Early Devonian bimodal volcanic rocks of Southwestern New Brunswick: petrography, stratigraphy, and depositional setting

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The coastal volcanic belt of the northeastern United States and New Brunswick consists of a bimodal sequence of marine to subaerial Silurian and Early Devonian volcanic and associated sedimentary rocks. The Mascarene lithostratigraphic terrane of New Brunswick is probably the northern extension of this belt. This paper describes the volcanic stratigraphy, eruptive and depositional styles, paleogeography and tectonic setting of a 125 km^2 area of the Mascarene terrane located along the coast of Passamaquoddy Bay. The area mapped includes a ~ 3.5 km thick bimodal and subalkaline volcanic sequence of interbedded rhyolitic and basaltic flows and pyroclastic rocks and terrigeneous shale and sandstone. These rocks were intruded by the St. George Batholith and overlain unconformably by the Late Devonian Perry Formation. The area is divided into 53 lithologic units which are mappable at a scale of 1:10,000. Rhyolitic rocks are volumetrically most important.

Hawaiian, Strombolian, Plinian and Vulcanian eruptive systems are represented. The mafic units form flow, scoria cone, phreatomagmatic tuff cone, and peperitic breccia deposits. The felsic units were emplaced as welded and nonwelded air-fall, ash cloud, ground and base surge, and pyroclastic flow deposits, as well as lava flows and domes. There are three cycles of mafic/felsic volcanism. The shale, sandstone and mudstone units in the lower part of the section are littoral deposits. The uppermost sedimentary rock unit is a fluvial deposit. The volcaniclastic units primarily contain air-fall volcanic fragments within the littoral sediments. Reworked volcanic rocks are rare. All the sedimentary units contain well-preserved cuspate and scoriaceous basaltic and rhyolitic glass shards, indicating deposition in a low-energy environment with rapid sedimentation rates. Sedimentation was concomittant with volcanism and there were no marked periods of volcanic quiescence. Facies analysis and unit morphology indicate eruptions from multiple small volcanic centres. The basaltic flows, however, consistently flowed from the north and northeast to the south suggesting eruption from a single rift system. Several depositional settings were considered, but considering constraints based on (1) composition of the volcanic rocks, (2) nature of volcanic cycles, (3) thickness of the sequence and the subsidence history, (4) rates of sedimentation, (5) facies relationships, and (6) synvolcanic structures, the most likely setting is a volcanic plateau lacking large calderas located within a continental rift.

La ceinture volcanique côtière du Nouveau-Brunswick et du nord-ouest des Etats-Unis comprend une série bimodale de volcanites marines à subaériennes, d'âge silurien à éodévonien, et les roches sédimentaires qui leur sont associées. La Lanière lithostratigraphique de Mascarene représente probablement l'extension septentrionale de cette ceinture au Nouveau-Brunswick. Cet article décrit la stratigraphie volcanique, les styles éruptifs et de dépôt, la paléogéographie et l'environnement tectonique d'une région de 125 km^2 au sein de la Lanière de Mascarene, sise le long du littoral de la baie de Passamaquoddy. La région levée renferme une série volcanique bimodale et subalcaline d'environ 3.5 km d'épaisseur formé d'un interlitage d'épanchements rhyolitiques et basaltiques, de pyroclastites, shales et grès. Ces roches furent recoupées par le Batholite de St. George et recouvertes en discordance par la Formation de Perry (Dévonien tardif). On divise la région en 53 unités lithologiques qui sont cartographiques à une échelle de 1:10,000. Les roches rhyolitiques dominent en terme de volume.

Les systèmes éruptifs hawaïen, strombolien, plinien et vulcanien sont présents. Les unités mafiques comprennent des dépôts de coulée, de cône de scories, de cône de tufs phréatomagmatique et de brèche de pépérite. Les unités felsiques se sont mises en place sous forme de retombées aériennes (soudées ou non), de nuées cinéritiques, de déferlantes basales et de coulées pyroclastiques, avec aussi des coulées et des dômes laviques. On reconnaît trois cycles volcaniques mafiques à felsiques. Les

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unités de shale, grès et mudstone présentes dans la partie inférieure de la section sont des dépôts littoraux. L'unité sédimentaire sommittale est un dépôt fluvial. Les unités volcaniclastiques renferment surtout des retombées aériennes de fragments sur les sédiments littoraux. Les volcanites remaniées sont rares. Toutes les unités sédimentaires contiennent des éclats de verre rhyolitique et basaltique cuspidés et scoriacés bien préservés, témoins d'un dépôt en contexte de faible énergie et fort taux de sédimentation. La sédimentation était synchrone du volcanisme et il n'y a aucune période prononcée de quiescence volcanique. Une analyse des faciès et de la morphologie des unités indique des éruptions émanant de plusieurs centres d'émission volcaniques punctiformes. Par contre, les coulées basaltiques s'épanchèrent de façon consistente du nord et du nord-est vers le sud, ce qui suggère une éruption à partir d'un système de rift unique. On a envisagé plusieurs environnements de dépôt, cependant le plus probable est un plateau volcanique dépourvu de grandes caldeiras et situé au sein d'un rift continental, vu les contraintes imposées par (1) la composition des volcanites, (2) la nature des cycles volcaniques, (3) l'épaisseur de l'assise et l'histoire de la subsidence, (4) les taux de sédimentation, (5) les relations de faciès et (6) les structures synvolcaniques.

[Traduit par le journal]

INTRODUCTION

The coastal volcanic belt of the northeastern United States and New Brunswick comprises marine to subaerial Silurian and Early Devonian volcanic and sedimentary rocks. The Mascarene lithostratigraphic terrane of New Brunswick as defined by Fyffe and Fricker (1987) probably forms the northeastern extension of the coastal volcanic belt as it comprises similar rocks (McCutcheon and Ruitenberg, 1987) (Fig. 1). Early workers (Bird and Dewey, 1970; Dewey and Kidd, 1974; and Wilson, 1966) suggested that the coastal volcanic belt is an ancient volcanic arc related to the closing of Iapetus Ocean, but Gates and Moench (1981) studied the coastal volcanic belt in the Machias-Eastport area in Maine, documented a bimodal volcanic sequence, and suggested an extensional tectonic setting. The correct interpretation of the coastal volcanic belt has important implications for interpreting the nature of the Acadian orogeny. This paper describes the stratigraphy, eruptive and depositional styles, paleogeography and tectonic setting of part of the Mascarene terrane based upon detailed mapping and stratigraphic studies. This type of study is important because the physical volcanology of volcanic sequences is indicative of tectonic setting.

The study area comprises the eastern part of the coastal volcanic belt south of the St. George Batholith. This portion of the belt is exposed along the coast of Passamaquoddy Bay and covers an area of about 125 km^2 (Fig. 2). Rocks in the study area have been correlated with volcanic formations in Maine ranging in age from Wenlockian to Gedinnian (Cumming, 1967; Hay 1967; Ruitenberg, 1968; Pickerill and Pajari, 1976). Pickerill and Pajari (1976) correlated the rocks with the Early Devonian Eastport Formation of Maine, and proposed that the New Brunswick rocks also be termed Eastport Formation. However, a recent U-Pb (zircon) age of 431 Ma for the Utopia granite (Mary Lou Bevier, personal communication, 1988), a part of the St. George Batholith which intruded the eastern part of the study area, suggests that the volcanic rocks may be as old as Llandoverian.

Field work was conducted during the 1984, 1986, and 1987 field seasons. Mapping was done on air photographs at 1:10,000 scale. Stratigraphic sections were described on a bed by bed basis. The most detailed previous maps of the coastal section of the Mascarene terrane are by Hay (1967), Whaley (1981) and Van Wagoner and Fay (1988). Other investigations include Gesner (1839), Matthew (1865), Bailey and Matthew (1872, 1876), MacKenzie (1940), MacKenzie and Alcock (1960), Perry and Alcock (1960), Cumming (1967) and Ruitenberg (1968).

GENERAL GEOLOGY

The study area consists of a sequence of interbedded rhyolitic and basaltic flows and pyroclastic rocks and red and green-grey shale and sandstone. These units are intruded to the north by the St. George Batholith and overlain unconformably to the south by the Upper Devonian Perry Formation. The map area has been divided into 53 lithologic units (Fig. 3a) and the lithology and depositional style has been determined for each unit (Fig. 3b) (Van Wagoner and Fay, 1988; Van Wagoner *et al.*, 1987, 1988; Van Wagoner, 1984, 1986). The younging direction is to the south and west and the units dip to the south and west defining a broad fold. The finer sedimentary rocks exhibit a consistently east-trending cleavage. The volcanic rocks are bimodal (mafic/felsic) and subalkaline, and the basaltic rocks have a within-plate geochemical affinity (Van Wagoner *et al.*, 1988; Van Wagoner and McNeil, in preparation). The extrusive sequence is cut by basaltic sills and dykes and rare rhyolitic intrusions. Sills and dikes are not shown on the map and are part of a separate study.

PETROGRAPHY AND THE INTERPRETATION OF ERUPTIVE AND DEPOSITIONAL STYLES

The area is characterized by a variety of eruptive styles, from multiple vent areas. The terminology used to describe the pyroclastic rocks is after Fisher (1966) and Schmid (1981). The usage of the term 'peperitic breccia' is from Cas and Wright (1987). The terminology of Ingram (1954) is used to describe bedding thickness. Although the rocks are hydrothermally altered, primary volcanic structures and textures are well preserved and the combination of outcrop and thin section observations allows interpretation of eruptive and depositional style.

