Early development and flysch sedimentation in Ordovician Taconic foreland basin, west-central Newfoundland

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During the Early to Late Ordovician the Taconic foredeep in west-central Newfoundland evolved from an underfilled to an overfilled state in response to cratonward advance, thickening, and erosion of the Taconic Orogen. Early orogen-derived sediment in the foreland basin consisted of middle(?) to lake Arenigian deep-water mudstones that accumulated on an inner (craton-facing) slope prism (uppermost parts of Shallow Bay and Green Point formations and correlative units). These deposits are interbedded with and overlie passive-margin slope sediments. In the middle Arenigian to early Llanvirnian, sand from the orogen formed several small, sand-rich submarine fans (Lower Head Formation and correlative units) on the lower reaches of the inner slope and basin plain. The fans may have been fed by closely spaced rivers draining the orogen, as presently occurs in western South America. Only proximal portions of these fans are now exposed. The flysch basin was narrow, constricted by the inner slope and the passive-margin slope, and located a short distance seaward from the buried hingeline of the proto-North American craton. As the orogen thickened sufficiently to override the crustal ramp, the carbonate shelf on the craton drowned, clastic depocentres migrated onto the foundered craton, and a thicker flysch (Mainland Sandstone) accumulated in Llanvirnian-Llandeilian time. In the Caradocian the foreland basin was overfilled with shallow-marine terrigenous sediments (Long Point Formation). Regional flysch dispersal was from a St. Lawrence promontory to a Quebec reentrant.

Entre l'Ordovicien précoce et tardif le bassin frontal taconique à Terre-Neuve occidentale a évolué d'un état sous-comblé à un autre sur-comblé, en réponse à l'avance vers le craton, l'épaississement et l'érosion de l'Orogène taconique. Au bassin frontal le premier dépôt en provenance de l'orogène a été des mudstones d'eau profonde, de l'Arénigien moyen(?) à tardif (sommets des formations de Shallow Bay et Green Point et des unités corrélatives), donnant lieu à un prisme de talus intérieur (faisant face au craton). Ces dépôts sont interstratifiés avec, et recouvrent, des sédiments de talus de la marge passive. Dès l'Arénigien moyen au Llanvirnien précoce se sont formés plusieurs petits cônes sous-marins, riches en sable provenant de l'orogène (Formation de Lower Head et des unités corrélatives), à la base du talus intérieur et au fond du bassin. Les cônes auraient été alimentés en sédiments par les riviéres peu espacées entre elles qui drainaient l'orogène, comme c'est le cas à present en Amérique du Sud occidentale. Seules les portions proximales de ces cônes sont exposés aujourd'hui. Le bassin de flysch était étroit, contraint entre le talus intérieur et le talus de la marge passive, et il était situé à peu de distance vers la mer de la hingeline enterré du proto-craton de l'Amérique du Nord. À mésure que l'orogène s'épaississait assez pour surmonter la rampe crustale, le plateau de carbonates a été inondé, les depocentres clastiques se sont deplacés au-dessus du craton affaisé, et une plus grande épaisseur de flysch (grès de Mainland) s'est déposé durant les temps du Llanvirnien-Llandeilien. Au Caradocien le bassin frontal a comblé avec des sédiments terrigènes marins peu profonds (Formation de Long Point). La dispersion régionale du flysch s'étendait du promontoire du St. Laurent jusqu'au ré-entrant du Québec.

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Introduction

Collisional orogens developed on rifted passive margins may ideally go through constructive, steady, or destructive states depending upon whether the rate of rock mass addition to the orogen is greater, equal, or less than the rate of mass loss (Jamieson and Beaumont 1988). A constructive state could be represented by the following events (Covey 1986; Tankard 1986; Beaumont *et al.* 1988; Jamieson and Beaumont 1988). During initial orogeny, slope-rise deposits are accreted to the advancing orogen. The increased load, however, is effectively compensated for by subsidence of attenuated continental crust underlying the slope-rise region, so the orogen remains largely below sea level and the foreland platform undergoes mild subsidence. Advance of the orogen is checked upon reaching the thicker, elevated continental crust underlying the buried crustal ramp and hingeline. Under continued compression, the orogen thickens, emerges regionally above sea level, and is subject to erosion. The platform will subside deeply and may be overthrust by the orogen.

