Devonian-Carboniferous igneous intrusions and their deformation, Cobequid Highlands, Nova Scotia

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Date Received October 12, 1993
Date Accepted December 15, 1993

Field relationships and regional distribution patterns of igneous rocks in the Cobequid Highlands provide information on sequential styles of deformation during the later Devonian and Carboniferous formation of the Magdalen Basin. New mapping and aeromagnetic data show that large diorite plutons have orthogonal outlines, suggesting that they occupy pull-apart space. Diorites both cut and are cut by granite plutons, with magma intermingling relationships suggesting co-existing magmas. Limited dating suggests that most plutonism occurred at about the Devonian-Carboniferous boundary and was preceded by mid to late Devonian volcanism in the eastern Cobequids; younger ages reflect alteration and/or deformation events. Granite veins in diorite plutons show strike-slip syn-magmatic deformation. Ductile thrust deformation of the western granite plutons and Fountain Lake Group was followed by brittle faulting and emplacement of dykes along zones of weakness showing east-west pull-apart. Magnetic data reveal that rocks similar to the major diorite plutons underlie much of the central and western Cobequid Highlands and the northeastern part of the Minas sub-basin. The diorite plutons may be an exposed representative of mafic magma that underplated much of the extensional Magdalen Basin. The structure of the Cobequid Highlands is dominated by east-west faults parallel to the Cobequid-Chedabucto Fault that at times acted as transfer faults for major extensional structures in the Magdalen Basin.

Les relations de terrain et les types régionaux de distribution des roches ignées dans les hautes terres de Cobequid fournissent des informations sur les styles séquentiels de déformation pendant la formation du bassin de la Madeleine. Une cartographie et des données aéromagnétiques récentes montrent que de grands plutons de diorite ont des contours orthogonaux, suggérant qu'ils occupent des espaces de transtension. Les diorites à la fois coupent des plutons de granite et sont recoupés par eux, avec des relations d'enchevêtrement de magmas suggérant leur coexistence. Quelques datations suggèrent que la plupart du plutonisme a eu lieu près de la limite Dévonien-Carbonifère et qu'il a été précédé par le volcanisme du Dévonien moyen à tardif dans les Cobequids orientales; les âges plus jeunes reflètent des événements d'altération ou de déformation. Des veines de granite dans les plutons de diorite montrent une déformation syn-magmatique en décrochement. La déformation ductile en chevauchement des plutons granitiques occidentaux et du Groupe de Fountain Lake a été suivie par un faillage cassant et la mise en place de dykes le long de zones de faiblesse montrant des rhombochasmes est-ouest. Les données magnétiques révèlent que des roches similaires aux plutons majeurs de diorite sont sous-jacentes à une grande partie des hautes terres de Cobequid centrales et occidentales et à la partie nord-est du sous-bassin de Minas. Les plutons de diorite pourraient être un échantillon affleurant du magma mafique qui s'est accumulé sous une grande partie du bassin d'extension de la Madeleine. La structure des hautes terres de Cobequid est dominée par des failles est-ouest parallèles à la faille Cobequid-Chedabucto qui, par moments, a agi comme une faille de transfert pour les structures majeures d'extension dans le bassin de la Madeleine.

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INTRODUCTION

Statement of the problem

The opening of the Magdalen Basin, in the Mid to Late Devonian and Carboniferous (Bradley, 1982; McCutcheon and Robinson, 1987), is synchronous with the major known deformation along the Cobequid-Chedabucto Fault (Fig. 1), which spans the Late Devonian (Guysborough County: Keppie and Dallmeyer, 1987) to Westphalian (Stellarton Basin: Yeo and Gao, 1987). The relationship between these two major tectonic features is unclear. Was basin formation independent of, or influenced by, the Cobequid-Chedabucto Fault zone? What was the role of the fault zone in providing a pathway for magmatic products related to basin extension?

The purpose of this paper is to describe recent field data from Devono-Carboniferous igneous rocks that provide information on the contemporary deformation of the Cobequid Highlands. This information is then related to the larger regional setting, using a new magnetic compilation as a guide. In this context, igneous rocks have two important attributes. First, they are themselves a product of a particular tectonic regime (in this case, probably extension) and second, sequential intrusion of igneous rocks allows sequences of deformational structures to be distinguished.

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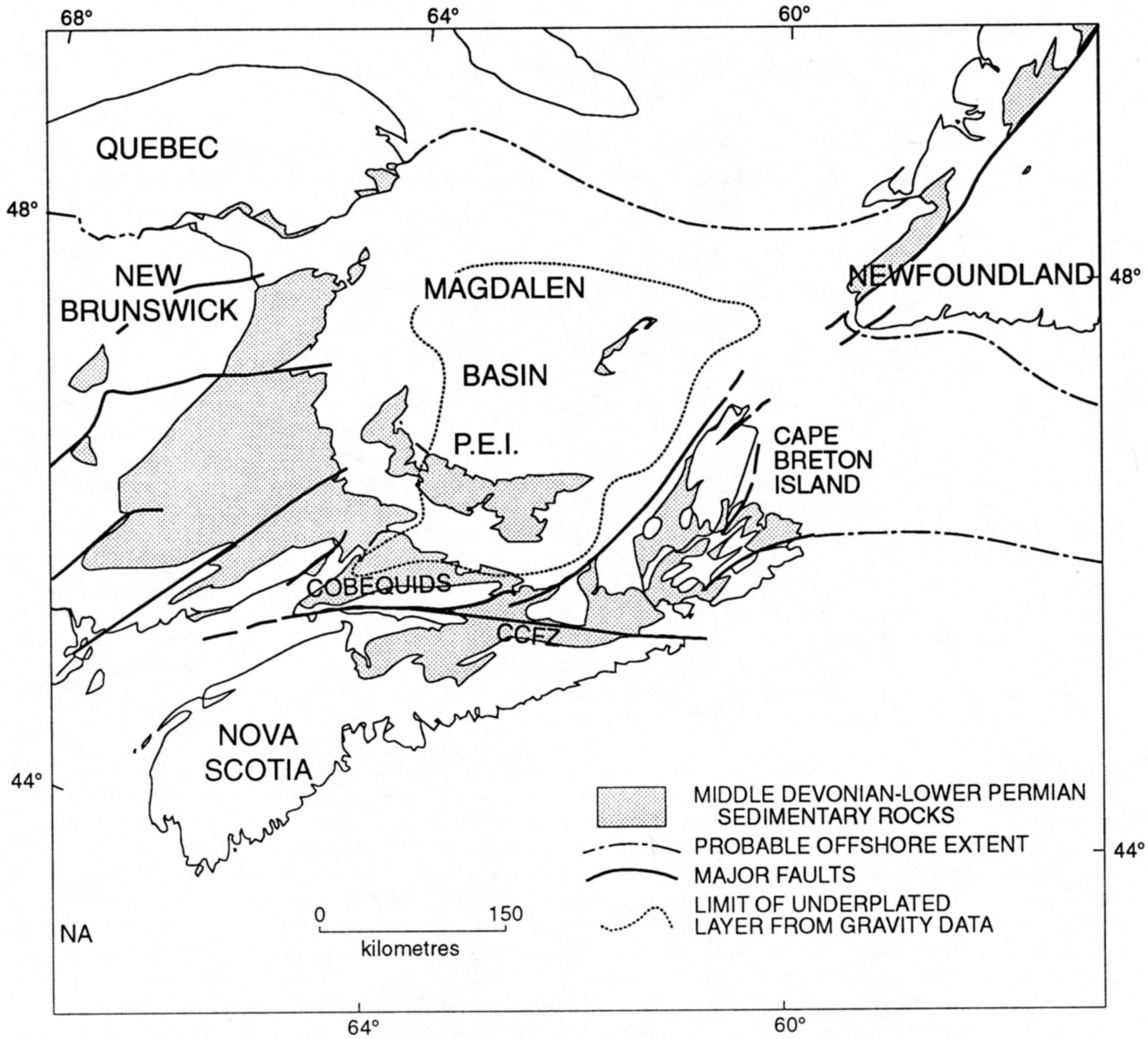

Fig. 1. Regional map showing tectonic setting of the Cobequid Highlands within the larger Magdalen Basin (stippled area). CCFZ = Cobequid-Chedabucto Fault zone.

Geological outline of the Cobequid Highlands

The Cobequid Highlands consist principally of Neoproterozoic Avalonian igneous and low-grade metasedimentary rocks, minor Ordovician (?), Silurian and early Devonian sedimentary rocks, late Devonian and early Carboniferous volcanic rocks (Fountain Lake Group), and earliest Carboniferous diorite and granite plutons (Donohoe and Wallace, 1982, 1985) (Fig. 2). Later Devonian and early Carboniferous clastic sediments (Murphy Brook Formation, Rapid Brook Formation, Falls Formation) contain some igneous detritus, but major supply of sediment to the Cumberland Basin and Minas sub-basin began in the late Namurian (Donohoe and Wallace, 1985; Ryan *et al.*, 1987).