Basaltic Rocks

Basalt flows (units Demf1, 2, and 3 and Dwmf3): These units are petrographically similar throughout the map area and comprise variable amounts of interbedded highly to sparsely amygdaloidal flows and in some cases very shallow-level intrusions, peperitic breccias and rare lenses of mudstone and siltstone (Fig. 4). The units range in thickness from 70 to 460 m. All of

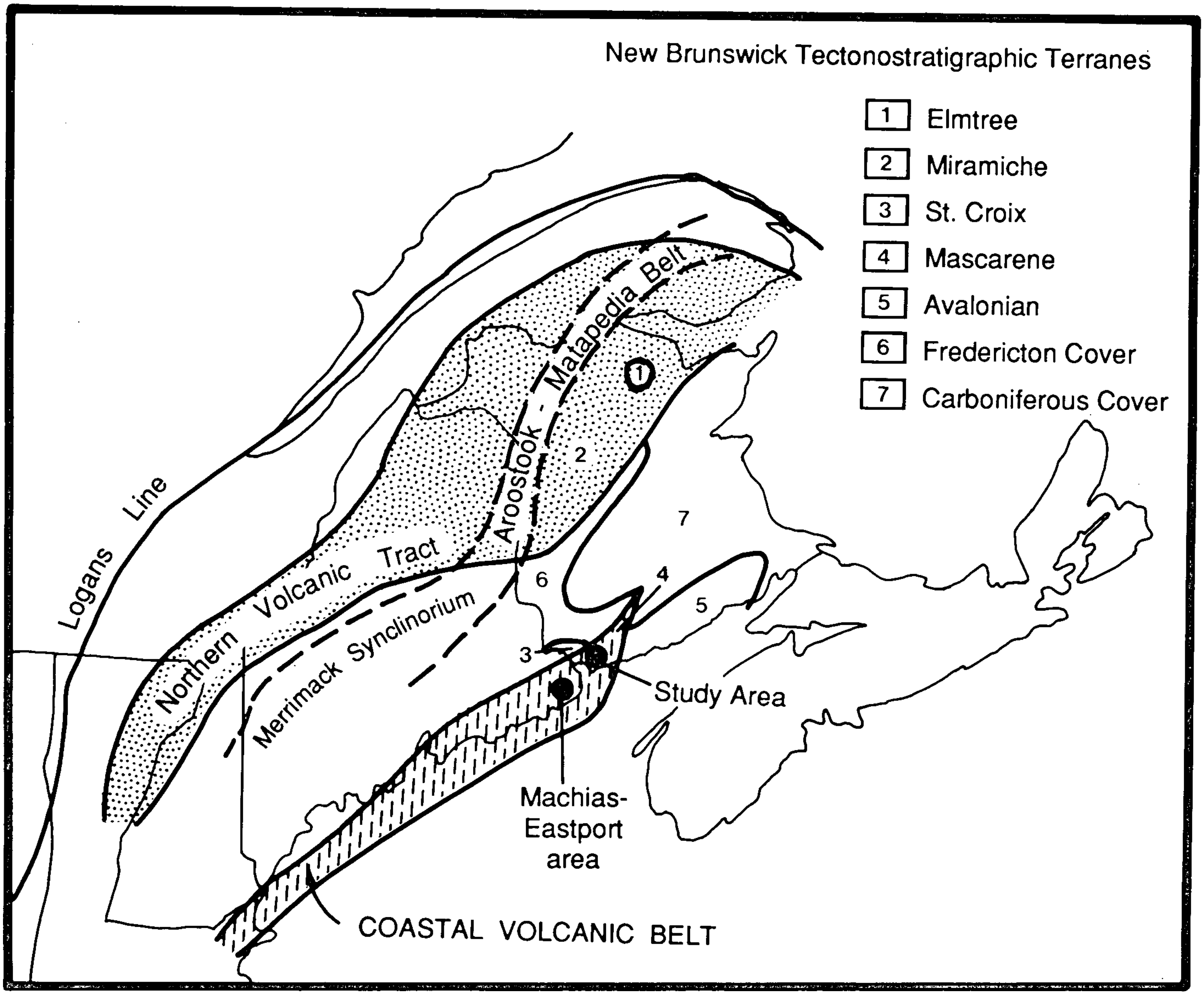


Fig. 1. Map of New England and the Maritime Provinces showing the location of the Silurian to Lower Devonian coastal volcanic belt (modified after Gates and Moench, 1981) and the tectonostratigraphic terranes of New Brunswick (from Fyffe and Fricker, 1987).

the basalt units thicken to the north or northeast (Figs. 3a, 5) and change laterally from being relatively massive in the north to comprising pahoehoe toes in the south. These characteristics indicate a northerly or northeastly source area, perhaps from the same or related rift systems.

The basalt flows are extensive sheet flows that range in thickness from 1-12 m. Where flow contacts are observed they are iron stained and have undulatory chill margins 2-3 cm thick. Groundmass is tachylitic and mostly altered to chlorite, quartz, epidote, and actinolite. Plagioclase microlites are commonly 50-60% of the flows, flow aligned, and altered to sericite, calcite and epidote. Other microlites are rare clinopyroxene (up to 0.1 mm and 20% of the microlites, and mostly altered to epidote and actinolite), and opaque minerals (up to 0.05 mm and 5% of microlites). Plagioclase phenocrysts are rare. Amygdules commonly form 5-15%, and are mostly 0.1-0.5 cm in diameter and rounded or elongate to irregular in shape. In unit Dwmf3 amygdules form up to 85%, and are up to 1.5 cm in size. Rare gas cavities up to 40 x 15 cm in size occur in units Dwmf3 and Demf2. The amygdules are filled with calcite, quartz, epidote, chlorite and rarely actinolite and pumpellyite.

The peperitic breccias are fluidized mixtures of quench-fragmented volcanic debris and sediment (Pichler, 1965; Honnorez and Kirst, 1975). The fragmentation occurs either when magma intrudes through (Pichler, 1965; Kokelaar, 1982) or when lava flows over (Waters, 1960; Schmincke, 1967) wet sediment. Because of the limited lateral control in this case, it is usually impossible to tell which happened. These breccia beds are 2-14 m thick and contain 30 to 90% mafic volcanic clasts in a very fine 'cherty' mudstone matrix (Fig. 4). Mafic clasts are the same as the flows described above, except that vesicles contain mudstone. Clasts are 2 mm-0.5 m in size, and pillow-like to angular in shape. Pillow-like fragments have delicate appendages of selvage that protrude into surrounding sediment, indicat-

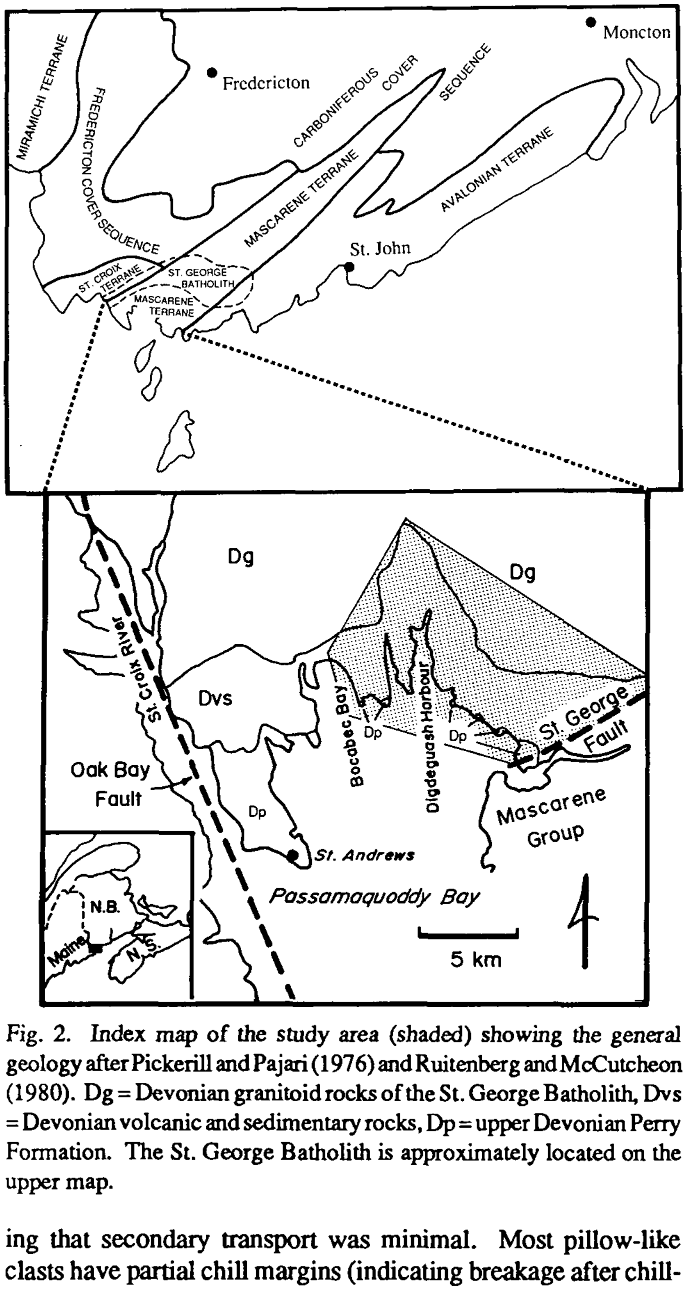


Fig. 2. Index map of the study area (shaded) showing the general geology after Pickerill and Pajari (1976) and Ruitenberg and McCutcheon (1980). Dg = Devonian granitoid rocks of the St. George Batholith, Dvs = Devonian volcanic and sedimentary rocks, Dp = upper Devonian Perry Formation. The St. George Batholith is approximately located on the upper map.

ing that secondary transport was minimal. Most pillow-like clasts have partial chill margins (indicating breakage after chilling), but rare clasts have complete chill margins. In some cases, the margins of clasts or entire clasts are broken in a jig-saw puzzle fashion indicating quench shattering. Breakage of clasts by thermal quenching rather than expansion of volatiles is also indicated by the lack of vesicle-controlled boundaries.

The matrix of the peperitic breccias is highly fluidized mudstone containing 15-50% silt- to fine sand-sized fragments in a clay matrix. Fragments include quartz, feldspar and mica, and rare altered mafic minerals, chert and basalt. The mudstone contains rare irregularly shaped vesicles. The quartz exhibits wavy extinction suggesting that it is derived from vein fillings in the mafic flows or surrounding rocks. Plagioclase occurs as tabular laths up to 0.1 mm in size. It probably originated from the associated mafic flows. The vesicles formed from vaporization of interstitial fluid heated upon contact with magma or lava. Fluidization of the sediment is indicated by soft-sediment deformation structures, best observed in the beds of sediment described below and by penetration of the mudstone into vesicles of the lava. Euhedral pyrite crystals are disseminated throughout the unit but concentrated in brecciated, peperitic and vesiculated zones.

