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**LA THÈSE A ÉTÉ
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AN ENSIALIC MARGINAL BASIN
IN WOPMAY OROGEN, NORTHWESTERN CANADIAN SHIELD

by

INGRID G. REICHENBACH, B.A., B.Sc.

A thesis submitted to the Faculty of
Graduate Studies and Research in partial fulfillment
of the requirements for the degree of
Master of Science, Department of Geology

Carleton University

Ottawa, Ontario

November, 1986

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in partial fulfillment of the requirements for
the degree of Master of Science

.....
Chairman, Department of Geology

.....
Thesis Co-Supervisor

.....
Thesis Co-Supervisor

Carleton University

November 24, 1986

ABSTRACT

The 1898Ma Bell Island Group occurs in the western part of Wopmay Orogen, an early Proterozoic orogenic belt developed on the western margin of the Archean Slave Craton. The group, 4km thick, comprises five formations, from oldest to youngest: 1) subaerially deposited conglomerate and sandstone (Beaverlodge Sandstone), 2) subaerially erupted calc-alkaline volcanic rocks ranging from basalt to rhyolite (Zebulon Formation), 3) shallow marine siliciclastics (Conjuror Bay Formation), 4) tholeiitic pillow basalt (Bloom Basalt), and 5) tholeiitic gabbro sills and dikes (Fishtrap Gabbro) interpreted to be comagmatic with the basalts. It unconformably overlies a sialic basement complex (Hottah Terrane) and is unconformably overlain by continental arc rocks of the Great Bear Magmatic Zone.

Based on depositional environment, chemistry, regional tectonic setting, and comparison with Mesozoic-Recent analogs, rocks of Beaverlodge Sandstone and the Zebulon Formation are interpreted to constitute part of a continental magmatic arc and the Conjuror Bay Formation, Bloom Basalt, and Fishtrap Gabbro represent material related to the formation of a younger marginal basin.

The tholeiitic lavas and intrusions of the Bell Island Group are similar in age, geochemistry, and lithology to the Akaitcho and Grant Groups, the lowermost stratigraphic units of the internal zone, suggesting that the three groups are correlative and were deposited within the same basin. If correct, then Wopmay Orogen is better considered to represent magmatism and tectonism related to an evolving Andean-type plate margin, rather than to the Wilson Cycle.

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CHAPTER 1: INTRODUCTION

The early Proterozoic Great Bear Magmatic Zone has been interpreted as a continental magmatic arc generated by eastward subduction of oceanic lithosphere (Hoffman and McGlynn 1977; Hildebrand 1981; Hildebrand et al., in press, a). In the vicinity of Hottah Lake, rocks of the Bell Island Group (Reichenbach 1985) - previously considered to be among the oldest of the zone - comprise subaerial lavas overlain by pillow basalts (McGlynn 1976; Hoffman and McGlynn 1977; Hildebrand 1984a). However, a poorly understood stratigraphy coupled with a lack of age constraints for these volcanic rocks prevented reliable correlations which in turn obscured their regional significance. In addition, the occurrence of a thick succession of pillow basalts is atypical of a continental arc and the tectonic setting of the basalts is therefore subject to speculation.

Rocks of the Bell Island Group have been previously mapped only on a reconnaissance scale; therefore, the author mapped them in detail as the field component of a master's thesis study. Principal objectives of the thesis were:

- 1) to produce a detailed geological map in order to document the stratigraphy and structure of the volcanic succession;
- 2) to characterize the rocks in terms of major and trace element geochemistry for comparison with younger rocks from well-understood tectonic environments;
- 3) to determine the age of the succession and thereby aid in regional

correlations;

4) to interpret the tectonic setting(s) of the group, and

5) to apply the conclusions to a regional tectonic model.

Earlier work in the study area includes that of Kidd (1936), McGlynn (1976, 1979), Wilson (1979), and Hildebrand et al. (1983, 1984).

REGIONAL GEOLOGY

The Bell Island Group crops out in the western part of the early Proterozoic Wopmay Orogen, a north-trending orogen that developed on the western side of the Archean Slave Craton. The orogen can be divided into three major tectonic zones (Fig.1), from west to east: Hottah Terrane, Great Bear Magmatic Zone, and Calderian Accretionary Wedge.

Hottah Terrane comprises deformed metasedimentary and metavolcanic rocks cut by both deformed intermediate plutons and undeformed leucogranites (Hildebrand and Roots 1985). It contains the oldest recognized magmatic suite (1958-1902 Ma) in Wopmay Orogen - all ages quoted in this report are based on U/Pb zircon data - and extends eastward beneath most of the Great Bear Magmatic Zone (McGlynn 1979; Hildebrand et al. 1983; Bowring and Van Schmus, in press; Hildebrand et al., in press, b). The presence of intermediate volcanic rocks and biotite-hornblende bearing plutons suggests that Hottah Terrane represents a continental magmatic arc either contiguous to (Hildebrand and Roots 1985), or allocthonous with (Hildebrand 1981; Hildebrand et al. 1983), the western margin of Slave Craton prior to 1900Ma.

Unconformably overlying Hottah Terrane is the Bell Island Group, which

Figure 1 Generalized geological map showing the distribution of Hottah Terrane, Bell Island Group, Labine Group, Great Bear plutons, Hornby Bay Group, and younger gabbro sills (modified from Hildebrand et al. 1983; 1984). C=Conjuror Bay, F=Fishtrap Lake, B=Bell Island Group, BL=Beaverlodge Lake. Inset map shows the location of Wopmay Orogen with respect to Slave Province and its tectonic zones. 1, Hottah Terrane and cover; 2, Great Bear Magmatic Zone; 3&4, Calderian Accretionary Wedge: 3, Hepburn metamorphic-plutonic zone; 4, Asiatic thrust-fold belt.

forms the principal subject of this report. The group is a complex sequence of regionally sub-greenschist facies sedimentary rocks, subaerial basaltic to rhyolitic lava flows, ash-flow tuff, pillow basalts, and hypabyssal gabbro sills. The Bell Island Group extends from Conjuror Bay in the north to Beaverlodge Lake in the south (Hildebrand et al. 1983; Hildebrand and Roots 1985; Reichenbach 1985) (Fig.1). In the Conjuror Bay area the group lies unconformably beneath Moose Bay Tuff of the Labine Group (Hildebrand 1982, 1984a,b), the oldest ash-flow tuff exposed in that area.

The easternmost zone of the orogen, the Calderian Accretionary Wedge, comprises in ascending order: 1) metavolcanic and metasedimentary rocks of the Akaitcho Group interpreted by Easton (1982) to represent rocks deposited within a continental rift; 2) a west-facing sedimentary prism which laps eastward onto Slave Craton and comprises the siliciclastic Odjick Formation overlain by the dolomitic Rocknest Formation (Hoffman 1972, 1973; Grotzinger and Hoffman 1983; Grotzinger, in press); and 3) an eastwardly-migrating synorogenic foredeep (Hoffman 1980a, 1981). These rocks, collectively termed the Coronation Supergroup (Hoffman 1981), were detached from their basement, tectonically thickened, folded and thrust eastward onto Slave Craton (Tirru 1983; Hoffman et al., in press) during what is termed the Calderian Orogeny (Hoffman and Bowring 1984; St-Onge et al. 1983). During the orogeny a suite of syn- to post-tectonic plutons (Hepburn Batholith) was emplaced into the Coronation Supergroup and generated regional metamorphic aureoles (St-Onge et al. 1984; Lalonde 1984; St-Onge, in press). The orogeny, and postulated synchronous deformation of Hottah Terrane has been interpreted as resulting from either collision of Slave Craton with an exotic Hottah Terrane (Hildebrand 1981; Hildebrand et al. 1983), or closure of a marginal basin

existing between Slave Craton and Hottah Terrane (Hildebrand and Roots 1985). U-Pb (zircon) ages (Bowring and Van Schmus, in press) bracket the deformation of the Calderian Accretionary Wedge between 1900Ma (late Akaitcho Group) and 1880Ma (post-tectonic Hepburn plutons).

The Great Bear Magmatic Zone contains the youngest magmatic suites (1878-1843Ma, Bowring 1984) exposed in the orogen. It is a 100km wide, north-trending linear belt that crops out over a strike length of 450km and unconformably overlies the Bell Island Group to the west (this report) and both Archean basement to Akaitcho Group (Easton 1982; Hoffman 1984b) and granites of Hottah Terrane to the east (Hildebrand et al., in press, b). The north-trending Wopmay Fault Zone approximately coincides with the boundary between the Calderian Accretionary Wedge and Hottah Terrane. The latter only locally extends east of the fault zone (Villeneuve, pers. comm.) which is a belt of mylonites and brittle faults (King et al. 1983; Hoffman 1984a; King 1985). The oldest rocks of the Great Bear Magmatic Zone occur along its western and eastern margins (Hildebrand et al., in press, a, b); rocks in the central part of the zone are younger and the overall structure of the Great Bear zone is therefore interpreted to be synclinal (Hildebrand and Bowring 1984; Hildebrand et al., in press, a). The magmatic suite is calc-alkaline, and the volcanic rocks range continuously from basalt to rhyolite, forming a typical basalt-andesite-dacite-rhyolite series (Hildebrand 1982; Hildebrand and Bowring 1984; Hildebrand et al., in press, a). The linear trend of the Great Bear Magmatic Zone, overall synclinal structure, regional tectonic setting, chemical composition, and magmatic evolution all support the conclusion that the Great Bear Magmatic Zone represents a continental magmatic arc related to easterly-directed subduction (Hildebrand 1982; Hildebrand et al., in press, a).

All of the rocks of western Wopmay Orogen, except for syenogranite plutons of the Great Bear zone emplaced between 1850-1840Ma (Bowring and Van Schmus, in press), are broadly folded about gently-plunging axes, generally of northwest trend, oblique to the overall trend of the zone (Hoffman and McGlynn 1977). The oblique trend and en echelon character of the folds suggest a dextral transpression of the zone (Hoffman 1980a; Hildebrand 1981), attributed to oblique ridge subduction (Hildebrand 1983; Hildebrand et al., in press, a). U-Pb zircon ages bracket this deformation between 1860Ma, the age of the youngest known folded rocks, and 1850Ma, the age of the oldest known post-folding syenogranite plutons (Bowring 1984).

Rocks in the western part of the orogen are cut by nearly vertical, northwest-trending, dextral transcurrent faults which have up to several kilometers of strike-slip displacement (Hoffman and McGlynn 1977). The faults are but one domain of a much larger regional set of transcurrent faults that extends throughout Wopmay Orogen (Hoffman 1980a, 1980b, 1984b) and adjacent parts of the northwestern Canadian Shield. The fault system is the result of east-west compression (Tirrul 1984) interpreted to originate from a 1810-1850Ma collision along the western margin of Hottah Terrane (Hoffman et al. 1982; Hildebrand et al., in press, a). In the eastern part of the orogen, where conjugate sets of faults occur, a regional pure shear model is compatible with geometric arguments and map reconstruction (Tirrul 1984).

CHAPTER 2: STRATIGRAPHY

The Bell Island Group, which unconformably overlies Hottah Terrane, is an assemblage of lava flows, sedimentary rocks, and hypabyssal intrusions characterized by complex interfingering and intrusive relations typical of most volcanic terranes. The group, which has a maximum exposed thickness of 4km, is here divided into five formations, from oldest to youngest: Beaverlodge Sandstone, Zebulon Formation, Conjuror Bay Formation, Bloom Basalt, and Fishtrap Gabbro. Hildebrand (1982, 1984a) named the Conjuror Bay Formation and Bloom Basalt and included them in the Labine Group; the other formations are newly named in this report. However, in the Conjuror Bay area, the subaqueous Bloom Basalt is overlain with angular unconformity by subaerial ash-flow tuff, also included within the Labine Group. I consider this unconformity to be of regional significance and in this report it is proposed to remove the Conjuror Bay Formation and Bloom Basalt from the Labine Group and include them within the Bell Island Group. The upper boundary of the Bell Island Group is placed at the top of Bloom Basalt (Reichenbach 1985).

Known regional extent of the Bell Island Group is from Conjuror Bay in the north, to Beaverlodge Lake in the south (Fig.1). A detailed geological map shows the major lithostratigraphic units of the Bell Island Group in the Hottah Lake area (Fig.2, back pocket). Other exposures of the group, to the north and south of Hottah Lake, are discussed elsewhere (Hildebrand et al. 1983; Hildebrand 1984a; Hildebrand and Roots 1985). Table 1 presents the

stratigraphic nomenclature and Figure 3 shows the major units, their thicknesses, and probable correlations within the group.

The present report is based on a total of four months of field work during the summers of 1983 and 1984. Mapping was done on 1:16 000 black-and-white aerial photographs enlarged from standard 1:63 360 photographs; the data were compiled on 1:25 000 topographic maps. Petrographic interpretations are based on a study of approximately 250 thin sections. Because most of the rocks in the study area are either aphyric or only sparsely porphyritic, names based upon chemical composition (see Chapter 5) are necessary for consistency. The volcanic rocks have been divided on the basis of their volatile-free SiO_2 content as follows:

basalt	less than 53% SiO_2
andesite	53-62% SiO_2
dacite	63-69% SiO_2
rhyolite	greater than 69% SiO_2

These divisions are slightly modified from Peccerillo and Taylor (1976) and Gill (1981), but coincide closely with names used in the study area based on textures, such as flow layering and devitrification features, estimated density, and phenocrysts. This suggests that in most rocks there have been only minor changes in SiO_2 content with alteration. Where chemical analyses are not available, the rocks have been classified on the basis of petrographic similarity to analyzed samples. The terminology for ash-flow-tuffs is that of R.L. Smith (Smith 1960a, b; Ross and Smith 1961) and grain size of pyroclasts is that of Fisher (1961) and Schmid (1981).

Table 1. Table of formations.

PALEOZOIC

Old Fort Island Formation conglomerate, sandstone
-- unconformity --

MIDDLE PROTEROZOIC

gabbro medium- to coarse-grained gabbro
-- intrusive contact --

EARLY PROTEROZOIC**Great Bear Magmatic Zone**

Yen Pluton granodiorite, monzogranite
-- intrusive contact --

Labine Group diverse assemblage of lava flows,
ash-flow tuff, sedimentary rocks
-- unconformity --

Bell Island Group

Fishtrap Gabbro gabbro, diabase
-- intrusive contact --

Bloom Basalt pillow basalt, breccia, tuff
dacite flow dacite flow and flow-breccia

Conjuror Bay Formation

upper member siltstone, mudstone, fine-grained
sandstone
lower member quartzarenite

Zebulon Formation

upper member rhyolite flows and breccias, minor
mafic-intermediate flows
ash-flow-tuff member rhyolite and dacite ash-flow tuff
lower member mafic-silic lavas and breccias;
bedded tuff

Beaverlodge Sandstone

conglomerate, sandstone, siltstone

-- unconformity --

Hottah Terrane

metavolcanic, metasedimentary
rocks; deformed, undeformed plutons

Figure 3 Stratigraphic sections of the Bell Island Group.
Inset diagram shows location of sections after strike-slip separation on the transcurrent faults is restored. Black; Hottah Terrane; dotted pattern, Bell Island Group; ticked pattern, younger rocks.

