POLYKINEMATIC EVOLUTION OF THE TEAKETTLE AND CARMANVILLE MELANGES IN THE EXPLOITS SUBZONE, NORTHEAST NEWFOUNDLAND

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NORTHEAST NEWFOUNDLAND

BY

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Abstract

The Carmanville Melange contains an impressive variety of sedimentary, igneous and metamorphic blocks in a silty shale matrix. Block lithologies include: pillowed basalts, gabbro, trondhjemite, greywacke, grey siltstone, rhythmically bedded grey siltstone and black shale, and polyphase deformed metamorphic rock. The polydeformed and metamorphosed rocks consist of variably strained pillow basalts, banded mafic metavolcanic rocks, and psammite, in a black pelitic matrix. This assemblage is interpreted as an earlier generation of melange (Teakettle melange), that now occurs as discrete blocks in the Carmanville Melange.

The Carmanville Melange is associated with distinctive coticule-bearing shales and siltstones of the Woody Island formation and fragmental volcanic rocks of the Noggin Cove Formation. All of these units are assigned to the Hamilton Sound complex, and distinguished from the adjacent Davidsville Group.

Structural and metamorphic contrasts between the Teakettle and Carmanville melanges are spectacular. Teakettle psammites locally exhibit overprinting of three phases of deformation, at least two with associated fabric development. The strong asymmetry of most of the structures, coupled with large scale boudinage, suggests a tectonic origin for the Teakettle melange or extreme deformation of an existing melange, at mid to deep crustal levels.

The Carmanville Melange formed at higher crustal levels. It has early,

asymmetrical layer-parallel shearing, produced by independent particulate flow, and asymmetrical, isoclinal folding in entrained stratified blocks. Later structures record increasing viscosity during deformation, progressing from folds and shear bands, to shearing on discrete surfaces and finally brecciation and cataclasis. Structures in the Carmanville Melange are interpreted as products of diapiric processes whereby a mobile matrix sampled and entrained of a wide variety of lithologies, with dramatic structural and metamorphic contrasts. The Carmanville Melange is therefore a non-stratigraphic unit, that has injected the Noggin Cove and Woody Island formations, and post-dates both. Diapiric mobility could have been driven by thrust imbrication, with attendant overthickening and overpressuring of wet sediments, at the base of an accretionary wedge.

Acknowledgements

This thesis would not have been possible without the guidance and support of my supervisor, Dr. Hank Williams. His keen insight and lively approach to geology is enough to keep even the rocks on their toes. With his lead, I have gained a profound respect for the problems and complexities encountered in Newfoundland geology; melanges in particular. Rarely without a jig cr reel in his head, his humour and good `spirits' typify that for which Newfoundland is most famous. Although I'll never be a `true Newfoundlander', I can say with confidence that I've known one.

The students, staff and faculty of the Department of Earth Sciences have all contributed, directly or indirectly, to the successful completion of my program here at Memorial University. Special thanks are extended to Gary Thompson, and the `Lizard Ladies', who guided me in my exploration of Newfoundland culture, and supplied a bounty of welcome distraction.

During my field season, the people of Carmanville, especially Gary and Yvonne Coilins, welcomed me like family. They did more for my musical career and provided greater entertainment than I could have gained, were I to have mapped the `Nashville Melange'. The block names on my map are a tribute to them.

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CHAPTER 1

Introduction

Studies of melange occurrences in Newfoundland have considerably advanced the understanding of the tectonic history of the northern Appalachians. Melanges associated with transported ophiolites (e.g. Bay of Islands, Advocate, St. Anthony, Coy Pond) are confined to tectonically controlled structural slices and clearly separate underlying rocks of continental affinity from overriding oceanic rocks, or they occur between oceanic slices. Mixtures of ophiolitic components and continental shelf sediments, in these types of melange, provide clear evidence that they were controlled by the obduction process.

In the northeast Exploits Subzone, melanges, such as the Carmanville, Dunnage and Dog Bay occurrences, constitute a large portion of the bedrock exposure. While the lithic associations and distributions are well known, their origin and tectonic significance are still poorly understood. Recent work in the Carmanville area (Williams et al., 1991; Williams, 1992; Currie, 1992; Johnston, 1992) has renewed interest in these melanges and provides the impetus for a detailed study of the Carmanville Melange.

1.1 Tectonic Framework

The Carmanville Melange is located in the northeastern portion of the oceanic Dunnage Zone (fig. 1.1.1; Williams, 1979; Williams et al., 1988). Island arc and back-arc

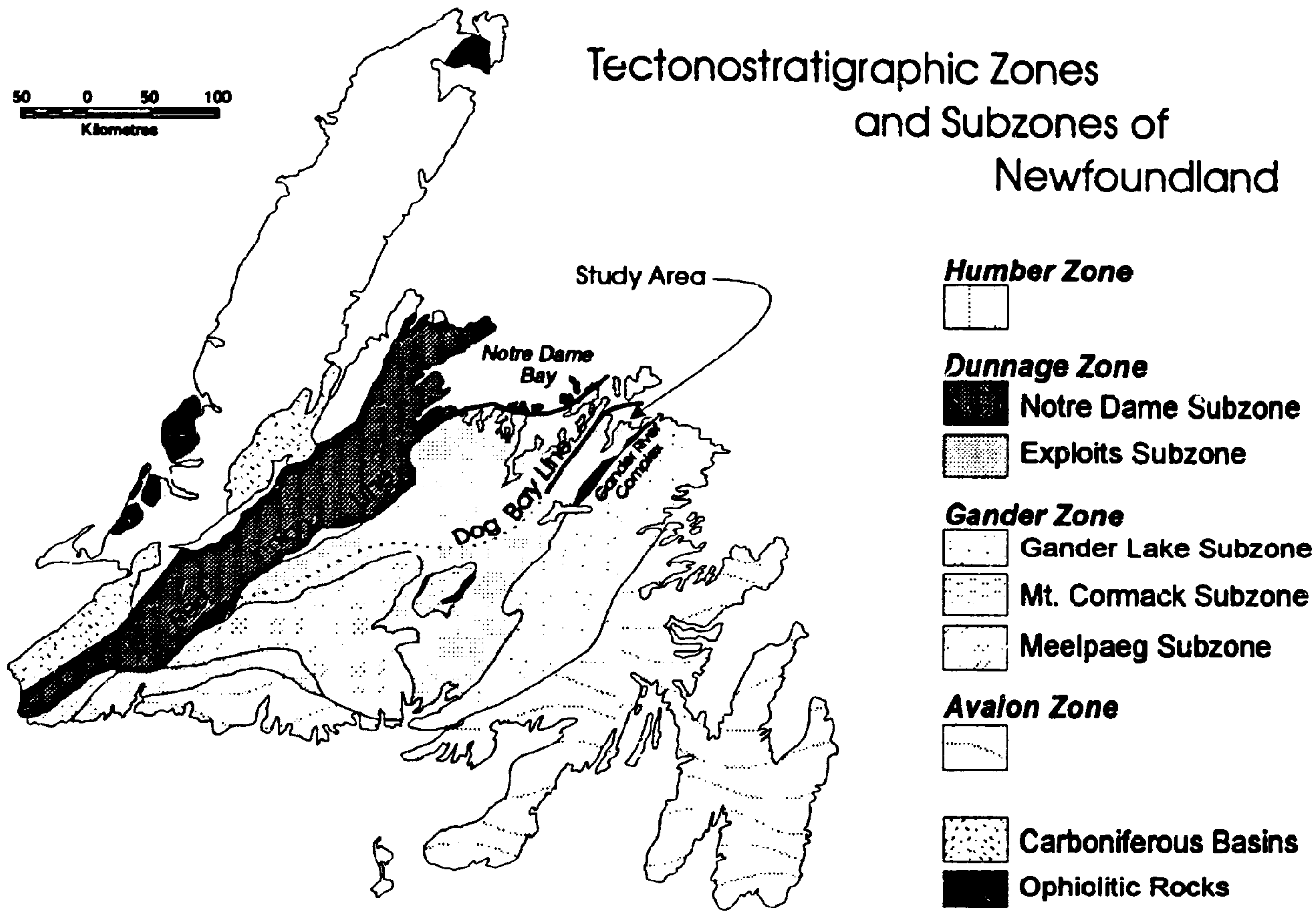


Figure 1.1.1 - Principal tectonic divisions of Newfoundland (after Williams et al., 1988)

basin rocks of the Dunnage Zone are generally viewed as the protracted remains of the early Paleozoic Iapetus Ocean (Williams, 1964; Wilson, 1966; Dewey and Bird, 1971; Stevens, 1970; Stockmal et al., 1987). The Late Cambrian-Early Ordovician rocks of Iapetus, are flanked by the Humber and Gander zones, which are believed to represent the opposing continental margins of Laurentia and Gondwana, respectively, that collided to form the Appalachian Orogen.

The Dunnage Zone is divided into the Notre Dame and Exploits subzones, which are defined by contrasts in Ordovician stratigraphy, structure, faunas, plutonism, lead isotopic signatures in mineral deposits, and geophysics, across the Red Indian Line (Williams et al., 1988). The Early Ordovician (late Arenig) history of the Appalachian Orogen involved the roughly synchronous obduction (Williams and Piasecki, 1990; Colman-Sadd et al., 1992) of ophiolitic rocks of the Notre Dame Subzone rocks westward, over the Humber Zone (Taconic Orogeny), and the Exploits Subzone eastward, over the Gander Zone (Penobscot Orogeny).

Faunal contrasts between the two Dunnage subzones persisted into the late Llanvirn-early Llandeilo, when Laurentian faunas first appeared in the various limestone deposits of the Exploits Subzone (McKerrow and Cocks, 1977; Boyce et al., 1988). The earliest sedimentologic link between the two subzones is provided by volcanic clasts of the Notre Dame Subzone (Roberts Arm Group), found in Late Ordovician-Early Silurian conglomerates and olistostrome in the Exploits Subzone (Nelson, 1981). Juxtaposition of the two subzones, along the Red Indian Line, therefore significantly post-dated obduction at their respective margins.

Some Ordovician marine volcanic and sedimentary rocks, of the Exploits Subzone, post-date the late Arenig ophiolite emplacement, and were deposited on allochthonous oceanic crust. These rocks locally extend onto the Gander Zone continental margin (e.g. Indian Bay Big Pond Formation; Wonderley and Neuman, 1984; O'Neill and Blackwood, 1989) and are therefore viewed as overlap or cover sequences, and do not have the same significance as rocks deposited on undisturbed ophiolitic substrate (Williams and Piasecki, 1990).

The Gander Zone has been divided into three subzones, separated geographically from each other by the overlying rocks of the Exploits Subzone (Williams et al,. 1988). They are the Gander Lake Subzone, named after the locality of the zone's type section, and the Mount Cormack and Meelpaeg subzones in central Newfoundland (Williams et al., 1988). All are believed to be continuous at depth (Keen et al., 1986), with the Mount Cormack and Meelpaeg subzones occurring as tectonic inliers or windows (Colman-Sadd and Swinden, 1984; Williams et al., 1988), within the Exploits Subzone.

The northeast Exploits Subzone is bounded in the northwest by local faults that define the Red Indian Line (Williams, et al., 1988). Its eastern boundary is drawn at the eastern margin of the Gander River Complex (O'Neill and Blackwood, 1989). This area of the Exploits Subzone is exceptional for its abundance of melanges. From northwest to southeast, these are: the Dunnage Melange, the Dog Bay Point Melange and the Carmanville Melange. All are dated or interpreted as Ordovician (Williams et al., 1991).

Silurian melanges, such as the Joey's Cove Melange (Arnott, 1983; Reusch, 1987) are also present. These occur in a marine greywacke-conglomerate sequence (Badger Group) that overlies Middle Ordovician black shale of the Exploits Subzone.

1.2 Regional Setting and Table of Formations

The Carmanville area (fig. 1.2.1) straddles the boundary between the Dunnage and Gander zones of Williams (1979), and thus, the transition between oceanic and continental realms. Here, the northeastern Exploits Subzone consists of the informal Hamilton Sound group (Currie, 1992; 1993), the Davidsville Group (Kennedy and McGonigal, 1972; Blackwood, 1982; O'Neill, 1991), and the Gander River Complex (O'Neill and Knight, 1988; O'Neill, 1991). The monotonous sandstones of the Gander Zone are represented by the Gander Group (Kennedy and McGonigal, 1972a; Blackwood, 1982; O'Neill, 1991). With the exception of the Hamilton Sound group, which is confined to the northeast coastal region, these units extend more than 100 kilometres southwestward, to Gander Lake, and beyond. Present definitions of these groups (see Table 1 for summary of formations) represent a long and varied history of nomenclature and interpretation (for review, see: Blackwood, 1982; O'Neill, 1991); and are based on the areas around Gander Lake (Blackwood, 1982) and Weir's Pond (O'Neill, 1991).

The Gander Group (Kennedy and McGonigal, 1972a; Blackwood, 1982; O'Neill and Blackwood, 1989; O'Neill, 1991) consists mainly of psammite, and semi-pelite, with

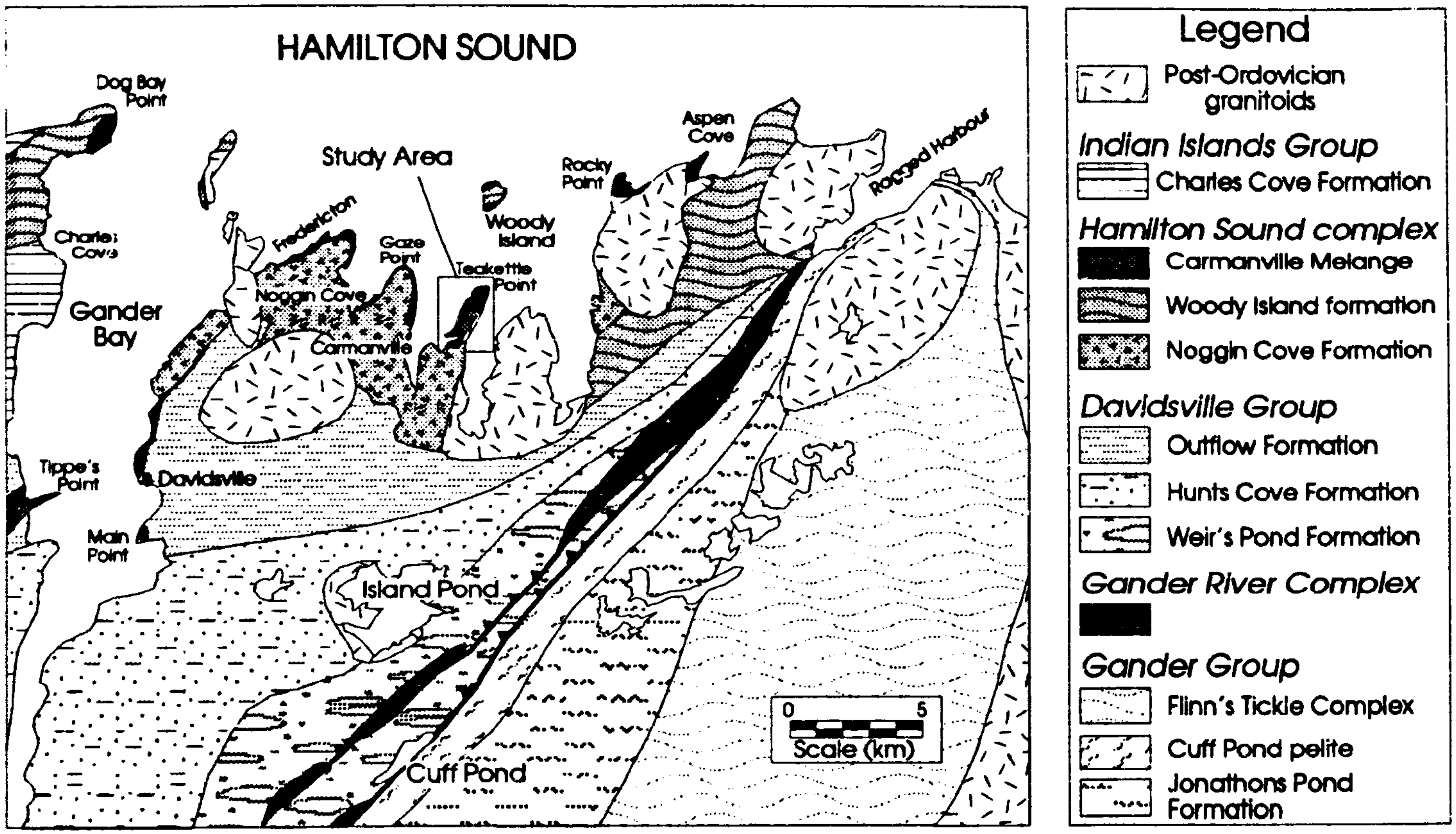


Figure 1.2.1 - Carmanville map area 2E\8. Units extended from Weirs Pond map area (O'Neill, 1991) by Currie, 1992. Nomenclature drawn from both sources: Hunts Cove Fm (O'Neill, 1991) = Round Pond shale (Currie, 1992); Outflow Fm (O'Neill, 1991) = Main Point shale (Currie, 1992); Cuff Pond pelite, Flinn's Tickle Complex, Woody Island formation (Currie, 1992), Noggin Cove Fm (Johnston, 1992), Carmanville Melange (Williams et al., 1991).

Table 1

Table of Formations

Period	Group	Unit	Lithology
Early Silurian	Indian Islands Group	Charles Cove Formation	siltstones and shales, thin fossiliferous limestone beds, and basal limestone breccia, greywacke, and chert pebble conglomerates
Erosional unconformity and locally faulted			
Early and Middle Ordovician	Hamilton Sound complex	Carmanville Melange	very poorly sorted blocks and fragments of: sandstone, pillowed basalts, gabbro, trondhjemite, siltstone, and Teakettle melange, in a black shaly matrix; ***TEAKETTLE MELANGE:*** blocks of older, polyphase deformed melange
		Intrusive contact	
		Woody Island Formation	alternating dark grey, very fine grained sandstone, dark grey siltstone, and shale, with distinctive coticule layers
		Contact relations unknown	
		Noggin Cove Formation	massive volcanic conglomerates, lesser amounts of medium bedded tuffs and lapilli breccias, minor pillowed basalt and black shale
Thrust contact (?)			
Middle to Late Ordovician	Davidsville Group	Outflow Formation	fine to coarse grained sandstone, locally containing shale intraclasts, interbedded with grey to black siltstone and slate, minor conglomerates
		Conformable contact	
Middle Ordovician		Hunts Cove Formation	monotonous sequence of grey to green and rarely purple shale
		Conformable contact	
Early to Middle Ordovician		Weir's Pond Formation	quartzose sandstone, conglomerate, quartz arenite, bioclastic limestone, and interbedded grey and graphitic black shale
Unconformity and thrust imbricated			*Not in contact (same age as Weir's Pond Fm)*
			Indian Bay Big Pond Formation: grey and maroon sandstone, black pelite, red and green siltstone, mafic pillows and intermediate volcanic rock (overlap sequence)
Early Ordovician or older	Gander River Complex		ultramafic, mafic plutonic and extrusive rocks, trondhjemite
Thrust contact			
early-Middle Ordovician to Middle Cambrian	Gander Group	Jonathon's Pond Formation	psammite, semipelite, lesser amounts of greyish-green pelite, minor mafic and calc-silicate rich layers

(after Blackwood, 1982; O'Neill, 1991; Johnston, 1992; Williams, 1992; Williams, et al., 1993; this study)

localized calc-silicate layers and rare mafic to intermediate intrusive bodies (Jonathon's Pond Formation). Marine volcanic and sedimentary rocks of the Indian Bay Big Pond Formation stratigraphically overlie the Jonathon's Pond Formation. These rocks have been included in the Gander Group of O'Neill and Blackwood (1989), but they are equivalent to Exploits Subzone lithologies and considered to be post-obduction overlap sequences (Williams and Piasecki, 1990). Inclusion of the Indian Bay Big Fond Formation in the Gander Group, may therefore be misleading.

The Jonathon's Pond Formation is unfossiliferous, but late Arenig-early Llanvirn cover rocks, of the Indian Bay Big Pond Formation (Wonderley and Neuman, 1984), limit these rocks to a Middle Ordovician and older age. Detrital titanites from the Jonathon's Pond Formation are Middle Cambrian (T. Krogh, pers. comm. to O'Neill, 1991), providing the earliest possible age of deposition.

The Gander River Complex (O'Neill, 1991) is a northeast striking, discontinuous unit of ultramafic, mafic and trondhjemitic rocks that extends from Gander Lake to the coast in Hamilton Sound. These rocks are believed to represent the ophiolitic substrate of the Davidsville Group and are in thrust contact with the Jonathon's Pond Formation. The Gander River Complex is not in contact with the Indian Bay Big Pond Formation. Locally, serpentinized ultramafic rocks are unconformably overlain by basal units of the Davidsville Group, that include conglomerate at Gander Lake (Kennedy, 1975) and fossiliferous limestone (late Arenig-early Llandeilo) at Weir's Pond (Blackwood, 1978). The presence of chromite detritus in an arenaceous basal sandstone of the Davidsville

Group near Weir's Pond suggests that exhumation and erosion of the underlying Gander River Complex was active in the late Arenig (O'Neill, 1991).

The Davidsville Group (Kennedy and McGonigal, 1972a; Blackwood, 1982) is divided into three units (O'Neill, 1991), which range in age from late Arenig to Caradoc. The basal conglomerates, quartz and arenaceous sandstones, bioclastic limestone and graphitic black shale, of the Weir's Pond Formation are unconformable on, and thrust imbricated with, the Gander River Complex. These rocks are conformably overlain by monotonous grey, green and rarely purple shales of the Hunts Cove Formation, which is in turn overlain by the Outflow Formation. The Outflow Formation contains fine- to coarse-grained sandstone with shale intraclasts, interbedded with grey to black siltstone and slate, with minor conglomerates. Currie (1992) extended the Weir's Pond Formation farther north into the Carmanville area. He used the names Barry's Pond conglomerate and Round Pond siltstones for a conformable sequence that overlies the Weir's Pond Formation in this area. This nomenclature is still evolving (Currie, 1992; 1993), therefore, O'Neill's (1991) formation names for the Davidsville Group are retained here for simplicity.

Rocks of the Gander River Complex and the Davidsville Group contain one generation of penetrative cleavage development that strikes northeast and generally dips steeply to the northwest. The Gander Group shows the effects of two strong phases of deformation, and the main foliation has a north-northeast trend. This contrast in structural development between the Exploits Subzone and Gander Zone rocks indicate a more complex, possibly longer, deformational history in the Gander Group (Kennedy and McGonigal,1972; O'Neill, 1991). A wide geographic separation and different tectonic development between the two areas is suggested by the Middle Ordovician rocks of the Davidsville Group and correlative rocks. For example, rocks of the Davidsville Group are unconformable on the Gander River Complex, but farther east at Indian Bay, the Indian Bay Big Pond Formation is conformable on the Gander Group (Williams and Piasecki, 1990).

Farther north, in the Hamilton Sound area, abundant volcaniclastic rocks of the Noggin Cove Formation (Johnston, 1992), chaotic rocks of the Carmanville Melange (this study), and distinctive coticule rich shales and siltstones of the Woody Island formation (Currie, 1992), abut the northeast trending units of the Davidsville Group. The contact marking the pronounced lithic contrast between the Hamilton Sound units and the Davidsville Group is poorly defined and interpreted as a fault. Definitions of the Hamilton Sound group have changed since the name was first introduced for the Noggin Cove Formation, Carmanville Melange, Woody Island siltstones, and units farther south (Currie, 1992; 1993). Differences in interpretation and nomenclature result from complexities presented by the Carmanville Melange and the lack of key relationships necessary to properly define the Hamilton Sound group. This study proposes that the Carmanville Melange is a diapiric intrusion rather than a stratigraphic unit. Accordingly, the Hamilton Sound group is changed to the Hamilton Sound complex. It includes the Carmanville Melange, the Teakettle melange, the Woody Island formation and the Noggin

Cove Formation. All other units previously assigned to the Hamilton Sound group (e.g.- Main Point shale and Wings Point greywacke; Currie, 1992; Round Pond shale, Currie, 1993) are dropped because they occur well away from Hamilton Sound, and descriptions of the Main Point shale and Wings Point greywacke (Currie, 1992; 1993) more closely resemble those of the Hunts Cove and Outflow formations of the Davidsville Group (O'Neill, 1991). Indeed the shales at Main Point were initially used as the type section for the Davidsville Group (Kennedy and McGonigal, 1972a).

The Noggin Cove Formation (Johnston, 1992) occurs in two large (5 and 10 km) discrete areas, that consist mainly of volcaniclastic debris flows, tuffs, lapilli tuffs, breccia, with minor basaltic pillow lava and black shale. Two main phases of deformation have been identified in these rocks. Early isoclinal folding, with a locally developed axial planar foliation, is overprinted at a high angle by a penetrative northeast trending cleavage associated with asymmetric, open to close folds. This main cleavage is parallel to the regional northeast structure of the Davidsville Group.

The Woody Island formation (Currie, 1992) contains alternating shale and siltstone beds from 5 to 10 centimetres in width. Thin (1-2 cm) Mn-rich layers are ubiquitous in this rock unit and are a characteristic feature. Olistostromal beds are also present on Woody Island. These have been included in the Carmanville Melange (Williams et al., 1991), but are not clearly traceable into the main body of the melange and may represent mobilization of locally derived material. Williams (1983) described a locally developed, early foliation of enigmatic origin, in the olistostromal horizons, that is overprinted by a stronger, penetrative cleavage that is axial planar to open, asymmetrical folds.

The main body of the Carmanville Melange occurs in coastal exposures along the periphery of the Noggin Cove Formation, and may be present in layers of the Woody Island formation. The melange is intimately associated with these units, but also occurs with rocks farther south, north of Davidsville, and across Gander Bay at Tippes Point. Spectacular examples of the Carmanville Melange are found on Teakettle Point, where the lithic and structural diversity is most striking. Pillowed basalts, commonly associated with limestone, sandstones and greywackes, gabbros, trondhjemites, siltstones and rhythmically bedded shales and siltstones, all occur as blocks in a black graphitic shale matrix.

Polyphase deformed and metamorphosed rocks outcrop in two areas at the north end of Teakettle Point. These rocks include psammite, deformed pillow lavas with associated marble, and layered mafic volcanics of questionable protolith. All of these lithologies exhibit variable degrees of deformation and metamorphism. They are distributed as blocks within a fine-grained, quartz veined, slaty matrix, imparting a 'block-in-matrix' texture to the assemblage, establishing it as a melange. Sharp, discordant contacts, with enclosing pebbly shale, demonstrate that the composite polyphase deformed melange rocks occur as discrete blocks in the Carmanville Melange. The strongly deformed metamorphic rocks are therefore interpreted to represent an earlier generation of melange. This older melange is named the Teakettle melange, and its two large (100 to 400 m) discrete occurrences, the Clyde Day and Otto Wheaton blocks. These blocks contain the best exposures of the polyphase deformed rocks of the Teakettle melange, locally exhibiting up to three phases of deformation and lower amphibolite facies metamorphism.

Lithologies in the Teakettle melange can be matched with lower grade equivalents in the Carmanville Melange. Both contain basaltic pillow lavas, commonly in association with marble or limestone, psammites represent greywackes, and the black pelitic slate matrix is a metamorphic equivalent to the lower grade shale matrix. The Teakettle melange is therefore lithologically comparable to some components of the Carmanville Melange, but apart from the obvious structural and metamorphic contrasts between the Carmanville and Teakettle melanges (fig. 1.2.2 a & b), they can be distinguished by: 1) the impressive lithic diversity, 2) the greater abundance of pebbly matrix in the Carmanville Melange, and 3) the pervasive quartz veining in the matrix of the Teakettle melange.

Contact relations between the Carmanville Melange and other units of the Hamilton Sound complex (Noggin Cove and Woody Island formations) are enigmatic. The distinguishing features of the Hamilton Sound complex include: the spatial distribution of the Noggin Cove and Woody Island formations with the Carmanville Melange, the coticule association of all three units, and that the nearest correlatives occur only towards the west (e.g. Carmanville and Dog Bay Melange = Dunnage Melange; Williams, 1992. Noggin Cove Formation = Loon Bay volcanics; Currie, 1993, pers. comm.). Correlation of the Noggin Cove Formation with the Loon Bay volcanics

Figure 1.2.2 a) Soft-sediment deformation in black and grey rhythmites: mixing of silty and shaly layers, with load structures (Carmanville Melange).

Figure 1.2.2 b) Intensely deformed laminated psammites. Fold in centre of photograph defined by composite crenulation fabric. Later brecciation cross-cuts all fabrics. (Teakettle melange)

suggests a Middle Ordovician or older age, for the volcaniclastic rocks, which is also a typical age for coticule (Mn-rich) bearing lithologies in the Exploits Subzone (Williams, 1992). Pebbly shales injecting adjacent rocks indicate that the emplacement of the Carmanville Melange must be, at least in part, younger than the other two units of the Hamilton Sound complex.

On the west side of Gander Bay, Williams et al. (1993) described a contact between dark, rusty, unfossiliferous shale with coticule nodules, which underlies a fossiliferous, coarse limestone breccia unit at the base of the Indian Islands Group. Correlations with neighbouring rocks suggest that the dark shale matches the Woody Island formation. Contacts between the Silurian Indian Islands Group and adjacent Ordovician rocks in the Carmanville area are faulted, but the abrupt lithic change implies a major erosional unconformity (Williams et al., 1993).

1.3 Previous Work in the Carmanville Melange

The first recognition and earliest description of melange around Carmanville was given by Kennedy and McGonigal (1972a), while subdividing the Gander Lake Group of Jenness (1963). They re-used the term Gander Lake Group for the meta-sedimentary, arenaceous lower unit of the original group. This change drew criticism (Bruckner, 1972; Jenness, 1972; Kennedy and McGonigal, 1972b) because it violated the Code of Stratigraphic Nomenclature (see Blackwood, 1982, for discussion). Thus, the arenaceous lower unit was named the Gander Group (Kennedy and McGonigal, 1972b). The name Davidsville Group was proposed (Kennedy and McGonigal, 1972a) for the middle and upper units of the Gander Lake Group and included all the rocks of the present Hamilton Sound complex. Polyphase deformation and greenschist to lower amphibolite facies metamorphism in the Gander Group was believed to pre-date deposition of the Davidsville Group and the contact between the two was therefore interpreted as a major angular unconformity.

Polyphase deformed and metamorphosed blocks of psammite, semi-pelite and metavolcanic rocks (Teakettle melange) in the Carmanville Melange were recognized by Kennedy and McGonigal (1972a) and correlated with the Gander Group. Because the melange was considered part of the Ordovician Davidsville Group, this occurrence of deformed Gander rocks (Kennedy, 1975) confirmed the validity of the Ganderian Orogeny.

Kennedy and McGonigal (1972a) also recognized contrasting metamorphic grades in the melange matrices. They attributed the abundant quartz veining and the slaty (as opposed to shaly) nature of the matrix surrounding the highly deformed blocks, to greater depths of burial and attendant metamorphism. They speculated that the melange may be a basal, stratigraphic member of the Davidsville Group, and that it may represent a zone of gravity sliding, or it may be an olistostrome.

Currie and Pajari (1977) saw no structural contrasts between the Gander and Davidsville groups of Kennedy and McGonigal (1972a), and believed the entire sequence to be conformable. According to Pajari and Currie (1978), the polydeformed blocks in the Carmanville Melange could have been derived from rocks of the Davidsville Group and deformed by soft-sediment deformation before metamorphism.

Pajari et al. (1979) conducted the first detailed study of the Carmanville Melange. Based on a tectonic model involving the emplacement of an allochthonous sheet of oceanic crust onto the Gander Zone, they believed that the Carmnville Melange represented major backsliding of large rafts and blocks (olistoliths) in post-Caradoc time, as a result of overthickening during pre-Llandeilo obduction. The Noggin Cove Formation was interpreted as an enormous raft in this melange.

They identified blocks of sedimentary, volcanic or volcaniclastic rock, and a few ultramafic blocks; all of which they matched with the nearby Gander River Complex. The black shale and siltstone matrix was believed to be "...derived solely from the disaggregation of thixotropic, unconsolidated sediment." (Pajari et al., 1979; p.1444), during the gravity collapse. The presence of ultramafic rocks in the melange, coupled with its spatial and presumed tectonic relationships to the Gander River Complex, led to the name Carmanville Ophiolitic Melange.

Pajari et al. (1979) also recognized pre-entrainment deformation in several blocks. They noted the different metamorphic grades of the matrices and suggested the highly strained rocks were perhaps part of an older matrix. They attributed these features to soft-sediment deformation and dynamothermal metamorphism, possibly generated in the sole of obducted ophiolite.

Several examples of shaly intrusions into blocks and surrounding rocks, on Woody Island, were also described by Pajari et al. (1979). These dykes were equated with the main body of the melange, and were employed to support an olistostromal or gravity slide model. The large amounts of pressure required to forcefully inject shale into weakness planes in adjacent units was considered to be a logical consequence of being overridden by an enormous raft of rock.

Williams (1983) studied the Carmanville Melange mainly on Woody (Green) Island. He showed that the apparent soft-sediment deformation/mobility of the melange, described by Pajari et al. (1979), could be explained in terms of hard rock deformation. Although soft-sediment structures were recognized (e.g. convolute bedding), along with the early fabric of enigmatic origin, he attributed most of the structures to *in situ* hard rock deformation. He did not speculate on the origins of the melange rocks at Teakettle Point.

Williams et al. (1991) recognized olistostromal and tectonic features (Teakettle melange) in the Carmanville Melange. They interpreted the strongly deformed and metamorphosed rocks as an early generation of melange, and suggested derivation by dynamic processes, whereby surficial olistostromes were deeply buried and subjected to dynamothermal conditions, then exhumed and recycled into a younger melange. The preferential distribution of the Carmanville Melange, at the coastal periphery of the large discrete occurrences of the Noggin Cove Formation, led Williams et al. (1991) to suggest that the Noggin Cove Formation was a structural slice above the melange, and that its emplacement controlled melange formation.

Johnston (1992) interpreted the Carmanville Melange as an olistostrome overlying the Noggin Cove Formation and transitional with, or beneath, the Woody Island formation. He believed that the mafic volcanic rocks in the melange were derived mainly from the Noggin Cove Formation. Rare earth element signatures of selected basalts in these areas display a gradation from back-arc and rifted-arc environments in the Noggin Cove Formation, to characteristic MORB patterns in the melange. Drawing an analogy between these rocks and those of the Lau Basin, in the South Pacific, and the Valu Fa Ridge, Johnston (1992) interpreted the Noggin Cove Formation as the remnants of an evolved, rifted-arc volcanic system. After the opening of a back-arc basin, later tectonic instability resulted in resedimentation of the volcanic pile and deposition of debris flow conglomerates, followed by olistostromal melange.