Mudstone and siltstone layers interbedded with the peperitic breccias are 1-5 m thick. These sedimentary layers are compositionally the same as the matrix of the peperitic breccias. Beds are 1 mm-1 cm thick and massive, normally graded, internally finely laminated, or rarely cross-laminated. Soft-sediment deformation structures are common and caused by a combination of density inversion and interaction of sediment with lava or magma. The sediments may be mudflat deposits similar to unit Dws6.

A 1 m thick bed of plagioclase-arkosic mudstone to medium-grained sandstone occurs near the base of unit Demf2. Grain size ranges from 0.05-0.3 mm. The layer contains 74% rock and mineral fragments in a clay matrix. Rock and mineral fragments are 92% fresh plagioclase (0.1-0.5 mm), 3% subangular volcanic quartz (0.1-0.5 mm), 3% euhedral authigenic or secondary pyrite altered to hematite (1-3 mm), rare epidote and authigenic zircon, and 2% rock fragments of rounded to subrounded basalt, chert, and mudstone. The clay matrix is mostly altered to chlorite and sericite. Beds are 1-3 cm thick, discontinuous, and massive or graded. Coarser mineral fragments form 'pebble trains' at the base of coarser beds. Lithic fragments are concentrated at the base of coarser and thicker beds. Authigenic pyrite occurs at boundaries between coarser and finer beds. Load structures are common along bedding planes. Basaltic volcanic material is interpreted to be the source of this sediment along with dilution from other terrigenous sources contributing the quartz, chert and mudstone. Rapid deposition and burial were required to preserve the feldspar grains.

This sequence of peperitic breccias and fluidized sediments formed by the interaction of lava or magma with cold, wet sediment. Quench fragmentation occurred around the margin of the flows or shallow-level sills producing the peperitic breccias. Intrusion of magma or mixing of lava with sediment resulted in the soft-sediment deformation. The emplacement of mafic lava above unconsolidated, uncompacted, wet sediment could create a density instability allowing lava to move down into the underlying sediment.

These units are interpreted to be subaerial to littoral pahoehoe flows and peperitic breccias that originated from a rift in the northern or northeastern part of the map area. Such flows are characteristic of a Hawaiian style of volcanism. The interpretation of the flows is based on the morphology of flow margins and their intimate association with littoral sediments. Although pahoehoe flows form in deep water (e.g., Ballard *et al.*, 1979), the great vesicularity of these flows, and the lack of hyaloclastite, relict palagonite, or other subaqueous rock associations indicates that these are subaerial flows.

Mafic pyroclastic rocks: (units Dwms, Dwtb2, Dwtb3)

Unit Dwms: Unit Dwms is a mafic scoria. The unit is thickest in the vicinity of section B-B' and thins to the north and south (Figs. 3, 5). Maximum thickness is about 82 m. Basaltic fragments are ash- to bomb-sized (up to 1 m in long dimension),

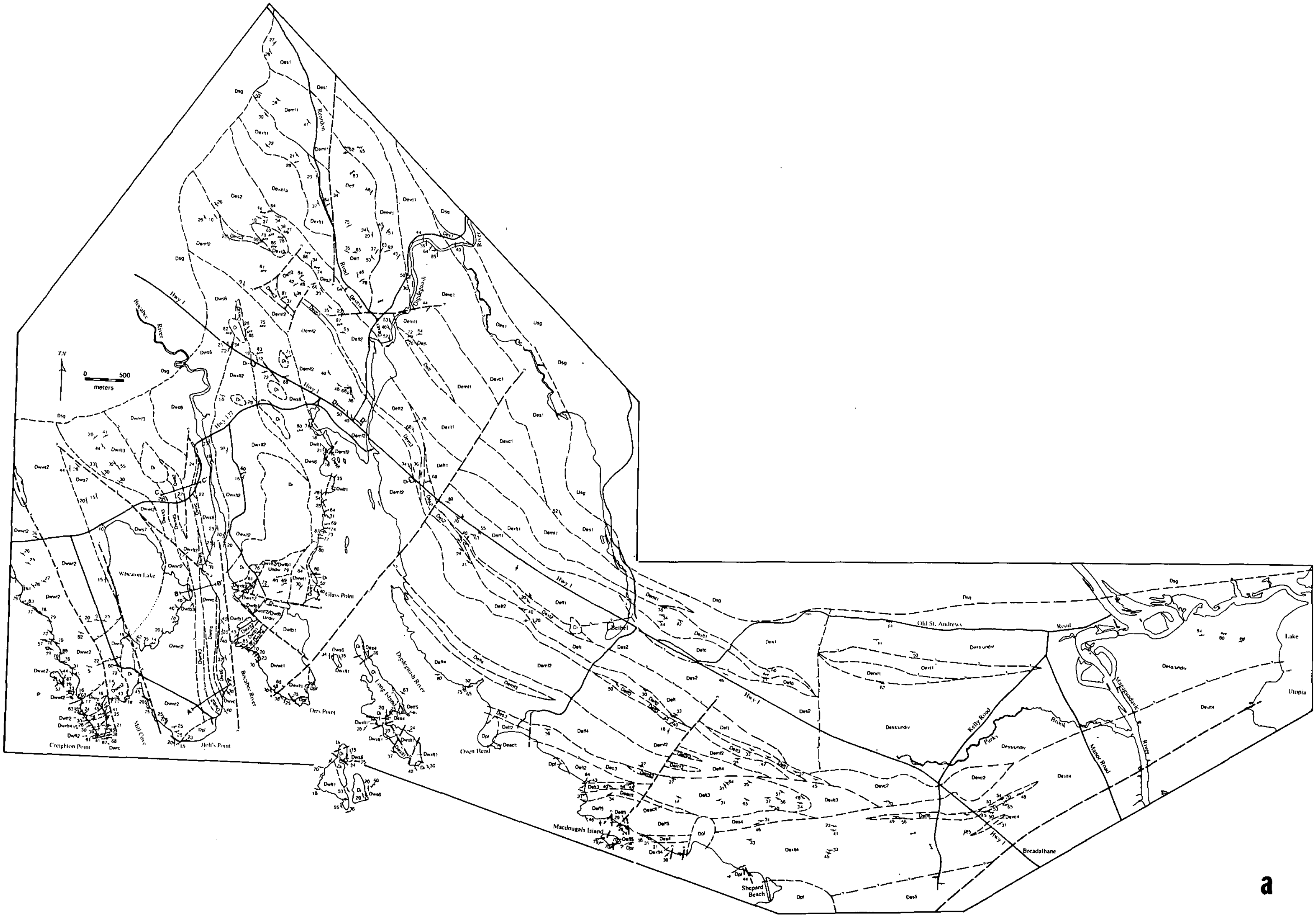
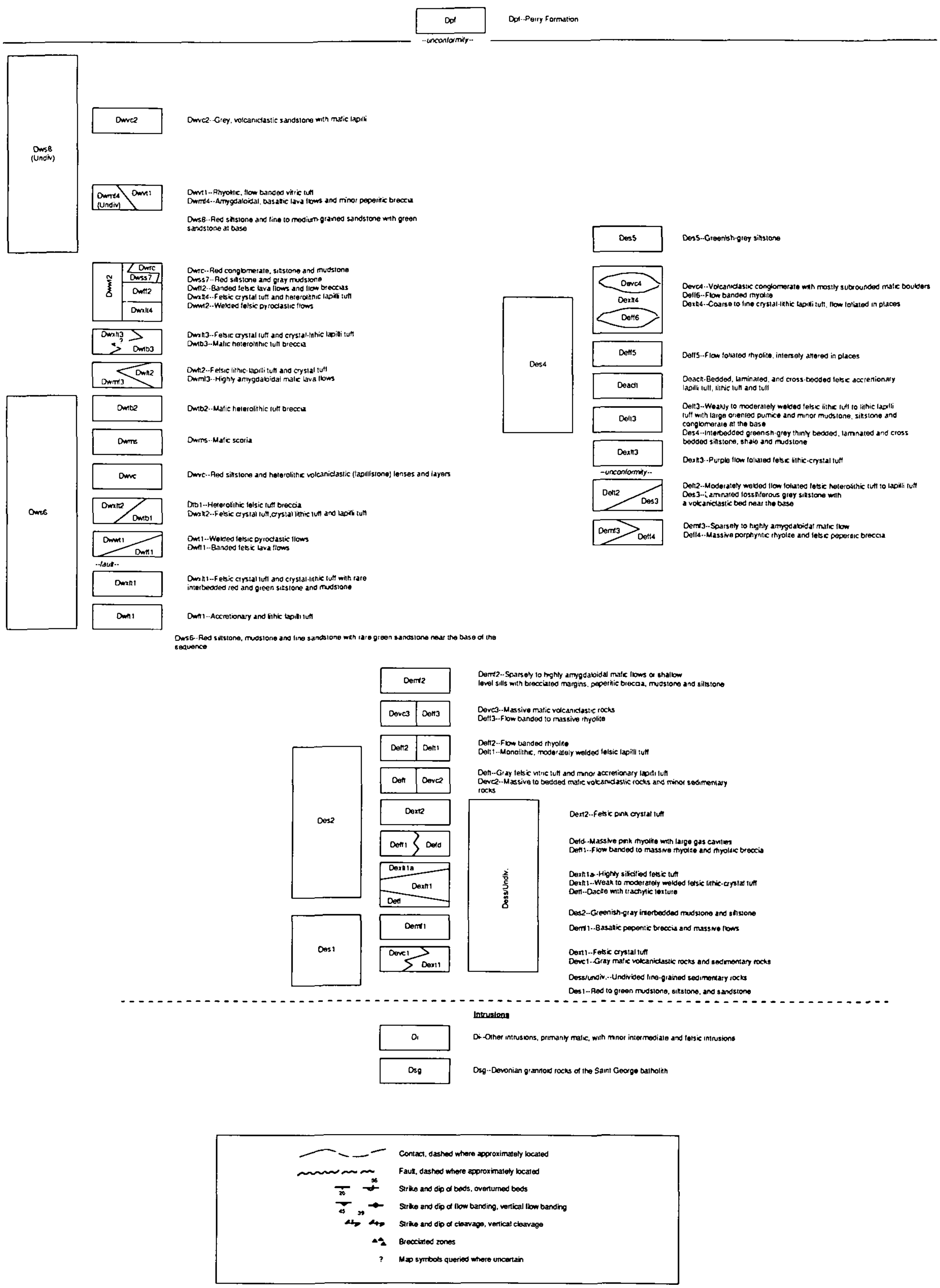


Fig. 3 (a) Geologic map of a portion of the Devonian volcanic and sedimentary rock sequence of the Passamaquoddy Bay area, southwest New Brunswick. (b) Explanation for geologic map.