BEAVERLODGE SANDSTONE

A fining upwards sequence of conglomerate and sandstone overlies Hottah Terrane from Fishtrap to Beaverlodge Lakes. The basal contact is an erosional unconformity which is typically well exposed (Plate 1A). Upper parts of the sandstone interfinger with intermediate and silicic lavas. The name Beaverlodge Sandstone is proposed here for this sequence. Although most of the known exposures of the formation occur in a strip from Beaverlodge to Fishtrap Lakes, some isolated exposures occur as roof pendants in younger granodiorite near the mouth of the Zebulon River (Hildebrand and Roots 1985). The best exposures and most complete sections occur along eastern and southern Bell Island. Total thickness of the formation increases westward from less than 1m to 200m (Fig.3).

Coarse-grained, poorly bedded to massive, polymictic, clast-supported conglomerate generally occurs at the base of the formation. The conglomerate contains angular to subrounded clasts, up to 15cm across, of silicic flow-layered lavas; vein quartz, basement gneissoids, mafic sedimentary rocks, jasper, and angular potassium feldspar fragments up to 4cm (Plate 1B). Volcanic rocks account for at least one-third of the total fragments. Locally, discontinuous beds (30 to 50cm thick) contain vein quartz pebbles to near exclusion of anything else (Plate 1C). At a few localities on eastern Bell Island, the conglomerate is underlain by 1-5m of medium-grained sandstone to arkosic granulestone, with discontinuous beds 1-15cm thick marked by changes in grain size. Some of the beds contain imbricated pebbles (up to 6cm) interpreted as lag deposits. Diffuse heavy mineral bands accentuate trough cross bedding.

Overlying the conglomerate is a fining upwards sequence of fine- to

Plate I

Sedimentary rocks of Beaverlodge Sandstone.

A) Lithic sandstone and conglomerate of the Bell Island Group unconformably overlying Hottah Terrane. Hammer head rests on the unconformity.

B) Polymictic conglomerate generally present near the base of Beaverlodge Sandstone. Note pen for scale in upper right of photo. C) Quartz-pebble conglomerate in channel scoured into sandstone.

D) Trough cross beds, common in the upper part of the formation, indicate paleocurrents to the west-southwest.

medium-grained, lithic arkose. Granulestone beds occur throughout, but decrease in abundance up section. The sequence is well-bedded; individual beds are normally graded and are 3-5cm thick. Trough cross beds are ubiquitous (Plate 1D) and indicate paleocurrents to the west-southwest. Local channels filled in with conglomerate occur in the granulestone and are in the range of 4-5m wide by 1-2m deep.

On eastern and southern Bell Island, a well-bedded, generally fining upwards volcanoclastic unit occurs at the top of Beaverlodge Sandstone. Exposed thickness is up to 8m. Beds 1mm to 3-4cm thick consist of alternating volcanogenic siltstone and wacke. The matrix of the wacke weathers dark-grey, or in places where it is hematized, dark-purple, and is attractively contrasted by angular red volcanic fragments and crystals of quartz, potassium feldspar and plagioclase. Sandstone lenses occur within the siltstone. Trough cross-bedding, scours, angular rip-ups of the siltstone, and slumps are common.

Based on sedimentary structures (channels, grading, cross-stratification), lateral and vertical changes in lithology and grain size, and overall immaturity, Beaverlodge Sandstone is interpreted as a subaerial alluvial fan complex (Hildebrand et al. 1983; Reichenbach 1985; cf. Nilsen 1982). Both the predominance of volcanic fragments and the intercalation of upper parts of the sequence with lava flows indicates that sedimentation was synchronous with volcanism.

ZEBULON FORMATION

Conformably overlying and locally interfingering with Beaverlodge Sandstone is a complex sequence of volcanic rocks and minor intercalated

volcaniclastic units, for which the name Zebulon Formation is proposed. The formation comprises 1.5km of aphyric mafic to silicic lavas and breccias, rhyolite and dacite ash-flow tuff, and aphyric to porphyritic rhyolite flow-domes. These units are respectively designated: the lower member, the ash-flow tuff member, and the upper member. Regional extent is from Fishtrap Lake in the north to Beaverlodge Lake in the south. The best exposures and most complete sections occur on Bell Island, and in the synclines and anticlines on the mainland directly to the east and northeast of Bell Island. Where the lavas and sandstone are in contact, rip-ups of sedimentary rocks occur in the basal portions of the lavas.

Lower Member

Lava Flows

The most striking feature of lava flows in the lower member is their predominantly aphyric nature. Only a few flows contain sparse plagioclase or quartz phenocrysts. In lieu of phenocryst assemblages, criteria for distinguishing flow units in the field were basal and flow-top breccias, distribution of amygdules, discontinuities in outcrop, and intercalated pyroclastic and volcaniclastic rocks. Subsequent chemical analyses, discussed in detail elsewhere in this report, generally agreed with field names and flow contacts.

Aphyric basalt flows with amygdaloidal basal portions are common; some crop out continuously for a strike length of several kilometres along eastern Bell Island and also on the mainland to the northeast of Bell Island (Fig.2). Although rhyolite flows are uncommon in the lower member, the occurrence of rhyolite breccias indicates that rhyolite flows were present, but are either not exposed or were not voluminous enough to be preserved. Lavas of andesitic-

dacitic composition are by far the most abundant and crop out in all areas where the lower member is exposed. Along western Bell Island, there are two separate andesite flows, probably filling paleovalleys eroded into the Beaverlodge Sandstone. Each is approximately 40m thick and separated by a similar thickness of arkose. Some intermediate flows, at least 150m thick with well developed columnar jointing (Plate 2A), may be intracanyon flows. Basal portions of the andesites and dacites are coarsely flow-layered (Plate 2B) parallel to bedding or platy jointed, becoming more massive higher in the flow. The weathered colour is highly variable, but in many places the intermediate to silicic flows are oxidized to a brick red to dark-purplish brown. Quartz, chlorite and carbonate amygdules are plentiful, and in places are strongly flow-lineated (Plate 2C). Flow-top breccias displaying devitrification and hydration features such as spherulites and perlitic fractures are common, particularly in the more silica-rich flows (Plate 2D).

In thin section, original igneous textures are well preserved, although primary mineral assemblages have been variably altered. The basalts are holocrystalline with subophitic to intersertal textures. One flow has fractured microphenocrysts of olivine altered to serpentine and chlorite; all other flows are aphyric. In the groundmass, plagioclase occurs as euhedral laths, displays Carlsbad and albite twinning, and in some flows defines a weak pilotaxitic texture. The plagioclase is slightly to intensely altered to saussurite, sericite, and carbonate (and probably albite). No fresh pyroxene is present in any thin sections, but anhedral clots of uraltite, chlorite, and carbonate attest to its former presence. Fine-grained iron-titanium oxide crystals are scattered throughout all thin sections.

Many of the andesites are similar to the basalts in texture, mineralogy,

Plate 2

Intermediate lavas of the lower member of the Zebulon Formation. A) Columnar jointed dacite flow is approximately 150m thick. B) Dacite lava showing flow layering which is parallel to bedding near the base of the flow. C) Intermediate composition flow with lineated, quartz-filled amygdules inferred to be elongate parallel to flow direction. D) Autobrecciated dacite flow showing perlitic fractures typical of intermediate lavas of the Zebulon Formation.

and alteration, except that the andesites lack olivine, contain more plagioclase, and generally are sparsely (1-2%) microporphyritic, although one flow on northern Bell Island contains approximately 15% tiny plagioclase laths (Plate 3B). Flow structures defined by aligned euhedral plagioclase microlites are well developed (Plate 3A,C). Euhedral to subrounded, blocky and lath-shaped plagioclase phenocrysts, ranging from 0.5-1.5mm, are set in a subophitic to cryptocrystalline matrix. The plagioclase is zoned and has internal sieve textures (Plate 3D). Low-silica andesites that occur on western Bell Island contain sparse uraltized pyroxene phenocrysts up to 2.5mm. Hornblende and/or biotite have not been positively identified, but opacitic patches appear to be pseudomorphs after these minerals (Plate 3B). Iron-titanium oxides occur as fine-grained euhedra to finely disseminated dust, the latter accounting for the dark grey colour of many andesite flows.

Original igneous textures and mineralogy in the dacites are somewhat obscured by devitrification and alteration. The dacites are predominantly aphyric. A few thin sections contain sparse quartz bipyramids and corroded quartz phenocrysts. Others contain less than 1% flow-aligned plagioclase microphenocrysts 0.25-0.5mm in size. The groundmass is a dense, cryptocrystalline assemblage of quartz, alkali feldspar, sericite, and iron-titanium oxides. Most thin sections exhibit a pervasive reddish stain due to finely disseminated hematite. Perlitic fractures (Plate 4A), spherulites, and flow banding occur in many thin sections. The devitrification and hydration textures of the dacite flows suggests that they were partly glassy when extruded.

Bedded Tuff

A useful stratigraphic marker is a light-green weathering, dacitic-

Plate 3

Photomicrographs of andesite flows of the Zebulon Formation. A) Pilotaxitic texture in holocrystalline andesite containing small Fe-Ti oxide euhedra. B) Abundant small phenocrysts of plagioclase, opacitic amphibole (arrow), and Fe-Ti oxides occur in-cryptocrystalline groundmass. Note amygdule in upper right corner. C) Flow-aligned plagioclase laths surrounded by cryptocrystalline matrix. D) Zoned plagioclase phenocryst exhibits internal sieve texture.

rhyolitic, well-bedded fragmental unit, present almost continuously along eastern and southern Bell Island, and discontinuously elsewhere. On eastern Bell Island it conformably overlies Beaverlodge Sandstone, where it forms the lowest stratigraphic unit of the Zebulon Formation; elsewhere, it occurs above the base of the formation and interfingers with lava flows. Maximum thickness of the unit is about 12m. Bedding within the unit is sharp to gradational and defined by differences in grain size. Porcellanite beds alternate with lithic-rich beds containing lapilli and blocks in a fine-grained tuffaceous matrix. Beds generally range from several millimeters to 3cm thick, although locally more massive beds are 0.5-2m thick. Fragments include angular lithic clasts of red flow-layered volcanics and dark-green cryptofelsite, the latter flattened parallel to bedding in some places, and crystals of potassium feldspar and clear quartz. Most lithic fragments are less than 1cm, but some coarse-grained beds contain fragments up to 6cm. Beds show normal and reverse size grading.

Based on the siliceous composition, well-sorted nature, fine overall grain size of the unit, and presence of phenocrysts and flattened formerly glassy fragments, this unit is interpreted to contain Plinian air-fall tuff and ash-flow tuff, possibly reworked locally.

Block-and-Ash Flows

A distinctive sequence of brick-red weathering, monolithologic breccias occur along eastern Bell Island. At its northern extent, it conformably overlies the bedded tuff; to the south, it interfingers with lava flows, as does the bedded tuff. The sequence crops out along strike for 2km and is up to 53m thick. The breccia sequence contains at least 8 units of variable thickness (1-10m), each with sharp lower and upper contacts. Within each of these units are two subunits: 1) a lower tuff that is locally thinly bedded (0.5-5cm), weathers

light green, and consists of red and green volcanic lapilli in an ashy matrix, and 2) an upper breccia with an excellent inversely graded base marked by a decrease in the amount of matrix and an increase in fragment size (Plate 4B). The contact between the lower tuff and upper breccia subunits varies from sharp (Plate 4B) to diffuse. The dominant fragments of the entire sequence are subangular to subrounded red rhyolitic blocks and boulders that are flow-layered, spherulitic, aphyric and amygdaloidal. Lower units also contain angular, dark-green cryptofelsite fragments (up to 12 cm) and sparse vein quartz and granitoid fragments. In thin section, the volcanic fragments contain sparse (1 per thin section) quartz and feldspar phenocrysts set in a cryptocrystalline matrix. Fragment size is greatest in the uppermost units, where rhyolitic blocks and boulders are commonly 1.5m across. This masks the brecciated nature of the upper units, because the fragments are so large and the matrix is so sparse, that at first glance the breccia resembles a lava flow.

These units are interpreted as repetitive cycles of air-fall tuff overlain by block-and-ash flows. The explosive event linked to the air-fall tuff likely triggered the dome collapse which resulted in block-and-ash flows. The block-and-ash flows are similar to those described by Perret (1935) and Westercamp and Traineau (1983) from Mt. Pelée, and to one example the author has seen in California which erupted from Panum Crater (Mono Craters) about 400 years ago. The red fragments are interpreted to be of similar composition to the green based on similar petrology and analogy with Cenozoic ash-flow tuff and rhyolite flows (Williams 1960; Crandell and Mullineaux 1973). The red fragments probably represent finely crystalline material from the stony interior of the dome that oxidized and devitrified during cooling, and the green fragments probably represent the quenched glassy exterior.

Plate 4

Photographs and photomicrographs of volcanic rocks of the Zebulon Formation. A) Photomicrograph of perlitic fractures in formerly glassy dacite flow. B) Air-fall tuff overlain by rhyolite block-and-ash flow with an inversely graded base marked by an increase in fragment size. C) Rhyolite ash-flow tuff with coarse spherulitic zone near the base grading upwards into massive interior. D) Eutaxitic foliation in upper portion of rhyolite ash-flow tuff.

Based on stratigraphic position, mineralogy, and chemistry, the closest exposed rhyolite source for the block-and-ash flows is several kilometers to the west (Fig.2, Bzrl), after separation along the transcurrent faults is restored. Alternatively, the block-and-ash flows may be related to a more proximal unexposed or eroded rhyolite dome. Similar but more massive rhyolite breccias that are intercalated with dacite flows in the syncline directly to the east of Bell Island may also be block-and-ash flows.

Ash-flow Tuff Member

Three to four hundred metres of intermediate and siliceous ash-flow tuff termed the ash-flow tuff member conformably overlies the lower member of the Zebulon Formation (Fig.3). The only complete section is exposed on central Bell Island. Exposures are excellent on the mainland to the east of Bell Island, but the ash-flow tuff member pinches out abruptly to the west and is completely absent on both western and northern Bell Island. Rhyolite flows and domes, or local volcanoclastic units and mafic to intermediate flows, conformably overlie the ash-flow tuff member.

Locally exposed at the base of the ash-flow tuff member is 2-4m of well-bedded, inversely graded tuff that mantles the irregular upper surface of older lava flows. Angular red aphyric volcanic fragments (less than 1cm) and basement derived quartz are present. This unit is interpreted as Plinian air-fall, premonitory to the overlying rhyolite ash-flow tuff.

Overlying the air-fall tuff (or lava flows of the lower member where the air-fall tuff is absent) is a mineralogically zoned, lithic-poor, terracotta weathering, simple cooling unit of rhyolite ash-flow tuff. The maximum thickness is about 350m. Only in the anticline to the northeast of Bell Island is there an anomalous 12m thick section of well-bedded volcanogenic siltstone,

sandstone, and conglomerate intercalated with the ash-flow tuff for a strike length of 200-300m (Fig.2). This indicates either local compound cooling, or an unrecognized fault that has repeated the ash-flow tuff member (as happens directly to the north, see Fig.2).

In most places, one-half to several metres above the base of the tuff is a coarsely spherulitic zone. Coalesced spherulites, individually up to 15cm in diameter, occur in continuous contact with one another for several metres upwards in the tuff (Plate 4C). Lithophysal cavities, up to 15cm in diameter and filled with quartz euhedra, are concentrated in the spherulitic horizon and also towards the top of the tuff. The spherulitic horizon is interpreted as the transition zone between the vitrophyre and completely devitrified zone based on younger examples seen in Cenozoic ash-flow tuffs of the San Juan volcanic field and Yellowstone Plateau.