The Cobequid Fault is a 500-m-wide fault zone marking the southernmost extent of crystalline rocks, but in most places it separates the upper Namurian Parrsboro Formation to the south from deformed early Carboniferous sediments (Londonderry and Greville River formations). Donohoe and Wallace (1982) mapped several major faults 1 to 5 km north of the Cobequid Fault and subparallel to it (Londonderry, Kirkhill and Rockland Brook faults).

Sequence of Late Paleozoic igneous events in the Cobequid Highlands

1. Older Fountain Lake Group

The Fountain Lake Group in the eastern Cobequid Highlands (Byers Brook and Diamond Brook formations) consists of felsic volcanics and basalt flows locally interbedded with sedimentary rocks. The Diamond Brook Formation contains Emsian-Eifelian and Tournaisian spores (Donohoe and Wallace, 1982). The volcanic rocks have yielded a whole-rock Rb/Sr isochron age of 387 ± 2 Ma (Pe-Piper *et al.*, 1989) (Fig. 3). These volcanic rocks occur in fault bounded blocks and show no clear relationship to plutonism. The Murphy Brook Formation of the

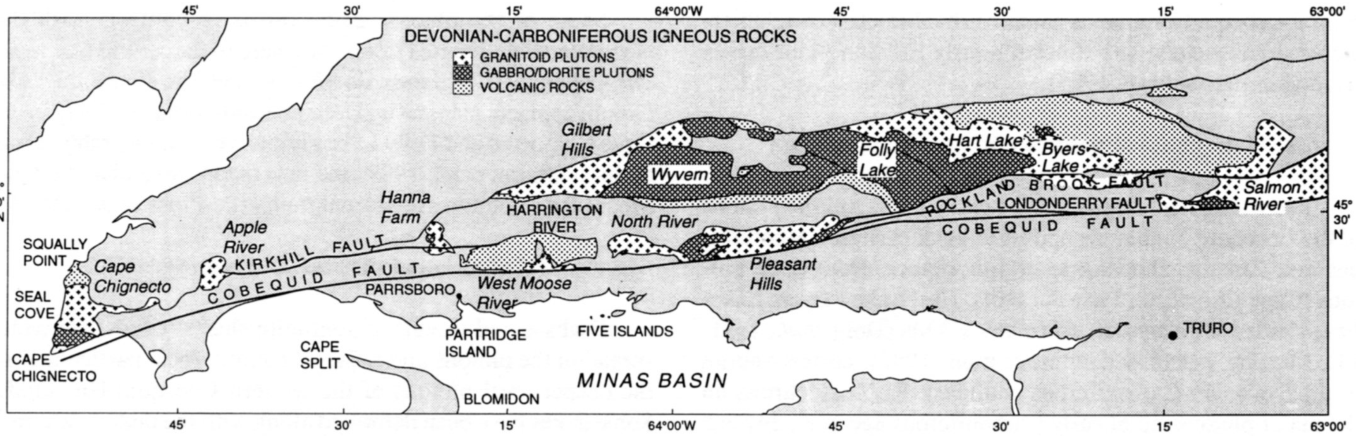

Fig. 2. Summary geological map of the Cobequid Highlands showing distribution of Devonian-Carboniferous igneous rocks. Boundaries modified from Donohoe and Wallace (1982) on the basis of our mapping and magnetic data.

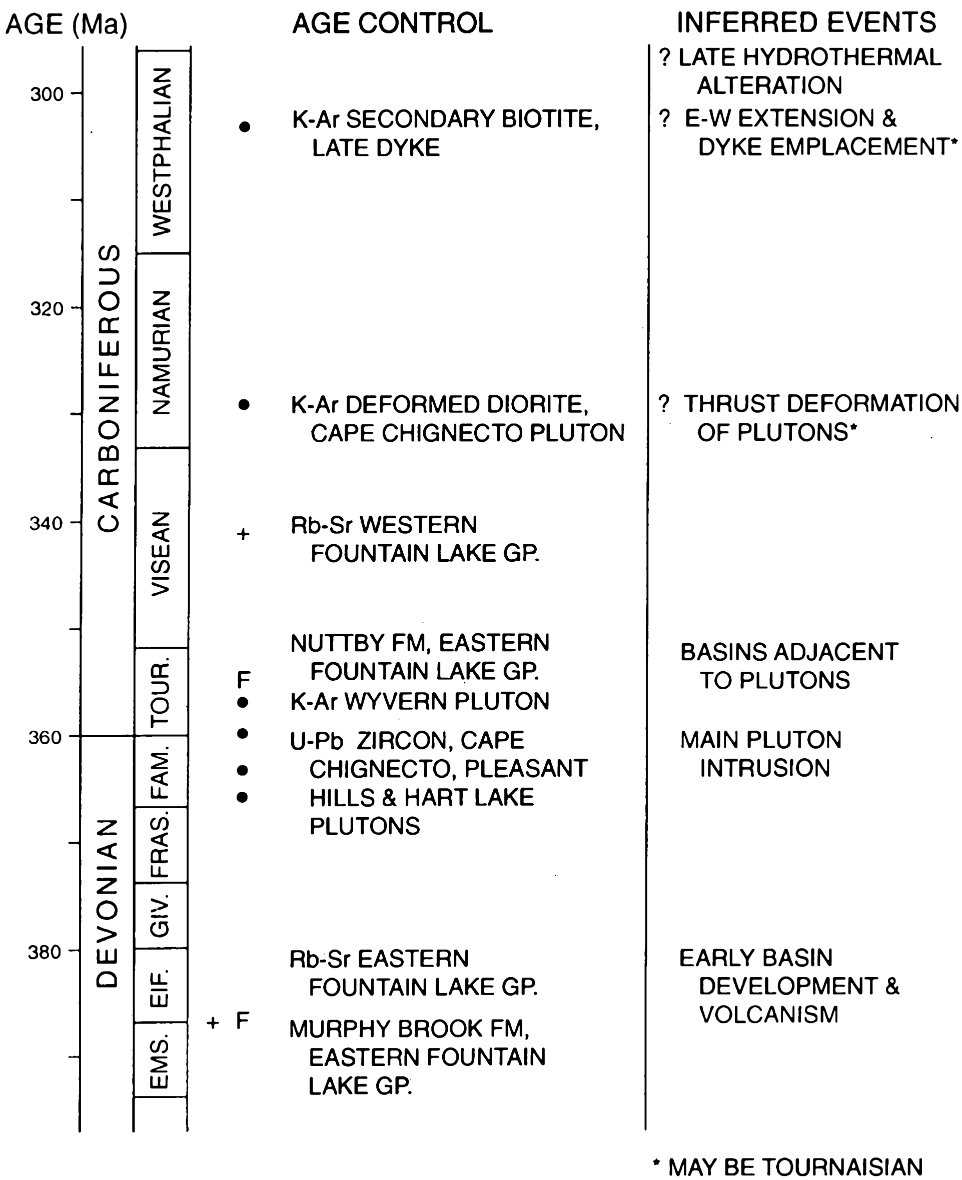

Fig. 3. Stratigraphic column showing available chronology and key Devonian-Carboniferous events in the Cobequid Highlands (modified from Nearing, 1992). F = fossil determinations from Donohoe and Wallace (1982, 1985). • = K/Ar and U/Pb radiometric age determinations for intrusive rocks (from Pe-Piper and Piper, 1987; Waldron *et al.*, 1989; Doig *et al.*, 1991). + = Rb/Sr "isochrons" for volcanic rocks from Pe-Piper *et al.* (1989). Errors on U-Pb ages are about ± 3 Ma, on K/Ar ages about ± 10 Ma, and on Rb/Sr ages on volcanic rocks ± 4 Ma. Note that interpretation of younger events is based only on K/Ar dates: these events may be older (cf. Pe-Piper and Koukouvelas, in press).

central Cobequid Highlands contains rhyolite-clast conglomerates and has yielded late Emsian - early Eifelian plant fossils (Donohoe and Wallace, 1985).