EXPLANATION



b

Fig. 3 Cont.

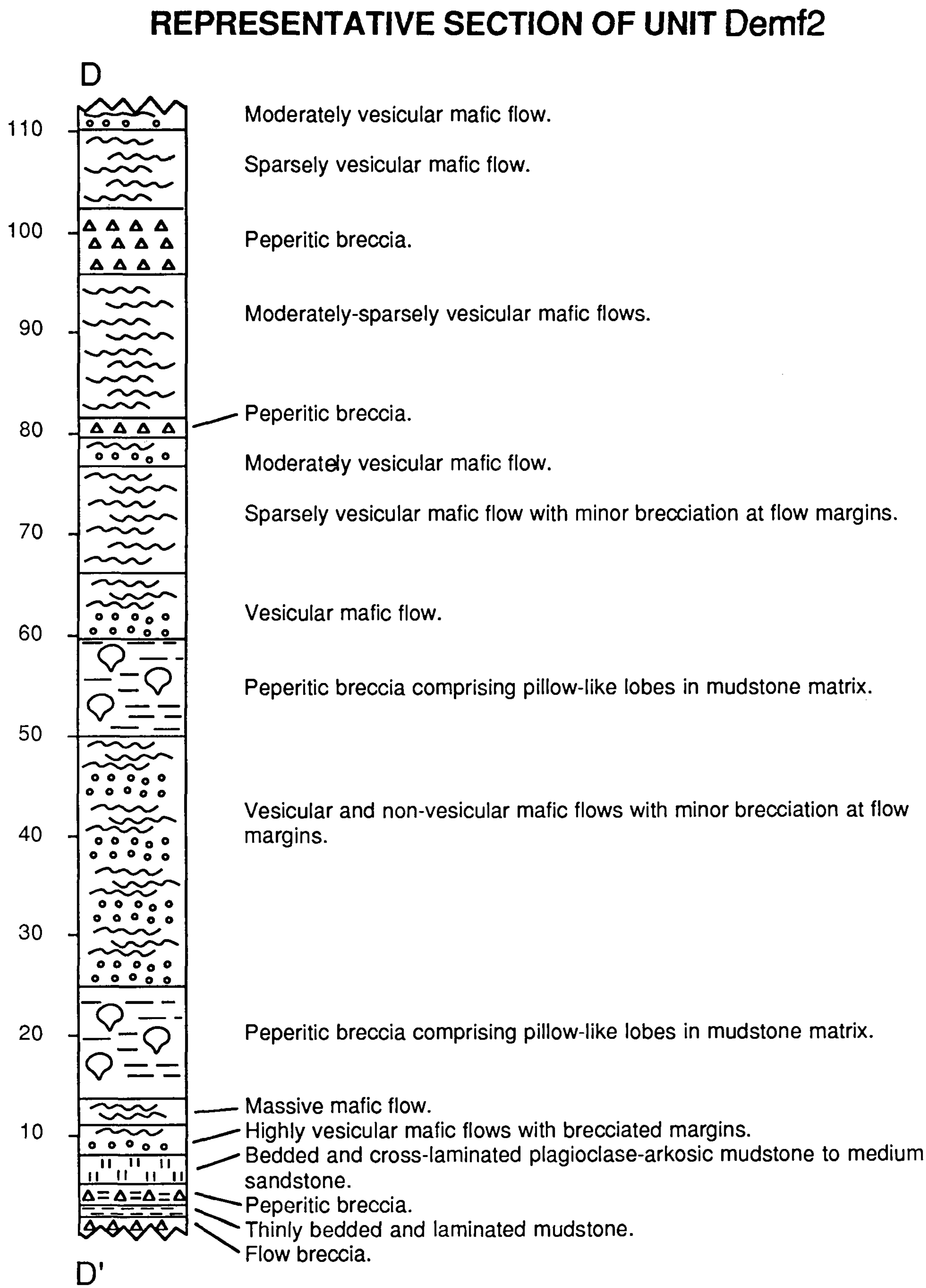


Fig. 4. Representative section of unit Demf2. See Figure 3a for location of section. Scale is in meters.

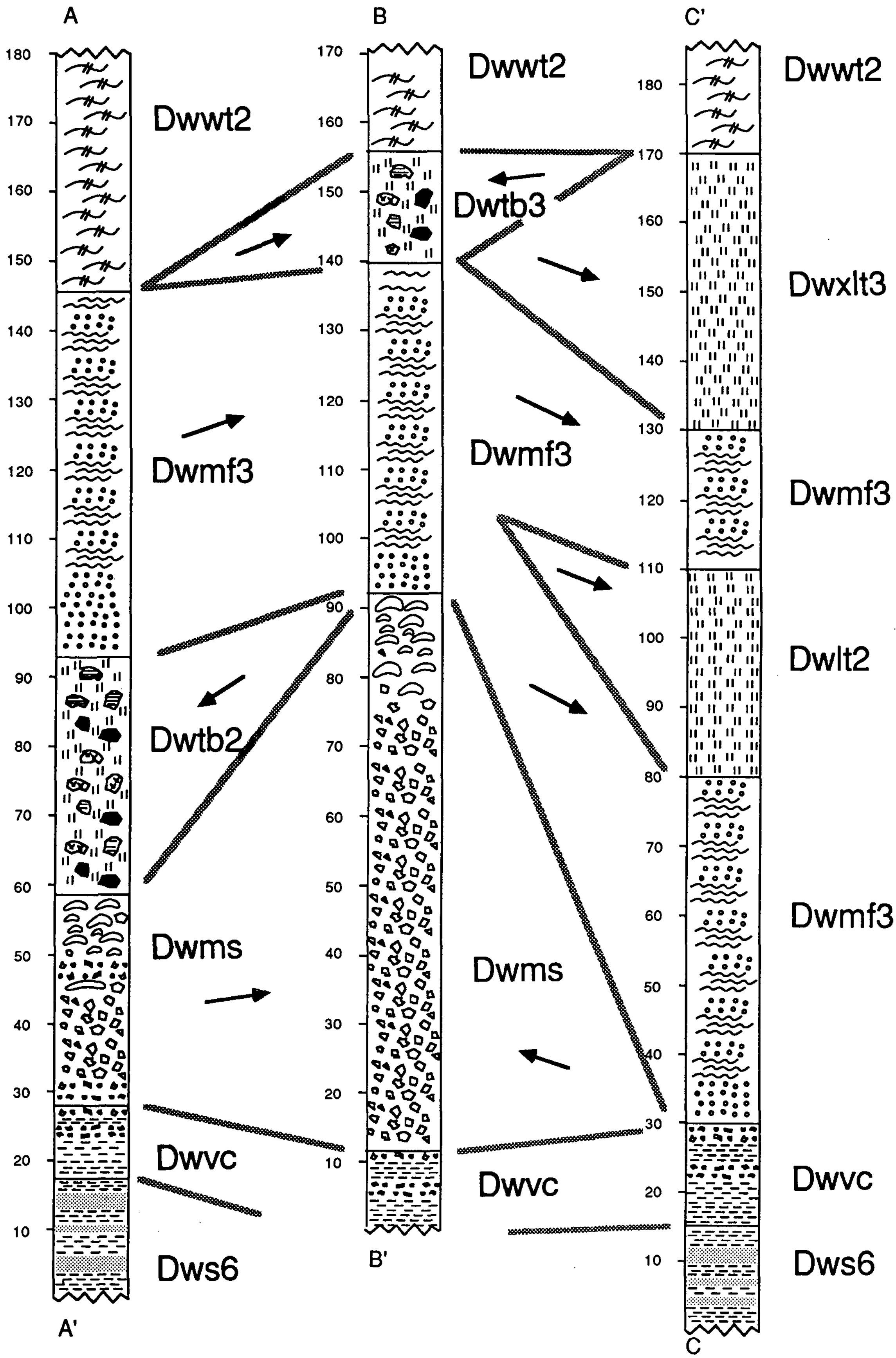


Fig. 5. A correlation of units from the upper part of the section. Arrows indicate direction to the source of some of the units. Location of the sections is shown on Figure 3a. Scale is in meters.

and commonly scoriaceous. The unit contains rare accidental siltstone fragments. There is no matrix. It is cemented by agglutination of fluid clasts and secondary calcite.

This unit is interpreted to be a mafic scoria cone, characteristic of the Strombolian style of volcanism. Proximity to the vent is suggested by the large size of some of the bombs. The accidental siltstone fragments suggest that the volcano erupted through tidal flat deposits. Scoria cones are poorly indurated and highly susceptible to weathering and erosion (e.g., Wood, 1980), so the thickness of the unit may represent an erosional remnant rather than the original form. Because erosion of a scoria cone tends to follow the original profile of the cone, it is suggested that the source of the cone was toward the center of the unit. The unit is not symmetrical around its thickest part, suggesting a wind direction toward the present south during eruption.