Flattened dark-red weathering pumice defining a eutaxitic foliation is present only near the base and top of the tuff (Plate 4D); elsewhere it apparently has been obliterated by welding and devitrification. The pumice is usually 2-3cm in length, although locally it is up to 20cm long; the flattening ratio is approximately 4:1. Near section 7 (Fig.3), a 10m thick, light-green weathering uppermost zone contains up to 20% highly flattened white pumice. Angular lithic fragments (usually 5mm, but up to 6cm) are sparse (3%) and predominately cognate (accessory). The tuff is mineralogically zoned, containing less than 1% clear, fractured quartz microphenocrysts near the base, and a maximum of 3-4% quartz (less than 5mm) and 1% potassium feldspar (1-3cm) near the top.

In thin section, subhedral quartz has embayed margins (Plate 5A) and the feldspar occurs as corroded, subhedral to anhedral crystals. Both the quartz

Plate 5

Photomicrographs of ash-flow tuff member of the Zebulon Formation. A) Resorbed quartz crystal with remnant bipyramidal outline in rhyolite ash-flow tuff. Densely welded matrix wraps around the quartz phenocrysts. B) Phenocryst rich upper part of rhyolite ash-flow tuff. The fractures in the altered feldspar crystals and quartz bipyramids are typical of this tuff. C) Vitriclastic texture in devitrified and oxidized matrix of rhyolite ash-flow tuff. D) Lithic fragments in intermediate ash-flow tuff surrounded by welded matrix. This lithic-rich tuff only occurs on Bell Island where it directly overlies the rhyolite ash-flow tuff.

and feldspar are highly fractured (Plate 5B). These are set in a vitroclastic matrix (Plate 5C) recrystallized to a dense assemblage of quartz, feldspar, sericite, and iron oxides (hematite).

A dark brown weathering, lithic-rich, densely welded (Plate 5D), intermediate composition ash-flow tuff fills paleovalleys in the upper surface of the rhyolite ash-flow tuff. It is present only on central Bell Island. Sparse (less than 1%) fractured quartz phenocrysts were the only phenocrysts observed. Accidental angular to rounded andesite fragments (1-180mm) account for up to one third of the rock. Highly flattened (20:1) orange and black pumice fragments reach a maximum of 30cm in diameter.

Upper Member

Rhyolite flow-domes and breccias characterize the upper member, although mafic to intermediate lavas are present. The lower boundary of the upper member corresponds to the top of the ash-flow tuff member, or, where this latter member is absent, the base of the stratigraphically lowest rhyolite flow. Regional extent of the upper member is from Beaverlodge Lake to central Hottah Lake. The mafic to intermediate lavas of the upper member are petrographically and chemically identical to those of the lower member.

The rhyolites range from aphyric to porphyritic. The most porphyritic flow occurs on central Bell Island (Bzr2, Fig.2) and contains 8% clear quartz phenocrysts (2-3mm) and 6% bladed to blocky potassium feldspar phenocrysts (up to 8mm). Because of its porphyritic nature, this unit was collected for U-Pb (zircon) dating (see Chapter 3). At the base of the flow is a monolithologic flow breccia, which grades into the massive internal lava. It contains amygdaloidal, flow-layered, quartz and potassium feldspar porphyritic blocks up to one metre across in a light green cryptofelsite matrix (Plate 6A).

Plate 6

Photographs and photomicrograph of rocks of the Zebulon and Conjuror Bay Formations. A) Rhyolite flow breccia, Zebulon Formation. B) Photomicrograph of finely flow-layered and spherulitic rhyolite flow, Zebulon Formation. C) Spherulitic zone at the base of a rhyolite flow, Zebulon Formation. D) Planar bedding in the upper member of the Conjuror Bay Formation. Dark, less resistant beds weather recessively and accentuate bedding.

Thin section examination reveals fractured and embayed quartz anhedral, slightly rounded quartz bipyramids, and potassium feldspar with embayed margins and incipient alteration to sericite and other unidentified minerals. The matrix is a cryptocrystalline intergrowth of quartz, feldspar, and iron-titanium oxides. Finely disseminated hematite gives the flow a brick-red color.

The close similarity between the mineralogy of this flow and the directly underlying rhyolite ash-flow tuff, suggests that they may be comagmatic, but tapping more crystal-rich lower portions of the magma chamber with time. However, the oxidation and potassium enrichment of both flows, due to secondary alteration (see Chapter 5), precludes any definitive conclusion.

On northern Bell Island is a light-grey weathering, finely (millimetre-scale) flow-layered rhyolite. Stratigraphic position with respect to the ash-flow tuff member is uncertain because the latter is absent in this locale (Bzrl, Fig.2). This flow is unique to the study area in that its volcanic vent is well exposed. Intrusive to extrusive relationships are illustrated in Figure 4. Later faulting bisects the vent and is responsible for an approximately 60° rotation of the northwestern half. An intrusive phase of the rhyolite crosscuts bedding of Beaverlodge Sandstone and disturbs bedding in the immediate vicinity of the contact. When the sandstone beds are restored to horizontal, the intrusive contact is near vertical. Up section the contact turns abruptly and the rhyolite conformably overlies Beaverlodge Sandstone. In both the extrusive and intrusive rhyolite prominent flow layers are parallel to the contact immediately adjacent to it, but are convoluted away from it. At the intrusive contact, there is a finely flow-layered marginal zone 8cm wide, defined by alternating light-green (formerly glassy) and white laminations. In sharp contact with the laminations is a 12cm-thick zone, containing abundant

Figure 4

Geological map illustrating rhyolite vent on central Bell Island. Later faulting bisects the vent and has rotated the northwestern half approximately 60°.

flattened quartz amygdules, that grades inwards to a zone characterized by more fine flow layering. At the base of the extrusive part of the flow, east of the volcanic neck, is a light-pink to buff weathering flow breccia. It contains from 20-80% fragments (1-12cm), identical in appearance to the aphyric rhyolite, in a light-green matrix. Minor exotic basalt fragments are locally present. The contact with the overlying rhyolite is gradational.

In thin section, this flow is virtually aphyric with sparse (less than 1%) feldspar phenocrysts (1mm). Definitive identification of the type of feldspar(s) is hampered by intense alteration. Relict Carlsbad and minor albite twinning is present in several phenocrysts, indicating that at least some of them were plagioclase. The matrix is cryptocrystalline, finely flow-banded (Plate 6B), and contains coarser microcrystalline lenses of quartz and feldspar. Perlitic fractures and spherulites (Plate 6C) attest to the original glassy character of much of the flow.

Other rhyolite flow-domes in the upper member are aphyric to sparsely porphyritic and are characterized by similar devitrification and hydration textures, alteration, and hematite staining to that already described. For regional distribution see Figure 2.

CONJUROR BAY FORMATION

A complex succession of sedimentary and pyroclastic rocks outcrops in the Conjuror Bay area. Hildebrand (1982, 1984a, c) named the sequence the Conjuror Bay Formation and divided it into a lower member of mature quartzarenite and an upper member comprising mudstone, tuff, sandstone, and conglomerate. The formation unconformably overlies Hottah Terrane and is in

turn overlain by a thick sequence of pillow basalts. In the Hottah and Beaverlodge Lake areas a similar sequence of sedimentary rocks conformably overlies the Zebulon Formation. The top of the sedimentary sequence is not exposed around Beaverlodge Lake, but interfingers with overlying pillow basalts in the Hottah Lake area. Based on lithology and stratigraphic position, it is proposed that sedimentary rocks conformably overlying the Zebulon Formation in the Hottah and Beaverlodge Lake areas are similar to those described by Hildebrand (1984a) in Conjuror Bay and are therefore correlated with and included in the Conjuror Bay Formation.

Exposures of the Conjuror Bay Formation around Hottah Lake are relatively poor; the best occur in synclines to the east and northeast of Bell Island (Fig.2). Elsewhere the formation occurs as thin, discontinuous slivers along intrusive contacts with gabbro sills that occur as resistant ridges forming curvilinear islands in Hottah Lake (Fig.2). It is likely that the less resistant formation occupies the more deeply eroded bays between sills. Estimated thickness of any one section is about 100-300m (Fig.3).

Both the lower and upper members are present in the Hottah Lake area, although not in a continuously exposed section. The lower member of the formation is a white to pink weathering, well-bedded, medium- to fine-grained, mature quartzarenite. Beds are lenticular and range from several centimetres to 1m thick, with laminations rich in heavy minerals which accentuate trough cross-bedding. Lenses of subrounded vein quartz pebbles occur locally.

The upper member contains siltstone, concretionary mudstone, chert, tuff, and fine-grained quartzarenite. It is well stratified and predominantly planar-bedded with continuous 1-15cm layers (Plate 6D). Individual strata are internally well-bedded to thinly laminated. Less resistant beds weather

recessively. Low angle cross-bedding, climbing ripples, and sinuous asymmetric ripples are present locally. Many beds show evidence of soft sediment deformation such as mud rip-ups, ball-and-pillow structures, slump folds, boudinaged layers, and contorted bedding. Where the sedimentary rocks are intruded by gabbro sills, the rocks have been metamorphosed to the albite-epidote-hornfels facies of Turner (1968).

In the Hottah Lake area, the overall fining upwards nature of the sequence, the maturity of the basal sedimentary rocks, the presence of ripple stratification, and the upwards transition from trough cross-stratification to parallel lamination, suggest a beach-to-offshore transgressive sequence (cf. Reinson 1984 and McCubbin 1982). This concurs with Hildebrand's (1984a) interpretation of the Conjuror Bay Formation to the north as marginal marine. In addition, the conformable relation between the Conjuror Bay Formation and the overlying pillow basalt sequence supports a subaqueous depositional environment, at least for the upper part of the Conjuror Bay Formation.

BLOOM BASALT

In the vicinity of Hottah Lake, one to two kilometres of pillow basalt, pillow breccia, hyalotuff, sedimentary rocks, and a dacite flow overlie the Conjuror Bay Formation. Locally, such as on the mainland to the northeast of Bell Island (Fig.2), the Conjuror Bay Formation is absent and the pillow basalt sequence lies directly on the Zebulon Formation. The top of the sequence is not exposed because younger Great Bear plutons intrude it; therefore, its original thickness is unknown. A thick pile of pillow basalt intruded by gabbro sills occurs in the Conjuror Bay area (Bloom Basalt of Hildebrand 1982,

1984a, c) at the same stratigraphic position and is considered correlative with basalts in the Hottah Lake area as first suggested by Hoffman and McGlynn (1977). It is proposed that the pillow basalt assemblage in the Hottah Lake area be included in Bloom Basalt. Thus, the formation has a lateral extent of 45km when separation along the transcurrent faults is restored (Fig. 3).

The lower contact of Bloom Basalt with the Conjuror Bay Formation is irregular, with bits of sediment squeezed up between basal pillows. Massive, monolithologic pillow breccias are common near the contacts and elsewhere in the pillow pile. Light-green, fine-grained, poorly bedded hyalotuff horizons as well as discontinuous mudstone and fine-grained sandstone beds occur locally. Shoreline exposures of the pillows in both cross-section and 3-dimensions are excellent; however, overall exposure of Bloom Basalt is not sufficient to determine whether the lavas were erupted from fissures or central vents. Randomly distributed amygdules, cavernous cores with pillow shelves (Plate 7C), and pipe vesicles radiating inwards from the selvages (Plate 7B) are abundant. The texture of the pillows varies considerably from nearly aphyric to extremely plagioclase porphyritic. Where porphyritic, plagioclase occurs as discrete megacrysts or in aggregates (glomerocrysts) of 2-5 plagioclase crystals. Amygdules and phenocrysts occur both internally and in the chilled selvages (Plate 7A).

In thin section, the basalts contain plagioclase, clinopyroxene, and iron-titanium oxides. Olivine has not been observed. Primary textures are well preserved, except near the margins of younger plutons where the pillows have been flattened. Many pillows have striking quench textures with acicular, swallow-tailed plagioclase set in a matrix of altered glass (Plate 7D). Others are holocrystalline, ophitic to subophitic intergrowths of euhedral plagioclase

Plate 7

Pillow basalts of Bloom Basalt. A) Plagioclase megacrystic and glomerocrystic pillow basalt. Note phenocrysts in the chilled selvages. B) Radiating vesicles in the outer margins of pillows. C) Triple decker pillow shelves (pen for scale). Bedding plane is nearly vertical to photo. D) Photomicrograph of pillow basalt clearly shows two generations of plagioclase crystals: large euhedral megacrysts and acicular, swallow-tailed quench crystals, surrounded by a cryptocrystalline matrix.

laths and poikilitic clinopyroxene crystals. Iron-titanium oxides occur as anhedral, interstitial grains and show exsolution lamellae. The glomeroporphyritic samples contain euhedral to subhedral plagioclase crystals of different size, shape, and orientation, in clusters generally less than 4cm, in hypocrystalline to holocrystalline matrixes. Alteration is highly variable: in some samples the groundmass plagioclase is relatively free of alteration and clinopyroxene is entirely altered to uralite and/or chlorite; in others, the clinopyroxene is relatively fresh and the groundmass plagioclase highly altered to saussurite and sericite. Plagioclase occurring as megacrysts and glomerocrysts is nearly completely saussuritized.

Pillowed flows are unanimously accepted as products of either subaqueous eruptions, or the flow of lava into water. Subaerial eruption for at least some of Bloom Basalt cannot be ruled out because vents are not exposed. However, based on the thickness and lateral extent of the pillowed flows, and the lack of any heterogeneous rounded epiclastic fragments suggesting subaerial erosion, the pillows are interpreted to have formed by subaqueous eruption. The subaerial to subaqueous transition between eruption of lavas of the Zebulon Formation and those of Bloom Basalt implies eruption of the basalt during, or closely following, subsidence. Oolitic and stromatolitic patch reefs intercalated at various horizons with the pillowed flows in the Conjuror Bay area (Hildebrand 1984a; 1984c) indicate that water depths remained shallow throughout the eruption of the 2km of pillow basalts and that the eruption of Bloom Basalt was during, and kept pace with, subsidence. The highly amygdaloidal nature of the pillow basalt implies water depths less than about 500m, because the amount and diameter of vesicles decreases sharply at depths greater than this (Moore 1965, 1970; Moore and Schilling 1973). Identification

of the stromatolite *Jacutophyton* (see Hildebrand 1984a), known only from environments interpreted as marine, taken together with observations that the basalt is pillowed, amygdaloidal, and intercalated with oolitic shoals, indicates a shallow marine depositional environment for Bloom Basalt.

Dacite Flow

The stratigraphically highest unit exposed in the Bell Island Group, and included within Bloom Basalt, is a flow-layered, potassium feldspar, plagioclase, and quartz porphyritic dacite flow with local brecciated zones (section 4, Fig.3). A Fishtrap Gabbro sill (see following section) intrudes the flow, but no stratigraphic contacts were observed. Stratigraphic position is based on the occurrence of pillow basalts in the immediate vicinity, and relative location with respect to other units after separation along the transcurrent faults is restored. However, the dacite flow clearly predates Fishtrap Gabbro.

FISHTRAP GABBRO

Gabbroic intrusions that cut all units described so far crop out from Beaverlodge Lake to Conjuror Bay. The gabbros consistently occur as north-trending dikes in the basement (Fig.5), oblique sheets in the lower units of the Bell Island Group, and sills (Plate 8A) where they intrude the Conjuror Bay Formation and Bloom Basalt (Fig.2). They and Bloom Basalt are overlain with angular unconformity by Moose Bay Tuff in the Conjuror Bay area (Hildebrand 1982, 1984a). The maximum aggregate thickness of gabbro sills is about equal in thickness (1-2km) to Bloom Basalt, although considerable variations occur along strike. The name Fishtrap Gabbro is proposed for these dikes and sills. They are the youngest rock unit of the Bell Island Group.