1.4 Problems with previous models

None of the foregoing models adequately explain the enigmatic internal features of the Carmanville Melange, nor its significance in existing regional geological and tectonic frameworks. Prominent shortcomings, or fundamental questions, are listed here:

1) The abundance of mafic volcanic rocks in the Teakettle melange blocks versus their absence in the Gander Group casts doubt on correlations made by Kennedy and McGonigal (1972a) between deformed melange blocks and the Gander Group.

2) The upper and lower melange levels of Kennedy and McGonigal (1972a), based on the degree of metamorphism in the matrix, are unfounded because the higher grade, highly deformed matrix rocks occur as discrete blocks, included in lower grade, mildly deformed melange matrix.

3) The idea that the structures in these blocks developed through soft-sediment deformation (Pajari and Currie, 1978) is rejected because of the widespread folding of metamorphic fabrics in the blocks and quartz veins in the matrix.

4) The gravity slide model of Pajari et al. (1979) implies an intimate association with the Gander River Complex. This model is suspect for 3 principle reasons: i) compared to the regional extent of the Gander River Complex, the Carmanville Melange is a relatively small, local occurrence; ii) if the melanges across the northeast Exploits Subzone are related, they form an east-west belt, that is discordant with the northeast-southwest trend of the Gander River Complex; iii) apart from a single occurrence in Aspen Cove, there are few ultramafic clasts in the melange, and this paucity of ultramafic clasts divorces the Carmanville Melange from the Gander River Complex (Williams et al., 1991).

5) The assumption that all the blocks in the melange are locally derived is at odds with the regional geology. Most of the blocks can be matched individually with units outside the melange, but, when viewed as a whole, the relative proportion of various lithologies is inconsistent with the neighbouring geology. For example, the Noggin Cove Formation contains the only large collection of mafic volcanics in the immediate area, but

the lack of coarse volcanic conglomerates of Noggin Cove Formation type in the melange argues against a direct link between the Noggin Cove Formation and Carmanville Melange volcanic blocks. Further, the abrupt depositional transition from volcaniclastic debris flows (NCF) to fine-grained shaly to silty melange (CM), with abundant sedimentary clasts, seems unlikely.

6) The setting and regional relations of the Carmanville Melange are further confused by the changing definitions of the Hamilton Sound complex, and relations with the Davidsville Group.

Following Williams et al. (1991), this study supports a tectonic, rather than stratigraphic, relationship between the Noggin Cove Formation and the Carmanville Melange. However, while melange distribution may be related to the emplacement of the Noggin Cove Formation (Williams et al., 1991), the great diversity of clast lithologies in the melange, and its obvious polygenetic history suggest that its formation must have had more complex controls.

1.5 Purpose and scope

The Carmanville Melange displays many problematic features that are difficult to explain in terms of normal sedimentary or tectonic processes. Among these are: 1) the nature and origin of the Teakettle melange rocks, 2) the juxtaposition of rocks with such extreme contrasts in structural and metamorphic styles, 3) the anomalous proportions of mafic volcanic and sedimentary rocks, compared to the regional geology, 4) conspicuous brecciation textures in greywackes and psammites, and 5) viscous mobility of the melange, as shown by pebbly shale injections.

The origin of the polydeformed and metamorphosed Teakettle melange blocks is the most enigmatic problem of the Carmanville Melange, because similar rocks are unknown elsewhere in the Exploits Subzone. Their significance and mode of incorporation into the Carmanville Melange is the chief purpose of this study. The fact that these blocks were derived from an older melange, raises the question of whether or not they represent a previous tectonic event that is unrecorded elsewhere (Ganderian Orogeny), and if not, how are they related to the melange forming process? It is unlikely that a tectonic event capable of producing polyphase deformation and amphibolite facies metamorphism would be confined to a few blocks. This study is therefore aimed at producing a polygenetic model, that addresses and rationalizes these concerns.

Approximately three kilometres of continuous outcrop on the shores of Teakettle Point, northeast of Carmanville South, provide the most complete exposures of the more important features in the Carmanville Melange. This peninsula was mapped in detail, at 1:5,000 scale, to improve upon existing maps.

The Hamilton Sound complex is introduced for clarity in the regional geological setting of the Carmanville Melange (section 1.2). The name Teakettle melange is proposed for the higher grade, polydeformed melange blocks at Teakettle Point, Gaze Point and the Fredericton shoreline. The two large occurrences, that form the type sections on the northeast head of Teakettle Point are named the Clyde Day and Otto

Wheaton blocks. These blocks were mapped in greater detail, to examine the structural relationships within the blocks and further constrain ideas about their origin. Other key blocks in the Carmanville Melange have also been named for ease of reference and sharper definition.

Major and trace element compositions of 25 mafic volcanic blocks were determined for comparisons between blocks in the Teakettle and Carmanville melanges, and with the Noggin Cove Formation. Five of the 25 samples were taken from deformed amphibolites of the Teakettle melange.

Finally, the origin of the Teakettle melange blocks is discussed, and a model, which allows their incorporation, is proposed for the emplacement of the Carmanville Melange.

CHAPTER 2

Geology of the Carmanville and Teakettle melanges

2.1 Carmanville Melange

Name, Definition and Distribution

The Carmanville Melange is exposed sporadically along the shore of Hamilton Sound, between Gander Bay and Aspen Cove (fig. 1.2.1). A former name, 'Carmanville Ophiolitic Melange' (Pajari et al., 1979), was given to all those rocks located within "...the geographic extent of matrix horizons". With no clear definition of 'matrix horizons', many occurrences of black shale, throughout the area, were mapped as melange. The Carmanville Ophiolitic Melange thus included the two large discrete occurrences of the Noggin Cove Formation, and broad upper parts of the Davidsville Group (Round Pond shale and Main Point shale). With this boundary condition for the extent of the melange, almost the entire Exploits Subzone could be included in the Carmanville Melange, as matrix horizons occur throughout. This criterion is clearly unsatisfactory and requires revision.

Williams et al. (1991) divorced the melange from the Gander River Complex and dropped 'ophiolitic' from the name, because: 1) although the melange locally shares a spatial relationship to the northeastern extremity of the Gander River Complex, the latter extends for an additional 150 kilometres southwestward, and 2) while mafic pillow lava and gabbro blocks in the melange may be of ophiolitic affinity, ultramafic rocks are extremely rare. The redefined Carmanville Melange also excluded the Noggin Cove Formation, and intact parts of the Davidsville Group.

The Carmanville Melange is here defined as disrupted black shale and siltstone, lacking intact bedding in the matrix, and which may contain any complement of exotic fragments or blocks. The melange occurs mainly on the northern periphery of the Noggin Cove Formation, at Teakettle Point, and along the shore between Fredericton and Noggin Cove. Other occurrences are found southeast of the Noggin Cove Formation along the east shore of Gander Bay, and across Gander Bay, in Victoria Cove. A pebbly shale unit, containing blocks of pillowed basalt, may be correlative and extends southwest from Tippe's Point. Western occurrences extend to the Dog Bay Line (Williams, 1992; Williams et al., 1993). Melange occurrences here and farther west to the Dunnage Melange may be correlatives. Olistostromal beds and a pebbly shale dyke, on Woody Island and nearby islands, have been included in the Carmanville Melange (Pajari et al., 1979). Two other occurrences are preserved on Rocky Point and in Aspen Cove. Farther east, the melange is truncated by the Rocky Bay and Aspen Cove plutons.

The Carmanville Melange is presumed to be continuous under Hamilton Sound, between the Noggin Cove and the Woody Island formations. If true, its greatest width would be approximately 6 kilometres north of English Harbour (fig. 2.1.1).

Description

The Carmanville Melange (fig. 2.1.1 - map in back pocket) is a chaotic mixture of a broad spectrum of lithologies incorporated as blocks in a fine-grained shaly to silty matrix. While a size gradation exists, from less than 1 millimetre to greater than 400 metres, the very poorly sorted clast population appears roughly bimodal. Fragments less than 3 centimetres are ubiquitous, with local concentrations of larger fragments and blocks occurring without any gradation. In the following description, `melange matrix' is arbitrarily set to include all fragments or clasts less than 3 centimetres; larger clasts are termed `blocks'.

Polyphase deformed and metamorphosed melange rocks, termed the Teakettle melange, form the largest blocks in the Carmanville Melange. Other major block-forming rock types in the enclosing Carmanville Melange include, in order of abundance: pillow lavas and other mafic flows, breccia and lapilli tuffs, greywacke and sandstone, rhythmically-bedded black shale and grey siltstone, gabbro, trondhjemite, siltstone with minor chert layers, limestone, and rhyolite. All these rock types are found on Teakettle Point, with low grade mafic volcanic rocks dominating southern exposures, gabbros and trondhjemites midway up the coast, and the Teakettle melange is found mainly at the northern point of the peninsula. Sedimentary blocks are dispersed throughout the melange. While strong lithological associations and a crude clustering of the blocks exist, this rock assemblage is markedly disordered.

Blocks

Mafic volcanic rocks are the most abundant block type and areally comprise 60-70% of the block load. Pillow lavas typically form large, prominent blocks (fig. 2.1.2 - Marshall Day Block) and are the most obvious component in the melange. These range from 5 to 100 metres across; the larger blocks are typically elongate and irregular in shape, while smaller ones are more equidimensional. The pillow basalts exhibit a wide variety of petrographic features and virtually every occurrence is distinct. Individual blocks are characterized by limestone filled pillow shelves (Sawyer and Barnes, 1983), spherulitic rims and selvedges (Marshall Day Block), peculiar `bullseye' patterns (fig. 2.1.3; Maisy Hicks Block), clear siliceous beads (Ron Boone Block), inter-pillow shales with sphalerite crystals (Vicki Hicks Block) and hydrogrossular (?) garnet (Ron Boone Block). Despite this diversity, all the blocks share an intimate association with limestone. In the Ron Boone Block, limestone forms a bed about 1 metre thick between pillow layers, but the most widespread occurrences are interpillow lenses or pods. Limestone also forms the matrix for a brecciated basalt block (Steven Hicks Block). Many of the pillowed basalts also share bedding contacts with greywacke and sandstone (Scott Hicks, Joan Hicks and Velma's blocks).

Minor massive flows form elongate blocks between 3 to 25 metres long and are rarely more than 2 metres thick. They are typically massive basalts but may have thin, wispy layers of finer grained material. Jackie's Block is a basalt flow interbedded with lapilli tuff. Olive-green, angular fragments less than 2 centimetres long make up about

Figure 2.1.2 - Well-preserved pillows (Marshall Day Block), essentially undeformed.

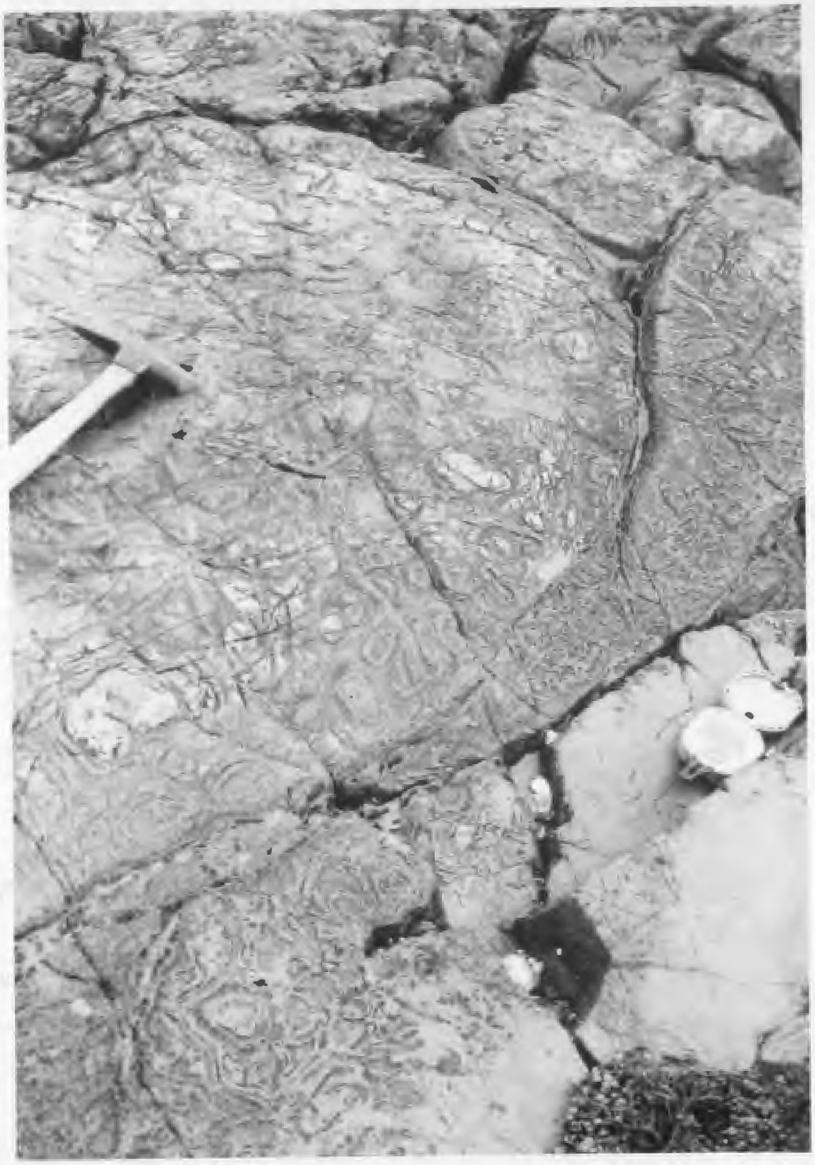


Figure 2.1.3 - `Bullseye' pillow pattern in large basalt pillows of the Maisy Hicks Block, at north end of Teakettle Point.

60% of the tuff, and all have white rims in contact with their volcaniclastic matrix.

The shapes of the larger mafic volcanic blocks appear to be mainly controlled by lithology, rather than deformation. Flow and bedded tuff blocks are elongate, with no obvious preferred orientation; while pillow lava blocks are roughly equidimensional.

Greywacke and sandstones are the most voluminous component of the melange in the smaller granule (<1 cm) to boulder (30 cm to 3 m) size range. They occur ubiquitously as angular to well-rounded fragments, with areally heterogeneous concentrations from less than 5% to more than 60%, in relation to melange matrix. Grain sizes range from very fine- to medium-grained sandstone with quartz granules. Some fragments show thin (mm scale) bedding, but most are massive. These rocks weather to a dusty beige. Some of the clasts have a distinctive flame-textured, purple sheen given by biotite, which may indicate minor hornfelsing. Boulder size sandstones and greywackes are commonly internally brecciated, with an intricate network of fine (1-5mm) fractures that appear to be shale filled. This texture was described by Cowan (1982), who first termed it 'web-structure'. The larger greywacke and sandstone occurrences (>10 m) are usually in stratigraphic contact (Joan Hicks and Velma's blocks), or interbedded with pillow basalt blocks (Scott Hicks Block). One large (15 X 5 m), massive greywacke block, between the Clyde Day and Otto Wheaton blocks, contains 5-10 centimetre long, irregularly shaped, calc-silicate lenses (Roy Collins Block). Olistostrome units in the Woody Island formation contain mostly shale clasts and greywacke blocks in a black shale matrix.

The most common bedded sections in the melange occur as rhythmically alternating 5-10 centimetre thick beds of black shale and grey siltstone. The best examples of these 'rhythmite' units are the Gary Collins and the Daniel Collins Blocks. Bed thicknesses are very persistent without much variation from block to block. These sections contain abundant pyrite and rare manganese nodules. They have a ubiquitous Fe-staining that largely obscures primary depositional features. Rare top indicators, such as graded bedding, give opposing younging directions. This indicates isoclinal folding.

Locally, in the Gary Collins Block, the siltstone layers are asymmetrically boudinaged and attenuated into lenses isolated in shale (fig. 2.1.4). A small area in the Daniel Collins Block, farther north, has been imparted with a phacoidal cleavage (fig. 2.1.5) that resembles the scaly clay ('*argille scagliose*') fabric described by Hsu (1968) and Cowan (1985).

These rhythmites locally contain layered, limestone lenses and pods. Pods are elliptical and typically 50 centimetres long, but one pod is approximately 1.5 metres long. These pods are concentrically zoned from the rims, with thin shaly layers, to the cores of relatively pure limestone. Bedding parallel lenses are between 5-20 centimetres wide and can attain lengths greater than 10 metres. At the southwest end of the Gary Collins Block, two limy pods occupy the same depositional horizon. These limestone occurrences are most likely *in situ* concretions, rather than transported boulders.

Figure 2.1.5 - Phacoidal cleavage in rhythmites (Daniel Collins Block). This block contains no foreign material.

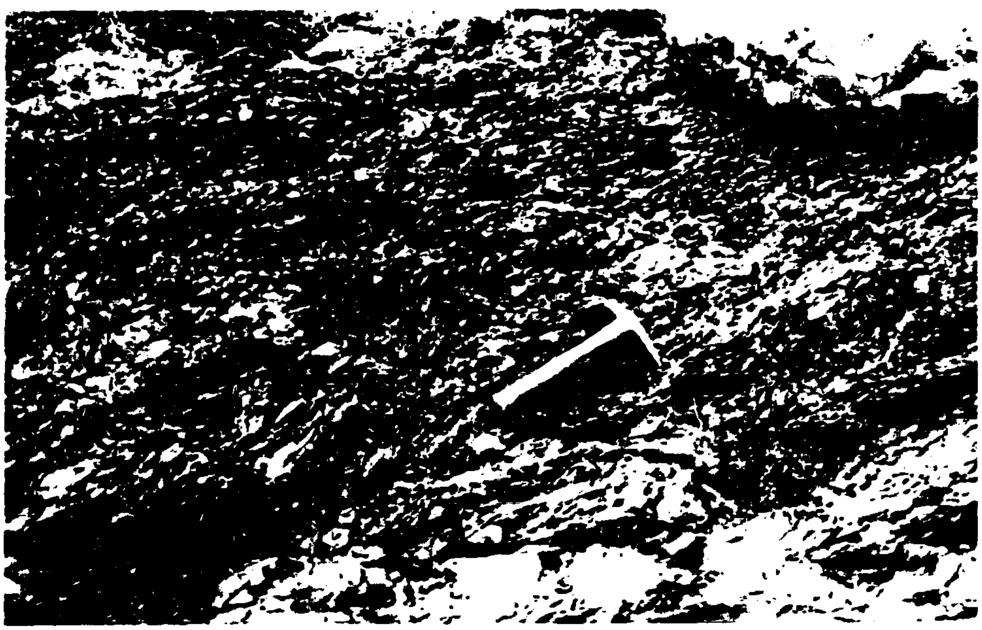


Figure 2.1.5 - Phacoidal cleavage in rhythmites (Daniel Collins Block). This block contains no foreign material.

Bedded siltstone and shale (fig. 2.1.6), of the Jennifer Collins Block, are in contact with the westernmost Teakettle melange block (Clyde Day Block). Siltstone layers are about 5 times as thick as the boudinaged 1 centimetre thick shale layers. Bedding thicknesses in this block are much more variable than in the rhythmites. Siltstone beds gradually thin westward, across strike, where exotic angular fragments have been incorporated into thickened shaly layers.

A large composite block of fine-grained gabbro and trondhjemite occurs halfway up the coast (Eugene Hicks Block). The gabbro is intensely cleaved and locally sheared at the contact with the trondhjemite. The trondhjemite does not display this strong cleavage, but is locally cut by 5 centimetre wide shear zones and everywhere exhibits two phases of internal brecciation. Unlike the shale filling in the brecciated greywacke and sandstone boulders, these brecciation fractures are filled with fine-grained quartz and locally derived trondhjemite fragments. This brecciation is a typical feature of trondhjemite in the Gander River Complex, but shows no obvious relationship to the melange. The trondhjemite is locally intruded by mafic dykes, 10 to 15 centimetres wide. The dyke walls are curved and billowy, with lobate terminations, suggesting they were emplaced into a viscous medium. However, the dykes do not appear to be brecciated.

The Yvonne Collins Block is a bedded, grey siltstone unit, with locally interbedded chert layers. The siltstone is laced with very fine quartz stringlets that commonly display very tight intrafolial folds. Hinges of these folds are mildly brecciated. Chert layers are 2-5 centimetres thick and occur in a 1 metre wide zone within the

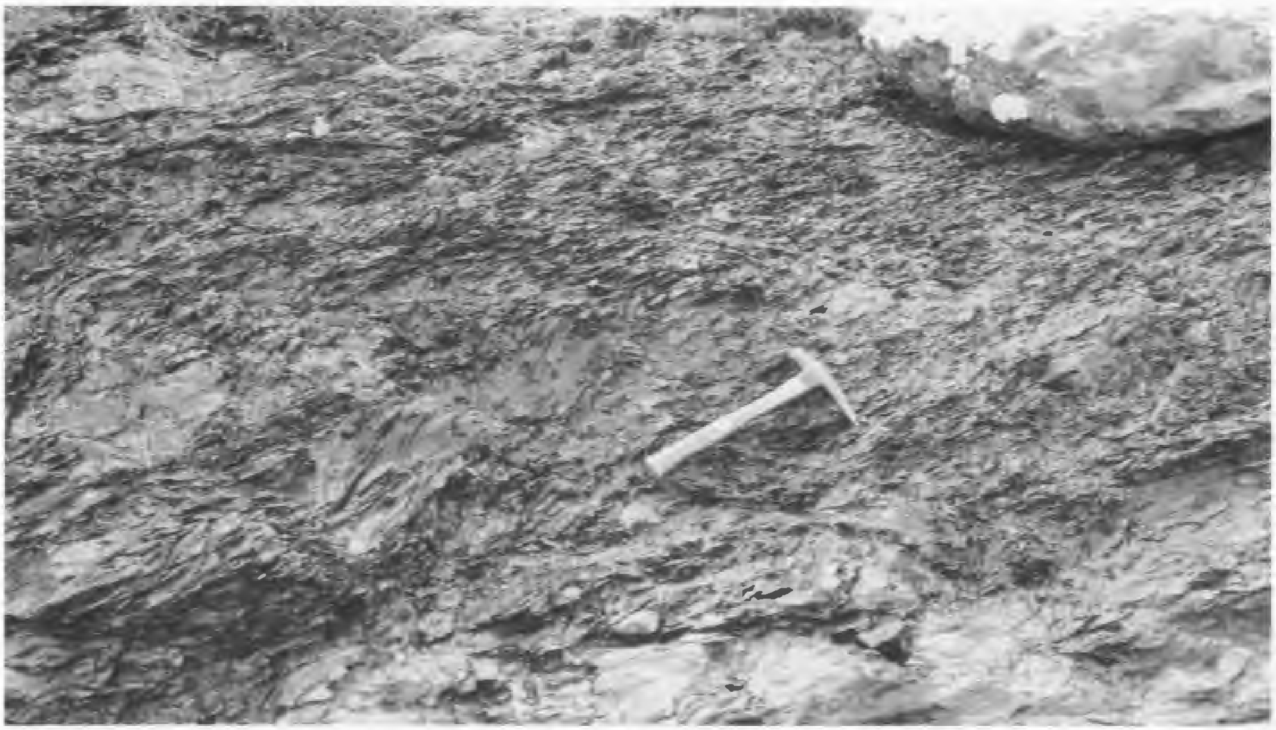


Figure 2.1.5 - Phacoidal cleavage in rhythmites (Daniel Collins Block). This block contains no foreign material.

siltstone (fig. 2.1.7). This cherty zone horizon outlines a chevron style fold for this narrow siltstone block.

A 3 metre wide rhyolite flow occurs on the northern periphery of the Bob Gillingham block, at the northwestern corner of the peninsula. The rhyolite contains abundant angular clasts of granitic composition and shaly material (fig. 2.1.8) floating in a dark, very fine-grained matrix. This texture strongly resembles the block-in-matrix texture of the Carmanville Melange, and is therefore not easily distinguished from it.

Matrix

The chaos and disorder of the melange is reflected and amplified on a smaller scale in the fine-grained matrix (fig. 2.1.9). Mesoscopically, the melange is a very poorly sorted collection of angular to rounded rock fragments of mainly sedimentary material, entrained in a shale matrix. Microscopically, the matrix is a mixture of silty shale and comminuted fragments of entrained clasts, and the variability of its composition, clast distribution and fabrics is extreme. Sedimentary fragments are the most abundant; they include: shale, siltstone, fine-grained sandstone and quartz-granule sandstone. A single clast of red shale, about 4 centimetres long, occurs immediately north of the Yvonne Collins block. Volcanic fragments are also present in minor amounts. They include: siliceous blebs, aphanitic and porphyritic basalt pebbles. All clast lithologies are angular to rounded, and show no preferred shape at any locality. A bluish metallic tint stains the black melange matrix in the vicinity of the Ron Boone Block, near the large bay on the

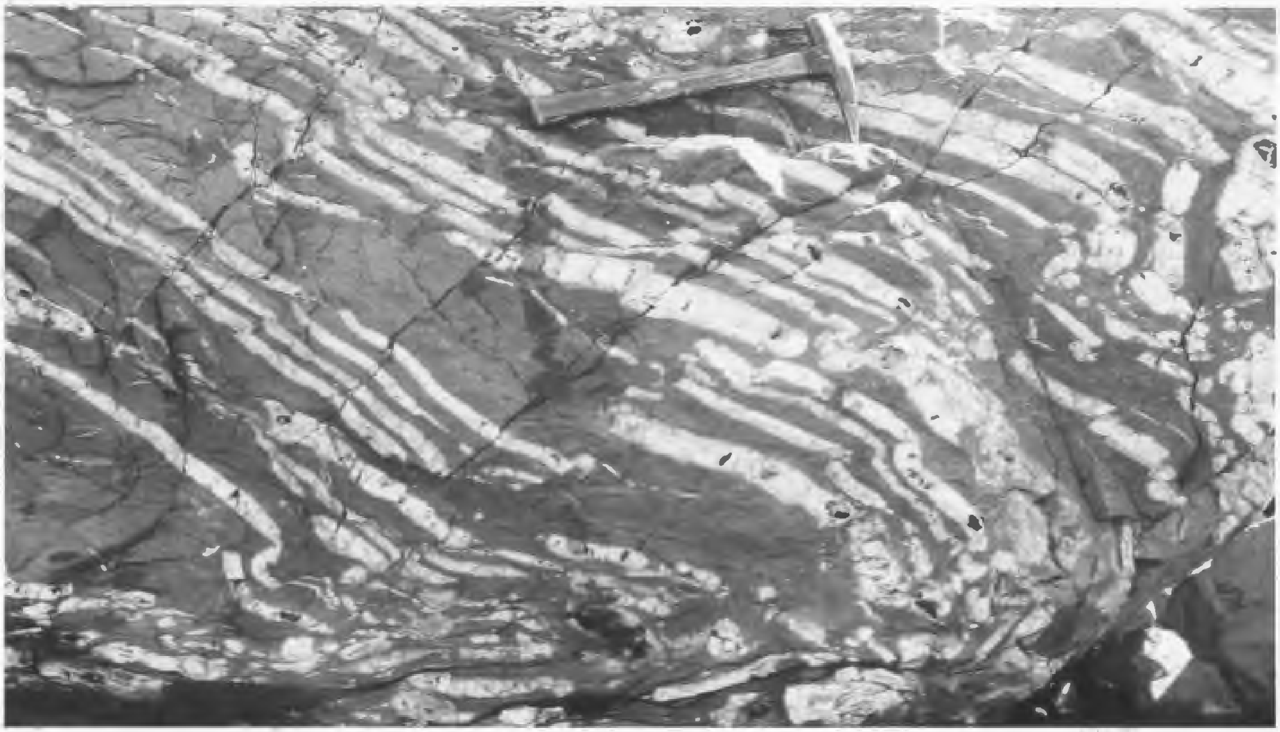


Figure 2.1.7 - Grey siltstone unit (Yvonne Collins Block), with interbedded chert layers. The chert layers highlight the chevron fold geometry of this block.

Figure 2.1.8 - Clast rich rhyolite, on north end of the Bob Gillingham Block of trondhjemite. Texture resembles melange matrix (compare fig. 2.1.9)

Figure 2.1.10 - Matrix dyke of silty shale crosses intact pillowed basalt of the Ellis Coles Block.

northwest corner of Teakettle Point. In thin section, this rock revealed high concentrations of microscopic garnets, strikingly similar to those found in coticule layers. However, the typical layering of coticules was not observed anywhere in the melange matrix.

In outcrop, the melange matrix appears mostly massive, but many areas show flow structures defined by discontinuous silty layers and elongate clasts aligned parallel to the main fabric orientation. This attenuation fabric wraps around larger clasts and contains intrafolial folds, defined by the planar siltstone layering.

The background matrix to the pebbles and the attenuated lenses, is generally dark and fine-grained. Some areas are lighter and slightly coarser grained. These zones are patchy and attenuated in the same way as siltstone layers elsewhere. Quartz granules, the same size as those in the quartz granule sandstones, and possibly derived from them, are also commonly dispersed throughout the matrix.

The pebbly matrix pierces cleavage planes and fractures of all lithologies. The best example on Teakettle Point is a matrix dyke 10 centimetres wide, that crosses an entire 4 metre block of mafic pillows (fig. 2.1.10; Ellis Coles Block). Here, the intrusive matrix contains siltstone pebbles up to 4 centimetres long. This matrix also includes elongate shale fragments less than 1 centimetre, and attenuated silty layers. All inclusions lie within a strong flow fabric, which wraps around the larger clasts. On Woody Island, a melange dyke with a very strong planar fabric is heavily quartz-veined, and truncates bedding at a high angle (Johnston, 1992). A narrow silty shale zone (50 cm), with similar

Figure 2.1.10 - Matrix dyke of silty shale crosses intact pillowed basalt of the Ellis Coles Block.

flow fabrics, pierces more than 4 metres into the Noggin Cove Formation, southeast of the Keith Collins Block in English Harbour. Clast loads in the dykes are lower, but their lithologies and fabrics generally fall within the variation of those found within the main body of the melange, and are believed to be genetically related to the melange.

Relations to Nearby Units

The Carmanville Melange is in contact with every unit of the Hamilton Sound complex. Contacts are everywhere sharp and have been variably interpreted as tectonic (Williams et al., 1991), depositional (Williams et al., 1991 - Woody Island; Johnston, 1992) and intrusive (Pajari et al., 1979; this study).

On Woody Island, melange horizons interdigitate with the Woody Island formation. These are generally viewed as olistostromal beds (Pajari et al., 1979; Williams et al., 1991; Currie, 1992). Pajari et al. (1979) also described intricate, intrusive relationships between the olistostromal beds and overlying siltstones, where centimetre scale shale fragments were injected and isolated in the siltstone beds.

Contacts between melange and the Noggin Cove Formation are commonly interrupted by rhythmically bedded, 5 centimetre thick, black shale and grey siltstone horizons, identical to the Gary Collins, Keith Collins and Daniel Collins blocks. These rhythmites, in places along the coast northeast of Fredericton, exhibit intact bedding, parallel to the contact with the Noggin Cove Formation. Closer to Fredericton, they are tightly folded with bedding and cleavage orthogonal to the contact. Where the rhythmites are absent, the melange intimately follows the periphery of the Noggin Cove Formation. It pierces joints or fractures in the volcanics along the Fredericton shoreline and south of the Keith Collins Block in English Harbour.

On the east shore of Gander Bay and north of Davidsville, the melange is partly in fault contact with the Noggin Cove Formation. There, the quartz filled fault is a late brittle structure that diverges from the sharp melange/volcanic contact. Near Davidsville, the Carmanville Melange is faulted against the Main Point shale (Johnston, 1992).

2.2 Teakettle melange

Definition and distribution

The Teakettle melange is a package of intensely deformed and metamorphosed rocks, that everywhere occur as blocks in the Carmanville Melange. The best examples of these rocks are found in the type areas on Teakettle Point (see insets, fig. 2.1.1): the Clyde Day and Otto Wheaton blocks. Here, the Teakettle melange consists of psammites, laminated psammites, amphibolitic pillow lavas, in the Clyde Day Block, and mainly layered mafic volcanics and laminated psammite in the Otto Wheaton Block. The fine-grained, black graphitic slate matrix, rich in quartz veins and blebs, is strongly deformed, and contains variably deformed rocks whose fabrics are discordant with those in the Teakettle melange matrix (fig. 2.2.1 a&b).

Figure 2.2.1 a) Typical quartz rich matrix of Teakettle Melange (upper right). Note discordance of fabrics and quartz veins between laminated psammite block and melange matrix (Clyde Day Block).

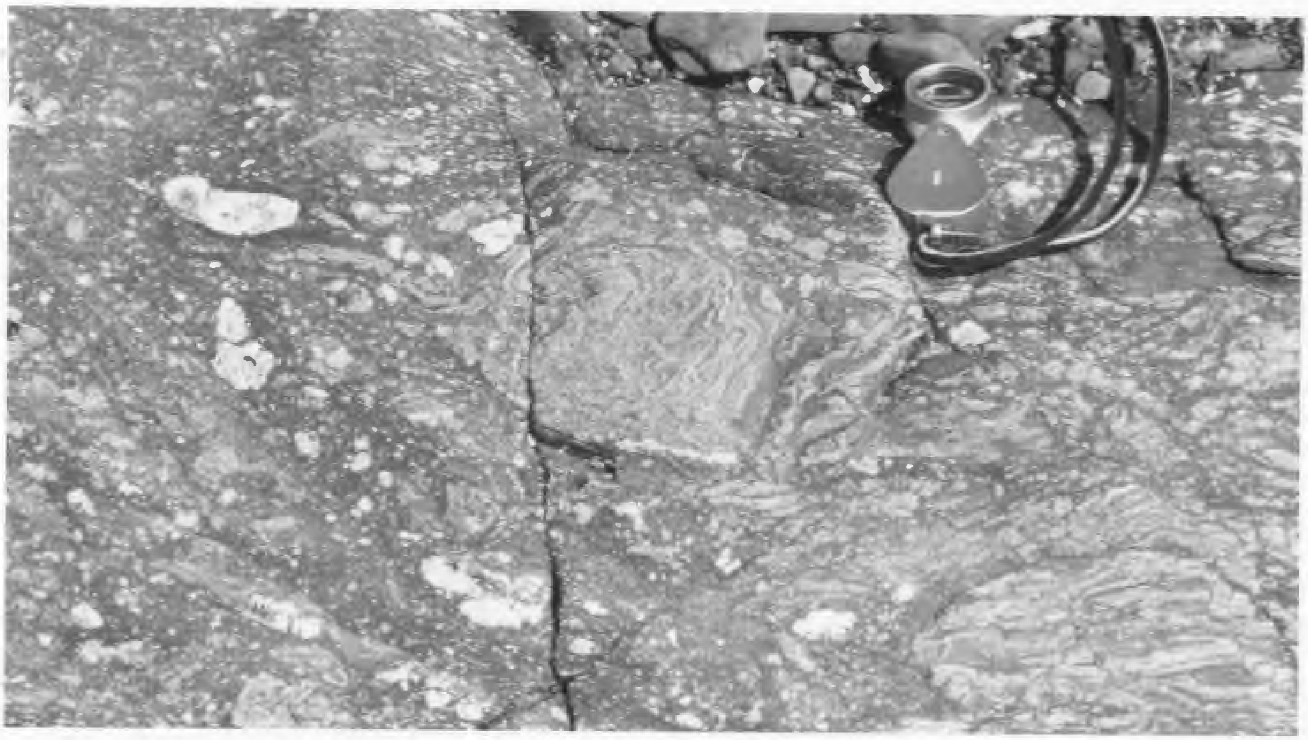


Figure 2.2.1 b) Isolated deformed clast floating in less quartz rich Teakettle melange matrix.