Units Dwtb2 and Dwtb3: Units Dtb2 and Dtb3 are massive to vaguely bedded heterolithic basaltic tuff breccia, with a maximum thickness of about 35 and 15 m, respectively. Both units thin rapidly away from the source (Figs. 3, 5). Beds are 30 cm to 6 m thick. Clasts form up to 60% and are up to 1 m, averaging 1-2 cm in size. They include siltstone, amygdaloidal and nonamygdaloidal basalt, gabbro, and rare cored bombs of lithic clasts rimmed by basalt. Clasts are mostly angular to subangular, but some of the basaltic clasts are bomb shaped. The matrix is nonwelded basaltic vitric tuff comprising angular and bubble wall glass shards, altered to chlorite.

Fragmented country rock is represented by the clasts of siltstone, gabbro, and angular accidental volcanic fragments. Glass shards in the matrix and some of the basaltic volcanic clasts comprise the magmatic material. The combination of blocky nonvesicular shards and vesicular shards suggests formation by a combination of vesiculating magma and steam quenching. Lack of welding indicates that temperatures were relatively low in the eruption system. On the basis of shard type, clast type and shape, vesicularity of clasts and shards and lack of welding, the tuff breccias are interpreted to be phreatomagmatic explosion breccias. The large clast size indicates a high energy eruption. Lack of primary depositional internal structures suggests origin as an air-fall deposit, probably around a tuff cone. Because these units would be poorly indurated when deposited, the shape of the deposit may reflect an erosional remnant.

Rhyolitic Rocks

Rhyolitic flows and domes units Deff1, Deff2, Deff3, Deff4, Deff5, Deff6, Defd, Detf, Dwff1, and Dwff2: There are three types of rhyolitic flows: pink aphyric flows (units Deff1,2,3,5 and 6, Defd, Dwff1 and Dwff2), pink porphyritic flows (Deff6), and a grey trachytic flow-banded rhyolite dome (Detf). These units apparently occur as domes (Deff1, Deff5, Deft and Defd) and flows (Deff2, Deff3, Deff4, Deff6, Dwff1, and Dwff2). Autobrecciation was observed at the margins of some of these units. Peperitic breccias are associated with Deff4 and Deff5. Inferred flow directions are based on variations in thickness. The units range in thickness from 60 to 350 m and have variable lateral extents (Fig. 3a).

The pink aphyric flows and domes are banded to massive. Flow bands are up to 1 cm thick, planar to undulating, and defined by variations in colour (from dark pink to buff) and grain size. The rocks commonly have micrographophyric texture, with plagioclase microlites rarely forming a felty texture. Plagioclase, and less commonly sanidine, rarely occur as glomerophyric phenocrysts. Primary structures include spherulites concentrated along flow bands and perlitic cracks near the tops of flows. Secondary phases include epidote, quartz, and rare fluorite.

The porphyritic rhyolite flow (Deff4) contains up to 20% commonly glomerophyric plagioclase and rare sanidine phenocrysts in a fine-grained micrographophyric to felty or pilotaxitic groundmass. Quartz phenocrysts are very rare. The feldspar phenocrysts are commonly zoned and altered to clay minerals. Mafic xenoliths are less than 3%, mostly a few centimetres, but up to 20 cm in size and rounded. Columnar joints, perpendicular to flow margins, are poorly developed throughout the unit. Flow foliation is weakly developed in places and defined by differential weathering.

Unit Detf is lense-shaped in outcrop, banded, and contains up to 70% microlites of alkali feldspar in a recrystallized silicic groundmass. Bands are light grey and dark grey, 1 mm to 1 cm thick, and defined by changes in abundance of microlites. The feldspar microlites are flow aligned giving the rock a trachytic texture.

Western Section (Dw) Pyroclastic Rocks

Bedded tuffs

Unit Dwlt1: Unit Dwlt1 is olive to brown accretionary and lithic lapilli tuff. It has a maximum thickness of about 50 m. Beds are up to 0.5 m thick, and internally massive, cross laminated, and normally and reversely graded from fine to medium ash. Climbing ripples occur locally.

Vitric clasts are subrounded pumice, up to 1 cm in size, and form up to 40% of some layers. Accretionary lapilli are in layers 1-2 cm thick, are 3 mm to 1 cm in diameter, and form up to 60% of the beds that contain them. Matrix is fine-ash tuff.

The occurrence of accretionary lapilli along with juvenile pumice fragments suggests that this unit originated by phreatomagmatic eruption (Fisher and Schminke, 1984). Most of the bedding structures are consistant with an air-fall deposit. However, the cross-stratification and climbing ripples require deposition by a current, and likely represent interbedded surge and air-fall deposits (Cas and Wright, 1987).

Unit Dwxlt1: Unit Dwxlt1 is interbedded crystal tuff and crystal-lithic tuff with rare red and green siltstone and mudstone. Maximum total thickness is about 100 m, but individual tuff units are 5 to 15 m thick and represent a sequence of flow and surge deposits with minor air-fall and siltstone sedimentation (Fig. 6). Only the ash-flow tuff at the top of the section exhibits welding. The absense of welding in most cases along with the thinness of most tuff beds suggests that this sequence was deposited relatively distal to source.

Units Dwxlt2 and Dwtb1: Unit Dwxlt2 is interbedded red to buff crystal tuff, crystal-lithic tuff and lapilli tuff, with rare interbeds of red siltstone. The unit fines to the north where tuff

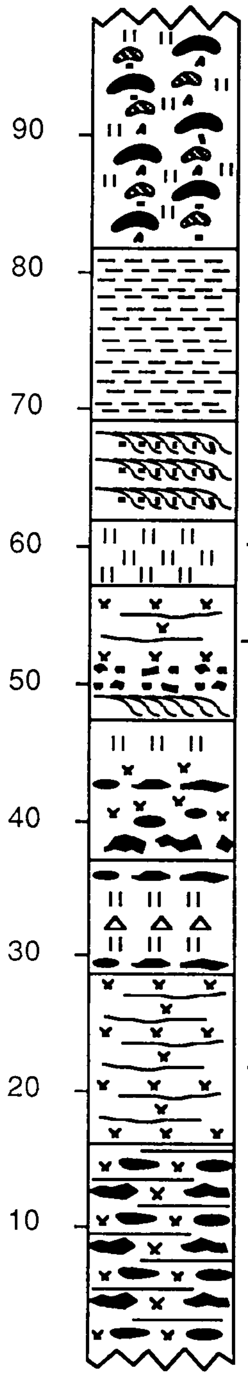


Fig. 6. Representative section of unit Dwxlt1. Location of section is shown on Figure 3a. Scale is in meters.

units appear cherty. There is some evidence of welding in the south. Maximum thickness is about 534 m. The unit is interbedded with Dwtb1 in the southern part of the map area. Unit Dwtb1 comprises heterolithic tuff breccias. Maximum thickness is about 115 m. This tuff breccia unit is interpreted to be a coarser facies of Dwxlt2.

In unit Dwxlt2, crystals form up to 15%, and are mostly feldspar. Lithic and vitric lapilli are 1 mm - 1 cm, subrounded to angular, form up to 90% of some layers, and include pumice, rhyolite, basalt, and rare mudstone. Welded beds contain fiamme. The pumice and fiamme are juvenile fragments; the other lithic fragments are accidental clasts, although the rhyolitic clasts may be cognate ejecta. Accretionary lapilli occur locally where they comprise up to 90% of reversely graded layers. They are up to 1 cm in diameter but mostly 2-3 mm. The matrix is fine to coarse ash. Devitrification textures are common and include spherulites, lithophysae, and granophyric recrystallization.

Beds are up to 2 m thick, internally massive, thinly laminated, normally graded, reversely graded, and multiply graded. Some of the welded tuffs exhibit convolute lamination, possibly due to rheomorphism (Schmincke and Swanson, 1967; Chapin and Lowell, 1979; Wolff and Wright, 1981).

This unit is interpreted to be a series of mostly magmatic pyroclastic fall and flow deposits. The increase in the degree of welding and grain size to the south suggests a southern source. The reversely graded accretionary lapilli layer indicates local hydroclastic air-fall activity.

The tuff breccias (unit Dwtb1) contain 30-80% pumice and rhyolite bombs, rhyolitic blocks, siltstone and basaltic lapilli, and locally fiamme. The pumice and rhyolite bombs and fiamme are probably juvenile fragments. The other clast types are cognate or accidental clasts. The breccias are massive or vaguely medium to thickly bedded. Beds are very rarely finely laminated and cross laminated. Rare bedding sags occur beneath larger pumice clasts.

Unit Dwtb1 is interpreted to be near-vent pyroclastic air-fall and rare ground surge deposits. The surge deposits are represented by the laminated and cross-laminated beds. Such beds are thin (<30 cm), typical of ground surge deposits that occur within air-fall deposits (Roobol and Smith, 1976). The other bedding structures are more typical of air-fall deposits, probably from a magmatic plinian or ultra-plinian eruption (e.g., Cas and Wright, 1987). The coarser pyroclastic air-fall deposits to the south and occurrence of welding indicate proximity to a vent area.

Units Dwlt2, Dwxlt3, and Dwxlt4: These units are well bedded lithic lapilli tuff, crystal-lithic lapilli tuff, and crystal tuff. They range in thickness from 30 to 65 m. The units are thinly to thickly bedded. Beds are internally massive, finely laminated, normally, reversely and symmetrically graded, locally flow banded and rarely cross laminated. Beds are discontinuous in places. Bedding sags occur locally.

The lithic lapilli tuff layers contain up to 90% angular to rounded cognate clasts of mafic volcanics, feldspar crystals and accidental siltstone fragments. The matrix is vitric and largely recrystallized.

The crystal tuffs form internally massive thin beds with up to 10% alkali feldspar crystals, and locally pumice fragments.

The crystal-lithic lapilli tuff layers contain up to 10% alkali feldspar crystals, and up to 70% mafic and felsic angular to subrounded lithic fragments up to 3 cm in size and locally flattened parallel to bedding suggesting welding. The matrix is pumice, rare bubble wall glass shards, and recrystallized vitric material. The juvenile fragments are ash, pumice and alkali feldspar. The cognate fragments are the mafic and felsic lithic clasts. Thicker layers are welded and contain 3-5% fiamme.

