Geology and geochemistry of Middle Jurassic and Early Cretaceous igneous rocks on the eastern North American continental shelf

by

Lubomir F. Jansa

Geological Survey of Canada

Atlantic Geoscience Centre

Bedford Institute of Oceanography

P.O. Box 1006, Dartmouth, Nova Scotia, B2Y 4A2, Canada

and

Georgia Pe-Piper

Department of Geology

St. Mary's University

Halifax, Nova Scotia, B3H 3C3, Canada

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ABSTRACT

Late Middle Jurassic and Early Cretaceous mafic dykes, sills, flows and locally associated volcaniclastics occur from the Baltimore Canyon Trough northwards to the Labrador Shelf. The late Middle Jurassic activity was of a short duration at about 140 m.y. and is documented here from the Georges Bank. The Cretaceous igneous activity, which is more regionally widespread, continued for about 40 m.y. (95-135 m.y.). All the rocks analysed are alkali basalts and related mafic rocks. Rocks from the Baltimore Canyon, Georges Bank and New England Seamounts show marked enrichment in light REE and many incompatible trace elements, and appear to have been derived by a small amount of partial melting of enriched mantle of the type associated with mantle plumes. In contrast, rocks from the Scotian Shelf and Grand Banks show slightly convex REE spectra and less enrichment in incompatible elements and appear to be derived from normal (non-enriched) mantle. Limited data for the Newfoundland Seamounts suggests that they are associated with a slightly enriched mantle source.

The regional geochemical differences noted between the Grand Banks - Scotian Shelf igneous province and the Georges Bank - Baltimore Canyon igneous province may reflect basic differences in mantle composition and evolutionary history. This may be related to the development of a mantle plume beneath the Georges Bank - Baltimore Canyon trough province.

The Cretaceous volcanism coincides with reactivation and formation of fracture zones as a result of changes in plate stresses culminating in separation of the Grand Banks and Iberia and initiation of rifting in the Labrador Sea.

The late Middle Jurassic igneous activity on Georges Bank led to the construction of several volcanic cones. The regional distribution of the volcanic ash suggests prevailing offshore winds, blowing to the east. The occurrence of both Middle Jurassic and Early Cretaceous buried volcanoes under the upper continental slope off Georges Bank sheds new light on the origin of the New England Seamount chain. An initial shear failure, which probably penetrated the upper mantle focussed on regional stresses to develop a propagating fracture zone which became the loci of igneous activity at its propagating tip. After decoupling of the continental plates and the initiation of seafloor spreading in the Labrador Sea (83-92 m.y.), the igneous activity ceased along the eastern North American margin and at the propagating tip of the New England Seamount fracture zone.

INTRODUCTION

In this report we present comprehensive geologic, petrographic and extensive geochemical data about Cretaceous and Jurassic igneous hypabyssal and volcanic rocks from three offshore sedimentary basins located on the Eastern North American margin and two adjacent seamount chains - the Newfoundland and New England Seamount chains. We discuss the stratigraphic position, petrology, and time and mode of emplacement of igneous rocks. We briefly comment on the seismic expression of individual igneous occurrences which include isolated sills, dykes, flows, buried volcanoes and a dyke swarm. An understanding of the igneous activity of the margins may prove to be an additional factor to be considered for correct interpretation of local geothermal gradients and assessment of organic matter maturity as related to oil exploration. As discovered by the oil industry, in the Baltimore Canyon Trough (Amato and Giordano, 1985), the maturity of organic matter may be increased by emplacement of igneous rocks.

King (1961) called attention to the vast system of basaltic dykes in eastern North America, pointing out their geographic pattern and the systematic change in trends along the eastern Appalachians. Weigand and Ragland (1970) named the dykes "the Eastern North American dolerite province", extending from South Carolina northward to Nova Scotia and Newfoundland. Most of these dykes are located in the Triassic rift basins of the Eastern North American continent. These dykes and associated sills are mostly of tholeitic composition and have provided radiometric age determinations between 240 and 160 m.y. (McHone and Butler, 1984; de Boer and Snider, 1979; Pe-Piper and Jansa, in press). Similar rocks are known to be present on the shelf off Nova Scotia and on the Grand Banks and are currently being studied by the authors.

A second group of Mesozoic igneous rocks includes plutonic intrusions, alkali stocks and plugs with numerous lamprophyre dykes and sills concentrated in the New England-Quebec area (McHone and Corneille, 1980; Eby, 1984; Creasy and Eby, 1983). These rocks have been assigned to the White Mountain magma series and their age range is approximately 235 to 100 m.y. (Foland and Faul, 1977; McHone and Butler, 1984). From their regional distribution and apparent continuation in the New England Seamount chain, Crough (1981) suggested that this igneous activity was the result of north-westward motion of the North American plate over the Great Meteor hotspot. This interpretation was disputed by McHone (1981), who ascribed the igneous activity to reactivation of intra-plate fracture zones by plate movement, a process originally advocated for this region by Foland and Faul (1977).

The J-anomaly Ridge off the southeastern Grand Banks (Fig. 1) represents enhanced extrusive activity at the mid-ocean ridge around Aptian time (Houghton et al., 1979). Similarly, rocks from the Newfoundland Seamount chain yield radiometric Early Cretaceous ages (Table 1). The age of the Fogo Seamounts located off the southwestern Grand Banks (Fig. 1) is unknown, but several authors have speculated that they are most probably also of Cretaceous age, even though a Late Jurassic age is not improbable. Most of the Fogo Seamounts are buried by a thick sedimentary prism of the outer continental slope and rise and cannot be sampled by standard oceanographic methods.

Extensive hydrocarbon exploration of the eastern North American margin has shown that Cretaceous magmatism is not restricted to the White Mountain igneous province and seamount chains. Igneous rocks, some of which are associated with volcaniclastics, have been found in six exploratory wells on the Grand Banks. Jansa and Pe-Piper (1985) documented the presence of Early Cretaceous alkaline volcanism on the continental shelf off Nova Scotia. Igneous rocks associated with pyroclastics were encountered in the Exxon Oil Company exploratory well 133-1 on Georges Bank. Hurtubise et al. (1985), on the basis of an absolute age date of 136 Ma, suggested that the diabases in this well are Cretaceous intrusives associated with the New England-Quebec igneous event. The southernmost occurrence of late Mesozoic igneous rocks is offshore New Jersey. Schlee et al. (1976), using geophysical data, identified a seismic feature which they interpreted to be a volcanic plug in the Baltimore Canyon Trough area. Emplacement of the "plug" resulted in an uplift of the area. They named the intrusion the "Great Stone Dome". Subsequently, six oil exploratory wells confirmed the presence of igneous rocks (Fig. 1). In addition, Cretaceous magmatism is known further to the north of the Grand Banks. Occurrences are known from the Sverdrup Basin, Canadian Arctic Island (Thorsteisson and Tozer, 1970; Balkwill and Fox, 1982; Ricketts et al., 1985; Trettin and Parrish, submitted; Fig. 1) and from the Labrador shelf (Umpleby, 1979; Johnson et al., 1982; McWhae et al., 1980).

We have examined occurrences of Cretaceous and Late Jurassic igneous rocks on the continental shelf between the Grand Banks and Baltimore Canyon trough, an area approximately 1200 km in length and averaging 150 km in width. The results of geologic, petrographic and geochemical studies of these rocks are reported here, with the exception of a bimodal suite of acidic and basic igneous rocks encountered in two wells on the Grand Banks. To date, we have been unable to resolve the age and origin of these rocks, which are thus omitted from this paper. Samples have been obtained through cooperation with the Exxon Exploration Company, Houston; Mobil Research and Development Corporation, Dallas; Gulf Oil Exploration, Houston; the Canada Oil and Gas Lands Administration; and the U.S. Minerals Management Service. In this study we have also included the Newfoundland and New England seamount chains, with samples provided by the Deep Sea Drilling Project and the Bedford Institute of Oceanography. Husky Oil Company and Bow Valley Industries provided some of the seismic data from the Brant area.

Methods

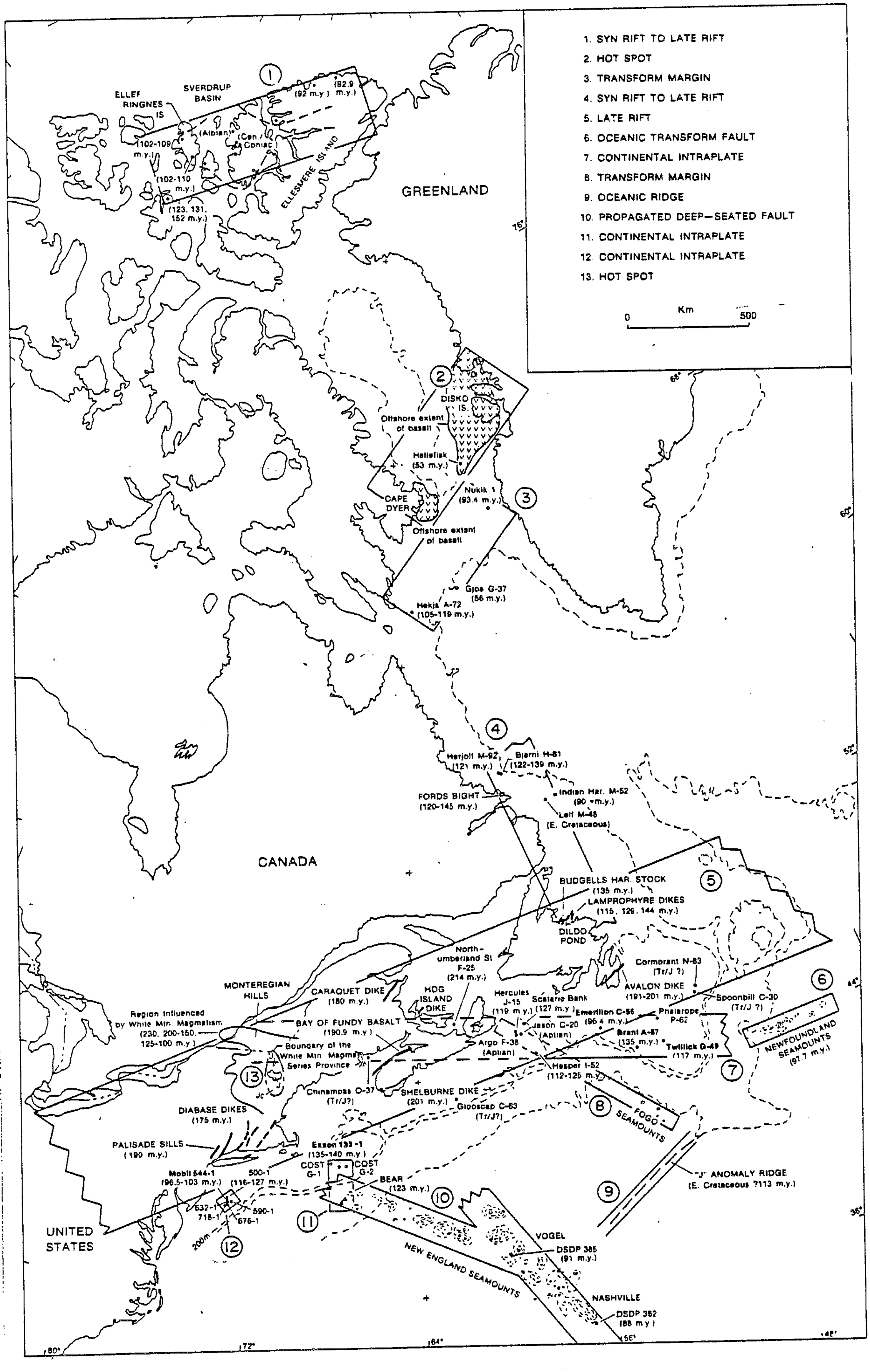

Figure 1. Map showing volcanic and subvolcanic rocks of Mesozoic-Cenozoic age on the eastern continental margin of North America. For full captions of all figures see p.66-69.

We have studied both drill cuttings and conventional core samples of both the igneous and the over- and underlying sedimentary rocks macroscopically and under the binocular microscope. Sieved samples of well cuttings have been examined in thin section in order to describe their petrographic composition and texture. These data were supplemented by information derived from mechanical logs and multichannel seismic profiles to determine the character of contacts and the composition of adjacent sedimentary rocks and to establish stratigraphic sequences. Fresh-looking chips of igneous rocks were hand picked under a binocular microscope and the purity of the samples was checked by preparation of thin sections from some of the separates.

Methods used for geochemical study are similar to those described by Jansa and Pe-Piper (1985). Except in the rare cases where core is available, igneous rocks have been separated from cuttings samples by a combination of heavy liquid flotation and hand picking. Major element analyses of cuttings samples were made by fusion and electron microprobe analysis (Mackay, 1981); major and trace element analyses of core samples have been made by X-ray fluorescence. Rare earth and other trace element analyses have been made by instrumental neutron activation analysis. Further details of methods and their precision are given by Jansa and Pe-Piper (1985). A list of all samples analyzed is given in Appendix 1. Mineral chemistry analyses were made by electron microprobe in the energy dispersive mode on selected polished thin sections, which were prepared from drill cutting samples and conventional core samples. Whole rock potassium-argon radiometric age analysis was performed on the freshest samples by

Krueger Geochronological Laboratory, Massachusetts, U.S.A.

The study of subsurface igneous rocks has several shortcomings when compared with the study of subaerial exposures. The first is the size of drilling chips, which average only several mm in diameter (see Plates 1 and 2), so that volcaniclastic particles coarser than lapilli, cannot be identified. Second, drill cuttings are sampled in 3 to 10 m intervals, with the sample homogenized over this interval. Third is the effect of cavings, which in sequences without enough compositional or textural difference makes it difficult to establish which of the drilling chips are in place and which might be caved from overlying beds. Fourth, it is often impossible to recognize if the volcaniclastic sediments are of autoclastic, hydroclastic or pyroclastic origin (Lajoie, 1979; Suthern, 1985; Batiza et al., 1984). Only indirect evidence such as co-occurrence of volcanic glass fragments and marine microfossils, shape and composition of volcanic particles, their volumetric content in individual beds and the occurrence of ash deposits in areas distant from the volcanic source, can be used to differentiate subaerial and subaquatic pyroclastic fall deposits and hydroclastic deposits (Honnorez and Kirst, 1975). The reader should be aware of these limitations when reading some of our conclusions.

In addition, we have encountered difficulty in dating igneous bodies. When these are associated with pyroclastic rocks, radiometric ages can be cross-checked with biostratigraphic age determinations of associated sediments. However dating of dykes is more difficult, since repeated radiometric age determinations provide a range of dates, particularly in basic rocks (Suter and Smith, 1979; Hyatsu, 1979; Pe-Piper and Jansa, 1986).

For this reason we undertook careful lithostratigraphic analysis of each of the occurrences discussed in this paper. From this study we concluded that a major discrepancy exists between the absolute age data and the new geologic time scale for the Jurassic as compiled by Harland et al. (1982) and Palmer (1983). The new data agree with van Hinte's geologic time scales (1976a, 1976b) which are used throughout the paper, and with the scale of Odin (1984).

Geologic setting

The eastern North American margin consists of a chain of sedimentary basins separated by basement highs (Fig. 2; Emery and Uchupi, 1972; Jansa and Wade, 1975; Klitgord and Behrendt, 1979; Jansa and Wiedmann, 1982). The basins and the interbasinal highs are floored by a basement which is of variable composition and origin, because it was assembled from different plates and microplates during Taconic and Acadian orogenesis (Osberg, 1978; Hatcher, 1978). The sedimentary fill of the basins, which reaches a thickness of up to 15 km, reflects the history of progressive subsidence of the edges of continental plates modified by eustatic sea level changes and tectonics in response to plate tectonics and the formation of the North Atlantic Ocean basin.

Mesozoic igneous and tectonic activity, as previously known from the coastal region of eastern North America, was thought to be very limited, and the offshore portion of the margin has been considered by many to be an unvolcanic and tectonically quiet, passive terrain. However, evidence of periodic, intensive tectonic activity on the Eastern North American margin is revealed by seismic and drilling data. The first post Late Triassic

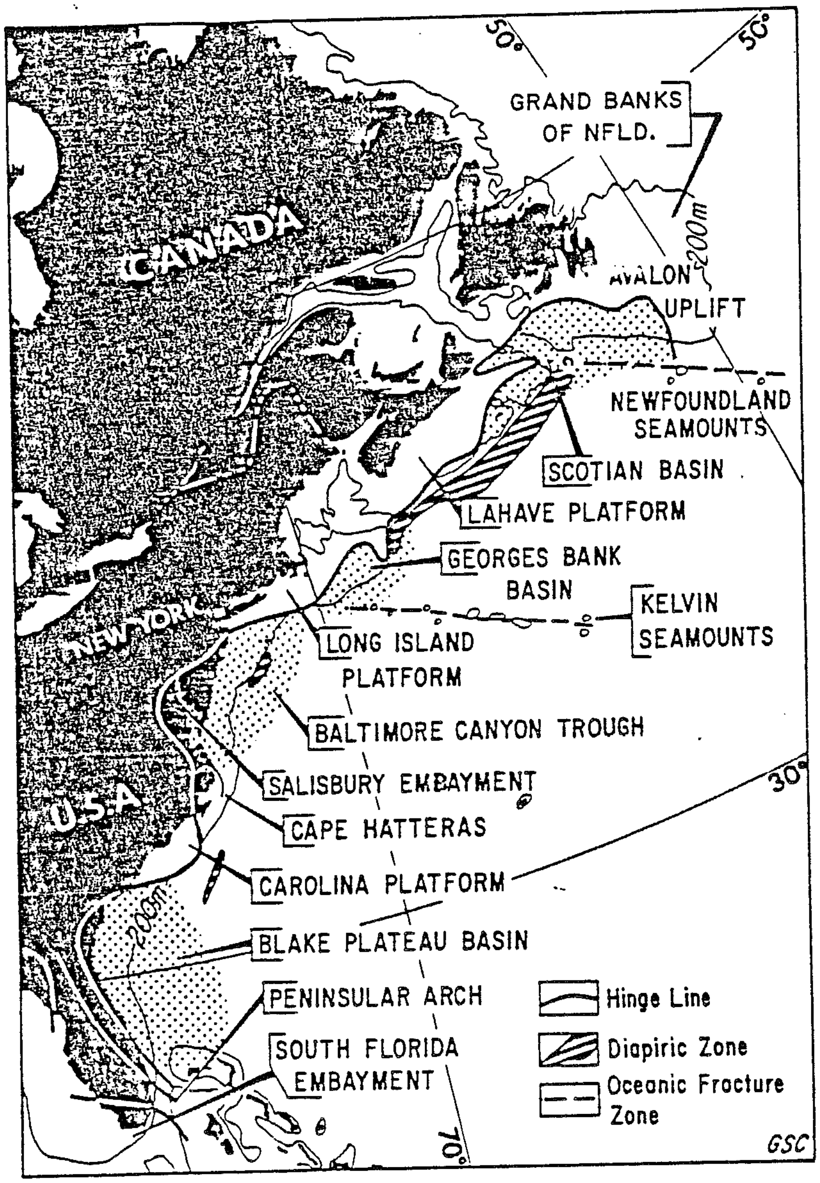

Fig. **2** Location map with major structural elements of the North-east American margin. Location of the major sedimentary basins is shown by dotted pattern distinct tectonic event resulting in the development of a regional unconformity has been recognized in the Scotian and Georges Bank basins (Jansa and Wade, 1975; Schlee and Jansa, 1981). The unconformity occurs in the lower part of the Early Jurassic succession, and above or at the level of the basalt "flows" on the Scotian Shelf. A subsequent minor tectonic disturbance can be identified from sedimentological data in the middle Jurassic section in the Scotian Basin and the Georges Bank area where a shallow-water carbonate platform is covered by continental clastics. A submarine unconformity or hiatus affecting latest Jurassic rocks observed in some offshore oil exploratory wells off Nova Scotia may be indirectly associated with tectonics. This is indicated by the development of an angular unconformity on the Grand Banks (Parson et al., 1985), which has been considered to be Kimmeridgian to Tithonian age. A most conspicuous tectonic disturbance has been recognized from seismic and sedimentological data on the Grand Banks (Amoco Canada and Imperial Oil, 1973; Jansa and Wade, 1975). Here an angular unconformity separates tectonically deformed, Early Cretaceous and older sequences from mainly horizontally lying Late Cretaceous and Cenozoic sediments (Figs. 3, 5). Although the tectonic deformation is complicated by extensive salt diapirism, the Avalon Unconformity is regionally extensive and is not limited only to the Grand Banks shelf area, but extends also to the deep continental margin (Gradstein, 1977; Parson et al., 1985). The Avalon Unconformity may be related to the Austrian tectonic phase (Jansa and Wiedmann, 1982). This tectonic disturbance is not recognizable south of the Grand Banks, even though minor nondepositional surfaces have been noted in oil exploratory