Other large blocks of Teakettle melange are found on the northern tip of Gaze Point (fig. 1.2.1) and along strike across Noggin Cove near Fredericton. The block at Gaze Point is 400 metres across and consists of olive green, strongly cleaved, banded greenschist. Minor amounts of melange matrix occur in a small cove on its western end. The occurrence northeast of Fredericton is more varied, and therefore similar to the Clyde Day Block. It contains psammites, laminated psammites and amphibolitic pillow lavas in a black, slaty, quartz matrix. Two smaller Teakettle melange blocks occur on Teakettle Point at the periphery of the Scott Hicks Block; one immediately northwest, the other southeast.

Description

Psammites generally form elongate blocks, from 3 to 100 metres long, and are commonly found in stratigraphic contact with amphibolitic pillow lavas in the Clyde Day Block, or layered mafic volcanic rocks in the Otto Wheaton Block. They occur with a wide variety of textures and range from biotite to staurolite grade metamorphism.

On the northern boundary of the Clyde Day Block, a black, mainly massive layer of psammite is juxtaposed with the low grade background melange matrix. This psammite has a very faint, biotite foliation and is locally cut by ptygmatically folded quartz veins. A few metres from the western edge of the Clyde Day Block, another psammite block has a very well developed, thin (1-5 mm), composite, gneissic lamination. Tiny, isoclinal folds can be traced in the thicker laminae, indicating that this is a transposed fabric. A larger psammite occurrence, near the southwestern edge of the Otto Wheaton Block, exhibits a similar transposed fabric that is overprinted by later folding. Laminated psammites commonly contain 5-10 centimetre long quartz lenses, surrounded by dark, pelitic melanosomes (fig. 2.2.2).

Another psammite block, 10 metres from the western border of the Otto Wheaton Block, has a strong foliation defined by muscovite and thin quartz veins. This foliation also displays multiple fold phases, each with its own episode of quartz veining. Psammites with thicker laminations (1-2 cm) are most abundant in the Otto Wheaton Block. These thick laminations are invariably boudinaged and erratically folded (fig.2.2.3). Fabrics in the psammitic rocks are commonly cut by breccia zones (fig. 2.2.4) that are filled with granulated, locally derived material.

Obvious pillow lavas occur only in the Clyde Day Block. In the Otto Wheaton Block, strongly cleaved, layered mafic volcanics may be highly strained pillow basalts or volcanic tuffs, however, the latter lithology is unknown in the Exploits Subzone. There is a remarkable variation in the degree of deformation in pillows of the Clyde Day Block. The least deformed pillows are easily recognized and preserved in the cores of larger blocks. The best example of amphibolitic pillows is found in the largest pillow block in the Clyde Day Block. Preserved bedding contacts occur between this pillow basalt block and psammite.

In other areas, strongly deformed pillows are not as easily recognized, and resemble cleaved mafic tuffs. On the north shore of the large bay in the Clyde Day

Figure 2.2.3 - Laminated psammites with thick laminations. The lamination is a transposed composite fabric that has been boudinaged, invaded by quartz veins and erratically folded (Otto Wheaton Block).

Figure 2.2.5 - Extremely high strain in pillow basalt block (Clyde Day Block). Pillows unrecognizable, but preserved pillow shelves (lower right), with marble filled layers indicate that at least parts of this rock were at one time pillowed basalts.

Figure 2.2.6 a) Highly strained pillow basalt (Clyde Day Block). Pillow shapes still recognizable and have an internal gneissic foliation.

Block, an excellent example of marble filled pillow shelves, similar to those in the Carmanville Melange, has been preserved in a highly strained pillow basalt section (fig. 2.2.5). In one block, a gneissic fabric has developed parallel to the main elongation direction of the strained pillows (fig. 2.2.6 a & b).

Layered mafic volcanic rocks commonly occur as very large blocks, from 50 to 400 metres long; the largest of which is on Gaze Point (fig.1.2.1). The Otto Wheaton Block contains two of these large blocks, and smaller occurrences are found in the Clyde Day Block. These are fine-grained, thinly-layered mafic rocks and compositionally monotonous. They possess a very strong, finely-spaced, pervasive cleavage that locally isolates discontinuous lenses of uncleaved rock.

All of these deformed and metamorphosed blocks are enclosed and locally intruded by a polyphase deformed and brecciated black slate matrix. The slaty matrix is heavily laden with boudined and deformed quartz plates, veins and pods. Most fabrics and structures in the metamorphic blocks, of the Teakettle melange, abut contacts with the surrounding Teakettle melange matrix at high angles; and the structures in this matrix are, in turn, discordant with those in the Carmanville Melange matrix.

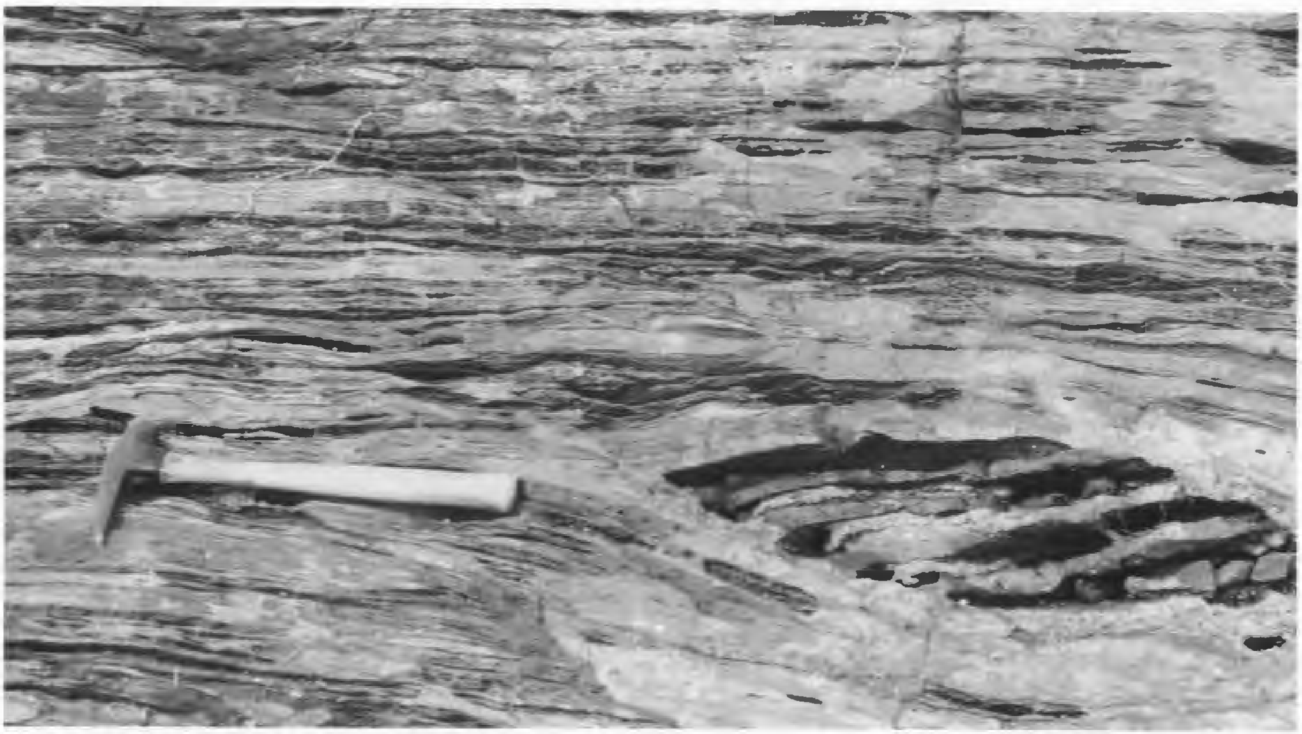


Figure 2.2.5 - Extremely high strain in pillow basalt block (Clyde Day Block). Pillows unrecognizable, but preserved pillow shelves (lower right), with marble filled layers indicate that at least parts of this rock were at one time pillowed basalts.

Figure 2.2.6 a) Highly strained pillow basalt (Clyde Day Block). Pillow shapes still recognizable and have an internal gneissic foliation.

Figure 2.2.6 b) Close up of gneissic foliation and pillow selvedge, in the area near lens cap (fig 2.2.6 a).

2.3 Discussion

It has been suggested (H. Williams, pers. comm.) that a `ghost stratigraphy' may be recognizable in the Carmanville Melange. This would be manifest as discontinuous horizons of equivalent or related blocks, separated by melange matrix, that mimic a relict stratigraphy. The main problem in identifying such a stratigraphy is that the internal structure of the melange is unknown; folded horizons cannot be delineated due to their lack of continuity, making them very difficult to trace.

Possible candidates outlining a potential `ghost horizon' are blocks of the Teakettle melange. Apart from smaller isolated occurrences, they all lie in a line roughly trending WNW-ESE (parallel to most of their internal fabrics), from Teakettle Point to Gaze Point and the Fredericton area. They are separated by water, as well as a peninsula formed by the Noggin Cove Formation. Alignment of Teakettle melange occurrences and parallelism of their internal structures are not currently understood.

Many blocks in the Carmanville Melange can be matched with rocks of the Davidsville Group, and other groups in Notre Dame Bay as follows: (1) red shale fragments may have been derived from the abundant red shales of the Weirs Pond Formation (Davidsville Group, O'Neill, 1991), (2) siltstone-hosted chert beds are very similar to those of the Main Point shale (Hamilton Sound group, Currie, 1992), (3) limestone-hosted basalt breccias resemble the Noggin Cove Formation (Johnston, 1992), the limestone-volcanic association is typical of the Summerford Group in Notre Dame Bay, (5) coticule rocks adjacent to the Ron Boone Block are typical of the Woody Island formation (Williams, 1992), (6) brecciated trondhjemites are typical of the Gander River Complex, north of Jonathon's Pond (unit 8, in GRUB of Blackwood, 1982), and on the northwest side of a roadcut on Route 330 (O'Neill, 1991). Most melange blocks are not entirely anomalous in a regional context. However, the preponderance of mafic pillow lavas in the melange is anomalous, and there is no source for the highly deformed and metamorphosed melange blocks. The chemistry of the basalts and the structures of both the Carmanville and Teakettle melanges are described in the following chapters to elucidate their geologic history, and therefore provide insight to their possible origins.

CHAPTER 3

Geochemistry of Mafic Volcanic Blocks

3.1 Introduction

The abundance of mafic volcanic blocks in the Carmanville Melange, compared to external units, invites geochemical characterization and comparison with other basaltic suites in the northeast Exploits Subzone

The mafic volcanic rocks in the Carmanville Melange have a typical greenschist facies metamorphic assemblage (actinolite/tremolite + chlorite + epidote + albite); those in the Teakettle melange occur with pelites that have a lower amphibolite facies assemblage, and are probably much higher grade. The immobility of certain elements during metamorphism and alteration (Pearce, 1975; Winchester and Floyd, 1976; 1977; Shervais, 1982; Swinden et al., 1990) allows comparison with modern volcanic rocks, and therefore distinction of ancient tectonic environments of magma generation.

Pressed pellets were prepared from the powders of 20 mafic rocks in the Carmanville Melange, and 5 from the Teakettle melange (see fig 3.3.1 for sample locations). Major and trace element data were obtained from these pellets using the X-ray fluorescence method described in Longerich (*in prep.*), which includes a detailed discussion of precisions and accuracies of this procedure. While the determination of light elements (Na, Mg, Al, Si, P, S, and Cl) from pressed pellets is not as accurate as those determined from fused pellets, the data is semi-quantitative and accuracy is sufficient for many applications (Longerich, *in prep.*). Heavy major elements (K, Ca, Ti, Mn, and Fe) are more easily determined with higher accuracy and, with matrix corrections, are comparable to values obtained from fused pellets. The major oxide values in this data set (Appendix I) yield generally low totals (avg.= 95%), perhaps due to the low accuracy determinations for the light elements. Trace element values are independent of the major oxides. One light element (Mg) and two heavy major elements (Ti, Fe) are used quantitatively in the foregoing analysis. Three high emission energy trace elements (Zr, Y, Nb) were also used and are considered reliable for the purposes of this study.

Of the 25 samples, 15 are unstrained pillowed basalts (two from Fredericton shoreline), 3 are highly strained pillowed basalts (Clyde Day Block, Teakettle melange), 2 are highly strained mafic tuff (Otto Wheaton Block, Teakettle melange), 2 are mafic volcanic flows, 1 is a massive gabbro, and 1 is a mafic dyke intruded into trondhjemite.

Discrimination diagrams were used to analyze the data. Significantly, the chemistries of the Teakettle melange volcanics are almost indistinguishable from those of the Carmanville Melange.

3.2 Discrimination Diagrams

During greenschist metamorphism and sea-floor hydrothermal alteration, it is generally agreed that the high field-strength elements (P, Ti, Y, Zr, Nb, Hf, Ta), Th, the transition metals (Sc, V, Cr, and Ni) and the rare earth elements are essentially immobile; while SiO_2, Na_2O, K_2O and most low field-strength elements (Cs, Rb, Ba, Sr) are mobilized under these conditions (Pearce, 1975; Winchester and Floyd, 1976; 1977; Shervais, 1982; Swinden et al., 1990). Syn-tectonic staurolite porphyroblasts (see Chapter 4) in pelites from the Teakettle melange, suggest lower amphibolite facies metamorphism. The presence of hornblende in metamorphosed mafic rocks is diagnostic of amphibolite facies metamorphism, but it is absent in the samples from the Teakettle melange. Typical greenschist facies minerals, epidote and chlorite, are also absent leaving the assemblage: actinolite/tremolite + albite +/- opaques. This assemblage may reflect a transitional stage between greenschist and amphibolite facies metamorphism, and these rocks are therefore interpreted as having been slightly affected by these higher grade conditions. In amphibolite facies rocks, Y, Nb, and TiO_2 remain immobile, while P_2O_5 and Zr show only very slight increases, and may still be used in discrimination diagrams (Winchester and Floyd, 1976; 1977).

Three distinct groups of magma types are distinguished in figure 3.2.1. The basalts group into: i) within plate basalts (WPB), ii) ocean floor basalts (OFB) or low-K tholeiites (LKT), and iii) one group has very low Ti values, and may belong to the calc-alkaline basalt (CAB) field (Mullen, 1983).

In figure 3.2.2, this low Ti group overlaps with the LKT group (area D). Both N-MORB (normal mid-ocean ridge basalt) and VAB (volcanic arc basalt) cluster in this area, and may not be distinguished further (Meschede, 1986). Samples of the WPB group, plot mainly in the within-plate alkali basalt (WPA) field.

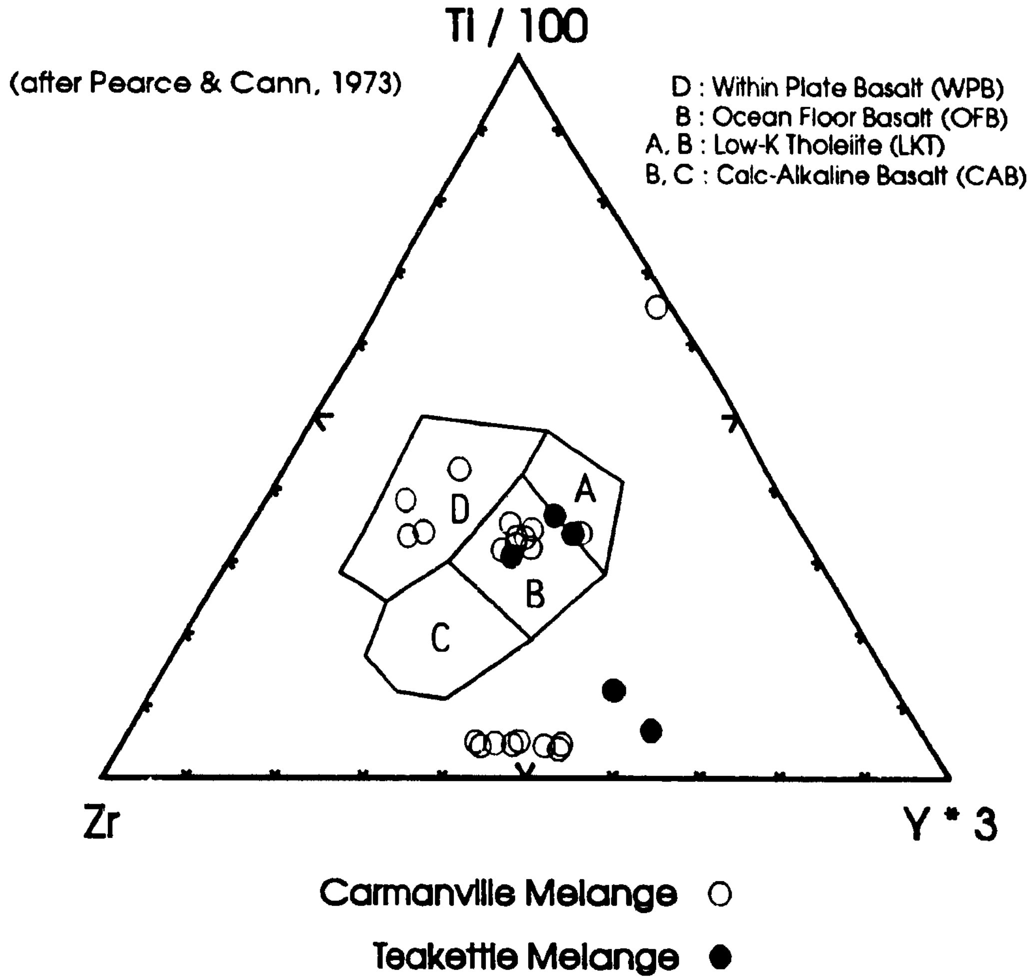


Figure 3.2.1 - Ti-Zr-Y discrimination diagram of basaltic rocks from the Carmanville and Teakettle melanges. The samples fall into three distinct groups: WPB, OFB, and a low Ti group. Note: Teakettle and Carmanville melanges both contain rocks with OFB and low-Ti chemical affinities.

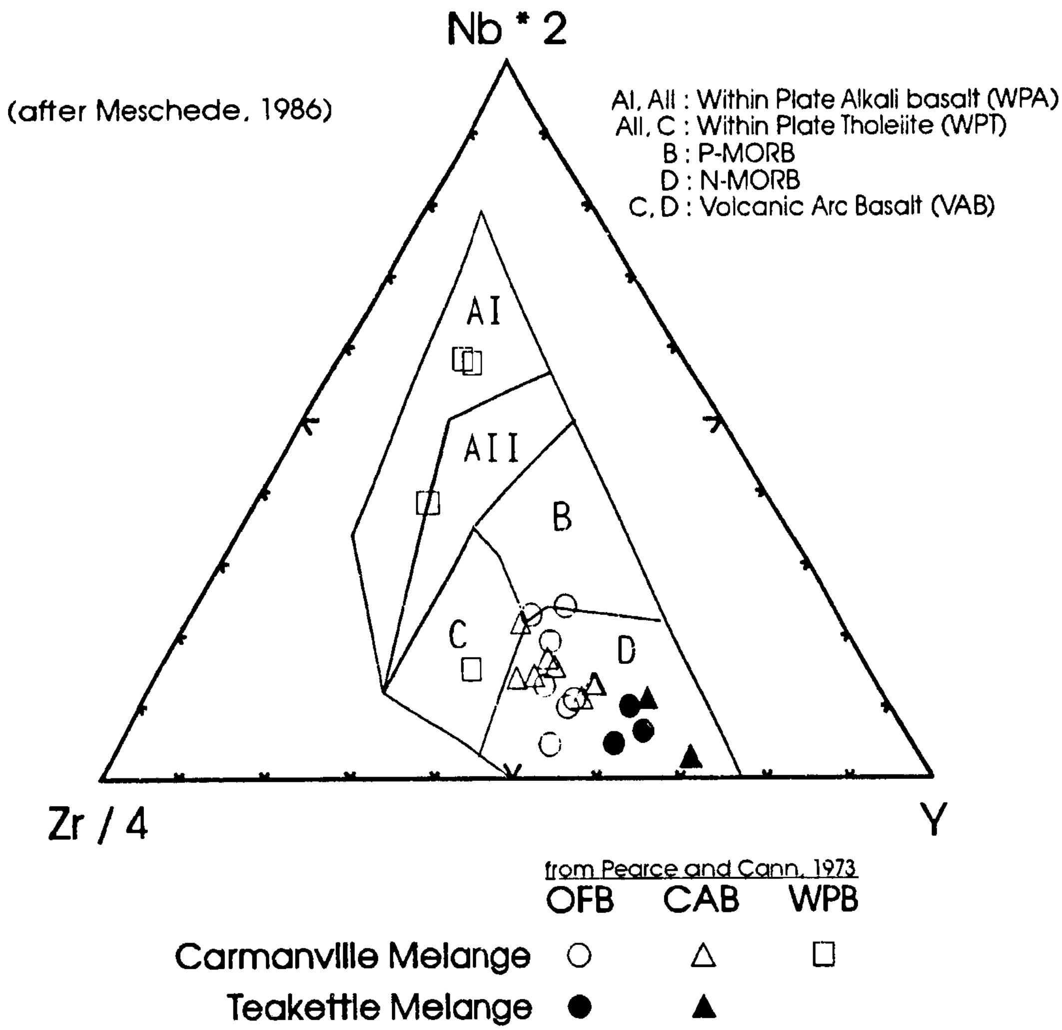


Figure 3.2.2 - Nb-Zr-Y discrimination diagram showing distribution of groups separated on Ti-Zr-Y plot of Pearce and Cann (1973), figure 3.2.1. Note: most samples fall into VAB or N-MORB fields, four samples (two from Fredericton shoreline) belong to within plate volcanic fields (WPA, WPT).

Comparisons between ancient pillow lavas and modern ocean floor basalts have shown that sub-seafloor metamorphism, at low water/rock ratios, may not substantially change the Mg# (molecular proportion 100MgO/[MgO+FeO]) of the rocks (Swinden et al., 1990). Figure 3.2.3 illustrates three separate fractionation trends on a plot of TiO_2 vs FeO^*/MgO, they are: tholeiitic with high TiO_2 (WPB group), tholeiitic with normal TiO_2 (Skaergaard)(LKT group), and invariant, low TiO_2 (CAB group). This shows that each group was derived from a distinct, fractionating magma; reinforcing the integrity of the groups. The consistent linear relationships between TiO_2 and FeO^*/MgO, further suggest that alteration and metamorphism have not substantially affected the Mg# of these rocks.

3.3 Discussion

Based on whole-rock geochemistry, this suite of basaltic rocks from the Carmanville and Teakettle melanges can be separated into three distinct tectonic groups: (1) WPB, (2) CAB/VAB, and (3) N-MORB. Petrographically, the individual groups are indistinguishable. They are typically porphyritic basalts with albite phenocrysts (15-50%; spherulitic in one block) in a groundmass of actinolite/tremolite (50-90%), chlorite (5-15%), epidote (0-10%), minor biotite (5-10%) and opaques (2-7%). Pillowed basalts of the Ron Boone Block contain garnets that are everywhere associated with calcite veins and most common in the pillow selvedges. These garnets are more likely a product of sea-floor hydrothermal activity (hydrogrossular), rather than high grade regional

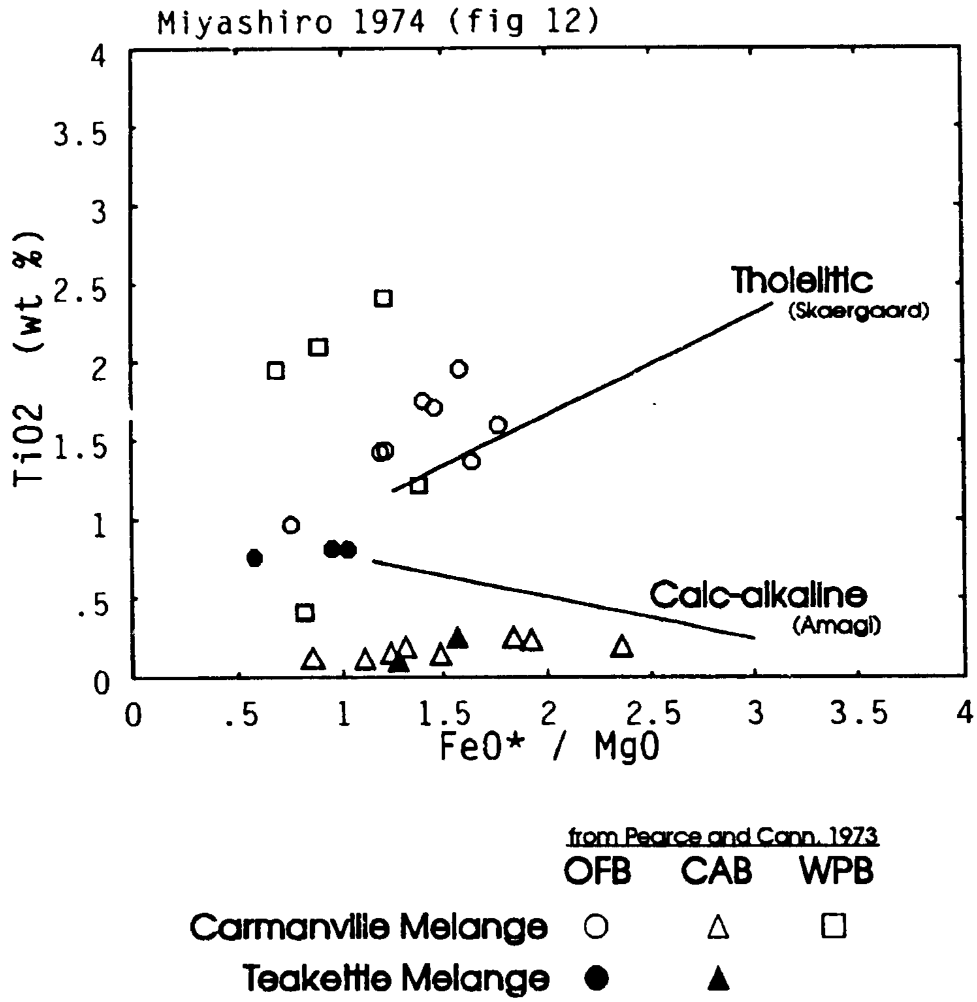


Figure 3.2.3 - TiO2 vs FeO/MgO. The three groups separated on the Ti-Zr-Y diagram of Pearce and Cann (1973) show separate fractionation trends. The CAB group is colinear with a tholeiitic line, and the WPB group, in part, forms a straight line above the tholeiitic line. The Teakettle Melange rocks are colinear with their respective groups.

metamorphism (pers. comm., Currie, 1993).

Both the N-MORB and calc-alkaline groups are represented in the Teakettle melange. The highly strained mafic tuffs have calc-alkalic affinities, and deformed pillows have both N-MORB and calc-alkaline signatures. Both of these groups are present in abundance in the Carmanville Melange. The lithological similarities between the two melanges are therefore enhanced by the trace element compositions.

The distribution of the different groups in the Carmanville and Teakettle melanges does not show any regular pattern (fig. 3.3.1). The 9 N-MORB rocks occur throughout the melange, alternating with the within-plate basalts in the south, and with the 7 calc-alkaline volcanic arc rocks in the northern half of the peninsula. The two pillow basalt samples taken from the shoreline northeast of Fredericton are within-plate basalts, as are the two mafic flows and the large gabbro body on Teakettle Point.

To explain the same geochemical affinities of volcanics within the Noggin Cove Formation and the Carmanville Melange, Johnston (1992) presented a model in which rifting of a volcanic arc led to the opening of a back-arc basin, followed by basinward deposition of reworked volcanics and melange. The Lau Basin was suggested as a modern analogue.

The geochemical results of this study mimic those reported by Johnston (1992). However, the lack of clear stratigraphic links between the Noggin Cove Formation and the Carmanville Melange casts doubt on temporal tectonic models founded on geochemical links between the two units. Furthermore, an olistostromal model, implying

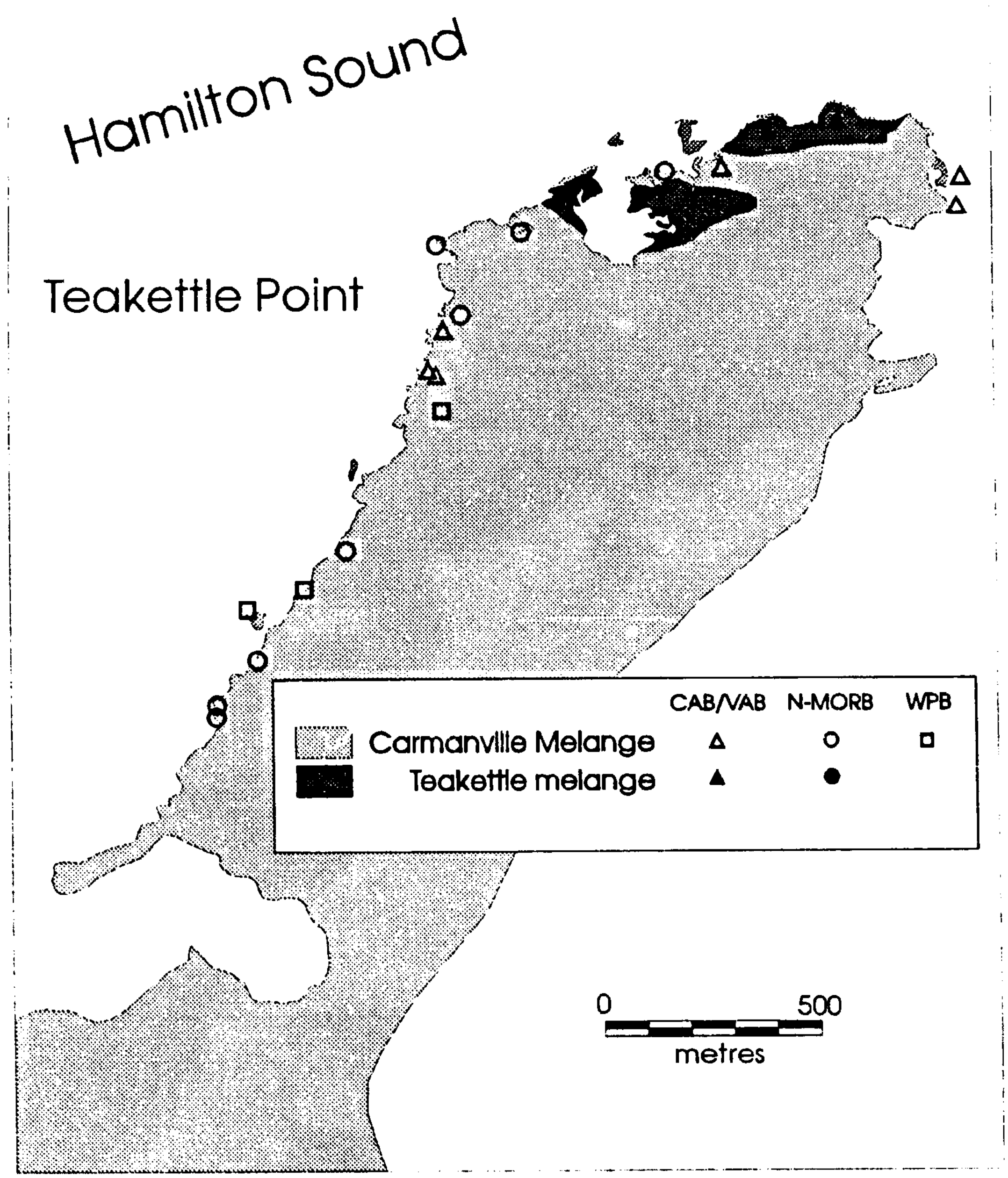


Figure 3.3.1 - Distribution of geochemistry samples on Teakettle Point. Note apparently random distribution of three groups, and both Teakettle and Carmanville melanges mainly contain volcanic arc and N-MORB rocks.

a similar source for the Noggin Cove Formation and the Carmanville Melange, cannot account for the polyphase deformation and metamorphism in the Teakettle melange, and does not predict similar chemical affinities of all volcanic rocks regardless of structural and metamorphic styles.

CHAPTER 4

Structural Styles in the Carmanville and Teakettle melanges

The Carmanville Melange displays features of soft-sediment deformation, penetrative ductile deformation and metamorphism, and cataclastic flow. Fabrics of the Carmanville and Teakettle melanges exhibit progressive strain histories, both with polyphase overprinting. Significantly, the melanges developed in two distinct deformation environments. This contrast in structural development provides important constraints on genetic models.

Soft-sediment deformation is best seen in the Carmanville Melange matrix and tectonic deformation in its entrained blocks, especially the Teakettle melange blocks (Clyde Day and Otto Wheaton blocks). The contrasting structural styles between the Carmanville Melange matrix, Carmanville Melange blocks and the Teakettle melange, are treated separately.

4.1 Carmanville Melange Matrix

Structural fabrics in the melange matrix reveal a progression from, ductile-plastic to brittle, cataclastic deformation. Colour bands formed by attenuated siltstone beds in the shale matrix define a discontinuous foliation that is very well developed in some places (fig. 4.1.1), and almost indiscernible in others (fig. 4.1.2). Locally, these siltstone layers display extreme boudinage and necking textures, resulting in a high degree of layer-parallel extension. Rare, rootless, isoclinal folds of thinned siltstone layers lie within this attenuated fabric (fig. 4.1.3). With higher degrees of attenuation, the small clast component of the melange increases (fig. 4.1.4). Equidimensional clasts interfere with the planar development of the fabric, while elongate clasts lie within the foliation. The fabric becomes more erratic around the larger inclusions, and the siltstone layers are progressively obliterated. The thicknesses of the siltstone layers in the matrix increase towards the lower strain areas, and locally, the layering is recognizable as preserved bedding (fig. 4.1.5). The attenuated siltstone layer foliation is the earliest fabric observed in the melange matrix, and serves as a marker to aid in defining later stages of deformation.