The thicker beds of units Dwxlt3 and Dwxlt4 are interpreted to be near-vent deposits of welded ash-flow tuffs. A magmatic eruption is indicated for unit Dwxlt3 by the vesicularity of the glass shards and the presence of pumice. The laminated tops of some of these thicker beds in unit Dwxlt 4 are probably ash cloud surge deposits, whereas the cross-bedded layer near the top of unit Dwxlt3 is interpreted to be a ground surge deposit (e.g., Cas and Wright, 1987). The interbedded thin massive tuff beds are probably air-fall deposits.

Banded and Densely Welded Tuffs

Unit Dwwt1 and Dwwt2: Units Dwwt1 and Dwwt2 comprise banded and welded ash flow tuffs with minor densely welded heterolitic tuff breccias. Maximum thickness of Dwwt1 is about 270 m. Unit Dwwt2 is about 1,130^{+} m thick.

The tuffs contain minor feldspar and rare mafic phenocrysts, and rare accidental angular basaltic lapilli. The groundmass is mainly microcrystalline quartz and feldspar produced by granophyric recrystallization of the orginal glassy groundmass (Lofgren, 1971). Other devitrification structures include local spherulites and lithophysae. Emplacement structures include flow banding, minor flow top brecciation, and local columnar joints. The flow banding is defined by extremely stretched pumice in many cases. Bands are <1 mm-15 cm thick, discontinuous, and undulating to complexly folded, possibly due to rheomorphism.

The tuff breccias contain abundant clasts of basalt, rhyolite, and rare gabbro. Clasts are up to 40 cm in size, and mostly subangular. Some of the rhyolitic clasts are slightly stretched due to flowage. Matrix is fine-grained banded rhyolite similar to the groundmass of the pyroclastic flows. The breccias generally fine upward by loss of large clasts.

These units are interpreted to be densely welded rhyolitic pyroclastic flows. The dense welding of the tuffs and coarseness of the tuff breccias suggests that these are relatively near-vent deposits.

Eastern (Lower) Section Pyroclastic Rocks

Massive Pyroclastic Flows

Units Dext1, Dexlt1, Delt1, Delt2, Delt3, Dexlt3, Dexlt4 and Dext2: The pyroclastic rocks of the eastern part of the map area make up the lower part of the section (Fig. 3). They are typically weakly to strongly welded, massive pyroclastic flows, ranging in thickness from 45 to 575 m. They vary from lapilli-tuff to tuff, and vitric particles dominate over lithic and crystal fragments. The vitric particles are pumice and glass shards. The pumice varies from 3 to 40% of the rocks and is commonly elongate, contorted and flattened due to flowage. The glass shards form up to 80% and are commonly platey bubble-wall shards resulting from fragmentation of pumice. The lithic fragments are ash to block size and composed mostly of non-vesicular mafic and felsic volcanic cognate ejecta, with sedimentary clasts. A well developed alignment bedding is defined by elongation and flattening of pumice and locally lithic clasts. Flow directions were determined by the morphology of the units and lateral variation in grain size and degree of welding. Unit Dexlt4 fines to the southwest, with the fining defined by loss of large, boulder-sized cognate ejecta. The matrix is primarily recrystallized vitric material. Unit Dexlt1 also fines to the southwest, with the fining defined by a decrease in the size of the pumice. In unit Delt3 the degree of welding decreases to the west. The abundance of vesiculated vitric particles suggests that the pyroclastic flows originated by column collapse (Wright *et al.*, 1980).

Bedded Pyroclastic Units

Unit Deft: This unit is a massive to rarely laminated grey-green rhyolitic tuff with minor accretionary lapilli tuff near the western extension of the unit. Laminae are internally graded by loss of larger vitric fragments. The unit has a maximum thickness of 230 m and thins to the west.

It consists of up to 80% platey and tricuspate glass shards. The fabric of the shards is isotropic, lacking any flow alignment or preferred orientation. Pumice only occurs in the middle and upper part of the unit where it forms up to 15%, ranges from 0.5 to 5 cm in length, has a wispy shape and is elongate parallel to bedding defining a flow foliation. Lithic and crystal fragments are rare (<2%) and include basalt, siltstone, and broken fragments of plagioclase. Accretionary lapilli occur in the western part of the unit, form up to 5%, are up to 1 cm in size, ovoid and commonly broken.

This unit is interpreted to be mainly an air-fall deposit on the basis of the isotropic fabric and the preservation of the tricuspate shape of the shards. Accretionary lapilli are a common component of air-fall deposits, being agglutinated by moisture in the eruption cloud (Brazier *et al.*, 1982; Carey and Sigurdsson, 1982), and in this case probably broke upon impact. The pumiceous layer near the top of the unit may be the remnant of a pyroclastic flow.

Unit Deaclt: This unit consists of interbedded tuff, lapilli tuff and accretionary lapilli tuff in beds 5 cm to 1.5 m thick. It has a maximum thickness of about 45 m.

The lapilli tuffs contain 3-15% angular to subangular fragments up to 2 cm in size which are 95% fine-grained rhyolite or pumice, rare coarse-grained rhyolite, and 4% pink orthoclase up to 4 mm in size. The fragments are mainly flattened due to flowage and oriented with long axes parallel to bedding. On bedding surfaces stretched vesicles in the pumice fragments define a lineation. Matrix is dark green-grey fine-ash tuff. Beds 2 cm to 20 cm thick are internally vaguely thinly bedded or laminated, locally cross laminated and reversely and normally graded with grading defined by variation in size and concentration of lapilli.

Accretionary lapilli tuffs contain up to 70% rounded, concentrically zoned accretionary lapilli, and up to 5% flattened pumice usually <1 mm thick, but up to 5 cm in length and elongate parallel to bedding. The accretionary lapilli are 3 mm to 2.5 cm in diameter and rounded to elongate parallel to bedding, or broken. Matrix is dark green-grey, fine- to coarse-ash tuff. Accretionary lapilli are concentrated in layers and lenses 5 cm to 20 cm thick. Within each bed, accretionary lapilli may be normally, reversely, or symmetrically graded. These layers and lenses may be internally laminated or low-angle cross laminated, defining megaripples approximately 40 cm x 1.5 m in size.

The tuffs are thinly bedded, laminated, and cross laminated. Beds are commonly lense shaped and 3 mm to 3 cm thick, and <20 cm in long. About half the lenses are distinctly to vaguely laminated or cross laminated. Thicker beds are massive or normally graded (from 2 mm to fine sand-sized grains) green-grey tuff. The thinner beds contain up to 50% pink flattened pumice, <1 mm thick, but up to 1 cm in length.

This unit is quite similar in structure, composition and thickness to a base surge deposit from a hydroclastic eruption (e.g., Fisher and Schmincke, 1984, Fig. 9-17) although the entire geometry of the deposit cannot be determined. The eruption was probably phreatomagmatic, with pumice representing the juvenile fragments. The abundance of steam in the eruption column would account for the occurrence of accretionary lapilli.

SEDIMENTARY UNITS

Non-volcaniclastic sedimentary rocks

Units Des1, Des2, Des3, Des4, Des5, and Dws6: These units comprise thinly to thickly bedded red siltstone, grey -green mudstone, and rare green to buff sandstone. Maximum unit thickness is 100 to 900 m, but the tops and bottoms of all units are not seen. Unit Dws6 fines to the north.

The thinner beds (1 cm to 2 m) are commonly planar, and internally massive, finely horizontally laminated, ripple cross-laminated, herring bone cross-laminated, or normally graded mudstone to siltstone. Other sedimentary structures are interference ripples, and lenticular siltstone ripples (up to 5 cm in height) in a mudstone matrix, oscillation ripples and mudcracks, and rare convolute lamination and load structures. Local bioturbation occurs as horizontal and vertical burrows. The mineral fragments include quartz, plagioclase, and mica.

The thinner beds of unit Dws6 contain up to 50% fossils of linguloid brachiopods, bilvalves, ostracods, rare gastropods, possible plant impressions, and vertical non-branching tubular burrows. The fauna are described by Pickerill and Pajari (1976).

The thicker beds (up to 2 m) are lensoid-shaped deposits of siltstone to fine sandstone. Lenses are vaguely horizontally laminated, low angle cross laminated, or ripple cross laminated. They rarely contain a basal lag gravel of siltstone rip-up clasts. Current ripple cross stratification modified by wave oscillation occurs in the rare sandstone lenses in unit Dws6 in the southern part of the map area. Upper surfaces of coarser beds preserve interference current ripples, polygonal mud cracks, rain drop impressions, and scratch and drag marks. Unit Des3 contains a

1.5 m thick basal pebble conglomerate with up to 40% angular to subangular fragments of rhyolite (50%), plagioclase crystals (30%), and basalt (20%). Bedding within this layer is defined by several poorly normally graded layers and by the concentration of clasts.

These units are interpreted to be peritidal (supratidal, intertidal, and subtidal) deposits (Friedman and Sanders, 1979; Evans, 1965; Ruitenberg and McCutcheon, 1978; Pickerell and Pajari, 1976; Elliott, 1978) based on the occurrence of shallow marine fossils, sedimentary structures, fine grain size and lack of reworking by waves. The sandstone deposits could be beach or bar deposits. The coarser lense-shaped beds are interpreted to be tidal channel deposits in the mud flat.

Unit Drc: Unit Drc consists of interbedded red conglomerate, siltstone and mudstone. It has a maximum thickness of 165 m. Pebbles and cobbles of amygdaloidal basalt, diabase, rhyolite, mudstone and siltstone are up to 5 cm in length and most clasts are subangular. The sand-sized particles are quartz, plagioclase, mica, and felsic volcanic rock fragments. The matrix is clay-sized material.

Beds are 0.5 cm to 1 m thick. The thickest beds tend to be the coarsest, but finer-grained beds form the largest percentage of the unit. The entire sequence coarsens upward and the abundance of volcanic clasts increases upward. Beds are massive, normally graded, current-ripple and ripple-drift cross laminated and parallel laminated. There is rare pebble imbrication in the conglomerate beds. Other sedimentary structures are current ripple marks, oscillation ripple marks, cut and fill forming conglomerate channels, mudcracks, shrinkage polygons, concretions up to 3 cm in diameter, and raindrop impressions.

