with a region of high sample density.

\*\* ND = not determined.

† Al number is defined as the molar ratio  $Al_2O_3/(K_2O+Na_2O+CaO)$ .

‡ K<sub>2</sub>O Index is defined by Bateman and Dodge (1970) as  $(K_2O \times 1000)/(SiO_2-45)$ .

the sides of the map are defined as trending north-south) with an average direction of N62E and one- $\sigma$  standard deviation of 7.6°. Only trends significant at the 90 percent confidence level or greater are plotted. This limit excludes only Ba and Na<sub>2</sub>O as all other parameters show statistically significant trends. A few of the chemical parameters have been projected onto a section parallel to the average of all trends (fig. 5B). The chemical variation with location shown on these plots demonstrates that the geographic variation is real and not a peculiarity of misapplied statistics.

The pattern that emerges, with SiO<sub>2</sub>, Al-number, K<sub>2</sub>O/Na<sub>2</sub>O, Rb, Rb/Sr, and especially K<sub>2</sub>O and K<sub>2</sub>O-index increasing to the west-southwest, and with the other parameters increasing to the east-northeast, is interpreted as a reflection of an increasing amount of older continental crustal material being involved in the production of the granitoids from east-northeast to the west-southwest. By analogy with chemical studies of batholithic rocks elsewhere in the world the compositional polarity dis-

played by GHI is compatible with their being emplaced along a continental margin with the continent lying to the west-southwest and a convergent plate boundary lying to the east-northeast.

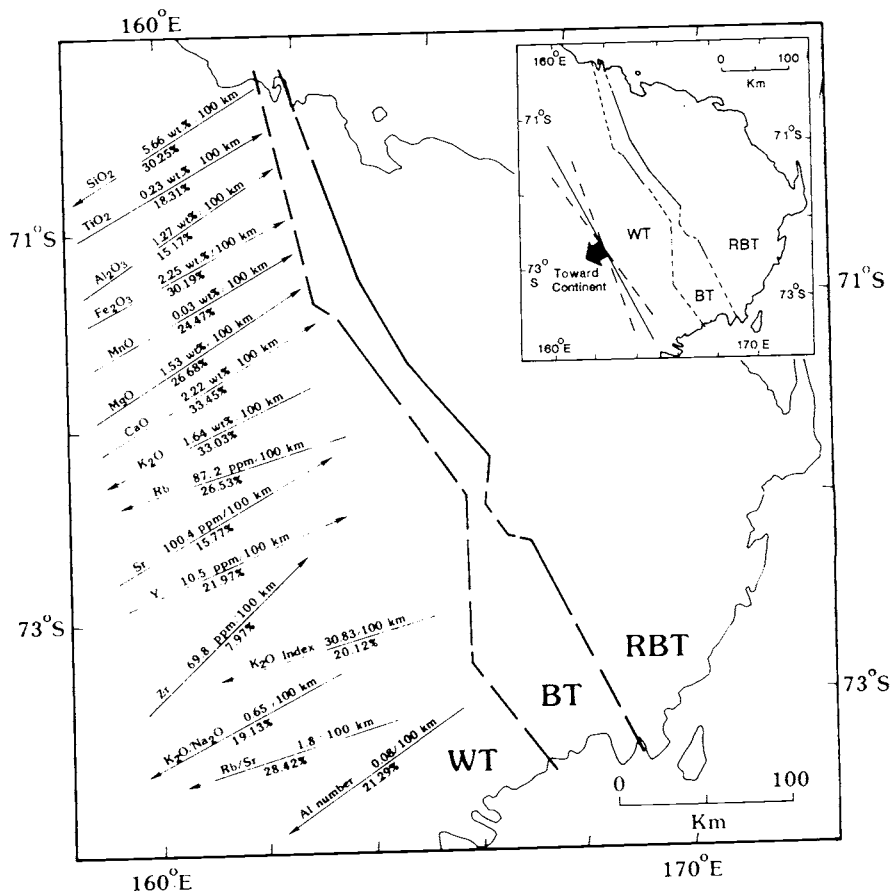
The average perpendicular to the trends plotted in figure 5A constitutes the best estimate of the trend or orientation of the continental margin during emplacement of the granitoids in the early Paleozoic. This orientation ( $\approx N30W$ , grid azimuth) is shown in figure 5A and is very close to the orientation of the boundary between I-types and dominantly S-types shown in figure 4. This leads to the conclusion that the orientation of the early Paleozoic margin of this part of Antarctica (essentially the EAC) is best approximated by the line in figure 5A or by the trend of the I-S boundary. The precise location of this margin is more of a problem but, with the present state of knowledge, is probably best placed at about the I-S boundary (fig. 4). There remains some question about this placement of the continental margin, but the nature of the WG metasediments indicates that it could not have been farther west. Also, the presence of exclusively I-type granitoids along the east-northeastern edge of WT is interpreted as evidence of a relatively mafic lower crust and so the actual margin may not have been located very far east-northeast of the position proposed here. This placement would imply that metasedimentary rocks in the Lanterman Range and the Aviator Glacier area (along the eastern margin of WT) were probably deposited as a clastic wedge along this continental margin.

Rb-Sr and Sm-Nd isotopic data for samples of GHI are not numerous and so cannot be treated statistically, but they do tend to corroborate the inferences from the major element chemistry. Summarized in table 4 are initial Sr-isotopic compositions, calculated for 18 whole-rock samples, and initial Nd-isotopic compositions, calculated for 5 whole-rock samples using an assumed age of 550 Ma. Sample locations are shown on a map (fig. 6A), and the data have been projected onto a section perpendicular to the proposed continental margin (Sr, fig. 6B; Nd, fig. 6C).

The  $\epsilon_{Sr}$  data in figure 6B clearly show that while all samples have a significant proportion of old (crustal) Sr, the amount increases steadily from east-northeast to west-southwest across the WT. The  $\epsilon_{Nd}$  data (fig. 6C) do not show a definitive trend, but the sample set is very small. In accord with the Sr data, all samples have  $\epsilon_{Nd}$  values indicative of involvement of old, isotopically evolved materials. However, one sample (EOG) has an  $\epsilon_{Nd}$  value that indicates less crustal involvement than the other four. This sample is an I-type granitoid from the east-northeast margin of WT, and so the  $\epsilon_{Nd}$  data tend to support the conclusion that there is more involvement of old crustal material in GHI from east-northeast to west-southwest.

Another aspect of GHI, which is important to regional geologic problems, is evident on figure 3B, the plot of initial  $\epsilon_{Nd}$  versus  $\epsilon_{Sr}$ . In other continental margin batholiths, granites inboard on the continent have  $\epsilon_{Nd}$  and  $\epsilon_{Sr}$  values that plot to the lower right, whereas granitoids on the outboard side of the batholithic province plot toward the oceanic correla-

Fig. 5  
Compositional trends of major and trace components for the Granite Harbour Intrusives based on first-order trend-surface calculations

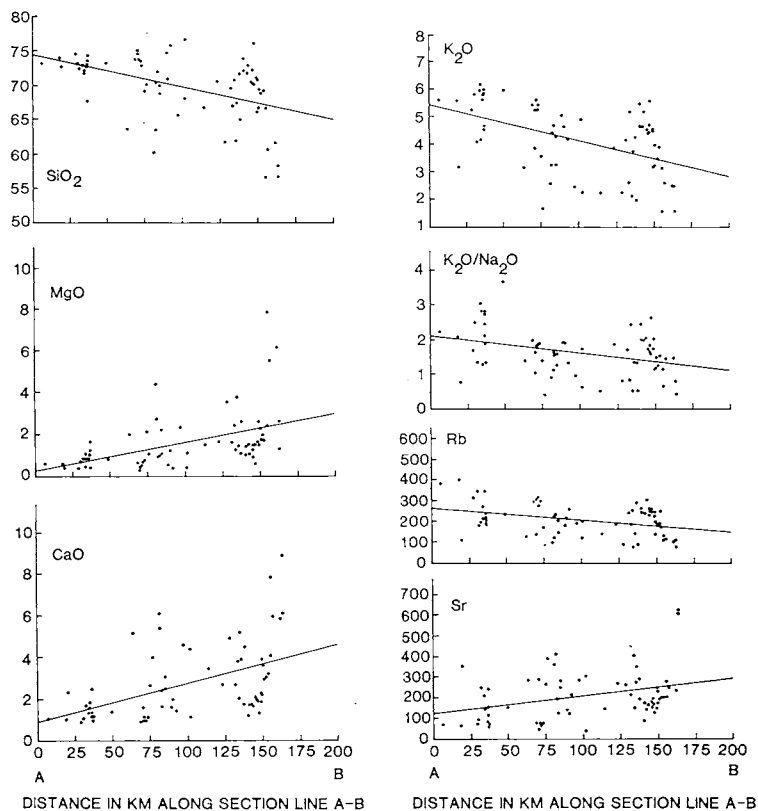


A. The arrows indicate the direction of maximum increase of the various parameters. Shown on each arrow, to the right of the parameter, is the slope of the model trend-surface. Also, beneath each arrow is the percentage of the total variance which is accounted for by the first-order model. Only parameters that are significant at a confidence level >90 percent are shown. These trends define a strong chemical polarity in the Granite Harbour Intrusives. Inset map showing the trend of the continental margin of Antarctica during the time of emplacement of the Granite Harbour Intrusives as inferred from the major and trace element polarity. The dashed lines represent one standard deviation uncertainty of the trends calculated for (5A). Note that the compositional polarity indicates the trend of the margin and not the actual position. The actual position may be best approximated by the I-S line shown on figure 4.

tion line on these diagrams (McCulloch and Chappell, 1982; Farmer and DePaolo, 1983). In terms of I- and S-type granites, I-types plot toward the oceanic correlation line (more mantle-like compositions), whereas S-types plot to the lower right (more crust-like compositions).