A high degree of asymmetry characterizes most of the overprinting structures. Low angle, extensional shears locally cut the siltstone foliation (fig. 4.1.6), but terminate within thicker shale layers. These shears have a geometry analogous to shear bands in mylonites and extend the layers to create asymmetric boudins. Small scale thrust faults, with associated hangingwal anticlines, locally affect the attenuated layers of siltstone and shale (fig. 4.1.7). In places, this foliation displays symmetric, open to tight folds, with sub-angular hinges and no axial planar fabric.

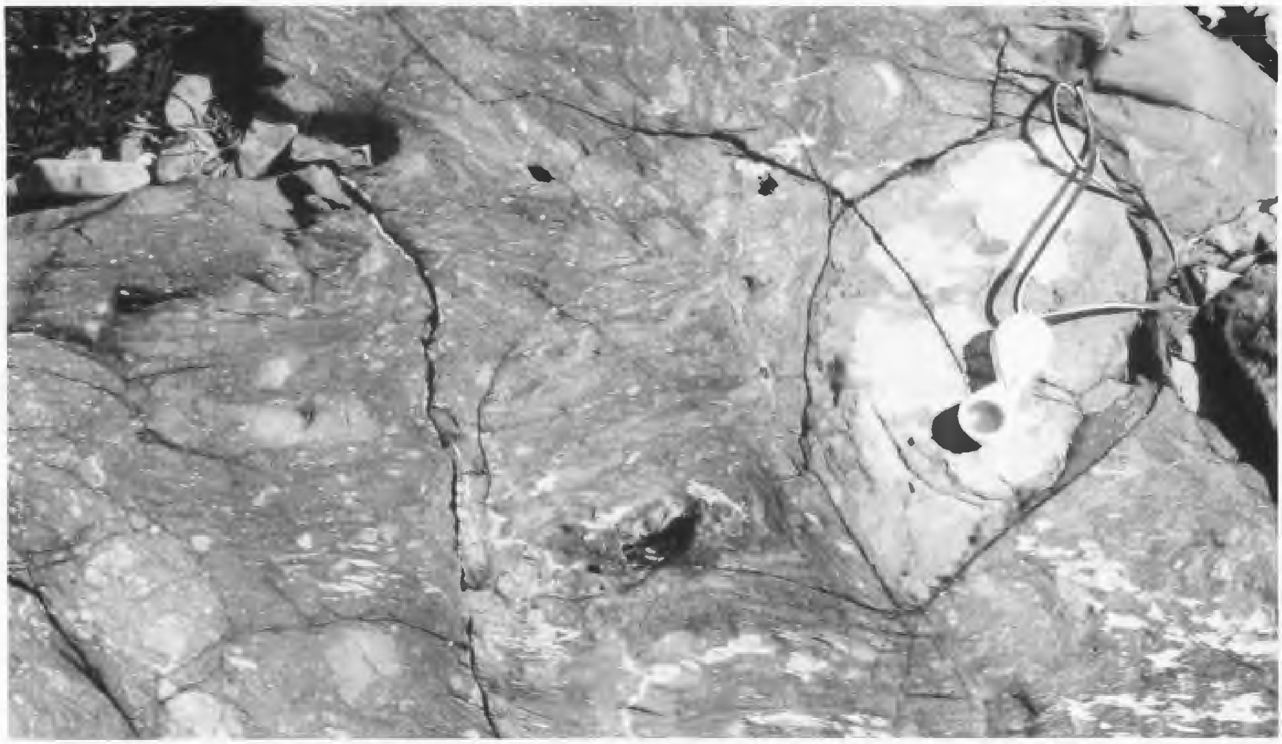


Figure 4.1.1 - Well-developed silty foliation in melange matrix, immediately north of the Yvonne Collins Block. Foliation follows the contour of the greywacke block.

Figure 4.1.2 - Silty fabric is absent in this example of the matrix. Photo taken on shoreline northeast of Fredericton.

Figure 4.1.3 - Thin section photomicrograph of silty Carmanville Melange matrix . Note isoclinal, intrafolial fold near top centre. It appears to form part of the foliation that defines the fold at the bottom of the photo with the sheared lower limb. (field of view is 1.2mm)

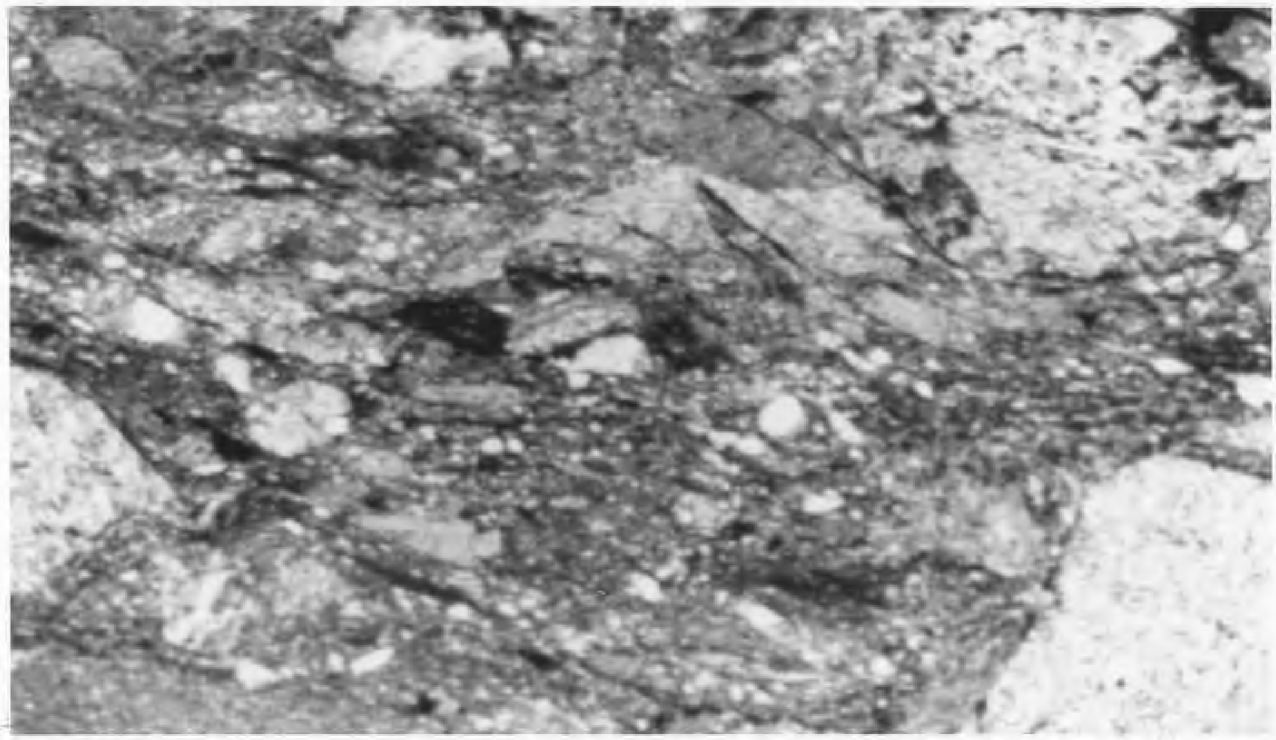


Figure 4.1.4 - Thin section photomicrograph of Carmanville Melange matrix with relatively high clast component and wide variety of lithologies. There are quartz granule sandstones, grey-beige siltstones, and a large volcanic clast in the top right corner. Note cleavage overprint (top left to bottom right) defined by dark, wispy flakes. (Field of view is 5.5mm)

Figure 4.1.5 - Rhythmically bedded siltstone and shale grades into clast bearing melange matrix, south of Jennifer Collins Block. Note relict siltstone beds and entrainment of small clasts.

Figure 4.1.6 - Photomicrograph showing shear bands that cut the silty shale foliation. In this example, sinistral shear is extending the thicker siltstone layer (centre) into an asymmetrical boudin. (Field of view is 5.5mm)

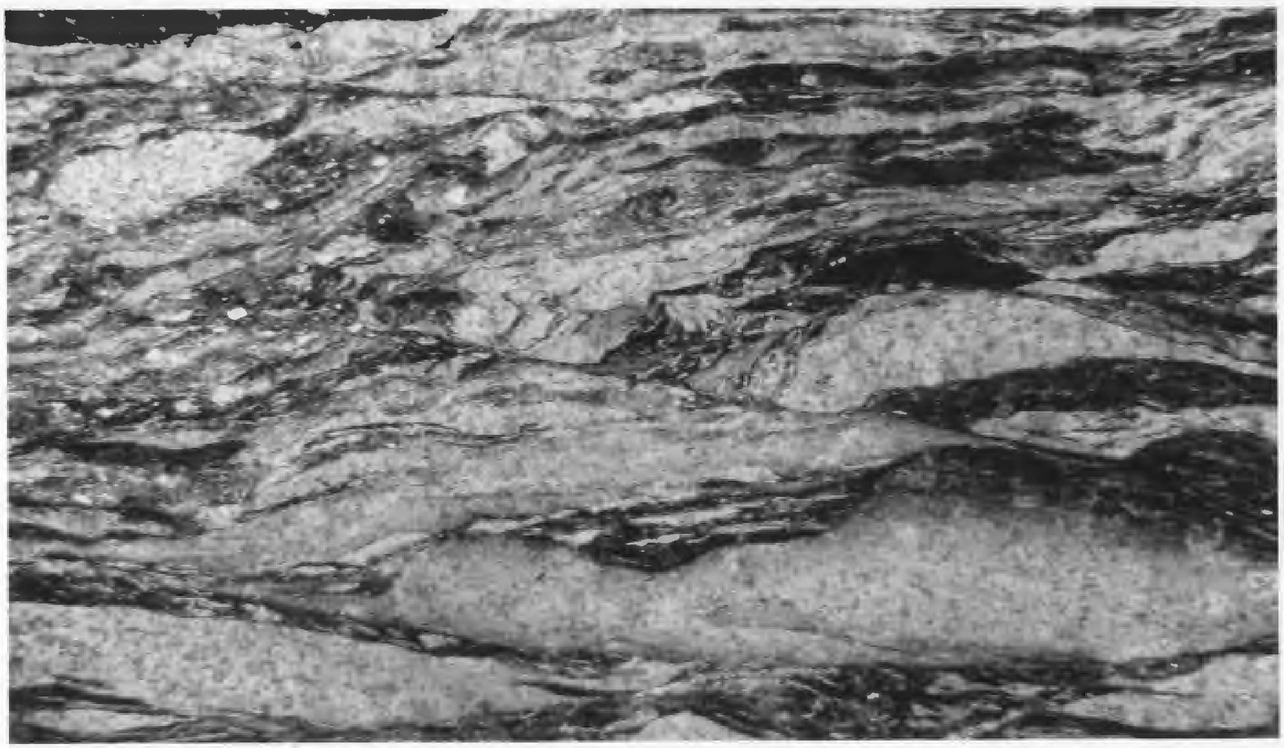


Figure 4.1.7 - Small scale thrusting (sinistral in this thin section) has produced asymmetrical folds of the silty foliation, which are then cut by discrete shears. The shear cuts the foliation at a high angle (centre), demonstrating that the fold developed first. (Field of view is 5.5mm)

Locally, mildly foliated fragments of melange matrix occur in more highly attenuated, thinly foliated matrix. Fragments range from elongate (fig. 4.1.8) to equant (fig. 4.1.9), and are most obvious where their internal foliation rests at high angles to the enclosing fabric. These fragments display varying degrees of fabric development. Some preserve only the thinned siltstone and shale foliation, and others exhibit folds and mixing with entrained clasts (fig. 4.1.10). Outside these fragments, the attenuated siltstone layers have an internal network of fractures, with thin zones of granulated siltstone on their margins.

A single phase of cleavage development locally overprints all the above structures, and generally forms parallel or sub-parallel to the matrix foliation. Apart from a minor anastomosing tendency, this cleavage appears very consistent. On a mesoscopic scale however, the cleavage is strongly influenced by larger blocks. The intensity of the cleavage increases at the periphery of isolated blocks, forming symmetrical strain augen. Where several blocks are close together, their augen interfere with each other, producing erratic deflections in cleavage orientation (fig. 4.1.11). The overall trend of the deflected cleavage is parallel to the regional northeast cleavage.

Late brittle shears cut all rocks and fabrics. This shearing is manifested by a set of conjugate faults (dextral: 320/90; sinistral: 190/81), with the principal shortening axis sub-parallel to NNW. The sinistral component of this set has accommodated most of the strain, and has developed into a wide zone (locally up to 10 metres) of network-like, brittle shear fractures with abundant quartz filling. The Eugene Hicks trondhjemite-

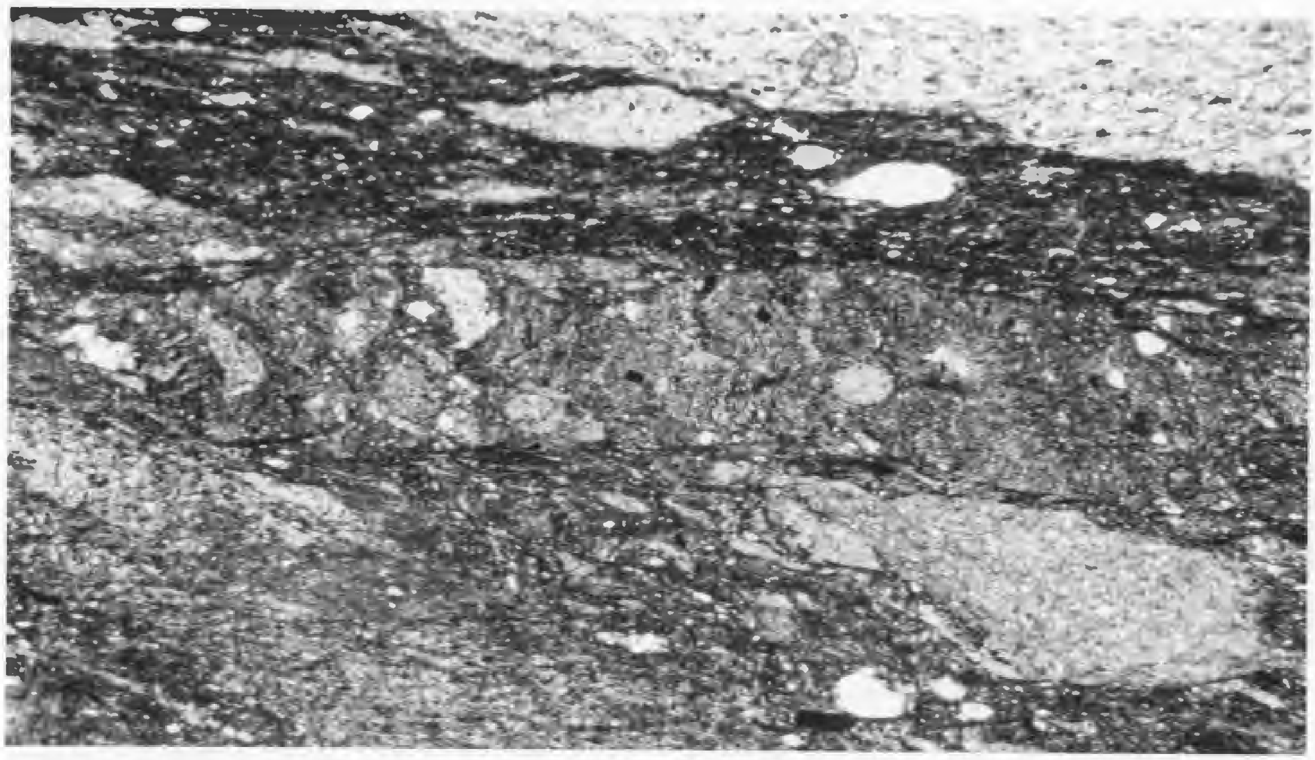


Figure 4.1.8 - Photomicrograph of an elongate clast of foliated melange matrix (across centre), with foliation perpendicular to external cataclastic foliation. (Field of view is 1.2mm)

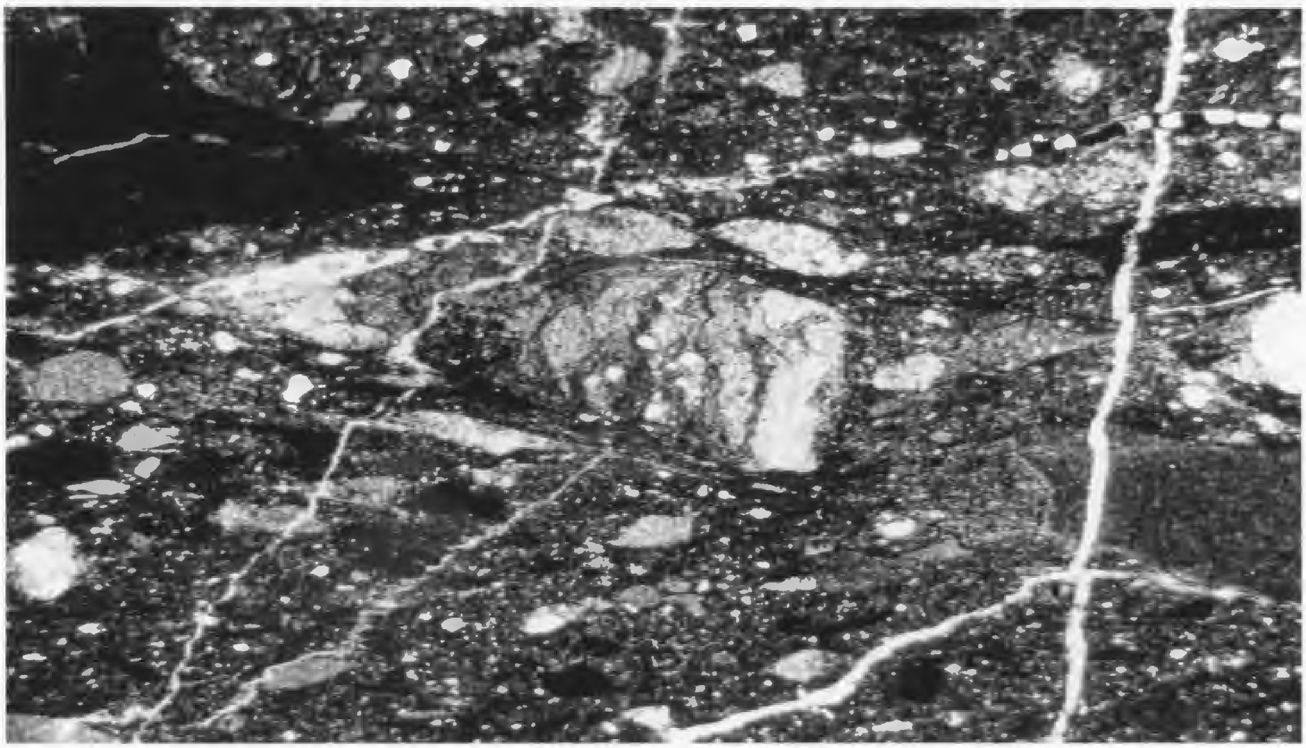


Figure 4.1.9 - Photomicrograph of an equant clast of foliated matrix (centre), with silty foliation perpendicular to external cataclastic fabric. (Field of view is 5.5mm)

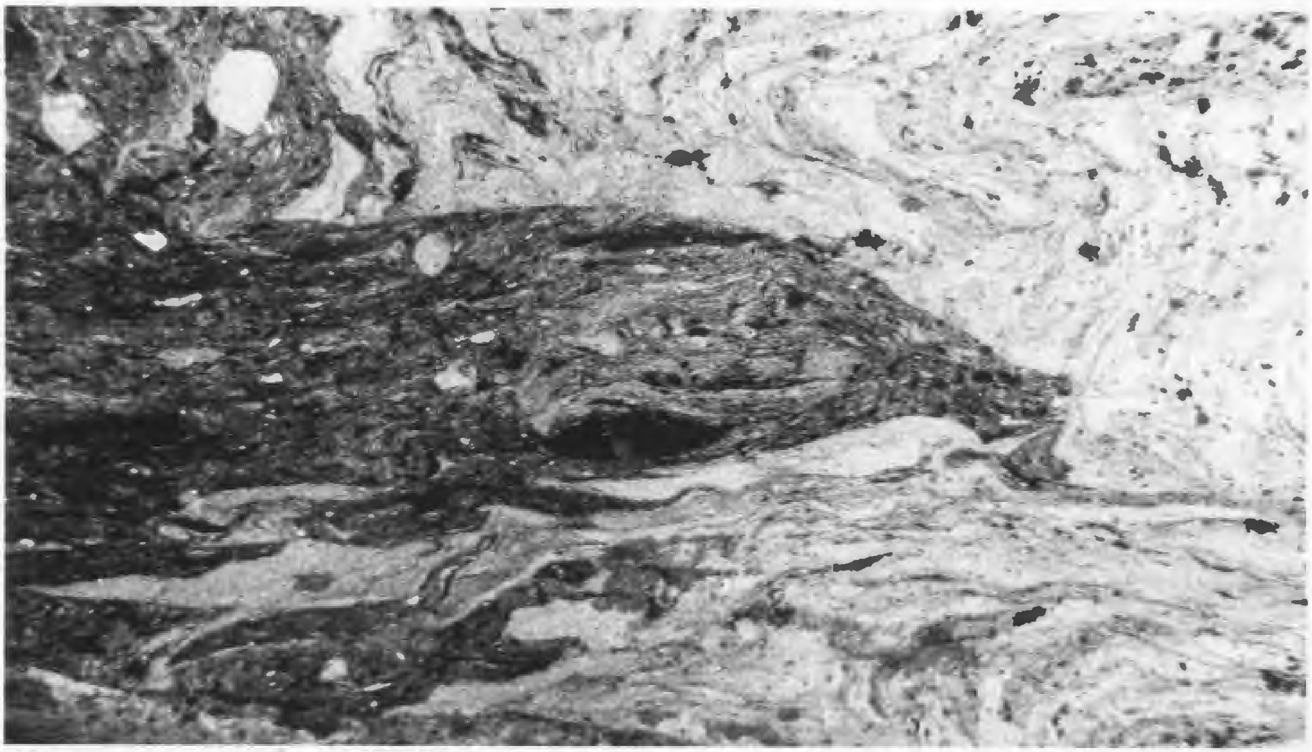


Figure 4.1.10 - Photomicrograph of folds and mixing in two varieties of Carmanville Melange matrix. (Field of view is 5.5mm)

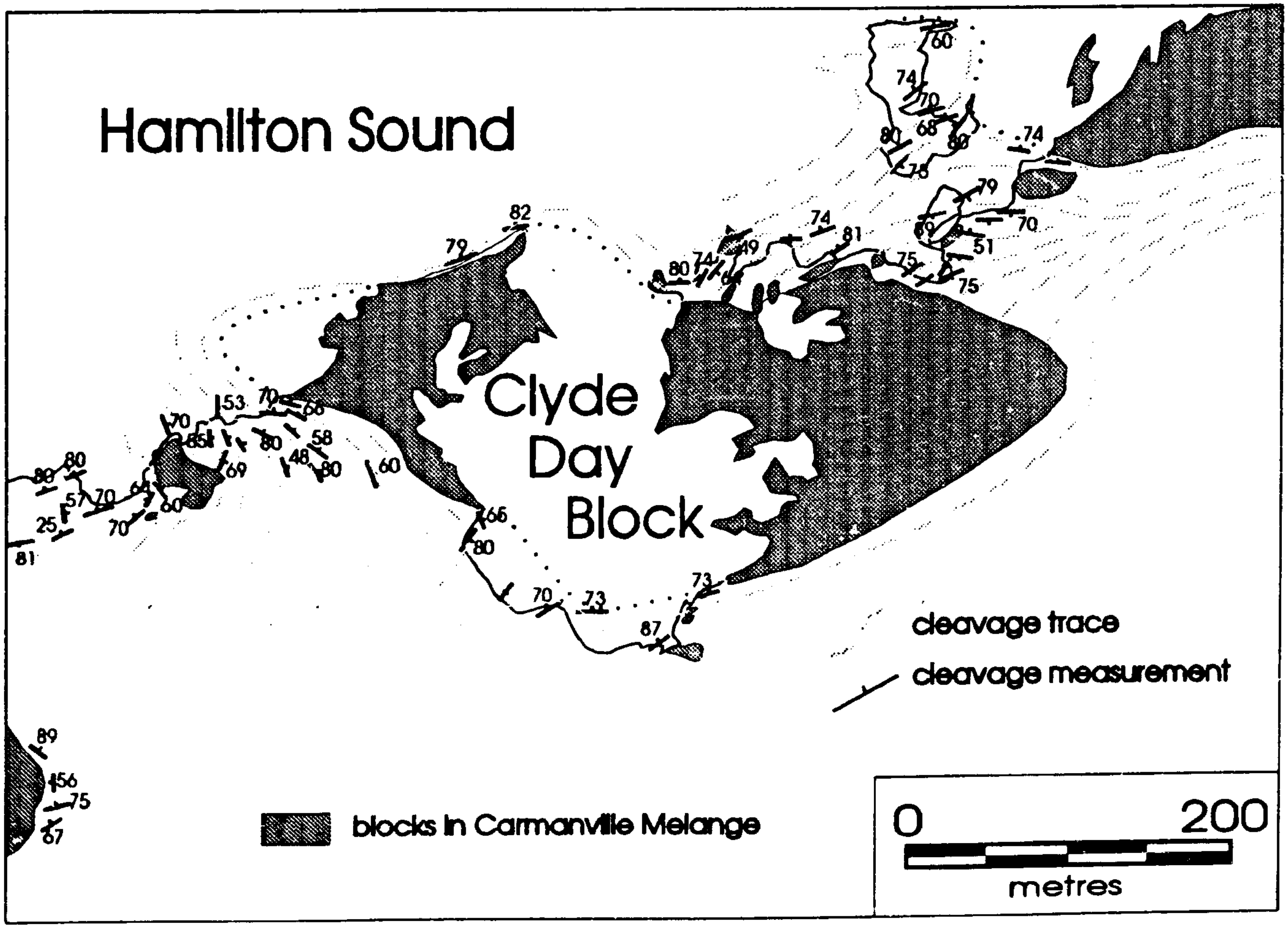


Figure 4.1.11 - Sketch of cleavage showing interference of blocks. This texture is mimicked on all scales, and can result in very erratic orientations, in areas with high clast content.

gabbro block lies along strike of this brittle shear zone and its distribution records a sinistral offset greater than 100 metres. This gabbro block has an intensely cleaved zone, associated with this shear, which extends laterally a few metres into the main gabbro body.

Discussion and interpretation of Carmanville Melange fabrics

The high strains demonstrated by the degree of necking in boudins of the siltstone layers and the presence of rootless isoclinal folds in the matrix foliation were achieved without plastic grain deformation. There is no evidence of grain deformation, such as undulose extinction in quartz, optical continuity of grains around fold hinges in the siltstone layer, grain breakage, or shape fabrics.. Nor is there any evidence of recrystallization in the quartz grains, which may have annealled earlier fabrics. Williams (1983) noted that deformation of quartz clasts, in the melange on Woody Island, has only resulted in minor amounts of undulose extinction, indicating very low internal strain in the grains. A lack of grain deformation and brittle cataclasis implies that the strain was achieved through independent particulate flow (IPF; Borradaile, 1981), referring to deformation solely by grain boundary sliding. Under low pressure and temperature conditions, this type of deformation requires a low degree of lithification and a low effective stress, normally due to elevated pore-water pressures (Brown and Orange, 1993). The fluid-like flow textures of this foliation and the lithologies involved are consistent with a high water content in the initial matrix. A lack of internal strain in quartz clasts

(Williams, 1983) demonstrates the degree of strain partitioning between clasts and matrix, which is compatible with a fluid-like flow.

The variation in intensity of the fabric, defined by the siltstone layers, records a gradual transition from bedded siltstone and mudstone to a viscous mobile melange matrix. The 10 centimetre wide dyke in the Ellis Coles pillow basalt block near the northern tip of the peninsula has a well developed siltstone-layer foliation with few foreign clasts (fig. 4.1.12), and resembles the bedded sections of siltstone and shale. Immediately outside this block, the melange matrix appears very similar to the dyke, but contains a greater variety of entrained clasts and is overprinted by later phases of deformation (fig. 4.1.13).

Later structures (thrust-related folds and shear bands) reflect a gradual increase in the viscosity of the material. These structures mark a change in deformation mechanisms from solely IPF to semi-brittle processes, recording changes in mechanical properties that may accompany compaction and lithification during a history of layer-parallel shear (Fischer and Byrne, 1987).

Preservation of bedded silty shale sections is most likely due to their higher siltstone content and therefore less pore water, reducing their susceptibility to IPF (Borradaile, 1981). Alternatively, these low strain areas may have been isolated by strain partitioning into the more highly deformed areas. This would also indicate a change in deformation mechanisms, from uniform flow to strain partitioning, as a result of strain hardening during progressive dehydration and lithification of the matrix

Figure 4.1.12 - Thin section of matrix dyke cutting Ellis Coles Block. Note well-developed silty foliation with very few entrained clasts. (Field of view is 5.5mm)

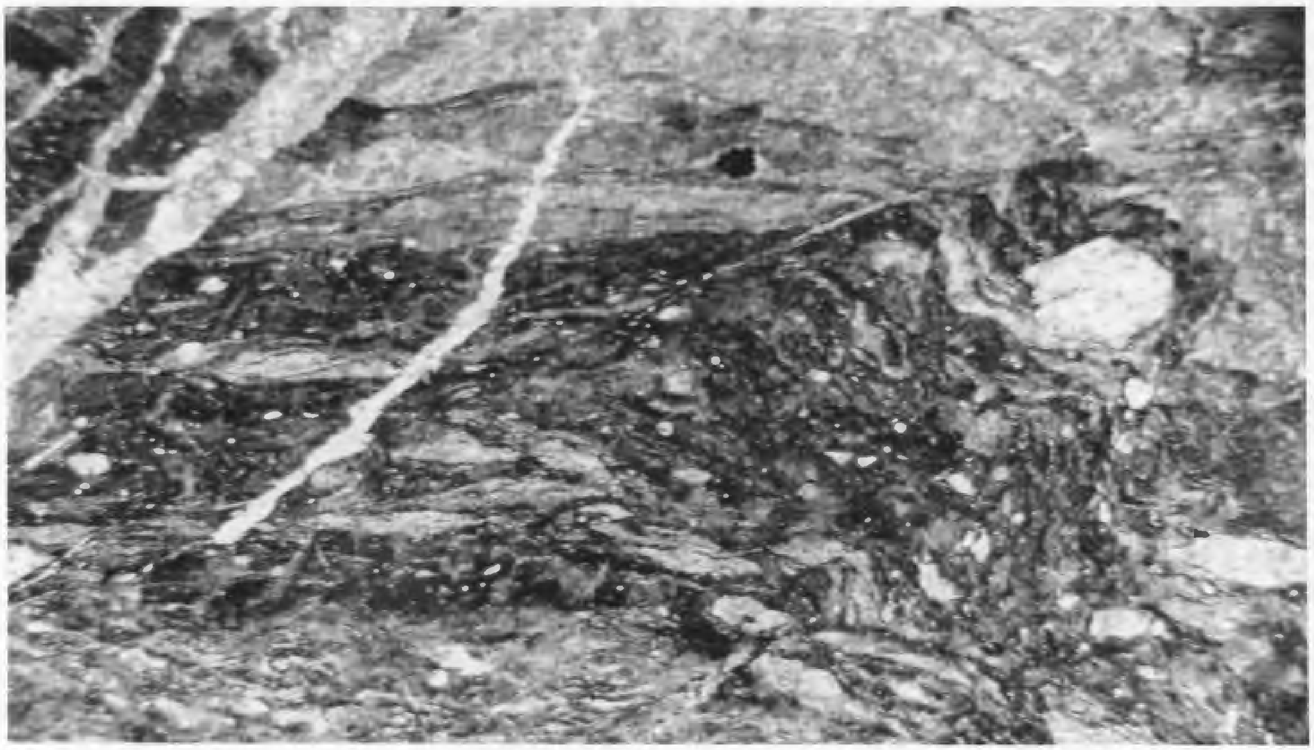


Figure 4.1.13 - The silty foliation in melange matrix immediately outside the Ellis Coles Block is more disaggregated and contains a greater proportion of small entrained clasts. It is also cut by thin quartz veins. (Field of view is 5.5mm)

Clasts of foreign sedimentary material (i.e. not silty mud) invariably deform by cataclastic processes and have undergone extensive grain size refinement, making the distinction between melange matrix and entrained material very artificial. Igneous rocks tend to occur mostly as larger blocks (>3m), and are probably less susceptible to granulation in the silty shale matrix because of competence contrasts. The recognition of the silty shale as a potential source for the initial melange matrix has allowed, at least, a conceptual distinction. If this is correct, the initial melange matrix consisted of siltstone and shale, and would have been devoid of any foreign clast material. There appears to be a positive correlation between the degree of deformation in the early foliation of silty shale and the proportion of entrained foreign clasts. This observation implies that clast incorporation is directly related to, if not controlled by, the mobilization of the melange.

The flow fabric or foliation of the melange matrix is, in places, difficult to recognize in outcrop. It is best seen on a freshly cut surface or in thin section. The variation in intensity of this fabric was therefore not mapped (except around the larger blocks, where it is extremely intense and exaggerated by later tectonic deformation). It is obvious, however, that high and low strain zones exist and probably reflect strain partitioning within the flowing melange.

The presence of only a single cleavage in the melange is in sharp contrast with the regional structure, and with many of the entrained blocks (Gary Collins, Keith Collins, Daniel Collins and Yvonne Collins blocks). All of these blocks have an early, bedding parallel cleavage, which is cut by the melange. The only structure shared by both the

Carmanville Melange matrix and adjacent rocks of the Noggin Cove and Woody Island formations is the regional northeast cleavage. This implies that entrainment of blocks in the melange, and its emplacement in the Hamilton Sound complex, occurred after the first cleavage was imposed on the region, and before the development of the regional northeast cleavage.

Johnston (1992) cited an example of parallelism between melange dykes and the regional northeast cleavage (S_2), on Woody Island, as evidence that mobility of the melange was syn-D_2, and therefore a result of hard rock deformation. This would be true if the melange was present and lithified prior to D_2. However, the degree of attenuation and fabric development that was achieved without plastic grain deformation requires a significant amount of mobility of the melange prior to lithification. Further, the presence of melange dykes cutting blocks in the melange, as well as injecting adjacent units, argues for long-lived or polyphase mobility. Foliated melange clasts entrained in more strongly foliated matrix shows that some of the mobility was achieved through brittle or cataclastic flow, but this must represent a late stage in the movement history, after the main melange fabric had been acquired. High fluid pressures can theoretically open fractures parallel to the XY (cleavage) plane of the strain ellipse (Gratier, 1987). The shale injections are therefore interpreted to have pierced pre-existing planes of weakness (S_2 cleavage) in the host rocks, implying that the intrusive mobility was, in part, post- or syn-D_2.