Sedimentation in the foreland basin will reflect the described orogenic events. In the initial stage, the topographically subdued orogen would provide a small amount of mostly fine-grained sediment to a deep, underfilled basin. Theoretical reasoning and studies of modern foredeeps (e.g., Karig *et al.* 1987) suggest that orogen-derived sediments may include (*i*) mud and fine siliciclastic sands eroded from loose sediments and projecting rocks on the orogen as they are uplifted above sea level, (*ii*) carbonate detritus from carbonate banks anchored on shallowly submerged areas of the orogen, and (*iii*) mass-wastage deposits from oversteepened submarine slopes in front of the advancing orogen. Part of this sediment will accrete the inner trench slope, building a craton-facing sedimentary slope prism flanking the orogen. A marked increase in sedimentation rates (Covey 1986), seismic downlap away from the orogen (Biddle *et al.* 1986), and diagnostic source-area indicators (Wuellner *et al.* 1986) should provide evidence for a reversal in provenance and initial derivation from the growing orogen. Contemporaneous input from a carbonate-mantled craton, as in early Paleozoic eastern North America, would likely be hemipelagic mud (e.g., outer slope of Timor Trough; Karig *et al.* 1987), with possible coarser debris from carbonate buildups. In a later stage, with a topographically higher orogen, coarse-grained orogen-derived clastic wedges would downlap onto the basin plain and may eventually overfill the foreland basin. The resulting basin fill at sites near the orogenic front would comprise passive margin slope-rise deposits passing upward into orogen-derived flysch through an interval of mixed craton and orogen provenance.

During the Ordovician Taconic orogeny in the Appalachians a foreland basin evolved on a Hadrynian – early Paleozoic rifted

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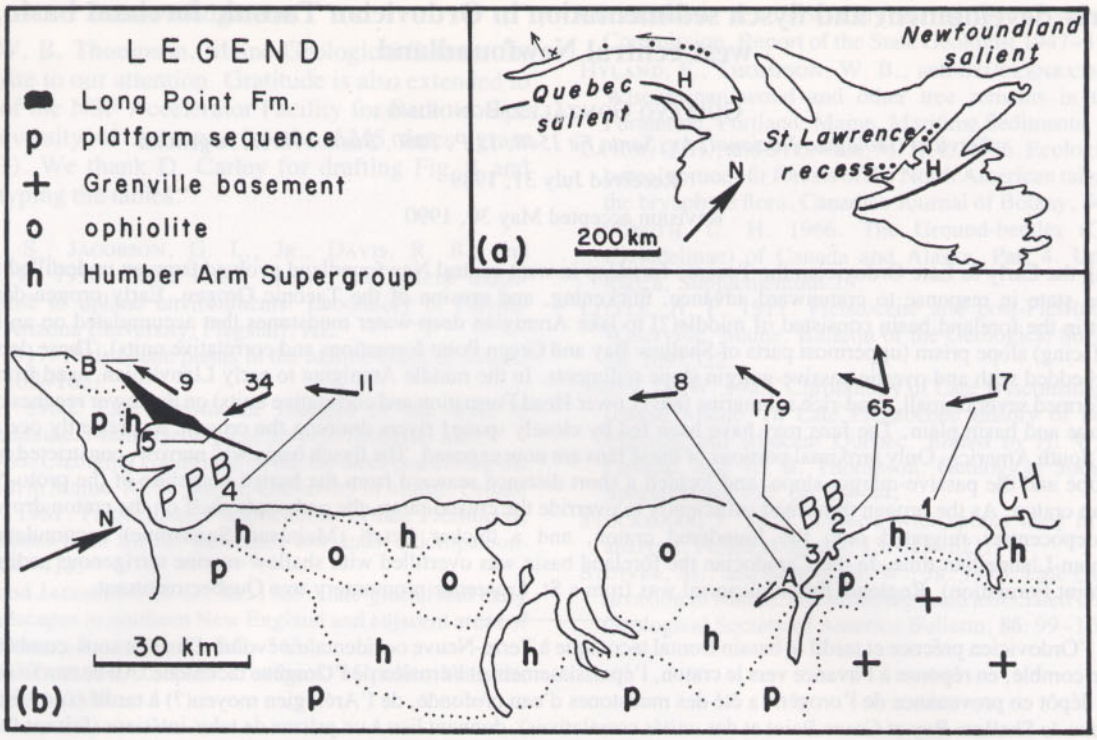