Figure 5 Rose diagram compiled from the trend of 47 Fishtrap Gabbro dikes intrusive to Hottah Terrane. North-trend of the dikes indicates east-west extension during basaltic volcanism.

Textures in the gabbros vary from fine-grained diabasic to coarse-grained equigranular, and from aphyric to plagioclase porphyritic. As in Bloom Basalt, plagioclase occurs as discrete megacrysts or as glomerocrysts typically 1-2cm in diameter (Plate 8D), although 10cm-size clots are not uncommon, and a few clusters are up to 20cm in diameter. For the most part, the plagioclase clots are randomly distributed throughout the sills, although in one location on an island in northeastern Hottah Lake the sills have spectacular alternating phenocryst-rich and phenocryst-poor layers (Plate 8B). In addition, one of the largest sills that crops out on numerous small islands northeast of Bell Island is zoned. A basal pyroxene poikilitic zone (Plate 8C) grades up into a plagioclase glomerocrystic interior zone (Plate 8D) with discontinuous pegmatite zones that contain pyroxene needles up to 8cm long towards the top (Plate 9A). The uppermost part of the sill is a fine-grained, nonporphyritic, diabasic border zone containing calcite and quartz amygdules to 10cm (Plate 9B).

A glomeroporphyritic gabbro similar to Fishtrap Gabbro occurs as a 500m thick intrusion in the Akaitcho Group, 120kms to the east (Easton 1981). Elsewhere in the Canadian Shield, they are similar to the "leopard rocks" in the Labrador Trough (Baragar 1967) and gabbroic sills in the Sleeper Islands (Cadieux 1980). In south Greenland, they texturally resemble sills from the Proterozoic Gardar alkali intrusions (Bridgwater and Harry 1968). Cullen *et al.* (1985) describe similar plagioclase ultraphyric basalts from the Galapagos Archipelago which they have termed abingdonites.

Mineralogically, petrographically, and texturally the gabbros are identical to the basalts they intrude except for their coarser grain size. They contain euhedral plagioclase laths, poikilitic clinopyroxene (Plate 8C), and interstitial iron-titanium oxides. Alteration is highly variable as in the pillow basalts. The

Plate 8

Photographs of Fishtrap Gabbro. A) Columnar jointed, nearly flat lying gabbro sill. B) Alternating plagioclase rich and plagioclase poor layers in gabbro sill, in northern Hottah Lake. C) Photomicrograph of pyroxene poikilitic zone near base of weakly zoned sill. D) Plagioclase glomerocrystic texture typical of many sills and dikes of Fishtrap Gabbro, and interior portion of zoned sill.

Plate 9

- A) Pegmatitic zone containing radiating acicular pyroxene crystals, upper part of zoned gabbro sill .
B) Large quartz-filled amygdale in upper portion of zoned gabbro sill. C) Abraded zircon crystals, -105/+74 size fraction, analyzed for U-Pb composition. D) Etched, euhedral zircon crystals, -105/+74 size fraction, displaying oscillatory igneous zoning. Note the lack of any inherited cores.

partly to completely saussuritized glomerocrysts are commonly surrounded by nearly continuous 1-3mm rims of unaltered feldspar. In both the pillow basalt and the gabbro, the An content of the interior of a typical megacryst (based on microprobe work by Morrison at Johnson Space Center) is An₈₆. An content of the thin, unaltered rims averages An₆₃ which is consistent, in general, with the matrix plagioclase. The calcic cores to the megacrysts are comparable to many Archean rocks (Morrison, pers. comm.) and to plagioclase phyric midocean ridge basalts (Stakes *et al.* 1984).

Bloom Basalt and Fishtrap Gabbro are interpreted as comagmatic based on their identical, distinctive, glomeroporphyritic textures and similar whole rock chemistry (Chapter 5). The presence of plagioclase megacrysts and glomerocrysts in the chilled selvages of pillows and border zones of sills indicates that the phenocrysts did not form in situ, but crystallized elsewhere and were transported to the site of emplacement. However, whether they crystallized from the same parental melt as the host rock or are xenocrystic in nature is unknown. The megacrysts/glomerocrysts are clearly in disequilibrium with the host melt as evidenced by both the significantly more sodic rims and the gap in An content between cores and groundmass plagioclase crystals. Slow crystallization under different pressure-temperature conditions would result in unzoned megacrysts and glomerocrysts of a different composition from late forming rims and groundmass plagioclase. This may partially explain the occurrence of fresh plagioclase groundmass crystals in the same rock as the saussuritized megacrysts and glomerocrysts because the two are of composition dissimilar enough to have different susceptibilities to subsequent alteration. Alternatively, the calcic cores may be xenocrystic and altered prior to incorporation within the host melt.

As a tentative conclusion, the clusters of plagioclase phenocrysts in both the pillow basalts and gabbro sills are regarded as products of early crystallization of the same magma that gave rise to the host rock. The occurrence of both aphyric and porphyritic sills and pillowed flows at all stratigraphic horizons suggests a complex magmatic plumbing system, possibly involving alternate tapping of individual magma chambers at various stages of crystallization or tapping different horizons of a single, chemically stratified magma chamber. The gabbro sills, which are more abundant and somewhat thicker where they intrude the Conjuror Bay Formation, may have been high-level magma chambers which fed upper parts of Bloom Basalt.

CHAPTER 3: U-PB (ZIRCON) AGE

U-Pb zircon data (Bowring and Van Schmus 1982, in press; Bowring 1984) based on 15 years of geological mapping provide constraints for some of the magmatic and tectonic activity during the development of Wopmay Orogen. However, questions remain regarding the exact age, regional significance, and tectonic setting of the Bell Island Group. To aid in clarifying these points, a porphyritic rhyolite flow of the Zebulon Formation was collected for U-Pb zircon dating. Figure 8 shows the sampling location.

ANALYTICAL METHODS

U-Pb zircon work was done at the Geochronology Laboratory of the Geological Survey of Canada. Zircons were separated from crushed rock sample using standard heavy liquid techniques, split into six size fractions, and further subdivided using a Frantz isodynamic magnetic separator. The least magnetic portions of the varying size fractions were hand-picked by the author in order to obtain the clearest, least fractured, inclusion-free euhedral zircons for analysis. These zircons were abraded to remove the surface regions which are most susceptible to chemical alteration and Pb loss (Krogh 1982). Zircons were dissolved and Pb and U separated using procedures modified from Krogh (1973). Concentration data were obtained using a mixed $^{205}\text{Pb}/^{235}\text{U}$ or a mixed ^{205}Pb - ^{238}U - ^{235}U tracer. Isotopic ratios were measured on a Finnigan-MAT

261 mass spectrometer equipped with a fully adjustable multiple collector and electron multiplier using a data collection procedure outlined by Roddick *et al.* (in press). Data points were evaluated by means of a modified York (1969) regression as outlined in Parrish and Van Breeman (1985). Errors on ages are quoted at the 95% confidence level.

RESULTS

Zircons separated for analysis were colorless or pale yellow and euhedral to stubby (length:width = 1:3) and contained no visible relict cores (Plate 9C). Analytical data are presented in Table 2. The six data points are discordant, but define a linear array on a concordia diagram that intersects the concordia curve at $1898.4 \pm 7.2 / -6.3$ Ma (Fig. 6). The $^{207}\text{Pb}/^{206}\text{Pb}$ intercept age is interpreted to reflect the time of extrusion and quenching of the flow. No geologic meaning is attributed to the lower intercept at 0 Ma. The discordant age pattern can be attributed to either inherited zircons or to lead-loss. Because the zircons analyzed contain no visible relict cores (Plate 9D), lead-loss is more likely. However, whether an episodic, continuous, or dilatancy model applies is not critical to the accurate interpretation of the primary age and is beyond the scope of this report.

DISCUSSION

Rocks of the Bell Island Group have previously been considered the oldest supracrustal rocks of the McTavish Supergroup and have been included within the Great Bear Magmatic Zone (Hoffman and McGlynn 1977; Hildebrand 1981;

Table 2. U-Pb analytical data.

Sample Fraction	wt (mg)	U (ppm)	Pb* (ppm)	Measured 206Pb/204Pb	Mole % 208Pb*	206Pb/238U	Isotopic Compositions 207Pb/235U	207Pb/206Pb	Isotopic Age 207Pb/206Pb
-105+74	0.032	527.1	186.7	3343	0.111	0.3276	5.254	0.1163	1900.3
-105+74	0.011	200.7	68.39	1020	0.116	0.3136	5.032	0.1164	1901.3
-149+105	0.079	417.3	73.74	5604	0.110	0.3060	4.895	0.1160	1896.0
-149+105	0.047	340.3	107.6	4881	0.115	0.2915	4.676	0.1163	1900.8
-149+105	0.080	326.4	107.8	3942	0.109	0.3065	4.913	0.1163	1899.3
-105+74	0.086	333.9	113.2	7505	0.109	0.3145	5.029	0.1160	1895.1

* Numbers refer to size of zircons in microns; all samples are abraded using method of Krogh (1982).

* Pb=radiogenic Pb content.

Blanks associated with these analyses were approximately 35 picograms Pb, 50 picograms U.

Figure 6 U-Pb concordia plot for zircon analyses from a
rhyolite flow of the Zebulon Formation.

Hildebrand et al. 1983, 1984; Reichenbach 1985; Hildebrand and Roots 1985). The Great Bear Magmatic Zone comprises all supracrustal and intrusive rocks of western Wopmay Orogen that post-date the deformation of Coronation Margin during the Calderian Orogeny (Hildebrand, pers. comm.), which is bracketed between 1900Ma and 1880Ma (Bowring and Van Schmus, in press). Because rocks of the Bell Island Group, themselves little deformed, overlie penetratively deformed rocks of Hottah Terrane, the deformation of which has been interpreted to be synchronous with the Calderian Orogeny (Hildebrand et al. 1983; Hoffman and Bowring 1984; Hildebrand and Roots 1985), they were previously considered to postdate the deformation of Coronation Margin. Several implications, therefore, arise from this date.

- 1) Rocks of the Zebulon Formation (Bell Island Group) predate the Calderian Orogeny and therefore should not be included within the Great Bear Magmatic Zone; it is proposed to remove the Bell Island Group from the Great Bear zone and consider them, instead, as cover rocks to Hottah Terrane.
- 2) The fact that rocks of the Zebulon Formation predate the Calderian Orogeny, are not penetratively deformed, yet unconformably overlie penetratively strained rocks of Hottah Terrane, necessitates that the main deformation in Hottah Terrane is pre-Calderian in age, and therefore of unknown origin. The deformation of Hottah Terrane is likely due to a complex history of heterogeneous strain, which may in part, but certainly not in entirety, be due to the Calderian Orogeny.
- 3) Present age constraints indicate a maximum of 25Ma elapsed between deposition of the Bell Island Group (1898Ma) and the Labine Group (1875Ma, Bowring and Van Schmus, in press). This suggests that the

locally exposed angular unconformity between Bloom Basalt (Bell Island Group) and the overlying Labine Group may represent a greater time gap than previously suspected and thus an unconformity of regional importance. Dating the dacite which occurs at the top of Bloom Basalt could confirm this.

4) The ca. 1898 Ma age suggests a correlation among Bloom Basalt, Fishtrap Gabbro, and rocks of the Akaitcho and Grant Groups to the east, based on similarities in age, composition, and lithology (see Chapter 6).

CHAPTER 4: STRUCTURAL GEOLOGY

Rigorous structural interpretations and reconstructions for the Bell Island Group are severely limited due to a lack of kinematic indicators and piercing points; unknown fault plane orientations, and reactivation of pre-existing structures. The oldest deformational structures recognized are broad, gently plunging folds having north-trending axes and minor subsidiary folds on their limbs. Similar folding has affected most rocks of the Great Bear Magmatic Zone although to the north and northeast, the regional trend of the fold axes is more northwesterly. This suggests that the folds of the Bell Island Group could be due to an earlier deformation such as the Calderian Orogeny, but there is no way to test this possibility. Strain fabric attributed to the folding has been recognized only in bedded tuffs. A low angle cleavage that forms an angle of 30-40° with the bedding plane and is steeper than bedding on both fold limbs.

These folds, and all the supracrustal rocks of the Great Bear Magmatic Zone are segmented by right-lateral, northeast-trending transcurrent faults. The faults are typical of those throughout Wopmay Orogen that have been interpreted as the result of east-west compression (Hoffman 1980b; Tirrul 1984). The faults, however, are not related to the folds, because different strain regimes are necessary to explain their nearly perpendicular respective orientations (Anderson 1951; Wilcox et al. 1973). A fabric possibly attributable to the east-west compression is a nearly vertical, north-south cleavage that is well developed only in bedded tuff.

Brittle faults of east-west and north-south orientation affect virtually all the rocks of the Bell Island Group. For instance, in areas with good stratigraphic control, east-trending faults having small amounts of displacement are prevalent (Fig.7). For the most part, dips of the fault planes could not be measured. These faults must postdate folding, because many of them cut fold axes. The faults could be interpreted as subsidiary strike-slip faults associated with the major transcurrent movements. However, assuming strike-slip displacement, the offset is both sinistral and dextral, which is incompatible with the dextral displacement along the transcurrent faults. A more reasonable interpretation is that they are normal faults, formed perpendicular to the north-south extension direction during transcurrent faulting.

Other faults trending north-northeast, with locally developed steep, north-trending cleavages along their traces, terminate at an oblique angle to a minor transcurrent fault cutting Bell Island (Fig.7). Relative offset between the faults cannot be accounted for by dextral strike-slip movement alone. One north-trending fault brings Hottah basement over rocks of the Zebulon Formation, and may be a reverse or thrust fault. One explanation for these faults is that they are earlier structures truncated by the transcurrent fault. A comparable thrust(?) fault is recognized to the northeast, on the other side of the transcurrent fault, where the ash-flow tuff member is repeated (Fig.2). An alternate explanation is that both the transcurrent faults and the faults at an oblique angle to them are synchronous. An estimate of the strike-slip separation along the transcurrent fault ranges from 1km in the northeast to close to zero in the southwest. Thus, one model might be that these faults are due to the termination of the transcurrent fault by splaying. The compressional

Figure 7 Simplified map of southern Bell Island illustrating faults.

structures (cleavages, reverse faults) of the secondary faults are compatible with this model, according to which the faults occur in an area of compression (cf. Chinnery, 1961). However, left-stepping dextral strike-slip faults also produce compression in the step-over area (Segall and Pollard 1980; Rodgers 1980). Unfortunately, there is neither exposure to the south of Bell Island, nor aeromagnetic data, where the left-stepping transcurrent fault would likely continue.

Many of the transcurrent faults that cut rocks of the Bell Island Group have a component of dip-slip movement. Perhaps this is a result of reactivation during a period of normal faulting which is recognized in rocks of the younger Hornby Bay Group (Hoffman and McGlynn 1977; McGrath and Hildebrand 1984).

No structures have been recognized as clearly synvolcanic. However, Figure 3 illustrates that the Zebulon Formation is restricted to the southern extent of the Bell Island Group, in contrast to the overlying Bloom Basalt, which extends as far north as Conjuror Bay. A possible interpretation is that the subaerial lavas were erupted in local fault bounded areas of subsidence. Synvolcanic subsidence is clearly substantiated by the overlying thick pile of pillow basalts which necessitate extension, perhaps with associated normal faulting, during their eruption; therefore, subsidence could have begun during early subaerial volcanism and culminated during, or shortly after, extrusion of the thick pillow basalt pile. Any synvolcanic structures have likely been reactivated during later episodes of deformation and their origin obscured.