2. Main phase of gabbro and granite plutonism

The widespread diorite/gabbro and smaller granite plutons of the Cobequid Highlands appear to be of earliest Carboniferous age. Zircons, showing some inheritance, from three plutons (Cape Chignecto, Pleasant Hills, Hart Lake - Byers Lake) have yielded U/Pb ages of 361 to 363 ± 3 Ma (Doig *et al.*, 1991; J.B. Murphy, personal communication, 1992), corresponding to the Devonian-Carboniferous boundary. Rb/Sr isochrons on the major plutons are of early Carboniferous age, e.g., 342 ± 5 for the West Moose River pluton, 349 ± 12 Ma for the Cape Chignecto pluton (Pe-Piper *et al.*, 1989), and 348 ± 9 Ma for the Hart Lake - Byers Lake pluton (Donohoe *et al.*, 1986). Comparison with the U-Pb ages dates suggests considerable hydrothermal alteration in the rocks following intrusion. The Wyvern diorite has yielded a K/Ar hornblende date of 357 ± 12 Ma (Krueger Geochron Labs, personal communication, 1987). The Cape Chignecto pluton shows northwest-vergent thrusting and the development of ductile fabrics that have yielded an age of 329 ± 11 Ma (K/Ar on biotite: Waldron *et al.*, 1989), suggesting that thrusting and unroofing had occurred by the Namurian.

Large areas in the eastern Cobequids have been mapped as either Fountain Lake Group volcanic rocks or Salmon River pluton granite (Donohoe and Wallace, 1982). Exposure is limited however, and the extent of plutonic rocks is unclear. The central Cobequid Highlands are dominated by the Folly Lake - Wyvern diorite pluton; it is associated with granite (Pleasant Hills, Hart Lake - Byers Lake, Gilbert Hills) and minor diorite plutons (Fig. 2). The Folly Lake diorite and the Hart Lake - Byers Lake granite appear essentially synchronous: they show lobate contacts and subtle intermingling similar to that described from subvolcanic magma chambers by Wiebe (1993). High-level lithologies including porphyries and inclusions of volcanic rocks occur in the Pleasant Hills and Hart Lake - Byers Lake granites; rapakivi granites are also common. In the western Cobequid Highlands, the plutons are predominantly of granite, with minor marginal gabbros. The Cape Chignecto pluton is cut by gabbro-diorite. Mafic dykes are common in all the plutons of the western Cobequid Highlands. The Cape Chignecto and North River plutons are at a slightly deeper structural level than the West Moose River pluton and the plutons of the central Cobequid Highlands (Pe-Piper *et al.*, 1991).

The Fountain Lake Group volcanic rocks of the western Cobequid Highlands appear broadly synchronous with intrusion of the plutons. Pyroclastic rocks become finer grained away from plutons. A Rb/Sr isochron on the Fountain Lake Group near the West Moose River pluton yielded an age of 341 ± 4 Ma, similar to Rb/Sr isochrons from the plutons (Pe-Piper *et al.*, 1989). In the Rapid Brook Formation, the basal conglomerate containing undeformed granite clasts is overlain by conglomerate with abundant volcanic clasts. The Tournaisian spores in part of the Diamond Brook Formation indicate that there was also earliest Carboniferous volcanism in the eastern Cobequid Highlands.

Some of the plutons show intrusive contacts with the Neoproterozoic Jeffers Group. Nowhere in the central and western Cobequid Highlands do plutons cut the Fountain Lake Group: contacts mapped by Donohoe and Wallace (1982) in the Cape Chignecto and Folly Lake plutons are demonstrably thrust faults (Waldron *et al.*, 1989; and new mapping) and in the West Moose River pluton are normal faults (Pe-Piper *et al.*, 1991).

3. Intrusion of diabase and microgranite

Diabase and minor microgranite sheets (dykes) are widespread in the plutons and adjacent country rock, particularly in the deeper-level plutons of the western Cobequid Highlands. Some dykes have been deformed along with the plutons whereas others cut almost all deformational structures. These dykes can be distinguished from Triassic igneous products by their petrology and geochemistry (Pe-Piper, 1991), but their precise age is uncertain. At Cape Chignecto, undeformed dykes cut thrust structures in the granites and Fountain Lake Group. The youngest radiometric age of 303 ± 11 Ma (mid-Westphalian) (K/Ar on green secondary biotite from a dyke northwest of the West Moose River pluton: Pe-Piper and Piper, 1987) probably dates a hydrothermal event rather than primary emplacement. No dated rocks younger than the Tournaisian Nuttby Formation are cut by dykes.

The youngest igneous rocks are gabbros with feldspar megacrysts, occurring in pod-like bodies tens of metres wide and hundreds of metres in length. They generally appear undeformed and cut earlier structures in the plutons. They cut mylonitically-deformed rocks in the Cobequid Fault zone. Geochemically, they resemble other Carboniferous mafic rocks, but they are undated.

DEFORMATION OF THE PLUTONS

Introduction

Many of the Carboniferous plutons of the Cobequid Highlands show local ductile deformation, some of which may be syn-magmatic, but most of which probably post-dates full crystallisation. A detailed study of the ductile structures is underway and will be published later; preliminary results are summarized by Pe-Piper and Koukouvelas (in press). In this paper we emphasise the cross-cutting relationships between deformed plutons and later dykes in the western Cobequid Highlands.

Cape Chignecto pluton and Squally Point volcanics

The Cape Chignecto pluton has a generally flat-lying mylonitic foliation with a strong northwest-directed mineral lineation and is thrust over the Fountain Lake Group to the north at Seal Cove (Waldron *et al.*, 1989). The Fountain Lake Group between Seal Cove and Squally Point contains flat-lying thrust and ramp structures that indicate northwest-directed brittle deformation (Fig. 4). Largely undeformed mafic dykes occupy some of the steeper thrust structures (B in Fig. 4). These thrust structures post-date intrusion of dykes striking 030° to 040° (A in Fig. 4). They are cut by predominantly north-south trending

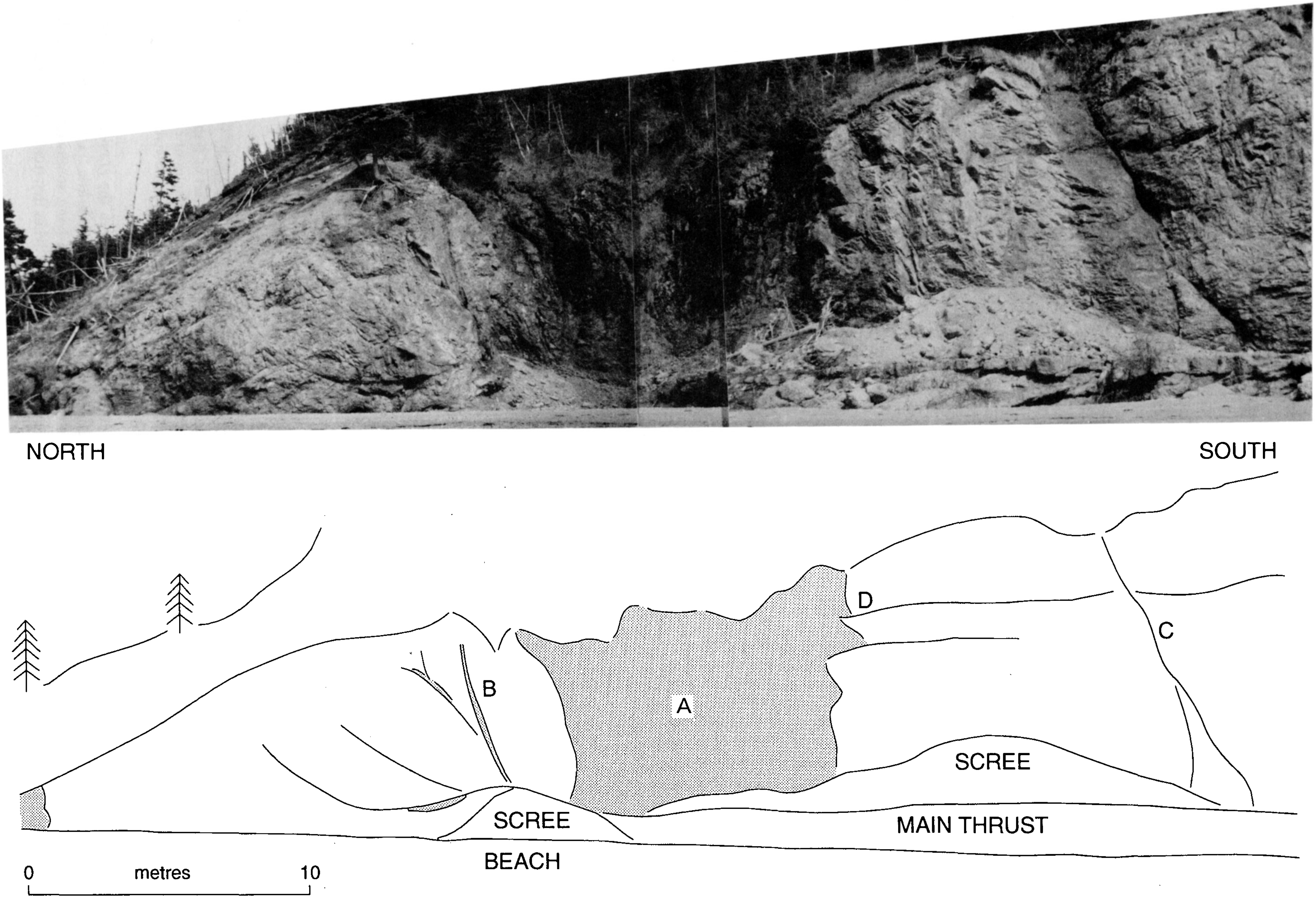

Fig. 4. Photograph and annotated sketch of thrust and ramp features in Fountain Lake Group rhyolites south of Squally Point. (A) early dyke striking 040° cut by main thrust; (B) minor diabase bodies, relatively undeformed, occupying splays of main thrust; (C) diabase dyke with 040° shear zone contact with rhyolite; (D) minor offsets of dyke on flat-lying planes.

dykes, locally composite, that are in places more than 10 m wide. Detailed mapping of these dykes has shown conjugate margins indicating that they formed by east-west extension (Fig. 5). In vertical section, many of the dykes also show conjugate margins, which may be due to complex stoping (Fig. 6). Some dykes appear to have igneous terminations at the thrust planes (e.g., dyke B in Fig. 6), which appear to have acted as transfer faults during extension. Minor re-activation of flat-lying structures has produced offsets in some dykes (T-T' and C in Fig. 6).