FIG. 1. (*a*) Major structural elements of the Taconic foreland region of the Canadian Appalachians. Salients and recess taken from Thomas (1977). Boundary of the Humber Zone (H) taken from Williams (1979). Black dots represent allochthonous Arenig–Llanvirn submarine-fan deposits exposed along the coast (data from Hiscott 1980; Hiscott *et al.* 1986; this paper, locs. 1–5 in Fig. 1*b*). Autochthonous Middle Ordovician submarine-fan deposits marked by an × (St.-Irénée and Beaupré formations; Belt and Bussières 1981). Small arrows indicate regional flysch dispersal. (*b*) Simplified geologic map of west-central Newfoundland, showing studied localities with Arenig–Llanvirn flysch: 1, Martin Point; 2, north of Rocky Harbour Bay; 3, south of Rocky Harbour Bay; 4, Black Point; 5, Rocky Point. Localities with Llanvirn–Llandeilo flysch: A, Norris Point formation; B, Mainland Sandstone. Paleocurrent vector means and number of measurements are given for each of these localities; origins of arrows are aligned with the regional trend of the foreland basin. CH, Cow Head; BB, Bonne Bay; PPB, Port au Port Bay.

continental margin and was the site of deposition of orogen-derived flysch during the late Early – Late Ordovician (Rodgers and Neale 1963; Stevens 1970; Williams 1979; Rowley and Kidd 1981; Shanmugan and Lash 1982; Quinlan and Beaumont 1984; Hiscott *et al.* 1986). Earliest flysch sedimentation occurred in the northern segment of the foreland basin and is presently represented by middle Arenigian to lower Llanvirnian immature sandstones resting on deep-water variegated mudstones in northern Gaspé Peninsula and west-central Newfoundland (Fig. 1*a*) (Stevens 1970; Hiscott *et al.* 1986; James *et al.* 1987). The mudstones are commonly interpreted as having been derived from the former passive continental margin, and initial flysch arrival is taken as the earliest manifestation of Taconic Orogen sources (Stevens 1970; Williams 1975; Hiscott *et al.* 1986; James *et al.* 1987; Bradley 1989). A later phase of flysch sedimentation occurred in the Middle and Late Ordovician on the foundered North American shelf, indicating a marked change in the structural setting of the foredeep (Stevens 1970; Klappa *et al.* 1980; Hiscott *et al.* 1986). Flysch depo-systems in Gaspé Peninsula are well constrained (Hiscott 1980; Hiscott *et al.* 1986), but comparatively little lithological and paleocurrent information has been published on the Newfoundland flysch. Although major features of the Gaspé Peninsula scenario hold true in Newfoundland, there exist significant differences with regard to the depositional setting of the early flysch and the nature of its substrate.

In western Newfoundland, middle Arenigian – lower Llanvirnian (Arenig–Llanvirn) flysch and underlying Lower Ordovician muddy sediments constitute the upper part of the allochthonous Humber Arm Supergroup (Hadrynian – Middle Ordovician; Stevens 1970) (Figs. 1*b*, 2). This paper discusses the provenance and sedimentary setting of these beds in an attempt to show that (*i*) the uppermost muddy sediments beneath the flysch were probably derived from the Taconic Orogen and underlaid an inner trench slope, and (*ii*) flysch accumulated at the base of this slope at a time when the Taconic Orogen was being thickened against the buried crustal ramp of the North American craton.