CHAPTER 5: WHOLE-ROCK CHEMISTRY

Based on field data alone, the Bell Island Group volcanic rocks were subdivided into two distinct, stratigraphically conformable sequences: 1) a heterogeneous, subaerial sequence (Zebulon Formation) and 2) a homogeneous, subaqueous sequence (Bloom Basalt). The differences between these two formations can be extended to major differences in their chemistry, a distinction which is critical to their tectonic interpretation.

ANALYTICAL METHODS

Major oxide and trace element analyses were done for the author at the Geological Survey of Canada by standard X-ray fluorescence, ICP-emission spectrometry, and atomic absorption techniques (see Table 3) - except for FeO (titration), H₂O (infrared detector), and CO₂ (infrared detector). Fe₂O₃ was calculated using Fe₂O₃T (XRF or ICP) - 1.11134 FeO (volumetric). Major and trace element analyses are listed in Tables 4-9. For sample locations see Figure 8. In the diagrams and discussion that follow, all analyses have been recalculated to 100% on a volatile-free basis.

ALTERATION

Volcanic rocks are notorious for their susceptibility to alteration. The

Table 3. Analytical Methods.

	AA	XRF	ICP	other	Sample Number
SiO ₂ , TiO ₂ , Al ₂ O ₃ ,	X				R84-86 R84-153 R84-173
MgO, Fe ₂ O ₃ (T), MnO,					R84-91 R84-154 R84-180
CaO, K ₂ O, P ₂ O ₅				83R-61 83R-68 83R-78 83R-80 R84-73A R84-81	R84-155 R84-186 R84-200 R84-202 R84-204 R84-235 R84-247
Na ₂ O	X				R84-102 R84-104 R84-105 R84-129 R84-131
Ba		X			R84-170 R84-172
SiO ₂ , TiO ₂ , Al ₂ O ₃ ,		X			R84-32 R84-227 R84-344
MgO, Fe ₂ O ₃ (T), MnO,					R84-46 R84-233 R84-3520
CaO, K ₂ O, Na ₂ O,					R84-79A R84-237 R84-3521
P ₂ O ₅					R84-120B R84-260A R84-359
					R84-121 R84-262 R84-360
					R84-147 R84-266 R84-361
					R84-151 R84-272 R84-370
					R84-178 R84-323 R84-379
Ba		X			R84-212 R84-336 R84-388
					R84-222 R84-338 R84-G5
FeO, H ₂ O, CO ₂			X	all samples	
Co, Cr, Cu, La,			X	all samples	
Ni, V, Yb, Zn					
Nb, Rb, Sr, Y, Zr		X		all samples	

Table 4. Chemical analyses of basalts of the Zebulon Formation. Major elements in weight % and trace elements in ppm. l, lower member; u, upper member.

	R84-104 _l	R84-46 _l	R84-186 _l	R84-102 _l	R84-227 _u	R84-172 _l	R84-120B _l
SiO ₂	46.60	48.80	48.40	49.00	48.30	49.90	49.50
TiO ₂	1.29	1.86	0.81	0.85	0.74	0.91	1.30
Al ₂ O ₃	16.00	16.50	16.10	16.80	13.80	16.80	16.70
Fe ₂ O ₃	5.20	6.60	6.20	5.20	3.90	4.50	7.20
FeO	5.90	4.90	5.00	5.60	6.00	5.50	2.60
MgO	5.93	5.88	5.66	7.59	9.90	5.34	1.25
MnO	0.39	0.35	0.45	0.29	0.26	0.31	0.56
CaO	6.39	6.00	7.61	6.32	6.73	6.02	6.82
Na ₂ O	3.60	4.16	3.80	2.84	2.90	5.19	3.81
K ₂ O	1.56	2.07	1.83	1.42	1.44	0.87	4.02
P ₂ O ₅	0.36	0.36	0.17	0.17	0.16	0.20	0.32
H ₂ O	3.60	2.90	2.30	3.30	3.30	2.40	1.70
CO ₂	3.40	1.10	2.10	1.70	1.90	1.40	5.50
total	100.40	101.60	100.60	101.20	99.6	99.50	101.40
V	190	290	180	210	220	190	260
Cr	310	110	440	310	840	32	69
Co	74	51	49	49	54	43	29
Ni	220	110	190	190	280	77	76
Cu	68	23	17	16	11	16	22
Zn	310	390	160	200	180	270	42
Rb	64	70	93	55	62	29	220
Sr	210	260	200	250	320	430	70
Y	24	37	21	16	19	22	28
Zr	140	200	88	78	76	100	160
Nb	9	7	6	5	8	5	10
Ba	240	590	330	190	370	160	140
La	30	39	27	30	19	26	35
Yb	2.6	3.4	2.4	1.7	1.9	2.5	2.7

Table 5: Chemical analyses of intermediate flows of the Zebulon Formation. Major elements in weight % and trace elements in ppin. l, lower member; u, upper member.

	R84-202 _u	R84-155 _l	R84-121 _l	R84-23 _l	R84-86 _l	R84-344 _u	83R-80 _l	R84-233 _l	R84-157 _l
SiO ₂	51.60	51.00	51.00	52.40	52.60	52.40	55.30	54.60	53.30
TiO ₂	0.90	0.81	1.47	0.82	1.36	1.67	1.25	1.31	1.44
Al ₂ O ₃	16.90	17.00	16.30	17.10	15.90	14.50	16.60	15.40	16.80
Fe ₂ O ₃	6.00	5.10	4.40	2.00	3.90	7.90	4.70	4.10	3.60
FeO	4.50	4.10	3.00	6.00	5.70	5.40	3.40	5.50	3.30
MgO	5.03	4.55	1.37	6.43	2.88	4.70	0.92	2.13	4.03
MnO	0.28	0.19	0.69	0.36	0.44	0.34	0.35	0.34	0.27
CaO	4.86	6.59	7.24	6.79	6.77	3.08	5.53	6.58	5.63
Na ₂ O	3.92	3.40	4.40	3.97	3.44	4.42	7.25	3.18	5.16
K ₂ O	3.00	2.40	3.75	1.91	2.69	1.42	1.00	1.76	1.72
P ₂ O ₅	0.19	0.21	0.48	0.19	0.48	0.33	0.42	0.45	0.51
H ₂ O	2.30	2.60	1.70	2.60	1.30	2.70	1.10	1.80	2.00
CO ₂	0.60	2.90	5.4	0:20	2.80	0.30	3.00	2.50	2.70
total	100.20	100.98	101.20	100.90	100.40	99.30	100.82	99.70	100.60
V	190	180	160	210	140	420	110	160	150
Cr	27	37	21	130	5	36	1	23	7
Co	38	38	21	31	30	48	11	31	35
Ni	87	100	21	71	45	39	31	26	36
Cu	17	12	34	18	14	2	11	12	3
Zn	120	140	69	300	120	490	91	180	250
Rb	120	85	210	54	130	48	33	67	59
Sr	290	290	89	550	300	78	120	370	200
Y	22	20	41	13	36	34	47	34	41
Zr	100	85	210	110	190	150	210	190	220
Nb	7	5	7	6	11	12	11	8	10
Ba	620	280	180	640	290	280	210	340	240
La	25	24	42	22	40	34	41	41	40
Yb	2.5	1.8	3.8	1.3	3.7	3.6	4.5	3.5	3.6

Table 5. (cont.)

	R84-32 _I	R84-105 _I	R84-200 _I	R84-73A _I	R84-129 _I	83R-1 _I	R84-336 _I	R84-147 _I
SiO ₂	56.50	57.10	58.80	58.00	58.90	58.00	61.30	62.20
TiO ₂	1.28	0.79	1.06	0.68	1.19	0.54	0.55	0.56
Al ₂ O ₃	17.70	15.90	16.80	15.60	16.40	15.20	14.80	15.30
Fe ₂ O ₃	4.30	3.00	3.10	2.60	4.20	1.80	8.90	1.70
FeO	2.70	3.30	4.50	3.80	3.60	5.00	0.70	3.70
MgO	1.91	2.94	2.43	5.02	1.41	7.36	0.77	3.94
MnO	0.11	0.17	0.21	0.16	0.38	0.26	0.03	0.14
CaO	2.28	5.81	3.91	4.95	6.35	2.99	0.52	3.12
Na ₂ O	5.34	3.11	4.97	3.50	3.88	2.70	0.51	3.18
K ₂ O	4.00	3.61	2.13	2.44	1.70	1.76	10.20	4.20
P ₂ O ₅	0.42	0.23	0.49	0.17	0.47	0.14	0.13	0.14
H ₂ O	1.70	2.00	1.30	2.30	0.70	3.70	0.90	1.70
CO ₂	2.50	3.10	0.30	1.70	1.50	0.30	0.10	1.60
total	100.80	101.20	100.20	101.10	100.80	99.88	99.60	101.59
V	110	130	46	130	92	130	130	110
Cr	14	76	0	84	7	290	250	100
Co	15	30	13	30	19	35	7	23
Ni	18	100	40	100	39	130	72	66
Cu	3	24	9	67	11	0	0	38
Zn	47	150	150	160	150	260	32	160
Rb	190	99	45	72	64	43	290	110
Sr	48	300	460	260	330	300	49	170
Y	42	21	48	19	41	13	21	19
Zr	220	150	460	130	210	110	130	130
Nb	11	10	14	8	10	10	8	9
Ba	270	590	530	530	290	380	1600	560
La	34	37	32	32	39	12	30	31
Yb	4.1	2.2	4.9	2.1	4.0	0.7	2.1	1.8

Table 5. (cont.)

	R84-360 ₁	R84-170 ₁	R84-154 ₁	R84-237 _u	R84-388 ₁	R84-178 ₁	R84-91 ₁	R84-153 ₁
SiO ₂	63.20	63.10	63.60	63.90	64.60	65.20	68.70	68.90
TiO ₂	1.06	0.90	0.57	0.71	0.48	0.50	0.54	0.53
Al ₂ O ₃	14.40	17.60	15.40	16.70	15.30	15.50	14.40	14.10
Fe ₂ O ₃	7.00	4.30	6.90	4.00	6.40	3.20	4.40	4.30
FeO	0.50	1.60	0.30	1.20	0.50	0.20	0.20	0.30
MgO	0.18	0.91	0.12	1.27	0.38	0.10	0.17	0.02
MnO	0.02	0.03	0.01	0.08	0.01	0.01	0.02	0.00
CaO	0.72	0.78	0.17	1.01	0.06	0.22	0.25	0.22
Na ₂ O	0.43	5.35	0.31	4.06	0.20	0.22	0.85	0.20
K ₂ O	10.90	3.38	11.00	5.21	10.10	12.00	9.64	10.40
P ₂ O ₅	0.46	0.41	0.13	0.24	0.01	0.13	0.14	0.15
H ₂ O	0.60	1.00	0.40	1.10	1.20	0.50	0.50	0.40
CO ₂	0.00	0.20	0.10	0.40	0.10	0.00	0.10	0.00
total	99.69	99.70	99.10	99.90	99.40	97.90	100.10	99.69
V	78	34	16	25	21	17	16	19
Cr	15	0	0	12	14	11	0	3
Co	6	11	4	6	3	3	6	5
Ni	45	32	31	24	29	20	39	37
Cu	2	3	1	37	0	4	8	5
Zn	17	38	23	71	26	40	26	23
Rb	380	150	300	160	330	300	290	270
Sr	48	90	10	49	13	17	25	23
Y	41	41	57	54	68	50	43	46
Zr	240	820	400	440	480	400	400	360
Nb	13	11	18	13	21	20	17	19
Ba	1500	410	330	760	780	440	560	510
La	49	33	53	51	42	55	61	68
Yb	3.4	5.6	5.7	5.2	5.0	4.6	4.3	4.4

Table 6. Chemical analyses of rhyolite ash-flow-tuff of the Zebulon Formation. Major elements in weight % and trace elements in ppm.

	R84-160	R84-361	R84-3521	R84-3520
SiO ₂	71.50	75.60	77.20	76.80
TiO ₂	0.14	0.08	0.13	0.14
Al ₂ O ₃	13.40	11.20	11.10	10.70
Fe ₂ O ₃	4.60	2.00	2.20	2.30
FeO	0.00	0.20	0.60	0.40
MgO	0.05	0.06	0.29	0.23
MnO	0.00	0.01	0.01	0.01
CaO	0.04	0.07	0.07	0.07
Na ₂ O	0.12	0.27	0.23	0.20
K ₂ O	8.48	9.32	7.16	6.70
P ₂ O ₅	0.08	0.04	0.02	0.05
H ₂ O	0.70	0.30	0.70	0.80
CO ₂	0.10	0.00	0.00	0.10
total	99.30	99.20	99.80	98.50
V	22	11	14	12
Cr	0	10	8	8
Co	8	1	2	2
Ni	26	25	27	19
Cu	12	0	5	0
Zn	35	49	19	19
Rb	290	260	210	210
Sr	21	15	17	15
Y	77	67	32	33
Zr	340	220	350	340
Nb	25	37	17	23
Ba	210	910	950	610
La	130	32	61	83
Yb	5.4	4.9	3.0	2.5

Table 7. Chemical analyses of rhyolites of the Zebulon Formation. Major elements in weight % and trace elements in ppm. L, lower member; U, upper member; *, hypabyssal intrusion.

	84-23 _U	84-24 _U	R84-262 _U	83R-84 _U	R84-373 _U	84-30 _U
SiO ₂	69.10	69.00	70.20	72.20	72.00	71.40
TiO ₂	0.66	0.63	0.26	0.08	0.08	0.11
Al ₂ O ₃	14.20	15.00	13.40	13.80	13.00	15.60
Fe ₂ O ₃	42.00	5.10	3.30	1.60	1.50	4.40
FeO	2.80	0.70	0.40	0.20	0.20	0.30
MgO	2.72	0.88	0.14	0.27	0.09	0.48
MnO	0.04	0.01	0.01	0.02	0.01	0.01
CaO	0.33	0.19	0.09	0.12	0.08	0.05
Na ₂ O	1.33	0.11	0.04	1.17	0.24	0.13
K ₂ O	4.19	4.99	9.80	9.06	10.90	4.84
P ₂ O ₅	0.15	0.14	0.04	0.02	0.01	0.03
H ₂ O	2.60	2.30	0.60	0.60	0.30	2.30
CO ₂	0.00	0.00	0.00	0.00	0.00	0.00
Total	100.20	99.09	98.40	99.14	98.60	99.70
V	41	35	22	4	10	11
Cr	17	12	9	2	5	7
Co	8	1	2	0	3	0
Ni	20	12	32	11	45	5
Cu	0	0	6	0	0	0
Zn	85	63	25	23	29	20
Rb	160	270	280	210	270	210
Sr	33	3	15	18	31	4
Y	50	165	48	22	26	48
Zr	420	460	240	130	310	330
Nb	21	22	22	16	16	28
Ba	500	250	1000	400	1700	40
La	66	82	52	26	19	36
Yb	4.0	4.8	4.1	2.8	3.1	3.6

Table 7. (cont.)