4.2 Entrained Blocks

Entrained blocks also show multiple phases of deformation, involving cleavage development and folding. These structures are not as intense as in the Teakettle melange and are associated with lower greenschist (chlorite grade) metamorphism, as opposed to upper greenschist/lower amphibolite facies in the Teakettle melange.

Soft-sediment, layer-parallel extension is apparent in the black and grey rhythmites, especially in the Gary Collins Block. Siltstone beds are attenuated and cut by extensional shears to produce asymmetric boudinage structures (fig. 4.2.1). Immediately adjacent to these attenuated zones, however, bedding remains intact and appears relatively undisturbed. Such abrupt heterogeneity of strain, with no gradation, implies heterogeneity in the rheology of the deforming medium. The presence of water, resident or transient, may allow strain softening and localization, during deformation.

Structures in the rhymites are overprinted by two later cleavages. The first, a finely-spaced (1-5 cm), bedding parallel cleavage, is most likely associated with isoclinal folding, as suggested by a well-defined, isoclinally folded limestone lens in the Keith Collins Block. Isoclinal folding readily explains the conflicting top indicators in the Gary Collins Block. The later cleavage is axial planar to moderately plunging (27-45 degrees), open to close folds, and parallel to the northeast trending cleavage. This cleavage is only locally developed, and more closely spaced in the fold hinges, where it produces spectacular rodding with the bedding parallel cleavage (fig. 4.2.2). A low angle thrust-related fold, with 2-3 metres of displacement, occurs near the southwestern end of the

Figure 4.2.1 - Necking and boudinage of siltstone beds transforms bedded sediments into foliated melange matrix. Note paucity of entrained clasts in early stage of melange formation.

Figure 4.2.2 - Overprinting of bedding parallel cleavage by spaced axial planar cleavage (Gary Collins Block), in hinge of folded rhythmite. Axial planar cleavage parallel to regional northeast trending cleavage. Early bedding parallel cleavage is truncated at the contact with melange.

Gary Collins Block. This structure cuts and folds the bedding parallel cleavage, but shows no relationship to the later northeast trending cleavage. Siltstone pebbles in disaggregated shale, concentrated in the fold hinge, are probably locally derived and directly related to this small fold. This relationship may provide a small scale analogue for the localization of larger melange bodies in the cores of hangingwall anticlines.

The other large rhythmite block (Daniel Collins Block) has a much more finely spaced, bedding parallel cleavage. Later folding of this cleavage has locally produced a mild crenulation fabric, with axial planes parallel to the regional northeast cleavage, and shallow plunging (00-11 degrees) fold hinges. The `argille scagliose' fabric in this block may be related to this later folding.

A folded contact between a crenulated rhythmite block and massive melange occurs on the coast northeast of Fredericton. An axial planar cleavage crenulates the bedding parallel cleavage in the rhythmites and passes into previously uncleaved, massive melange matrix.

Grey siltstones of the Yvonne Collins Block display two episodes of very fine (1-2 mm) quartz veining: one parallel to bedding, the second parallel to a strong biotite foliation, that is axial planar to tight asymmetrical folds. Possible cordierite porphyroblasts overgrow this foliation, but have locally overgrown unfoliated biotite grains. One of the porphyroblasts has an internal `Z' fold, outlined by the biotite foliation. The various stages of deformation recorded in the porphyroblasts indicate that growth was syn-deformation, and probably related to the tight folds and second quartz veining episode. Sector zoning suggests that they may be cordierite porphyroblasts, giving the low grade metamorphic assemblage: biotite + cordierite + quartz. The relict porphyroblasts have been partially retrograded to chlorite. This assemblage is absent in the surrounding lower grade melange matrix.

The Yvonne Collins Block also contains thrust-related folds, outlined by brittly fragmented chert layers (fig. 2.1.7). The entire unit outlines a chevron style fold, that has produced mild brecciation in the steeply plunging, to sub-vertical hinges. No cleavage has developed with this fold, but its axial plane is parallel to the regional northeast cleavage.

The Marshall Day pillowed basalt block has a rim, on its southern edge, of approximately 5 metres of mildly deformed pillows separating undeformed pillows from melange. The deformed rim appears to have been invaded by minor amounts of matrix shale, and has a very strong Fe-staining on the pillows. This is the only place in the Carmanville Melange where this relationship between pillows and matrix was observed. It suggests continued shearing and deformation in the melange, or the deformation may have developed prior to incorporation.

Internal brecciation is a conspicuous feature common to almost all greywacke or sandstone boulders larger than about 10 centimetres (fig. 4.2.3 - a & b). These blocks are internally disrupted by a network of web-texture (Cowan, 1982) fractures, filled with shale and/or dark, granulated sandstone. The density and spacing of the fractures increases

Figure 4.2.3 a) Brecciated greywacke on west shore of Carmanville Harbour with web-texture. Density of fractures increases towards rim of block. This block has been reshaped by regional deformation and lies within the regional northeast fabric.

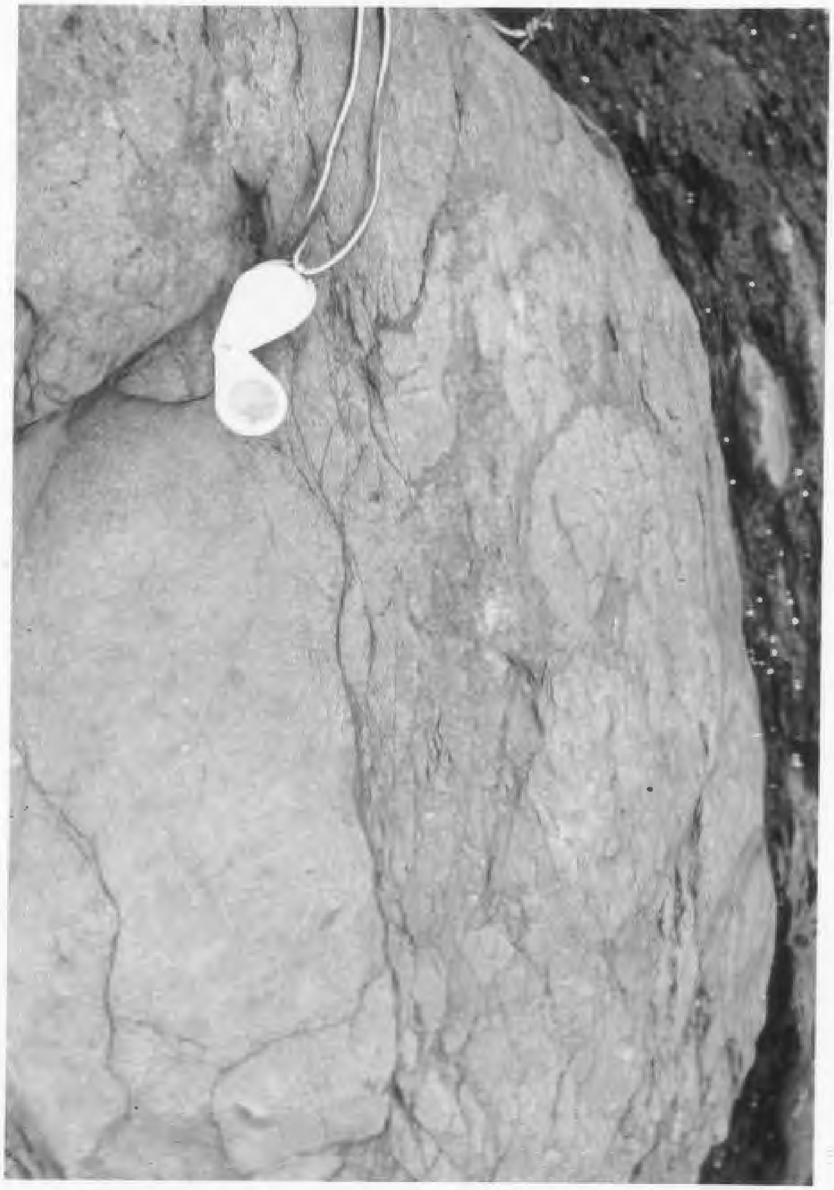


Figure 4.2.3 b) Close up of block rim (fig. 4.2.3 a), showing network of shale filled fractures on brecciated edge of greywacke block.

from core to rim. Outer fragments, removed from the main blocks, occur in the melange matrix, yet they tend to maintain the outline of their original boulder shape. Rare 'tails', entrained into the external fabric of the matrix do not show any obvious asymmetry, and the only obvious bulk strain is a positive volume change.

Discussion and interpretation of structures in entrained blocks

The only structures in the rhythmites and bedded siltstone/chert sections that are coincident with structures in the melange are the open to close folds with axial planes parallel to the regional northeast trending cleavage. All structures in these bedded sections, overprinted by this folding phase, are truncated at their contacts by melange, and must have developed prior to incorporation into the melange.

Early fabrics in the rhythmites, attenuation, and boudinage of bedding and shear bands are similar to those seen in the melange matrix.. These features record early phases of layer-parallel horizontal extension, possibly related to vertical loading, overpressuring and progressive dewatering. Asymmetrical, isoclinal folding, and thrust-related folding overprint these early structures and record the initiation of layer-parallel, compressional shearing, following lithification of the sediments. These structures are discordant with the melange matrix structures and therefore developed prior to entrainment, as coherent blocks, in the melange.

Quartz veinlets and syn-deformational porphyroblasts indicate a slightly higher grade of metamorphism in the grey siltstone of the Yvonne Collins Block compared to surrounding rocks. This suggests derivation from deeper levels. However, the Yvonne Collins Block, and the rhythmite blocks have all experienced a phase of asymmetrical folding before incorporation into the melange.

The Gary Collins, Keith Collins, Daniel Collins and Yvonne Collins blocks have all been folded about the regional northeast cleavage. The fold hinge orientations of each block, however, vary between horizontal to vertical. Because the plunge of fold hinges is controlled by the original dip of the folded layer, this variation illustrates a disparity in the attitudes of these blocks before folding. Since there is no evidence for a previous folding event, the differing attitudes of the blocks probably reflect the lack of a preferred orientation of large tabular bodies in the melange, possibly due to differential rotation during melange formation.

The peculiar `web-texture' brecciation in the sandstones has been desciibed in many melanges (Cowan, 1982; 1985; Barber et al., 1986; Pickering et al., 1988; Orange, 1990). The intricate piercement of shale into the fractures indicates that the brecciation took place *in situ*, and must be a consequence of the melange forming process. Piercement of matrix shales into the blocks, causing expansion and disruption is attributed to higher fluid pressures in the matrix than in the blocks (Barber et al., 1986). Fluid pressures in diapiric shale masses are known to be as high as 0.9 times the lithostatic load (Musgrave and Hicks, 1968). This contrast in fluid pressure results from the differing compressibilities of shale and sandstone. The flowing shales may compress in response to loading, and thereby redistribute some of the lithostatic load to the pore fluids, while fluids in the less compressible sandstones retain their original hydrostatic pressure. The overpressured pore fluids in the shale may then inject areas of lower fluid pressure in the sandstones, carrying siltstone and clay particles into the fractures. Pressure contrasts may intensify when gases held in solution in the pore fluids come out of solution in regions of lower confining pressure, and expansion and brecciation may be explosive (Barber et al., 1986).

4.3 Teakettle melange

Clyde Day Block

The Clyde Day Block (fig. 2.1.1) is a lens shaped block, dominated by the strongly deformed, quartz veined, slaty matrix. Structures in this matrix are highlighted by the extensive amounts of quartz veins, lenses and pods. The main fabric is a fine lamination of 2-3 millimetres thick quartz layers, with a spacing of equivalent thickness. It is accompanied by a strong biotite foliation, believed to be gneissic in origin. Large scale structures in this foliation are difficult to define because of extensive brecciation, and the layers cannot be traced for more than a few tens of centimetres. Where structures can be seen they are almost always erratically disposed, asymmetrical folds. Mild brecciation is associated with most of this folding.

In some places, there is a strong shear fabric imposed on the matrix. Quartz veins 1 to 2 centimetres thick have been extended, forming boudins 5 to 10 centimetres long.

The quartz biotite lamination is absent in these places, and may have been obliterated by shearing.

The highest degree of brecciation in the matrix appears to be associated mostly with psammitic blocks. Here, the brecciation is so intense, nothing remains of earlier fabrics, and quartz blebs or pods occur in a completely disaggregated slate matrix. These zones are generally confined to within 2 metres of the entrained blocks of the Teakettle melange.

The Clyde Day Block contains the best examples of strained pillows in the melange. In one large pillow block, the highest strains are concentrated on its periphery and a dramatic gradation to low strain has left the pillows in the core intact (fig. 4.3.1). Elongation of the pillows is parallel to the contacts between the block and the matrix. Along strike, a separate block of highly strained pillows displays pillow aspect ratios of more than 20:1 (fig.4.3.2). The lensic outcrop shape of these two pillow blocks, coupled with their strain pattern indicates that it may be a large scale boudin. The colinear position of the two pillow lava blocks strongly suggests that boudinaging took place *in situ*, within the Teakettle melange slate matrix. Most of the blocks in the Clyde Day Block share this lens shape. The formation of 'megaboudins' appears to be the principal deformation mechanism responsible for progressive stratal disruption, leading to the development of the 'block-in-matrix' texture in this area.

Bedding contacts are locally preserved between alternating psammitic and mafic volcanic (mostly pillows) lenses. The psammites, characteristically, have a much stronger metamorphic fabric than the volcanic rocks. In places, the psammites display more than one phase of deformation. Psammitic rocks with bedding contacts against mafic volcanics tend to be the least strained, and commonly have a strong foliation parallel to a coarse (1-3 cm) pelitic/psammitic layering. These layers locally define minor 'S' folds, approximately 10 centimetres in amplitude.

Away from the mafic volcanics, the foliation in some psammites is fine (<1 cm), and very well developed. This foliation crenulates an even finer (<1 mm) fabric. The finer crenulated fabric is only seen locally in the block, but consistently has an isoclinal 'S' shaped asymmetry (fig. 4.3.3). A periclinal synform was found in psammite with a similar composite fabric (fig. 4.3.4), near the southern boundary of the Clyde Day Block. There is a family of quartz lenses, parallel to the main foliation, that are bordered by quartz-poor pelitic melanosomes.

The main composite fabric is locally crenulated at a low angle, also with a sinistral thrust asymmetry (fig. 4.3.5), and is kinked, in places, with a dextral vergence. The kinks form in linear zones 1-2 centimetres wide, and between 40-55 degrees away from the main foliation. Dextral kinks with this morphology and relative orientation conflict with the main sinistral vergence of other structures. The penetrative foliation is also locally brecciated (fig. 2.2.5) and clearly cut at contacts with the slaty matrix.

Figure 4.3.1 - Strain variation in large pillow occurrence in the Clyde Day Block. Large, well-preserved pillow basalts in background grade into highly strained rim, where pillows meet sheared matrix slate. This high strain zone in basalt follows the contours of the block.

Figure 4.3.2 - Highly strained pillow basalt. This rock forms part of a `megaboudin' train, in the northeastern part of the Clyde Day Block.

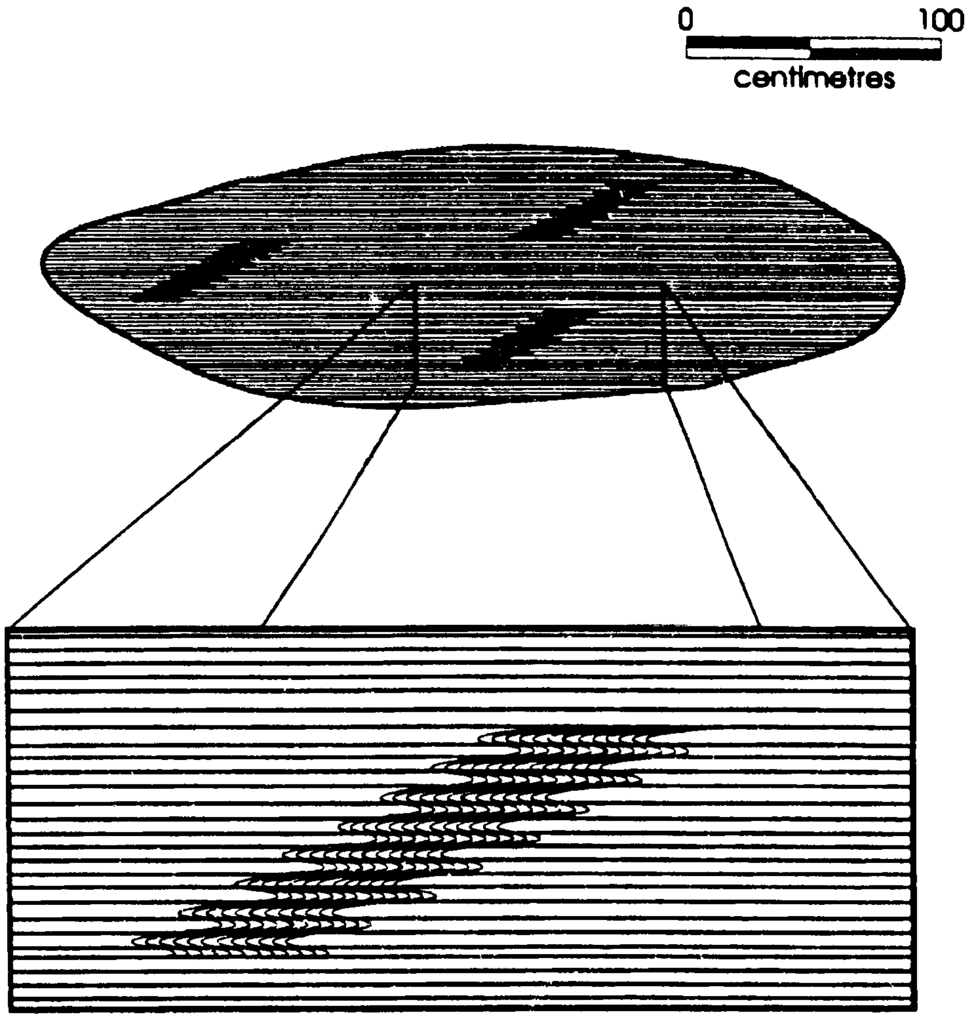


Figure 4.3.3 - Sketch of early, isoclinal 'S' folds, overprinted by strong axial planar fabric. The crenulations are only locally developed, and probably mark the hinges of earlier folds. The asymmetrical, layer-parallel geometry is compatible with isoclinal thrust folding. Thickening in this way, may have resulted in the development of the strong axial planar fabric. (laminated psammite in Teakettle melange, Clyde Day Block)

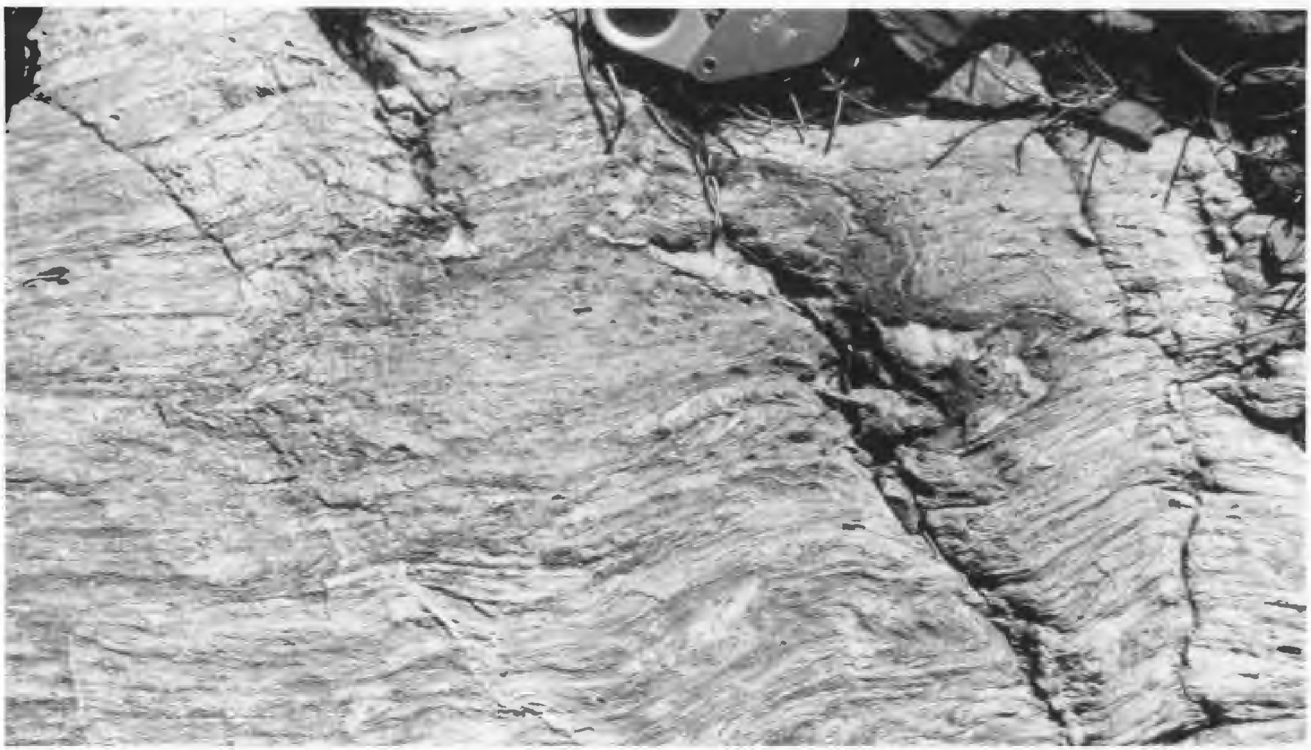


Figure 4.3.4 - Periclinal synform in laminated psammites (Clyde Day Block). Early foliation outlines irregular elliptical shape of fold. Outside the fold, this foliation is transposed by the axial planar fabric. Note that fold hinges left and right dip moderately towards centre of fold.

Figure 4.3.5 - Laminated psammite cut by low angle asymmetric crenulation cleavage. The crenulated fabric is elsewhere seen as a composite foliation, axial planar to asymmetric isoclinal folds (Clyde Day Block).

Otto Wheaton Block

Psammitic to semi-pelitic rocks in this area display the most spectacular overprinting structures in the melange. One laminated psammite block, at the western end of the Otto Wheaton Block (fig. 4.3.6 a), shows an excellent example of an isoclinal fold, that has been refolded about a tight, upright, chevron fold. The two fold hinges appear to be coaxial, producing a Type III interference pattern (Ramsay and Huber, 1987).

The dominant fabric that defines the two fold phases is a crenulation cleavage (fig. 4.3.6 b), recording a still earlier phase of deformation. The fine crenulated lamination is a quartz-biotite foliation that is overgrown by abundant staurolite porphyroblasts. Internal structures in the porphyroblasts show varying degrees of crenulation; some porphyroblasts overgrow a planar, undeformed fabric, while others overgrow progressively tighter crenulations of this foliation. The external fabric around the porphyroblasts is also a quartz-biotite crenulation cleavage, but with a much finer spacing.

Nearby, a grey semi-pelite also shows overprinting of three phases of deformation. This rock has a very fine lamination, and fine quartz veins associated with each stage of foliation development outline the structures very well. Figure 4.3.7 shows a mushroom fold or Type II interference pattern (Ramsay and Huber, 1987), outlined by a single quartz vein. A muscovite foliation can be seen to follow this fold. This quartz vein is assumed to represent the first generation of veining and associated foliation. Isoclinal folding produced a second foliation/quartz fabric, that can be seen elsewhere. The last phase of deformation produced tight angular folds, forming this mushroom shape. This last folding

Figure 4.3.6 a) Coaxial fold interference pattern in laminated psammite of Otto Wheaton Block. Early isoclinal folds with strong axial planar fabric are refolded by upright, tight folds, with no associated fabric. Pencil location is enlarged in figure 4.3.6 b).

Figure 4.3.6 b) Close up of limb of fold of figure 4.3.6 a). The strong penetrative fabric that defines the fold is a composite, crenulated fabric. The early crenulated fabric is a gneissic foliation, which is only locally preserved at high angles to the main fabric (pencil tip).

Figure 4.3.7 - Mushroom fold of quartz vein, in foliated grey semi-pelite (Otto Wheaton Block). This fold defines an early phase of isoclinal, asymmetric folding, overprinted by a tight symmetrical fold. Note: fine foliation, axial planar to latest fold phase, also has associated quartz veins.

phase also developed an axial planar foliation, that is elsewhere developed as a crenulation foliation, with parallel quartz veins (fig. 4.3.8). In one location, a planar set of small-scale dextral kinks overprint this fabric.

The large blocks of layered mafic volcanic rocks in the Otto Wheaton Block are very strongly cleaved (fig. 4.3.9) and locally brecciated. The easternmost block is in stratigraphic contact with psammite, and the contact is traversed orthogonally by a strong metamorphic foliation (fig. 4.3.10). These rocks are openly folded with an axial plane approximately parallel to the regional northeast cleavage, but with no associated fabric.

Discussion and interpretation of structures in the Teakettle melange

The most impressive feature of the deformation in the Clyde Day Block is the persistence of a sinistral asymmetry throughout all phases of deformation, and in every block. Apart from the minor late dextral kinks, folds are invariably 'S' shaped with axial planes at a low angle or parallel to the main fabric. Asymmetric, low angle crenulations, overprinting these fabrics, share the same vergence. The lensic outcrop shapes of the megaboudins reflect a mild 'Z' shaped asymmetry, that mimics S-C fabric orientations, for a sinistral sense of shear. Regardless of block size, shape, or relationship to the matrix, deformation is characterized by a large component of left-lateral, non-coaxial shear strain. The small dextral kinks may simply represent minor pertubations in this strain field. Late stage brecciation, cutting all structural and metamorphic fabrics, particularly in the matrix and psammitic blocks, records a dramatic change in deformation

Figure 4.3.8 - The tight folds that form the mushroom fold in fig. 4.3.7 locally occur as open chevron kinks of the penetrative fabric. Axial planes are locally quartz veined.

Figure 4.3.9 - Typical appearance of fine-grained, layered mafic volcanics in Otto Wheaton Block. They are most likely highly strained pillows.

Figure 4.3.10 - Stratigraphic contact, between layered mafic volcanics (top) and quartz veined laminated psammite (6" below hammer). Strong metamorphic fabric is perpendicular to contact (Otto Wheaton Block).

mechanisms operating on these rocks. This brecciation is predominantly concentrated in the slaty matrix, and most intense in proximity to the psammitic blocks. The psammitic blocks also commonly display discrete zones, forming networks of brittle deformation.

The structures in the Otto Wheaton Block are much more variable. Internally, the psammites all show an early phase of asymmetrical, isoclinal folding, similar to the structures in the Clyde Day Block. Later deformation, however, produced tight chevron folds more typical of a coaxial strain field. The structural orientations also vary from block to block, and the shapes of the blocks are more equidimensional than in the Clyde Day Block. These deformational features may also be produced in a non-coaxial strain field, through strain partitioning between the competent blocks and the flowing matrix. Lister and Williams (1983) have suggested that such competence contrasts lead to the inability of an interface to support shear stress, thus promoting coaxial deformation within the competent block, while non-coaxial strain is partitioned into the flowing matrix. The discordance of structural orientations and the geometries of fold interference patterns (Type II vs. Type III, Ramsay and Huber, 1989) may reflect differential rigid body rotation of the blocks during progressive deformation.

The presence of staurolite, biotite, and quartz in the laminated psammites of the Otto Wheaton Block indicates lower amphibolite facies metamorphism (Yardley, 1989). The variation in the internal fabrics of the porphyroblasts suggests that they are syntectonic staurolites, and that lower amphibolite facies conditions were reached during the development of the dominant crenulation foliation.

Structures displayed by blocks contained in the Teakettle melange are everywhere cut by the Teakettle melange matrix. Further, all structures within the Teakettle melange are discordant with those of the Carmanville Melange, and sharp contacts between the two melanges can be traced to show that the Teakettle melange resides as blocks in the Carmanville Melange. Deformation and metamorphism in the psammites and mafic volcanics therefore developed prior to entrainment in the Teakettle melange, and the composite Teakettle melange represents an older, polyphase deformed and metamorphosed melange, that has been recycled into the Carmanville Melange.

The abundant quartz veining in the matrix of the Teakettle melange is another major difference from the Carmanville Melange. The presence of these veins demonstrates the importance of the role of fluids. Wether they are internally derived from dewatering of the melange protolith, or channelled from external sources is unknown and beyond the scope of this study. A fluid inclusion study of these veins, compared to the less abundant veining in the Carmanville Melange, may yield helpful information to further constrain the pressure-temperature contrasts between the two melanges.

CHAPTER 5

Origin of the Teakettle melange and Emplacement of the Carmanville Melange

Any model for the Carmanville Melange must include: 1) a feasible source for the observed assemblage of entrained rocks, especially, the Teakettle melange blocks, 2) a tectonic environment capable of producing multiple phases of hard and soft rock deformation and metamorphism, before incorporation into the melange, and 3) an emplacement mechanism that explains the polykinematic history of the melange and is consistent with the regional tectonic history.

5.1 Introduction

Since their initial recognition (Greenly, 1919), melanges have been the subject of considerable interest (Hsu,1968; Raymond, 1984; Cowan,1985; Lash, 1987; Horton and Rast, 1989). The enigmatic nature of melanges is reflected by the general lack of consensus that prevailed for many years concerning their definition, genesis and tectonic significance (see Raymond, 1984, for review). The currently accepted definition for melange is: '...a mappable unit made up of blocks and fragments contained in a matrix of finer-grained material' (Hibbard and Williams, 1979; Raymond, 1984; Cowan, 1985;

Lash, 1987; Orange, 1990). Styles of melange genesis roughly fall into three categories (Lash, 1987): (1) sedimentary or olistostromal, involving gravitationally-driven downslope sliding and associated disruption of variably lithified sediments, (2) tectonic melanges generated by disruption and mixing of originally coherent sequences along fault zones, and (3) diapiric intrusion of water-rich sediments.

Several characteristic features differentiating between melange forming mechanisms have been documented (Cowan, 1985; Raymond, 1984; Lash, 1987; Orange, 1990), yet these criteria remain equivocal. Orange (1990, p.935) provides an excellent overview of the ambiguities of these criteria, which is selectively synthesized here.

A pervasive scaly cleavage, or '*argille scagliose*', is a commonly reported fabric in melanges, and has been proposed as diagnostic evidence for fault-zone melanges (Cowan, 1974; Knipe and White, 1977; Moore and Karig, 1980) and diapiric melanges (Barber et al., 1986). Local occurrences of this fabric have also been reported from olistostromal melanges (Phipps, 1984; Baltuck et al., 1985; Larue and Huddleston, 1987). While the presence of a stratigraphic framework and lack of exotic clasts may imply olistostromal origins, Lash (1987) combined stratigraphy and pervasive deformation to infer "in situ accretion-related deformation" in his type I melange. High-angle, cross-cutting relationships, between melange and neighbouring rocks, are usually limited to intrusive melanges (Torrini et al., 1985; Barber et al., 1986; Pickering et al., 1988), but olistostromes may also have sharp contacts with surrounding units (Cook et al., 1972; Abbate and Sagri, 1981). Phacoidal clasts tend to be restricted to tectonic melanges

(Byrne, 1984; Tabor, 1987; Orange, 1990), but highly angular to rounded clasts occur in both diapiric (Pickering et al., 1988; Barber et al., 1986) and olistostromal melanges (Abbate and Sagri, 1981; Jacobi, 1984; Cook et al., 1972; Lash, 1987). Presumably more reliable criteria include: extensive cataclasis, and pervasive regional deformation for tectonic melanges (Byrne 1984), web-texture of clasts in diapiric melanges (Barber et al., 1986; Pickering et al., 1988), and mud injections (especially as cross-cutting dykes) into cracks in clasts are believed to be indicative of a diapiric origin (Barber et al., 1986; Brown, 1987; Talbot and von Brunn, 1989).

A cursory review of the literature reveals that there is no single, definitive criterion for any of the three accepted types of melange generation. Web-texture in psammites or greywackes is considered by some as characteristic of diapiric melanges, but this texture is present in the tectonized, olistostromal Companion Melange, in western Newfoundland (H. Williams, pers. comm.). Mud injections and melange dykes simply reflect fluid over pressuring and subsequent release. They can therefore occur anywhere these conditions exist, and are not, therefore, restricted to diapiric melanges. Phacoidal cleavage or 'argille scagliose' textures have been reported from all three types of melanges, and likely depend more on deformation rates, rheology, temperature and pressure considerations, rather than melange genesis. In the Carmanville Melange phacoidal cleavage occurs in a *block* in melange, *not* in the matrix. Clearly, the genetic history of a melange cannot be isolated by the presence or absence of any single feature. The only viable strategy is one that incorporates regional tectonic, detailed structural and lithological considerations, and that uses them in concert with the above textural features. When viewed in this way, the Teakettle and Carmanville melanges each record very distinct histories for which genetic models may be proposed, and reveal features to help constrain these models.

5.2 Origin of the Teakettle melange

The Clyde Day Block is characterized by its pervasive asymmetrical deformation. Small scale, thrust-related folding, low-angle crenulations and layer-parallel asymmetric extension, are all features that are expected in overthrust shear zones. The consistency in vergence of all structures, and between the blocks and matrix, further suggests that all are related products of a progressive deformation event.

This event involved early overthrusting with concomitant thickening, resulting in the development of the small scale, thrust-related folds and axial planar crenulation cleavage defined by biotite. This early fabric is ubiquitous in the deformed psammites, of both the Clyde Day and Otto Wheaton blocks. The volcanic blocks tend to resist folding, and only develop a strong penetrative cleavage. The difference in styles of deformation between the volcanics and the psammites is almost certainly due to contrasts in competence rather than deformation environments.

Continued overthrusting may have controlled small scale low-angle asymmetric crenulations in psammites of the Clyde Day Block, but much higher strain in the Otto

Wheaton Block, where the second phase of deformation produced isoclinal, asymmetric folds. This contrast in structural styles may reflect the relative timing of incorporation into the melange, where much of the non-coaxial strain is partitioned into the flowing matrix, rather than being accomodated by the block. Rigid body rotation of blocks, with lower aspect ratios in the viscous matrix, could lead to further development of discordant structural overprinting (e.g. Type II vs Type III interference patterns). Persistent shearing, in the melange matrix, pinched and swelled some of the large, tabular blocks to form the megaboudins. The behaviour of rigid inclusions in a viscous matrix undergoing non-coaxial strain is discussed in Ghosh and Ramberg (1976), and applied to melange processes in Cowan (1990), Orange (1990), and Needham (1987). The foregoing interpretation of post-incorporation deformation is consistent with their ideas.