The important feature of GHI data is that the array in figure 3B does not extend toward mantle compositions as far as do other conti-

Fig. 5 (continued)



B. Representative plots of various chemical parameters against distance. Each parameter has been projected onto a line parallel to the average "maximum slope direction" (parallel to the average direction of the line in (A)). These graphs clearly document that the calculated variations shown in (A) are very real variations with position.

mental margin batholithic provinces. This may, of course, be a product of the small sample set and surely points out the need for more work on this problem. However, because most of the rock types present in GHI are represented and because the samples represent a wide geographic distribution, this restricted array in figure 3 may be real. If so, these data may be interpreted as evidence that GHI exposed in NVL represent, approximately, the inboard half of a continental margin batholithic province. In view of the geologic discontinuity between WT and BT, this interpretation is plausible. Support for this view comes from recent work on WG in which Grew, Kleinschmidt, and Schubert (1984) have apparently identified the inboard portion of a paired metamorphic belt.

*Admiralty Intrusives.*—The recognition of three groups of granitoids in AI based on different  $K_2O$  trends and the observation that these groups

TABLE 4

Calculated initial Sr and Nd isotopic compositions for the  
Granite Harbour Intrusives\*

Region	Sample	$^{87}\text{Sr}/^{86}\text{Sr}_{(550\text{Ma})}$ **	$^{143}\text{Nd}/^{144}\text{Nd}_{(550\text{Ma})}$ †	$^{143}\text{Nd}/^{144}\text{Nd}_{(550\text{Ma})}$ ‡
Aviator Glacier	EME	0.7083	63.1	
	EOG	0.7085	66.6	
	EOG*	0.7091	74.3	0.510830
	ELR	0.7121	117.2	
	ELR*	0.7122	118.5	0.510738
	ECC	0.7117	111.9	
	ENV	0.7108	98.4	
	EQJ	0.7190	215.8	
	EUR	0.7108	99.0	
	EUR	0.7080	59.3	
Lanternman Range	ESO	0.7100	87.4	
	EYQ	0.7113	105.8	
	EYZ	0.7117	111.5	
	EYT	0.7081	60.4	
	EYM	0.7066	39.1	
Alamein Range	EYS	0.7101	88.6	
	ETC	0.7098	84.2	
	ETC*	0.7104	92.6	0.510710
EUC	EUC	0.7095	80.0	
	ANGZ5*	0.7148	155.3	0.510704
Daniels Range	ANGZ7*	0.7095	80.9	0.510685
	ANGZ8*	0.7148	155.3	0.510704

\* Compositions calculated from data in table 1 are annotated with an asterisk. All others were calculated with data produced at the Rb-Sr geochronology lab, Department of Geological Sciences, University of British Columbia, Vancouver, BC (Stump, Borg, and Armstrong, unpublished; also in Borg, ms, 1984).

\*\* Sr compositions were calculated relative to a Uniform Reservoir (UR) using the following relations (after Farmer and DePaolo, 1983):

$$\left(\frac{^{87}\text{Sr}/^{86}\text{Sr}}{^{87}\text{Sr}/^{86}\text{Sr}}\right)_{\text{corrected}} = \left(\frac{^{87}\text{Sr}/^{86}\text{Sr}}{^{87}\text{Sr}/^{86}\text{Sr}}\right)_{\text{sample}} - (e^{\lambda t} - 1) \left(\frac{^{87}\text{Rb}/^{86}\text{Sr}}{^{87}\text{Sr}/^{86}\text{Sr}}\right)$$

t = time before present in years; t = 0, indicates the measured value

† Nd compositions were calculated relative to a Chondritic Uniform Reservoir (CHUR) using the following relations (after Farmer and DePaolo, 1983):

$$\left(\frac{^{143}\text{Nd}/^{144}\text{Nd}}{^{143}\text{Nd}/^{144}\text{Nd}}\right)_{\text{corrected}} = \left(\frac{^{143}\text{Nd}/^{144}\text{Nd}}{^{143}\text{Nd}/^{144}\text{Nd}}\right)_{\text{sample}} - (e^{\lambda t} - 1) \left(\frac{^{147}\text{Sm}/^{147}\text{Nd}}{^{143}\text{Nd}/^{144}\text{Nd}}\right)$$

t = time before present in years; t = 0, indicates the measured value

‡ Sm decay constant:  $\lambda = 6.54 \times 10^{-12} \text{yr}^{-1}$

were not randomly distributed (low- $K_2\text{O}$  trend in the south, high- $K_2\text{O}$  trend in the north, as shown in fig. 7) led to this investigation of regional compositional variation with geographic position. Data sources and trend-surface calculations are the same as cited for GHI. Forty-three analyses of Al were available, but because of the density of Wyborn's (unpub. data) samples in the Yule Bay region, only 8 of the 16 available analyses were selected to represent that area. Inclusion of all 43 available analyses in the

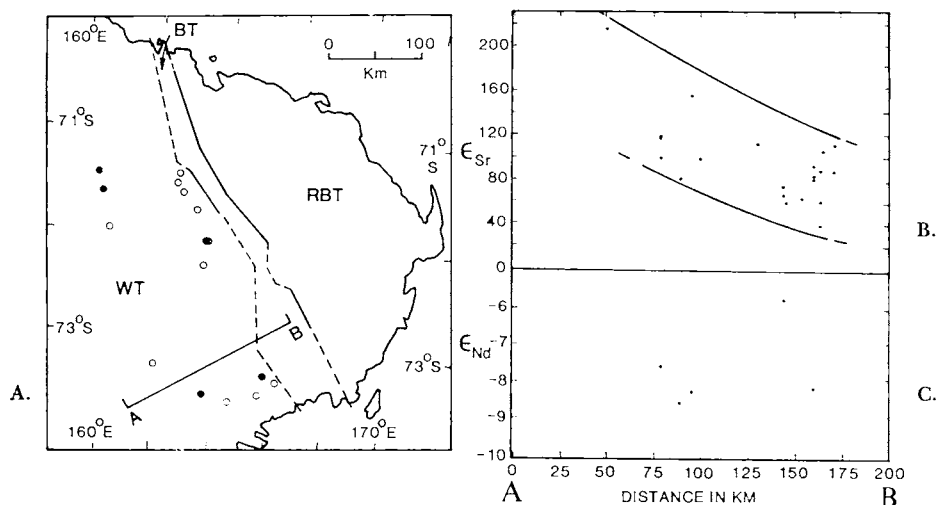


Fig. 6. Initial  $\epsilon_{Nd}$  and  $\epsilon_{Sr}$  compositions of the Granite Harbour Intrusives.

A. Map showing locations of samples for which Sm-Nd (filled circles) and Rb-Sr (all circles) data are available (table 4). The section A-B is parallel to the average compositional polarity and hence perpendicular to the inferred trend of the lower Paleozoic margin of Antarctica.

B.  $\epsilon_{Sr}$  projected onto section A-B.

C.  $\epsilon_{Nd}$  projected onto section A-B.

Although not plotted here, initial Sr isotopic compositions for the southern Daniels Range reported by Kreuzer and others (1981) and Vetter and others (1983) are similar to the values reported here for the southern Daniels Range.

trend-surface calculations does not change the ultimate results, though details of the statistics are affected (actually strengthening the statistical significance of the trends).

The results of these calculations are given in table 5 and are shown graphically in figure 8. These trend-surface calculations clearly demonstrate that AI vary significantly with geographic position, and a well-defined compositional polarity is indicated. This polarity crosses obliquely the rather uniform northwest-trending structural grain in BT and RBT. Compared with similar studies of batholithic terranes in southern California (Baird, Baird, and Welday, 1974) and in southern Alaska (Reed, Miesch, and Lanphere, 1983), the magnitude of the trends in AI as well as the statistics relating to their significance or strength are similar.

The directions of maximum change (irrespective of + or - slope) for the compositional trends considered significant at the 90 percent confidence level are all fairly similar (fig. 8A). The trend azimuths range from N4W to N45E (relative to grid north) with an average direction of N17E and one- $\sigma$  standard deviation of 18°. The pattern that emerges, with  $K_2O$ , Rb,  $K_2O/Na_2O$ , Rb/Sr, and  $K_2O$ -index increasing to the north-northeast, and with  $Al_2O_3$ , MnO, CaO,  $Na_2O$ , and Sr increasing to the south-southwest, is interpreted as a reflection of increasing influence of continental

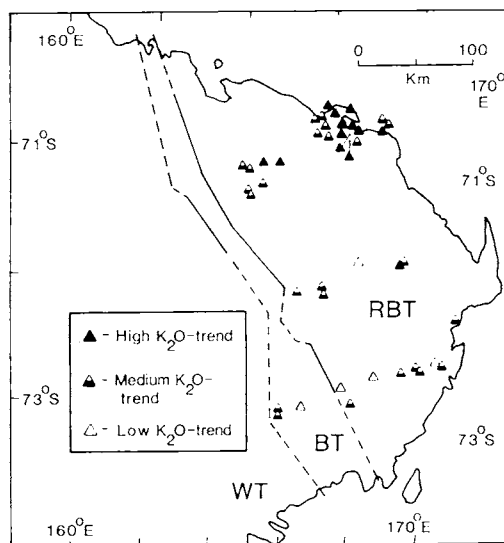


Fig. 7. Geographic distribution of low, medium, and high  $K_2O$ -trend granitoids of the Admiralty Intrusives. Open symbols = low  $K_2O$ -trend; half-filled symbols = medium  $K_2O$ -trend; filled symbols = high  $K_2O$ -trend.

crustal material in the production of the granitoids from the south-southwest to north-northeast (fig. 8A). This compositional polarity is compatible with emplacement of AI in a continental margin where (relative to present orientations) the continent lay to the north-northeast and a north-northeastwardly dipping subduction zone existed to the south-southwest. This is a drastically different polarity than is observed in GHI. Barring an absurd interpretation of nearly  $180^\circ$ , post-Devonian, *in place* rotation of BT and RBT along the rectilinear fault boundary between WT and BT, the compositional polarity of AI indicates that they were not emplaced on the margin of East Antarctica.