General setting and stratigraphy

The Humber Arm Supergroup is exposed in coastal western Newfoundland between Cow Head in the north-northeast and Port au Port Bay in the south-southwest (Fig. 1*b*). Detailed work was carried out around Rocky Harbour Bay in outer Bonne Bay (locs. 2 and 3, Fig. 1*b*) and at Black Point and Rocky Point in Port au Port Bay (locs. 4 and 5, Fig. 1*b*). The Arenig–Llanvirn flysch in Bonne Bay is included in the Lower Head Formation (Fig. 2) (James *et al.* 1987); flysch deposits in Port au Port Bay are not formally named. Petrographic and regional considerations indicate an eastern (present coordinates) source for the flysch (Stevens 1970; Williams 1975; Hiscott 1984). The flysch is conformably underlain by Middle Cambrian to Lower Ordovician strata comprising varying proportions of black, red, and green mudstone and shale, yellow-weathering dolostone, light grey ribbon limestone and limestone breccia, and radiolarian chert that represent slope and basinal environments off the

proto-North American continental margin (Fig. 2) (Stevens 1970; Williams 1975; James and Stevens 1986; James *et al.* 1987; Lindholm and Casey 1989). In Bonne Bay these beds are included in the Shallow Bay Formation (James *et al.* 1987); in Port au Port Bay they are not formally named. These deposits are herein collectively referred to as the preflysch section. Maximum thicknesses in the studied areas are 200 m for the flysch and 500 m for the preflysch section, with stratigraphic base and top not exposed.

The Humber Arm Supergroup structurally overlies an autochthonous Lower Cambrian – Middle Ordovician platform carbonate to flysch succession locally capped by Upper Ordovician shallow-marine deposits of the Long Point Formation (Rodgers and Neale 1963; Rodgers 1965; Stevens 1970). In Bonne Bay, the Rocky Harbour Mélange occurs at the tectonic contact (Williams *et al.* 1985). The autochthonous succession reflects the flexural foundering of the proto-North American craton and an increasing influx of orogen-derived detritus that partly overfilled the foreland basin (Stevens 1970; Klappa *et al.* 1980; Stockmal *et al.* 1987; Bradley 1989). Easterly derived autochthonous Llanvirn-Llandeilo flysch occurs in southeast Bonne Bay (Norris Point formation of Williams *et al.* 1985) (loc. A, Fig. 1*b*) and western Port au Port Bay (Mainland Sandstone of Schillereff and Williams 1979) (loc. B, Fig. 1*b*). The Norris Point flysch, approximately 0.3 km thick, shows numerous buff-weathering dolomitic turbidites and grades up into the Rocky Harbour Mélange. The Mainland Sandstone, approximately 1.8 km thick, is conformably(?) overlain by the Long Point Formation (Rodgers and Neale 1963; Stevens 1970).

The preflysch section

The preflysch section in Bonne Bay (Shallow Bay Formation) comprises, in ascending order (*i*) Tremadocian – middle Arenigian red and black shale and chert, reflecting starved basin conditions, and (*ii*) middle to upper Arenigian green and black shale and mudstone, dolostones, and resedimented limestones, intercalated near the top with quartzose turbidites derived from the orogen (Hubert *et al.* 1977; Hiscott and James 1985; James and Stevens 1986; James *et al.* 1987). Massive flysch follows above. In Port au Port Bay, the preflysch section shows relatively less chert, dolostone, and limestone and more green and red shale intercalated with quartzose turbidites in the upper part. The Shallow Bay Formation accumulated on the passive-margin slope (James and Stevens 1986; James *et al.* 1987), and a similar setting is likely for correlative beds in Port au Port Bay.