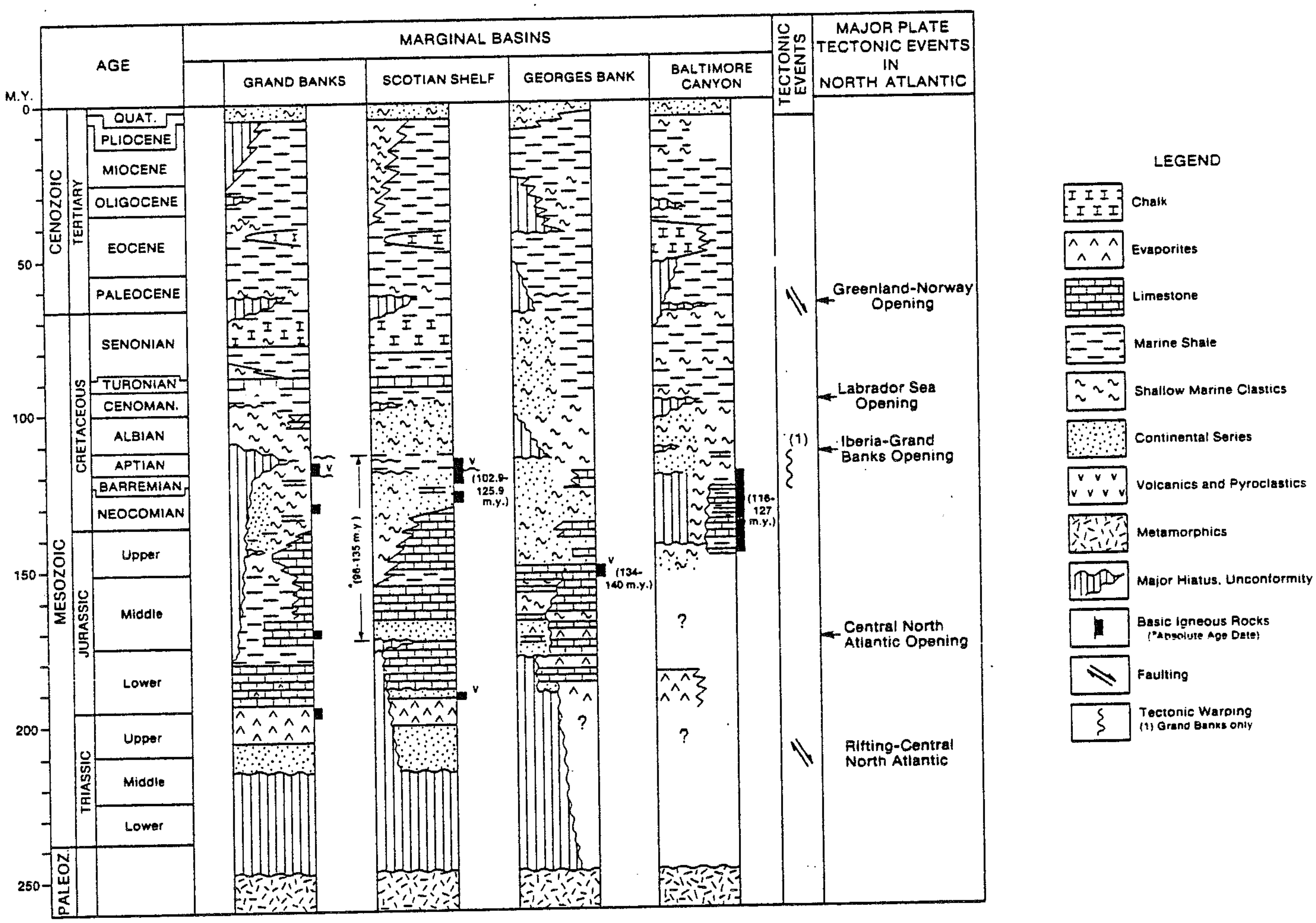

Figure 3. Stratigraphic diagram of marginal basins.

wells in the Aptian shales of the Scotian Basin and Baltimore Canyon Trough (Fig. 3).

A review of Mesozoic igneous activity in eastern North America shows that the Middle to Late Triassic igneous activity, which is associated with early rifting, is surprisingly rare (McHone and Butler, 1984; Pe-Piper and Jansa, 1986) when compared to some more recent rift regions such as the Afar. In eastern North America the first intensification of magmatic activity occurred near the Jurassic-Triassic boundary, spanning the interval from 200 to 180 m.y. It is marked by the occurrence of diabase sills and dykes from South Carolina northward to Newfoundland (Gottfried et al., 1983; Weigand and Ragland, 1970; Papezik and Hodych, 1980; and others). The paleomagnetic data suggests that igneous activity may have began earlier (218 to 244 m.y.) in South Carolina than north of it (de Boer and Snider, 1979). McHone and Butler (1984) interpreted this igneous activity as a result of separation of the North American and African continental plates, which does not find full support in the deep sea drilling data (Winterer and Hinz, 1984). Younger igneous activity onshore is virtually unknown from areas other than New England and adjacent Quebec (Foland and Faul, 1977; McHone and Butler, 1984). This region experienced extensive Early Cretaceous intrusion of alkalic syenite, gabbro plutons and lamprophyre dykes dated 95-135 m.y. (ibid.). After a long period of relatively nonmagmatic evolution of the eastern North American margin the next very limited phase of igneous activity has been documented from the Eocene of Virginia by Dennison and Johnson (1971).

Offshore the periodicity of igneous activity was similar to the onshore areas as pointed out later in this report. It was relatively intensive during the Late Triassic-Early Jurassic, which was followed by a period of quiescence, with only a few extrusions documented during Middle Jurassic time in the study area. This contrasts strongly with Early Cretaceous time, when igneous activity was extensive, as documented by oil exploratory drilling from the Grand Banks to the Baltimore Canyon Trough. On the Scotian Shelf buried volcanoes and associated feeder dykes, described by Jansa and Pe-Piper (1985) belong to the same Early Cretaceous event.

The Late Cretaceous and Tertiary were tectonically quiet periods on the eastern North American margin. During this time tectonic and magmatic activity seems to have shifted to the northern end of the Labrador Sea and Davis Strait area as a result of rifting affecting the Labrador Sea and Baffin Bay region. Igneous activity on the Labrador Shelf and coast dates from 145 ± 6 m.y. to 90 ± 4 m.y. In this context it should be noted that a time span of 92-152 m.y., similar to that of the Labrador Shelf, has been recorded for the bimodal suite of subalkaline mafic dykes, sills, flows, rhyolitic granitic rocks, and minor pyroclastics intercalated with sedimentary rocks located at western Axel Heiberg, Ellesmere and Ellef Ringnes Islands, Arctic Canada (Fig. 1, Thorsteinsson and Tozer, 1970; Balkwill, 1978; Ricketts et al., 1985; Trettin and Parrish, submitted). The youngest igneous rocks, dated 30-40 m.y., occur in the Davis Strait area (Clarke, 1977; Umpleby, 1979; Johnson et al., 1982).

Tectono-volcanic provinces

The brief account of Mesozoic-Cenozoic tectonic and igneous history from the eastern North American margin given above shows that the igneous activity was not a continuous or haphazard series of events, but shows a clear tendency to be associated with identifiable tectonic events. Similar relationships are seen in the northwestern European Mesozoic-Cenozoic (Ziegler, 1982) and in the New England area (McHone and Butler, 1984). Furthermore, the igneous activity was restricted to relatively narrow zones (Fig. 1) despite a wide spectrum of tectono-volcanic events from rift related igneous activity to intraplate oceanic and continental volcanism, as well as propagating transform faults and hotspots. Detailed geochemical and isotopic studies are needed to verify our preliminary assignment of different igneous activities to various tectonic events.

The geographical distribution of individual tectono-volcanic "provinces" (Fig. 1) shows the spatial relation between individual "provinces", some of which overlap or even intersect. One of the most interesting features is the scissor shape of two Lower Cretaceous igneous provinces (South Grand Banks-Orpheus Graben, marked by No. 7 on Fig. 1, and New England Seamounts-New England, marked by No. 10 on Fig. 1) which meet at the White Mountain-Monteregian Hills area (No. 13 on Fig. 1), known for extended igneous activity, and frequently related in the literature to a hotspot (Foland and Faul, 1977; Crough, 1981). Some of the tectono-igneous provinces extend from the offshore to the adjacent land (Fig. 1). However, since all the land sections are formed mainly of Paleozoic rocks, the basic dykes and sills found here have usually been interpreted as Paleozoic in age. One such occurrence of dykes in the Northumberland Strait area, previously interpreted as Carboniferous in age, are demonstratably Triassic dykes (Pe-Piper and Jansa, 1986). The post-Acadian rocks do not show any significant metamorphism and thus distinction of Late Paleozoic and Mesozoic igneous rocks is impossible without absolute age data.

Stratigraphy and petrology of igneous bodies

The Grand Banks of Newfoundland

Igneous rocks, some associated with volcaniclastic sediments, were encountered on the Grand Banks in six oil exploratory wells (Amoco-Imperial-Skelly Brant P-87 and Twillick G-49, Elf et al. Emerillon C-56, Amoco-Skelly Mallard M-45, Amoco-Imperial-Skelly Spoonbill C-30 and Amoco-Imperial Cormorant N-83, Fig. 1). The latter two occurrences (Amoco Canada Petroleum Company Ltd., 1972, 1973a) were late Triassic-Early Jurassic igneous events and are thus not included in the present study. A bimodal suite of acidic and basic igneous rocks (basalt, rhyolite, trachyte) and volcaniclastic rocks was encountered in the Mallard M-45 well, however, the origin of these rocks is not yet resolved and thus this occurrence is not included in this report.

Amoco-Imperial-Skelly Brant P-87

The Brant P-87 well is located approximately 225 miles south of St. John's, Newfoundland (Fig. 1). The well penetrated dominantly clastic sedimentary rocks of Tertiary and Cretaceous age and bottomed in igneous rocks at 3588 m (T.D., Amoco Canada Petroleum Company Ltd., 1973b) (Fig. 4). A second, stratigraphically higher level with igneous rocks has been found at 2843-2898 m. A sequence of sandstones, shales and "breccias" of acidic rocks 562 m thick separates the lower igneous unit from the upper igneous unit.

The lower igneous unit is 128 m thick (3460-3588 m). Mechanical log

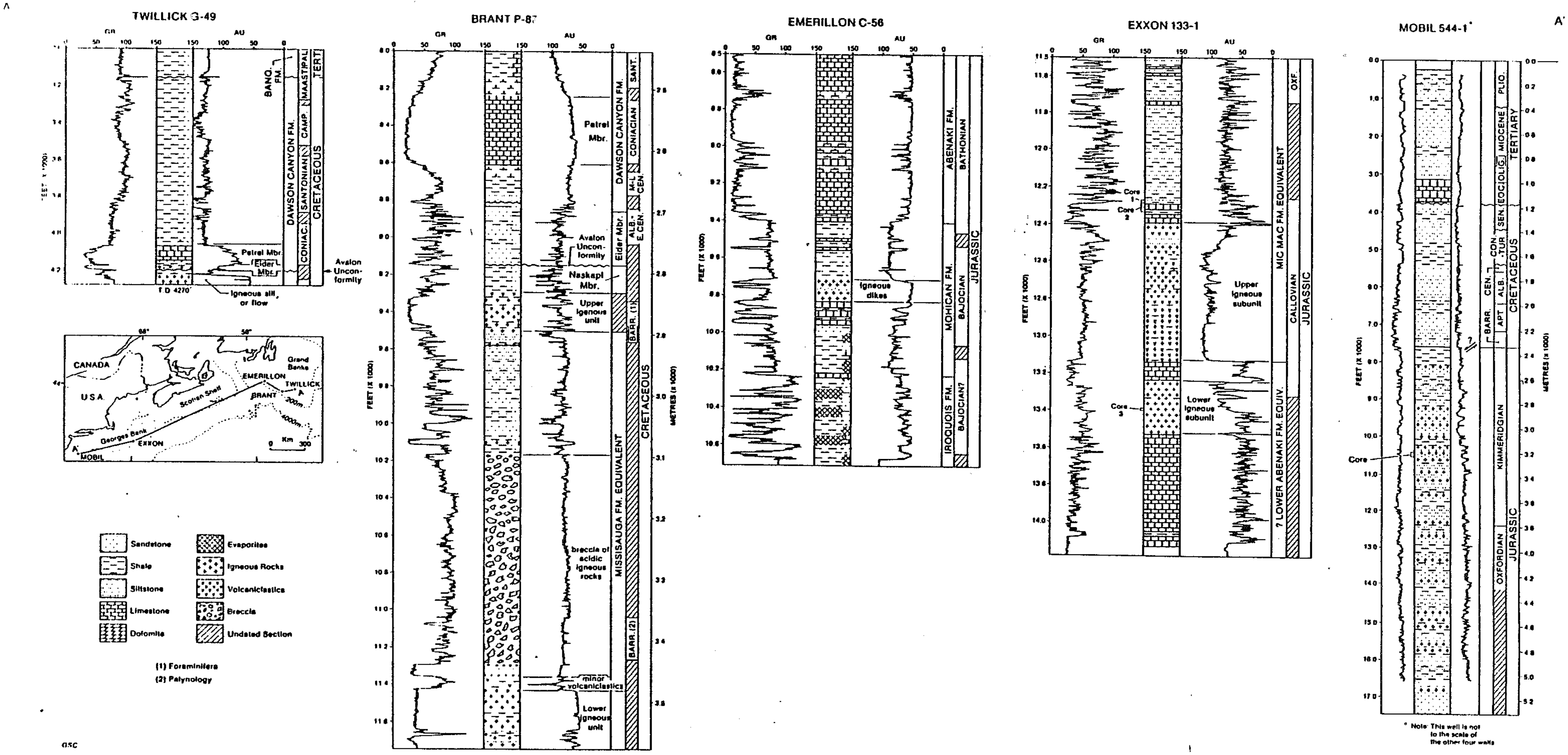

Figure 4. Lithologic profiles of studied oil exploratory wells which show the stratigraphic position of igneous and/or volcanic rocks.

data and the study of drill cuttings indicate the presence of at least five igneous bodies (flows or sills) of a fine to medium crystalline basalt which are 3 to 42 m thick in a zone from 3485 to 3588 m. Individual bodies are separated by thin beds of argillaceous siltstone and mudstone except the uppermost two bodies which are adjacent to one another. The basalt is dark grey, mottled in places and finely crystalline, and contains plagioclase crystals with an average length of 0.1 mm. The basalt becomes coarser towards the center of individual bodies, with feldspars increasing in length from 0.1 to 0.3 mm. Nearer the margins of the bodies, the rocks have an increasingly trachytic texture and rare vesicles are filled by chlorite. The thinnest basalt unit, which is only 1 m thick, is vesicular with feldspar laths less than 60 microns in length. The lower igneous unit is overlain by 15 m of light grey calcareous and silty mudstone. In the mudstone are intercalated thin beds and intermixed fragments of highly vesicular glass, welded tuff or pumice, with vesicular glass enclosing fragments of fine crystalline basalt and feldspar (Plate 1, Fig. C). The systematic changes in crystal size through the individual igneous bodies, the presence of vesicles, and the presence of overlying pyroclastic rocks suggests that the igneous bodies are flows. The occurrence of nannofossils, including frequent Nannoconus in the interbedded siltstones and shales suggest that at least some of the basalt was subaquatically extruded in a submarine environment.

Thin section study of fresh-looking diabase rock chips from the lower igneous unit shows that the major components of the rock are 30-70% plagioclase, 15-25% iron- titanium oxides and 15-25% clinopyroxenes (Plate

1, Fig. A). The texture of the rock is trachytic, intergranular and rarely intersertal. In the latter case, the lath shape plagioclase crystals are enclosed in pools of devitrified, deep brown glass. The composition of groundmass plagioclase varies from $An_{49}Ab_{48}Or_{3}$ to $An_{73}Ab_{26}Or_{1}$. Rare plagioclase phenocrysts (maximum size 1.5-0.05 mm) are also present, with a compositional range from $An_{84}Ab_{16}Or_{0.3}$ to $An_{56}Ab_{42}Or_{2}$. They show normal zoning (extreme case observed: core $An_{77}Ab_{22}Or_{1}$; margin $An_{56}Ab_{42}Or_{2}$) or reverse zoning (core $An_{80}Ab_{19}Or_{1}$; margin $An_{84}Ab_{16}Or_{0.3}$). K-feldspar with a composition of $An_{23}Ab_{57}Or_{20}$ has only been observed interstitially or as an overgrowth on bytownite crystals. The clinopyroxene is present in two forms; as fresh microphenocrysts 30 μm in length and as larger phenocrysts, usually altered to chlorite and/or smectite. The composition of clinopyroxene ranges from $Wo_{44}En_{41}Fs_{15}$ to $Wo_{42}En_{40}Fs_{18}$. Biotite occurs in traces. Fresh olivine has not been found, but reddish crystals are common and probably represent altered olivine. Calcite is also present either as a filling of rare cavities or as scattered grains in the matrix.

The upper igneous unit consists of at least four basalt bodies, 3 to 18 m thick and separated by dark grey shale. The basalt is more coarsely crystalline than in the lower igneous unit (Plate 1, Fig. B) and much more vesicular, with vesicles in some samples constituting more than 80% of the rock. Tuffs and sediments with volcanic shards are found intercalated within the middle and at the top of the unit. One of the igneous bodies shows a marked decrease in crystal size towards the top of the unit, has a highly vesicular texture and the opaque minerals have a skeletal texture, which indicates rapid cooling of the surface of the body. The sediments intercalated with the igneous bodies are glauconitic silty mudstones of marine origin. The presence of pyroclastics and highly vesicular basalts indicates that the upper igneous unit is a mixture of lava flows, pyroclastic rocks and possibly of shallow subsurface sills.

Thin section examination of the igneous rocks from the upper unit shows that these rocks are similar in composition to the basalts of the lower igneous unit, but the composition and texture are more similar to the basalts of the Lower Igneous Unit of the Hercules, Jason and Argo wells on the Scotian Shelf (Jansa and Pe-Piper, 1985).

Stratigraphy

Biostratigraphic data and seismic correlation with other wells indicate that the lower igneous unit was extruded during the deposition of the Lower Cretaceous Missisauga Formation (Fig. 4), dated on the Scotian Shelf as Berriasian to Barremian. The lower igneous unit is overlain by sediments with late Barremian palynomorphs (Davies, 1984). A whole rock K/Ar age of 135 ± 6 m.y. from the lower igneous unit is of Valanginian age according to the time scale of Harland et al. (1982) and Berriasian age according to that of Van Hinte (1976b).

The upper igneous unit overlies, possibly unconformably, the Missisauga Formation. Interbedded strata contain late Barremian foraminifera (Gradstein, 1977). The upper igneous unit was emplaced during early Naskapi Shale Member time (Jansa and Wade, 1975), which according to extensive biostratigraphic studies in the Scotian basin is of late Barremian to Aptian age (Barss et al., 1979).

Seismic reflection profiles across the Brant structure show that both igneous units produced high amplitude reflections concordant with the surrounding sedimentary beds. The lower igneous body is seismically better defined (Fig. 5), with a regional extent of at least 5.5 km. The concordant position of the igneous bodies with the underlying sediments suggests that they are either lava flows or sills.