Though the compositional polarity is defined by only 10 significant trends of the 19 parameters considered and though the sample set is of modest size, the chemical trends are real and may actually be better than the statistics would indicate. Figure 8B shows various chemical parameters projected onto a section parallel to the average direction (N17E; grid azimuth) calculated for the 10 trends significant at the 90 percent C.L. As exemplified by plots of CaO,  $K_2O$ , and  $K_2O$ -index versus distance along the section toward the north-northeast, the statistically significant trends are distinct and quite obviously real. However, similar plots for  $SiO_2$ ,  $Fe_2O_3$ , and Al-number, which have trends not significant at the 90 percent C.L., actually show reasonable geographic variation. Thus, as with GHI, the distinct compositional polarity is clearly not a product of fortuitous statistics but rather is a real feature of AI.

Mineralogic characteristics of AI also reflect, though less distinctly, the compositional polarity (fig. 8B). Inspection of modal data given by

TABLE 5

Summary of trend surface calculations for the Admiralty Intrusives\*

Chemical Parameter	Significance level of the linear model	Percent of variance explained by the model	Grid azimuth of maximum increase	Slope
SiO <sub>2</sub>	89.18	12.98	18°	1.31 wt%/100km
TiO <sub>2</sub>	71.92	7.63	134°	0.05 wt%/100km
Al <sub>2</sub> O <sub>3</sub>	97.28	20.17	184°	0.38 wt%/100km
Fe <sub>2</sub> O <sub>3</sub>	81.09	9.89	134°	0.43 wt%/100km
MnO	96.76	19.29	200°	0.01 wt%/100km
MgO	76.77	8.72	222°	0.36 wt%/100km
CaO	93.80	16.04	176°	0.41 wt%/100km
Na <sub>2</sub> O	99.99	47.36	214°	0.33 wt%/100km
K <sub>2</sub> O	99.98	41.43	7°	0.54 wt%/100km
K <sub>2</sub> O/Na <sub>2</sub> O	99.99	52.31	18°	0.23 /100km
Al number**	78.91	9.27	39°	0.02 /100km
K <sub>2</sub> O Index†	99.99	44.39	357°	15.40 /100km
Rb	99.99	44.51	7°	37.0 ppm/100km
Sr	99.30	26.63	225°	54.0 ppm/100km
Y‡	96.64	19.11	59°	7.0 ppm/100km
Zr	56.27	5.04	120°	10.0 ppm/100km
Ba	64.59	6.28	285°	47.0 ppm/100km
Rb/Sr	99.59	29.08	39°	0.7 /100km

\* Data used in these calculations are from Wyborn (unpublished data) and from Borg, Stump, and Holloway (1986; see also Borg, ms, 1984). Analyses of splits of the same rock powders at the two labs at which these data were produced demonstrate that interlab variations are small for all elements, and so the data from the two labs can be directly compared with a high degree of confidence (Borg, ms, 1984). Where these calculations might be affected by interlab variations, a note has been made. To avoid bias in the calculations due to high sample density of Wyborn's data in the Yule Bay region, 8 analyses of the 16 available were excluded from the calculations. Inclusion of these data does not change the results although details of the statistics are affected, actually strengthening the statistical significance of the trends.

\*\* Al number is defined as the molar ratio  $Al_2O_3/(K_2O+Na_2O+CaO)$ .

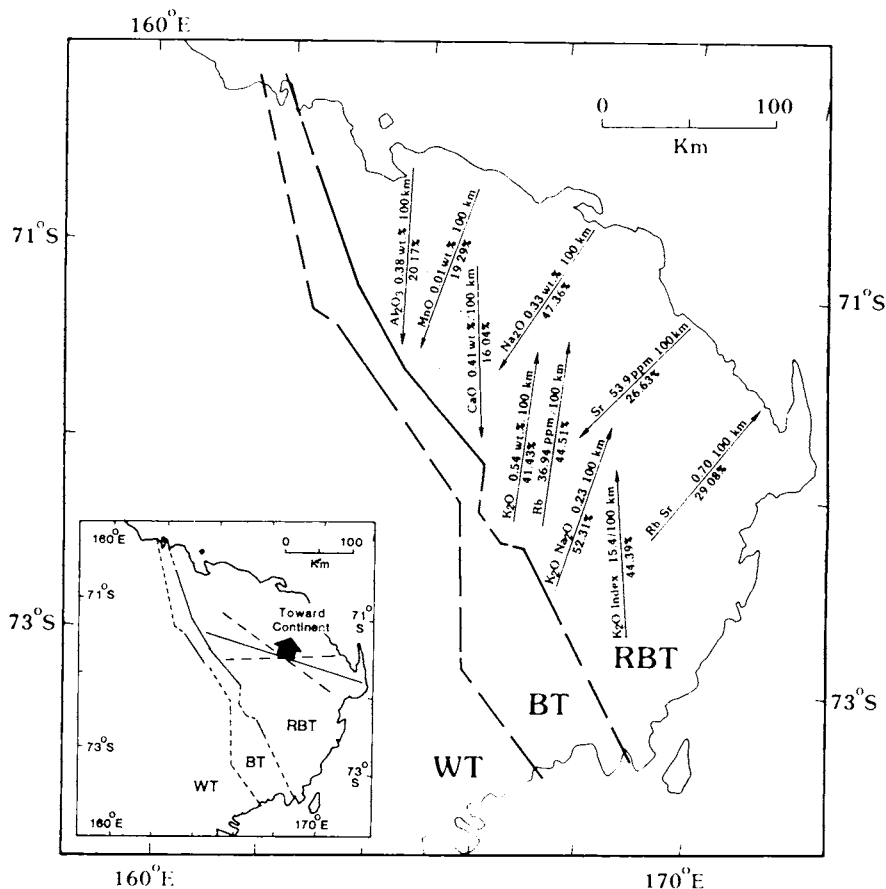
† K<sub>2</sub>O index is defined by Bateman and Dodge (1970) as  $(K_2O \times 1000)/(SiO_2 - 45)$ .

‡ Though the computations for Y suggest a significant correlation with position, and the trend is similar to trends of other parameters, the Y trend is not considered further in this paper. This is because the slope of the trend is only twice the range of variation between the two labs at which the data were produced and because all Wyborn's data are from the north and east.

Borg (ms, 1984) and Borg, Stump, and Holloway (1986) indicates that there is a tendency for hornblende to be more abundant in the southern granitoids (range, 2 to 15 v. percent; avg. 7 v. percent) relative to the northern granitoids (range, trace-8 v. percent; avg. 2 v. percent). This sort of mineralogical trend was mentioned by Wyborn (1981) in a discussion of northern relative to central (coastal) granitoids. Also, within rocks of similar silica content, the northern granitoids tend to contain slightly more K-feldspar and slightly less plagioclase than the southern granitoids. This latter characteristic results in the classification of the northern granitoids as granodiorites and monzogranites, whereas the southern samples are classified as tonalites and granodiorites.

Fig. 8

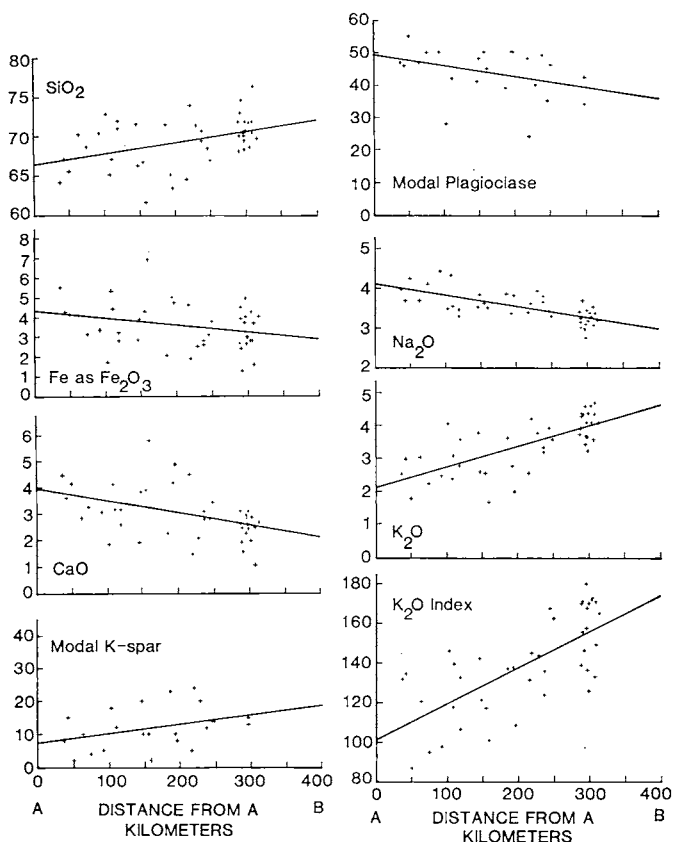
Compositional trends of major and trace components for the Admiralty Intrusives based on first-order trend-surface calculations.



A. The arrows indicate the direction of maximum increase of the various parameters. Shown on each arrow, to the right of the parameter, is the slope of the model trend-surface. Also, beneath each arrow is the percentage of the total variance accounted for by the first-order model. Only parameters significant at a confidence level >90 percent are shown. These trends define a strong chemical polarity in the Admiralty Intrusives. Inset map showing the trend of a continental margin in the BT and RBT at the time of emplacement of the Admiralty Intrusives as inferred from the compositional polarity. The dashed lines represent one standard deviation uncertainty of the trends calculated for (A). Note that this inferred continental margin trend should not be interpreted as the actual position but only as the orientation.

Initial Sr and Nd isotopic compositions calculated using an assumed age of 400 Ma (table 6) support the inferences made from the major and trace element compositional polarity. In figure 9, the sample locations are plotted on a map and the data have been projected onto a section parallel to the average direction of the significant (at 90 percent C.L.) chemical compositional trends (perpendicular to the inferred continental margin trend on fig. 8A).

Fig. 8 (continued)



B. Representative plots of various chemical and mineralogical parameters against distance. Each parameter has been projected onto a line parallel to the average "maximum slope direction" (parallel to the average direction of the lines in (A)). These graphs clearly document the validity of the variations calculated by the first-order trend-surface analysis. This chemical polarity is also reflected by model mineralogy. Plots of K-spar and plagioclase versus distance display this mineralogical variation with geographic position quite well.