The middle–upper Arenigian interval in Bonne Bay is conspicuously rich in dolostone (Lobster Cove Member of James *et al.* 1987). The dolostone is a mudstone comprising detrital dolomite with euhedral overgrowths and up to 20% silt-size quartz and commonly forms thin (<3 cm), intensely burrowed beds with sharp to gradual bases alternating with green and black mudstone (González-Bonorino 1979; James *et al.* 1987). At the top of the preflysch section immediately beneath the massive flysch, dolostone beds are more silty and show scoured bases and normal grading. Locally (loc. 3, Fig. 1*b*, 1400 m south-southeast of Rocky Harbour Bay), the dolostone includes scattered fragments of chert and limestone up to 20 cm across. The sharp bases and graded bedding suggest deposition of the dolestone beds from turbidity currents.

The Arenig–Llanvirn flysch

The Arenig–Llanvirn flysch is sand rich and comprises approximately 75% olive green to dark grey lithic wackes

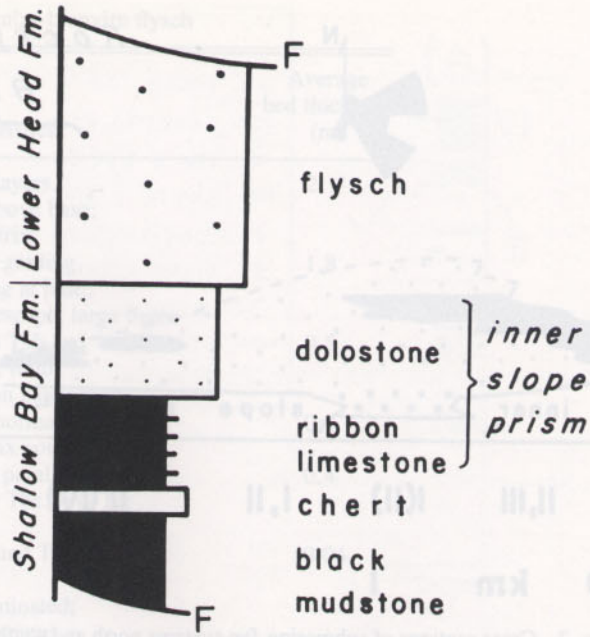

FIG. 2. Schematic lithostratigraphy for the Humber Arm Supergroup exposed around Rocky Harbour Bay in outer Bonne Bay (locs. 2 and 3 in Fig. 1*b*). Chert is datum in Fig. 3. Formational names from James *et al.* (1987).

(average matrix content 20%), 25% dark grey calcareous mudstone, and minor polymictic conglomerate. In Bonne Bay, the flysch also includes a minor proportion of buff-weathering dolomitic siltstone and rare beds of light grey bioclastic and micritic limestone. The framework composition of wackes from Bonne Bay and Port au Port Bay is $Qm_{55}L_{38}F_7$. The contact with preflysch beds varies from sharp to interbedded over a few metres (<20 m). In Bonne Bay the paleotopography of this contact could be approximately reconstructed with datum on a persistent chert interval (Fig. 3).

Facies and facies organization

Seven sedimentary facies can be distinguished in the flysch deposits. These facies are summarily described in Table 1 and classified according to the generalized facies scheme of Pickering *et al.* (1986). The facies are grouped into four facies associations (FA): FA I, thick-bedded sandstone and conglomerate; FA II, medium-bedded sandstone packets; FA III, slurried and rippled sandstone; and FA IV, mudstone and dolomitic siltstone. Rare intercalated allodapic limestone beds are not included in a facies association.

FA I: thick-bedded sandstone and conglomerate

FA I is characterized by up to 10 m thick beds of coarse-grained, disorganized and organized (parallel-stratified and rarely cross-stratified) sandstone (90% of facies) and organized conglomerate (5%) with pebbles to boulders (<1.2 m across) of chert and limestone. Beds are amalgamated or separated by partings of silty mudstone (5%), and erosive bottoms are rare (Fig. 4*a*, lower two-thirds). FA I is present at all localities and comprises most of the channel fill (approx. 100 m thick) north of Rocky Harbour Bay (loc. 2, Figs. 1*b*, 3), where it occurs in the lower parts of fining- and thinning-up trends (Fig. 4*a*). FA I forms 100 m thick bodies at Black Point (loc. 5, Fig. 1*b*), where it fills an erosive channel, and also at Rocky Point (loc. 6, Fig. 1*b*).