Amoco-Imperial-Skelly Twillick G-49 well

The Twillick G-49 oil exploratory well is located approximately 85 km east of the Brant well (Fig. 1). After penetrating 1278 m of Tertiary and Upper Cretaceous sediments, it encountered a major unconformity (probably the regional Avalon Unconformity) underlain by 9 m of oxidized clay, interpreted by us as a soil horizon. Fragments of highly altered diabasic rock are enclosed in the reddish clay. This soil horizon in turn overlies a 15 m thick porphyritic diabase, in which the well bottomed at 1320 m (Fig. 4, Amoco Canada Petroleum Company Ltd., 1974). 50 cm of conventional core have been obtained from the diabase, which is light greenish grey and porphyritic, with phenocrysts of highly altered plagioclase up to 2.5 mm in diameter with about 5% of the clinopyroxene up to 3.6 mm in size. The phenocrysts occur either dispersed through the fine crystalline groundmass or as crystal aggregates. The crystalline matrix has plagioclase laths that average 0.35 mm in length, and they constitute 65-80% of the rock. The crystal size sharply decreases toward the top of the igneous body. Other mineralogical constituents are clinopyroxene (5-10%), magnetite (4-7%), chlorite (5-10%), epidote (4-5%), sphene (~ 2%) and occasional biotite. Veinlets of quartz and calcite cut the diabase. The analysis of a fresh feldspar crystal shows that it is of labradoritic composition ($An^{54}Ab^{45}Or^{1}$).

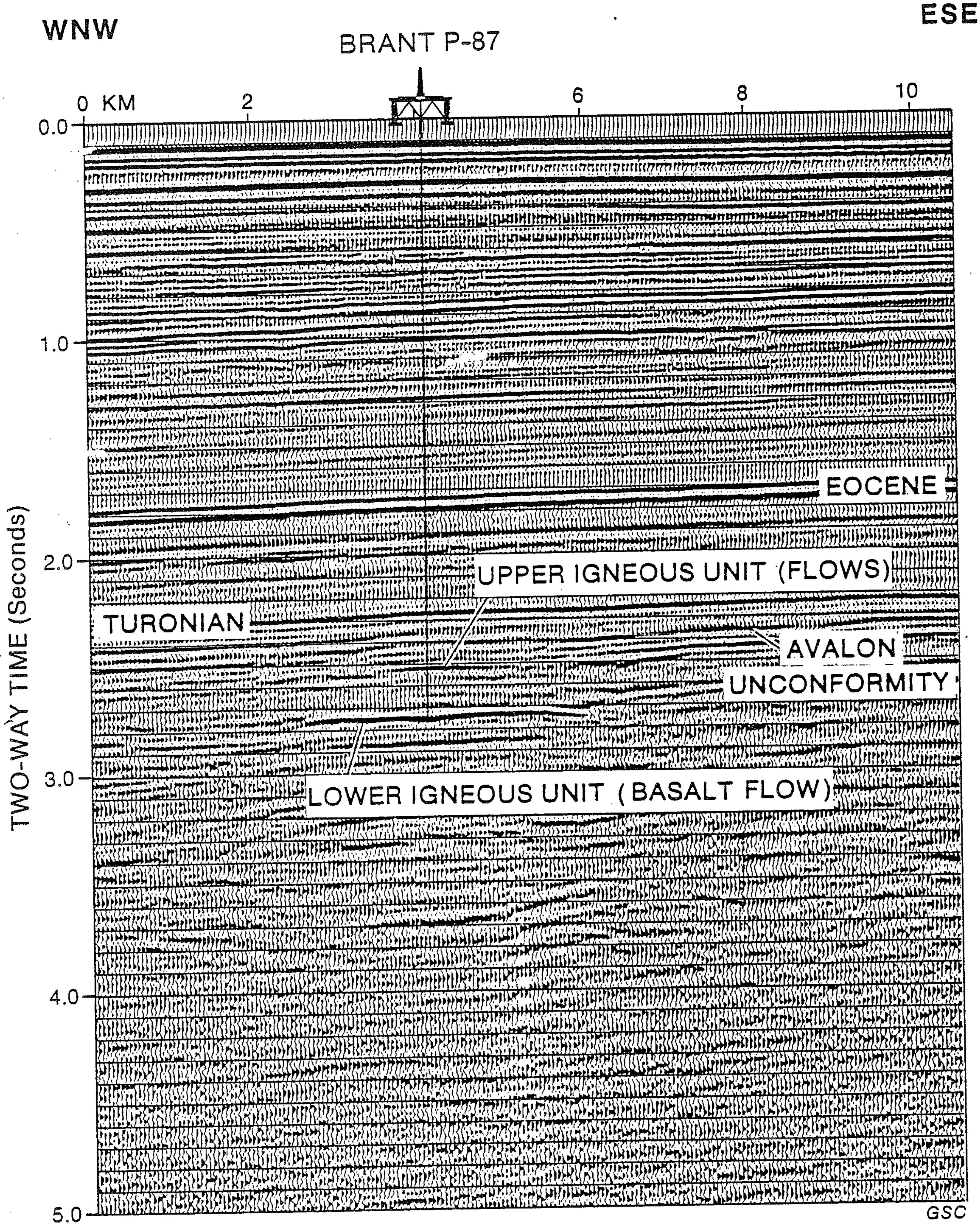

Figure 5. Multichannel reflection seismic profile across the Brant well, Grand Banks, Newfoundland. Notice strong horizontal reflectors produced by the basalt flows.
(Amoco Group seismic line No.30252)

Sanidine and biotite are also present as interstitial grains. The clinopyroxene grains are commonly fresh and show a range of compositions from $Wo_{45}En_{40}Fs_{15}$ to $Wo_{43}En_{39}Fs_{18}$. The diabase is variably altered, with the main alteration product being chlorite and epidote. Thin needles of ?natrolite become more frequent toward the top of the unit, where the alteration is especially intensive. Here the rock is altered into a mixture of clay minerals, chlorite, calcite, quartz and veinlets of iron oxide.

No volcaniclastic sediments have been found associated with the diabase. From the changes in the crystallinity toward the top of the igneous body, and the weathering of its uppermost part, we suggest that the diabase was emplaced as a shallow subsurface sill or thick subaerial flow. The well bottomed in the lower part of this thick igneous unit, without completely penetrating it. The weathering of the body indicates that it was emplaced before or at the time of the Avalon unconformity. The unconformity, which is dated regionally as late Aptian, at this location spans a longer time period (Late Aptian to Turonian). Whole rock K/Ar dating of the diabase gave an age date of 117 ± 5 m.y. (Aptian).

At this locality, the seismic reflection profile crossing the well does not provide any evidence of an igneous body. The reflector is probably masked in a strong impedance contrast between the Avalon Unconformity and the closely underlying Paleozoic basement. The small thickness of the diabase might contribute to the lack of resolution.

Elf et al. Emerillon C-56 well

The Emerillon C-56 well is located 110 km NW of the Brant well (Fig. 1). The well penetrated 3277 m of Tertiary to Jurassic sedimentary rocks and bottomed in the early Jurassic dolomites intercalated with evaporites and clastics (Fig. 4). The sequence described in the Elf et al. Well History Report (Elf Oil Exploration and Production, Canada, 1974) from 2975 to 2996 m as arkose and salt-and-pepper sandstone has been found to be mainly igneous rock. This igneous rock overlies an oolitic limestone with a sharp contact and similarly has sharp contact with the overlying sandstone-shale sequence. The resistivity log shows variation in porosity which may reflect changes in composition throughout the igneous sequence suggesting the presence of about 6 different igneous bodies. The uppermost two are separated by a 6 m thick sandstone. The density log similarly indicates the presence of denser, less porous zones, 1 to 3 m thick, alternating with more porous zones. However, thin section examination of cuttings from the lower part of the igneous unit does not show any variation in crystal size or other changes which would allow distinction of individual igneous bodies using petrographic criteria.

The igneous rock, as studied in cuttings, is a light grey, holocrystalline, porphyritic monzodiorite. It is very fine-grained in the upper part of the unit and becomes coarser toward the lower part of the igneous unit. The monzodiorite is composed of 15-20% phenocrysts of feldspar with laths up to 2.5 mm in length, which are frequently zoned, and of clinopyroxene up to 1.5 mm in length. The clinopyroxene crystals are mostly fresh and the analyzed grains show a range in composition from $Wo_{42}En_{42}Fs_{16}$ to $Wo_{46}En_{39}Fs_{15}$. The crystalline groundmass has an average crystal length of 0.3 mm and consists of feldspars (40-60%), chlorite (10-20%), Fe-Ti oxides (~ 5%), clinopyroxene (2-5%), and biotite (2%). Other minerals identified are calcite and natrolite. The rock shows variable degrees of alteration with plagioclases kaolinized and with the groundmass being replaced by chlorite. The chlorite is green, dusty green, brownish, and colorless. Albite is also present.

Alteration is most intense in the upper part of the igneous unit and decreases with depth, but increases again near its base. Here the change in the alteration is accompanied by a decrease in crystal size and the appearance of skeletal structure of mafic minerals. The study of drilling chips has not revealed the presence of volcanic or pyroclastic sediments, which were observed in some other wells.

The dipmeter log data indicates a change of dip from the regional dip of 10°S to about 25-40°SE at the boundaries of the igneous body. Within the body, internal high angle dips of 66°SE probably represent fractures in the monzodiorite, which might parallel the margin of the igneous body. The igneous rocks occur within a Middle Jurassic clastic sequence (Ascoli, 1981b). A monzodiorite sample at 2990 m provided a K/Ar age of 96.4 ± 3.8 m.y. on biotite. From the above evidence we conclude that the dioritic rock is probably a zone of dykes oriented NW-SE.

A seismic reflection profile located close to the Emerillon well shows the presence of several faults, but it does not show any seismic feature suggesting the presence of igneous rocks. This is as expected with dykes, as the reflection seismic method is unsuited for imaging near-vertical features (Badley, 1984).

<u>Georges Bank</u>

Volcaniclastic sediments in the Georges Bank region (Fig. 1) were first recorded in the COST G-2 well by Amato and Simonis (1980). A zone of green tuffs composed of green and grey, vesicular, devitrified volcanic glass and very fine fragments of crystalline, chloritized basalt form about 5% of samples between 3572 and 3627 m in the above well with the dominant component being a limestone. Small fragments of a greenish-grey tuff were recovered in a conventional core at 3600 m (Amato and Simonis, 1980). In 1981, the Exxon Oil Company drilled exploratory well 133-1, located in Lydonia Canyon Block No. 133, 50 km west of the COST G-2 well (Fig. 1). The well encountered a sequence of dark-grey and greenish-grey basalts and diabases, instead of a reef as predicted from seismic data interpretation. The study of drill cuttings and of conventional core #4 revealed the presence of pyroclastic rocks and basalts between 3776 and 4120.1 m. Compositional variability allows subdivision of the whole sequence into 3 units (Fig. 4). The lower unit (4120-4042 m), 78 m thick, is composed of medium dark grey and greenish grey, fine crystalline diabase. It overlies thinly bedded, micritic limestones at 4120 m, with a sharp boundary and is similarly overlain by a 36 m thick, pale to brownish grey micritic limestone (4003-4042 m) (Fig. 4). Minor changes in diabase composition are reflected in the presence of more leucocratic igneous beds, as observed in the interval between 4084 and 4097 m. These beds are easily recognized on mechanical logs by their higher density.

Dipmeter data show that the regional dip beneath the lower diabase unit is 2°SSE. The dip at the base of the unit is 16°SSE, and some dips in the middle of the unit vary between 40 and 60°NE. At the top of the unit the dip decreases to 10°NW.

Petrographic study of the drill cuttings and of the core shows that the diabase is composed of 10-20% phenocrysts of fresh or altered olivine in a crystalline matrix of feldspars and opaque minerals (Plate 1, Fig. D). The phenocrysts of olivine are about 0.25 mm in diameter, commonly accumulated in patches and spots, but are also dispersed through the rock. The altered olivine is replaced by brownish and greenish colored chlorite. Occasionally both highly altered and fresh crystals of olivine occur in the same rock fragment. The phenocrysts are set in an intergranular matrix composed of laths of plagioclase 0.1 to 0.2 mm in length, iron-titanium oxides (15-20%), interstitial grains of K-feldspar ($An_7Ab_{44}Or_{49}$) and rare small grains of clinopyroxene. The plagioclase is andesine ($An_{39}Ab_{56}Or_5$ to $An_{43}Ab_{49}Or_8$). Feldspars are fresh in unaltered samples and show minor degrees of kaolinization in altered rocks.

The samples show a minor variation in the grain size (length of feldspar laths 0.08 to 0.2 mm) and in the intensity of alteration (from 90% fresh to 40% altered). Millimeter-thick chrysotile veins occur occasionally. Porphyritic and intersertal textures are present; also textures which show various degree of alignment of feldspars, with subparallel oriented feldspars producing a trachytic texture. The observed compositional variability, lack of vesicular texture (which otherwise is common in the overlying volcanic rocks), and the interpretation of density and dipmeter logs suggests that the diabase unit is a zone of approximately 17 dykes, with individual dykes 1 to 14 m thick.

The middle unit (4003-4042 m) is micritic to biomicritic limestone enclosing a few ostracod and mollusc shell fragments and rare fecal pellets.

This faunal assemblage suggests a lagoonal depositional environment. Study of drill cuttings indicates two possible intercalations of volcanic tuff near the top of the unit.

The upper unit (4003-3776 m) is a pyroclastic sequence intercalated with thin basalt flows. The pyroclastic rocks are composed of dark green devitrified vesicular glass, lapilli agglomerates, tuffs and sand-sized obliquely shaped clasts of very finely crystalline, vesicular basalt with well aligned plagioclases (Plate 2, Figs. A and B). The dipmeter data indicate an initial dip of 26 to 40° that decreases upward over 61 m to 8 to 10°. This is followed by two other intervals of similar thickness, with a similar upward decrease in dip. We interpret this variation as documentation of several periods of volcanic cone construction and erosion in a submarine environment. Mechanical logs and drill cuttings study suggests that the second interval was accompanied by more extensive extrusion of basalts with individual flows only a few tens of centimetres thick. The highly vesicular basalt at the top of this middle constructional interval is oxidized, suggesting a brief period of subaerial weathering. Similarly the uppermost 24 m of the upper interval show mixing of oxidized, highly vesicular basalts and tuffs.

The pyroclastic unit is overlain by about 34 m of light brownish grey, fossiliferous micrite with subordinate medium grey, calcareous shale. In conventional cores #1 and #2 (3734-3768 m) the dark grey micritic limestone, with traces of anhydrite, is intercalated with grey silty shale, calcareous shale with coalified debris and minor very fine-grained calcareous sandstone.

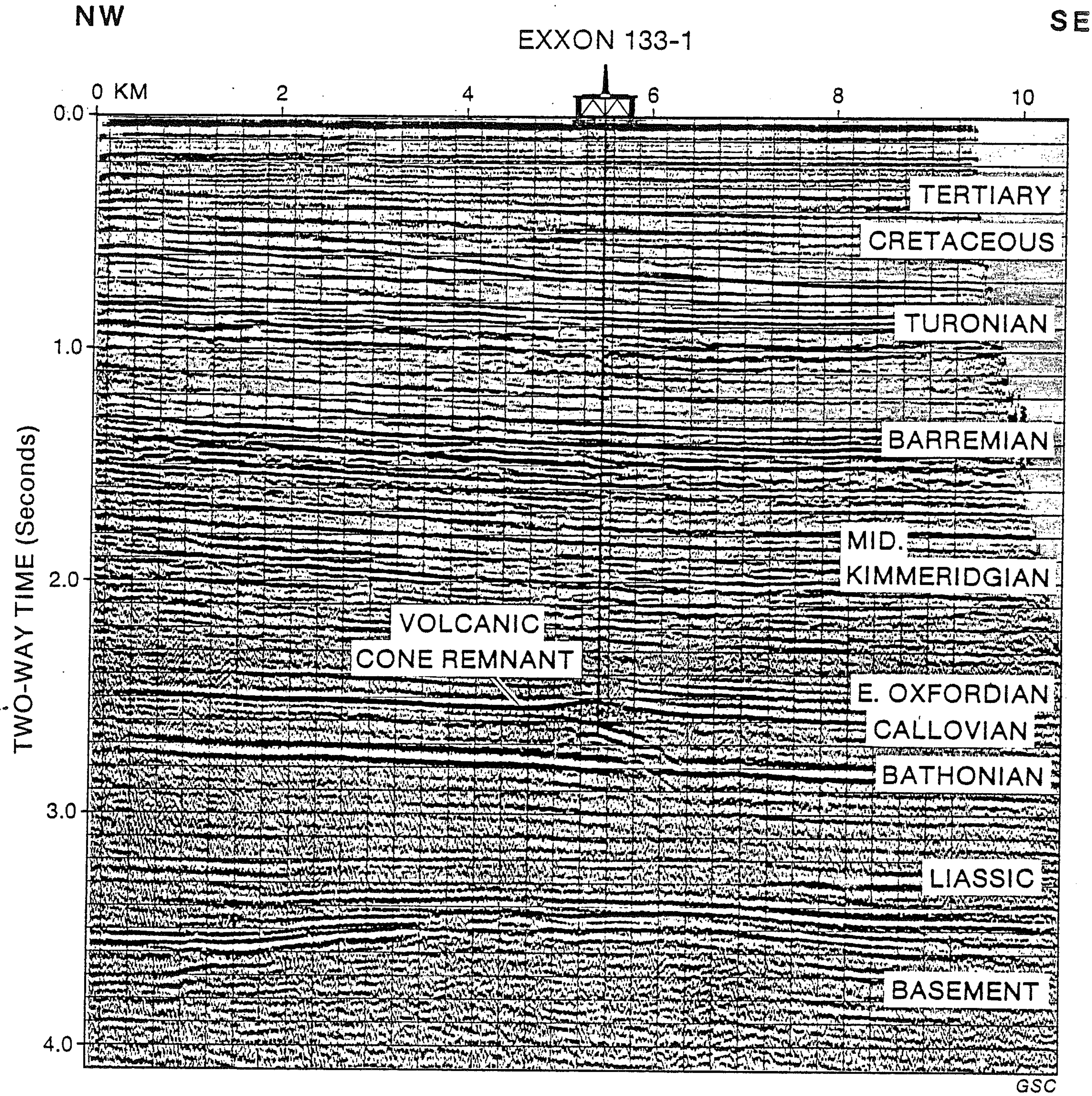

Figure 6. Multichannel reflection seismic profile across the Exxon Block 113-1 well, Georges Bank. The remnant of a volcano apron is shown by dotted pattern.
(Exxon Exploration Line EK789)

From the studies of samples and mechanical logs we interpret the volcanic sequence in the Exxon Lydonia Canyon Block 133-1 well as a remnant of a buried volcanic cone of a Strombolian type, constructed in a shallow carbonate lagoon. The basalt dyke zone which underlies the carbonates of the middle unit we consider to be feeder dykes. Slight variations in the petrographic composition of the dykes suggests several periods of intrusion.

Multichannel reflection seismic profile data provide additional support to the above interpretation. A seismic line (Fig. 6) shows a well defined mound structure about 0.1 sec. in height, which overlies, but does not disturb, a strong horizontal reflector. In the lower half of the structure the seismic reflectors are short and disrupted, some are curved, but mostly dip towards the outer perimeter of the mound. Some of them are probably diffractions off fractures and or faults produced during dyke emplacement. It is doubtful that the two strong inclined reflectors just below the cone (as seen on Fig. 6) are the feeder dykes, however, such a possibility cannot be totally excluded. The seismic signature of the upper half of the mound is different. The volcaniclastic rocks show as a transparent pod-like structure about 3600 m in length and the low sloping flanks extend the structure for an additional 1000 m on each side. The lens is about 0.5 sec thick and has a sedimentary drape over it which probably resulted from differential compaction. The lens shares internal structure and external morphologic features with sedimentary rocks, particularly with reefs, as was originally interpreted. It represents a construction period of a volcanic edifice, principally of pyroclastic rocks. The misinterpretation of volcanic cones does not always need to be a disappointment for the oil industry, since some volcanic mounds similar in size and composition to that on the Georges Bank are oil producers in Japan (Kujiraoka, 1980).

Buried remnants of volcanoes of similar construction to that drilled on Georges Bank were described from the Orpheus Graben off Nova Scotia (Jansa and Pe-Piper (1985), where they were of late Early Cretaceous age. Multichannel reflection seismic data from the continental slope off Georges Bank also reveals buried seamounts or volcanoes in this region. Two such structures, located south of the Lydonia Canyon near the Bear Seamount can be seismically correlated to the volcanic rocks in the Exxon 133-1 well (Wade, submitted), which indicates that Jurassic igneous activity in this area was quite extensive.