Distinct trends are displayed by plots of both initial  $\epsilon_{Nd}$  (fig. 9B) and initial  $\epsilon_{Sr}$  (fig. 9C) against distance. Both  $\epsilon_{Nd}$  and  $\epsilon_{Sr}$  data indicate involvement of old, isotopically evolved material, and the regular geographic variations indicate a greater influence of old crustal material in granitoid genesis from south-southwest to north-northeast. These variations are in accord with the major and trace element polarity of AI, and whether attributed to mixing models (Farmer and DePaolo, 1983) or to systematic variations in the lower crustal granitoid source rocks (McCulloch and Chappell, 1982), they support the hypothesis of emplacement along a continental margin with the continental "inboard" direction to the north-northeast. With respect to a mixing model, the systematic variation of  $\epsilon_{Nd}$  and  $\epsilon_{Sr}$  requires more interaction (through assimilation and fractional

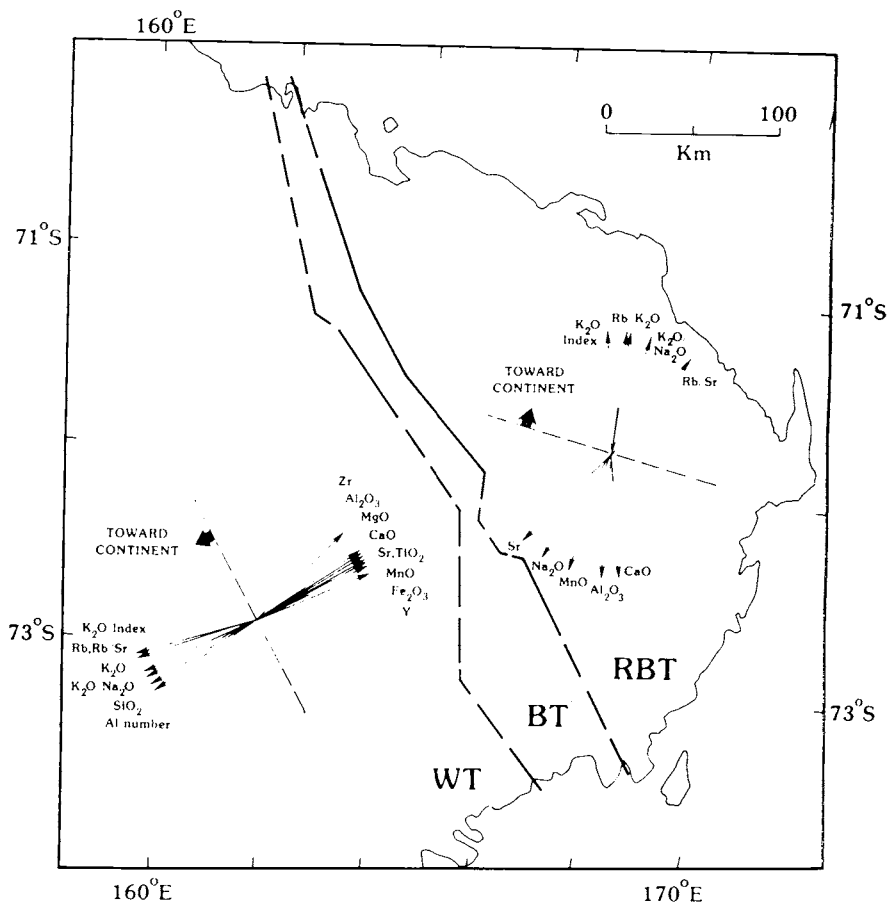


Fig. 10. Summary of the major and trace component polarity for the Granite Harbour Intrusives and for the Admiralty Intrusives. The two temporally and spatially separate groups of granitoids display distinct and drastically different polarities which demonstrate that they represent granitoid plutonism on two different continental margins. The BT + RBT must, therefore, be an allochthonous crustal entity.

The Devonian AI are found only within BT and RBT in NVL. As with GHI of WT, regional compositional variations of AI clearly define a marked chemical polarity (figs. 8 and 10). This polarity is drastically different from that displayed by GHI and is not compatible with emplacement of AI within an orogenic province on the margin of the EAC. Instead, it indicates that AI were emplaced along the margin of a continent which, relative to the present configuration of BT + RBT, lay to the north-northeast, as depicted in figure 10. This is interpreted as strong evidence that BT and RBT are allochthonous terranes into which Devonian AI were emplaced prior to assembly with WT to produce the present configuration. The recent report of pre-Admiralty granitoids on the northern coast of NVL by Vetter and others (1984) fits well with in-

terpretations made here and provides additional strong evidence that old continental crust lay to the north-northeast of the BT + RBT.

Nd and Sr isotopic data corroborate the inferences made with the major and trace element compositional polarity. Figure 11 is a diagram of a crustal section across NVL onto which initial  $\epsilon_{Nd}$  and  $\epsilon_{Sr}$  compositions have been projected. In WT the section parallels the trend of the polarity defined by GHI and then bends northward across BT and RBT running parallel to the polarity defined by AI.

For GHI, initial  $\epsilon_{Sr}$  values show a clearly defined regional variation which is consistent with inferences from major and trace element trends in demonstrating more involvement of isotopically evolved material from east-northeast to west-southwest within WT. Initial  $\epsilon_{Nd}$  is not quite so definitive as a progressive trend but does show that the one sample with the least "crustal" character is found along the northeast margin of WT. These isotopic characteristics of GHI may be interpreted to indicate crustal thickening from east-northeast to west-southwest within WT during emplacement of GHI, as shown on figure 11.

Within BT and RBT, initial  $\epsilon_{Nd}$  and  $\epsilon_{Sr}$  values for AI vary in a remarkably regular fashion from the south-southwest to the north-northeast (fig. 11). The most "crustal-like" values occur in the north-northeast, while the least "crustal-like" (and most "mantle-like") values occur in the south-southwest. These regular variations support the inference made from the major and trace element compositional trends that AI represent granitoids emplaced along the margin of an allochthonous terrane. The isotopic data for AI may be interpreted as evidence of crustal thickening from south-southwest to north-northeast within BT + RBT during emplacement of these granitoids (fig. 11).

The striking isotopic discontinuity between GHI and AI is quite evident on figure 11 and emphasizes the significance of these granitoids to crustal structure and tectonics. Isotopic discontinuities such as this are strong indicators of geologic discontinuities in the lower crust. That this discontinuity coincides with the boundary between WT and BT is compelling evidence for significant lower crustal differences between WT and BT. These terranes, therefore, may be separated by a major plate boundary, perhaps a transform fault. Because the isotopic variation of AI is regular across the Leap Year Fault, which separates BT from RBT, the lower crust in these terranes is thought to be a continuum, and hence the Leap Year Fault does not appear to be a major plate boundary. This evidence supports the inference by Wright and Findlay (1984) that the Leap Year Fault does not separate "exotic" terranes. Thus, the pronounced isotopic discontinuity between WT and BT + RBT and the isotopic continuity between BT and RBT support the hypothesis of an allochthonous origin of BT + RBT. The hypothesis that the crustal boundary between WT and BT + RBT is a transform may be supported indirectly by the granitoid data (especially the  $\epsilon_{Nd}$  and  $\epsilon_{Sr}$  data on fig. 11). The fact that the isotopic compositions of GHI appear to represent the "inboard" side of a

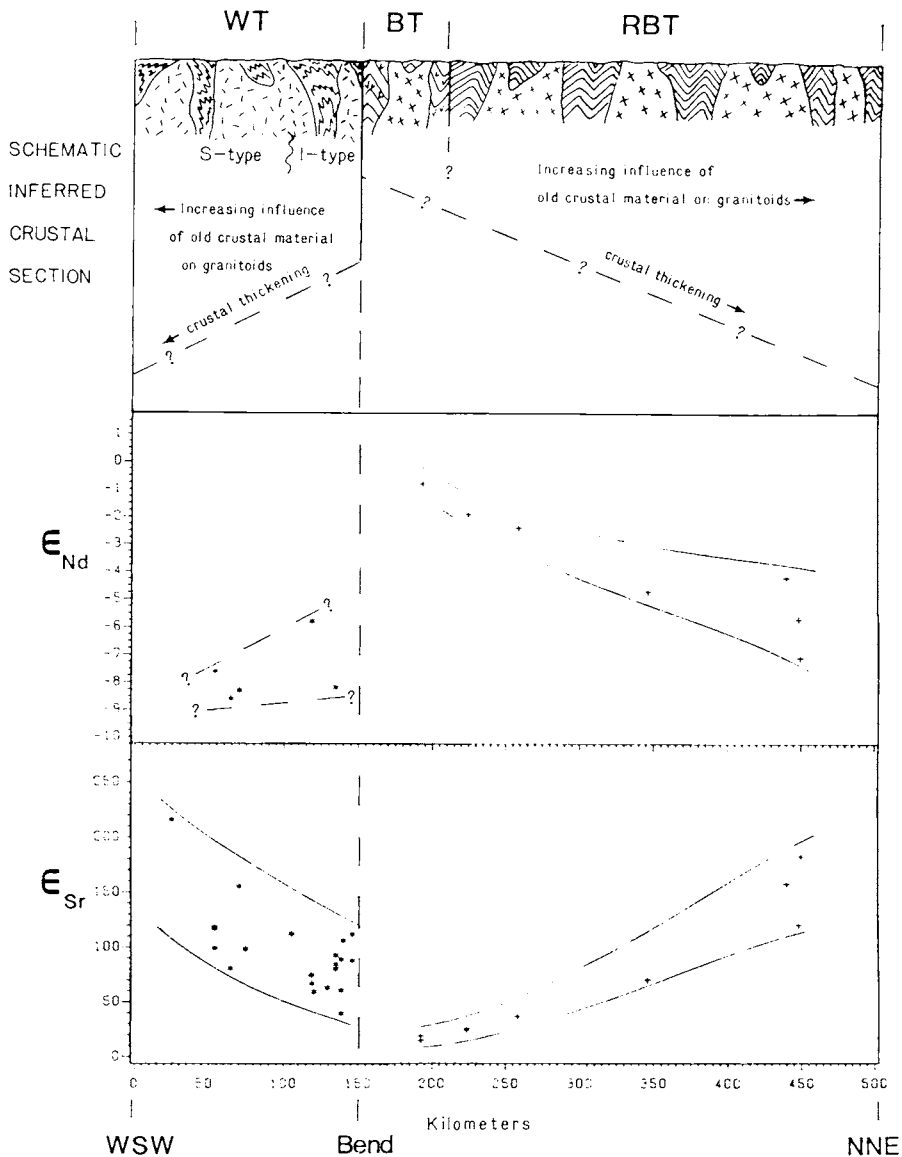


Fig. 11. Initial  $\epsilon_{Nd}$  and  $\epsilon_{Sr}$  of the AI and GHI plotted against distance along an inferred crustal section in NVL. The section runs parallel to the compositional polarity of the two groups of granitoids (see fig. 10) with a bend at the boundary between the WT and the BT. These isotopic data, along with the compositional polarity of the granitoids and the surface geology, allow interpretation of crustal structure in NVL. The isotopic data emphasize the discontinuity in the surface geology between the WT and the BT and are interpreted as evidence that the lower crust beneath the WT is distinct from the lower crust beneath the BT + RBT. The schematic inferred crustal section shows crustal thickening to the west-southwest in the WT and to the north-northeast in the BT + RBT which is inferred from models of continental margin granite genesis. The isotopic continuity among the AI in the BT and RBT support the interpretation that the lower crustal material in these regions is a continuum. Thus, this isotopic data strongly support an allochthonous origin for the BT + RBT. See text for further discussion.