Judging from the scouring bottoms and normal grading but

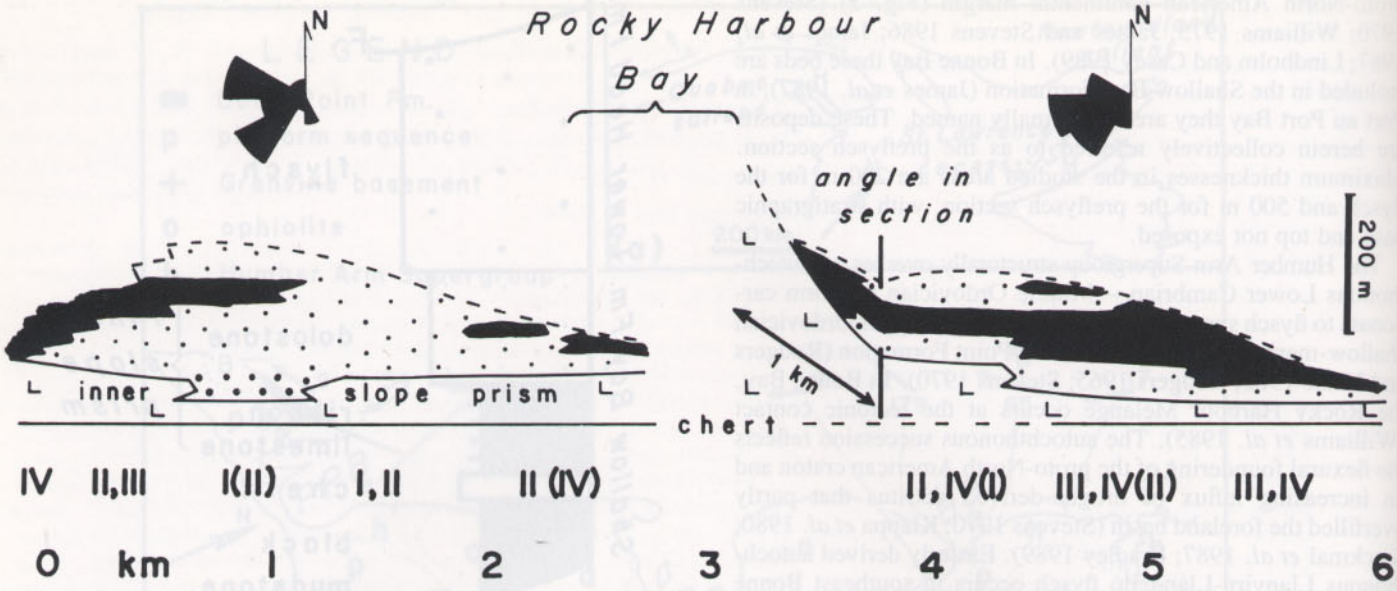

FIG. 3. Cross sections of submarine-fan systems north and south of Rocky Harbour Bay (locs. 2 and 3). Chert unit is datum. Up-fan direction is away from the reader; cross sections are parallel to the inferred basin axis. Convex-up top of fans given by preserved thicknesses measured in 14 correlative stratigraphic sections. Roman numbers give dominant and (subordinate) sedimentary facies associations in the flysch bodies. Internal fan stratigraphy is schematic but based on measured sections. Thick dots in northern fan represent conglomerate in channel axis; black strata are marginal mudstone and mud blankets. Paleocurrent rose diagrams plotted for each fan, with north directions rotated relative to the cross sections. Scale in kilometres at bottom is uncorrected for structural shortening.

also inverse grading and matrix-supported clasts (Table 1), deposition of FA I requires the combined action of high-concentration turbidity currents and debris flows. North of Rocky Harbour Bay (Fig. 3), the marked lateral expansion of the channel fill following initial deposition, the lack of deep scouring, and the scarcity of interbedded mudstone are attributed to frequent channel migration and a braided pattern. The coarse grain size and great thickness of the FA I deposits and the erosive (at Black Point) to interbedded (at Rocky Harbour Bay and Rocky Point) relationships with preflysch strata suggest proximal sedimentation on the lower reaches or at the foot of a slope. Typical levee facies (e.g., Walker 1985) were not recognized, which is consistent with shallow, frequently shifting channels.