Stratigraphy

The presence of pyroclastic rocks in the Exxon 133-1 well allows us to establish the timing of the igneous activity using biostratigraphic data. We have first used the lithostratigraphic correlation with the COST G-2 well (Amato and Simonis, 1980) and regional reflection seismic data to establish the stratigraphic position of the volcanic rocks and the timing of the extrusion. The Exxon 133-1 well is located approximately half way between the COST G-1 and COST G-2 wells. The stratigraphic framework for both wells is firmly established (Amato and Simonis, 1980; Amato and Bebout, 1980). The biostratigraphic data for the COST G-2 well as recently updated by Ascoli (1981a) indicate that the volcanic glass in the COST G-2 well is intercalated within late Callovian-early Oxfordian age sediments. This part of the sedimentary sequence was correlated by Jansa and Wiedmann (1982) to the lower part of the late Jurassic Abenaki Formation of the Scotian Shelf. Lithologic and seismic correlation between the COST G-2 and the Exxon 133-1 well (Wade, submitted) confirm that the horizon with volcanic glass in the COST G-2 well is correlative and thus synchronous with the pyroclastics in the Exxon 133-1 well. This correlation has been confirmed by biostratigraphy. According to the Exxon Exploration Company Paleontology Group (G. Study, M. Crane pers. comm., 1986) palynology indicates a Callovian age for the top of the pyroclastic sequence as well as for the sediments intercalated with the basalts of the lower diabase unit in the Exxon 133-1 well.

A fresh sample from the Exxon 133-1 well at 4106 m, analyzed by Krueger Geochronological Laboratory, Massachusetts, U.S.A., provided a whole rock K/Ar age of 140 ± 6 m.y. The same laboratory analyzed two samples from conventional core taken from 4111 and 4112 m which provided K/Ar ages of 137 ± 6 m.y. and 134 ± 6 m.y. (Exxon Exploration Company, D.G. Blair written communication, 1984) (Table 2). Considering that the core samples are slightly altered, the results of these age determinating are surprisingly close and we consider the result from the unaltered sample (140 ± 6 m.y.) to be the age of the intrusion. According to the geologic time scales of Harland et al. (1982) and Palmer (1983) this age is Early Cretaceous (as interpreted by Hurtubise et al., 1984). However, such an interpretation is in sharp disagreement with the biostratigraphically derived age for the extrusion which according to both above time scales should occur close to 160 m.y.

Since we have previously successfully cross-correlated biostratigraphically and isotopically derived ages for similar, Early Cretaceous basalts and volcanic rocks from the Scotian Shelf (Jansa and Pe-Piper, 1985), and there is such a close cluster of radiometric dates for the Exxon 133-1 samples, the disagreement in the age interpretation may indicate that neither Harland's nor the Geological Society of America geologic time scales are correct for the Jurassic Period (Jansa and Williams, in prep.). The absolute age dates we have obtained are in better agreement with Van Hinte's (1976a) Jurassic time scale, where the Oxfordian/Callovian boundary is placed at 149 m.y.

Baltimore Canyon Trough

A nearly symetrical dome structure, named the Great Stone Dome by Schlee *et al.* (1976), was identified from seismic reflection profiles in the approximate center of the offshore Baltimore Canyon Trough sedimentary basin. The Dome was interpreted to be the result of emplacement of an igneous stock (Lippert, 1983; Fig. 7). It produced an uplift about 2 km high and 5-8 km in diameter, disturbing sedimentary strata up to 15 km from the center of the Dome (Lippert, 1983). The Dome was then eroded during a period of about 10 m.y. and covered by up to 2400 m of Late Cretaceous to Cenozoic clastic rocks, with the basal beds being marine sandstones of Aptian age (Crutcher, 1983). Six wells are located over the structure, which show that the structure is not an igneous stock or plug, but results from intrusion of a dyke swarm. The seismic profile across the structure (Fig. 7) does not show a transparent zone as would be expected if a batholith or an igneous stock cored the structure. Neither does it show the presence of high contrast reflectors due to sills as we have seen at the

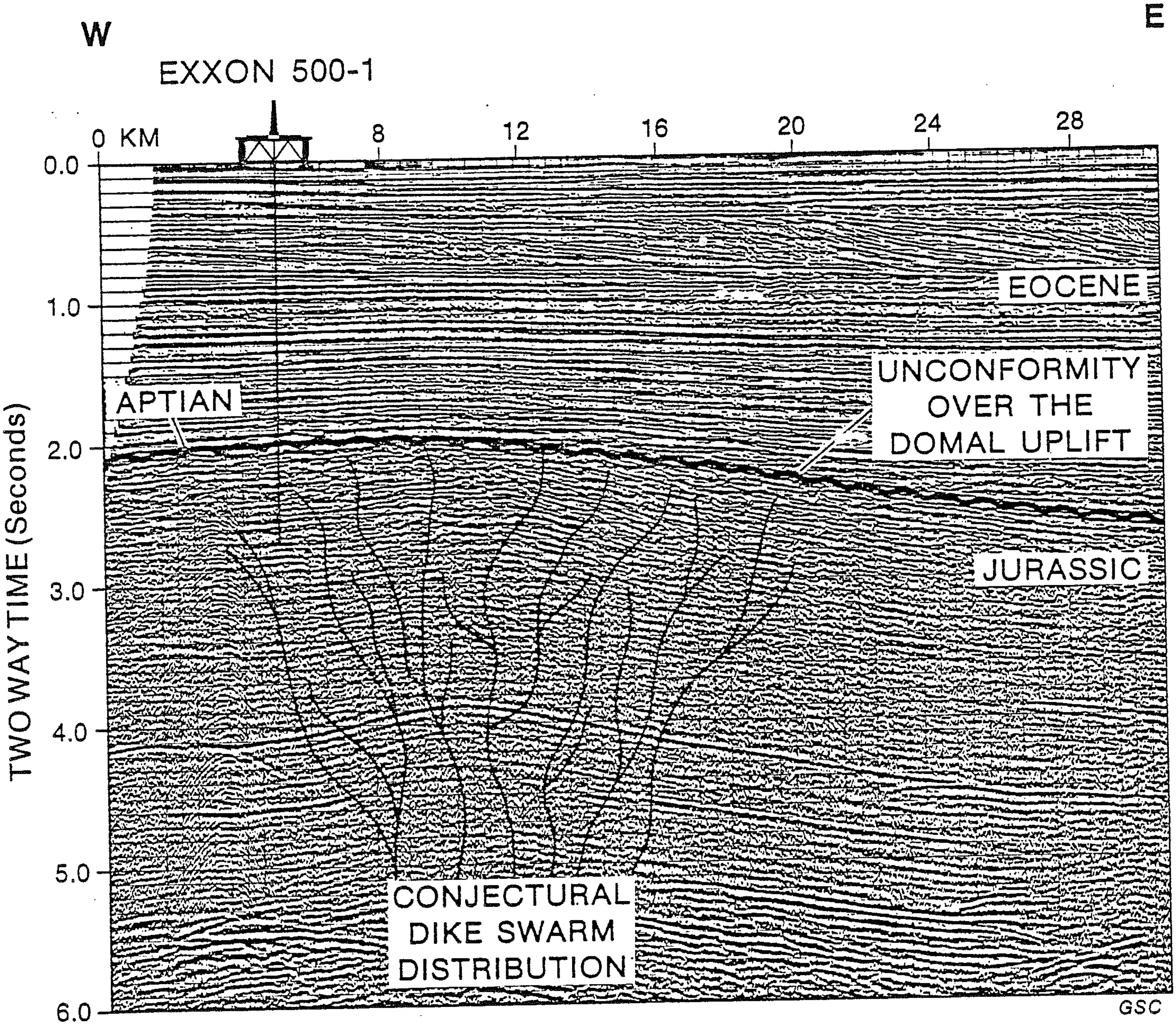

Figure 7. Multichannel reflection seismic profile across "Great Stone Dome", Baltimore Canyon Trough. Note the domal uplift and erosion surface at 2 sec. (Exxon Exploration line NJ 7718)

Brant well.

The six oil exploratory wells located over the "Great Stone Dome" which encountered igneous rocks within the Mesozoic sedimentary stata are: Exxon 500-1, Mobil 544-1, Mobil 544-2, Conoco 590-1, Shell 632-1, and Houston Oil and Minerals 676-1 (Fig. 7). Variable numbers of dykes were intersected by the above wells, with 22 encountered in the Mobil 544-1 well (Fig. 4), and only 4 igneous beds in the adjacent Mobil 544-2 well. The thickness of the dykes varies from about 1 m to 12 m. Stratigraphically all the igneous rocks are intercalated with Lower Cretaceous-Late Jurassic sedimentary strata. We have petrographically studied igneous rocks from the Mobil 544-1, Conoco 590-1 and Exxon 500-1 wells. Macroscopic examination of cuttings from Mobil 544-1 demonstrated only minor variations in composition and textural characteristics between individual igneous bodies, with the exception of one thin unit discussed below. The igneous rocks are medium grey, light grey and light olive grey in colour, finely crystalline, mafic rocks with some samples being microcrystalline to aphanitic. Only a few filled vugs or vesicles were observed. Additionally there are rare patches of coarse calcite which may be void filling or a replacement of completely altered phenocrysts of pyroxene. The vugs are filled by calcite, or calcite forms a rim with the centre of the void filled by zeolite or chlorite. Calcite also occurs as hair-line veins which cut the rocks and probably represent healed fractures.

Microscopic examination shows that the textures of these rocks approach the panidiomorphic texture typical of lamprophyres, with euhedral phenocrysts of pyroxene in an anhedral felsic matrix (Plate 2, Fig. C). In some slightly coarser crystalline beds the texture is more equigranular. The igneous rocks are composed of clinopyroxene (10-15%), potassium feldspar (25-30%), analcime (10-20%), biotite (7-10%), magnetite (8-12%), calcite (10-15%), chlorite (~ 10%), and plagioclase feldspar (10-15%). Accessory minerals include apatite, epidote, clay minerals, hematite and pyrite. Some of the crystal outlines are reminiscent of olivine which has been completely replaced by calcite. Olivine is more common in the Conoco 590-1 well than in Mobil 544-1 well. The clinopyroxene is often the only phenocrystal phase present and it may occur as crystals with the typical stubby habit up to 1 mm in length. It is colourless or light green in thin section, frequently zoned and often altered. Pyroxene is altered to chlorite and/or calcite. The alteration is always similar in a single drilling chip, but varies between individual chips. The K-feldspar crystals (sanidine with a composition from $Or_{77}Ab_{21}An_{1}$ to $Or_{40}Ab_{49}An_{11}$) occur interstitially, whereas the plagioclase (oligoclase to andesine; from $An_{13}Ab_{81}Or_{6}$ to $An_{57}Ab_{55}Or_{8}$) occurs as small microliths to small randomly oriented lath-shaped crystals with a composition of An_{50} to An_{65}. Analcime occurs in some samples deeper than 3000 m (e.g. the analyzed sample at 4093 m). Some of the analcime is void filling, but most occurs in the matrix together with the K-feldspar. Biotite is present as small euhedral to subhedral crystals with hexagonal outlines 0.02 to 0.15 mm across and elongated crystals up to 0.2 mm in length. The small crystals are evenly distributed and are not noticeably altered. Magnetite is unusually abundant in all of these samples as small equant crystals up to 0.05 mm across. The composition and texture of these mafic rocks indicates that they belong to the potassium-rich suite of

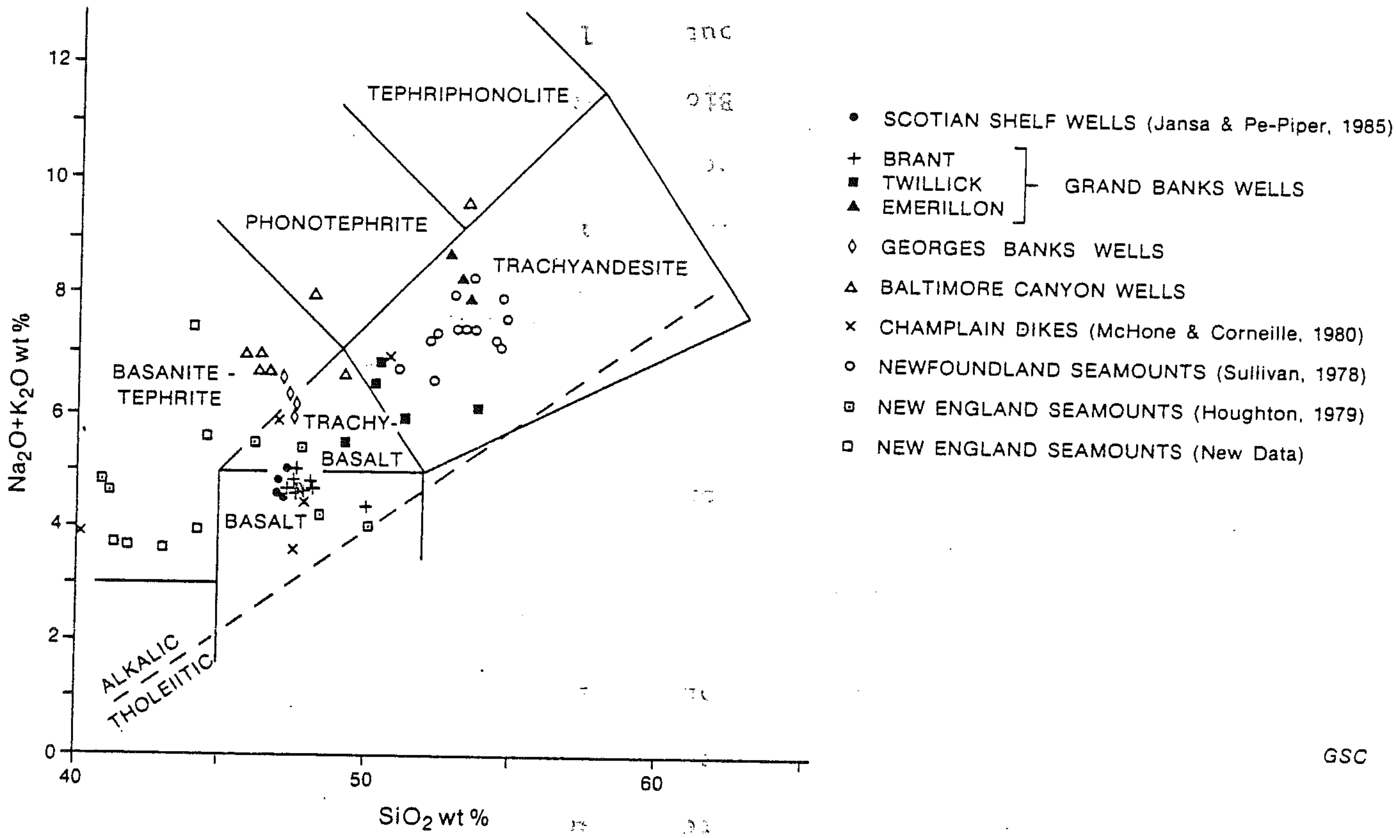

Figure 8. Plot of total alkalis against silica for whole rock samples used in this study, to illustrate alkali nature of the rocks, and their nomenclature after Zanettin (1984).

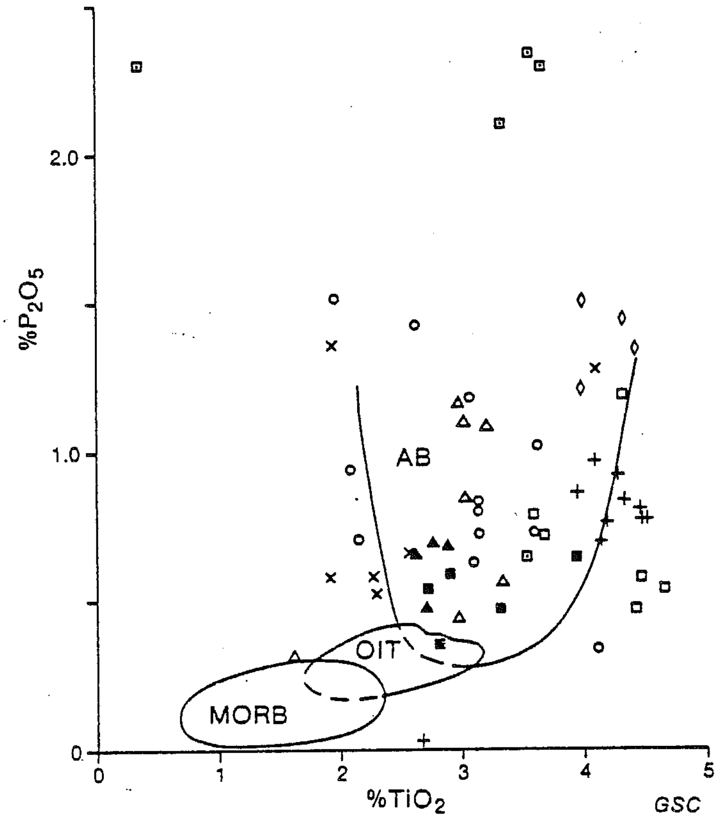

Figure 9. Plot of P_2O_5 against TiO_2 (after Ridley et al., 1974) showing alkaline character of the rocks studied. AB - alkaline basalt, OIT - ocean island tholeiite, MORB - Mid Atlantic

trachybasalts and lamprophyres.

An exception to this very uniform lamprophyric suite is a tephriphonolite which occurs at 4093-4100 m. It is a greyish-orange pink, fine to medium crystalline, felsic rock composed of interpenetrating tabular crystals of feldspar with minor iron oxide (10%), chlorite (3%) and traces of zeolite (Plate 2, Fig. 4). Feldspar is extensively replaced by sericite.

In the samples we have examined from both wells we have not found any conclusive evidence for subaerial extrusion. Volcaniclastic or pyroclastic rocks are absent. The holocrystalline nature of the mafic rocks suggest that they are intrusive rocks. The variable number of lamprophyre beds in wells located over the Great Stone Dome document that they are part of a dyke swarm. Our data does not allow us to exclude the possibility that a few of these rocks may have been emplaced as sills. The domal uplift associated with the dykes intrusion indicates that the dykes are likely to be arranged in a radial pattern.

Stratigraphy and absolute age data

The stratigraphic position of the lamprophyres, as can be interpreted from biostratigraphic and absolute age data in the files of the U.S. Minerals Management Service, spans the ?late Jurassic to the Neocomian, with the highest occurrence in the Barremian in Mobil 544-1 well (Table 1 and 2). In this well, a whole rock K/Ar age of 96.5 ± 5 m.y. has been obtained from lamprophyre at 2919.6 m and a biotite K/Ar age of 143 ± 7 m.y. and Rb/Sr age of 103 ± 4 m.y. from a conventional core sample of a lamprophyre at 3187 m. In the Exxon 500-1 well, the well data includes three whole rock K/Ar age dates from 3627 m, 3639 m and 3648.4 m with the corresponding ages of 127 ± 5 m.y., 118 ± 5 m.y. and 116 ± 5 m.y. (Table 2). The 143 ± 7 m.y. age of the concentrated biotite from the Mobil 544-1 well is thus too old since the host sediments have been biostratigraphically dated as Barremian. We suggest that the error may be either due to excess of radiogenic argon in the biotite or alternatively it may result from mixing of biotites from the lamprophyre with biotite of the micaceous arkosic sandstone which the dyke intrudes. The sample for isotope age dating was taken 30 cm above the contact with the sandstone, but since the dykes are usually highly dipping (most dykes in New England have dip greater than 70°, McHone, 1978), the sample could be less than 10 cm from the contact with the sandstone. Additional evidence for the timing of the intrusion is provided from the dating of the angular unconformity over the "Great Stone Dome" which developed as a result of the domal uplift by the instrusion. This unconformity is interpreted as intra-Barremian on paleontological evidence (Amato and Giordano, 1985).

ROCK GEOCHEMISTRY

Whole rock major element chemistry

Whole rock analyses have been made on a total of 40 samples from the Grand Banks, Georges Bank and Baltimore Canyon. These are compared with 45 published analyses of mafic rocks of similar age from the Scotian Shelf (Jansa and Pe-Piper, 1985), Newfoundland Seamounts (Sullivan, 1978) and New England Seamounts (Houghton, 1979).

All the analysed mafic rocks have between 46 and 54% SiO_2 on an H_2O-

and CO_2-free basis. In the IUGS nomenclature (Zanettin, 1984), they fall in the basalt, trachybasalt, basanite-tephrite and trachyandesite fields (Fig. 8). Rare samples from Mobil 544-1 (Baltimore Canyon) fall in the tephriphonolite and phonotephrite fields. Hypabyssal rocks from Emerillon C-56 (Grand Banks) fall in the monzodiorite field of Streckeisen (1976).