continental margin magmatic province might be explained if the "out-board" side had been replaced by BT + RBT by movement on this transform.

On the basis of the granitoid data presented here, however, the preferred model of Weaver, Bradshaw, and Laird (1984, fig. 7) can be ruled out. The evidence for excluding this model is twofold. First, the regional compositional trends in AI of their model should be nearly opposite to the observed polarity. Second, there is no evidence that AI were emplaced into WT as terrane "stitching" granites as they suggest. Both field relations and chemical and isotopic data indicate that AI were emplaced only in BT and RBT. These two points are also somewhat difficult to reconcile with a relatively simple model of continuous westward subduction and continental collision, as envisaged by Gibson and Wright (1985), Kleinschmidt (1985), and Tessensohn (1985). Thus, it appears that the tectonic scenario for the development of NVL is unresolved.

The constraints which can be placed on tectonic models by the GHI and the AI data are:

1. Isotopic continuity of AI in BT and RBT indicates these terranes have been part of a continuous, but possibly varying, crustal unit, at least since emplacement of AI during the Devonian.

2. The isotopic discontinuities between, and different compositional polarities of, GHI and AI indicate that the continental crust in WT is significantly different than the continental crust in BT + RBT and indicate an allochthonous origin for BT + RBT.

3. The regular isotopic variations with position as well as the chemical polarity in AI can be explained by: (A) a north-northeasterly dipping subduction zone which, relative to present orientations, probably existed to the south-southwest of BT + RBT during emplacement of AI, and/or (B) crustal thickness and perhaps lower crustal age of BT + RBT increasing to the north-northeast.

4. If the AI are viewed as subduction related granitoids, then their polarity requires that BT + RBT was juxtaposed to the WT sometime after their emplacement in the Devonian. If AI are not viewed as directly related to subduction then the polarity may not offer any insight to the timing of tectonic events. However, the apparent absence of AI in the WT tends to support an interpretation of AI emplacement in BT + RBT followed by juxtaposing of these terranes against WT.

5. Isotopic compositions and polarity of GHI and AI suggest that the continental outboard portions of each of these plutonic provinces is missing. Any models for the tectonic evolution of NVL must account for this situation.

Mid- to late-Paleozoic (post-Admiralty) magmatic rocks occur at scattered localities within NVL. These include the Salamander Granite Complex (SGC), Gallipoli Rhyolites, and volcanics at Mt. Black Prince and Lawrence Peaks. At present, however, these rocks provide no constraints on

tectonic models for NVL (Borg, Stump, and Holloway, 1986; Borg and Stump, 1987). The fact that Black Prince and Lawrence Peaks volcanics occur in BT and RBT, which have been shown to be related by this study, may indicate that they are related to a common volcanic province. However, there is no basis at all for correlating Gallipoli Rhyolites with either Black Prince or the Lawrence Peaks Volcanics, and, thus, the most that can be said with certainty is that the presence of these three volcanic entities establishes that late Paleozoic volcanism occurred in each of the three terranes.

The SGC appears to be emplaced into WT, but no contacts are known. It may have been related to volcanism but correlation with Gallipoli Rhyolites, and thus a firm tie to WT is excluded because of chemical differences. For the present, therefore, the SGC and Gallipoli Rhyolites appear to represent distinct occurrences of Carboniferous magmatic rocks in WT, and they do not provide any constraints to tectonic models. Though not likely, it is possible that the SGC may be within BT. In this case, the SGC would simply represent another aspect of magmatic activity within BT + RBT during the Carboniferous.

The new information on the Paleozoic granitoids, presented here, requires that the tectonic evolution of NVL be viewed in terms of two separate crustal entities, the WT and the BT + RBT. The most plausible sequence of events in the development of NVL is outlined in table 7. The WT developed on the margin of the EAC as rocks of WG were folded, metamorphosed, and intruded by GHI in middle to late Cambrian time. Although rocks of BT and RBT may have developed together, final assembly of these terranes, via thrusting on the Leap Year fault, occurred prior to emplacement of AI. This event is probably represented by the metamorphism and folding of the rocks in these terranes. Juxtaposing of BT + RBT against WT is interpreted to have occurred after emplacement of Devonian AI and may have occurred somewhat later. The presence of Beacon rocks depositionally overlying BSG on the western side of the Leitch Massif (Essensohn, 1981) constrains the assembly of BT + RBT with WT to be pre-Beacon (presumably Permian in this area). The nature and age of the Lanterman Fault (between WT and BT) as well as the tectonic setting of the mid- to late-Paleozoic volcanics and the SGC remain important problems which may provide further constraints.

In view of the key position occupied by NVL in reconstructions of Gondwana, the relationships discussed above have important implications to the assembly and perhaps the initial break-up of this portion of the supercontinent. For example, a comparison of the chemical and isotopic signatures of the granites of NVL with those of southern and southeastern Australia would provide a logical test for the reconstruction proposed by Stump, White, and Borg (1986). Also, these findings imply that adjacent areas along this margin of Gondwana may contain allochthonous crustal blocks similar to BT and RBT. Integration of these relationships with the geology of West Antarctica, southern and southeastern Australia,

TABLE 7

Sequence of tectonic events inferred for northern Victoria Land

<u>Age</u>	<u>Wilson Terrane</u>	<u>Bowers and Robertson Bay Terranes</u>
~ 60-100 Ma	Break-up of the Antarctic-Australian segment of Gondwana. The configuration of the three terranes in NVL just prior to break-up must have been essentially as it is today as constrained by the continuity of the magnetic anomalies on the floor of the Southern Ocean between Antarctica and Australia.	
Jurassic	Emplacement of Ferrar dolerite sills and lava flows.	
Permian	Widespread deposition of the Beacon Supergroup.	Sediments of the Beacon Supergroup are present at one outcrop in the BT.
-----		
Juxtaposing of the terranes must have occurred by this time as indicated by the presence of Beacon Supergroup rocks in the Wilson and Bowers Terranes.		
-----		
Carboniferous	Emplacement of Gallipoli Rhyolites and Salamander Granite Complex.	Emplacement of Black Prince and Lawrence Peaks Volcanics after the A1, or possibly concurrent with latest A1.
-----		
Juxtaposing may have occurred as early as the Carboniferous but must have occurred after emplacement of the A1. This is based on the interpretation that the A1 were emplaced along a continental margin.		
-----		
Devonian		Emplacement of A1 along a continental margin with the continent to the NNE (relative to present orientation).
Ordovician-Silurian(?)		Folding of Bowers Supergroup and Robertson Bay Group. Folding may have accompanied thrusting (Bowers over Robertson Bay), which assembled the BT with the RBT.
Middle-Late Cambrian	GHI emplacement along the East Antarctic continental margin associated with a convergent plate boundary. Now only the "inboard" portion of the batholithic terrane is left.	Development of a Cambrian magmatic arc and associated sediments (Bowers Supergroup). Deposition of turbidites (Robertson Bay Group). Just where these two lithologic groups developed and any relationship between them is unknown.
Cambrian	Deformation/metamorphism of the Wilson Group.	
Precambrian(?)	Deposition of the Wilson Group along the margin of East Antarctica.	

Tasmania, and New Zealand is of paramount importance in further resolving the tectonic history of the region.

ACKNOWLEDGMENT

Field work was done under the auspices of the U.S. Antarctic Research Program. Special thanks go to pilots, crew, and ground support personnel of the U.S. Navy Antarctic Development Squadron VXE-6 who provided transportation in the field. The analytical work done by Dr. H. Hensel at the Australian National University is gratefully acknowledged.

Funding for this work was provided by NSF grants DPP8019991 and DPP8216281.