	R84-180 _U	R84-212 _U	R84-260A _U	R84-79A*	R84-222 _U	R84-359 _I	R84-204 _U	R84-247 _U
SiO ₂	75.30	76.40	76.10	75.80	76.00	76.50	78.60	79.60
TiO ₂	0.12	0.12	0.09	0.04	0.12	0.07	0.13	0.13
Al ₂ O ₃	13.20	13.40	12.20	12.50	10.90	11.30	11.90	11.00
Fe ₂ O ₃	2.60	0.50	0.40	0.10	1.60	0.90	1.10	1.10
FeO	0.00	0.30	0.40	0.20	0.30	0.20	0.00	0.00
MgO	0.24	0.13	0.20	0.18	0.14	0.05	0.30	0.01
MnO	0.01	0.01	0.03	0.01	0.01	0.01	0.01	0.00
CaO	0.04	0.07	0.27	0.09	0.08	0.07	0.09	0.04
Na ₂ O	0.07	0.17	0.05	0.16	0.18	0.13	0.38	0.05
K ₂ O	7.94	9.10	8.81	8.80	8.55	9.04	7.24	8.16
P ₂ O ₅	0.04	0.02	0.02	0.02	0.01	0.03	0.06	0.04
H ₂ O	0.90	0.50	0.70	0.60	0.50	0.30	0.70	0.50
CO ₂	0.10	0.00	0.40	0.10	0.00	0.00	0.10	0.10
total	98.70	100.90	99.87	98.70	98.40	98.70	100.70	100.80
V	29	5	6	4	10	7	12	13
Cr	12	3	3	3	5	4	7	4
Co	8	3	3	2	3	1	6	4
Ni	28	38	37	19	21	11	29	30
Cu	18	10	36	36	65	0	10	15
Zn	27	18	76	47	18	10	14	22
Rb	240	240	270	180	280	230	180	240
Sr	15	23	29	17	12	14	18	20
Y	39	42	27	57	70	23	55	40
Zr	280	300	210	90	230	240	190	250
Nb	17	22	52	21	30	18	17	32
Ba	330	1500	1400	460	470	300	430	390
La	50	31	6	19	92	46	61	42
Yb	4.6	4.7	4.0	5.8	5.8	2.9	4.0	4.5

Table 8. Chemical analyses of Bloom Basalt. Major elements in weight % and trace elements in ppm.

	R84-266	83R-78	83R-68	C84-152	R84-338	83R-62
SiO ₂	47.60	48.60	50.00	50.70	49.30	67.10
TiO ₂	0.84	1.15	1.18	1.18	1.08	0.40
Al ₂ O ₃	17.10	15.40	14.30	14.40	13.40	16.30
Fe ₂ O ₃	1.50	2.20	2.90	2.30	2.40	1.20
FeO	9.10	8.80	9.80	10.60	9.70	3.40
MgO	8.18	6.81	6.49	8.06	7.44	1.76
MnO	0.23	0.20	0.36	0.27	0.23	0.05
CaO	11.00	11.10	10.50	7.65	9.70	0.39
Na ₂ O	2.20	2.06	3.35	3.72	2.80	0.67
K ₂ O	1.08	0.88	0.29	0.52	0.52	5.90
P ₂ O ₅	0.09	0.14	0.14	0.12	0.13	0.15
H ₂ O	2.30	3.30	2.10	1.70	3.30	2.50
CO ₂	0.10	0.20	0.00	0.00	0.20	0.20
total	101.40	101.00	101.42	101.39	100.30	100.15
V	270	290	310	340	350	57
Cr	170	130	54	140	280	44
Co	59	47	47	51	52	8
Ni	150	94	70	65	78	37
Cu	73	150	130	87	120	4
Zn	120	95	110	160	140	34
Rb	28	8	2	11	9	290
Sr	180	210	110	100	150	28
Y	14	23	29	31	20	37
Zr	54	75	81	79	71	170
Nb	4	5	7	8	4	16
Ba	320	110	90	140	150	850
La	17	20	21	11	14	23
Yb	1.8	2.5	2.6	2.1	2.2	3.1

Table 9. Chemical analyses of Fishtrap Gabbro. Major elements in weight % and trace elements in ppm.

	R84-272	C84-151	R84-379	R84-173	R84-G5	83R-61	R84-98
SiO ₂	49.90	50.30	49.50	49.50	49.50	49.60	50.70
TiO ₂	1.54	1.19	0.84	1.15	0.78	1.15	2.13
Al ₂ O ₃	13.50	14.50	16.20	14.20	15.40	13.70	13.70
Fe ₂ O ₃	3.50	2.00	1.30	4.60	1.20	2.30	8.20
FeO	9.90	10.70	7.80	8.00	7.90	9.90	6.60
MgO	5.57	6.57	8.13	6.69	8.32	6.75	4.15
MnO	0.29	0.36	0.14	0.24	0.19	0.24	0.22
CaO	11.30	9.25	9.70	9.48	9.80	7.58	8.24
Na ₂ O	2.28	3.29	2.20	1.95	2.64	3.98	2.39
K ₂ O	0.47	0.58	1.27	1.22	0.64	0.28	0.70
P ₂ O ₅	0.16	0.12	0.08	0.14	0.09	0.14	0.41
H ₂ O	2.30	2.50	3.30	2.60	3.10	3.80	2.40
CO ₂	0.20	0.10	0.10	0.60	0.20	0.30	0.50
total	101.00	101.58	100.68	100.48	99.89	99.79	100.46
V	430	340	260	300	250	310	330
Cr	35	79	230	130	180	56	32
Co	51	46	46	48	52	48	41
Ni	58	57	160	91	140	68	90
Cu	240	120	53	150	90	120	65
Zn	120	150	89	130	110	120	210
Rb	7	12	41	40	6	2	14
Sr	140	200	210	140	190	85	260
Y	33	26	15	24	10	27	47
Zr	96	75	52	74	45	87	200
Nb	7	5	3	5	0	7	13
Ba	150	150	190	130	110	80	290
La	25	14	12	19	12	21	44
Yb	3.7	1.9	1.6	2.3	1.5	2.8	4.5

main reason for this is the well-known metastable nature of volcanic glass (Morey 1954). Not surprisingly, all the rocks sampled for analysis have undergone some degree of alteration with the consequent development of low-grade mineral assemblages. The type of alteration is, of course, determined by the original composition of the rock (see Fisher and Schminke 1984); variations in degree and style of alteration therefore occur both within and among the Zebulon Formation, Bloom Basalt, and Fishtrap Gabbro.

Basalts and andesites of the Zebulon Formation have high and variable $\text{Fe}_2\text{O}_3/\text{FeO}$ ratios (0.33-2.77%) and H_2O contents (0.70-3.70%) characteristic of hydrated and oxidized phases. High CO_2 contents (0.20-5.50%) are attributed to the alteration of ferromagnesian minerals to carbonate, evident in thin section. For the dacite-rhyolite range, H_2O contents (0.30-2.60%) are variable and CO_2 contents (0.00-0.40%) low. $\text{Fe}_2\text{O}_3/\text{FeO}$ ratios reach a peak in the dacites (2.69-23.00), decreasing in the rhyolites (0.50-14.67) as total iron content also decreases.

The most striking alteration involves a sharp increase in K_2O and a decrease in Na_2O in rocks containing greater than 63% SiO_2 (Fig.9). Some samples contain greater than 12% K_2O and less than 0.30% Na_2O . Other chemical changes accompanying the K_2O increase are dramatic increases in Rb, Ba and $\text{Fe}_2\text{O}_3/\text{FeO}$, and variable decreases in CaO, MgO, Al_2O_3 and Sr (Fig.10). TiO_2 , REE, and trace elements, excepting Sr, Ba and Rb, are not noticeably affected. Similar alteration has been noted in Tertiary rhyolites from the Datil-Mogollon volcanic province in New Mexico, where potassium-enriched rhyolite contains 6-11.5% K_2O , compared to about 4-5% K_2O in the unaltered rock (Chapin et al., 1978; Chapin and Lindley, in press). Numerous other workers have also documented K_2O metasomatism in volcanic rocks (e.g.

Figure 9 Harker variation diagrams for rocks from the Zebulon Formation. Note the presence of a continuous compositional suite from basalt to rhyolite. Sharp changes in contents of many oxides at 63% SiO_2 are due to alteration (see figure 10).

Figure 10 Selected major and trace elements are plotted against K_2O for samples with SiO_2 at $62 \pm 2\%$, in order to compare altered and nonaltered samples standardized with respect to silica. Sharp increase in K_2O is accompanied by increases in Rb, Ba, and Fe_2O_3/FeO and decreases in Na_2O , CaO , MgO , Al_2O_3 , and Sr. TiO_2 , REE, and remaining trace elements are not noticeably affected. Similar alteration is noted in sea-floor rhyolites and in evaporitic basins in the southwestern United States.

Lipman 1965; Keith et al. 1978; Izett 1981; Ekren et al. 1984; Gust et al. 1985). Of particular interest, sea-floor rhyolites studied by Munha et al. (1980) are enriched in potassium and have characteristic K-feldspar + hematite + quartz + illite-montmorillonite assemblages. Along the same line, Sheppard and Gude (1968) documented rhyolitic tuffs altered progressively from glass to zeolites to potassium feldspar due to diagenesis in a moderately to highly saline environment, and cite experimental work indicating that the formation of zeolites and potassium feldspar, rather than clay minerals, is favored by relatively high alkali-ion to hydrogen-ion ratios.

The characteristic mineral assemblages of dacitic-rhyolitic lavas of the Zebulon Formation, discussed in an earlier section, are K-feldspar + quartz + hematite. Well preserved textures are indicative of partly glassy flows that recrystallized to this assemblage at a later date. Based on similarities with Cenozoic lavas altered by interaction with saline fluids, it is suggested that rocks of the Zebulon Formation were similarly altered. Interbedded basalt and andesite flows have primary holocrystalline textures, which may explain why they were much less affected by this alteration.

Alteration by saline fluids is highly likely for two reasons: 1) the conformably overlying Conjuror Bay Formation is interpreted as marginal marine, and 2) lavas of the Zebulon Formation were erupted shortly prior to, or during, regional extension and subsidence, resulting in the formation of a hydrographic basin. Interestingly, Chapin and Glazner (1983) have pointed out that many areas of K-metasomatism in the southwestern United States are areas of regional extension or caldera collapse.

Bloom Basalt and Fishtrap Gabbro are the least altered rocks in the Bell Island Group: $\text{Fe}_2\text{O}_3/\text{FeO}$ ratios average 0.20% and CO_2 contents are low

(0.00-0.60%). High and variable H₂O contents (1.70-3.80%) may either indicate a high primary water content, or be attributable to the presence of hydrated phases such as uraltic amphibole - or a combination of both.

RESULTS

Rocks of the Zebulon Formation form a continuous compositional series from basalt to rhyolite (Fig.9). On an AFM diagram (Fig.11), those with relatively unaltered alkalis plot entirely within the calc-alkaline field and exhibit no iron enrichment. For the basalt-andesite range, TiO₂ values (0.56-1.9%) are low and K₂O values (0.91-4.27%) and average Al₂O₃ contents (16.9%) are high. REE analyses are only available for La and Yb; La/Yb ratios (9-17) are high, suggesting that the Zebulon Formation is LREE-enriched. Trace elements display several trends: 1) Rb, Ba, Zr, Y, Nb, and Yb all correlate positively with SiO₂ content, albeit Yb very weakly, 2) Zn, Sr, Co, and V display a negative correlation with SiO₂, 3) Cr, Ni, and Cu have higher values in basalts, but decrease rapidly to a constant value for the andesite-rhyolite range, and 4) La is fairly constant, but more variable with increasing SiO₂ content. The basalts are LIL element (Sr, K, Ba, Rb) enriched and are depleted in high field strength elements - that is elements having small ionic radii and low radius/charge ratios (Nb, P, Zr, Ti, Y, Yb) - relative to N-MORB. This enrichment in LIL elements may be primary, a result of secondary alteration (Philpotts *et al.* 1969; Hart *et al.* 1974; Cann 1970), or a combination of both.

Major and trace element analyses for Bloom Basalt and Fishtrap Gabbro are reported in Tables 8 and 9 respectively; the basalts and gabbros are chemically indistinguishable. Using the classification scheme of Irvine and

Figure 11 AFM diagram for least altered rocks from the Bell Island Group. Dividing line between tholeiitic and calc-alkaline fields from Irvine and Baragar (1971). Zebulon lavas plot almost entirely within calc-alkaline field, Bloom Basalt and Fishtrap Gabbro plot in tholeiitic field. N.B. Ten gabbro analyses are from Wilson (1979).

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Baragar (1971), they range from olivine to quartz normative. No alkaline rocks are present. On an AFM diagram (Fig.11), Bloom Basalt and Fishtrap Gabbro plot in the tholeiitic field, although they do not exhibit a pronounced tholeiitic differentiation trend because there is little compositional variation between samples. Ratios of Y/Nb are greater than 3, also indicating a tholeiitic character (Pearce and Cann 1973). SiO_2 contents of the tholeiites range from 48.08-51.97%. In general, they are slightly evolved, with total iron content between 9.1-14.8%.

DISCUSSION

Lavas of the Zebulon Formation have chemical compositions that closely resemble those characteristic of arcs built upon continental crust. For example:- 1) continental arc rocks comprise a basalt-andesite-dacite-rhyolite suite, are calc-alkaline, and tend to have high Al_2O_3 and low TiO_2 (Miyashiro 1974; Ewart 1979, 1982; Ewart and LeMaitre 1980); 2) erupted magmas from the continental arc suites are, for compositions greater than 51% SiO_2 , consistently enriched in K_2O , by comparison with the island arc suites (Ewart 1982); 3) calc-alkaline orogenic lavas show strong relative enrichment in the light REE's and have high (ca. 10) La/Yb ratios (Ringwood 1977; Baker 1982); and 4) calc-alkaline basalts from active continental arcs are enriched in LIL elements and contain low abundances of the high field strength elements relative to N-MORB (Ewart 1982; Atherton et al. 1985; Pearce 1983).

TiO_2 contents (0.81-1.56%) of Bloom Basalt and Fishtrap Gabbro are intermediate between averages for island arc tholeiites and MORBs (Jakes and Gill 1970; Kay et al. 1970; Basaltic Volcanism Study Project 1981) and overlap

with TiO_2 values for marginal basin basalts (Hawkins 1977). Ni (57-160ppm) and Cr (32-280ppm) levels are relatively low and Rb (2-41ppm), Ba (80-320ppm) and K_2O (0.29-1.31%) are moderately high relative to N-type MORB (Sun *et al.* 1979; Tarney *et al.* 1981). Overall, they are LIL-element enriched relative to MORB, with values similar to island arc tholeiites (Pearce *et al.* 1981) and marginal basin basalts (Saunders and Tarney 1984). However, it cannot be ruled out that some of the high and variable K, Ba, and Rb values are due to secondary alteration, because basalts typically gain these elements during sea-floor diagenesis (e.g. Philpotts *et al.* 1969; Hart *et al.* 1974). Water content, which may be primary, is higher than normal MORB but similar to marginal basin basalt glasses (Tarney *et al.* 1981).

Ti, Y, Zr, Nb, Cr, V, and REE are typically immobile during low temperature alteration and metamorphism (eg. Philpotts *et al.* 1969; Cann 1970; Bloxam and Lewis 1972). Average Zr/Y ratios (3.4) overlap with those of ocean floor basalts and island arc tholeiites, but are lower than ratios for continental basalts which are generally around 7.5 (Pearce and Cann 1973; Floyd *et al.* 1976). The tholeiites have Ti-Y-Zr abundances similar to modern oceanic tholeiites (Sun and Nesbitt 1977) and plot on a Ti-Y-Zr diagram (Fig.12) in the ocean-floor basalt field. La/Yb ratios (5.2-9.8) imply slight LREE enrichment, in contrast to the generally flat, or LREE depleted patterns of MORB (Kay *et al.* 1970). In terms of Ti and V, the tholeiites have overlapping to higher Ti/V ratios (20-50) than typical island arc tholeiites (less than 20), but Ti/V ratios similar to MORB and continental flood basalts, although lower absolute abundances than the latter. The tholeiites therefore fall in the same field on a Ti/V discrimination diagram (Fig.13) as marginal basin basalts, which overlap both island arc tholeiite and MORB ratios, with MORB-like abundances most common (Shervais 1982).