The rock type and structures of this unit are consistent with an alluvial fan deposit (Reineck and Singh, 1975) on the slope of a volcanic edifice. The scour and fill, current ripple cross bedding and lamination, and gravel lag deposits are characteristic of braided channels on an alluvial fan. The massive conglomerates and those with imbricated clasts are probably mudflow deposits. Upward coarsening of the sequence represents either progradation of the fan or migration of channels across the fan.

Volcaniclastic Rocks

Unit Dwvc: Unit Dvc is bedded brownish red siltstone similar to unit Dws6, with lenses and beds of green volcanic fragments (Fig. 5). Maximum thickness is about 40 m. The abundance of volcaniclastic layers increases upward to 90%, the unit coarsens upward, and bed thickness increases upward from 2 mm-3 cm to 10-30 cm. Most layers are lensoidal but irregular in shape due to soft-sediment deformation.

Red siltstone layers contain ~1-25% volcanic fragments, and are horizontally laminated, massive or very rarely ripple laminated. Coarse volcaniclastic layers are massive or rarely normally graded.

The lithic clasts of the siltstone and volcaniclastic layers are up to pebble sized, mostly subrounded, and heterolithic. The clast types are siltstone rip-ups, amygdaloidal and non-amygdaloidal mafic volcanic fragments, bubble wall and blocky mafic glass shards, and rare armoured siltstone lapilli mantled by volcanic glass, and rhyolitic fragments.

This unit is interpreted to be a tidal mudflat faces, like unit Dws6, which was proximal to an intermittently active mafic volcano(es). The volcanic fragments are interpreted to be air-fall deposits because most (except the glass shards) are too large to have been transported by weak tidal currents. The rare volcanic fragments within the siltstone beds are scoriaceous fragments which were light enough to be transported by tidal currents. Little reworking and rapid burial, due to high sedimentation rates in a low energy environment, is indicated by the excellent preservation of the glass shards and glass surrounding armoured fragments.

Unit Devc1: This unit comprises interbedded green-grey siltstone to fine sandstone and coarse basaltic volcaniclastic rocks. The volcaniclastic layers become dominant upward in the section. Maximum thickness is 344 m.

The siltstone is thinly laminated to very thinly bedded. Beds are internally massive or finely laminated. The mineral grains are angular to rarely subrounded quartz, alkali feldspar, plagioclase, and rare detrital zircon, up to 0.1 mm in size and forming up to 70% of the rock. The lithic fragments are rare angular massive rhyolite up to 1 cm in size. The matrix is a mixture of secondary minerals including biotite, actinolite, zoisite, biotite, and calcite.

The volcaniclastic layers comprise clasts of reworked vesicular basalt and basaltic scoria, laminated siltstone, and crystals in a grey-green siltstone to fine sandstone matrix, as described above. The volcanic fragments are angular and up to 10 cm in size. These fragments become more abundant upward in the section, but the volcaniclastic sequence fines upward by loss of larger clasts and an increased percentage of siltstone matrix. Siltstone clasts are angular to subangular pebbles and cobbles with rare boulders up to 1 m in size. Crystal fragments are mainly plagioclase. The volcaniclastic layers are thinly to thickly bedded. Beds are commonly lens-shaped and discontinuous. Bedding structures include normal and reverse grading, cross bedding, pebble trails, and soft-sediment load structures and faults. The volcaniclastic layers probably represent fluvial reworking of a nearby mafic tuff erupted onto the tidal flat sediments.

Units Devc2 and Devc3: These units are mixed mafic and felsic volcaniclastic rocks. The lower third of the units are thickly laminated to medium bedded but they are massive at the top. The upper contacts of these units are highly oxidized.

The lower bedded sequences consist of up to 30% subrounded to subangular vesicular basalt (up to 2 cm), up to 30% nonvesicular fine-grained plagioclase micro-phyric basalt (up to 0.5 mm), up to 30% quartz grains, some of which may be silicic shards or rhyolitic fragments (<0.1 mm), 10% fragments of undetermined origin (up to 1 mm) altered to brown clays, and rare altered plagioclase. Grain size is continuous from 2 cm down to 1 mm with no separate matrix. Beds are commonly planar and internally massive. Bedding structures include rare channels, ripple marks and normal grading.

The massive upper part of the units is vaguely normally graded over the entire thickness. Near the bottom grain size varies from 5 mm to 30 cm with no fine matrix. Near the top grain size is commonly 1 cm to 0.1 mm (maximum 6 cm). These layers comprise up to 80% subrounded to subangular basaltic scoria (30 cm to 0.2 mm), up to 50% relict platey and pumiceous silicic shards (to 0.3 mm), up to 10% rhyolitic fragments (to 0.75 cm), up to 2% siltstone (1-2 mm), and rare plagioclase crystals and fragments of welded tuff (to 4 mm). The abundance of silicic shards and rhyolite fragments increases upward in the section.

These units may represent fluvial reworking of a felsic tuff cone, based on the presence of reworked shards, volcanic fragments demonstrating a volcanic provenance, and sedimentary structures suggesting reworking in a fluvial environment. Such a senario accounts for the abundance of felsic glass shards, the mixed population of mafic and felsic fragments, and the sedmentary structures.

Unit Devc4: Unit Devc4 is a massive mafic volcaniclastic rock. The unit appears chaotic, lacking bedding or sorting. It contains 10 to 40% subrounded to subangular volcanic fragments in a dark green-grey silt-sized matrix. The clasts are up to 30% vesicular and nonvesicular basalt up to 15 cm in size, up to 5% flow banded and porphyritic rhyolite, and up to 5% mudstone to siltstone up to 5 cm in size. This unit is interpreted to be a mudflow deposit.

STRATIGRAPHY

The stratigraphy is easier to conceptualize in the composite section (Fig. 7). The sequence is about 3.5 km thick and covers a lateral extent of about 18.5 km. Correlation is based on the most laterally extensive units. Correlation becomes difficult and somewhat questionable between the eastern and western parts of the map area above unit Demf2. The western half of the map area is considered to interbedded in part and sits conformably above the eastern part of the map area, but it is possible that the structure is more complex. The other problem is correlation across the Bocabec River fault, where correlation is based on continuity of unit Dws6 across the fault.

The stratigraphic analysis portrayed in the composite section (Fig. 7) shows that the eruptive sequence is bimodal (mafic-felsic) and that there are three cycles of mafic-felsic volcanism. Consistent with the compostional variation several types of eruptive systems are represented. Hawaiian and Strombolian volcanism is indicated by the mafic scoria cone (Dwms) and mafic flow deposits (Demf1, 2, and 3, and Dwmf3). More explosive Plinian or Sub-Plinian eruptions are indicated by some of the eastern section massive pyroclastic flows and the western section bedded tuffs and banded and densely welded tuffs. Phreatomagmatic (Vulcanian) volcanism is suggested for some of the felsic lapilli-tuff units which contain accretionary lapilli (Deaclt, Dwlt1 and parts of Dwxlt2) and the mafic tuff breccias (Dwtb2 and Dwtb3).

There is evidence for most types of pyroclastic deposits including air-fall, pyroclastic flows and ash cloud and ground surge deposits. Both welded and nonwelded varieties of these deposits occur and there is some evidence for rheomorphism. In parts of the section, mafic flows or shallow-level sills show evidence for interaction with wet sediment producing a sequence of peperitic breccias.

There are no clear periods of volcanic quiescence marked by continuous sedimentary horizons, and the volcanic cycles are not separated by, but are interbedded with sedimentary rocks. The sedimentary rocks contain abundant exceptionally well preserved glass shards. The excellent preservation of these shards indicates that sedimentation was rapid in a low energy environment, because any amount of reworking would destroy these delicate clasts. In addition, volcaniclastic layers such as Dwvc contain an abundance of air-fall deposits of basalt and basaltic glass shards indicating nearby basaltic volcanism.

Of the volcanic rocks, the felsic rocks are most abundant. Felsic lava flows are common and apparently quite extensive, although the nature of the exposure does not permit precise interpretation of the shapes and volumes of the flows.

Flow direction is variable and is actually more complex than schematically illustrated on the cross section, providing evidence for several small eruptive centres. Mafic flows are consistently from the northwest suggesting that they were erupted from a single rift system. Other units such as Dwms, Dwtb2, and Dwtb3, have limited aerial extent and are probably near their vent area.

Volcanic rocks are interbedded with mainly fine-grained tidal flat sedimentary rocks over almost the entire thickness of the sequence, although fluvial deposits occur in the upper part of the section. Reworked volcanic rocks (labelled vc) are rare.

DEPOSITIONAL SETTING

There are several possible depositional settings for the stratigraphy documented. The sequence could have been deposited (1) near the peak or on the flank of a stratovolcano, (2) in an intracaldera setting, (3) in an extracaldera setting, or (4) on a volcanic plateau lacking large caldera sequences. The constraints important to proper interpretation of depositional setting are (1) the composition of the volcanic rocks, (2) the nature of cycles of volcanism, (3) the thickness of the sequence and the subsidence history, (4) the rates of sedimentation, (5) the facies relationships, and (6) the synvolcanic structures. The salient aspects of these constraints in the map area are as follows:

(1) The volcanic rocks are bimodal, subalkaline, and have a within plate tectonic affinity (Van Wagoner *et al.*, 1988) suggesting an extensional tectonic setting.

(2) Volcanism is cyclic with basaltic flows preceding rhyolitic volcanism.

(3) The sequence has a minimum thickness of 3.5 km (ignoring compaction and any missing section), it is mainly associated with littoral facies sedimentary rocks, and it lacks major unconformities, indicating that both volcanism and sedimentation were roughly continuous and that the rate of volcano construction was equal to and sometimes exceeded the rate of subsidence.