The analysed rocks show several geochemical features that indicate that they are alkali mafic rocks. In a plot of total alkalies versus silica (MacDonald and Katsura, 1964; Frey and Clague, 1983, Fig. 8) and a plot of P_2O_5 versus TiO_2 (Ridley et al., 1974, Fig. 9) they fall in the alkali field. All fresh samples fall within the "within plate basalt" field of Pearce (1976).

The alkalis plot of Hughes (1972) has been used to identify those samples which appear highly altered (Fig. 10). On this plot, many of the New England and Newfoundland Seamount samples fall outside the "igneous spectrum" because of alteration by sea water. These analyses have been excluded from further consideration.

In relatively primitive rocks such as these alkali basalts, certain major element ratios can be used as crude indicators of differentiation. The FeO/(FeO+MgO) ratio is an indicator of the degree of olivine and pyroxene crystallisation, whereas the CaO/Al_2O_3 ratio is sensitive to clinopyroxene and plagioclase crystallisation (Fig. 11). The relatively high Fe/Mg ratio suggests that most samples have experienced considerable olivine fractionation. The samples with CaO/Al_2O_3 values in the range 0.54 to 0.66 are shown below to have no trace element evidence for major fractionation by either clinopyroxene or plagioclase.

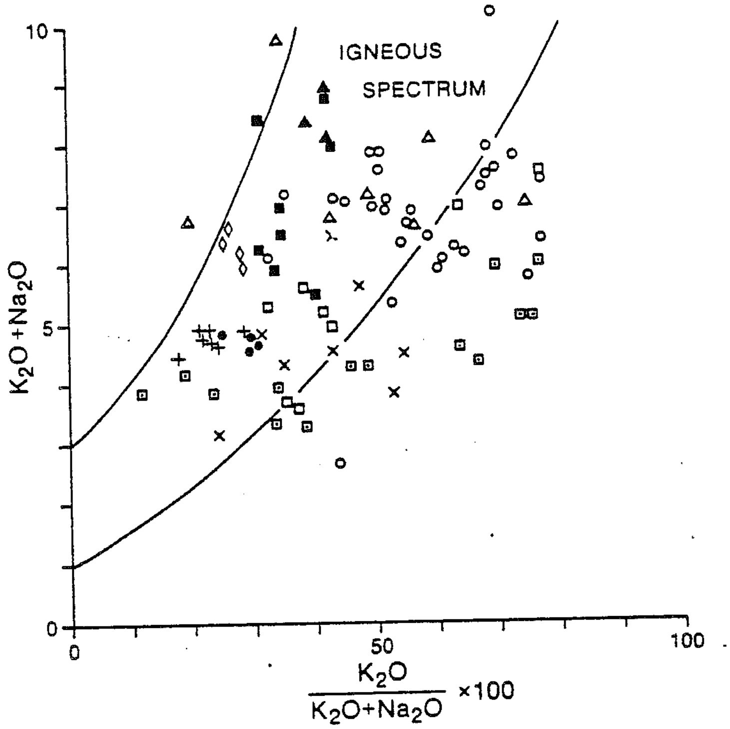

Figure 10 . Plot of total alkalis against potash to total alkali ratio (after Hughes, 1972) for whole rock samples used in this study, showing those samples that fall within the "igneous spectrum".

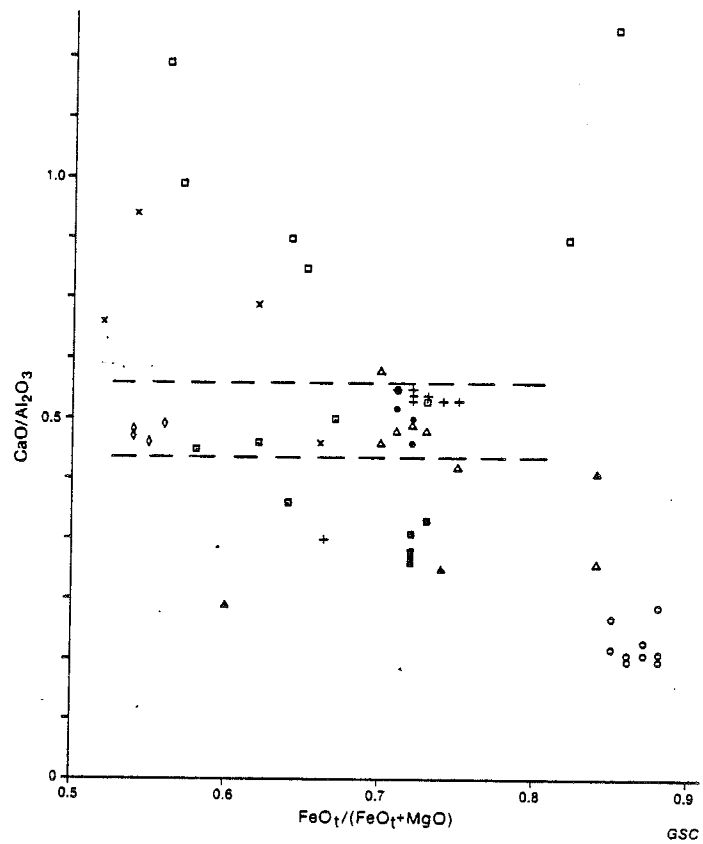

Figure 11. Plot of Cao/Al_2O_3 against FeO_t/FeO_t+MgO for rock samples used in this study (Table 3). Rocks with CaO/Al_2O_3 between 0.54 and 0.66 (dashed lines) have experienced little plagioclase or clinopyroxene fractionation.

Trace element chemistry

Trace element variation in the various rocks examined can be displayed on MORB-normalised plots (Figs. 12 and 13) showing the degree of incompatibility of the element (following Pearce, 1982). Care must be taken in comparing these data, since different trace elements have been determined for different rock suites.

Rocks from the Baltimore Canyon are strongly enriched in the elements Sr to Ti, with over 50 times MORB values for Rb, Ba, Th and Ta. The degree of enrichment (or depletion) decreases steadily from Ba to Cr. The diorites from Emerillon are also strongly enriched in the elements K to Ta, but show less extreme concentrations than Baltimore Canyon samples.

Brant P-87 and Twillick G-49 similarly show a steady decrease in relative abundance from Ba to Cr, but with slight plateaus at Ba to Ta and Hf to Ti. Absolute enrichment in Ba to Ta is between 15 and 25. Although fewer elements have been determined from Hercules G-15 and Hesper I-52, they appear to show a pattern of similar shape, but less absolute enrichment. There is no Ba determination, but there is a Th-Ta plateau at 10 to 13, and a Hf to Ti plateau.

Trace element data from the Champlain dykes are very limited. They are distinctive in showing approximate MORB values of the elements Ti to Cr. However, Ba is enriched 30-100 times over MORB values, and Sr to Rb is enriched 5 to 20 times. Phosphorous enrichment is variable, from 4 to 20 times.

The reliability of trace element data from the seamounts is suspect, because the rocks are highly altered. The New England Seamounts are unusual

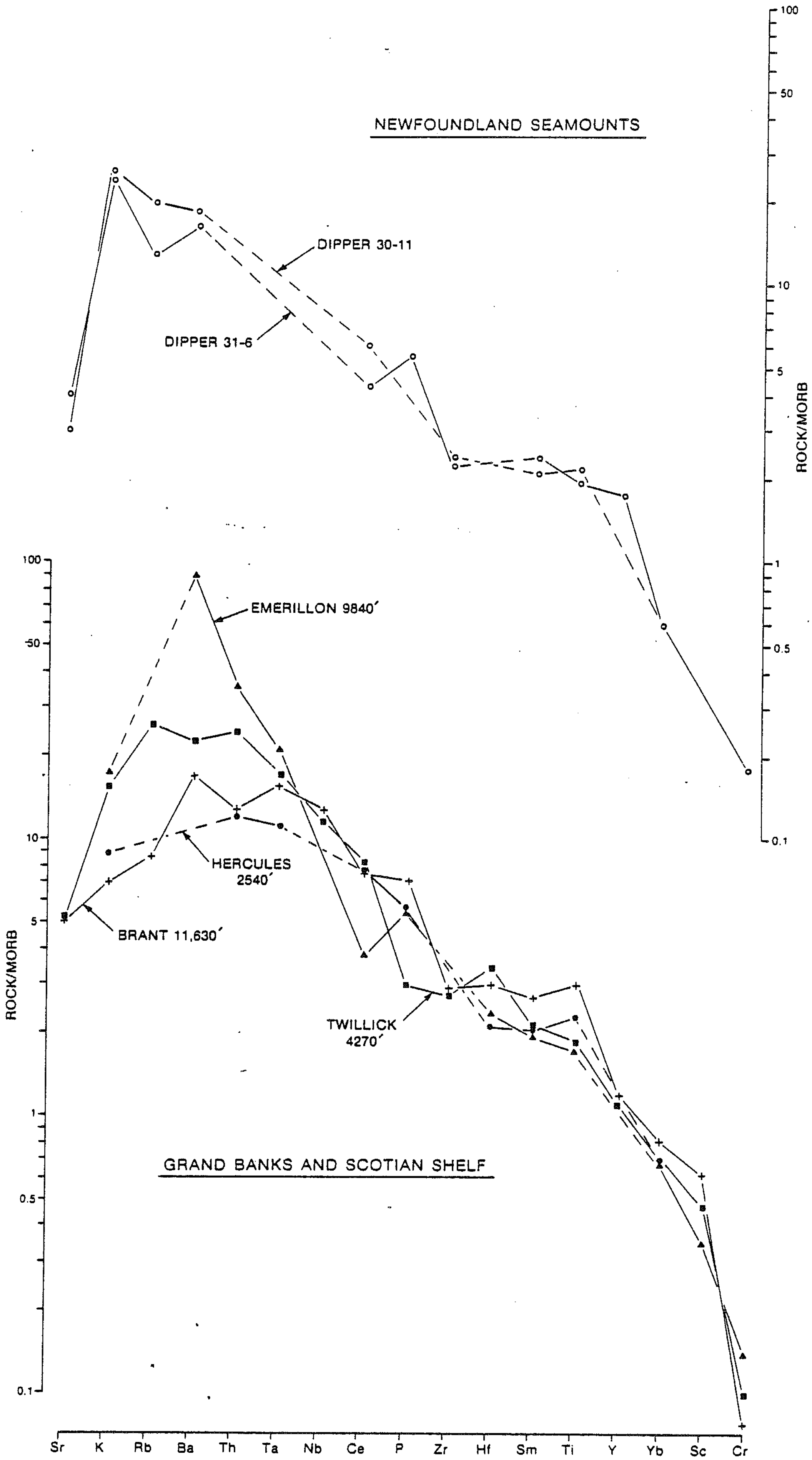

Figure 12. Selected trace element abundances relative to MORB, for samples from the Newfoundland Seamounts (data from Sullivan, 1978), Grand Banks and Scotian Shelf.

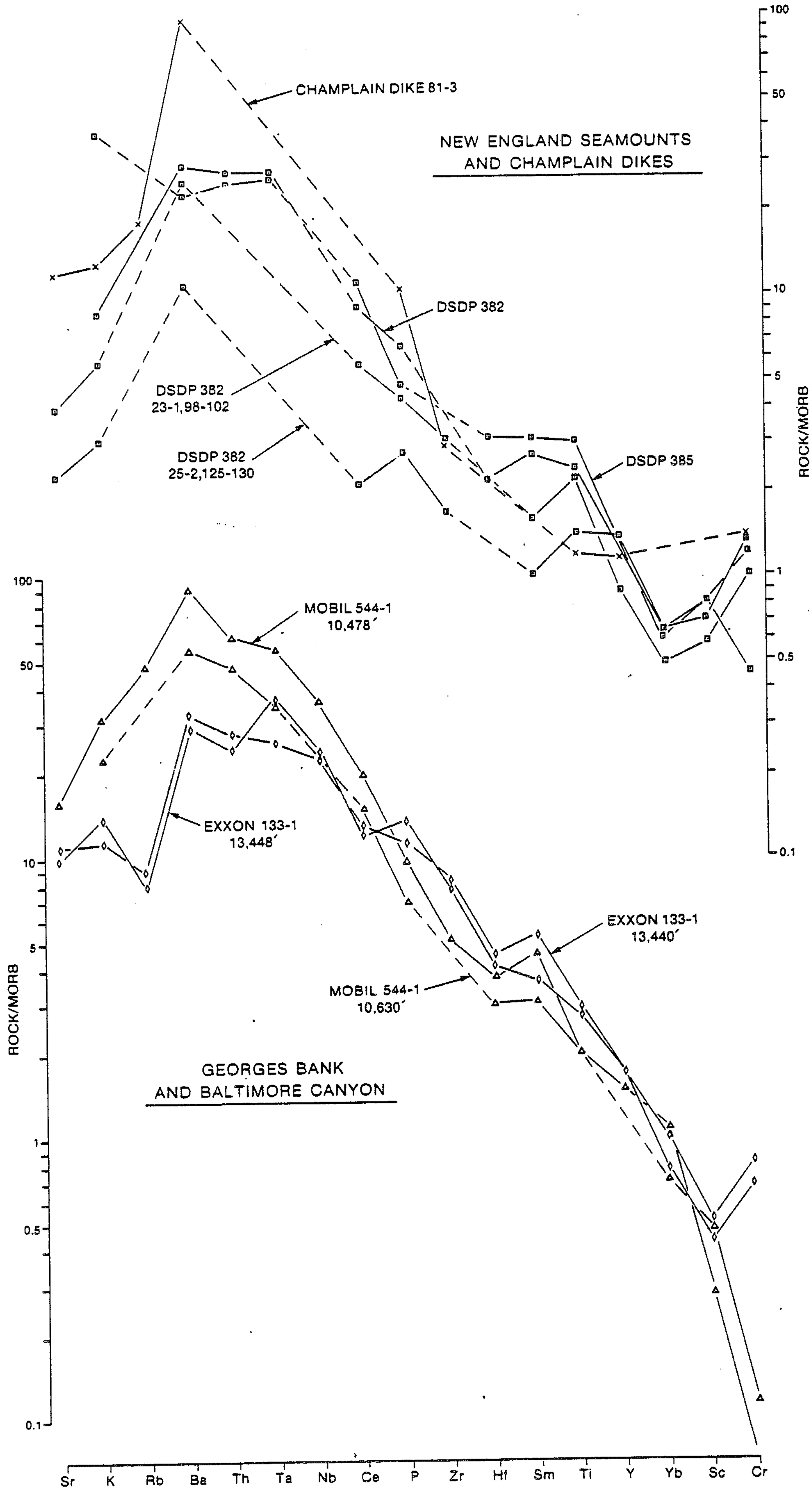

Figure 13. Selected trace element abundances relative to MORB, for samples from Georges Bank, Baltimore Canyon, New England Seamounts (data in part from Houghton, 1979) and Champlain dikes.

in being enriched in Ti and some samples have a positive P anomaly. Cr is close to MORB values, whereas Y, Yb and Sc are depleted. The Newfoundland Seamounts are strongly enriched in K to P, somewhat enriched in Zr to Y (with a positive Sm anomaly) and highly depleted in Cr.

Plots of Zr against TiO_2 and Zr/Y (Fig. 14) suggest that most of the rocks formed in a "within plate" tectonic environment although some Newfoundland Seamount samples fall in the MORB field.

On the Ti/Y against Nb/Y plot (Fig. 15), some Newfoundland Seamount samples have very low Ti/Y ratios and thus plot in the MORB field. Other samples from the Newfoundland Seamounts and all samples from the New England Seamounts and the continental shelf plot in the WPB field. High Nb/Y ratios occur in samples from the Baltimore Canyon, Georges Bank and the New England Seamounts (only one sample), falling in the "alkali" subfield; other samples fall in the "transitional" (i.e. subalkali) sub-field.

Rare earth elements

Rare earth element spectra (Fig. 16) show similar groupings of samples to the MORB-normalised trace element plots (which of course include some common data).

Samples from the Baltimore Canyon, Georges Bank and the Emerillon C-56 well all show strong enrichment in light REE (La 150 to 300 times chondrite values), with a steady decrease in enrichment to Lu values of 12 to 16 times chondrite values. The spectra are steepest in the intermediate REE (Nd to Tb).

Samples from Brant P-87 and Twillick G-49 have heavy REE abundances slightly in excess of these from Baltimore Canyon, but rather flat light REE

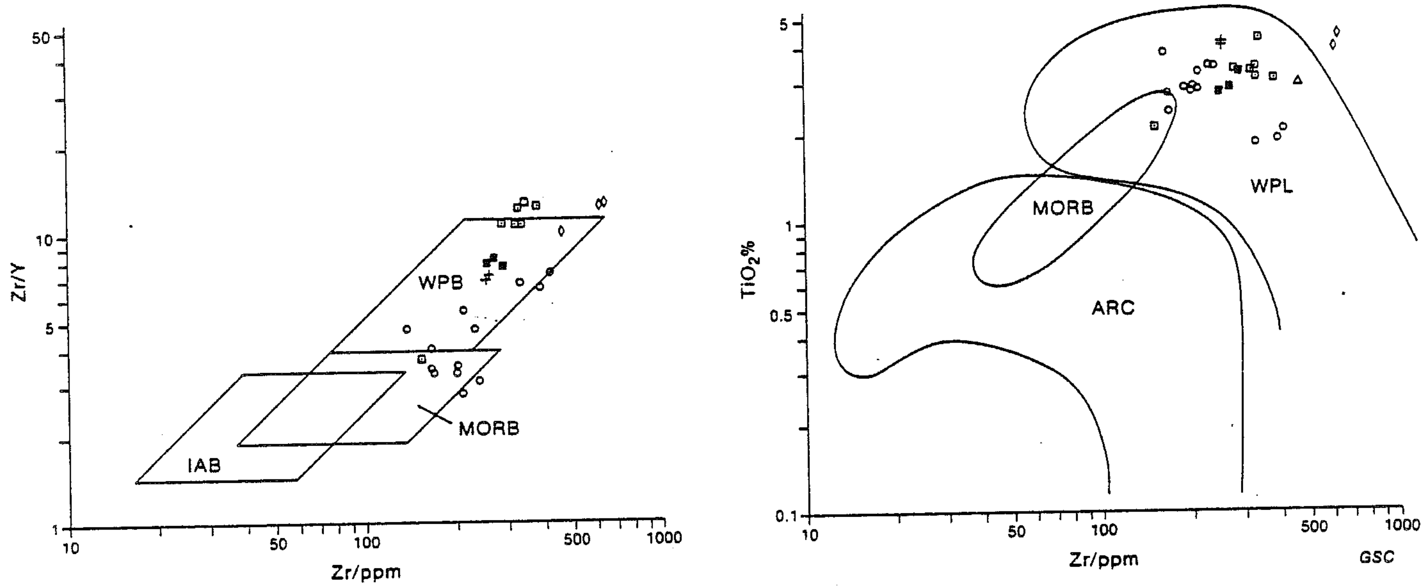

Figure 14. Plots of TiO_2 against Zr (after Pearce, 1982) and Zr/Y against Zr (after Floyd and Winchester, 1975) for whole rock samples used in this study showing the general "within plate basalt" character.

abundances with La values of 100 to 130, resulting in a convex-up spectrum. Hesper I-52 and Hercules G-15 samples show similar convex-up spectra but are a little less enriched than those from Brant P-87 and Twillick G-49.

The New England Seamounts have straight or concave-up REE spectra, with La values of 30 to 200 and a positive Eu anomaly in some samples.

The Newfoundland Seamounts data appear to be of rather low precision. The general trend of the spectra is straight, with La values from 80 to 250. The more enriched samples differ from those of the Baltimore Canyon, Emerillon C-56 and Georges Bank in having rather high REE values (20 to 40, compared with 10-20 times chondrite).

Interpretation of geochemical data

The relatively low Mg/Fe ratio and low abundance of Cr in all the continental shelf igneous rocks indicates that they are not primary magmas, but have undergone some degree of fractional crystallisation. The Georges Bank and some New England Seamount analyses have the highest Mg/Fe ratio and CaO/Al_2O_3 ratios, in the range 0.5-0.7 (Fig. 11). Similar CaO/Al_2O_3 ratios occur in the Baltimore Canyon, the Scotian Shelf, and in Brant P-87, but Fe enrichment is greater. These uniform CaO/Al_2O_3 ratios, the lack of a Eu anomaly, and the absence of significant La and Ce enrichment relative to Nd, despite considerable enrichment in Sm compared with HREE, suggest that there has been no significant fractionation of either plagioclase nor clinopyroxene, and that olivine fractionation has probably predominated in all of these cases. However, both Twillick G-49 and Emerillon C-56 have lower CaO/Al_2O_3 ratios, suggesting the role of minerals other than olivine and iron-titanium oxides in fractional crystallization.