FA II: medium-bedded sandstone packets

Facies association II consists of interbedded normally graded sandstones (80%) and mudstone (20%) that form packets 2–10 m thick. Individual packets comprise 3–20 beds (Fig. 4*b*) and are persistent across available exposure (commonly ranging between 20 and 50 m) without evidence of channeling. They may include one or more thickening-up sequences (Figs. 4*b*, 4*c*). Syndepositional bedding joints (Parkash 1970) and buff-weathering cementation bands enriched in dolomitic mud are common features of the sandstone beds (Fig. 4*d*). North of Rocky Harbour Bay FA II occurs in upper parts of thinning-up trends within the channel fill (Fig. 4*a*) and locally along the northern margin of the channel (Fig. 4*b*). South of Rocky Harbour Bay FA II is dominant in the northern outcrops and is locally deformed into large slump folds. FA II is a minor constituent of the flysch at Black Point and Rocky Point.

The ubiquitous normal grading, scarcity of internal lamination, and erosive sole marks (Table 1) indicate that FA II beds were deposited from high-density turbidity currents. Sandstone packets are interpreted as reflecting growth and abandonment of sandstone lobes at the mouths of channels represented by FA I. Slumped beds reflect moderately high sea-floor gradients underlying the area of lobe growth; interlobe relief may suffice for slumping.

FA III: slurried and rippled sandstone

Facies association III consists of roughly similar proportions of thin- to medium-bedded slurried sandstones and calcareous rippled sandstones, with up to 40% interbedded mudstone (Fig. 4*c*). Rippled sandstones show superimposed multiple sets of ripple-drift cross-lamination of sinusoidal and type C varieties (Jopling and Walker 1968); a few beds attain thicknesses of 1–4 m (Fig. 4*b* at top). Facies association III is common only in Bonne Bay, where it occurs on the muddy fringe to the channel north of Rocky Harbour Bay, and south of the sections dominated by FA II south of Rocky Harbour Bay (Fig. 3).

Judging from the fluted bottoms, internal lamination, and normal grading (Table 1), rippled sandstones were deposited from low-density turbidity currents. Accumulation of the thicker (approx. >1 m) beds must have taken considerable time, possibly a day to several days on the basis of calculations (Allen 1971) and experimental data (Ashley *et al.* 1982). It is postulated that these beds were deposited from continuously fed turbidity currents. Such flows may be generated by river discharge during flood stages (Heezen *et al.* 1964). Slurried sandstones, in turn, are generally interpreted as having accumulated from debris flows or high-density turbidity currents (Hiscott and Middleton 1979). They may have originated from the local slumping of muddy and watery lobe-fringe sands. Such an origin could account for the lateral transition and similarities (bed thickness, bedding joints; Table 1) between packet-forming medium-bedded sandstones and slurried sandstones. Facies association III occupies positions marginal to the sand-lobe areas.

FA IV: mudstone and dolomitic siltstone

Facies association IV is characterized by sandstone-free

TABLE 1. Facies in the Arenig–Llanvirn flysch

Facies[a]	Characteristics[b]	Average bed thickness (m)
Polymictic conglomerate (A2)	p–b; sandstone interlayers, large clasts float above base; coarse-grained matrix	2
Thick-bedded sandstone (B1.1, B2)	c–p; delayed normal grading, rare inverse grading at base; imbrication; fluid escape; large flutes	1.8
Medium-bedded sandstone (C2.2)	m–c; mostly Ta, less Tab and Tac; bedding joint; fluid escape; cementation band; flutes	0.5
Slurried sandstone (C1.1)	m–c; bedding joint; normal grading; high matrix content	0.4
Rippled sandstone (C2.1, C2.2)	f–m; ripple-drift and parallel lamination; mostly Tbc, less Tc; flutes	0.4
Dolomitic siltstone (D2.1)	Mostly Tb, less Tbc and Tc	0.04
Mudstone (E1.1)	Massive to faintly laminated; dolomitic and calcareous	—