Figure 12 Ti-Y-Zr discrimination diagram (Pearce and Cann 1973) for rocks of Bloom Basalt and Fishtrap Gabbro. Ti-Y-Zr abundances are similar to modern oceanic tholeiites and plot in the ocean floor basalt field. Within-plate basalts i.e. ocean island or continental basalts plot in field D, ocean-floor basalts in field B, low-potassium tholeiites in fields A and B, and calc-alkaline basalts in fields C and B.

Figure 13 Ti/V discrimination diagram (Shervais 1982) for rocks of Bloom Basalt and Fishtrap Gabbro (both closed circles). Ti/V ratios are transitional between island arc tholeiites (IAT) and MORB and plot in the marginal basin basalt field (MB). Ti/V ratios from rocks of the Akaitcho Group (open circles) overlap with those from Bloom Basalt and Fishtrap Gabbro.
(CT: continental tholeiite field)

Overall, Bloom Basalt and Fishtrap Gabbro have Ti-Y-Zr abundances similar to MORB, but have LIL element values and La/Yb ratios similar to island arc tholeiites. Their tholeiitic chemistry, TiO_2 values and Ti/V and Zr/Y ratios are similar to both MORB and IAT. This 'transitional' chemistry is typical of some marginal basin basalts, although such basalts can be extremely chemically varied, even within the same basin (Stern 1979; Saunders *et al.* 1979, 1982; Tarney *et al.* 1981; Saunders and Tarney 1984).

Petrogenesis

Although varying degrees of alteration rule out any detailed discussion of the petrogenesis of volcanic rocks in the Bell Island Group, a fundamental chemical difference between the Zebulon Formation and Bloom Basalt/Fishtrap Gabbro is manifested by a calc-alkaline versus tholeiitic character. The differences between the calc-alkaline and tholeiitic series cannot be explained by fractionation, but are more likely due to varying degrees of partial melting and depth of melting (e.g. Mysen 1978, 1982; Masuda and Aoki 1979; Hart and Allegre 1980; Hutchison 1982; Onuma *et al.* 1983). In conclusion, the calc-alkaline and tholeiitic basalts of the Bell Island Group represent different parental melts which reflect a change in tectonic setting.

CHAPTER 6: SYNTHESIS

VOLCANIC EVOLUTION

The Bell Island Group is an assemblage of volcanic and sedimentary rocks with complex interfingering relations typical of most continental volcanic fields. Beaverlodge Sandstone, the oldest formation of the group, unconformably overlies a previously deformed and metamorphosed sialic basement complex. The formation is a fining upwards sequence of conglomerate and arkosic and lithic sandstone; undeformed volcanic clasts predominate. It is interpreted to represent a synvolcanic, subaerially deposited alluvial fan complex. An assemblage of calc-alkaline volcanic rocks, named the Zebulon Formation, overlies and interfingers with the sandstone. The formation comprises, in ascending order, mafic to intermediate aphyric lavas intercalated with minor rhyolite block-and-ash flows and bedded tuff, a thick (350m) rhyolite ash-flow tuff, and several distinct rhyolite flow-domes intercalated with minor mafic to intermediate flows. The dominantly aphyric nature of most flows suggests high temperatures of extrusion. Overall, the volcanic rocks form a basalt-andesite-dacite-rhyolite suite. However, exact petrogenetic relations among units are unclear due to alteration and insufficient geochronological constraints. Except for small hypabyssal intrusions, no plutonism directly related to this phase of magmatism is recognized.

Subsequent magmatism and sedimentation record a transition from a

subaerial to a subaqueous depositional environment. The Conjuror Bay Formation, which conformably overlies the Zebulon Formation, contains rippled and cross-bedded mature quartzarenite and planar bedded siltstone and mudstone deposited in a marginal marine setting. Tholeiitic pillowed flows of Bloom Basalt overlie the sedimentary rocks and are intercalated with oolitic and stromatolitic patch reefs. Textures of the basalt range from aphyric to plagioclase megacrystic and glomerocrystic. Eruption in shallow water is suggested by the intercalated patch reefs and highly vesicular nature of the basalts. Gabbro sills intrusive into the pillowed flows are interpreted as comagmatic, based on similar distinctive textures and chemistry. Feeders to the flows and sills occur as north-trending gabbroic dikes that cut the sialic basement complex.

In conclusion, the Bell Island Group records a transition from: 1) subaerial to subaqueous deposition, 2) a continental to a marginal marine environment, 3) calc-alkaline to tholeiitic magmatism, and 4) a basalt-andesite-dacite-rhyolite suite to a fundamentally basaltic suite.

TECTONIC SETTING

Any tectonic interpretation for the Bell Island Group must integrate the stratigraphy, chemistry, structure, and overall volcanic evolution of the group, in addition to its regional geological setting. Some important points to consider for interpretation of the tectonic setting of the group are: 1) volcanic rocks of the Bell Island Group were erupted through and onto sialic crust (Hottah Terrane); 2) magmatic evolution of the group is from a heterogeneous calc-alkaline series (Zebulon Formation) to a homogeneous tholeiitic basalt suite

(Bloom Basalt and Fishtrap Gabbro); 3) the depositional environment was subaerial during calc-alkaline magmatism and subaqueous during tholeiitic magmatism; and 4) the subaqueous environment is interpreted as shallow marine.

Volcanic rocks of the Zebulon Formation form a calc-alkaline basalt-andesite-dacite-rhyolite suite, with rocks of intermediate composition most abundant. Calc-alkaline series rocks occur mainly in island and continental margin arcs, although they do occur infrequently in other environments such as continental and oceanic rifts, ocean islands, and tholeiitic basalt provinces (Miyashiro 1975; Gill 1981). However, basalts usually predominate in the latter settings, and associated intermediate rocks generally differ from arc volcanics in TiO_2 contents and other respects (Gill 1981). The Zebulon Formation is closely comparable in both chemical composition and styles of volcanism to Cenozoic continental arcs. The formation is a high-K calc-alkaline suite with low TiO_2 content and high La/Yb , Al_2O_3 , and K_2O values similar to continental arcs related to subduction such as the Andes (Thorpe and Francis 1979), the San Juan volcanic field (Steven and Lipman 1976), the Cascades (McBirney 1978; McBirney and White 1982), Japan (Kuno 1959; Miyashiro 1974; Aramaki and Ui 1982), Kamchatka (Erlich *et al.* 1979; Erlich and Volynets 1979), and the Alaskan Peninsula (Burk 1965; Marsh 1982).

On a regional scale, the Zebulon Formation both overlies and is overlain by volcanic-plutonic suites best interpreted as continental arcs. They are respectively: Hottah Terrane (Hildebrand and Roots 1985), and the Great Bear Magmatic Zone (Hildebrand 1982; Hildebrand *et al.*, in press, a). Spatially and temporally, the regional tectonic setting of the Zebulon Formation therefore is compatible with a continental magmatic arc.

In contrast to rocks of the calc-alkaline series, tholeiitic basalts occur in almost all tectonomagmatic settings, and as a result numerous geochemical discriminant diagrams have been developed to determine the tectonic setting of basic volcanic rocks, where this cannot be ascertained from the geology. In the case of Bloom Basalt and Fishtrap Gabbro, the benefit of both detailed mapping within a regional context coupled with geochemistry allows the elimination of several possible tectonic settings. For instance, oceanic intraplate volcanism (e.g. Hawaii), though tholeiitic in character, has neither major or minor element chemistry, nor geological setting, in common with Bloom Basalt and Fishtrap Gabbro (Basaltic Volcanism Study Project 1981). It is not unusual for island arcs to have both calc-alkaline and tholeiitic suites; however, the tholeiitic suite is older than the calc-alkaline suite as a rule (Jakes and White 1972; Gill 1981), the reverse of the Bell Island Group. In island arcs that do have tholeiitic basalts, such as Japan (Kuno 1959), the basalts do not occur in successions several kilometres thick, as does Bloom Basalt. In addition, typical island arcs are not built upon sialic crust (Baker 1982; Miyashiro 1974).

Predominantly basaltic magmatism, of the bimodal rhyolite-basalt suite, occurs in Cenozoic volcanic fields characterized by extension. In the Great Basin of the western United States, the transition from predominantly calc-alkaline intermediate rocks to fundamentally basaltic volcanism is considered to be an effect of regional extension indicated by Basin and Range normal faulting and the intrusion of numerous dikes (Christiansen and Lipman 1972; Christiansen and McKee 1978; Scholtz et al. 1971). Mid-ocean ridges, extensional features related to sea-floor spreading, and marginal basins, related to extension within a magmatic arc, are both characterized by basaltic volcanism (Kay et al. 1970; Hawkins 1977; Saunders and Tarney 1984). The

subaerial to subaqueous transition evident in rocks of the Bell Island Group, coupled with a sharp change in chemical composition to predominantly basaltic magmatism, and the consistent northerly trend of feeder dikes in the basement, when taken together, clearly indicate an extensional stress regime during at least the tholeiitic phase of magmatism. The prevailing stress regime during the early subaerial eruptions is uncertain.

Marginal basin rocks are the one volcanic group that share all the salient features with Bloom Basalt and Fishtrap Gabbro, such as: association with a change from calc-alkaline to tholeiitic magmatism (Tarney et al. 1981); predominance of basaltic magmatism with chemistry transitional between mid-ocean ridge basalts and arc tholeiites (Hawkins 1977; Tarney et al. 1981; Saunders and Tarney 1984); and eruption during extension, subsidence, and marine inundation (Karig 1971a, b).

In conclusion, the Bell Island Group can easily and logically be interpreted to represent volcanism within an extending and subsiding continental arc. Karig (1971a, b) referred to extensional basins lying behind island arcs and floored by oceanic crust as marginal basins. However, there is no evidence that extensional processes associated with eruption of Bloom Basalt led to the generation of oceanic crust. In addition, the basin formed in an arc that developed on continental, rather than oceanic crust. The term ensialic marginal basin is therefore appropriate. Marginal basins in intra-oceanic settings are indeed more common than at continental margins, possibly due to the thickness, strength, and rigidity of continental, as opposed to oceanic lithosphere (Toksoz and Bird 1977). Nonetheless, several well-documented examples of marginal basins formed at continental margins exist: the Mesozoic marginal basins of southern Chile (Dalziel et al. 1974; Saunders et al. 1979;

Bartholomew and Tarney 1984), central Chile (Aberg *et al.* 1984), and central Peru (Atherton *et al.* 1983, 1985); and Cenozoic marginal basins such as the proto-Gulf of California (Karig and Jansky 1972, Saunders *et al.* 1982), Okinawa Trough (Letouzey and Kimura 1985), Japan Sea (Uyeda and Miyashiro 1974), and Bransfield Strait (Weaver *et al.* 1979). These basins may be floored by either attenuated continental crust (e.g. central Chile), or by oceanic crust (e.g. southern Chile). Thus, the tectonic setting of the Bell Island Group is considered analogous to these Mesozoic to Recent examples of continental arc-ensialic marginal basin pairs.

REGIONAL CORRELATIONS

About 120km east of the Bell Island Group, in the internal zone of Wopmay Orogen, metavolcanic and metasedimentary rocks of the Akaitcho Group occur at the base of the Coronation Supergroup (Hoffman *et al.* 1973; Easton 1982; Hoffman 1984b). Regional metamorphic grade ranges from greenschist to granulite grade (Easton 1982) and, to an extent, metamorphism is spatially related to the Hepburn Batholith (St-Onge 1981). The group is structurally complex, which hinders accurate thickness estimates and correlations along strike (St-Onge *et al.* 1982; King, in press). However, Easton (1980, 1982) defined a very generalized stratigraphy, in ascending order: pillowed and massive basalt flows and sills, arkosic turbidites, bimodal submarine volcanic complexes, and both pelitic and carbonate sedimentary rocks. U-Pb (zircon) ages for rhyolites in the upper Akaitcho Group, and the correlative Grant Group, range from 1895-1902Ma (Bowring 1984; Bowring and Van Schmus in press).

The overall eruptive sequence of the Akaitcho basalts (see Easton 1982) proceeded from evolved continental tholeiites, through continental tholeiites, to oceanic tholeiites. Respective REE patterns vary from LREE enriched to flat. La/Yb ratios range from 1.2-9.2. The basalts have Ti-Y-Zr abundances similar to oceanic tholeiites, and on a Ti-Y-Zr diagram plot in the ocean floor basalt field. Based on stratigraphy and chemistry, rocks of the Akaitcho Group are interpreted to be continental rift deposits (Hoffman *et al.* 1978; Easton 1980, 1981, 1982).

An understanding of the relationship between Akaitcho Group and Coronation Margin is somewhat unclear due to structural complexity, lateral facies changes, and key units yet to be dated in ongoing geochronological studies. However, observations to date include: 1) in the Kapvik Lake area (Easton 1982; Hoffman 1984b), exposed basement that lies unconformably beneath the Akaitcho Group has a U-Pb (zircon) age of 2569 ± 10 Ma (Bowring and Van Schmus, in press); 2) necessity of a continental source terrane for the voluminous arkoses and granite cobble-bearing conglomerates of the Akaitcho Group (Easton 1980, 1982) that have both Archean (2700 Ma) and early Proterozoic (2035 Ma) detrital zircon ages (Bowring and Van Schmus, in press); 3) rhyolites within the group are considered volumetrically too large to have been fractionated from basaltic magma and are interpreted as crustal melts (Easton 1982); and 4) consistent association of Akaitcho units with thrusted Archean continental crust fragments (King, in press). Thus, the data strongly suggest that the Akaitcho Group was deposited close to, or directly onto, either Archean (Slave Craton?) and/or early Proterozoic (Hottah Terrane?) continental crust.

Relationships between rift deposits of the Akaitcho Group and overlying

passive-margin siliciclastics of the Odjick Formation (Hoffman 1972, 1973) are no less complex. Easton (1980, 1982) interprets pelites of the Odjick Formation to conformably overlie Akaitcho Group rocks east of the Hepburn Batholith. In addition, King (in press) discusses a possible lateral transition between rift facies of the Akaitcho Group and passive margin facies of the Odjick Formation in the south-central part of the internal zone. Because rocks of the Odjick Formation undisputedly onlap Archean crust of the Slave Province (Hoffman 1972, 1973), the interpretation of a conformable and/or transitional relationship between the Odjick Formation and Akaitcho Group is critical, because if correct it indicates that at least part of the Akaitcho Group was deposited directly onto Archean of the Slave Province and not exotic Archean crust.

Bloom Basalt and Fishtrap Gabbro of the Bell Island Group are similar to rocks of the Akaitcho and Grant Groups in terms of:

- 1) lithology: predominance of basaltic rocks and lack of intermediate composition ones, similar plagioclase glomeroporphyritic gabbro sills, presence of intercalated sedimentary rocks, and eruption in a marine environment;
- 2) geochemistry: tholeiitic character, La/Yb ratios, Ti/V ratios (Fig.13), and Ti-Y-Zr abundances; and
- 3) age (?): although neither Bloom Basalt nor Fishtrap Gabbro has been dated, a rhyolite flow at the top of the underlying Zebulon Formation is 1898 ± 7 Ma, which overlaps with ages clustering around 1900 Ma from the Akaitcho Group; because the Bell Island Group is a conformable sequence, there is no reason to suspect that rocks of Bloom Basalt or Fishtrap Gabbro are significantly younger than 1898 Ma.