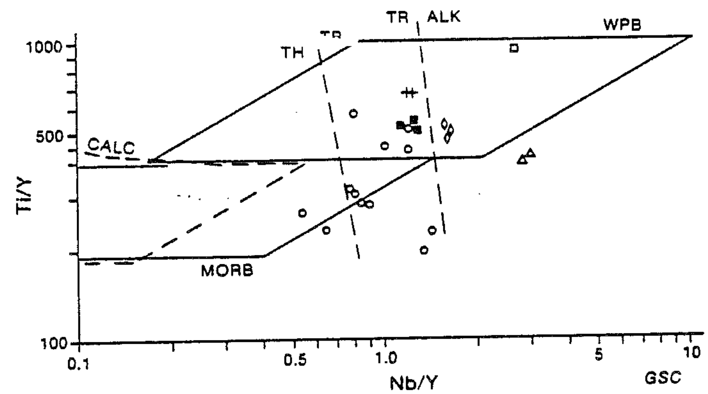

Figure 15. Plot of Ti/Y against Nb/Y (after Pearce, 1982) for representative rock samples that fall within the "igneous spectrum".

Rocks from the Georges Bank, Baltimore Canyon and the New England Seamounts have relatively straight REE spectra. Normal primary alkali olivine basalts from, for example, Hawaii (Clague and Frey, 1982) and Ross Island (Sun and Hanson, 1975) show similar spectra. The magmas with these straight spectra appear to be derived from mantle substantially enriched in LREE (with La Ce Nd, all enriched several times relative to a normal MORB source) typical of the P-type MORB of Le Roex et al. (1983). The convex-up REE spectra for Brant P-87, Twillick G-49, Hesper I-52 and Hercules G-15 are distinctive and unusual. Kay and Gast (1973) report one similar analysis from Hawaii (U-Hill#1). A partial melting process similar to that proposed for Hawaiian type alkali basalts acting on less enriched mantle (with LREE depletion and REE spectra similar to N-type MORB) could lead to the spectra of the Scotian Shelf, Brant P-87 and Twillick G-49. The Georges Bank, Baltimore Canyon and New England Seamounts are also enriched in Ba, Th and Ta relative to the Scotian Shelf-Brant-Twillick rocks; similar enrichment occurs in P-type MORB. This distinction of normal and enriched mantle sources is confirmed by a Ta-Hf-Th plot after Wood et al. (1979).

Marked La-enrichment occurs in rocks from Emerillon C-56, which petrologically appears more highly fractionated, and in the most highly altered samples from the New England Seamounts.

Trace element data for both the Newfoundland Seamounts and the Champlain Dykes are sparse. However, both show steep gradients in the range Ce to Hf on the MORB-normalised plots, a characteristic seen in rocks inferred to have an enriched mantle source.

The ratios of Ti and Nb to Y (Fig. 15) are believed to reflect mantle

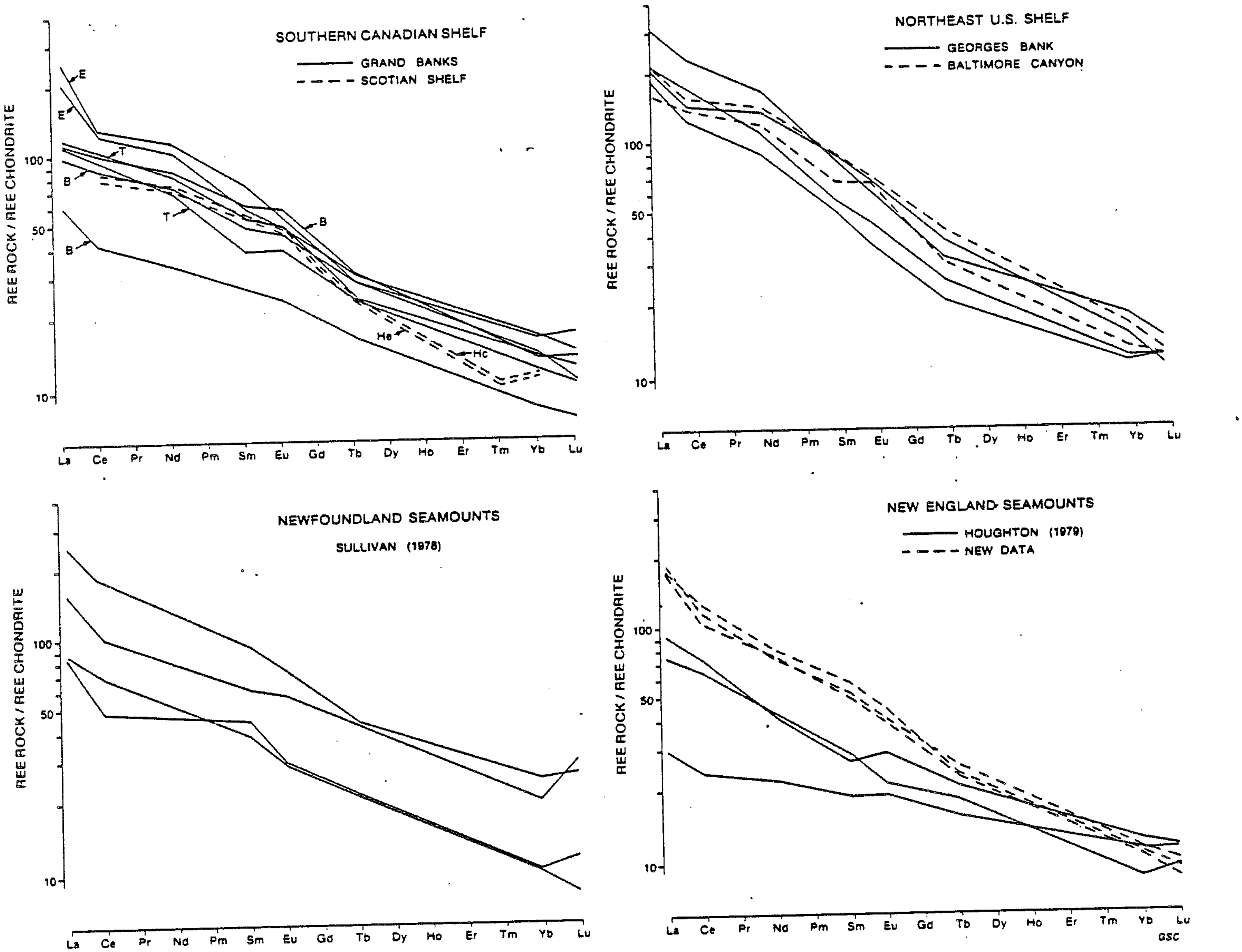

Figure 16. REE spectra for Grand Banks, Georges Bank and Baltimore Canyon igneous rocks, together with selected analyses from the Scotian Shelf (Jansa and Pe-Piper, 1985), Newfoundland Seamounts (Sullivan, 1978), and New England Seamounts (Houghton, 1979) and new data.

heterogeneity, and to be only slightly modified by subsequent differences in melting and fractional crystallization. The Ti-Nb-Y data confirm that the study area is underlain by two different mantle types (by this we mean mantle of different evolutionary history or origin), one underlying the southwest continental margin (Georges Bank, New England Seamounts and Baltimore Canyon) and another type present under the northeastern continental margin (Scotian Shelf, Grand Banks and possibly the Newfoundland Seamounts).

Major element variations are less easily interpreted. There are considerable variations in K, P and Ti, but no systematic geographic variation was detected. Thus, for example, titanium content is low (<3%) in the Champlain dykes, the Twillick volcanics and the Newfoundland Seamounts and relatively high (~ 4%) in the Georges Bank and the Brant volcanics and the Hesper sills.

MINERAL CHEMISTRY

Mineral phases present

The mineral phases present in representative samples from all the localities have been determined by electron microprobe (Cambridge Instruments Microscan 5 with Ortec energy-dispersive analyser, at Dalhousie University). The primary phases include plagioclase, potash feldspar, biotite, clinopyroxene, Fe-Ti oxides, olivine and kaersutite. The common secondary minerals are chlorite, smectite, iddingsite, zeolites and calcite. Representative analyses of the most common primary and secondary minerals are given in Tables 5 and 6. Clinopyroxenes are considered in more detail below.

Clinopyroxenes

Average chemical compositions of clinopyroxenes (Fig. 17 and Table 6) indicates that pyroxenes from the Baltimore Canyon trough are salites, those from the Newfoundland Seamounts (data of Sullivan, 1978) are diopsides and those from the Scotian Shelf and Grand Banks are augites, using the nomenclature of Deer et al. (1971). No clinopyroxenes were analysed in the Georges Bank samples. Only three analyses are available from the Champlain Dykes (McHone and Corneille, 1980); all are salites, but show a wide range of chemical composition. Clinopyroxenes from the New England Seamounts (Pe-Piper and Jansa, submitted, a) are complexly zoned, with cores of Al-Ti augite and/or Fe-rich salite and rims of titanaugite. It is noteworthy that in Figure 11, pyroxenes with a high hedenbergite plus acmite component (i.e. the augites from the Scotian Shelf and Grand Banks) occur only in those rocks believed to be derived from a mantle with little enrichment.

The alkaline character of all the pyroxenes is shown in a Ti versus Ca+Na plot (Fig. 18, after Leterrier et al., 1982). The Baltimore Canyon pyroxenes are more calcic than those from other continental shelf basalts. The least calcic pyroxenes are from Emerillon and the Newfoundland Seamounts. The New England Seamount and Scotian Shelf pyroxenes are most titaniferous and those from the Newfoundland Seamounts least so.

Several authors (e.g. Wass, 1979) have suggested that the Al^{vi} to Al^{iv} ratio is an indicator of the pressure conditions under which clinopyroxenes are formed. Samples from the Scotian Shelf and Grand Banks, together with some Newfoundland Seamount samples and the titanaugite rims

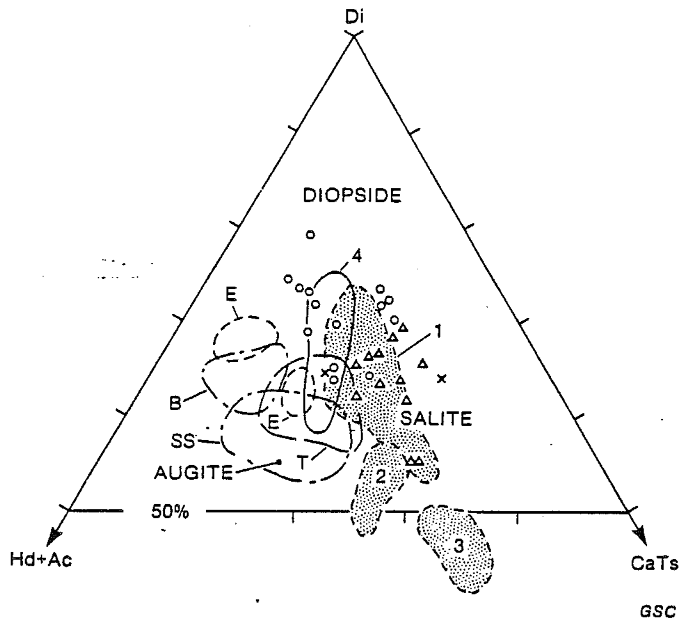

Figure 17. Clinopyroxene compositions plotted on a Diopside - Hedenbergite + Acmite - Ca Tschermaks molecule ternary diagram. All available analyses from the Newfoundland Seamounts (Sullivan, 1978) and Baltimore Canyon are plotted.

from the New England Seamounts have low Al^{vi} to Al^{iv} ratios, suggesting a low pressure origin (Fig. 19). There is independent evidence (Pe-Piper and Jansa, submitted (a)) that the Al-Ti augite and Fe-salite from the New England Seamounts have a mantle origin: they have an Al^{vi} to Al^{iv} ratio similar to that of the Baltimore Canyon salites and the Newfoundland Seamount diopsides. We therefore suggest that these latter clinopyroxenes are also of high pressure origin.

In the apparently high-pressure New England Seamount and Baltimore Canyon samples (and probably also the Champlain Dykes samples) clinopyroxene appears to have crystallised before plagioclase, so that Ca activity was high at the time of clinopyroxene crystallisation. In contrast, the clinopyroxenes in the Grand Banks and Scotian Shelf wells appear to be low pressure forms and textural evidence suggests that plagioclase started to crystallize before clinopyroxene. The variations in Ti may similarly be related to the time of appearance of Fe-Ti oxides at the liquidus.

GEOCHEMICAL SYNTHESIS

The geochemistry of all the rocks studied indicates that they are typical within-plate alkaline rocks. Most samples have experienced considerable olivine fractionation and lesser clinopyroxene fractionation. Fractionation involving other phases is minor except in rocks from Twillick G-49 and Emerillon C-56. Trace element compositions can thus be related relatively simply to mantle source composition.

Comparison with the calculations of Sun and Hanson (1975) and Clague and Frey (1982) indicates that the observed major and trace element

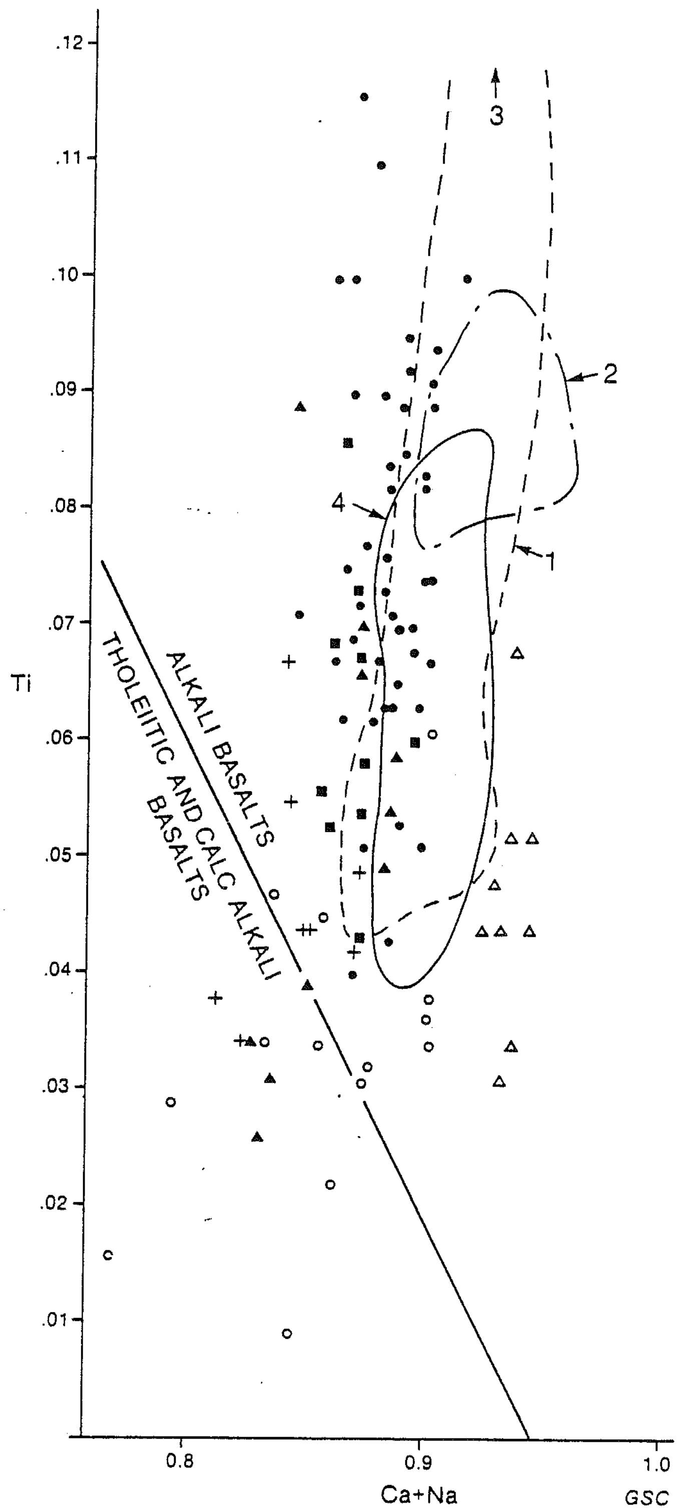

Figure 18. Discrimination diagram for clinopyroxene electron microprobe analyses from Leterrier et al. (1982). Analyses for Scotian Shelf after Jansa and Pe-Piper (1985); for Newfoundland Seamounts after Sullivan (1978); for the New England Seamounts after Pe-Piper and Jansa (submitted (a)): 1-4 are as in Figure 17.

distribution could be produced by 5 to 15% partial melting of a garnet-lherzolite source, followed by substantial olivine fractionation.

We distinguish two igneous provinces on the basis of variations in all the geochemical parameters that we have examined. One province includes the Scotian Shelf and Grand Banks: it was derived from partial melting of mantle similar in composition to N-type MORB. The other comprises the Georges Bank basin, Baltimore Canyon trough and the New England Seamounts: it was derived from partial melting of enriched mantle similar to the P-type mantle of Le Roex _et al_. (1983). The Newfoundland Seamounts show characteristics intermediate between these two provinces. For example, the REE spectra appear intermediate in character; there is substantial enrichment in several trace elements, as in the Georges Bank - Baltimore Canyon province; but Nb/Y ratios are closer to those of the Grand Banks - Scotian Shelf province. These magmas were probably derived from mantle showing slight P-type enrichment.

Samples from the New England Seamounts and Baltimore Canyon, both characterised by a P-type MORB mantle source, contain high pressure clinopyroxene phenocrysts. In contrast, samples from the Scotian Shelf and Grand Banks, derived from N-type MORB mantle, contain only low pressure clinopyroxenes. This difference might be due to the chemical differences in the two types of mantle, or to differences in physical evolution or origin of magmas in the two areas. We know of no chemical reasons favouring the crystallization of clinopyroxenes in P- rather than N-type upper mantle. The complexly-zoned New England Seamount clinopyroxenes (Pe-Piper and Jansa, submitted (a)) provide evidence of either mixing of small batches of magma

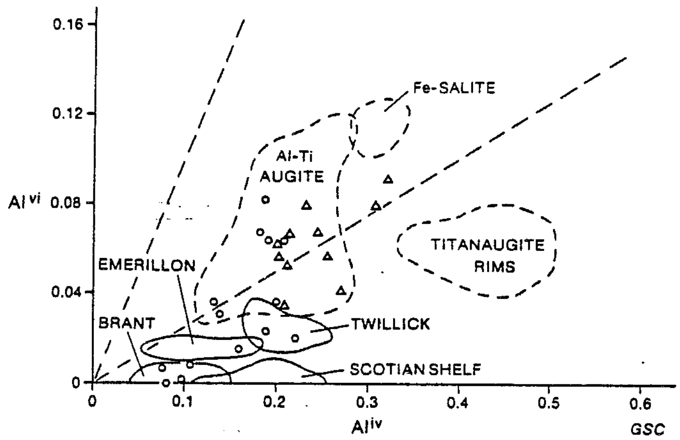

Figure 19. Plot of Al^{iv} against Al^{vi} for pyroxenes from basalts, determined by electron microprobe. All available analyses for Newfoundland Seamounts (Sullivan, 1978) and Baltimore Canyon are plotted. Fields of analyses are shown by solid lines for the Grand Banks wells and all wells on the Scotian Shelf. Fields for New England Seamounts shown by dashed lines from Pe-Piper and Jansa (submitted (a)). Dashed lines from Wass (1979) proposed limits of high-pressure pyroxenes.

or rapid changes in physical conditions. Since these features are not seen in the Scotian Shelf - Grand Banks samples, we suggest that they may result from the same processes as those that led to the enrichment of the mantle.