(4) Rates of sedimentation were rapid, indicated by the excellent preservation of delicate cuspate and pumiceous glass shards in the volcaniclastic sedimentary rocks, the fresh feldspar in the rare arkosic sandstones, and the excellent preservation of the smaller basaltic tuff and scoria cones.

(5) The volcanic sequence includes both proximal and distal facies that originated from several different vent areas. Reworked volcanic rocks are rare.

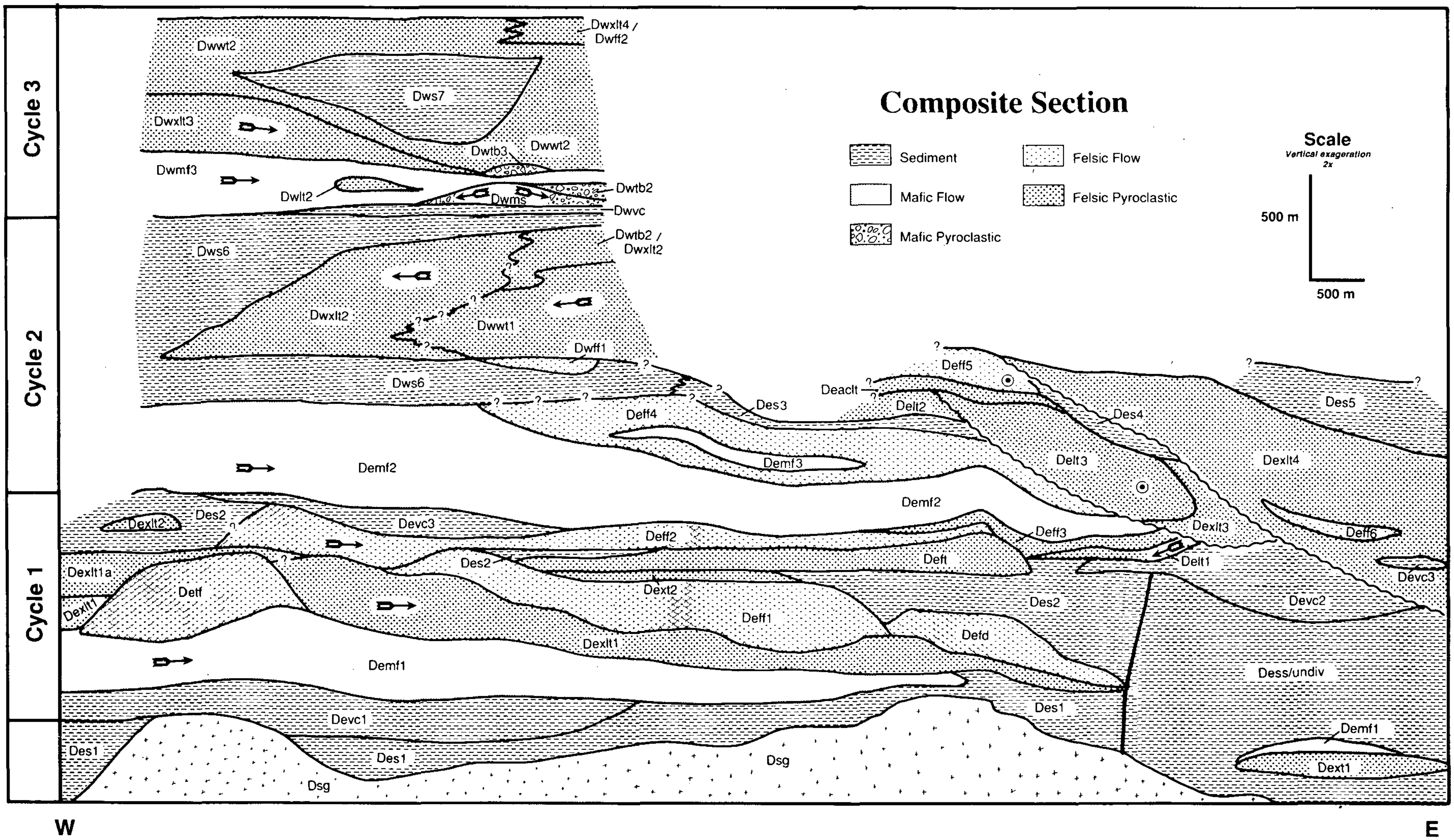


Fig. 7. Composite section of the stratigraphy of the map area. The three cycles of mafic/felsic volcanism are indicated on the left. Arrows indicate the major component of flow direction in the plane of the section. Circled dots indicate flow direction perpendicular to the page.

(6) The mafic flows seem to have originated from the same rift or vent area, but feeder dikes were not commonly observed. Rhyolitic feeder dikes were observed in the east side of the map area. Most are perpendicular to the strike of the flows and do not form ring structures. Zones of volcanic megabreccias were not observed. Most of the faults are minor.

The sequence is probably not part of a stratovolcano. Most stratovolcanoes are andesitic, although some associated with rift valleys have alkalic and bimodal compositions (e.g., Williams, 1982). The interfingering of littoral sedimentary rocks with volcanic rocks suggests deposition on the flank of a volcanic edifice, but in many cases these littoral sediments are interbedded with proximal facies volcanic rocks (welded tuffs and coarser air-fall deposits). In addition, the flanks of stratovolcanoes commonly have abundant volcanogenic debris flows which are lacking here (Williams and McBirney, 1979; Vessell and Davies, 1981; Voight *et al.*, 1981; Janda *et al.*, 1981). The upper portion of a volcanic edifice would also be a likely depositional setting for these rocks, but is not the preferred hypothesis because of the association with distal facies volcanic rocks (e.g., fine, unwelded pyroclastic flows and basaltic lava flows with pahoehoe toes).

It is tempting to ascribe the sequence to an intracaldera setting, thus interpreting the broad fold as a depositional feature around the edge of a large caldera. The St. George Batholith would then be the remains of the magma chamber beneath the caldera. There are, however, some problems with this interpretation. Mega- and meso-collapse breccias, commonly associated with the walls of calderas (e.g., Lipman, 1976 and 1984) were not observed. It could be that the map area was distal to these structures, but also absent are the thick and voluminous pyroclastic flow deposits that are common as caldera fill sequences (Byers *et al.*, 1976; Smith, 1960; Smith and Bailey, 1969; Christiansen, 1979). The volume of pyroclastic flows is, however, related to the size of the magma chamber and the diameter of the caldera, so a smaller caldera would produce thinner, lower volume flows (Smith, 1979). Cyclic volcanism is also a common characteristic of caldera-fill sequences climaxing with large volumes of pyroclastic material (e.g., Christiansen, 1979). Such cycles are not obvious in our area. If the map area is an ancient small caldera fill sequence, then it becomes difficult to explain the great thickness of the sequence, which is at least as thick or thicker than most large cauldrons (Fiske and Tobisch, 1978; Lipman, 1984; Akeny *et al.*, 1986; Byers *et al.*, 1976). None of our thicker pyroclastic flow sequences are bounded by boundary faults, characteristic of intercaldera ash flows associated with caldera collapse (Lipman, 1984). Finally, intracaldera sedimentary deposits are commonly associated with periods of volcanic quiescence and caldera collapse. The sedimentary rocks include coarse clastic deposits shed from the caldera walls, the resurgent core, or from volcanoes within the caldera, and finely bedded lacustrine deposits (e.g., Lipman, 1984; Oftendahl, 1978; Smith and Bailey, 1968). In the map area, sedimentation is concomitant with volcanism, fine tidal-flat facies dominate and lacustrine deposits were not observed.

It is unlikely that this is an extracaldera sequence because if it were, the rhyolitic lava and pyroclastic flow units would be expected to thicken toward a caldera source (Byers *et al.*, 1976). Instead, the lithologic units have multiple source areas (Fig. 7). If there were multiple small calderas close together, there should be evidence for them, as the vent areas for some of the pyroclastic deposits are known.

The final, and preferred interpretation is that this sequence comprises a volcanic plateau such as the the Eastern Snake River Plain, or the plateaus of the East Africa Rift System, which form in areas of continental extension (e.g., Williams, 1978; Leeman, 1982). This interpretation is consistent with the bimodal and within-plate geochemical affinity of the rocks (Bonnichsen, 1982; Leeman, 1982). These modern plateau sequences are equivalent in thickness (Stanley, 1982; Braile *et al.*, 1982; Ekren *et al.* 1980; Williams, 1978, 1982; Oftendahl, 1978) to the composite section (Fig. 7). Major caldera structures are absent from much of the Eastern Snake River Plain (Ekren *et al.*, 1982, 1984; Bonnichsen, 1982) such that flow directions are variable and flows originate from small vent areas, also similar to the map area. The migration of mafic magma initiates melting in deeper and smaller magma chambers. Such volcanism produces very hot, densely welded pyroclastic flows that are sometimes difficult to distinguish from felsic lava flows (Ekren *et al.*, 1984) comparable to unit Dwwt2 in the western part of the map area. A similar relationship between mafic and felsic volcanism could have produced the cycles of mafic/felsic volcanism recognized in the map area, with the basaltic tuff breccias recording interaction of the migrating basaltic magma with ground water. Eruption from smaller magma chambers could also explain the thinnner and more variable volcanic units and the complex interfingering of distal and proximal facies. The formation of a plateau, rather than an unstable volcanic edifice, explains the lack of volcanogenic debris flows. The occurence of alluvial fan sediments higher up in the section may represent sedimentation off a fault scarp, a common feature of intracontinental rift basins (Selley, 1976; Nilsen, 1982). Subsidence can be quite rapid in continental rifts especially if associated with significant crustal attenuation and loading (e.g., Sheridan, 1978). Such rapid subsidence and accompanying burial would account for the superb preservation of delicate glass shards in the sedimentary and volcaniclastic units, the preservation of the easily erodable scoria and tuff cones, and (assuming no eustatic sea level changes) the maintance of the sequence near sea level.

Some of the questions that remain then are (1) is the crustal attenuation associated with a mantle hot spot, (2) is there other evidence for deeper and smaller magma chambers, (3) is partially melted Avalon basement the source of the voluminous rhyolitic rocks, and (4) what is the source of the basaltic flows?

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