## REFERENCES

- Adams, C. J. D., Gabites, J. E., and Grindley, G. W., 1982, Orogenic history of the Central Transantarctic Mountains: New K-Ar age data on the Precambrian-Lower Paleozoic basement, in Craddock, C., ed., *Antarctic Geoscience*: Madison, Univ. Wisconsin Press, p. 817-826.
- Adams, C. J. D., Gabites, J. E., Wodzicki, A., Laird, M. G., and Bradshaw, J. D., 1982, Potassium-Argon geochronology of the Precambrian-Cambrian Wilson and Robertson Bay Groups and Bowers Supergroup, northern Victoria Land, Antarctica, in Craddock, C., ed., *Antarctic Geoscience*: Madison, Univ. Wisconsin Press, p. 543-548.
- Armstrong, R. L., 1978, K-Ar dating: Late Cenozoic McMurdo Volcanic Group and dry valley glacial history, Victoria Land, Antarctica: *New Zealand Jour. Geology Geophysics*, v. 21, p. 685-698.
- Atherton, M. P., McCourt, W. J., Sanderson, L. M., and Taylor, W. P., 1979, The geochemical character of the segmented Peruvian coastal batholith and associated volcanics, in Atherton, M. P., and Tarney, J., eds., *Origin of Granite Batholiths*: Kent, Shiva, *Geochem. Evidence*, p. 45-64.
- Atherton, M. P., and Tarney, J., eds., 1979, *Origin of Granite Batholiths*: Kent, Shiva, *Geochem. Evidence*, 148 p.
- Baird, A. K., Baird, K. W., and Welday, E. E., 1974, Chemical trends across Cretaceous batholithic rocks of southern California: *Geology*, v. 2, p. 493-496.
- 1979, Batholithic rocks of the northern Peninsular and Transverse Ranges, southern California, in Abbott, P. L., and Todd, V. R., eds., *Mesozoic Crystalline Rocks*: San Diego State Univ. Dept. Geol. Sci., p. 111-132.
- Baird, A. K., and Miesch, A. T., 1984, Batholithic rocks of southern California—A model for the petrochemical nature of their source materials: U.S. Geol. Survey Prof. Paper 1284, 42 p.
- Barker, F., 1981, Introduction to special issue on granites and rhyolites: A commentary for the nonspecialist: *Jour. Geophys. Research*, v. 86, p. 10131-10135.
- Barrett, P. J., Grindley, G. W., and Webb, P. N., 1972, The Beacon Supergroup of East Antarctica, in Adie, R. J., ed., *Antarctic Geology and Geophysics*: Oslo, Universitetsforlaget, p. 319-332.
- Bateman, P., 1983, A summary of critical relations in the central part of the Sierra Nevada batholith, California, U.S.A., in Roddick, J. A., ed., *Circum-Pacific Plutonic Terranes*: Geol. Soc. America Mem. 159, p. 241-254.
- Bateman, P., and Dodge, F. W. C., 1970, Variations of major chemical constituents across the central Sierra Nevada batholith: *Geol. Soc. America Bull.*, v. 81, p. 409-420.
- Borg, S. G., ms, 1980, Petrology and geochemistry of the Wyatt Formation and the Queen Maud Batholith, upper Scott Glacier area, Antarctica: M.S. thesis, Arizona State Univ. Tempe, 100 p.
- 1983, Petrology and geochemistry of the Queen Maud Batholith, central Transantarctic Mountains, with implications for the Ross Orogeny, in Oliver, R. L., James, P. R., and Jago, J. B., eds., *Antarctic Earth Science*: Canberra, Australian Acad. Sci., p. 165-169.
- ms, 1984, Granitoids of northern Victoria Land, Antarctica: Ph.D. dissert., Dept. Geology, Arizona State Univ., Tempe, 355 p.
- Borg, S. G., Chappell, B. W., McCulloch, M. T., Stump, E., Wyborn, D., and Holloway, J. R., 1984, Compositional polarity of granitoids with implications to regional geology, northern Victoria Land, Antarctica [abs.]: *Geol. Soc. America Abs. with Programs*, v. 16, p. 450.
- Borg, S. G., and Stump, E., 1987, Paleozoic magmatism and associated tectonic problems of northern Victoria Land, Antarctica: *Geophys. Mon. Ser.*, v. 40, p. 68-76.
- Borg, S. G., Stump, E., and Holloway, J. R., 1986, Granitoids of northern Victoria Land, Antarctica: A reconnaissance study of field relations, petrography and geochemistry, in Stump, E., ed., *Geological Investigations in northern Victoria Land*: Am. Geophys. Union, Antarctic Research Ser., v. 46, p. 115-188.
- Bradshaw, J. D., Andrews, P. B., and Field, B. D., 1983, Swanson Formation and related rocks of Marie Byrd Land and a comparison with the Robertson Bay Group of northern Victoria Land, in Oliver, R. L., James, P. R., and Jago, J. B., eds., *Antarctic Earth Science*: Canberra, Australian Acad. Sci., p. 274-279.

- Bradshaw, J. D., and Laird, M. G., 1983, The pre-Beacon geology of northern Victoria Land: A review, *in* Oliver, R. L., James, P. R., and Jago, J. B., eds., *Antarctic Earth Science: Canberra, Australian Acad. Sci.*, p. 98-101.
- Bradshaw, J. D., Laird, M. G., and Wodzicki, A., 1982, Structural style and tectonic history in northern Victoria Land, *in* Craddock, C., ed., *Antarctic Geoscience: Madison, Univ. Wisconsin Press*, p. 809-816.
- Bradshaw, J. D., Weaver, S. D., and Laird, M. G., 1985, Suspect terranes and Cambrian tectonics in northern Victoria Land, Antarctica, *in* Howell, D. G., ed., *Tectonostratigraphic Terranes of the Circum-Pacific Region: Houston, Circum-Pacific Council for Energy and Mineral Resources*, p. 467-479.
- Burrett, C. F., and Findlay, R. H., 1984, Cambrian and Ordovician conodonts from the Robertson Bay Group, Antarctica, and their tectonic significance: *Nature*, v. 307, p. 723-726.
- Chappell, B. W., and White, A. J. R., 1974, Two contrasting granite types: *Pacific Geology*, v. 8, p. 173-174.
- Compston, W., and Chappell, B. W., 1979, Sr-isotopic evolution of granitoid source rocks, *in* McElhinny, M. W., ed., *The Earth: Its Origin, Structure and Evolution: London, Academic Press*, p. 377-426.
- Condie, K. C., 1976, *Plate Tectonics and Crustal Evolution: New York, Pergamon Press*, New York, 288 p.
- Cooper, R. A., Jago, J. B., MacKinnon, D. I., Simes, J. E., and Braddock, P. R., 1976, Cambrian fossils from the Bowers Group, northern Victoria Land, Antarctica (preliminary notes): *New Zealand Jour. Geology Geophysics*, v. 19, p. 283-288.
- Cooper, R. A., Jago, J. B., Rowell, A. J., and Braddock, P., 1983, Age and correlation of the Cambrian-Ordovician Bowers Supergroup, northern Victoria Land, *in* Oliver, R. L., James, P. R., and Jago, J. B., eds., *Antarctic Earth Science: Canberra, Australian Acad. Sci.*, p. 128-131.
- Craddock, C., 1972, Antarctic Tectonics, *in* Adie, R. J., *Antarctic Geology and Geophysics: Oslo, Universitetsforlaget*, p. 449-455.
- Crowder, D. F., 1968, Geology of a part of northern Victoria Land: U.S. Geol. Survey Prof. Paper 600-D, p. 95-107.
- DePaolo, D. J., 1980, Sources of continental crust: Neodymium isotope evidence from the Sierra Nevada and Peninsular Ranges: *Science*, v. 209, p. 684-687.
- 1981a, A neodymium and strontium isotopic study of Mesozoic calc-alkaline granitic batholiths of the Sierra Nevada and Peninsular Ranges, California: *Jour. Geophys. Research*, v. 86, p. 10470-10488.
- 1981b, Nd in the Colorado Front Range and implications for crust formation and mantle evolution in the Proterozoic: *Nature*, v. 291, p. 193-196.
- 1981c, Trace element and isotopic effects of combined wallrock assimilation and fractional crystallization: *Earth Planetary Sci. Letters*, v. 53, p. 189-202.
- DePaolo, D. J., and Wasserburg, G. J., 1976, Nd isotopic variations and petrogenetic models: *Geophys. Research Letters*, v. 3, p. 249-252.
- 1979, Petrogenic mixing models and Nd-Sr isotopic patterns: *Geochim. et Cosmochim. Acta*, v. 43, p. 615-627.
- Dickinson, W. R., 1975, Potash-depth (K-h) relations in continental margin and intra-oceanic magmatic arcs: *Geology*, v. 3, p. 53-56.
- Dow, J. A. S., and Neall, V. E., 1972, A summary of the geology of the lower Rennick Glacier, northern Victoria Land, Antarctica, *in* Adie, R. J., ed., *Antarctic Geology and Geophysics: Oslo, Universitetsforlaget*, p. 339-344.
- 1974, Geology of the lower Rennick Glacier, northern Victoria Land, Antarctica: *New Zealand Jour. Geology Geophysics*, v. 17, p. 659-714.
- Elliot, D. H., 1975, Tectonics of Antarctica: A review: *Am. Jour. Sci.*, v. 275-A, p. 45-106.
- Farmer, G. L., and DePaolo, D. J., 1983, Origin of Mesozoic and Tertiary granite in the western United States and implications for Pre-Mesozoic crustal structure: 1. Nd and Sr Isotopic Studies in the Geocline of the Northern Great Basin: *Jour. Geophys. Research*, v. 88, p. 3379-3401.
- Faure, G., Eastin, R., Ray, P. T., McLelland, D., and Shultz, C., 1979, Geochronology of igneous and metamorphic rocks, central Transantarctic Mountains, *in* Laskar, B., and Rao, C. S., eds., *Fourth International Gondwana Symposium Papers*, v. 1, January, 1977, p. 805-813.
- Field, B. D., and Findlay, R. H., 1983, The sedimentology of the Robertson Bay Group, northern Victoria Land, *in* Oliver, R. L., James, P. R., and Jago, J. B., eds., *Antarctic Earth Science: Canberra, Australian Acad. Sci.*, p. 102-106.