The development of P-type or enriched MORB may be related to the activity of mantle plumes active beneath spreading ridges (Le Roex et al., 1983). Within-plate alkali basalts with trace element characteristics similar to those in the Georges Bank-Baltimore Canyon igneous province, such as those of Hawaii (Kay and Gast, 1973; Clague and Frey, 1982), are associated with mantle plumes. We thus suggest as one possible interpretation that the large amount of trace element enrichment of the mantle associated with the Georges Bank-Baltimore Canyon igneous province is associated with mantle plume activity. If the high-pressure pyroxenes are a consequence of this enrichment process, then the latest stages of plume activity must be of a similar age to that of the volcanism. However, an alternative to the above explanation is that the differences in the characteristics of the mantle sources (P- and N-type MORB mantle) are the result of the different geologic histories of these igneous provinces. A brief examination of the geologic map shows that the N-type MORB province is located in the area generally considered to be underlain by the Avalon microcontinent (Schenk, 1978). In contrast, the P-type MORB province is underlain by the Piedmont Zone of the Appalachian Mountain belt, represented by an assemblage of island arcs and Paleozoic subduction zones welded together during the Caledonian and the Acadian Orogeny (Ordovician and Devonian, Osberg 1978; Hatcher, 1978).

Discussion

The study of Mesozoic igneous rocks on the eastern North American continental shelf shows a widespread and almost synchronous phase of middle Early Cretaceous volcanism extending from the Baltimore Canyon Trough to the Grand Banks and continuing northward onto the Labrador Shelf. This activity was represented by sub-volcanic intrusions and lavas with pyroclastics intercalated within marine or littoral sediments. This widespread volcanic event correlates with or just slightly predates the formation of the major Avalon Unconformity on the Grand Banks.

Whole rock geochemical analysis of these rocks (Jansa and Pe-Piper, 1985; Pe-Piper and Jansa, submitted (b)) shows that all fall in the alkali field in a P_2O_5 versus TiO_2 plot (Fig. 9) and within the "Within-Plate Basalt" field of Floyd and Winchester (1975) (Fig. 14).

Geochemical data point to derivation from two different mantles (Pe-Piper and Jansa, submitted (b)). The igneous rocks on the Grand Banks as well as the Scotian Shelf are derived from unenriched upper mantle in contrast to igneous rock located on the Georges Bank and Baltimore Canyon Trough which are associated with an enriched, plume-type mantle.

The timing of the igneous activity, which approximately spanned 40 m.y. from about 135 to 95 m.y., concentration of the igneous occurrences along the outer edges of the continental margins and the within-plate geochemical signature of the igneous rocks, all suggest that the igneous activity is mainly related to the formation and reactivation of fractures and/or fracture zones as a result of changes in crustal stresses at continental plates boundaries. Indeed the reflection seismic data show the presence of fractures near some of the igneous occurrences, such as near the Brant P-87 and Emerillon C-56 wells. The exceptionally broad co-occurrence of igneous activity extending for more than 25° of latitude and concentrated in that part of the continental crust which was thinned as a result of plate tectonic processes indicates that these two processes are interrelated. Some of the plate tectonic events which may be responsible for generation and/or changes in the crustal stress field are initiation of rifting in the Labrador Sea (about 140 m.y.) and final separation of the North American and European continental plates between the Grand Banks and Iberia. The latter separation is dated by development of a post-rift unconformity in the Late Aptian (approximately 115 m.y.) off the Galicia Bank (Boillot et al., 1986) and on the Grand Banks where it correlates with the Avalon Unconformity. Reflection seismic profiles from the Grand Banks shelf and from the deep continental margin off the Grand Banks and Iberia (Amoco and Imperial, 1973; Parson et al., 1985; Montadert et al., 1979) show that there was a sharp curtailment of faulting and block tilting from the period which preceeded the post-rift unconformity to a widespread, gentle margin subsidence, probably primarily due to aoling, after this event. This means that separation of the continental plates led to the release of stresses at the continental margins.

The dipmeter data available in only three offshore wells suggests that the Early Cretaceous dykes are oriented NNW and NW and the late Middle Jurassic dykes (Exxon 133-1 well) are oriented NE-SW. This orientation of the Early Cretaceous dykes on the continental shelf is broadly similar to the orientation of dykes in northern New England (McHone, 1981). The orientation also corresponds fairly well to the orientation of the recent minimum stress component in eastern Canada (Hasegawa et al., 1985; Podrouzek and Bell, 1985) which the former authors explained to be generated by the spreading at the mid-Atlantic Ridge.

The cause of the late Middle Jurassic volcanism on the Georges Bank may have been of a different origin. Both spatially and temporally, the Georges Bank volcanics lie along a linear trend which on the northwestern end is represented by the Early Jurassic igneous phase of the White Mountain volcanism, dated from 200 to 156 m.y. (Foland and Faul, 1977; see also Table 1), and with the late Cretaceous volcanism of the New England Seamount chain on the southeast. This lineament is nearly 2000 km long and about 100-200 km wide. Duncan (1984) demonstrated a systematic decrease in age of the New England Seamounts to the southeast, with the most northwestern seamount, Bear Seamount, yielding dates of 83.7 to 103.4 m.y. Vogt and Tucholke (1979) estimated the age of the Bear Seamount as approximately 120 m.y. on the basis of known absolute age dates and seafloor spreading rate. This time progression of the age of the seamounts has been widely used as an argument for the hotspot origin of the chain as discussed by Crough (1981), Vogt and Tucholke (1979) and Duncan (1984). Multichannel reflection seismic data from the continental slope off the Georges Bank confirms a middle Cretaceous age for Bear Seamount (Wade, submitted) as predicted from the age-distance graph for the seamounts by Vogt and Tucholke (1979). However, seismic profiles also show several volcanic cones of early Late Jurassic age near the Bear Seamount. These can be seismically correlated to the extrusives encountered in the Exxon Lydonia Canyon Block 133-1 well. The co-occurrence of two distinct igneous events in the same region is difficult to reconcile with the hotspot hypothesis, even though the geochemical data here presented can be interpreted to be pointing to the existence of a plume-enriched mantle beneath the Georges Bank and Baltimore Canyon Trough. Further, the time progression of the termination of the volcanic activity along the New England Seamount chain is reasonably well established by new radiometric age analysis (Duncan, 1984) and any theory of the origin must explain this trend. Neither the hotspot theory (Crough, 1981) nor the intra-plate fracture zone activated by plate movement (Foland and Faul, 1977) alone can be fully reconciled with the new data and the apparent multiple ages of volcanism near the Bear Seamount. We suggest that a mantle plume located under New England led to the development of a shear failure in the crust. Such an established "zone of weakness" could have been a starting point for the development of a propagated deep seated fracture which would penetrate deep into the upper mantle. The trace of this inferred crustal tear could be represented by the New England Seamount lineament. A unique occurrence of high pressure pyroxenes in the basalts from the New England Seamounts (Pe-Piper and Jansa, submitted (a)) could be additional evidence in support of a rapid transport of magma from the mantle to the plate surface, which can be accomplished most easily by magma rapidly changing composition along a fracture zone.

The theory that the New England Seamount chain is related to a propagating fracture can be also argued on the basis of the absolute age determinations for the seamounts and the known plate tectonic processes in the northern North Atlantic. We do not consider the similarity in observed ages for the igneous activity on the eastern North American margin and those from New England Seamounts to be coincidental. The dated rocks from the New England Seamounts, which are grab samples and drilled vesicular breccias mantling the volcanic cones, represent the time of cessation of igneous activity rather than its beginning. Because of the high alteration of the samples, the dates provide an upper limit for the ages. The oldest age of igneous activity is 103 m.y. for the westernmost located Bear Seamount where the seismic evidence indicates that the igneous activity was initiated during the late Lower Cretaceous. The youngest dated volcanicity is 81.9 m.y. from the Nashville Seamount (Duncan, 1984). Thus the general time span of the volcanicity is similar to that observed on the continental shelf.

There are no absolute age dates available for the Corner Rise Seamounts which lie about 800 km to the east off the Nashville Seamount. But since these seamounts do not lie on the New England Seamounts trend, it is possible that these two features are not related. Thus we consider the Nashville Seamount (Fig. 1) to represent the effective termination of the New England Seamount chain. The absolute age of 81.9 m.y. is the youngest for this seamount, but considering the inprecision associated with the dating of sea water altered basalts, the obtained date is minimal and the true age might be older. What was the significant plate tectonic event in the northern North Atlantic about 80-90 m.y. ago? According to Srivastava and Tapscott (in press), the separation of the continental plates and the initiation of the continental drift between Labrador and Greenland was initiated at anomaly 34, which is variably dated at 83-92 m.y. (LaBrecque _et al._, 1977; Harland _et al._, 1982). Thus we suggest that, as the North American and Greenland continental plates separated, the plate tectonic stress field substantially changed. At this time not only did volcanic activity on the central eastern North American margin ceased, with a new focal point concentrated in the Davis Strait area (Clarke, 1977), the volcanic activity along the propagating fracture zone represented by the New England Seamount chain ceased concurrently.

The occurrence of pumice, welded tuffs, crystal fragments and highly vesicular glass fragments, as observed in the Brant P-87 well, suggests explosive volcanism and mixing of pyroclastics and hydroclastic particles. The presence of marine microfossils with the volcaniclastics suggests that deposition occurred in a shallow marine shelf environment. Similar conditions can be postulated for the late Jurassic igneous activity on the Georges Bank. Here the data discussed in this paper point to the existence of a volcanic cone, with several stages of cone building. Low relief and subaerial exposure of the postulated cone is suggested by the intercalated oxidized horizons and capping by shallow marine carbonate. The explosive nature of the volcanism is well established here, since deposits from an ash plume, which was generated in the Exxon 133-1 well area, were identified at the same stratigraphic level in the COST G-2 well (Amato and Simonis, 1980). The COST G-2 well is located 39 km due east of the Exxon 133-1 well. The presence of devitrified vesicular glass throughout 55 m of a limestone-shale sequence confirms that the period of eruptive volcanism was reasonably extensive and prolonged. If we use an average 8-10 cm/1000 yr sedimentation rate as established for the Jurassic of the Canadian continental margin for calculation of the length of the volcanicity, then the eruptions continued here intermittently for about 0.5 m.y.

The lack of volcaniclastic rocks in another well located 30 km northwest from the source of the ash plumes (COST G-1 well) suggests that during Callovian the Georges Bank area was under the influence of prevailing offshore winds, blowing to the east. It is also evidence that the volcaniclastic occurrences in the COST G-2 well are not a result of cone erosion and local sediment transport.

Summary

Late Jurassic and Early Cretaceous mafic dykes, sills, flows and locally associated pyroclastic rocks are present on the eastern North American shelf from Labrador to the Baltimore Canyon trough.

1. Compositionally, the igneous rocks are alkali basalts and diabases of "within plate" geochemical characteristics. The dyke swarm in the Baltimore Canyon trough consists of lamprophyric basanites, tephrites and very rare tephriphonolites.
2. Geochemically both the late Middle Jurassic and Cretaceous igneous rocks of the eastern North American margin are derived from 5-15% partial melting of a garnet lherzolite in the upper mantle. The rocks have experienced considerable olivine fractionation.
3. Two igneous provinces are distinguished. The Grand Banks-Scotian Shelf igneous province rocks were derived from N-type MORB mantle, whereas the Georges Bank-Baltimore Canyon-New England Seamount province were derived from P-type MORB mantle.
4. The differences in upper mantle geochemistry between these two igneous provinces could be the result of hotspot plume activity in the Georges Bank-Baltimore Canyon province or alternatively reflect different

geologic history of the mantle underneath these two provinces. The N-type MORB mantle seems to be associated with the Avalon microcontinent, and the P-type MORB mantle with the Piedmont Zone of the Appalachian Mountain belt.

5. Radiometric data indicate that the Cretaceous igneous activity continued for about 40 m.y. (95-135 m.y.), with most of the igneous activity concentrated close to 120 m.y.

6. The igneous occurrences seem to be located near inferred major fractures or fracture zones. Reactivation and formation of fractures and associated volcanism may have resulted from changes of the stress field as the Grand Banks-Iberian plate separated about 115 m.y. ago, and as the rifting process was initiated between Labrador and Greenland during the early Cretaceous.

7. The late Middle Jurassic (Callovian, ~ 140 m.y.) igneous activity is currently known only from the Georges Bank, where it led to the construction of several volcanic cones. Associated explosive volcanism continued for about 0.5 m.y. The regional distribution of the ash layers points to the existence of prevailing offshore winds blowing to the east at this time in this area.

8. Co-occurrence of mid-Jurassic buried volcanoes and mid-Cretaceous seamounts on the upper continental slope of the Georges Bank contradicts the simple explanation of the New England Seamount chain as the product of a hotspot. An upwelling mantle plume located under New England identified from the new geochemical data could have caused the development of shear failure surfaces penetrating into the upper mantle.

Such an established deep seated zone of weakness could have been the locus for development of a propagated fracture zone, which became the focus of igneous activity at the propagating tip of such a fracture. Any change in the direction of plate stresses may have reopened the pathway along this inferred fracture zone and allowed magma to reach the surface. The magmatic activity along this lineament ceased after the Labrador and Greenland continental plates separated about 90 m.y. ago.

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FIGURE CAPTIONS

Figure 1. Map showing volcanic and subvolcanic rocks of Mesozoic-Cenozoic age on the eastern continental margin of North America. On this figure we have indicated the ages of these occurrences as known either from absolute age dating (see Table 1 for detailed references) or as derived from stratigraphic position of the igneous rocks. During compilation of the figure we have noticed that igneous rocks of broadly similar ages are preferentially concentrated into elongated zones. We have drawn schematic boxes around these zones. From the ages of enclosed igneous rocks and tectonic affinity of the rocks we suggest a tectono-volcanic origin for each of those boxed areas, however, this assignment needs to be tested geochemically.

Figure 2. Map showing location of major Mesozoic sedimentary basins (shown by dotted pattern) and basement highs separating the basins on the eastern North American continental margin (arter Jansa and Wiedmann, 1982).

Figure 3. Stratigraphic diagram of marginal basins.

Figure 4. Lithologic profiles of studied oil exploratory wells which show the stratigraphic position of igneous and/or volcanic rocks. Gamma ray and sonic logs are plotted on the sides of a litholog. The insert shows location of the wells.

Figure 5. Multichannel reflection seismic profile across the Brant well, Grand Banks, Newfoundland. Notice strong horizontal reflectors

produced by the basalt flows. The seismic character changes at the Avalon Unconformity from weak, discontinuous, faulted reflectors to parallel, continuous reflectors above the unconformity. (Amoco Group Line No. 30252)

Figure 6. Multichannel reflection seismic profile across the Exxon Block 113-1 well, Georges Bank. The remnant of a volcano apron is shown by dotted pattern. The inclined short reflectors underneath the cone are diffractions probably of faults resulting from feeder dykes emplacement. Notice that the Bathonian reflector which underlies the volcano is not interrupted and is undeformed. (Exxon Exploration Line No. EK 789)

Figure 7. Multichannel reflection seismic profile across "Great Stone Dome", Baltimore Canyon Trough. Note the domal uplift and erosion surface at 2 sec. Also notice that some of the reflectors can be followed from the flanks of the dome through the dome. The dome is the result of an emplacement of a dyke swarm. (Exxon Exploration Line No. NJ 7718)

Figure 8. Plot of total alkalis against silica for whole rock samples used in this study, to illustrate alkali nature of the rocks, and their nomenclature after Zanettin (1984). Alkali - tholeiitic divide from MacDonald and Katsura (1964.

Figure 9. Plot of P_2O_5 against TiO_2 (after Ridley <u>et al</u>., 1974) showing alkaline character of the rocks studied. AB - alkaline basalt, OIT - ocean island tholeiite, MORB - Mid Atlantic Ridge basalts.

Figure 10. Plot of total alkalis against potash to total alkali ratio (after

Hughes, 1972) for whole rock samples used in this study, showing those samples that fall within the "igneous spectrum".

Figure 11. Plot of Cao/Al_2O_3 against FeO_t/FeO_t+MgO for rock samples used in this study (Table 3). Rocks with CaO/Al_2O_3 between 0.54 and 0.66 (dashed lines) have experienced little plagioclase or clinopyroxene fractionation. Increasing FeO_t/FeO_t+MgO reflects increasing olivine fractionation.

Figure 12. Selected trace element abundances relative to MORB, for samples from the Newfoundland Seamounts (data from Sullivan, 1978), Grand Banks and Scotian Shelf. Elements plotted in order of increasing incompatibility. (MORB values and order of elements after Pearce, 1982).

Figure 13. Selected trace element abundances relative to MORB, for samples from Georges Bank, Baltimore Canyon, New England Seamounts (data in part from Houghton, 1979) and Champlain dikes. Elements plotted in order of increasing incompatibility. (MORB values and order of elements after Pearce, 1982).

Figure 14. Plots of TiO_2 against Zr (after Pearce, 1982) and Zr/Y against Zr (after Floyd and Winchester, 1975) for whole rock samples used in this study showing the general "within plate basalt" character.

Figure 15. Plot of Ti/Y against Nb/Y (after Pearce, 1982) for representative rock samples that fall within the "igneous spectrum".

Figure 16. REE spectra for Grand Banks, Georges Bank and Baltimore Canyon igneous rocks, together with selected analyses from the Scotian Shelf (Jansa and Pe-Piper, 1985), Newfoundland Seamounts

(Sullivan, 1978), and New England Seamounts (Houghton, 1979) and new data. Abbreviations for southeastern Canadian shelf: B = Brant, E = Emerillon, Hc = Hercules, He = Hesper, T = Twillick.

Figure 17. Clinopyroxene compositions plotted on a Diopside - Hedenbergite + Acmite - Ca Tschermaks molecule ternary diagram. All available analyses from the Newfoundland Seamounts (Sullivan, 1978) and Baltimore Canyon are plotted. Fields for New England Seamount samples from Pe-Piper and Jansa (submitted (a)): 1- Al-Ti augite, Site 382; 2- Fe-salite, Site 382; 3- titanaugite rims, Site 382; 4- Fe-Ti augite, Site 385. Fields are also shown for clinopyroxenes from the Grand Banks and Scotian Shelf wells. (B = Brant, E = Emerillon, SS = Scotian Shelf, T = Twillick)

Figure 18. Discrimination diagram for clinopyroxene electron microprobe analyses from Leterrier _et al_. (1982). Analyses for Scotian Shelf after Jansa and Pe-Piper (1985); for Newfoundland Seamounts after Sullivan (1978); for the New England Seamounts after Pe-Piper and Jansa (submitted (a)): 1-4 are as in Figure 11.

Figure 19. Plot of Al^{iv} against Al^{vi} for pyroxenes from basalts, determined by electron microprobe. All available analyses for Newfoundland Seamounts (Sullivan, 1978) and Baltimore Canyon are plotted. Fields of analyses are shown by solid lines for the Grand Banks wells and all wells on the Scotian Shelf. Fields for New England Seamounts shown by dashed lines from Pe-Piper and Jansa (submitted (a)). Dashed lines from Wass (1979) proposed limits of high-pressure pyroxenes.

TABLES

APPENDIX 1. Samples which meet the criterion of the igneous spectrum of Hughes (1972).