West Moose River pluton

The northern margin of the West Moose River pluton is a steeply-dipping igneous contact, or is marked by high-angle faults. The southern margin in many places is marked by the Cobequid Fault, but in the east there is a steep igneous contact with Jeffers Group. Near the Cobequid Fault, granite is mylonitic with mineral lineations of quartz and feldspar trending generally north-south (Fig. 7A).

Most rocks from the central part of the West Moose River pluton are pervasively fractured, with fractures cutting both large crystals and finer groundmass (where present). This fracturing is generally on subparallel joint sets, and, in places, offsets of dykes or development and deformation of cleavage in dykes allows a sequence of events to be distinguished. At the margins of some dykes, fracturing is more irregular and resembles dilational fractures described from mineralised plutons (Hibbard, 1980). Some of these fractures are filled by diabase, but many contain vein quartz and stringers of ferromagnesian minerals.

The oldest diabase sheets are sub-horizontal sills with associated minor dykes (0.2-2 cm wide) occupying fractures in the granite striking east-west and northeast-southwest (Fig. 7A). These early diabase sheets are commonly deformed (particularly near the Cobequid Fault zone) to give a flat lying foliation and a north-south trending mineral lineation. The northeast-southwest dykes show sinistral shear deformation. The diabase sheets are cut by later dykes striking 145° that show further sinistral shear deformation. Both granite and diabase sheets are cut by brittle fractures striking 075° to 110°. The least deformed dykes strike 180° and are offset dextrally by the east-west brittle fractures.

North River pluton

Both diabase and microgranite hypabyssal rocks cut the North River pluton and the surrounding country rock. Pe-Piper (1991) showed that mafic intrusions identified as being earlier from cross-cutting relationships contain less TiO_2 than undeformed, later intrusions. The central and northern parts of the pluton are almost undeformed, but the southern part shows substantial deformation associated with southwest-dipping faults. C-S structures suggest southwest-directed motion on these faults and some of this deformation is taken up in diabase sills, which show southwest-plunging mineral lineations (Fig. 7B). Like those in the West Moose River pluton, these diabase sills have associated dykelets occupying fractures in the granites. Otherwise, dykes are rare in the southern part of the pluton: those that have been found trend almost due east (090°). Further north, the dominant fabric in the granite is an east-west striking (070° to 090°) subvertical brittle fracture. The fracture sets striking 070° cut the flat lying southwest-verging faults and in turn are cut by diabase dykes that trend north-south (Fig.

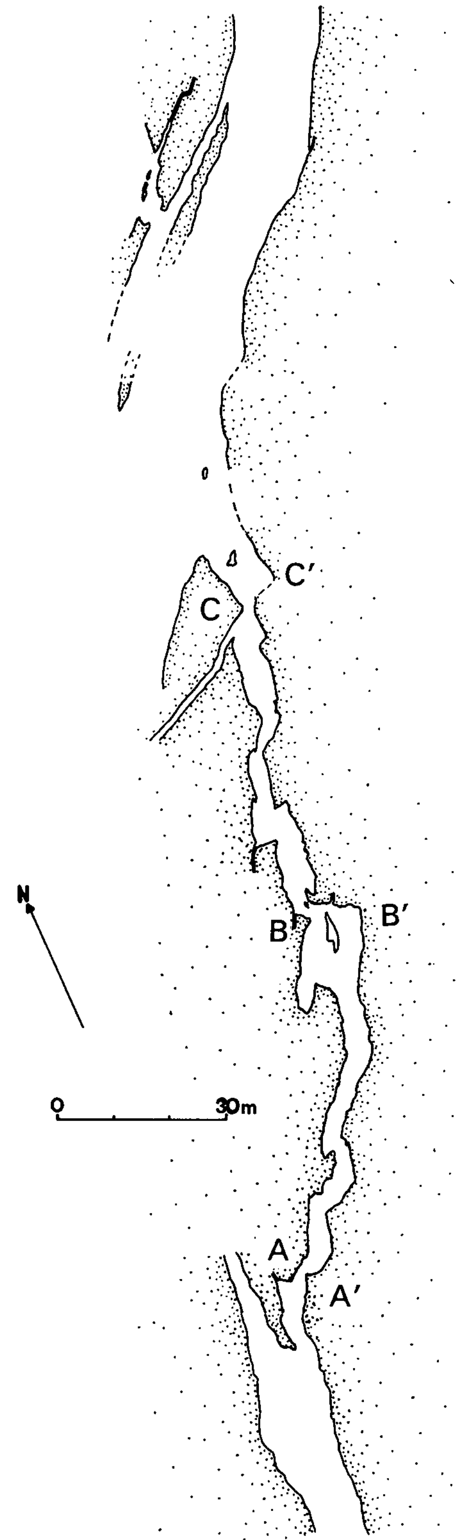

Fig. 5. Map of extensional dykes south of Squally Point, showing the east-west extension recognised from offset of features on conjugate margins. A-A', B-B' and C-C' are examples of conjugate features. Lack of perfect conjugacy is a result of some vertical motion during offset (cf. Fig. 6).