All the deformational features described above are consistent with the criteria for recognizing 'shear zone' or tectonic melanges (Orange,1990). Asymmetric, layer-parallel extension has been cited as the mechanism by which the 'block-in-matrix' texture is generated, both in tectonic melanges (Needham, 1987; Ring et al., 1989; Orange, 1990), and in olistostromes (Cowan, 1982). However, structural fabrics, overprinting, metamorphic mineralization, and tectonic thickening, recorded by the Teakettle melange, are inconsistent with a surficial gravity slide model, and are best explained by layer-parallel shear in conjunction with vertical loading.

The combination of high asymmetrical strains and tectonic thickening has prompted many workers (e.g. Cowan, 1985; Fischer and Byrne, 1987; Lash, 1987;

Needham, 1989) to associate some tectonic melanges with the various thrust zones in accretionary wedge environments. Furthermore, high fluid pressures, low effective stresses, and low states of lithification are also conditions expected in a thrust stacking or accretionary environment.

The extensive layer-parallel shearing, asymmetric isoclinal folds and low-angle crenulations, record a progressive deformation history that affected initially flat-lying rocks. The persistence of layer-parallel shear, once incorporated into the melange matrix, suggests deformation in the basal section of the wedge, which is characterized by sub-horizontal shearing. Brittle deformation (brecciation and extensive quartz veining) in the blocks and especially in the matrix, records a transition into an environment of lower confining pressures during the latest stages of melange development. This transition may have resulted from transport into shallower structural levels.

The Teakettle melange blocks may have therefore followed a tectonic history, that began in a basal thrust zone of an accretionary prism or a thrust imbricated, stacking sequence (fig. 5.2.1). This environment is expected to produce intense shearing and vertical loading, leading to staurolite grade or higher metamorphism. Rocks of the Teakettle melange had to be removed from these metamorphic conditions before incorporation into the Carmanville Melange. This may have been achieved through underplating onto the hangingwall, resulting in transport to higher levels in the wedge, during progressive overthrusting. With continued advancement of the wedge, fresh wet sediments might be introduced below the decollement. These sediments would be subject

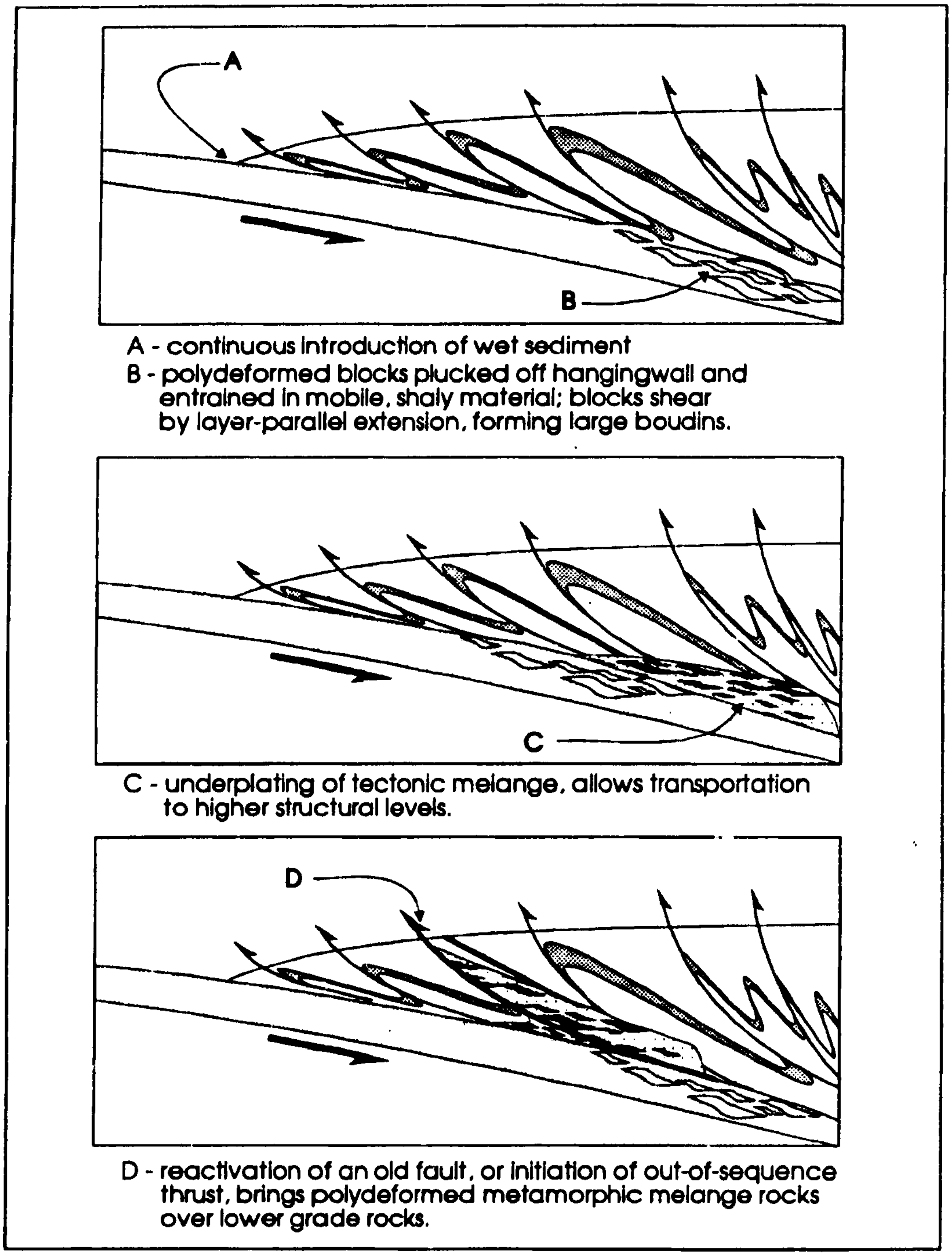


Figure 5.2.1 - Developmental model for the Teakettle melange

to a rapid rise in fluid pressures, which might ultimately induce mobilization of the viscous material into zones of weakness in the wall rock where they could pluck clasts or blocks of foreign material. If mobilization of this viscous material were to invade the hangingwall, they could be expected to entrain partially exhumed, underplated rocks, similar to blocks in the Teakettle melange. Once isolated in the shearing matrix, the plucked hangingwall blocks could experience continued deformation (asymmetric boudinage, coaxial folding) and rigid body rotation.

Lower confining pressures may be brought about through incorporation into an out-of-sequence thrust (i.e. not at the front of the wedge) into the hangingwall section. Out-of-sequence thrusts cut across earlier thrusts at low angles, allowing greater distances of lateral translation. Here, the progressive reduction in confining pressures, and increased viscosity driven by dewatering and continued shearing, could lead to cataclastic deformation.

5.3 Emplacement of the Carmanville Melange

The Carmanville Melange exhibits features that have been used to identify tectonic and diapiric melanges. Progressive asymmetrical deformation in the matrix and overprinting of structures showing successively higher viscosities were used by Fischer and Byrne (1987) to identify melanges in the Kodiak Islands, Alaska, as a package of underthrusted sediments disrupted by shearing at the base of an accretionary wedge. The deformation fabrics in the matrix of the Carmanville Melange show a similar evolution, implying a tectonic origin. However, the presence of the web-texture in sandstones and the pervasion of matrix dykes and finer injections are features considered to be indicative of diapiric origin (Barber et al., 1986; Pickering et al., 1988; Brown 1987; Orange, 1990). As stated earlier, these textures cannot uniquely distinguish melange forming mechanisms, and must be reconciled using additional evidence.

Several features of the Carmanville Melange imply a similar origin to that of the Teakettle melange:

1) The lithologies, and lithic associations in the Teakettle melange can be matched to lower grade equivalents in the Carmanville Melange.

2) The Teakettle melange is intimately associated with, and occurs only within the Carmanville Melange.

3) Early structures in the blocks entrained by the Carmanville Melange are morphologically similar to early structures in the Teakettle melange. For example, bedded sections, residing as blocks in the Carmanville Melange (rhythmites, siltstone), show an early phase of asymmetrical isoclinal folding with a penetrative axial planar cleavage (some with quartz veining), that predates incorporation into the melange.

The early history of the Carmanville Melange is therefore interpreted to have had a similar tectonic origin, at the base of an accretionary wedge. The lower grade assemblage may indicate that similar deformation processes were occurring at different structural levels. Later stages of development produced significantly different features in the Carmanville Melange; for example:

1) the much wider variety of lithologies in the Carmanville Melange contrasts with the Teakettle melange,

2) the dominance of equidimensional blocks, as opposed to phacoidal shapes or lensic shapes,

3) large tabular bodies are not boudinaged within the shaly matrix, nor do they show a preferred orientation with the matrix foliation,

4) fabrics in the Carmanville Melange matrix do not have the consistent asymmetry displayed by the Teakettle melange matrix and are locally very erratic,

5) the only post-incorporation deformation in the Carmanville Melange produced upright to reclined, open to tight, angular folds associated with the main regional cleavage,

6) the abundance of small, entrained clasts, and the paucity of quartz veins and blebs in the Carmanville Melange matrix contrasts with the Teakettle melange matrix.

These features strongly suggest a diversion from tectonic melange processes, at some point in the melange history, and require a much different model for mobility. The early tectonic features of the Carmanville Melange blocks imply a basal thrust environment for these rocks. Pre-lithification, layer-parallel asymmetric extension in the rhythmites (Gary C[illegible]s Block), suggests an even earlier history of vertical loading, on sediments with high fluid pressures (Fischer and Byrne, 1987). Therefore, these rocks may have originally formed part of the underthrusted sediment pile, below the decollement. Overprinting of asymmetrical, isoclinal folding, and layer-parallel cleavage development, is compatible with an environment of continued loading and concomitant shearing.

The earliest structures in the matrix siltstone-layer foliation, reflect an identical development history, consistent with overthrusting and high fluid pressures. The matrix protolith was probably also introduced to the system as a wet sediment, in the basal decollement. This early fabric is best seen in the pebbly shale dykes in the Ellis Coles Block, and south of the Keith Collins Block where a silty shale dyke cuts the Noggin Cove Formation. It seems likely that these melange dykes are a good representation of the matrix in its earlier stages of mobility, having been sheltered from later deformation by its host block.

The presence of melange dykes, structural discordance with the adjacent Woody Island and Noggin Cove formations, and web-texture further support the idea of an environment of high fluid pressures and injection. The progressive development of more viscous structures and eventually cataclastic flow demonstrates the importance of mobility in this melange genesis. The lack of phacoidal blocks and further deformation in the blocks, indicate the cessation of tectonic mechanisms. Also, the local discordance of the matrix foliation around some of the larger blocks is incompatible with the continuation of tectonic melange processes. Nor would the apparent inconsistency of asymmetry in the melange fabric be expected in a tectonic shearing environment. The only type of melange genesis that can adequately account for all these features is one of diapiric mobility, which commenced after early stages of thrusting.

The melange is therefore interpreted to have initiated as a shear zone melange, at the base of an overthrusting sequence or accretionary wedge; shortly followed by a diapiric upwelling through this wedge, thereby plucking and entraining wallrock material during its ascent (fig. 5.3.1). Incorporation of Teakettle melange blocks requires that the out-of-sequence thrust sheet containing them, lie directly in the path of the uprising melange.

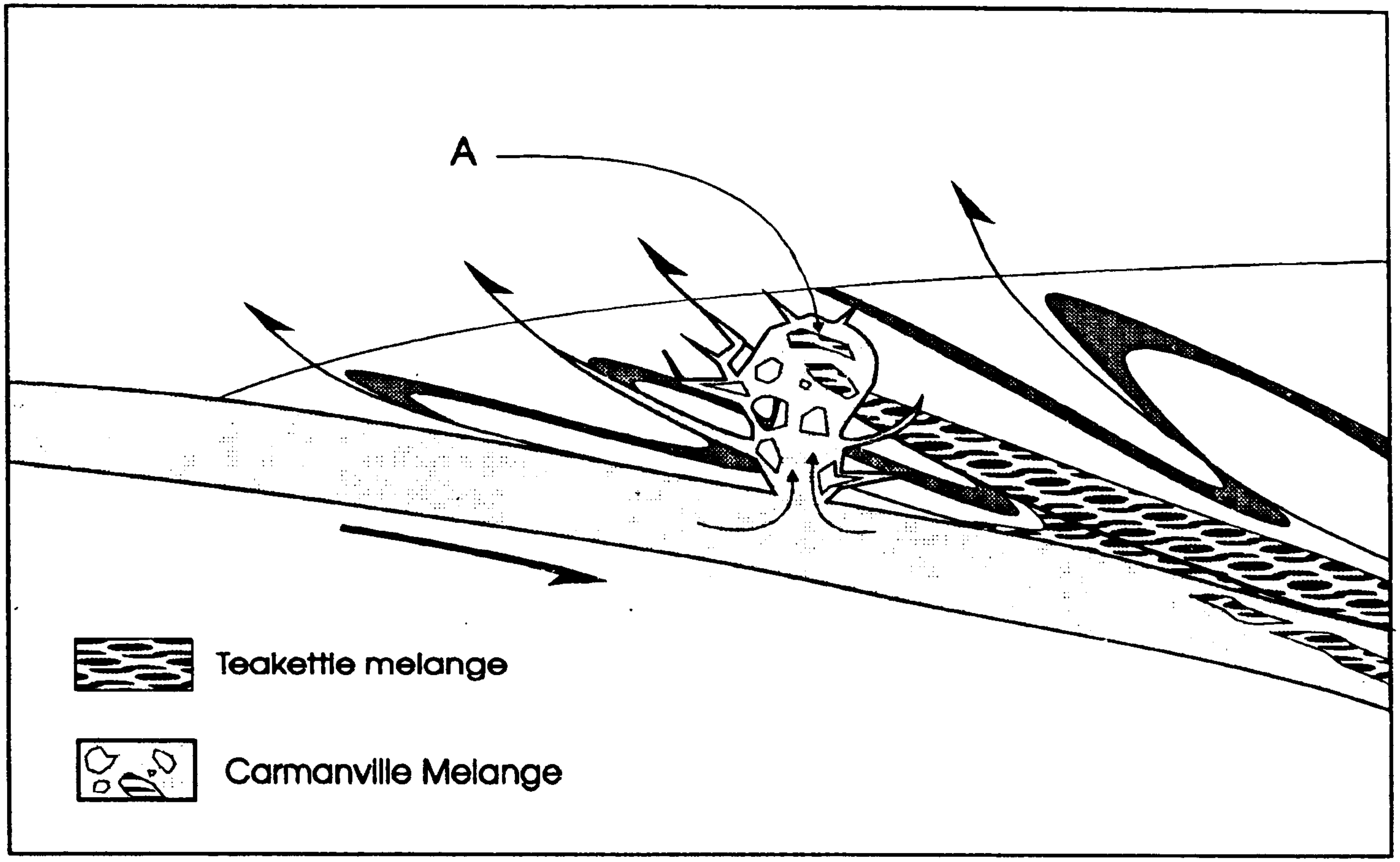


Figure 5.3.1 - Emplacement model for the Carmanville and Teakettle melanges. Diapiric ascent through thrust imbricated wedge, allows melange to sample a wide variety of country rocks, including Teakettle melange (A).

5.4 Discussion of the model

Lithological associations and polyphase structural histories have been used to show that the Carmanville Melange and the Teakettle melange formed through the interplay of dynamic processes involving thrusting, overpressuring, and diapiric mobility. Previous models that have been proposed for the Carmanville Melange include: olistostromal (Kennedy and McGonigal, 1972a; Pajari et al., 1979; Johnston, 1992), and possibly tectonic (Williams et al., 1991). An olistostromal origin for the Carmanville Melange is not likely for two main reasons:

1) Intrusive melange dykes in the Woody Island and Noggin Cove formations indicate that mobility post-dates both units. Furthermore, evidence of high fluid content during mobility (e.g. silty foliation, pervasive quartz veins, independent particulate flow) strongly suggests that the dykes are not hard rock (post-deposition/compaction) features.

2) Structural contrasts between the Carmanville Melange matrix and adjacent rocks argue against stratigraphic links between them.

3) The lithic assemblage of blocks in the Carmanville Melange contrasts with the neighbouring geology. The paucity of Noggin Cove Formation type volcaniclastics and the abundance of pillow lavas and sedimentary clasts in the melange casts doubt on derivation from nearby sources, nor is there any known regional source for the lithic load of the Carmanville Melange. Additionally, an abrupt change in lithofacies, from volcaniclastic debris flows, to sediment dominated melange with pre-deformed clasts is unlikely.

Tectonic melanges are large scale analogues of fault gouge. The fine-grained matrix is derived through extensive granulation and cataclasis of the wall rock. Blocks are plucked from the wall rock and continue to deform in the matrix. Some foreign clasts may be introduced at the toe of the overriding slab, and recycled into the fault zone. Many features of the Carmanville Melange are incompatible with this process of melange development:

1) Block shapes are dominantly equidimensional, as opposed to phacoidal.

2) Blocks rarely show any type of post-entrainment deformation, that would suggest a shearing environment.

3) The paucity of Noggin Cove and Woody Island formation blocks in the melange, and the preponderance of foreign material, is difficult to explain in terms of a tectonic origin.

4) To generate a tectonic melange that is at least 5 kilometres thick, and dominated by fine-grained matrix, shearing and overthrusting would have had to be extremely intense and large scale. No evidence of deformation on this scale is recorded in the wall rock.

5) The erratic nature of the foliation also conflicts with generation by shearing.

While not a unique solution, a diapiric model for emplacement can account for all of the above features of the Carmanville Melange as follows:

1) Intrusive dykes are a common and expected feature of any rising diapiric body.

2) A diapir rising through a stack of structurally imbricated slices has the

opportunity to sample a wide variety of lithological assemblages, with diverse structural and metamorphic histories.

3) Wet, unlithified shales are known to flow and ascend diapirically through modern accretionary prisms, and thus provide an attractive source for the large volumes of melange matrix.

4) Blocks transported in a rising diapir would not experience extensive ductile deformation because most of the strain would be partitioned into the flowing matrix. During transportation the blocks would undergo significant rigid body rotation, and might deform dominantly by cataclasis on their edges. Thus, equidimensional shapes will be favoured in the flowing matrix.

5) The matrix would be forced to wrap around large blocks, thus producing the erratic foliations in the matrix.

6) In addition, a rising diapir could transport its entrained blocks into shallower levels, where confining pressures would be significantly reduced. This type of environment could produce the web texture in psammites, and lead to more cataclastic deformation, like brecciation of the matrix. Also, the elliptical shape of the melange is easily accounted for in a diapiric model.

If the Carmanville Melange is a diapiric melange, and generated by overpressuring and thrusting in an accretionary wedge, then thrust slices should be identifiable in the regional geology. The Hamilton Sound complex is a strong candidate for an imbricate thrust slice, due to its structural and lithic contrasts with the adjacent Davidsville Group.

The basal Davidsville Group is thrust imbricated with the Gander River Complex, and together, they were thrust on top of the Gander Group. An aeromagnetic anomaly, modelled by Miller (1988), in the Gander Group, might be an imbricate sheet of Exploits Subzone material at depth (Miller, 1988; O'Neill, 1991). The magnetic anomaly may also represent ophiolitic basement to the Gander Group, implying that the Gander River Complex does not mark the eastern limit of ophiolitic rocks. While thrusting is not uncommon in these rocks, there are significant contrasts in timing and orientations of the various structures. Thrust imbrication of the Gander River Complex within the Davidsville Group is Arenig, or older, based on the age of its unconformity with Davidsville conglomerates (O'Neill, 1991), and predates structural juxtapositioning with the Gander Group. In the Carmanville area, the Noggin Cove Formation is interpreted to be in thrust contact with the Caradocian Main Point shales, although this contact may have been remobilized and does not necessarily reflect their original relationship.

Tentative lithological links between blocks in the Carmanville Melange and nearby units present a potential continuity to the region. If true, the Carmanville Melange could have sampled a cross-section of the entire northeast Exploits Subzone and parts of the Gander Zone. The ages of entrained blocks could thus be as old as Middle Cambrian (Jonathon's Pond Formation).

CHAPTER 6

Implications and Conclusions

6.1 Implications

Age

The tortuous emplacement path of the Carmanville Melange demonstrates its highly time-transgressive nature. Mobilization of an initially wet, viscous, silty shale into a thrust imbricated section allows the melange to sample rocks with a wide cross-section of ages. Some may be significantly older than the melange matrix; for example, the Teakettle melange unit shows several phases of deformation prior to entrainment in the Carmanville Melange. Reciprocally, soft-sediment, layer-parallel extension in the rhythmite blocks suggests that it may have experienced a similar history to the matrix. The alternating sequence of siltstone and shale beds, further accentuates the similarity between the melange matrix and the rhythmites and they may be lateral equivalents. These rocks, together with the matrix shales, likely represent the youngest rocks in the melange. No systematic search for fossils was performed, although several limestone blocks have been previously checked for conodonts (by Felicity O'Brien) and were found to be unfossiliferous. While blocks in the melange place only loose constraints on the age of emplacement, the structural relationships between the melange and surrounding units provide valuable information on the relative timing.

The Carmanville Melange is structurally bounded by the Noggin Cove and the Woody Island formations. Both units have cleavages that are cut by melange dykes. The single cleavage in the melange is axial planar to open to tight, upright chevron style folds. The overall trend of these structures is consistent with the regional structure east of the Dog Bay Line (Williams et al., 1993). In contrast, all deformation activity in the matrix, that predates the single cleavage, is confined to the melange and is discordant with external structures. The emplacement of the Carmanville Melange therefore, post-dates early phases of deformation in the Noggin Cove and Woody Island formations, but pre-dates the development of the ubiquitous regional northeast cleavage.

Based on chemostratigraphic correlations between the Noggin Cove Formation and the Tea Arm Volcanics of the Exploits Group, the Noggin Cove Formation is interpreted as Middle Ordovician or older (Johnston, 1992). The Tea Arm Volcanics are overlain conformably by the Strong Island Chert, which contains Llanvirn graptolites (Dec et al., 1992; Williams et al., 1992). Cross-cutting of the Noggin Cove Formation by the Carmanville Melange indicates that some of the mobility must be Middle Ordovician, or younger.

The age of the overprinting, northeast, regional cleavage is uncertain (Williams et al., 1993). Karlstrom et al. (1982), stated that it was largely post-Middle Silurian, although probably diachronous, and locally, may have begun in Ordovician times. West of the Dog Bay Line, structural styles of the main regional fabric are similar, but have opposite vergence (pers. comm. Williams, 1993). The Dog Bay Line records a major phase of Silurian transpressive ductile deformation (Williams et al., 1993). Stages of melange formation pre-date the transpressive deformation, and are believed correlatable to the Dunnage Melange (circa 465Ma, Hibbard and Williams, 1979), implying disruption in the Middle Ordovician (Williams, 1992).

The overpressuring and mobilization of the Carmanville Melange was likely a result of regional-scale overthrusting. Major overthrusting in the northeast Exploits Subzone may have begun in Ordovician times and continued into the Silurian (Karlstrom et al., 1982). Generation of the Carmanville Melange probably took place during this phase of major overthrusting in the Middle Ordovician. Final emplacement pre-dated the major transpressive event that produced the regional cleavage.

Correlations

Similarities in block lithologies and proportions between the Carmanville Melange and the Dunnage Melange have prompted all previous investigators to correlate the two units (Kennedy and McGonigal, 1972a; Pajari et al., 1979; Karlstrom et al., 1982; Williams, 1992; 1993). Similar features between the two include:

1) abundant micaceous greywackes with dark glassy, smoky quartz grains of unknown source in both the Dunnage and Carmanville Melanges,

2) associations with coticule-bearing shales,

3) abundant mafic volcanic blocks (mostly pillowed basalts) commonly with limestone lenses,

4) matrices rich in sedimentary clasts,

5) presence of metamorphosed and polyphase deformed psammitic blocks (gradations observed in Dunnage, from massive greywacke to cleaved greywacke and kinked psammitic schist; Williams, 1994),

6) common web-texture (Hibbard and Williams, 1979),

7) intrusive shales in entrained blocks and surrounding units (Hibbard and Williams, 1979),

8) internal structural histories that are discordant with external/regional deformation (Hibbard and Williams, 1979), and

9) evidence for both soft-sediment and tectonic deformation (Hibbard and Williams, 1979).

The assertion of recent studies in the northeast Exploits Subzone, that east-west correlations are the dominant pattern, is also in agreement with a Dunnage-Carmanville melange link.

Mafic volcanic rocks, with limestone associations in the Carmanville Melange, are lithologically very similar to those in the Dunnage Melange; however, they do not agree geochemically. Most of the basalt blocks in the Carmanville Melange plot in the MORB field, or have island arc chemistries. Only 4 blocks from the Carmanville-Fredericton area display ocean island affinities (WPB), which are the typical basalt type in the Dunnage Melange (Wasowski and Jacobi, 1985). In this context, the Dunnage Melange and the Carmanville Melange are not strictly correlative.

The findings of this study indicate that the siting of the Carmanville Melange is controlled by an intrusive mode of emplacement, and therefore cannot be correlated to the Dunnage Melange in a stratigraphic sense. The commonality of internal complexities between the two melanges, in particular, the presence of recycled psammitic schists, web-texture, and melange matrix intrusions, suggest that the Dunnage Melange may also have had a diapiric stage in its evolution. The internal turmoil of the Dunnage Melange is additionally complicated by its relationship with the Coaker Porphyry (Hibbard and Williams, 1979; Lorenz, 1984).

Regional Tectonics

Diapiric emplacement of the Carmanville Melange, initiated in a high shear strain environment, requires a large amount of tectonic loading, in a large shear zone. Major overthrusting in Middle Ordovician times (Karlstrom et al., 1982) was most likely responsible for the asymmetric loading and subsequent mobilization of the melange. This initial phase of overthrusting is a typical feature in the tectonic evolution of eastern Notre Dame Bay (Karlstrom et al., 1982), and could also have been partly responsible for emplacement of the Dunnage Melange. This interpretation implies that the early history of the northeast Exploits Subzone resembled that of an accretionary wedge, or it may have been a foreland fold and thrust belt with southeast vergence (O'Brien, 1993).

East-west correlations are obscured by the interference of Silurian movement on the Dog Bay Line (Williams et al., 1993), but it remains clear that the structural and lithological trends in the northeast Exploits Subzone are oblique to the northeast trend of the Gander River Complex. Southeast directed thrust imbrication, leading to the present configuration, may mark a change in the Middle Ordovician dynamic evolution of Exploits/Gander interaction. Alternatively, it may represent progressive deformation in the trailing margin of the Exploits Subzone during obduction.

Resolution of these ideas is hindered by the paucity of outcrop in the northeast Exploits Subzone, and thus the exposure of key contact relationships. The models proposed in this thesis arose from a very detailed study of a small area. A move towards this kind of detailed structural approach, in future studies, may help to elucidate some other problems in the immediate area, in particular, the relationship between the Hamilton Sound complex and the Davidsville Group.

6.2 Conclusions

1) The Teakettle melange blocks have a markedly distinct structural history, that is incongruous with, and predates incorporation into, the main body of melange. The strong asymmetry of pre- and post-incorporation deformation, with attendant metamorphism in these blocks, indicate that they were generated in an environment of high shear strain under conditions that locally reached lower amphibolite facies metamorphism. The formation of 'megaboudins' was responsible, in part, for the 'block-in-matrix' texture in these melanges.

2) All bedded sections, within the Teakettle and Carmanville melanges, share an

early history of asymmetrical, isoclinal folding associated with an axial planar cleavage or foliation. This is interpreted to have been formed by progressive overthrusting in an accretionary wedge.

3) The progressive overprinting of structures in the Carmanville Melange records a gradual increase in viscosity from soft-sediment deformation dominated by independent particulate flow, through ductile deformation producing folds and shear bands, then extensive brittle cataclasis. This history of deformation is believed to reflect progressive dewatering of initially overpressured, water rich sediments, and contrasts sharply with the structures of surrounding units.

4) Melanges provide excellent windows into the progressive dynamics of thrust stacking sequences. Due to their mobile nature, they will tend to record subtleties in the strain histories, not seen in more coherent rocks. However, also because of this mobility, overprinting and translation of structures are extensive and possibly prohibit kinematic interpretation. The subtleties in the dynamics of melange deformation, when used in concert with better constrained regional structural analysis, could greatly expand our current understanding of orogenic development.

The ideas presented in this thesis are not unique solutions to the Carmanville and Teakettle melanges problem. They are proposed as the simplest and most reasonable models that best explain the observed relationships. There is still much work to be done in the area, and it is hoped that these ideas, true or not, will help direct the considerations of future investigators.

6.3 Summary

The melanges of the northeast Exploits Subzone have long been a source of lively debate and intrigue. Detailed studies of their components, structures and relations to nearby units, are lacking. Several important aspects of the Carmanville and Teakettle melanges have been elucidated by this study, and are listed below.

1) Lithologies in the Teakettle melange can be matched with lower grade equivalents in the Carmanville Melange:

- Deformed pillow lavas and layered mafic volcanics of the Teakettle melange share the same chemistries, and associations with limestone, as the pillowed basalt rocks in the Carmanville Melange.
- Teakettle melange psammites match Carmanville Melange greywackes and all are of unknown origin.
- The black pelitic schist in the Teakettle melange is equivalent to the lower grade pebbly mudstone and graphitic shale matrix of the Carmanville Melange.

2) There are great differences in the proportions of blocks and matrices, and structural and metamorphic styles, between the Teakettle and Carmanville melanges.

3) Rocks and their proportions in the Carmanville and Teakettle melanges are not a proportionate sampling of regional rocks. There are very few Gander River Complex lithologies, few Noggin Cove lithologies, and a preponderance of unknown greywackes.

4) The Carmanville Melange is not a stratigraphic unit of the Hamilton Sound complex, and is therefore not a simple olistostrome, although it contains some features

typical of olistostromes.

5) Since no obvious source or record of the structural and metamorphic style of the Teakettle melange exists in the Exploits Subzone, its exhumation and other features are the result of processes and recycling in the melange itself.

6) Greywacke blocks of the Carmanville Melange almost everywhere show internal brecciation, or web-texture, with ramifying networks of black shale penetrating and surrounding greywacke clasts. This texture is not present in volcanogenic lithologies. Brecciation is also a common feature in the psammites and pelitic matrix of the Teakettle melange, but not its volcanic blocks. These effects are directly related to melange forming processes.

7) Teakettle melange metamorphic blocks have fabrics that are truncated by structures in its matrix, which are, in turn, truncated by the Carmanville Melange.

8) The flow foliation in the Carmanville Melange matrix wraps around large clasts, and plucks fragments from their peripheries. This suggests that the internal chaos of the melange is acquired as a result of its mobility, rather than a primary feature.

9) The single cleavage in the Carmanville Melange matrix contrasts with the two cleavages retained in the Noggin Cove and Woody Island formations. All sedimentary blocks on Teakettle Point contain at least one foliation that predates incorporation into the Carmanville Melange.

References

Abbate, E., and Sagri, M. 1981. Olistostromes in the Oligocene Macigno Formation (Florence area). in Lucchi, F.R. (ed.), Excursion guidebook with contributions on sedimentology of some Italian basins: Bologna, Italy, International Association of Sedimentologists, 2nd European regional meeting, p.165-203.

Arnott, R.J. 1983a. Sedimentology of Upper Ordovician-Silurian sequences on New World Island, Newfoundland: Separate fault-controlled basins? Canadian Journal of Earth Sciences, v. 20, p. 345-354.

Baltuck, M., Taylor, E., and McDougall, K. 1985. Mass movement along the inner wall of the Middle America Trench, Costa Rica. in von Huene R., Aubouin, J., and others, Initial reports of Deep Sea Drilling Project, v. 84, p. 551-570.

Barber, A.J., Tjokrosapoetc, S., and Charton, T.R. 1986. Mud volcanoes, shale diapirs, wrench faults and melanges in accretionary complexes. American Association of Petroleum Geology Bulletin, v. 70, p. 1729-1741.

Blackwood, R.F. 1978. Northeastern Gander Zone, Newfoundland. in Report of Activities for 1977, R.V. Gibbons (ed.); Newfoundland Department of Mines and Energy, Mineral Development Division, Report 78-1, p. 72-79.

1982. Geology of the Gander Lake (2D/15) and Gander River (2E/2) area; Newfoundland Department of Mines and Energy, Mineral Development Division, Report 82-4, 56 p.

Borradaile, G.J. 1981. Particulate flow and the formation of cleavage. Tectonophysics, v. 72, p. 305-321.

Boyce, W.D., Ash, J.S., and Dickson, W.L. 1993. The significance of a new bivalve fauna from the Gander map area (2D/15) and a review of Silurian bivalve- bearing faunas in central Newfoundland. in Current Research (1988). Newfoundland Department of Mines, Geological Survey branch, Report 93-1, p. 187-194.

Brown, K.M. 1987. Structural and physical processes in accretionary complexes: The role of fluids in convergent margin development. Unpub. PhD Thesis, University of Durham, Durham, England, p. 175.

Brown, K.M., and Orange, D.L. 1993. Structural aspects of diapiric melange emplacement; the Duck Creek Diapir. Journal of Structural Geology, v. 15 (7), p. 831-847

Bruckner, W.D. 1972. The Gander Lake and Davidsville groups of northeastern Newfoundland: New data and geotectonic implications; Discussion, Canadian Journal of Earth Sciences, v. 9, p. 1778-1779.

Byrne, T. 1984. Early deformation in melange terranes of Ghost rocks formation, Kodiak Islands, Alaska. in Raymond, L.A. (ed.) Melanges Their Nature, Origin and Significance, Geological Society of America, Special Paper 198.

Colman-Sadd, S.P. 1984. Geology of the Cold Spring Pond map area (west part) 12A/1, Newfoundland, in Current Research; Newfoundland Department of Mines and Energy, Mineral Development Division, Report 84-1, p. 211-219

Colman-Sadd, S.P., and Swinden, H.S., 1984. A tectonic window in central Newfoundland? Geological evidence that the Appalachian Dunnage Zone may be allochthonous, Canadian Journal of Earth sciences, v. 21, p. 1349-1367

Colman-Sadd, S.P., Dunning, G.R., and Dec., T. 1992. Dunnage-Gander relationships and Ordovician orogeny in central Newfoundland: A sediment provenance and U/Pb age study, American Journal of Science, v. 292, p. 317-355.

Cook, H.E., McDaniel, P.N., Mountjoy E.W., and Pray, L.C. 1972. Allocthonous carbonate debris flows at Devonian bank ("reef") margins, Alberta, Canada, Bulletin of Canadian Petroleum Geology, v. 20, p. 439-497.

Cowan, D.S. 1974. Deformation and metamorphism of the Franciscan subduction zone complex northwest of Pacheco Pass, California, Geological Society of America Bulletin, v. 89, p. 1623-1634.