In summary, based on lithology, geochemistry, and age, Bloom Basalt and Fishtrap Gabbro are correlated with rocks of the Akaitcho and Grant Groups. If this conclusion is correct, then rocks of these formations and groups were erupted and emplaced within the same basin. This basin is here termed the Akaitcho Seaway.

PLATE TECTONIC MODEL

Previous interpretations for the tectonic evolution of Wopmay Orogen have proposed a Wilson Cycle model (Hoffman 1980a) involving crustal stretching, with deposition of rift facies rocks (Akaitcho Group) and development of a passive margin (Odjick and Rocknest Formations). This was followed by margin collapse into a foredeep concurrent with collision of an exotic terrane (Hottah Terrane, Hildebrand 1981) with Slave Craton above a west-dipping subduction zone (Hoffman 1980a). This collision (Calderian Orogeny) produced a metamorphic-plutonic internal zone (St-Onge et al. 1982, 1983, 1984) and a thin-skinned thrust-fold belt (Tirru 1982, 1983). Following collision, an east-dipping subduction zone led to the formation of a calc-alkaline continental arc, Great Bear Magmatic Zone (Hildebrand 1981; Hildebrand and Bowring 1984). However, the geology, geochemistry, and geochronology of the Bell Island Group suggests that the orogen better represents evolving tectonism and magmatism in a continental-arc - back-arc complex (Fig. 14). Thus, modifications to the tectonic model for Wopmay Orogen resulting from research on the Bell Island Group agree in essence with preliminary models recently proposed by Hildebrand and Roots (1985) and Hildebrand et al. (in press, a), but for some alternate reasons.

Figure 14

Tectonic model for the Bell Island Group: A) eastward subduction beneath Hottah Terrane, interpreted to be contiguous to Slave Craton at this time, results in the initiation of the "Zebulon arc" with eruption of lavas of the Zebulon Formation; B) extension within the arc leads to subsidence, marine inundation, and formation of an ensialic marginal basin; C) tholeiitic pillow basalt of Bloom Basalt and the Akaitcho Group, and associated gabbro sills, are erupted and emplaced within a marginal basin setting; and D) basin closure results in the Calderian Orogeny.

In the model presented here, the lower calc-alkaline suite (Zebulon Formation) of the Bell Island Group is interpreted to represent a continental arc formed above an east-dipping subduction zone. Extension within the arc led to subsidence, marine inundation, and eruption of tholeiitic basalts (Bloom Basalt) and emplacement of hypabyssal sills (Fishtrap Gabbro). Tholeiitic volcanic rocks and sills of the Akaitcho and Grant Groups, in the internal zone to the east, are correlated with Bloom Basalt and Fishtrap Gabbro of the Bell Island Group. Tholeiitic rocks of all three groups are therefore considered to have formed within the same marginal basin.

Rocks deposited on the western side of the Akaitcho Seaway (Bloom Basalt) are pinned to Hottah Terrane by feeder dikes (Fishtrap Gabbro) that can be traced from basement rocks into the overlying pillow basalts; rocks deposited on the extreme eastern side (Akaitcho Group) unconformably overlie Archean basement. If it is assumed that the Archean basement is not exotic with respect to Slave Craton, then the model presented here requires Hottah Terrane to have been part of Slave Craton during deposition of Beaverlodge Sandstone and that volcanic rocks of the Zebulon Formation resulted from easterly directed subduction. Hildebrand and Roots (1985) hypothesized that a Hottah arc was contiguous to Slave Craton prior to a 1900Ma rifting event, and that deformation of Hottah Terrane was caused by basin closure (Calderian Orogeny). However, because nonpenetratively strained rocks of the Bell Island Group unconformably overlie penetratively strained rocks of Hottah Terrane, and the Bell Island Group predates the Calderian Orogeny, the penetrative deformation of Hottah Terrane cannot have been caused by the Calderian Orogeny. The origin of the deformation in rocks of Hottah Terrane remains problematic.

Details on the original size of the basin are complicated by deformation during basin closure and cover by younger rocks of the Great Bear zone. Assuming a simplistic model of one continuous basin, an estimate for its width is 150km, obtained by measuring the greatest distance between correlative units perpendicular (E-W) to the ancient continental margin. This is necessarily a minimum width, because deformation during the Calderian Orogeny resulted in tectonic shortening, and may have involved subduction or underthrusting of part of the basin floor. The only quantitative estimates of shortening are from work in the foreland thrust-fold belt using down-plunge projections (Tirrul 1982, 1983). Tirrul's minimum estimate of shortening (E-W) is 40%. Thus, as an absolute minimum estimate, the width of the basin was 216km.

Uncertainties surround the nature of the floor of the basin. Along the western margin, Bloom Basalt was erupted through sialic crust. At this locale, the marginal basin deposits directly overlie the Zebulon Formation. Thus, present exposures of the Bell Island Group are proximal to the arc, and only tholeiites that erupted during the early stages of extension are exposed. To the east, all of the Akaitcho and Grant Groups exposures are consistently associated with fragments of Archean basement. In addition, voluminous rhyolites of the Akaitcho Group are interpreted as crustal melts (Easton 1982). Based on observations to date, it is unlikely that new oceanic crust was ever generated within the marginal basin. However, future mapping in Wopmay Orogen may reveal outliers of marginal basin rocks that could resolve this question.

CHAPTER 7: SUMMARY OF CONCLUSIONS

1. The 4.5km thick Bell Island Group sits unconformably upon an older sialic basement complex (Hottah Terrane). It contains five formations, from oldest to youngest: 1) subaerially deposited conglomerate and sandstone (Beaverlodge Sandstone), 2) subaerially erupted calc-alkaline volcanic rocks ranging in composition from basalt to rhyolite (Zebulon Formation), 3) shallow marine siliciclastics (Conjuror Bay Formation), 4) tholeiitic pillow basalts (Bloom Basalt), and 5) tholeiitic gabbro sills and dikes (Fishtrap Gabbro) interpreted to be comagmatic with the basalts.
2. The subaerial, calc-alkaline basalt-andesite-dacite-rhyolite suite (Zebulon Formation) is interpreted to represent volcanism of a continental arc.
3. The tholeiitic pillow basalts (Bloom Basalt) and co-magmatic gabbroic intrusions (Fishtrap Gabbro) have chemical characteristics transitional between MORBs and arc tholeiites. This, coupled with east-west extension during tholeiitic magmatism as documented by the north-trend of coeval gabbroic dikes, suggests that the upper subaqueous formations of the Bell Island Group were deposited within a north-trending marginal basin.
4. A U-Pb zircon age of 1898Ma, obtained from a rhyolite flow in the Zebulon Formation, implies that: 1) the penetrative deformation of Hottah Terrane

occurred prior to the Calderian Orogeny; and 2) rocks of the Bell Island Group are coeval with rocks of the Akaitcho and Grant Groups and should not be included within the Great Bear Magmatic Zone.

6. Based on similarities in lithology, chemistry, and age, tholeiitic rocks of the Bell Island Group (Bloom Basalt, Fishtrap Gabbro) are correlated with rocks of the Akaitcho and Grant Groups. This implies that rocks of all three groups were deposited in the same marginal basin and supports a back-arc setting for Coronation Margin.

7. If the Akaitcho, Grant, and Bell Island Group were all deposited within the same marginal basin, and are not exotic with respect to the Slave Craton and the rest of Coronation Margin, then the arc-like volcanic rocks of the Zebulon Formation resulted from easterly-directed subduction as there was no ocean to the east. Extension within the arc led to the formation of an ensialic marginal basin between Hottah Terrane and Slave Craton. Implications of this model are: 1) the Calderian Orogeny is the result of closure of the marginal basin rather than a deformational event caused by collision between Slave Craton and an exotic microcontinent; and 2) Wopmay Orogen may represent tectonism and magmatism in an evolving Andean-type plate margin, rather than a Wilson Cycle.

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3 of/de 3

NEED

118°30'
65°15'

Handwritten notes or markings along the right edge of the page, possibly indicating a list or sequence of items.

118°30'
65°15'

25'

20'

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20'

15'

LEGEND

Cenozoic

q Quaternary cover: drift, eskers, raised beaches

Paleozoic

Col OLD FORT ISLAND FORMATION: conglomerate, sandstone

Middle Proterozoic

younger gabbro: medium- to coarse-grained; well-developed ophitic texture; forms northeast trending sheets

Early Proterozoic

GREAT BEAR MAGMATIC ZONE

YEN PLUTON: biotite-hornblende granodiorite, monzogranite

BELL ISLAND GROUP

FISHTRAP GABBRO: equigranular and plagioclase glomerocrystic gabbro sills and dikes; interpreted to be comagmatic with Bloom Basalt

BLOOM BASALT: ophitic and plagioclase glomerocrystic basalt and

GREAT BEAR MAGMATIC ZONE

ophitic texture

crystic gabbro

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ophitic texture;

crystic gabbro sills

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equigranular and plagioclase glomerocrystic gabbro sills and dikes; interpreted to be comagmatic with Bloom Basalt

BLOOM BASALT: aphyric and plagioclase glomerocrystic pillow basalt and pillow breccia

GREAT BEAR MAGMATIC ZONE

Y YEN PLUTON: biotite-hornblende-granodiorite, monzogranite

BELL ISLAND GROUP

FISHTRAP GABBRO: equigranular and plagioclase glomerocrystic gabbro sills and dikes; interpreted to be comagmatic with Bloom Basalt

BLOOM BASALT: aphyric and plagioclase glomerocrystic pillow basalt and pillow breccia

hyalotuff, mudstone, fine grained sandstone

flow-banded dacite flow and breccia containing 1% potassium feldspar and quartz phenocrysts; exposure limited to one island in central Hottah Lake

Bc CONJUROR BAY FORMATION:

Bcl Lower Member: cross-bedded quartzarenite

Bcu Upper Member: siltstone, concretionary mudstone, tuff, and fine grained sandstone; predominantly planar bedded with minor crossbedding and ripples; prevalent slump folds, rip-ups and boudinaged layers

Bz ZEBULON FORMATION:

undifferentiated siliceous hypabyssal intrusions interpreted to be related to magmatism of the Zebulon Formation

Upper Member: characterized by rhyolite flow/domes, but mafic-intermediate flows, breccias, and sedimentary rocks are also present

rhyolite 4: undifferentiated, sparsely porphyritic rhyolite flows and breccias containing about 1% potassium feldspar and quartz phenocrysts

rhyolite 3: red aphyric flow and breccia; finely flow-banded; microamygdaloidal; stratigraphically overlies rhyolite 2

rhyolite 2: porphyritic rhyolite flow and breccia containing 15% phenocrysts of quartz and potassium feldspar; stratigraphic relation to Bzr1 is unknown; U-Pb zircon age is 18.8 Ma

rhyolite 1: light grey aphyric vent facies rhyolite intrusion, flow, and breccia; finely flow-banded; only found on northern Bell Island

Bzu mafic-intermediate flows: basalt; andesite; dacite; similar to lavas of lower member except for stratigraphic position

volcaniclastic rocks: well-bedded to massive rhyolite breccia, normal and inversely size-graded; minor lithic sandstone

Bzt Ash-flow Tuff Member:

rhyolite ash-flow tuff containing up to 5% phenocrysts, zoned from mostly quartz near the base to quartz and potassium feldspar towards the top; lithic-poor, eutaxitic, and near the base, coarsely spherulitic

lithic-rich dacite ash flow tuff containing less than 1% quartz and plagioclase phenocrysts, and flattened pumice fragments up to 30cm in diameter; overlies Bzt; exposed only on central Bell Island

Lower Member: complex sequence of lava flows and less voluminous breccias, tuff, and sedimentary rocks; lavas are characteristically aphyric to sparsely porphyritic and predominantly andesites and dacites; not listed in stratigraphic order

basalt; some flows contain sparse altered microphenocrysts of olivine

plagioclase phenocrysts, and flattened pumice fragments up to 30cm in diameter

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592

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andesite; dacite;
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Bell Island

oluminous breccias,
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listed in stratigraphic

ocrysts of olivine

L A K E

592

L A K E

HOTTAH LAKE

complex sequence of lava flows and less voluminous breccias, tuff, and sedimentary rocks; lavas are characteristically aphyric to sparsely porphyritic and predominantly andesites and dacites; not listed in stratigraphic order

basalt: some flows contain sparse altered microphenocrysts of olivine

plagioclase phenocrysts, and flattened pumice fragments up to 30 cm in diameter; overlies Bzrt; exposed only on central Bell Island

Lower Member: complex sequence of lava flows and less voluminous breccias, tuff, and sedimentary rocks; lavas are characteristically aphyric to sparsely porphyritic and predominantly andesites and dacites; not listed in stratigraphic order

basalt: some flows contain sparse altered microphenocrysts of olivine

andesite: aphyric to sparsely porphyritic andesite flows with up to 1-2% plagioclase phenocrysts, along with minor pyroxene

Bzd dacite: aphyric to sparsely porphyritic dacite flow and breccias containing less than 1% microphenocrysts of plagioclase; perlitic fractures, spherulites and coarse flow banding common

Bzr rhyolite: massive rhyolite breccias and minor flows, aphanitic to sparsely quartz-phyric; Bzrb, intercalated rhyolite breccia and tuff interpreted as block-and-ash flows

Bzs undifferentiated lithic sandstone, mudstone, and conglomerate

Bzbt bedded tuff: generally well-bedded ash- to block-sized volcanogenic fragments, crystals of potassium feldspar and quartz, and flattened pumice in an ash matrix; interpreted as Plinian air-fall and ash-flow tuffs, in places possibly reworked

Bbs BEAVERLODGE SANDSTONE: Fining upwards sequence comprising poorly bedded conglomerate; trough crossbedded granulestone to medium-grained sandstone, and volcanogenic siltstone

HOTTAH TERRANE

H undifferentiated metavolcanic and metasedimentary rocks and deformed and undeformed plutons

Drift covered area (boundary)

Geological boundary (defined, approximate)

Bedding (horizontal, inclined, vertical)

Flow banding (inclined, vertical)

Eutaxitic foliation

Cleavage (inclined, vertical)

Lineation (inclined)

Fault (defined, approximate; tick indicates dip)

Thrust fault (teeth indicate upthrust side)

Anticline

Syncline

oluminous breccias, aphyric to sparsely listed in stratigraphic

ocrysts of olivine

ts up to 30 cm in Island

oluminous breccias, aphyric to sparsely listed in stratigraphic

ocrysts of olivine

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Handwritten mark resembling a stylized 'U' or '7'.

100-100

100-100

BEAVER LODGE

Thrust fault (teeth indicate upthrust)

Anticline

Syncline

HOTTAH LAKE AREA

Scale 1:25'000

kilometres

0

2 kilometres

FIGURE 2

65000

EA

kilometres

EA

kilometres

65000

RIVER

RIVER

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FIGURE 8

BEAVER LODGE

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A
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BELL

ISLAND

BELL

ISLAND

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180±

180±

CAMSELL

BELL

180±

180±

H O T T A H

T T A

180±

180±

180±

CAMSELL

ZEBULON

180±

T T A H

2620

199

END

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FIN