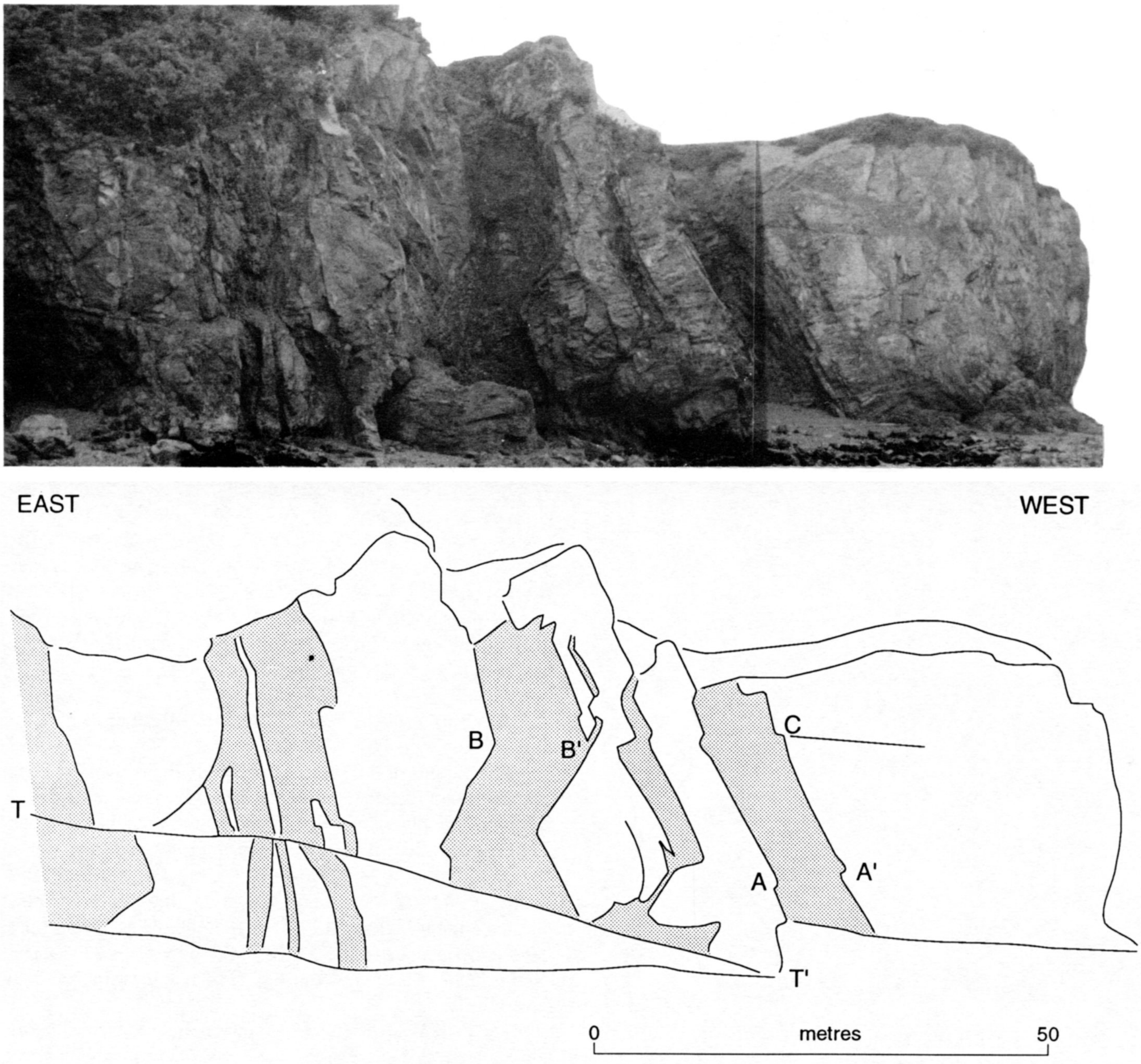

Fig. 6. Photograph and annotated sketch of late dykes cutting Fountain Lake Group rhyolites immediately east of Squally Point. T-T' is thrust plane. A-A', B-B' are examples of conjugate dyke margins. C is minor offset of dyke along flat-lying plane.

7B). In the central and northern part of the pluton, flat lying sills are common and are continuous with northeast-trending dykes: they show variable amounts of shear deformation. Dykes trending north-south are locally continuous with those trending northwest-southeast and both commonly show shear deformation, although some are undeformed. These dykes also show brittle dextral offset on the east-trending fractures. Shear zones, in places mylonitic, are the last major structures and cut the east-west fractures that dextrally offset north-trending dykes.

The northern margin of the North River pluton is a subvertical igneous contact. Except for a southward extension of medium-grained granite in the southwestern corner of the pluton, where igneous contacts are seen, the entire southern margin of the pluton appears faulted. To the west, an apparent continuation of this fault has a large throw, juxtaposing Fountain Lake Group with Jeffers Group.

Within late Proterozoic country rock west of the pluton, exposed in the Harrington River, a microgranite sill shows mylonitic deformation (H in Fig. 7B) that is inconsistent with the limited strain in the country rock, suggesting that deforma-

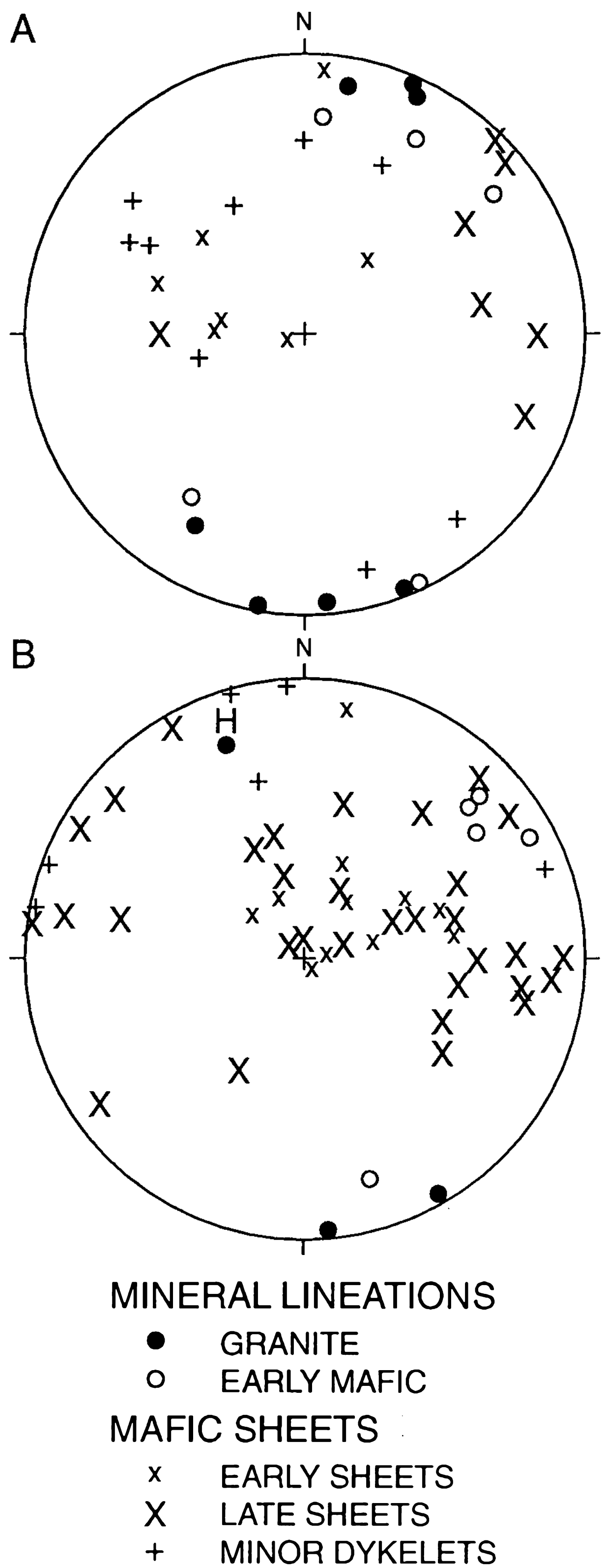

Fig. 7. Stereograms showing orientation of mafic sheets and mineral lineations in (A) West Moose River pluton and (B) North River pluton. H = granite dyke in Harrington River.

tion occurred when the sill was hot. In country rock northwest of the North River and West Moose River plutons, diabase dykes are commonly oriented about 055° or about 005° (db in Fig. 8). The northeast-trending dykes locally pass into sills. These relationships are similar to those observed in the North River pluton. In addition, microgranite dykes (g in Fig. 8) are widespread: some form composite dykes with diabase, but most occupy a variety of orientations and tend to be wider than the diabase dykes.

Synthesis of mafic sheets in the West Moose River and North River plutons

Ductile mylonitic deformation affected granites near the southern margin of both plutons and a microgranite sill in the Harrington River: mineral lineations trend approximately north-south. Subsequent brittle deformation of the granites resulted in flat lying fractures that became pathways for diabase sills and associated steep fractures trending northeast and east. Some of these sills experienced further ductile deformation producing north-trending mineral lineations. Later dykes trend north or southeast and show some shear deformation. Least-deformed mafic bodies include sills and north-trending dykes.

As in the Cape Chignecto pluton, the development of flat-lying structures appears to be followed by extension related to dextral shear along the Cobequid Fault, producing pull-apart on pre-existing fractures. Dykes thus occupy quite a wide range of orientations. They were subsequently affected by dextral slip on east-west fractures and sinistral slip on fractures at a high angle to the master fault. Dextral offset of north-south planes may be the last severe deformation.

Plutons of the central Cobequid Highlands

The plutons of the central Cobequid Highlands have been examined in a reconnaissance manner only. The ductile deformation of the Pleasant Hills pluton along the Rockland Brook Fault has been described by Miller *et al.* (1989) (see also Miller, 1991). The pluton appears to be at a higher structural level than those further west: there is a variety of granites and porphyries present (Selway, 1991). In general, dykes and sills are less common than in the North River pluton: those mapped show orientations and relationships similar to those in the North River pluton.

The Folly Lake pluton, from both reconnaissance mapping and magnetics, appears to be considerably deformed. Flat-lying mylonitic zones are present in the central part of the pluton. The mapped southwestern contact with the Fountain Lake Group is a thrust contact. Granitic veins cutting gabbro/diorite commonly show a preferred orientation and contain lineated phenocrysts that appear to have been oriented before full crystallisation of the veins. Rare diabase dykes, many of which trend north-south, show conjugate pull-apart features similar to those near Squally Point (Fig. 5) indicating east-west extension.

The Wyvern pluton and associated intrusive rocks occupy a series of east-west trending fault-bounded blocks, with a distribution rather different from that mapped by Donohoe and Wallace (1982) (Piper *et al.*, 1994). As in the Folly Lake pluton, the orientation of felsic veins and feldspar phenocrysts suggests some syn-magmatic deformation.