Cowan, D.S., 1982. Deformation of partly dewatered and consolidated Franciscan sediments near Piedras Blancas Point, California, in Legget J.K., (ed.), Trench-forearc geology, Geological Society of London Special Publication 10, p. 439-457

1985. Structural styles in Mesozoic and Cenozoic melanges in the western Cordillera of North America, Geological Society of America Bulletin, v. 96, p. 451-462

1990. Kinematic analysis of shear zones in sandstone and mudstones of the Shimanto Belt, Shikoku, southwest Japan, Journal of Structural Geology, v. 12 (4), p. 434 - 441.

Currie, K.L. 1992. A new look at Gander-Dunnage relations in Carmanville map area Newfoundland, in Current Research, Part D; Geological Survey of Canada, Paper 92-1D, p. 27-33.

1993. Ordovician-Silurian stratigraphy between Gander Bay and Birchy Bay, Newfoundland, in Current Research, Part D; Geological Survey of Canada, Paper 93-1D, p. 11-18.

Currie, K.L. and Pajari, G.E. 1977. Igneous and metamorphic rocks between Rocky Bay and Ragged Harbour, northeastern Newfoundland, in Report of Activities, Part A; Geological Survey of Canada, Paper 77-1A, p. 341-346.

Dec, T., Swinden, S., and Floyd, J.D. 1992. Sedimentological, geochemical and sediment-provenance constraints on stratigraphy and depositional setting of the Strong Island Chert (Exploits Subzone, Notre Dame Bay), in Current Research, Part D; Newfoundland Department of Mines, Geological Survey of Canada, Report 92-1, p. 85-96.

Dewey, J.F. and Bird, J.M. 1971. Origin and emplacement of the ophiolite suite: Appalachian ophiolites in Newfoundland, Journal of Geophysical Research, v. 76, p. 3179-3206.

Fischer, D., and Byrne, T. 1987. Structural evolution of underthrusted sediments, Tectonics, v. 6 (6), p. 775-793.

Ghosh, S.K., and Ramberg, H. 1976. Reorientation of inclusions by combination of pure shear and simple shear, Tectonophysics, v. 34, p. 1-70.

Gratier, 1987. Pressure solution-deposition creep and associated tectonic differentiation in sedimentary rocks, in Jones, M.E. and Preston (eds), Deformation of sediments and sedimentary rocks, Geological Society of London Special Publication 29.

Greenly, E. 1919. The Geology of Anglesey, Geological Survey of Great Britain Memoir 1, 980 p.

Hibbard, J.P. and Williams, H., 1979. Regional setting of the Dunnage Melange in the Newfoundland Appalachians, American Journal of Science, v. 279.

Horton and Rast, 1989 (eds). Melanges and Olistostromes of the U.S. Appalachians, Geological Society of America, Special Paper 228.

Hsu, K.J. 1968. Principles of melanges and their bearing on the Franciscan-Knoxville paradox, Geological Society of America Bulletin, v. 79, p.1063-1074.

Jacobi, R.D. 1984. Modern submarine sediment slides, melange and the Dunnage Formation in north-central Newfoundland, in Raymond, L. (ed.), Melanges: Their nature, origin, and significance. Geological Society of America, Special Paper 198, p. 126-130.

Jenness, S.E. 1963. Terra Nova and Bonavista map areas, Newfoundland (2D E1/2 and 2C), Geological Survey of Canada, Memoir 327, 184 p.

1972. The Gander Lake and Davidsville groups of northeastern Newfoundland: New data and geotectonic implications: Discussion, Canadian Journal of Earth Sciences, v. 9, p. 1779-1781

Johnston, D.H. 1992. The Noggin Cove Formation, Carmanville Melange: island arc rifting in northeast Newfoundland, Unpubl. M.Sc. Thesis, Memorial University of Newfoundland, St. John's, Newfoundland, Canada.

Karlstrom, K.E., van der Pluijm, B.A., and Williams, P.F. 1982. Structural interpretation of the eastern Notre Dame Bay area, Newfoundland: regional post-Middle Silurian thrusting and asymmetrical folding, Canadian Journal of Earth Sciences, v. 19, p. 2325-2341.

Keen, C.E., Keen, M.J., Nichols, B., Ried, I., Stockmal, G.S., Colman- Sadd, S.P., O'Brien, S.J., Miller, H., Quinlan, G., Williams, H., and Wright, J. 1986. Deep seismic reflection profile across the northern Appalachians; Geology, v. 14, p. 141-145.

Kennedy, M.J., 1975. Repetitive orogeny in the northeastern Appalachians - new plate models based upon Newfoundland examples, Tectonophysics, v. 28, p. 39-87.

Kennedy, M.J. and McGonigal, M.1972a. The Gander Lake and Davidsville groups of northeastern Newfoundland: new data and geotectonic implications. Canadian Journal of Earth Sciences, v. 9, p. 452-459.

1972b: The Gander Lake and Davidsville groups of northeastern Newfoundland: new data and geotectonic implications (reply), Canadian Journal of Earth Sciences, v. 9, p. 1781-1783.

Knipe, R.J., and White, S.H. 1977. Microstructural variation of an axial plane cleavage around a fold - a H.V.E.M. study, Tectonophysics, v. 39, p. 355-380.

Larue, D.K., and Huddleston, P.J. 1987. Foliated breccias in active portuguese Bend landslide complex, California: Bearing on melange genesis, Journal of Geology, v. 95, p. 407-422.

Lash, G.G. 1987. Diverse melanges of an ancient subduction complex, Geology, v. 15, p. 652-655.

Lister, G.W., and Williams, P.F. 1983. The partitioning of deformation in flowing rock masses. Tectonophysics, v. 92, 1-33.

Lorenz, B. E., 1984. A study of the igneous intrusive rocks of the Dunnage Melange, Newfoundland, unpubl. Ph.D. thesis, Memorial University of Newfoundland.

Longerich, H.P., *in prep.*. The analysis of pressed pellets of geological samples using wavelength dispersive X-ray Fluorescence spectrometry, *prepared for submission to:* X-Ray Sectrometer.

McKerrow, W.S. and Cocks, L.R.M. 1977. The location of the Iapetus Ocean suture in Newfoundland, Canadian Journal of Earth Sciences, v. 14, p. 488-495.

Meschede, M. 1986. A method of discriminating different types of mid-ocean ridge and continental tholeiites with Nb-Zr-Y diagrams. Chemical Geology, v. 12, p.587-590

Miller, H.G. 1988. Geophysical interpretation of the geology of the northeast Gander Terrane, Newfoundland, Canadian Journal of Earth Sciences, v. 25, p. 1161-1174.

Moore G.F., and Karig, D.E. 1980. Structural geology of Nias Island, Indonesia: implications for subduction zone tectonics, American Journal of Science, v. 280, p.193-223.

Mullen, E.D. 1983. MnO-TiO_2-P_2O_5: a minor element discrimination for basaltic rocks of oceanic environments and its implications for petrogenesis, Earth and Planetary Science Letters, v. 62, p. 53-62.

Musgrave, A.W. and Hicks, W.G., 1968. Outlining shale masses by geophysical methods, in Braunstein, J. and O'Brien, G.D. (eds), Diapirism and Diapirs, a symposium, American Association of Petroleum Geology, Memoir 8.

Needham, D.T. 1987. Asymmetric extensional structures and their implications for the generation of melanges. Geology Magazine, v. 124 (4), p. 311-318.

Nelson, K.D. 1981. Melange development in the Boones Point Complex, north-central Newfoundland, Canadian Journal of Earth Sciences, v. 18, p. 433-442.

O'Brien, B.H., 1993. A mappers guide to Notre Dame Bay's folded thrust faults: Evolution and regional development, in Current Research; Newfoundland Department of Mines, Geological Survey Branch, Report 93-1, p. 279-291.

O'Neill, P.P. 1991. Geology of the Wier's Pond area, Newfoundland (NTS 2E/1). Newfoundland department of Mines and Energy, Geological Survey Branch, Report 91-3.

O'Neill, P.P. and Blackwood, F. 1989. A proposal for revised stratigraphic nomenclature of the Gander and Davidsville groups and the Gander River Ultrabasic Belt of northeastern Newfoundland. in Current Research; Newfoundland Department of Mines, Mineral Development Division, Report 88-1, p. 165-176.

O'Neill, P. and Knight, J.1988. Geology of the east half of the Wier's Pond (2E/1) map area and its regional significance, in Current Research (1988); Newfoundland Department of Mines, Mineral Development Division, Report 88-1, p. 165-176.

Orange, 1990. Criteria helpful in recognizing shear-zone and diapiric melanges. Geological Society of America Bulletin, v. 102, pp. 935-951.

Pajari, G.E. and Currie, K.L. 1978. The Gander Lake and Davidsville Groups of northeastern Newfoundland: a re-examination. Canadian Journal of Earth Sciences, v. 15, p. 708-714.

Pajari, G.E., Pickerill, R.K., and Currie, K.L. 1979. The nature, origin and significance of the Carmanville Ophiolitic Melange, northeastern Newfoundland, Canadian Journal of Earth Science, v. 16, p. 1439-1451.

Pearce, J.A. 1975. Basalt geochemistry used to investigate past tectonic environments on Cyprus, Tectonophysics, v. 25, p. 41-67.

Pearce, J.A., and Cann, J.R. 1973. Tectonic setting of basic volcanic rocks determined using trace element analyses, Earth and Planetary Science Letters, v. 19, p. 290-300.

Phipps, S. P. 1984. Ophiolitic olistostromes in the basal Great Valley sequence, Napa County, northern California Coast ranges, in Raymond L.A. (ed) Melanges: Their nature, origin, and significance, Geological Society of America, Special Paper 13, p. 126-130.

Piasecki, M.A.J. 1988. A major ductile shear zone in the Bay d'Espoir area, Gander Terrane, southeastern Newfoundland, in Current Research; Newfoundland Department of Mines, Mineral Development Division, Report 88-1, p. 135-144.

Pickerill, P.K., Pajari, G.E., Jr., and Currie, K.L. 1978. Carmanville map-area, Newfoundland; the northeastern end of the Appalachians, in Current Research, Part A; Geological Survey of Canada, Paper 78-1A, p. 209-216.

Pickering, K.T., Agar,S.M., and Ogawa,Y.,1988. Genesis and deformation of mud injections containing chaotic basalt-limestone-chert associations. Geology, v. 16 (10), p. 881-885.

Ramsay, J.G., and Huber, M.I. 1987. The techniques of modern structural geology: Volume 2: Folds and fractures. Academic Press, London.

Raymond, L.A. 1984. Block content in melange mapping; a caveat. Abstracts-with-Programs-Geological-Society-of-America, v. 16 (6), p. 631.

1984. (ed.) Melanges: their nature, origin and significance, Geological Society of America, Special Paper 198.

Reusch, D.N. 1987. Silurian stratigraphy and melanges, New World Island, north central Newfoundland, in David, C.R. (ed.), Centennial Field Guide, v. 5, Geological Society of America, p. 463-466.

Ring, U., Ratschbacher L., Frisch W., Biehler D., and Kralik M. 1989. Kinematics of the Alpine plate-margin: structural styles, strain and motion along the Penninic-Austroalpine boundary in the Swiss-Austrian Alps, Journal of the Geological Society of London, v. 146, p. 835-849.

Sawyer, E.W. and Barnes, S.-J. 1983. Pillow Shelves: determination of bedding direction and structural facing direction from shelves in deformed pillow lavas, Canadian Journal of Earth Science, v. 20 (9).

Shervais, J.W. 1982. Ti-V plots and the petrogenesis of modern and ophiolitic lavas. Earth and Planetary Science Letters, v. 59, p. 101-118.

Stevens, R.K. 1970. Cambro-Ordovician flysch sedimentation and tectonics in west Newfoundland and their possible bearing on a Proto-Atlantic Ocean, in Lajoie, J. (ed.), Flysch sedimentology in North America, Geological Association of Canada, Special Paper 7, p. 165-178.

Stockmal, G.S., Colman-Sadd, S.P., Keen, C.E., O'Brien, S.J., and Quinlan, G. 1987. Collision along an irregular margin: a regional plate tectonic interpretation of the Canadian Appalachians, Canadian Journal of Earth Sciences, v. 24, p. 1098-1107.

Swinden, H.S., Jenner, G.A., Fryer, B.J., Hertogen, J., and Roddick, J.C. 1990. Petrogenesis and paleotectonic history of the Wild Bight Group, an Ordovician rifted island arc in central Newfoundland, Contributions to Mineralogy and Petrology, v. 105, p. 219-241.

Tabor, R.W. 1987. A Tertiary accreted terrane: Oceanic basalt and sedimentary rocks in the Olympic Mountains, Washington, Geological Society of America Centennial Field Guide: Cordilleran Section, p.377-382.

Talbot, C.J., and von Brunn, V. 1989. Melanges, intrusives and extrusive sediments and hydraulic arcs, Geology, v. 17, p. 446-450.

Torrini, R., Jr., Speed, R.C., and Matoili, G.S. 1985. Tectonic relationships between forearc basin strata and the accretionary complex at Bath, Barbados, Geological Society of America Bulletin, v. 96, p. 861-874.

Wasowski, J.J. and Jacobi, R.D.1985. Geochemistry and tectonic significance of the mafic volcanic blocks in the Dunnage melange, north-central Newfoundland, Canadian Journal of Earth Sciences, v. 22, p.1248-1256.

Williams, H. 1964. The Appalachians in northeastern Newfoundland: A two-sided symmetrical system, American Journal of Science, v. 262, p. 1137-1158.

1979. Appalachian Orogen in Canada, Canadian Journal of Earth Science, Tuzo Wilson volume, v. 16, p. 792-807.

1992. Melanges and coticule occurrences in the northeast Exploits Subzone, Newfoundland, in Current Research; Part B; Geological Survey of Canada, Paper 89-1B, p. 55-66.

1993. Stratigraphy and structure of the Botwood belt and definition of the Dog Bay Line in northeastern Newfoundland, in Current Research, Part B; Geological Survey of Canada, Paper 93-1D, p.19-27.

1994. The Dunnage Melange, Newfoundland revisited, in Current Research, Geological Survey of Canada, Paper 94-1D, p. 1-9.

Williams, H. and Piasecki, M.A.J. 1990. The Cold Spring Melange and a possible model for Dunnage-Gander zone interaction in central Newfoundland, Canadian Journal of Earth Science, v. 27, p. 1126-1134.

Williams, H., Colman-Sadd, S.P., and Swinden, H.S. 1988. Tectonic-stratigraphic subdivisions of central Newfoundland, in Current Research, Part B; Geological Survey of Canada, Paper 88-1B, p. 91-98.

Williams, H., Currie, K.L. and Piasecki, M.A.J. 1993. The Dog Bay line: A major Silurian tectonic boundary in northeast Newfoundland, Canadian Journal of Earth Science, v. 30, p. 2481-2494.

Williams, H., Piasecki, M.A.J., and Johnston, D. 1991. The Carmanville Melange and Dunnage-Gander relationships in northeast Newfoundland, in Current Research, Part D; Geological Survey of Canada, Paper 91-1D, p. 15-23.

Williams, P.F. 1983. Timing of deformation and the mechanism of cleavage development in a Newfoundland melange, Maritime Sediments and Atlantic Geology, v. 19, p. 31-48.

Williams, S.H., O'Brien, B.H., Colman-Sadd, S.P., and O'Brien, F.H.C. 1992. Dunnage Zone graptolites - an extension of the age range and distribution of certain Ordovician formations of the Exploits Subzone, in Current Research; Newfoundland Department of Mines, Report 92-1, p. 203-210.

Wilson, J.T., 1966. Did the Atlantic close and then re-open? Nature, v. 211, p. 676-681.

Wilson, J.T., Hanson, R.E. & Grunow, A., 1989. Multistage melange formation within an accretionary complex, Geology, v. 17 (1), p. 11-14.

Winchester, J.A., and Floyd, P.A. 1976. Geochemical magma type discrimination: Application to altered and metamorphosed basic igneous rocks Earth and Planetary Science Letters, v. 28, p. 459-469.

Winchester, J.A., and Floyd, P. A. 1977. Geochemical discrimination of different magma series and their differentiation products using immobile elements, Chemical Geology, v. 20, p. 325-343.

Wonderley, P.F. and Neuman, R.B. 1984. The Indian Bay Formation: fossiliferous Early Ordovician volcanogenic rocks in the northern Gander Terrane, Newfoundland, and their regional significance, Canadian Journal of Earth Science, v. 21, p. 525-532.

Yardley, B.W.D. 1989. An introduction to metamorphic Petrology, Longman Group U.K. limited.

Appendix I

Sample	M05609H	M05610O	M05611P	M05612P	M05613Q	M05614R	M05616T	M05617T	M05618U
SiO2	44.25	51.51	50.25	43.26	44.37	49.37	47.50	29.77	29.83
TiO2	1.26	1.36	1.36	1.06	1.87	1.68	0.38	0.21	0.19
Al2O3	12.50	14.69	13.78	17.72	9.09	12.85	10.15	14.53	13.51
Fe2O3*	10.72	8.43	9.86	10.50	15.30	12.85	12.49	23.72	24.46
MgO	5.87	6.22	7.44	6.85	20.10	8.26	13.73	11.60	11.48
MnO	0.17	0.14	0.17	0.28	0.36	0.17	0.22	0.35	0.38
CaO	14.86	8.10	8.73	3.97	5.08	7.42	6.14	5.66	6.13
Na2O	3.43	4.95	4.34	2.30	0.38	3.73	2.96	0.18	0.20
K2O	0.24	0.15	0.12	2.91	0.88	0.84	0.13	1.74	0.96
P2O5	0.11	0.09	0.12	0.06	0.16	0.13	0.02	0.45	0.48
total	93.71	95.91	96.40	89.26	98.01	97.46	93.95	90.39	89.70
Zr	77.08	87.08	94.37	53.98	130.59	97.03	0.59	124.98	118.06
Y	24.48	27.47	27.14	10.51	16.26	29.32	3.91	35.73	30.56
Nb	5.15	5.80	7.49	2.14	15.23	3.94	LD	5.48	4.78
Sr	239.20	291.64	248.11	354.94	83.36	119.26	152.93	138.43	124.74
Rb	7.56	1.63	0.75	96.00	51.70	13.14	5.00	86.49	49.15
Cr	689.86	469.50	418.98	378.55	1078.41	106.89	739.07	324.70	315.40
Ni	156.37	132.85	111.91	83.98	587.55	71.21	138.64	110.89	114.88
U	LD	LD	LD	LD	LD	LD	LD	LD	LD
Th	2.00	1.50	1.13	2.13	1.26	2.06	1.59	1.79	2.01
Pb	LD	LD	LD	5.59	LD	2.09	LD	7.21	6.02
Cu	86.46	81.00	59.51	3.64	74.73	6.79	8.64	17.10	61.31
Zn	46.38	35.47	51.21	40.36	98.10	88.06	58.23	128.60	137.07
Ga	18.60	13.82	13.27	14.40	15.97	17.71	11.54	24.61	23.76
As	LD	LD	LD	40.60	LD	LD	LD	30.74	22.27
Sc	50.01	46.44	42.26	57.51	35.99	56.65	54.72	60.26	59.94
V	336.61	292.08	307.46	226.15	307.80	372.76	328.59	537.87	530.76
S	82.77	80.36	64.49	92.81	114.71	41.38	36.97	180.11	247.19
Cl	52.68	10.30	33.71	140.22	48.69	38.78	73.87	137.64	142.53
Ba	185.34	205.13	198.99	960.51	329.95	48.48	97.18	213.09	183.21
Ce	LD	LD	LD	LD	LD	LD	LD	LD	LD

Sample	M05619V	M05620T	M05621P	M05622L	M05623H	M05624D	M05625Z	M05626V	M05627R
SiO2	45.90	41.55	50.46	46.40	47.58	45.21	50.53	46.33	48.90
TiO2	0.08	0.11	0.14	0.12	0.17	0.17	0.10	1.62	1.88
Al2O3	14.83	12.02	15.12	11.62	11.79	12.18	13.24	12.52	11.95
Fe2O3*	14.42	14.73	9.41	14.03	17.40	15.55	11.36	15.43	15.59
MgO	10.13	15.51	6.84	8.50	6.66	10.66	9.20	9.49	8.84
MnO	0.32	0.29	0.20	0.21	0.27	0.47	0.20	0.26	0.22
CaO	5.41	6.44	7.43	9.29	6.29	8.74	8.72	6.02	7.13
Na2O	3.13	1.03	4.05	2.36	3.83	1.41	3.34	2.45	2.90
K2O	0.33	1.42	0.77	0.21	0.30	0.70	0.17	1.78	0.09
P2O5	0.06	0.09	0.14	0.08	0.14	0.12	0.07	0.12	0.16
total	95.49	94.43	96.19	94.09	96.25	97.09	98.13	96.26	97.95
Zr	22.31	66.33	95.13	64.46	108.36	93.39	60.05	100.43	111.91
Y	14.20	20.61	25.33	25.73	42.66	30.11	21.98	35.29	38.04
Nb	0.27	3.68	6.70	3.07	5.18	4.82	2.25	3.74	3.65
Sr	104.82	66.29	359.14	79.57	60.36	136.64	56.19	90.57	37.36
Rb	7.33	56.28	41.71	3.87	7.76	27.13	5.26	64.81	0.79
Cr	273.80	809.26	638.15	161.07	68.36	114.89	835.18	316.98	139.90
Ni	76.84	283.60	185.18	58.36	56.29	49.35	184.52	95.11	56.27
U	LD	LD	LD	LD	LD	LD	LD	LD	LD
Th	0.68	1.64	1.11	LD	LD	LD	LD	LD	LD
Pb	LD	LD	4.40	0.59	3.31	LD	LD	LD	LD
Cu	6.32	25.68	53.73	85.79	92.45	161.06	106.22	35.16	64.95
Zn	129.22	76.72	48.79	83.45	106.42	109.51	57.70	95.63	102.55
Ga	22.72	14.69	13.44	16.53	19.03	19.92	13.02	16.82	19.32
As	LD	12.98	LD	LD	LD	LD	29.98	21.54	LD
Sc	52.56	37.05	46.51	51.28	51.74	64.27	46.35	47.60	47.30
V	396.66	284.28	270.60	369.96	504.52	423.31	316.39	408.37	492.26
S	56.41	49.36	293.93	63.06	222.82	666.84	180.71	57.72	474.89
Cl	73.37	17.71	98.76	47.25	21.50	54.80	41.24	27.34	70.73
Ba	30.64	344.67	498.47	25.04	319.86	87.64	34.08	266.83	8.29
Ce	LD	LD	14.04	7.58	LD	LD	LD	LD	LD

Sample	M05628N	M05629J	M05630Z	M05631Q	M05632H	M05633Y	M05634P
SiO2	45.67	51.78	44.52	61.43	50.01	42.87	52.46
TiO2	0.93	0.73	0.75	1.57	0.78	2.25	1.98
Al2O3	12.35	14.66	13.46	11.48	15.18	13.69	12.46
Fe2O3*	11.94	7.51	12.74	9.89	8.93	14.82	10.44
MgO	14.18	11.67	11.16	5.03	8.43	10.98	10.51
MnO	0.18	0.18	0.29	0.16	0.20	0.24	0.14
CaO	9.54	6.67	8.85	4.24	8.65	7.08	3.83
Na2O	1.69	3.86	1.07	5.39	3.68	2.22	2.50
K2O	0.49	0.54	1.48	0.04	0.68	0.44	0.99
P2O5	0.07	0.04	0.03	0.11	0.05	0.38	0.38
total	97.40	97.99	94.80	99.53	96.96	95.37	95.99
Zr	51.16	35.25	34.70	110.72	36.33	190.25	156.58
Y	18.29	16.83	14.69	33.72	18.34	26.14	24.48
Nb	4.91	1.42	0.60	1.52	0.97	51.50	43.39
Sr	202.87	546.03	181.92	227.17	200.70	269.79	275.41
Rb	8.65	23.59	51.75	0.09	22.51	15.92	34.26
Cr	1130.52	1063.45	1316.65	18.40	1164.60	640.30	690.80
Ni	314.57	248.08	312.90	7.64	235.65	143.04	108.39
U	LD	LD	LD	LD	LD	LD	LD
Th	LD	LD	LD	LD	LD	4.23	LD
Pb	LD	LD	7.10	LD	LD	LD	LD
Cu	91.32	6.31	54.22	11.70	69.32	53.32	42.53
Zn	58.82	40.38	64.88	69.22	39.28	88.60	48.41
Ga	14.54	12.36	12.25	12.81	11.08	19.57	13.78
As	50.72	13.31	235.22	LD	26.07	50.48	LD
Sc	37.64	45.93	39.66	33.45	44.27	43.68	28.84
V	273.93	267.90	267.27	410.06	254.80	285.22	206.60
S	159.99	32.20	170.52	222.97	107.94	372.02	71.89
Cl	20.16	55.93	57.75	38.41	32.50	37.46	117.37
Ba	12.96	193.71	108.48	99.92	304.33	176.00	336.60
Ce	LD	LD	LD	LD	LD	LD	40.96

LEGEND

Silurian/Devonian

15	ROCKY BAY PLUTON: granite, undeformed
14	UNNAMED DIORITE

Ordovician

Carmanville Melange

13a / 13b	MELANGE MATRIX: a) pebbly mudstone, with a variety of clasts and blocks (listed below); b) undifferentiated melange and blocks.
12	MAFIC VOLCANIC ROCKS: dominantly pillow basalts, minor pillow breccias and mafic flows, all with associated limestone
11	GREYWACKES: grey–brown to beige, medium grained, slightly hornfelsed, blocks range from mm to 10's of metres; typically brecciated.
10	BLACK & GREY RHYTHMITES: alternating shales and siltstones (5–10cm thick), ubiquitous Fe staining, contain locally isolated pods of limestone.
9	DIABASE/GABBRO: as dykes intruding trondhjemites or discrete (100m) block.
8	TRONDHJEMITE: internally brecciated, locally cut by minor shears.
7	SILTSTONE: light grey, fine grained, with very fine (1mm) quartz laminations.

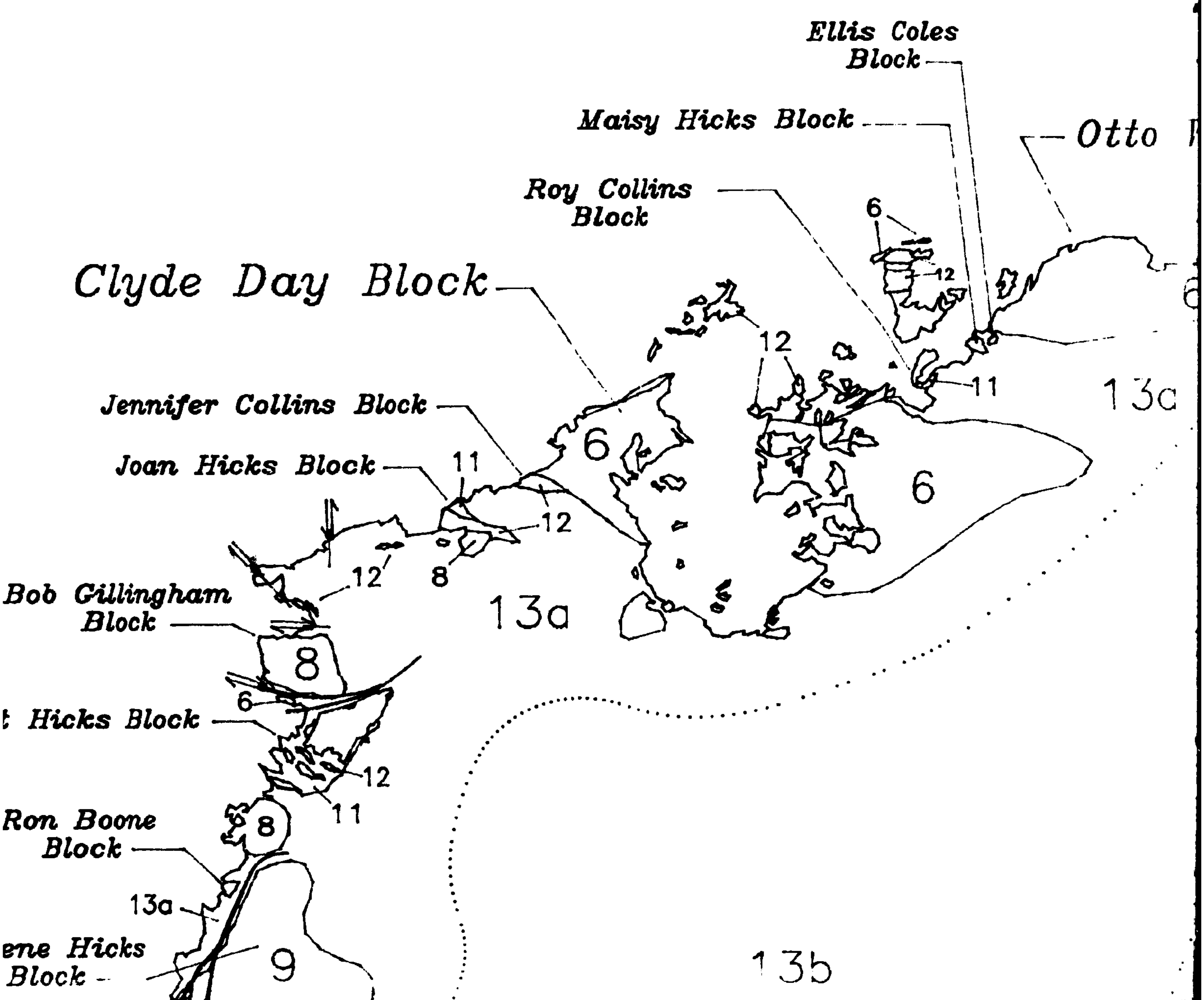
Teakettle melange

6	POLYDEFORMED BLOCKS: discrete blocks of melange with earlier tectonic history (Clyde Day and Otto Wheaton blocks)
	MELANGE MATRIX: black slate with abundant