- Findlay, R. H., and Field, B. D., 1982, Black Prince volcanics, Admiralty Mountains: Reconnaissance observations: *New Zealand Antarctic Rec.*, v. 4, p. 11-14.
- 1983, Tectonic significance of deformations affecting the Robertson Bay Group and associated rocks, northern Victoria Land, Antarctica, in Oliver, R. L., James, P. R., and Jago, J. B., eds., *Antarctic Earth Science: Canberra, Australian Acad. Sci.*, p. 107-112.
- Findlay, R. H., and Jordan, H., 1984, Volcanics at Mt. Black Prince and Lawrence Peaks, northern Victoria Land, Antarctica: *Geol. Jahrb.*, v. B60, p. 143-152.
- Gair, H. S., 1964, Geology of upper Rennick, Campbell and Aviator Glaciers, northern Victoria Land, in Adie, R. J., ed., *Antarctic Geology: Amsterdam, North-Holland*, p. 188-198.
- 1967, The geology from the upper Rennick Glacier to the coast, northern Victoria Land, Antarctica: *New Zealand Jour. Geology Geophysics*, v. 10, p. 309-344.
- Gair, H. S., Sturm, A., Carryer, S. J., and Grindley, G. W., 1969, The geology of northern Victoria Land, in Bushnell, V. C., and Craddock, C., eds., *Geologic Maps of Antarctica: New York, Am. Geog. Soc., Antarctic Map Folio Ser.*, v. 12, pl. XII.
- Gastil, G., 1983, Mesozoic and Cenozoic granitic rocks of southern California and western Mexico, in Roddick, J. A., ed., *Circum-Pacific Plutonic Terranes: Geol. Soc. America Mem.* 159, p. 265-275.
- Gibson, G. M., and Wright, T. O., 1985, Importance of thrust faulting in the tectonic development of northern Victoria Land, Antarctica: *Nature*, v. 315, p. 480-483.
- Grew, E. S., Kleinschmidt, G., and Schubert, W., 1984, Contrasting metamorphic belts in north Victoria Land, Antarctica: *Geol. Jahrb.*, v. B60, p. 253-263.
- Grindley, G. W., 1981, Precambrian rocks of the Ross Sea region: *Royal Soc. New Zealand Jour.*, v. 11, p. 411-423.
- Grindley, G. W., and Oliver, P. J., 1983, Post-Ross Orogeny Cratonisation of northern Victoria Land, in Oliver, R. L., James, P. R., and Jago, J. B., eds., *Antarctic Earth Science: Canberra, Australian Acad. Sci.*, p. 133-139.
- Grindley, G. W., and Warren, G., 1964, Stratigraphic nomenclature and correlation in the western Ross Sea region, in Adie, R. J., ed., *Antarctic Geology: Amsterdam, North-Holland*, p. 314-333.
- Gunn, G. M., and Warren, G., 1962, Geology of Victoria Land between the Mawson and Mullock Glaciers, Antarctica: *New Zealand Geol. Survey Bull.*, v. 71, 157 p.
- Hamilton, W., 1964, Tectonic map of Antarctica—A progress report, in Adie, R. J., ed., *Antarctic Geology: Amsterdam, North-Holland*, p. 676-680.
- 1965, Diabase sheets of the Taylor Glacier region, Victoria Land, Antarctica: *U.S. Geol. Survey Prof. Paper* 456, 71 p.
- 1967, Tectonics of Antarctica: *Tectonophysics*, v. 4, p. 555-568.
- 1972, The Hallett volcanic Province, Antarctica: *U.S. Geol. Survey Prof. Paper* 456-C, 62 p.
- Harrington, H. J., 1958, Nomenclature of rock units in the Ross Sea region, Antarctica: *Nature*, v. 182, p. 290.
- Harrington, H. J., Wood, B. L., McKellar, I. C., and Lenson, G. J., 1964, The geology of Cape Hallett-Tucker Glacier district, in Adie, R. J., ed., *Antarctic Geology: Amsterdam, North-Holland*, p. 220-228.
- 1967, Topography and geology of the Cape Hallett District, Victoria Land, Antarctica: *New Zealand Geol. Survey Bull.*, v. 80, p. 1-100.
- Ishihara, S., 1977, The magnetite-series and ilmenite-series granitic rocks: *Mining Geology*, v. 27, p. 293-305.
- Kistler, R. W., Ghent, E. D., and O'Neil, J., 1981, Petrogenesis of garnet two-mica granites in the Ruby Mountains, Nevada: *Jour. Geophys. Research*, v. 86, p. 10591-10606.
- Kistler, R. W., and Peterman, Z. E., 1973, Variations in Sr, Rb, K, Na, and initial  $^{87}\text{Sr}/^{86}\text{Sr}$  in Mesozoic granitic rocks and intruded wall rocks in central California: *Geol. Soc. America Bull.*, v. 84, p. 3489-3512.
- 1978, Reconstruction of crustal blocks of California on the basis of initial strontium isotopic compositions of Mesozoic granitic rocks: *U.S. Geol. Survey Prof. Paper* 1071, 17 p.
- Kleinschmidt, G., 1981, Regional metamorphism in the Robertson Bay Group area and in the southern Daniels Range, north Victoria Land, Antarctica: *Geol. Jahrb.*, v. B41, p. 201-228.
- 1985, Early Paleozoic westward directed subduction at the Antarctic Pacific margin: Evidence from metamorphic belts in northern Victoria Land [abs.]: *Gondwana Symposium*, 6th, The Ohio State Univ., Columbus.

- Kleinschmidt, G., Roland, N. W., and Schubert, W., 1984, The metamorphic basement in the Mountaineer Range, north Victoria Land, Antarctica: *Geol. Jahrb.*, v. B60, p. 213-251.
- Kleinschmidt, G., and Skinner, D. N. B., 1981, Deformation styles in the basement rocks of north Victoria Land, Antarctica: *Geol. Jahrb.*, v. B41, p. 155-200.
- Kreuzer, H., Höhdorf, A., Lenz, H., Vetter, U., Tessensohn, F., Müller, P., Jordan, H., Harve, W., and Besang, C., 1981, K/Ar and Rb/Sr dating of igneous rocks from north Victoria Land, Antarctica: *Geol. Jahrb.*, v. B41, p. 265-273.
- Laird, M. G., 1981, Lower Palaeozoic rocks of Antarctica, in Holland, C. H., ed., *Lower Palaeozoic of the Middle East, Eastern and Southern Africa, and Antarctica*: Chichester, John Wiley & Sons Ltd., p. 257-314.
- Laird, M. G., Andrews, P. B., and Kyle, P. R., 1974, Geology of northern Evans Névé, Victoria Land, Antarctica: *New Zealand Jour. Geology Geophysics*, v. 17, p. 587-601.
- Laird, M. G., Andrews, P. B., Kyle, P., and Jennings, P., 1972, Late Cambrian fossils and the age of the Ross Orogeny, Antarctica: *Nature*, v. 238, p. 34-36.
- Laird, M. G., and Bradshaw, J. D., 1982, Uppermost Proterozoic and Lower Paleozoic geology of the Transantarctic Mountains (Review Paper), in Craddock, C., ed., *Antarctic Geoscience*: Madison, Univ. Wisconsin Press, p. 525-534.
- , 1983, New data on the Lower Paleozoic Bowers Supergroup, northern Victoria Land, in Oliver, R. L., James, P. R., and Jago, J. B., eds., *Antarctic Earth Science*: Canberra, Australian Acad. Sci., p. 123-126.
- Laird, M. G., Bradshaw, J. D., and Wodzicki, A., 1982, Stratigraphy of the upper Precambrian and lower Paleozoic Bowers Supergroup, northern Victoria Land, Antarctica, in Craddock, C., ed., *Antarctic Geoscience*: Madison, Univ. Wisconsin Press, p. 535-542.
- Laird, M. G., Cooper, R. A., and Jago, J. B., 1977, New data on the lower Palaeozoic sequence of northern Victoria Land, Antarctica, and its significance for Australian-Antarctic relations in the Palaeozoic: *Nature*, v. 265, p. 107-110.
- LeCouteur, P. C., and Leitch, E. C., 1964, Preliminary report on the geology of an area southwest of the Upper Tucker Glacier, northern Victoria Land, in Adie, R. J., ed., *Antarctic Geology*: Amsterdam, North-Holland, p. 229-236.
- Liew, T. C., and McCulloch, M. T., 1985, Genesis of granitoid batholiths of Peninsular Malaysia and implications for models of crustal evolution: Evidence from a Nd-Sr isotopic and U-Pb zircon study: *Geochim. et Cosmochim. Acta*, v. 49, p. 587-600.
- Loiselle, M. C., and Wones, D. R., 1979, Characteristics of anorogenic granites [abs.]: *Geol. Soc. America Abs. with Programs*, v. 11, p. 468.
- McCulloch, M. T., and Chappell, B. W., 1982, Nd isotopic characteristics of S- and I-type granites: *Earth Planetary Sci. Letters*, v. 58, p. 51-64.
- Miller, C. F., and Bradfish, L. J., 1980, An inner Cordilleran belt of muscovite-bearing plutons: *Geology*, v. 8, p. 412-416.
- Moore, J. G., 1959, Quartz diorite boundary line in the western United States: *Jour. Geology*, v. 67, p. 198-210.
- Mortimer, G., Schmidt-Thome, M., and Tessensohn, F., 1984, Stratigraphic problems in the upper part of the Bowers Supergroup, north Victoria Land, Antarctica: *Geol. Jahrb.*, v. B60, p. 83-103.
- Nathan, S., 1971a, Potassium-argon dates from the area between Priestley and Mariner Glaciers, northern Victoria Land, Antarctica: *New Zealand Jour. Geology Geophysics*, v. 14, p. 504-511.
- , 1971b, Geology and petrology of the Campbell-Aviator divide, northern Victoria Land, Antarctica. Part 2-Paleozoic and Precambrian rocks: *New Zealand Jour. Geology Geophysics*, v. 14, p. 564-596.
- Nathan, S., and Shulte, F. J., 1968, Geology and petrology of the Campbell-Aviator divide, north Victoria Land, Antarctica: *New Zealand Jour. Geology Geophysics*, v. 11, p. 940-975.
- Nathan, S., and Skinner, D. N. B., 1971, Recent advances in the Pre-Permian geology of northern Victoria Land, in Adie, R. J., ed., *Antarctic Geology and Geophysics*: Oslo, Universitetsforlaget, p. 333-337.
- Nelson, B. K., and DePaolo, D. J., 1984, 1,700-Myr greenstone volcanic successions in southwestern North America and isotopic evolution of the Proterozoic mantle: *Nature*, v. 311, p. 143-146.
- Oliver, R. L., 1964, Some basement rock relations in Antarctica, in Adie, R. J., ed., *Antarctic Geology*: Amsterdam, North-Holland, p. 259-264.
- Picciotto, E., and Coppez, A., 1964, Bibliography of absolute age determinations in Antarctica (addendum), in Adie, R. J., ed., *Antarctic Geology*: Amsterdam, North-Holland, p. 563-569.