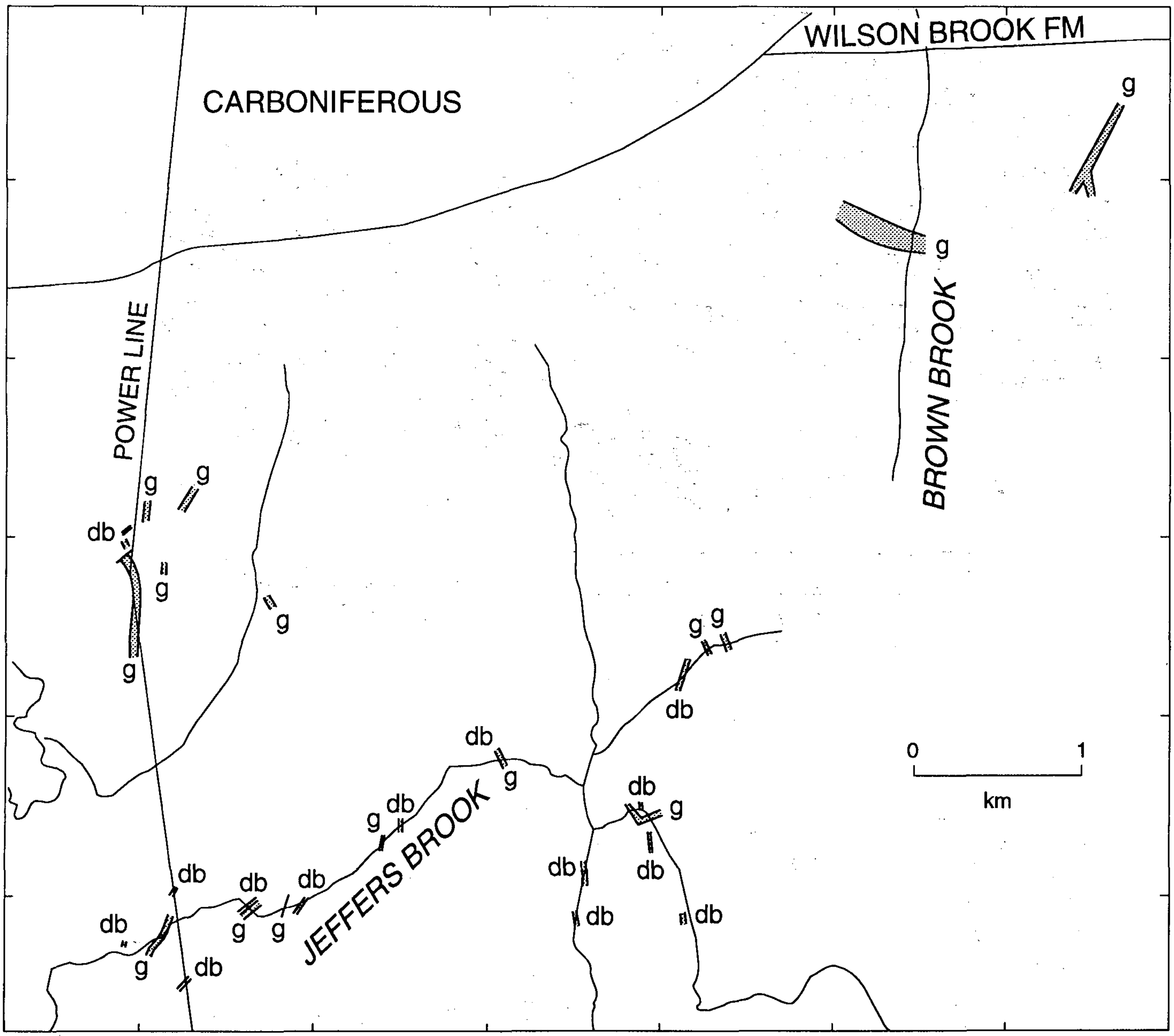

Fig. 8. Map of the area between Jeffers Brook and Brown Brook showing major Carboniferous microgranite and diabase dykes intruded into Neoproterozoic rocks (modified from Pe-Piper and Turner, 1988a). In general, all brook and powerline sections have been examined for dykes.

REGIONAL MAGNETIC DATA AND ITS INTERPRETATION

Data

Regional magnetic data are used to better understand the regional setting of the plutons and to better define the distribution of igneous phases, particularly in areas of poor exposure. Total field magnetic data (reduced to the pole) have been gridded at 200 m intervals and displayed as a shadowgram (Fig. 9). The first vertical derivative, which emphasises the anomalies due to shallow sources, has also been plotted (Fig. 10). Both maps are overlain with simplified geological boundaries, as shown in Figure 2, which also shows all the localities described below. Original plots from which interpretations were made were at 1:100 000.

The total magnetic field is high beneath the entire eastern Cobequid Highlands, west to the Folly Lake diorite. This high field extends west to the latitude of Parrsboro in two subparallel belts, corresponding to the belts of plutons along the southern and northern margins of the highlands. An equally high magnetic field extends 10 to 15 km south of the Cobequid Fault, including most of the Minas Basin. Shorter wavelength positive anomalies correspond to known outcrops of the North Mountain Basalt from Five Islands to Partridge Island and in the Blomidon - Cape Split area (locations shown in Fig. 2). A belt of lower magnetic field extends westwards from the Folly Lake pluton to Parrsboro, corresponding to Neoproterozoic, Silurian,

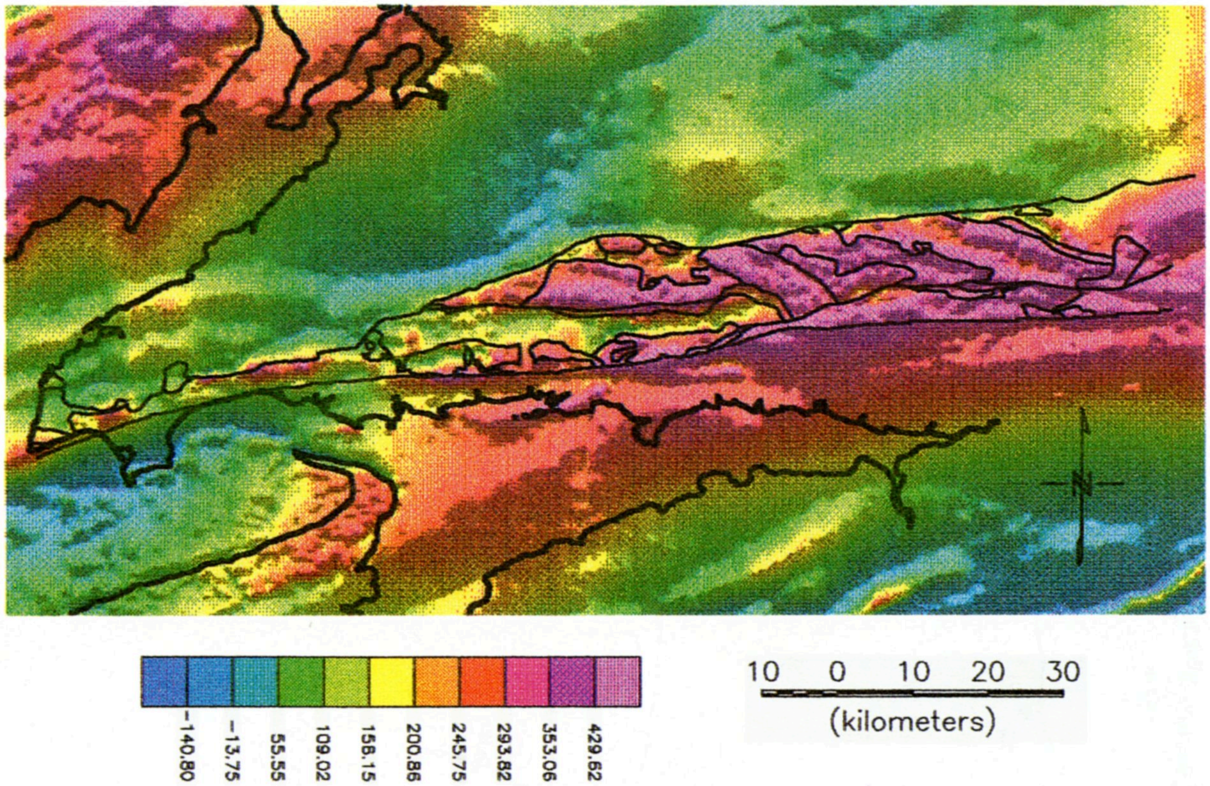

Fig. 9. Magnetic total field map of the Cobequid Highlands. Key to geologic units in Figure 2.