New England Seamounts				
(Houghton, 1979)				
382-23-1, 98-102	A	type 2		
382-23-3, 113-116	C			
382-24-2, 63-67	F			
382-25-1, 129-131	G			
382-25-2, 91-95	H	type 4		
382-25-2, 125-130	J	type 5		
(Pe-Piper and Jansa, 1986)				
382-25-2, 105-107g				
382-25-2, 107-109g				
*382-25-2, 107-109			REE	
382-25-2, 105-107			REE	
*385-23-1, 97-99				
*385-23-1, 148-150			REE	
Newfoundland Seamounts				
(Sullivan, 1978)				
Scruncheon 25/19	3			TE
Dipper 30/1	9		(REE)	TE
Dipper 30/2	10			TE
Dipper 30/5	11			TE
Dipper 30/11	12		(REE)	TE
Dipper 31/2	13			TE
Dipper 31/4	14			TE
Dipper 31/5	15			TE
Dipper 31/6	16		(REE)	TE
Dipper 31/14	17			TE
Dipper 31/17	18			TE
Dipper 31/21	19			TE
Dipper 31/25	20		(REE)	TE
Brant				
P-87 11710-11720				
P-87 11700-11710				
P-87 11640-11650				
P-87 11630-11640			REE	
P-87 11620-11630				TE
P-87 11610-11620				TE
P-87 11510-11520				
P-87 11480-11490				
P-87 11470-11480			REE	
P-87 9370			REE	

Twillick			
G-49 4270		core REE	TE
G-49 4260-4270			TE
G-49 4250-4260			
G-49 4240-4250			TE
G-49 4230-4240		REE	
Emerillon			
C-56 9840		REE	
C-56 9810			
C-56 9780		REE	
Georges Bank			
Exxon 133-1		core REE	TE
Exxon 133-1 13500-13530			TE
Exxon 133-1 13470-13500			
Exxon 133-1 13440-13470		REE	
Baltimore Canyon			
Mobil 544-1 10630-10650		REE	
Mobil 544-1 10478		REE	TE
*Mobil 544-1 13430-13450		REE	
Mobil 544-1 10350-10370			
*Mobil 544-1 10070-10090			
*Mobil 544-1 9770-9790			
Mobil 544-1 9550-9570		REE	
Champlain dikes (McHone and Corneille, 1980)			
MM-1	2		TE
MT-1	3		TE
BU-4	5		TE
BU-8	6		TE
BU-15	7		TE
PL-2	8		TE

*indicates new analysis that is used although it does not fall within the igneous spectrum

TABLE 1 (continued)

Location	Rock type	Age	Reference
Monteregian Hills	Granites and syenites in stocks and White Mountain Batholith	200-156 Ma	7
	Subvolcanic intrusions (a) carbonatite, foyaite etc., (b) gabbro, diorite, etc., (c) nordmarkite granite, etc.	(a)117-120 Ma (b)129-141 Ma	5,6
LABRADOR SHELF	Basalt flows and tuffs	90-145 Ma	18
DAVIES STRAIT REGION	basalts lamprophyres	51.4-59.4 Ma 30.6-39.5 Ma	21
	olivine rich plateau basalts, lamprophyres, minor trachytes, alkalic volcanics	119-105, 93.4±4.7 Ma 56±3 Ma	22, 23
SVERDRUP BASIN	bimodal suite of intrusives and volcanics consisting of gabbro, granitic and hybrid rocks; subalkaline basalts, flows, dykes and sills	152±6 Ma 131±6 Ma 123±6 Ma 100-102 Ma	24
	quartz diorite	92.0±1.0 Ma	25

Age: Ages with error limits are single radiometric dates; age ranges are based on multiple radiometric dates (but may exclude extreme dates); stage names indicate ages of interbedded sediment.

References: 1 - Amoco Canada and Imperial Oil Ltd., 1974; 2 - Jansa and Pe-Piper, 1985; 3 - Sullivan and Keen, 1977; 4 - Sullivan, 1978; 5 - Gold, 1967; 6 - Eby, 1984; 7 - Foland and Faul 1977; 8 - Creasy and Eby, 1983; 9 - McHone and Corneille, 1980; 10 - McHone and Butler, 1984; 1 - Houghton et al., 1979; 12 - Vogt and Tucholke, 1979; 13 - Wanless et al., 1967; 14 - Mobil 544-1A well, Baltimore Canyon Data File, U.S. Minerals Management Service; 15 - Exxon 500-1, Baltimore Canyon, data provided by Exxon Oil Company Houston (1985); 16 - Exxon 133-1, Lydonia Canyon, Georges Bank, data provided by Exxon Oil Company, Houston (1985); 17 - Duncan, 1984; 18 - Umpleby, 1979; 19 - Jansa and Pe-Piper, 1986; 20 - Wanless et al., 1965; 21 - Parrott and Reynolds, 1975; 22 - Klose et al., 1982; 23 - Johnson et al., 1982; 24 - Balkwill and Fox, 1982 25 - Trettin and Parrish, in press; 26 - Wanless et al., 1979.

Table 2. K-Ar Chronology analytical data*

Location	Age	Av % K	K^{40} ppm	Ar^{40} ppm
GRAND BANKS				
Brant P-87				
3535.7m (lower igneous unit)	135±6 Ma	1.010	1.232	.01005
Emerillon G-56				
2990m	96.4±3.8 Ma	3.055	3.727	.02156
GEORGES BANK				
Exxon Block 133-1				
4105.6m	140±6 Ma	1.941	1.941	.01637
4111.4m	137±6 Ma	1.663	2.028	.01682
4111.7m	134±6 Ma	1.680	2.050	.01660
BALTIMORE CANYON TROUGH				
Exxon Block 500-1				
3621-3630m	127±5 Ma	3.520	4.294	.03308
3630-3639m	118±5 Ma	3.876	4.729	.03370

* Analysis by Krueger Geochron Laboratories, Cambridge, Massachusetts, U.S.A.

TABLE 3 (continued)

	Twillick G-49					Emerillon C-56			Georges Bank (Exxon 133-1)			
	1301.4 m (core)	1298.4–1301.4 m	1295.4–1298.4 m	1292.3–1295.4 m	1289.3–1292.3 m	2999–3002 m	2990–2993 m	2981–2984 m	4111–4112 m	4115–4124 m	4105.6–4115 m	4096.5–4105.6 m
SiO_2	54.25	51.76	53.47	50.69	49.03	53.31	53.67	52.85	47.02	47.55	47.37	47.45
TiO_2	2.82	2.90	2.72	3.31	3.94	2.80	2.71	2.64	3.97	4.30	3.97	4.41
Al_2O_3	15.68	16.04	16.30	15.62	16.38	17.94	18.19	17.82	14.16	14.39	14.42	14.46
FeO_t	10.33	11.18	9.95	11.60	12.16	7.00	6.66	8.15	10.22	9.72	10.21	9.69
MnO	0.11	0.17	0.18	0.14	0.12	0.05	0.05	0.02	–	0.01	0.03	0.04
MgO	3.66	4.41	3.97	4.58	4.52	4.66	1.23	2.87	8.70	9.30	8.34	8.19
CaO	5.93	5.86	5.85	6.47	7.05	5.26	9.30	6.21	7.85	8.35	8.10	8.24
Na_2O	4.53	4.20	4.24	3.87	3.33	5.81	4.58	5.08	4.89	4.28	4.76	4.46
K_2O	2.35	2.24	1.94	1.96	2.14	2.60	3.43	3.71	1.71	1.67	1.59	1.72
P_2O_5	0.37	0.59	0.54	0.47	0.64	0.69	0.48	0.65	1.50	1.45	1.22	1.34
Total	100.03	99.35	99.16	98.71	99.31	100.12	100.30	100.00	100.02	100.02	100.01	100.00

TABLE 3: Chemical analyses of the Grand Banks, Georges Bank and Baltimore Canyon mafic rocks

	Brant P-87									
	3569–3572 m	3566–3569 m	3547.8–3551 m	3544.8–3551 m	3541.7–3544.8 m	3538.7–3541.7 m	3508–3511 m	3499–3502 m	3496–3499 m	2856–2859 m
SiO_2	47.16	47.29	47.45	47.37	47.58	47.60	48.05	48.26	47.92	50.38
TiO_2	4.46	4.49	4.43	4.35	4.21	4.12	3.95	4.28	4.08	2.68
Al_2O_3	14.99	14.70	14.81	14.62	14.50	14.53	14.71	14.91	14.86	17.36
FeO_t	12.05	12.62	12.81	13.34	13.30	13.26	12.80	12.62	12.71	11.88
MnO	0.27	0.18	0.18	0.22	0.21	0.21	0.27	0.19	0.22	0.01
MgO	4.72	5.10	5.10	5.17	5.12	4.93	4.69	4.52	4.35	6.27
CaO	9.78	9.50	9.38	9.40	9.22	9.30	9.34	9.42	9.34	6.99
Na_2O	3.77	3.69	3.72	3.61	3.52	3.52	3.65	3.66	3.74	3.62
K_2O	1.18	1.11	1.11	1.08	1.11	1.08	1.11	1.13	1.17	0.76
P_2O_5	0.77	0.77	0.81	0.84	0.78	0.70	0.86	0.92	0.97	0.03
Total	99.15	99.45	99.80	100.00	99.55	99.25	99.43	99.91	99.36	99.98

TABLE 3 (continued)

	Baltimore Canyon Trough (Mobil 544-1)						
	3240–3246 m	3193.7 m	4093.4–4099.5 m	3154.7–3160.7 m	3069–3075.4 m	2978–2984 m	2911–2917 m
SiO_2	46.45	48.21	53.47	46.32	46.60	45.88	49.21
TiO_2	3.06	2.99	1.64	3.20	2.99	3.33	2.95
Al_2O_3	16.14	17.13	19.00	16.64	16.88	15.11	15.69
FeO_t	11.98	10.10	7.45	11.60	11.26	12.41	11.26
MnO	0.18	0.10	–	0.20	0.20	0.13	0.24
MgO	4.88	3.35	1.42	4.41	4.31	5.27	4.74
CaO	9.43	8.86	6.92	9.71	9.88	10.23	8.72
Na_2O	3.54	3.32	6.38	3.89	5.42	1.77	2.99
K_2O	3.43	4.78	3.35	2.87	1.29	5.22	3.68
P_2O_5	0.84	1.16	0.31	1.08	1.11	0.57	0.43
Total	99.93	100.00	99.94	99.92	99.94	99.92	99.91

TABLE 4: Rare-earth-element concentrations (ppm)

Sample No.	La	Ce	Nd	Sm	Eu	Tb	Yb	Lu
Brant P-87								
3544.8-355 m	32.40	75.90	44.14	8.95	3.14	1.33	2.78	0.36
3496-3499 m	37.79	90.20	51.25	10.90	1.01	1.50	2.62	0.45
2856-2859 m	19.90	36.00	20.20	4.89	1.65	0.80	1.71	0.26
Twillick G-49								
1301.4 m (Core)	36.42	83.30	41.68	6.99	2.70	1.11	2.33	0.35
1289.3-1292.3 m	38.08	90.80	48.10	9.63	3.38	1.41	3.28	0.48
Emerillon C-56								
2999-3002 m	17.43	38.51	24.30	6.59	2.08	0.98	2.36	0.58
2981-2984 m	66.55	107.2	60.50	10.50	3.38	1.13	2.67	0.41
Exxon 133-1								
4111-4112 m	53.36	121.9	71.17	12.14	4.59	1.44	2.59	0.40
4096.5-4105.6 m	71.20	139.0	84.20	17.00	4.94	1.96	3.23	0.43
Mobil 544-1								
4093.4-4099.5 m	66.70	127.0	79.30	15.70	4.78	1.82	3.03	0.39
3240-3246 m	71.03	150.9	67.22	10.31	3.16	1.21	2.38	0.40
3193.7 m (Core)	102.2	200.5	100.8	15.13	4.17	1.58	3.63	0.48
2911-2917 m	61.24	110.8	53.51	9.18	2.51	0.98	2.24	0.40
New England Seamounts								
382-25-2 (107-109cm)	59.60	101.0	48.20	9.33	2.75	1.15	2.13	0.36
382-25-2 (105-107cm)	56.50	91.40	44.60	8.77	2.61	1.04	2.07	0.31
385-25-2 (148-150cm)	57.70	111.0	53.30	10.30	3.05	1.06	2.04	0.28

LE 5: Trace element concentrations (ppm) in representative samples

ll	Brant P-87		Twillick G-49			Exxon 133-1		Mobil 544-1	New England Seamounts
pth	3541.7-3544.7 m	3538.7-3541.7 m	1301.4 m	1298.4-1301.4 m	1292.3-1295.4 m	4111-4112 m	4115-4124 m	3193.7 m	385-23-1 (97-99cm)
Ba	380	389	529	498	416	653	686	2174	309
Rb	17	17	53	47	35	16	18	97	48
Sr	619	626	608	542	525	1240	1316	1880	434
Y	37	36	33	33	38	50	50	46	27
Zr	258	258	256	269	290	618	632	461	346
Nb	45	45	41	41	45	81	80	127	74
Th	2	4	6	4	-	-	-	2	2
Pb	21	13	10	9	7	-	4	15	4
Ga	27	26	24	21	25	24	29	27	17
Zn	264	173	116	119	127	117	129	147	105
Cu	38	38	17	20	18	67	60	31	29
Ni	26	25	15	12	15	188	175	12	34
V	325	319	239	266	299	161	158	375	184
Cr	16	16	30	14	17	232	233	-	26

	CHLORITES		BIOTITES			ZEOLITES
Well	Twillick G-49		Emerillon C-56		Mobil 544-1	Emerillon C-56
Depth	(1289.3-1292.3 m)	(1292.3-1295.4 m)	(2990-2993 m)	(2990-2993 m)	(3193.7 m)	(2990-2993 m)
SiO_2	28.23	26.99	31.09	35.30	36.54	49.72
TiO_2	-	-	0.03	5.68	5.10	-
Al_2O_3	16.66	17.80	13.48	11.43	14.84	23.56
FeO_t	31.55	33.11	30.12	18.28	18.08	-
MnO	0.18	0.29	0.25	0.17	0.30	-
MgO	11.45	10.50	13.82	11.80	12.50	-
CaO	0.11	0.11	0.13	-	0.15	0.75
Na_2O	-	-	0.07	0.58	-	13.40
K_2O	-	-	0.06	8.89	9.11	0.06
BaO	-	-	-	n.d.	1.14	-
Total	88.18	88.80	89.05	92.14	96.61	87.49
Number of Analysis	6	6	6	6	5	5

.E 7: Average electron microprobe analyses

	BR	TW	EM	SS	BC	NS
)$_2$	50.51 (0.99)	47.98 (0.83)	49.46 (1.66)	47.61 (0.97)	47.92 (1.29)	49.97 (1.39)
)$_2$	1.655 (0.36)	2.19 (0.44)	1.90 (0.70)	2.70 (0.68)	1.66 (0.38	1.20 (0.46)
O_3	2.35 (0.56)	4.73 (0.74)	3.65 (1.35)	4.03 (0.79)	6.67 (1.18)	4.31 (1.62)
)*	10.46 (0.78)	9.48 (0.82)	9.43 (0.51)	11.41 (0.83)	7.49 (0.49)	7.51 (1.77)
)	0.22 (0.06)	1.97 (0.05)	0.31 (0.06)	0.22 (0.07)	0.05 (0.07)	0.07 (0.08)
O	13.79 (0.38)	13.18 (0.55)	13.56 (0.91)	12.29 (0.40)	13.18 (0.84)	15.16 (1.02)
)	20.68 (0.28)	21.08 (0.34)	20.64 (0.42)	20.42 (0.28)	23.44 (0.15)	21.31 (0.94)
$_2$O	0.19 (0.10)	0.24 (0.09)	0.51 (0.12)	0.49 (0.10)	0.14 (0.13)	0.23 (0.21)

- Brant P-87 lower igeneous body; TW - Twillick G-49; EM - Emerillon C-56; SS - Scotian Shelf
.isa and Pe-Piper, 1985); BC - Baltimore Canyon; NS - Newfoundland Seamounts (Sullivan,
).

ndard deviations are given in parenthesis.

= total Fe recalculated as FeO.

the New England Seamounts there are several types of clinopyroxene present; analyses are
en in Pe-Piper and Jansa (submitted (a)).

PLATE 1

A. Fine-grained basalt showing subtrachytic texture, with plagioclase microlites (p) and augite (a) and Fe-Ti oxide grains. Brant A-87, 3775 m, plane polarized light. Scale bar 0.2 mm.

B. Hollocrystalline basalt showing subophitic texture with plagioclase (p), augite (a) and Fe-Ti oxides. Brant A-87, 2871 m, plane polarized light. Scale bar 0.2 mm.

C. Pyroclastic rock with glass shards (s), chloritized spherulites (c) and feldspar crystal fragments (f). Brant A-87, 3475m, plane polarized light. Scale bar 0.2 mm.

D. Hollocrystalline basalt composed of plagioclase laths (p), olivine (o) and Fe-Ti oxide crystals. Lydonia Canyon 133-1, 4087 m, plane polarized light. Scale bar 0.2 mm.

PLATE 2

A. Pyroclastic rock composed of vesicular lava fragments and various glass-rich fragments cemented by silica. Lydonia Canyon 133-1, 3923 m, plane polarized light. Scale bar 0.2 mm.

B. Vesicular lava with vesicules filled by spherulitic chlorite (v), altered glass (g) and plagioclase microlites (p), all set in a dark coloured Fe-Ti oxide matrix. Lydonia Canyon 133-1, 3831 m, plane polarized light. Scale bar 0.1 mm.

C. Hollocrystalline mafic rock showing hypidiomorphic granular texture with plagioclase (p), hornblende (h), Fe-Ti oxides, biotite (b) and pseudomorphs after olivine (o). Baltimore Canyon 544-1, 2978 m, plane polarized light. Scale bar 0.2 mm.

D. Trachyte with plagioclase (p), Fe-Ti oxides and scattered calcite (c) crystals. Baltimore Canyon 544-1, 5000 m, crossed Nicols. Scale bar 0.2 mm.

Plate 1

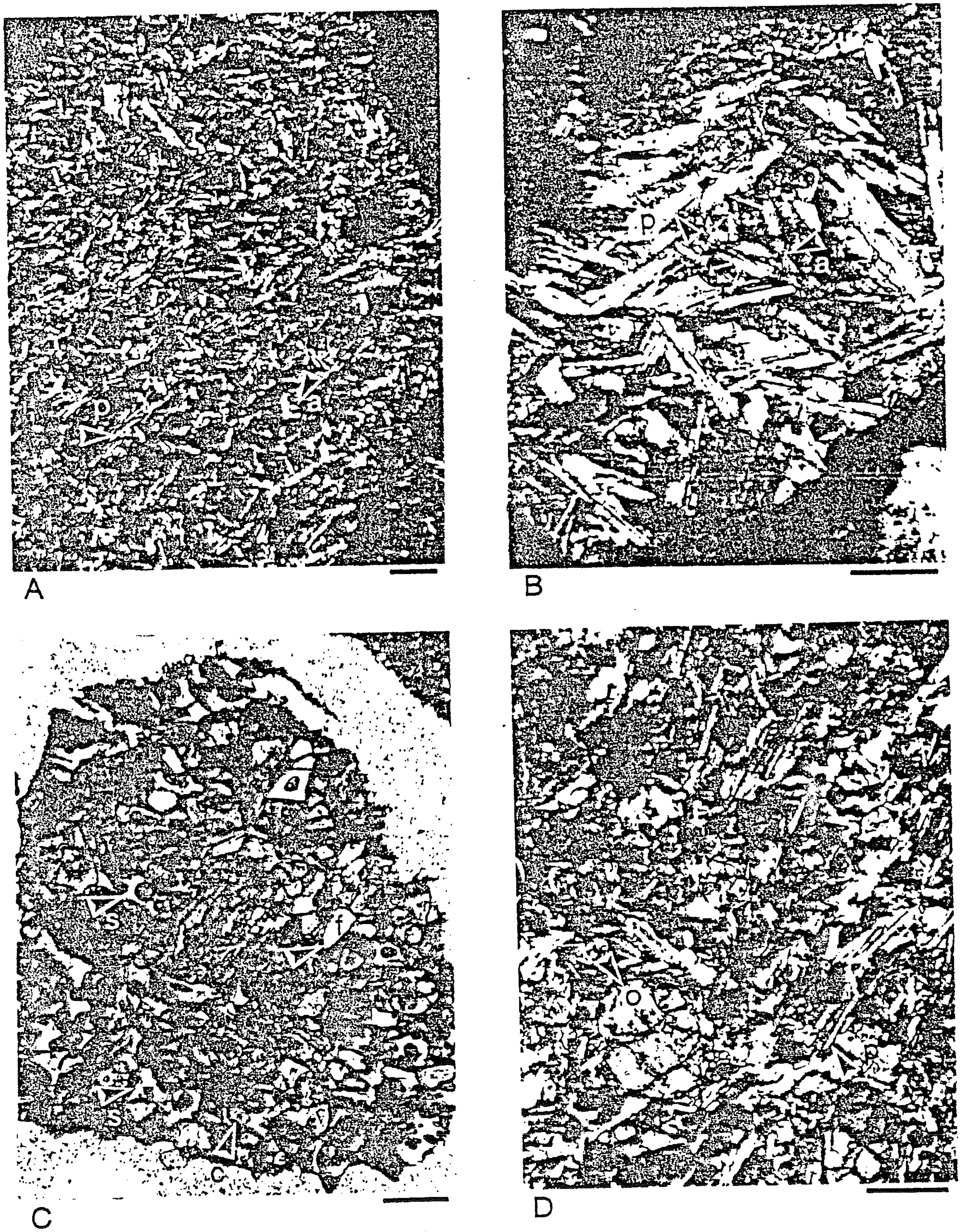

Plate 2