- Pitcher, W. S., 1979, The nature, ascent and emplacement of granitic magmas: *Geol. Soc. London Jour.*, v. 136, p. 627-662.
- 1982, Granite type and tectonic environment, in Hsü, K. J., ed., *Mountain Building Processes*: London, Academic Press, p. 19-40.
- Presnall, D. C., and Bateman, P. C., 1973, Fusion relationships in the system  $\text{NaAlSi}_3\text{O}_8$ - $\text{CaAl}_2\text{Si}_2\text{O}_7$ - $\text{KAlSi}_3\text{O}_8$ - $\text{SiO}_2$ - $\text{H}_2\text{O}$  and generation of granitic magmas in the Sierra Nevada batholith: *Geol. Soc. America Bull.*, v. 84, p. 3181-3202.
- Rastall, R. A., and Priestley, R. E., 1921, The slate-greywache Formation of Robertson Bay: Natural History Report, British Antarctic Expedition 1910-13; *Geology*, v. 1, p. 121-129.
- Reed, B. L., Miesch, A. T., and Lanphere, M. A., 1983, Plutonic rocks of Jurassic age in the Alaska-Aleutian Range batholith: Chemical variations and polarity: *Geol. Soc. America Bull.*, v. 94, p. 1232-1240.
- Riddolls, B. W., and Hancox, G. T., 1968, Geology of the upper Mariner Glacier region, north Victoria Land, Antarctica: *New Zealand Jour. Geology Geophysics*, v. 11, p. 881-899.
- Roddick, J. A., ed., 1983, *Circum-Pacific Plutonic Terranes*: *Geol. Soc. America Mem.* 159, 316 p.
- Saunders, A. D., Tarney, J., and Weaver, S. D., 1980, Transverse geochemical variations across the Antarctic Peninsula: Implications for the genesis of calc-alkaline magmas: *Earth Planetary Sci. Letters*, v. 46, p. 344-360.
- Silver, L. T., Early, T. O., and Anderson, T. H., 1975, Petrological, geochemical and geochronological asymmetries of the Peninsular Ranges batholith: *Geol. Soc. America Abs. with Programs*, v. 7, p. 375-376.
- Skinner, D. N. B., and Ricker, J., 1968, The geology of the region between the Mawson and Priestley Glaciers, north Victoria Land, Antarctica. Part 1—Basement meta-sedimentary and igneous rocks: *New Zealand Jour. Geology Geophysics*, v. 11, p. 1009-1040.
- Stem, C. R., and Stroup, J. B., 1982, The petrochemistry of the Patagonian Batholith, Ultima Esperanza, Chile, in Craddock, C., ed., *Antarctic Geoscience*: Madison, Univ. Wisconsin Press, p. 135-142.
- Streckheisen, A., 1976, To each plutonic rock its proper name: *Earth Sci. Rev.*, v. 12, p. 1-33.
- Strong, D. F., and Dickson, W. L., 1978, Geochemistry of Paleozoic granitoid plutons from contrasting tectonic zones of northeast Newfoundland: *Canadian Jour. Earth Sci.*, v. 15, p. 145-156.
- Stump, E., 1973, Earth evolution in the Transantarctic Mountains and West Antarctica, in Tarling, D. H., and Runcorn, S. K., eds., *Implications of Continental Drift to the Earth Sciences*, v. 2: London-New York, Acad. Press, p. 909-924.
- ms, 1976, On the Late Precambrian-Early Paleozoic metavolcanic and meta-sedimentary rocks of the Queen Maud Mountains, Antarctica, and a comparison with rocks of similar age from southern Africa: Ph.D. dissert., The Ohio State Univ., Columbus, 212 p.
- 1982, The Ross Supergroup in the Queen Maud Mountains, in Craddock, C., ed., *Antarctic Geoscience*: Madison, Univ. Wisconsin Press, p. 565-570.
- Stump, E., Holloway, J. R., Borg, S. G., and Armstrong, R. L., 1983a, Discovery of a Tertiary granite pluton, northern Victoria Land: *Antarctic Jour. U.S.*, v. 18, p. 17-18.
- Stump, E., Holloway, J. R., Borg, S. G., and Lapham, K. E., 1982, Geological investigations of early to middle Paleozoic rocks, northern Victoria Land: *Antarctic Jour. U.S.*, v. 17, p. 17-18.
- Stump, E., Laird, M. G., Bradshaw, J. D., Holloway, J. R., Borg, S. G., and Lapham, K. E., 1983b, Bowers graben and associated tectonic features cross northern Victoria Land, Antarctica: *Nature*, v. 304, p. 334-335.
- Stump, E., White, A. J. R., and Borg, S. G., 1986, Reconstruction of Australia and Antarctica: Evidence from granites and recent mapping: *Earth Planetary Sci. Letters*, v. 79, p. 348-360.
- Stumm, A. G., and Carryer, S., 1970, Geology of the region between Matusевич and Tucker Glaciers, northern Victoria Land, Antarctica: *New Zealand Jour. Geology Geophysics*, v. 13, p. 408-435.

- Tessensohn, F., 1981, The basement units of northern Victoria Land: *Royal Soc. New Zealand Jour.*, v. 11, p. 461-464.
- 1984, Geological and tectonic history of the Bowers Structural Zone, north Victoria Land, *Antarctica: Geol. Jahrb.*, v. B60, p. 371-396.
- 1985, Early Paleozoic westward directed subduction at the Antarctic Pacific margin: Evidence from the tectonic history of northern Victoria Land [abs.]: *Gondwana Symposium*, 6th, The Ohio State Univ., Columbus.
- Tessensohn, F., Duphorn, K., Jordan, H., Kleinschmidt, G., Skinner, D. N. B., Vetter, U., Vetter, T., Wright, T. O., and Wyborn, D., 1981, Geological comparison of basement units in north Victoria Land, *Antarctica: Geol. Jahrb.*, v. B41, p. 31-88.
- Vetter, U., Lenz, H., Kreuzer, H., and Besang, C., 1984, Pre-Ross granites at the Pacific margin of the Robertson Bay Terrane, north Victoria Land, *Antarctica: Geol. Jahrb.*, v. B60, p. 363-370.
- Vetter, U., Roland, N. W., Kreuzer, H., Höhndorf, A., Lenz, H., and Besang, C., 1983, Geochemistry, petrography, and geochronology of the Cambro-Ordovician and Devonian-Carboniferous granitoids of northern Victoria Land, *Antarctica*, in Oliver, R. L., James, P. R., and Jago, J. B., eds., *Antarctic Earth Science: Canberra, Australian Acad. Sci.*, p. 140-143.
- Wade, F. A., and Couch, D. R., 1982, The Swanson Formation, Ford Ranges, Marie Byrd Land—Evidence for and against a direct relationship with the Robertson Bay Group, northern Victoria Land, in Craddock, C., ed., *Antarctic Geoscience: Madison, Univ. Wisconsin Press*, p. 609-616.
- Weaver, S. D., Bradshaw, J. D., and Laird, M. G., 1984, Geochemistry of Cambrian volcanics of the Bowers Supergroup and implications for the early Paleozoic tectonic evolution of northern Victoria Land, *Antarctica: Earth Planetary Sci. Letters*, v. 68, p. 128-140.
- White, A. J. R., 1979, Sources of granite magmas [abs.]: *Geol. Soc. America Abs. with Programs*, v. 11, p. 539.
- White, A. J. R., and Chappell, B. W., 1977, Ultrametamorphism and granitoid genesis: *Tectonophysics*, v. 43, p. 7-22.
- 1983, Granitoid types and their distribution in the Lachlan Fold Belt, southeastern Australia, in Roddick, J. A., ed., *Circum-Pacific Plutonic Terranes: Geol. Soc. America Mem.* 159, p. 21-34.
- White, A. J. R., Williams, I. S., and Chappell, B. W., 1976, The Jindabyne Thrust and its tectonic, physiographic and petrographic significance: *Geol. Soc. Australia Jour.*, v. 23, p. 105-112.
- 1977, Geology of the Berridale 1:100,000 Sheet: *New South Wales Geol. Survey, Australia*, 138 p.
- Wodzicki, A., Bradshaw, J. D., and Laird, M. G., 1982, Petrology of the Wilson and Robertson Bay Groups and Bowers Supergroup, northern Victoria Land, *Antarctica*, in Craddock, C., ed., *Antarctic Geoscience: Madison, Univ. Wisconsin Press*, p. 549-554.
- Wones, D. R., 1980, A comparison between granitic plutons of New England, U.S.A. and the Sierra Nevada batholith, California, in Wones, D. R., ed., *The Caledonides in the U.S.A.: Virginia Polytech. Inst. Mem.* 2, Dept. Geol. Sci., p. 123-130.
- Wright, T. O., 1981, Sedimentology of the Robertson Bay Group, north Victoria Land, *Antarctica: Geol. Jahrb.*, v. B41, p. 127-138.
- 1985, Thrust tectonics in northern Victoria Land [abs.]: *Gondwana Symposium*, 6th, The Ohio State Univ., Columbus.
- Wright, T. O., and Findlay, R. H., 1984, Relationships between the Robertson Bay Group and the Bowers Supergroup—New progress and complications from the Victory Mountains, north Victoria Land: *Geol. Jahrb.*, v. B60, p. 105-116.
- Wright, T. O., Ross, R. J., Jr., and Repetski, J. E., 1984, Newly discovered youngest Cambrian or oldest Ordovician fossils from the Robertson Bay terrane (formerly Precambrian), northern Victoria Land, *Antarctica: Geology*, v. 12, p. 301-305.
- Wyborn, D., 1981, Granitoids of north Victoria Land, *Antarctica*—Field and petrographic observations: *Geol. Jahrb.*, v. B41, p. 229-249.
- 1983, Chemical control on stratigraphic relations in northern Victoria Land and some possible relations with SE Australia [abs.], in Oliver, R. L., James, P. R., and Jago, J. B., eds., *Antarctic Earth Science: Canberra, Australian Acad. Sci.*, p. 145.