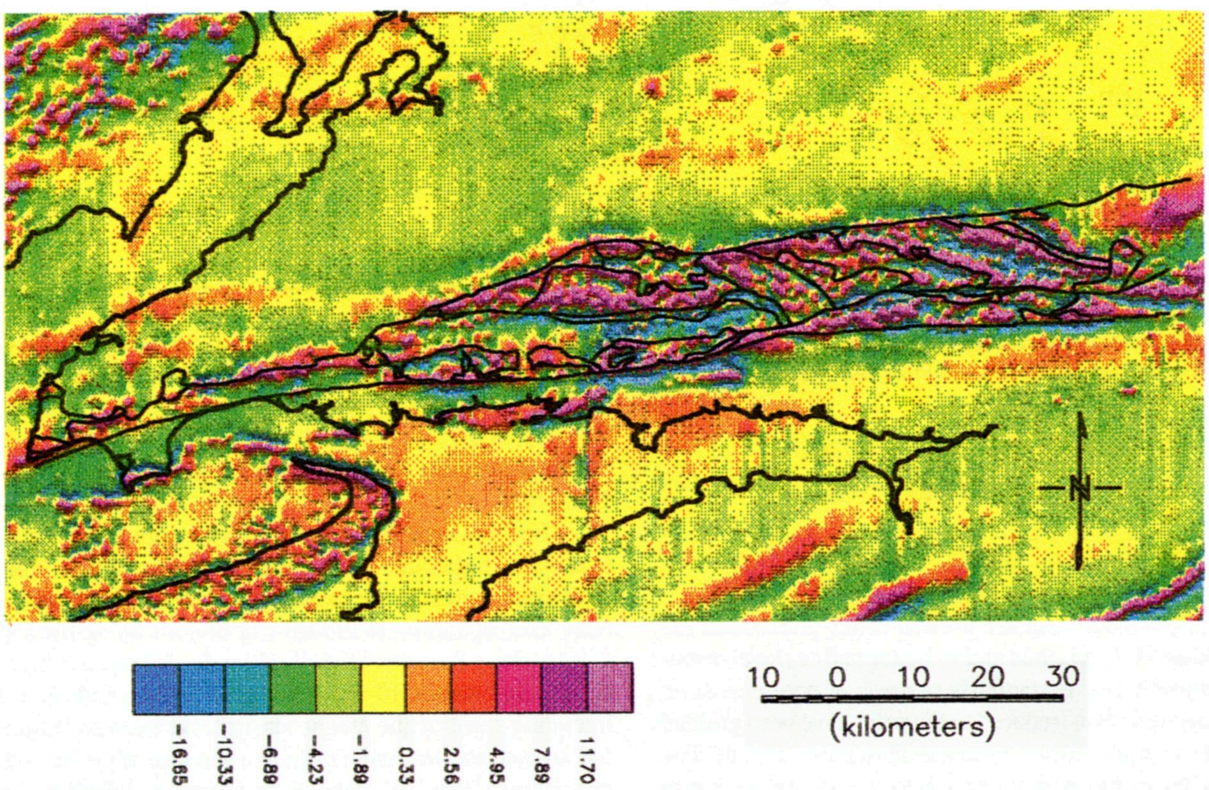

Fig. 10. Magnetic first vertical derivative map of the Cobequid Highlands. Key to geologic units in Figure 2.

and Devono-Carboniferous sedimentary rocks. The magnetic field is also lower west of Parrsboro, except for a few small anomalies between the Cobequid and Kirkhill faults, some of which correspond to known diorite outcrops in the Cape Chignecto pluton, but others must be sourced by rocks obscured by Carboniferous sediments. Two possibly analogous, but less pronounced, linear zones of positive anomalies occur 8 km and 15 km north of the Cobequid Fault in this area west of Parrsboro, corresponding approximately to the Spicer Cove and Sand Cove faults of Ryan *et al.* (1990).

Interpretation

The magnetic data has been used as a guide to re-interpreting the position of geologic boundaries in areas of limited outcrop. For example, the southwestern margin of the Folly Lake pluton is poorly constrained by outcrops, and Figure 2 shows an interpretation of this boundary that is different from the map of Donohoe and Wallace (1982). Within the Folly Lake pluton strong southeast-trending magnetic lineaments are visible: preliminary mapping suggests that these may be related to southwest-directed thrust faulting.

Strong linear trends in the total magnetic field and first derivative trend east-west in the western Cobequid Highlands and northwest-southeast in the eastern Cobequid Highlands north of the Rockland Brook Fault. In the west, many of these trends correspond to significant faults that we have mapped. The Kirkhill Fault (Pe-Piper and Turner, 1988b) extends westwards through the southern margin of the Apple River pluton to the Cape Chignecto pluton and eastward to the northern margin of the North River pluton. New mapping around the Wyvern pluton (Piper *et al.*, 1993) has shown a series of fault blocks bounded by east-west faults, and the southern margin of the Gilbert Hills and Wyvern plutons appears bounded by a major fault.

From the Folly Lake pluton eastward, the prominent northwest-southeast magnetic trends north of the Rockland Brook Fault, in part, correspond to faults mapped by Donohoe and Wallace (1982). Other trends cross poorly exposed areas of the Folly Lake and Hart Lake - Byers Lake pluton and may mark faults. Reconnaissance mapping in the Folly Lake pluton has shown the presence of mylonitic shear zones.

The extremely high magnetic field in the eastern and central Cobequid Highlands suggests that many plutons and the Fountain Lake Group may be underlain by gabbro-diorite, which is visible at the surface in the voluminous Wyvern and Folly Lake plutons. This is in strong contrast to the lower magnetic anomalies associated with the largely granite plutons in the west.

DISCUSSION

The abundance of mafic magmatic products

The most striking feature of the igneous activity along the Cobequid Fault is the enormous amount of gabbro/diorite that reached the upper crust in the earliest Carboniferous, notably in the Folly Lake and Wyvern diorites (Fig. 2), which have a combined surface area of 300 km^2. The magnetic data suggest that the subsurface extent of mafic rocks is even greater. The Cobequid Fault zone does not mark the southern limit of the major magnetic anomaly, which extends southwards to near Truro and the south coast of the Minas Basin. South of this, the prominent linear anomalies of the Meguma Group are visible. This may indicate that the Meguma-Avalon contact lies south of the Cobequid Fault and continues seawards off the Yarmouth area of southwestern Nova Scotia (Keen *et al.*, 1991).

Geochemically, the diorites are of tholeiitic composition (Pe-Piper *et al.*, 1989) suggesting that they originated by mantle upwelling associated with rifting. The granites are A-type granites, interpreted as resulting from melting of lower crust by gabbroic magma (Pe-Piper *et al.*, 1991).

Marillier and Verhoef (1989) and Marillier and Reid (1990) showed from gravity, deep seismic reflection, and seismic refraction data that a high-density, high-velocity lower crustal layer underlies most of the Magdalen Basin. This they interpreted as underplated mafic igneous rocks, similar to those inferred from other major extensional basins. They suggested that one explanation for the observed gravity distribution is that this underplated layer is particularly thick near the northern and southern parts of the basin. The volume and geochemistry of the major mafic plutons of the central Cobequid Highlands suggests that they are probably the surface expression of major underplating. The change in magnetic and gravity anomalies beneath the western Cobequids suggests that this area was beyond the limit of major underplating.

The Margaree granite in western Cape Breton Island (O'Beirne-Ryan *et al.*, 1986) is petrographically and geochemically similar to the rapakivi granites of the Cobequid Highlands and has a similar Rb/Sr isochron (343 ± 17 Ma). It is noteworthy that it occurs at the margin of a major magnetic anomaly beneath the southwestern Gulf of St. Lawrence (Geological Survey of Canada, 1988), similar to that beneath the central Cobequid Highlands.

Intrusion space for the plutons

The plutons of the Cobequid Highlands tend to be bounded by the major faults recognised from mapping and the magnetic anomaly patterns. Where plutons have been mapped in detail, such as the West Moose River (Pe-Piper *et al.*, 1991) and North River (Pe-Piper, 1991) plutons, marginal facies are seen adjacent to major faults. This suggests that these faults played an important role in providing space and pathways for magma. This is also indicated by the line of plutons and magnetic anomalies associated with the Cobequid Fault zone in the western Cobequid Highlands.

The origin of the space for plutons and pathways for erupted magmas are presumably associated in some manner with transtension in the broad Cobequid Fault zone. Seismic reflection data from the Gulf of St. Lawrence (Durling and Marillier, 1990) show that the early extension of the pull-apart Magdalen Basin took place on northeast-striking faults, with the accumulation of the Horton Group approximately during the latest Devonian and Tournaisian (Martel *et al.*, 1993). At the time of the basal Windsor Group (mid Visean) there was a change in tectonic style. The Cobequid plutons were emplaced during the main phase of extension of the Magdalen Basin and are approximately synchronous with sedimentation of the Horton Group. Formation of ramp space by northeast-striking listric faults terminating against a transfer-like Cobequid Fault lineament may have provided the space for intrusion of some of the plutons, with the voluminous diorite derived from the magma chamber that eventually underplated the Gulf. The northeast-striking dykes north of the western plutons (Fig. 8), parallel to the faults in the Magdalen Basin, may thus be related to this extension. Alternatively, they may be related to the northwest-directed thrusting of the plutons (Waldron *et al.*, 1989).