Scott

Euge

Teakettle Point



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; b) undifferentiated

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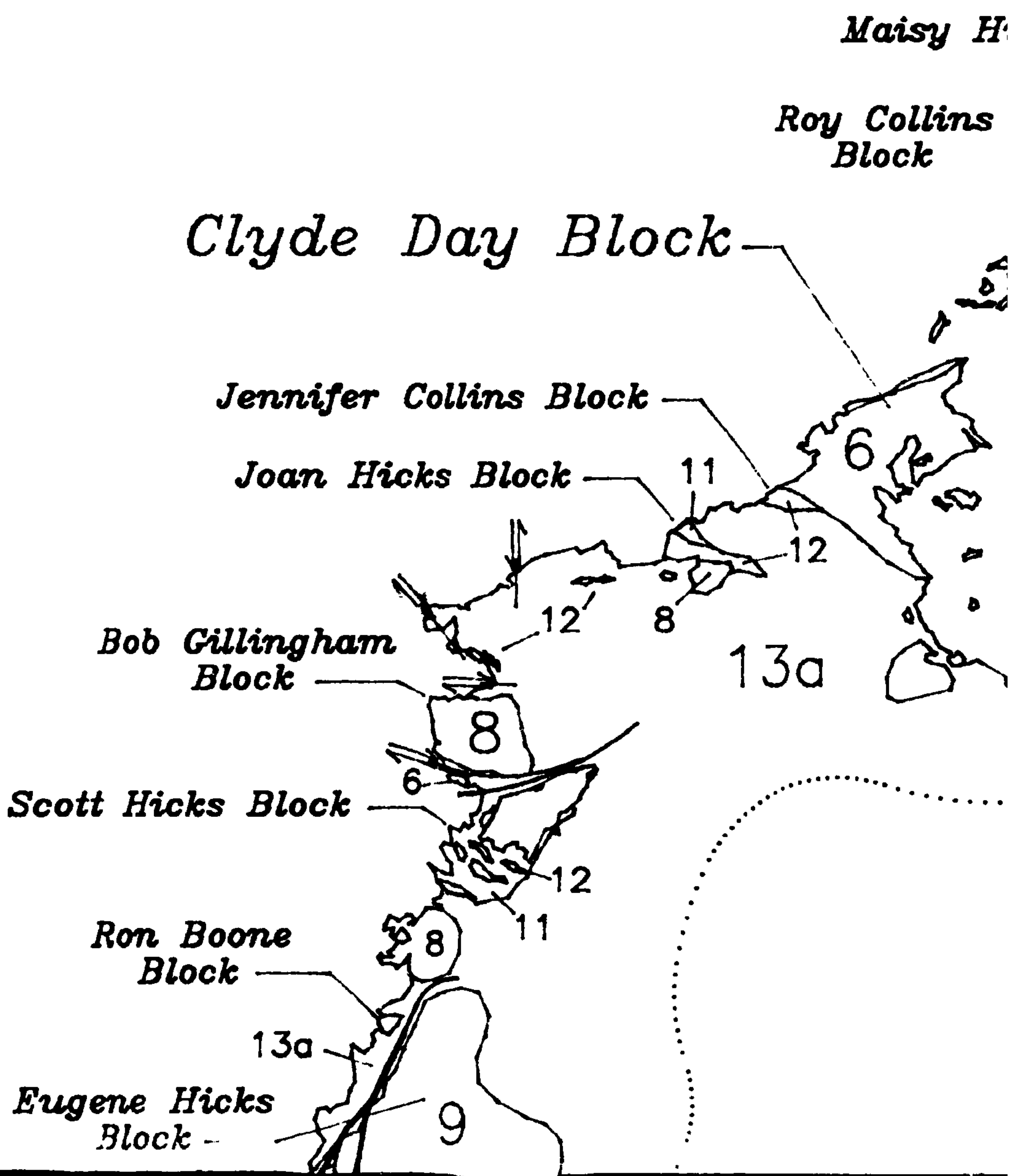
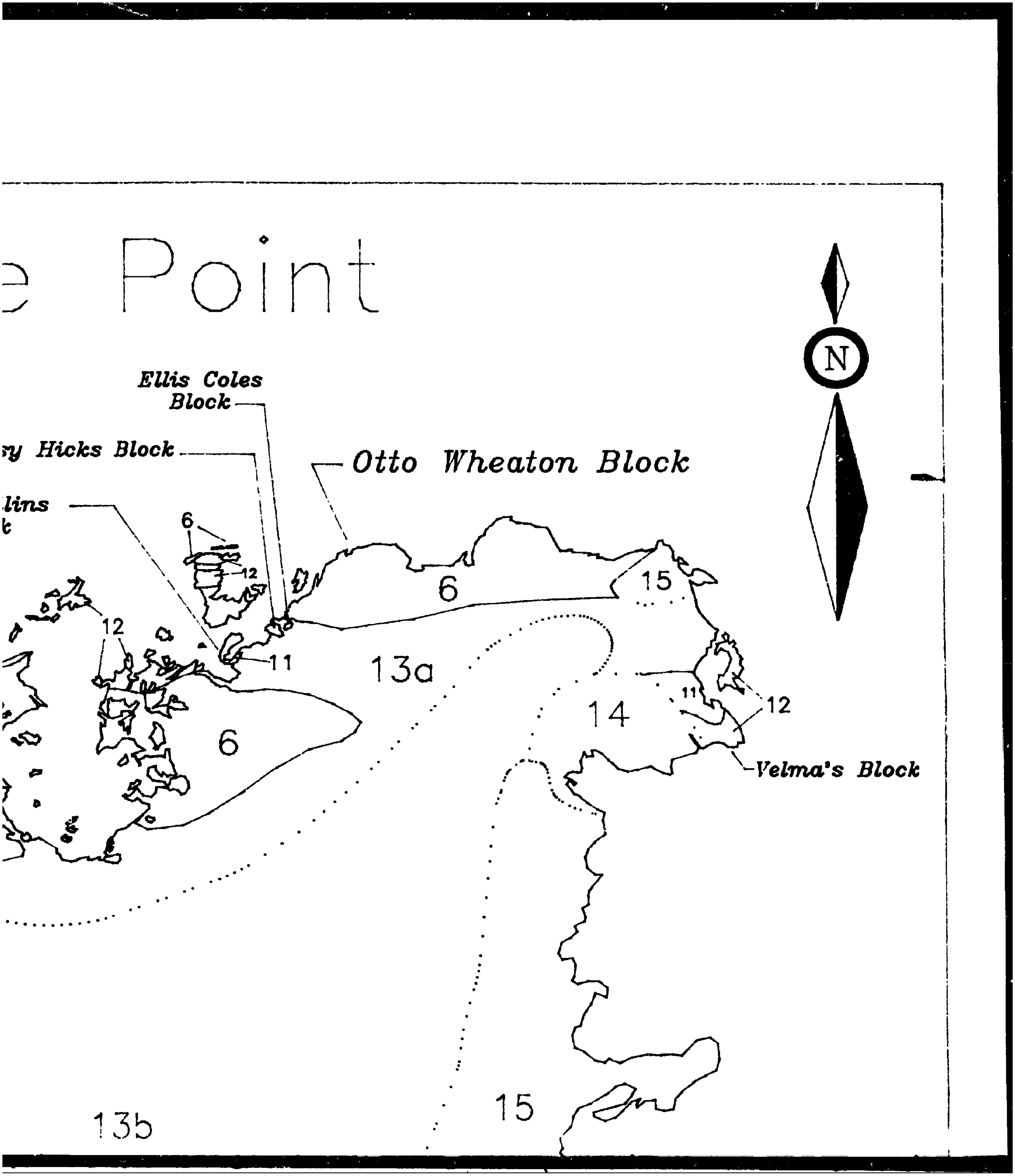
Clyde Day and Otto

late with abundant

Teakettle





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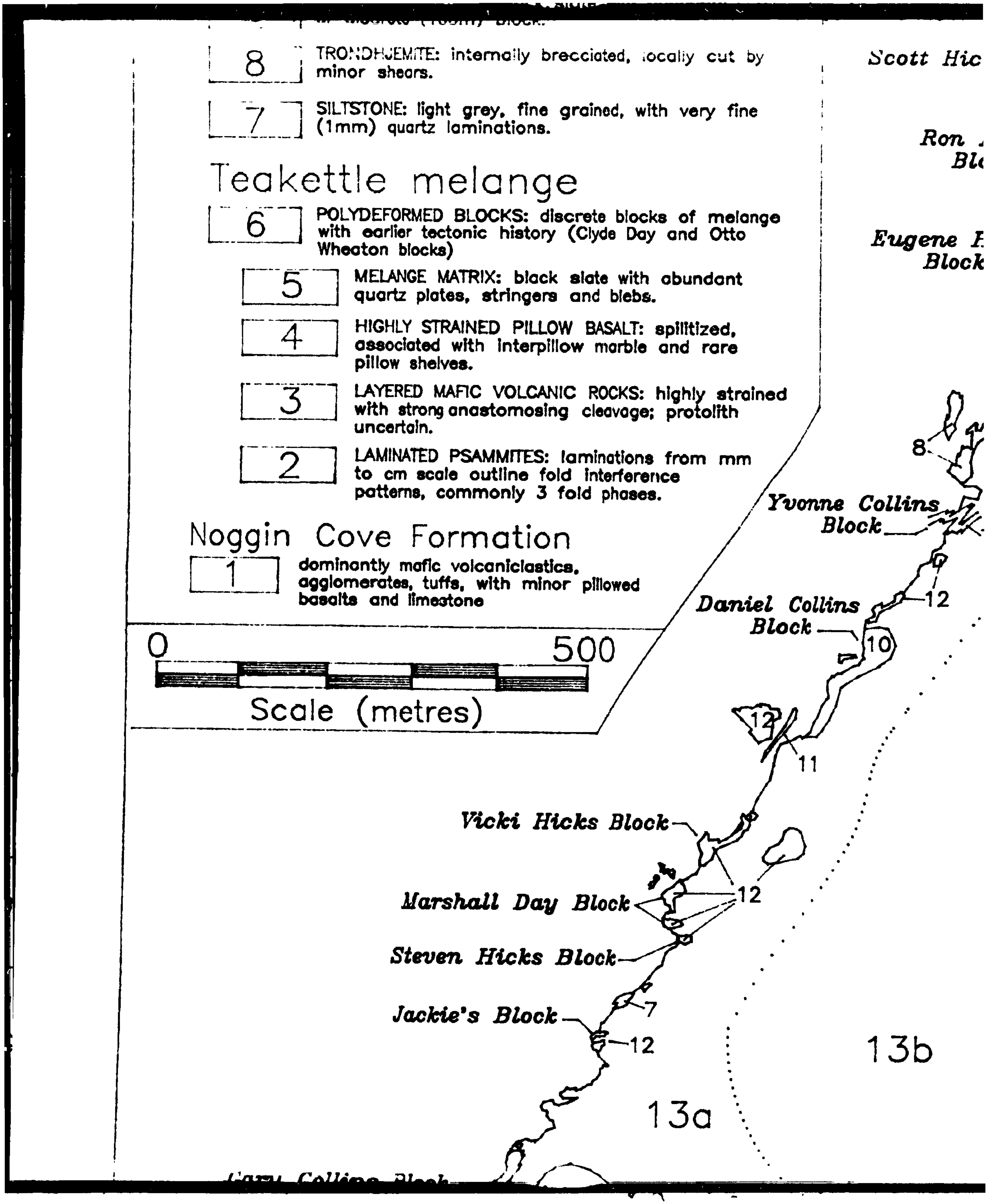
8 TRONDHJEMITE: internally brecciated, locally cut by minor shears.
7 SILTSTONE: light grey, fine grained, with very fine (1mm) quartz laminations.
Teakettle melange
6 POLYDEFORMED BLOCKS: discrete blocks of melange with earlier tectonic history (Clyde Day and Otto Wheaton blocks)
5 MELANGE MATRIX: black slate with abundant quartz plates, stringers and blebs.
4 HIGHLY STRAINED PILLOW BASALT: spilitized, associated with interpillow marble and rare pillow shelves.
3 LAYERED MAFIC VOLCANIC ROCKS: highly strained with strong anastomosing cleavage; protolith uncertain.
2 LAMINATED PSAMMITES: laminations from mm to cm scale outline fold interference patterns, commonly 3 fold phases.
Noggin Cove Formation
1 dominantly mafic volcaniclastics, agglomerates, tuffs, with minor pillowed basalts and limestone
0 500
Scale (metres)
Yvonne Collins Block
Daniel Collins Block
Vicki Hicks Block
Marshall Day Block
Steven Hicks Block
Jackie's Block
8
12
10
12
11
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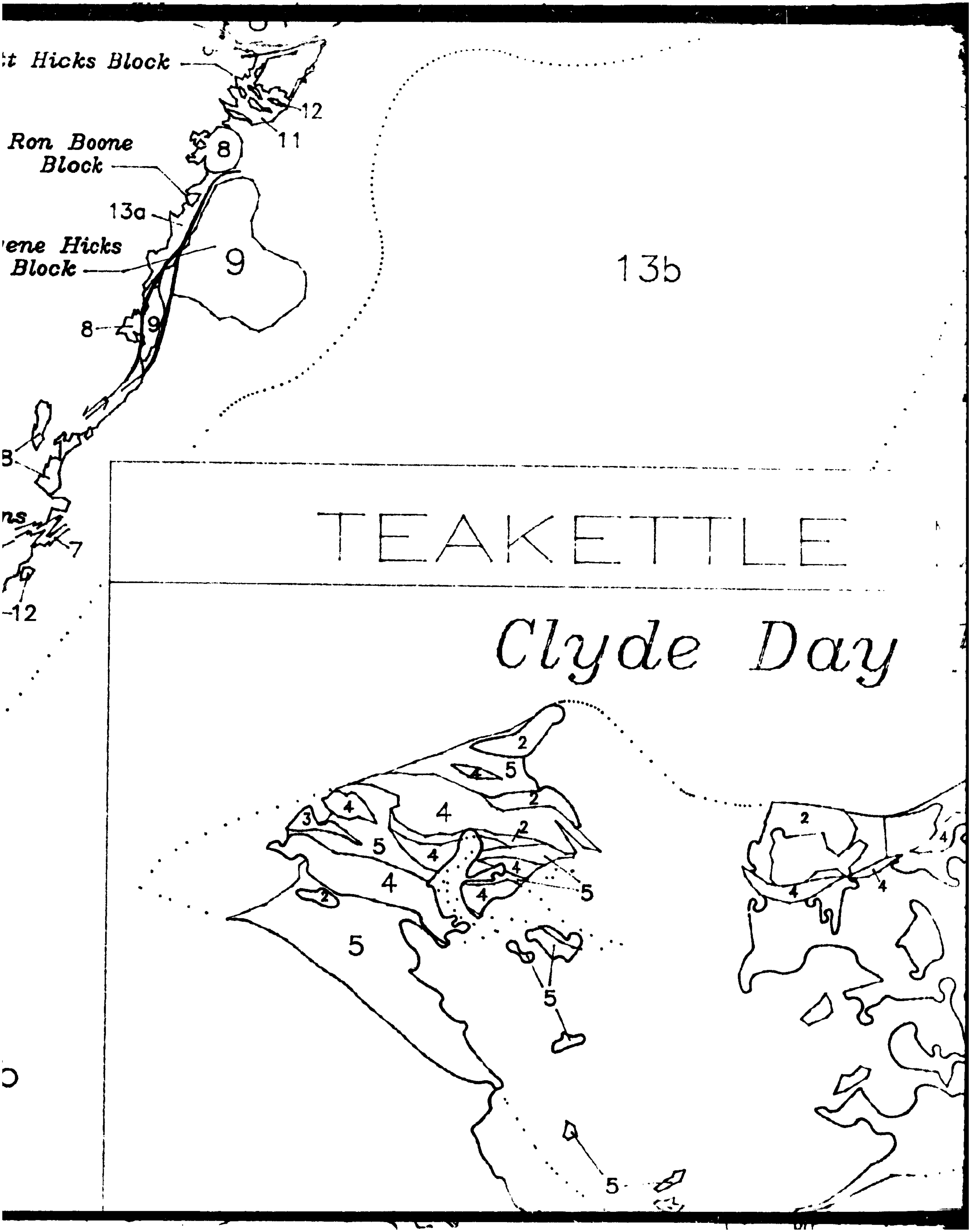
7
12
13a
13b



t Hicks Block
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11
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13a
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TEAKETTLE
Clyde Day
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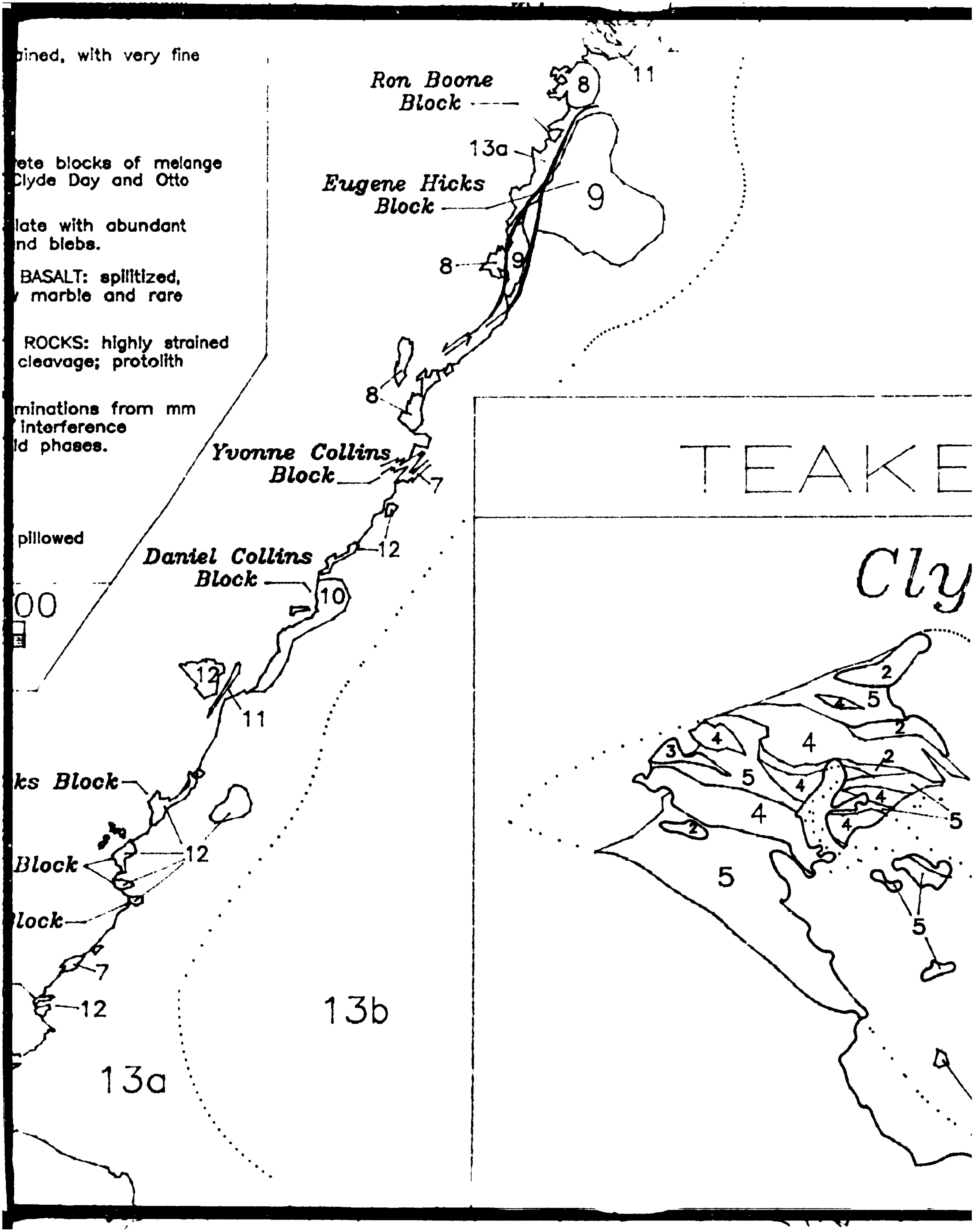

ained, with very fine
ete blocks of melange
Clyde Day and Otto
late with abundant
nd blebs.
BASALT: spilitized,
marble and rare
ROCKS: highly strained
cleavage; protolith
minations from mm
interference
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Block
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Eugene Hicks
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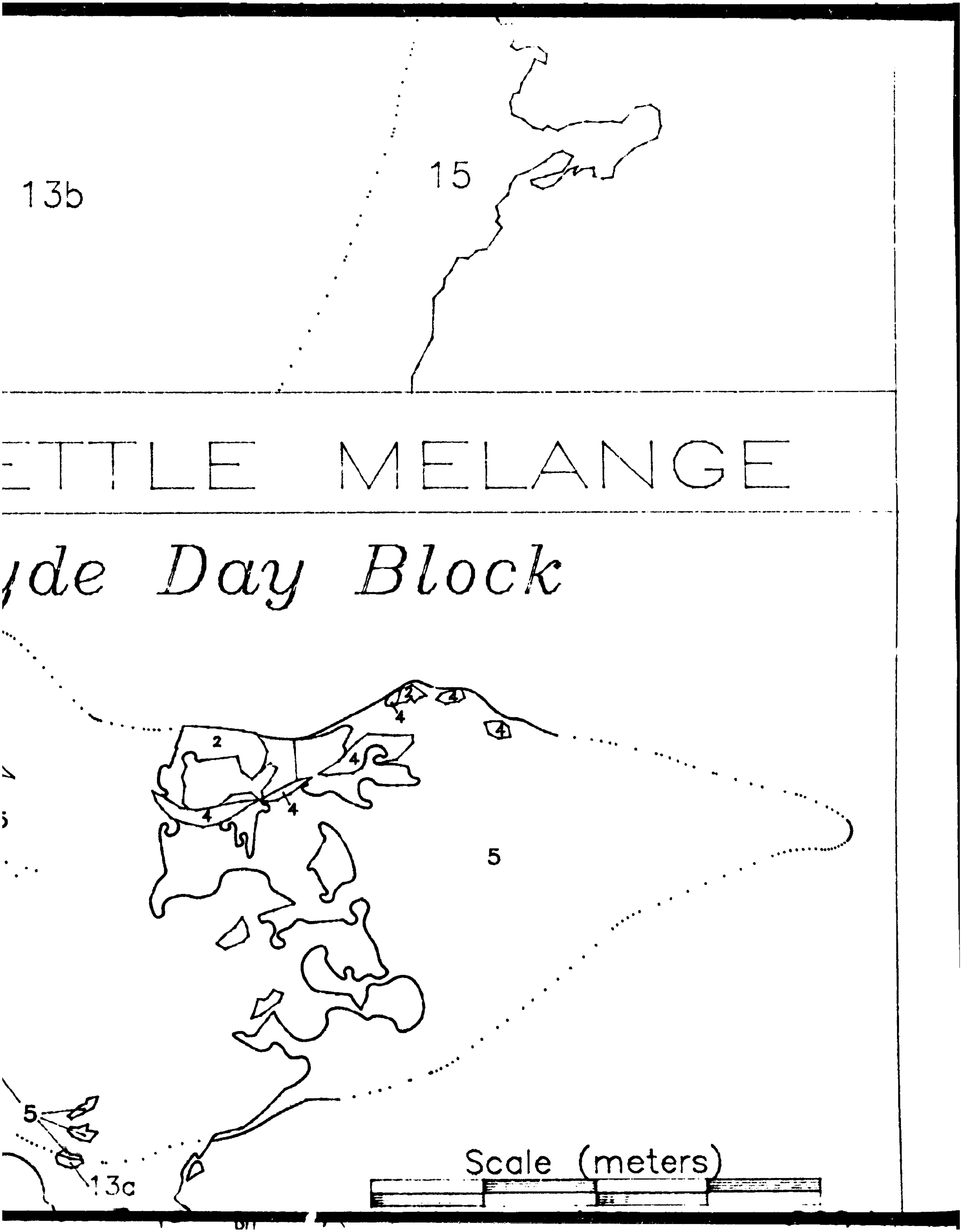

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ETTLE MELANGE
yde Day Block
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4
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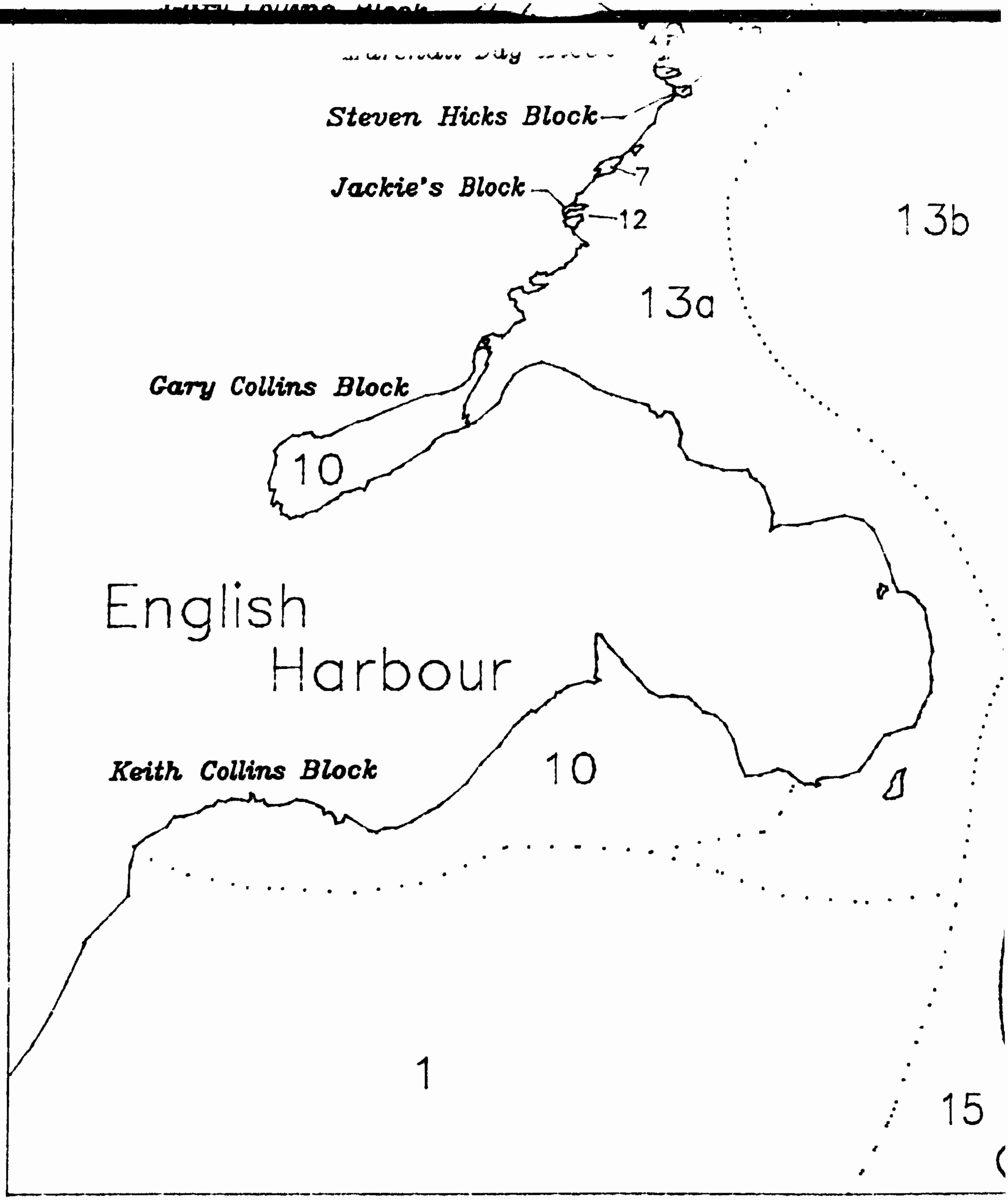
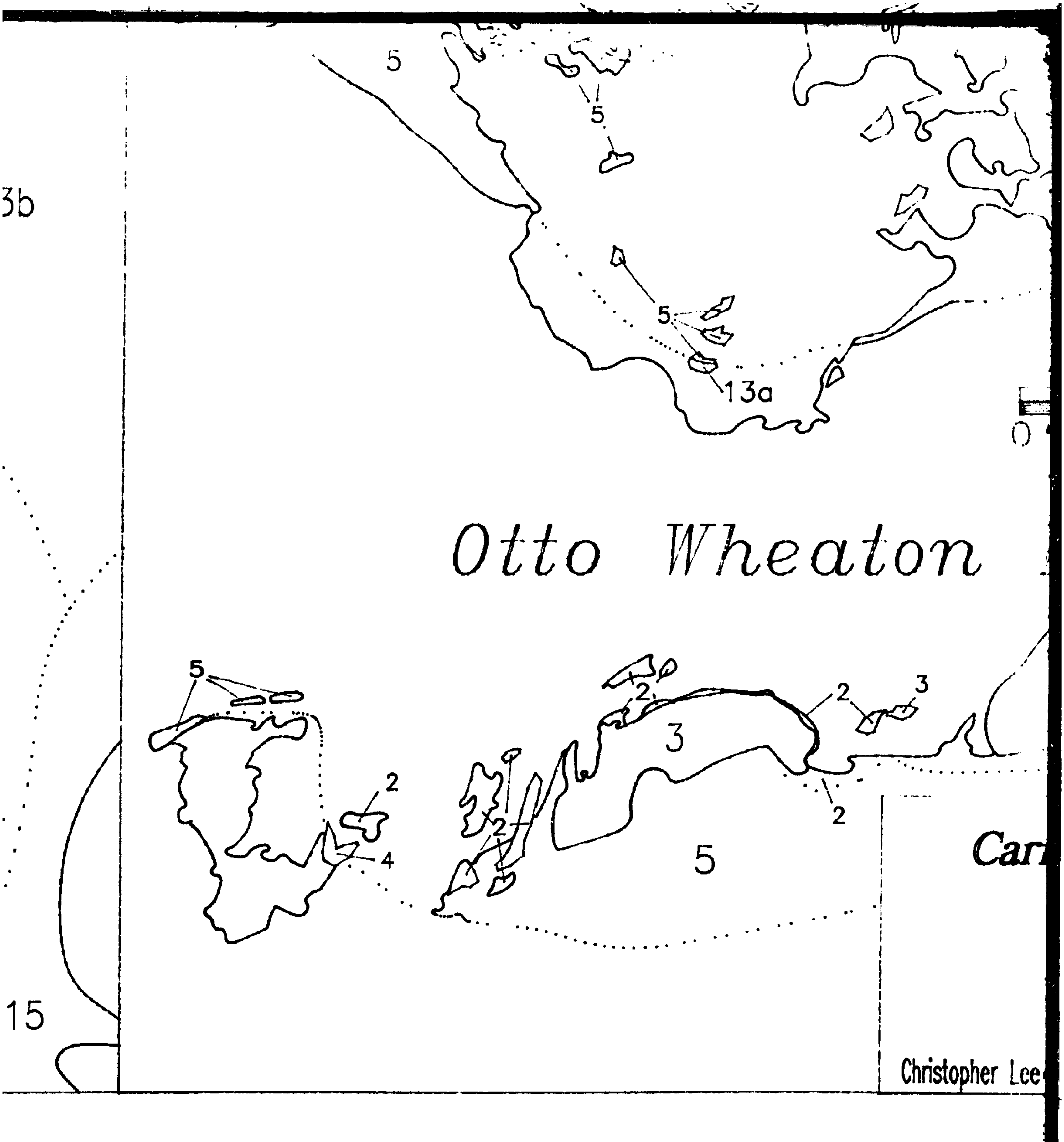
13c
Scale (meters)


Steven Hicks Block
Jackie's Block
7
12
13b
13a
Gary Collins Block
10
English
Harbour
Keith Collins Block
10
1
15



3b
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13a
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Otto Wheaton
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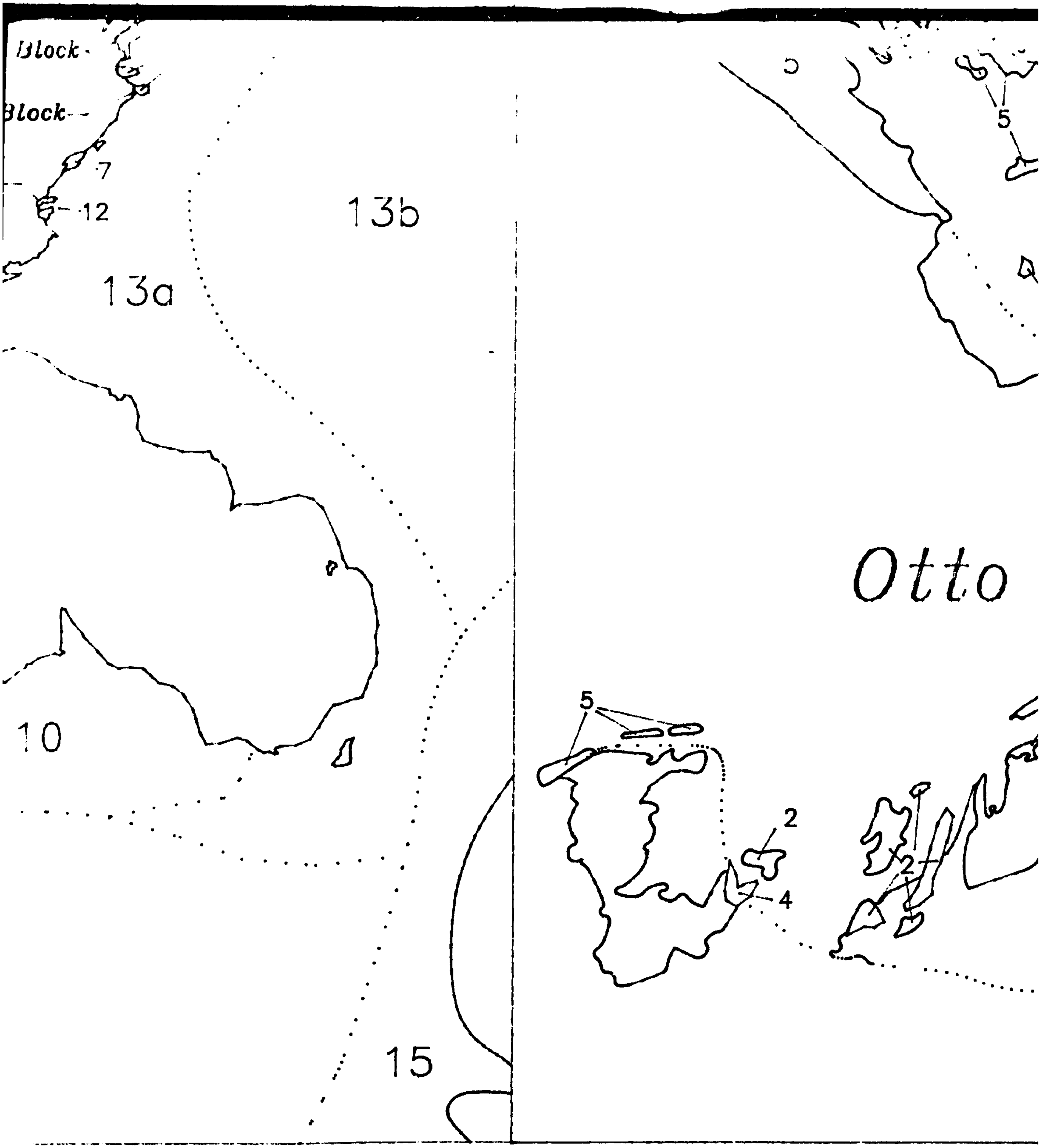
Car
15
Christopher Lee


Block
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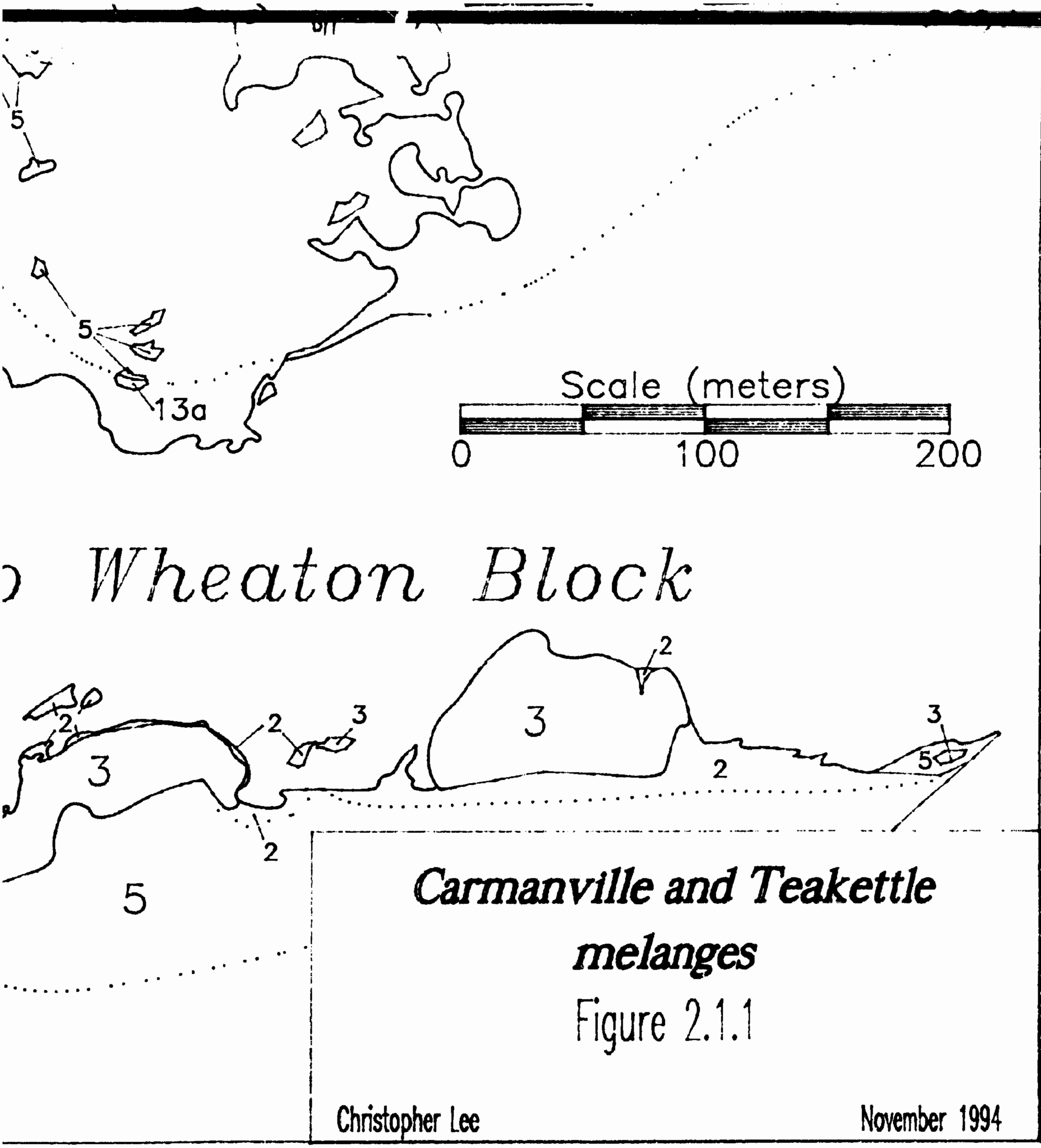

Carmanville and Teakettle melanges

Figure 2.1.1

Christopher Lee

November 1994