Regional distribution of igneous products near the West Moose River pluton

On a small scale, the relationship between mafic and felsic igneous rocks and faulting is illustrated by the systematic change in igneous products from east to west in the West Moose River pluton and adjacent Fountain Lake Group (Fig. 11). In the east, gabbro is abundant and the Fountain Lake Group is predominantly basalt (Donohoe and Wallace, 1982). In the central part of the pluton, the only mafic rocks are in small sills and dykes. Mafic rocks are absent in the western part of the pluton; this is mirrored by the Fountain Lake Group consisting exclusively of rhyolite. [Basalt mapped north of Davidson Brook by Donohoe and Wallace (1982) is part of the Jeffers Group.] In the east, the gabbro terminates abruptly against the north-south Harrington River fault, which offsets the Cobequid Fault sinistrally. Although Donohoe and Wallace (1982, 1985) have shown post-early Jurassic motion on north-trending faults, the abrupt change in fault pattern across the Harrington River fault suggests that it is a reactivated older feature.

The preponderance of mafic rocks is interpreted as reflecting easy pathways for magma to the surface; granitic rocks reflect trapping of hotter mafic magma and significant crustal melting. The mafic rocks may be related to pull-apart without rotation under conditions of dextral shear. The McCarthy Brook rocks lie between faults that are slightly oblique to the Cobequid Fault zone and trend east-northeast. These faults may well have formed initially as Riedel shears, and their location may be related to the presence of the Harrington River fault, which has the appropriate orientation for a conjugate Riedel shear. Dextral motion on the Cobequid Fault zone would lead to pull-apart on the eastnortheast faults.

Sequence of deformation events recorded by the plutons

Deformation of the Cobequid Highland plutons shortly after intrusion is indicated by deformed diabase dykes and diabase dykes occupying wrench-related fractures. The Cape Chignecto pluton shows northwest-vergent thrusting and the development of ductile fabrics. The West Moose River pluton shows similar fabrics vergent to the north-northeast that appear to pass northwards into south-dipping brittle thrusts. It is not known whether the compressional event indicated by the northwest-southeast magnetic lineaments in the Folly Lake pluton and the thrusting of diorite over Fountain Lake Group is correlative. Regionally, these compressional events might correspond either to the change in tectonic style between the Horton and Windsor groups (Durling and Marillier, 1990) or to the Namurian uplift of the Cobequid Highlands which resulted in the shedding of large amounts of coarse sediment to the adjacent basins (Ryan *et al.*, 1987). Durling and Marillier (1993) also recognise compression at this time.

This compressional phase was followed by brittle deformation associated with dextral strike-slip motion along the Cobequid Fault, which resulted in the upper Carboniferous pull-apart of the Stellarton Basin (Yeo and Gao, 1987). Fractionated mafic magmas continued to be intruded during this brittle deformation phase: the youngest radiometric age is 303 ± 11 Ma (mid-Westphalian: Fig. 3) on green biotite from a dyke northwest of the West Moose River pluton (Pe-Piper and Piper, 1987). Elsewhere in Nova Scotia, mafic dykes cut some Horton Group rocks on the south side of the Minas Basin (R. Moore, personal communication, 1993) and in Cape Breton Island (Lynch *et al.*, 1993), but no Carboniferous dykes are known to cut younger rocks. However, mid-Westphalian volcanic rocks occur on the central New Brunswick platform and in the Magdalen Islands (Fyffe and Barr, 1986), and the George Island dyke in Prince Edward Island is early Permian (Greenough *et al.*, 1988). In the Meguma Terrane, Westphalian strike-slip motion is also recognised from renewed evidence of shear events dated at 325 to 320 Ma (Dallmeyer and Keppie, 1987) and intrusion of the 315 Ma Wedgeport plutons (Cormier *et al.*, 1988). Mafic and volcanic rocks, which may be correlative with the later dykes, are also associated with the Cobequid-Chedabucto Fault zone in Guysborough County (Cormier, 1992) and southern Cape Breton (Grammatikos, 1992).

The post-magmatic north-south dextral high-angle faulting of the Cobequid plutons is related to the north-south faults mapped by Donohoe and Wallace (1982). Pe-Piper and Loncarevic (1989) recognised similar faults from offsets in magnetic anomalies. Both interpreted these faults as associated with the Late Triassic rifting of the Fundy Basin.

CONCLUSIONS

Extension of the Magdalen Basin that began in the mid-Devonian led to underplating from gabbroic melts beneath the central and eastern Cobequid Highlands. Mid to late Devonian volcanism preceded the voluminous mafic intrusions that are approximately synchronous with deposition of the Horton Group, which records the most rapid subsidence in the Magdalen Basin. The great volume of diorites indicates that extension played an important role in the emplacement of the plutons. Associated hypabyssal intrusions strike northeast-southwest, parallel to Horton Group bounding faults in the Gulf of St. Lawrence. The presence of conglomerates in the Falls and Rapid Brook formations suggests some positive relief in the earliest Carboniferous.

The style of subsidence in the Magdalen Basin appears to have changed at about the time of Windsor Group deposition. At about the same time in the Cobequid Highlands, there is evidence of the development of north-directed thrusts, and by the mid-Namurian, voluminous detritus was shed from the Highlands (Ryan *et al.*, 1987). Wide dykes associated with east-west

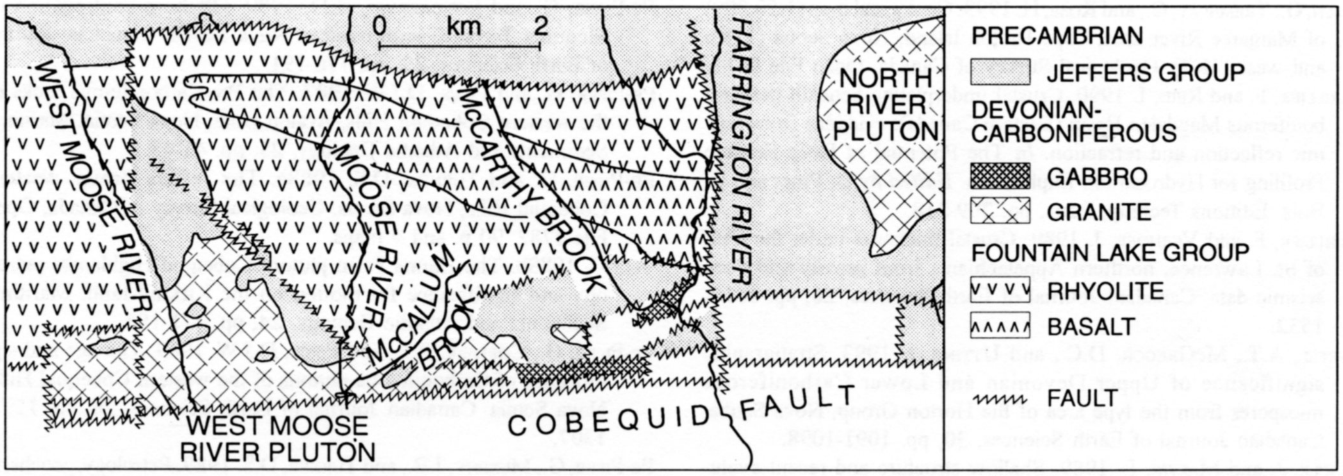

Fig. 11. Map showing distribution of mafic and felsic phases near the West Moose River pluton (modified from Pe-Piper and Turner, 1988a). For explanation, see text.

extensional pull-apart post-date the thrusting and may be associated with Namurian or Westphalian strike slip motion on the Cobequid Fault.

A modern analogue of the relationship of the Cobequid Fault to the extensional Magdalen Basin may be the relationship of the North Anatolian Fault to the extensional Aegean Basin since the mid Miocene. Stress fields near the North Anatolian Fault have changed over periods of a few million years (Mercier *et al.*, 1989), and the fault has functioned at time as a transfer and at times as a basin bounding listric fault (Mascle and Martin, 1989). Much more detailed work, particularly better geochronology, will be necessary to understand the Cobequid Fault, which was active for tens of millions of years.

Acknowledgements

We thank various students, past and present, who have been involved in aspects of this work, in particular Dave Pass, Joe Nearing, Marg Zeeman and Tim Doucette. John Waldron and Steve McCutcheon provided assistance with specific field interpretations. Dave Pass assisted with the Squally Point work. This work has been supported by NSERC grants, EMR Research Agreements and indirectly by Canada-Nova Scotia MDA funding to GPP, and GSC funding to BDL and DJWP. Reviews by François Marillier, Marie-Claude Williamson, Dan Kontak and Peter Wallace improved the manuscript. Geological Survey of Canada contribution 37493.

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