[a]Codes refer to classification in facies scheme of Pickering *et al.* (1986).
[b]Maximum grain size: f, fine; m, medium; c, coarse sand; p, pebble; b, boulder. Ta, Tb, Tc: Bouma (1962) codes for, respectively, massive, parallel-laminated, and rippled intervals in turbidites.

sequences of dark grey mudstone up to 15 m thick that may contain thin beds of buff-weathering dolomitic siltstones (Figs. 4*a*–4*d*). The dark grey mudstone is structureless to finely laminated with black mudstone. Beds of dolomitic siltstone commonly show sharp bases, parallel and ripple lamination, and normal grading, although bioturbation has homogenized many beds. Facies association IV is present at all localities, although dolomitic siltstones are restricted to Bonne Bay. In Bonne Bay FA IV deposits occur marginally to the sand bodies or intercalated between sandstone packets (Fig. 3).

Judging from the sharp bases, normal grading, and influx transverse to the basin axis (see Table 2 and Paleocurrents), dolomitic siltstones accumulated from turbidity currents. They were not, however, deposited from the same flows that brought in most of the sand because nowhere is a wacke capped by a dolomitic siltstone. The dolomitic beds indicate a recurrence of sedimentary conditions typical of the upper preflysch section. The dark grey to olive-green mudstone is presumed to be terrigenous because of colour similarities with the mudstone associated with sandy turbidites in FA II. The greater part of the mudstone could have been deposited from the tails of sandy turbidity currents and dilute mud suspensions. The intercalated laminae of black mud, on the other hand, likely are pelagic. Facies association IV represents marginal regions in the depositional systems and mud blankets that accumulated during temporary cessation of sand deposition (Normark 1978; Walker 1978).

Paleocurrents

Arenig–Llanvirn flysch strata are thrust imbricated and tilted. Bed strike is northeast, and dips are moderate except at Rocky Point (loc. 5; NW/vert.) where the strike of the carbonate platform also changes markedly. Paleocurrent measurements are corrected for local tilt only; no additional correction is attempted for the Rocky Point data. Discussion is centred on the more numerous measurements from Bonne Bay. Reconstructions of Ordovician foreland basin in the Canadian Appalachians suggest that the axis of the flysch basin(s) approximately followed the present-day tectonic strike (Hiscott *et al.* 1986; James and Stevens 1986). For western Newfoundland this implies an average south-southwest trend for the basin axis.

The Arenig–Llanvirn flysch yielded 314 paleocurrent measurements (Fig. 1*b*) from a variety of sedimentary structures, mainly in lithic sandstones (Table 2*a*). One cross-bedded calcarenite intercalated in the flysch gave southwest flow. Overall, south-southwest to southwest flow directions are dominant and indicate transport oblique and parallel to the basin axis, following a regional south-southwest gradient. Where data are more abundant, westward flow components transverse to the basin axis are well developed (Fig. 3). In Bonne Bay, westward measurements mainly come from the channel deposits north of Rocky Harbour Bay and from the sandstone packets south of Rocky Harbour Bay and are intrepreted as a record of flows across a craton-facing slope. In the muddy northern fringe of the channel north of Rocky Harbour Bay, rippled sandstones yielded northward flow components and suggest a radial dispersal pattern about westward feeder channels.

Discrimination of flow components by facies reveals statistically significant differences. Vector means from medium- and thick-bedded sandstones of FA I and FA II (classes 1, 2, 3, and 6 in Table 2*b*) are insensitive to structure type and fairly consistent to the southwest. In contrast, ripple means from beds of rippled sandstone and dolomitic siltstone (classes 4 and 5 in Table 2*b*) trend more westerly than sole marks in lithic sandstones (Table 2*c*).

This is interpreted as reflecting differences in transport mode and degree of confinement of the flows by the channels. The dolomitic siltstones, associated with mud blanket sedimentation, were deposited from unchannelized flows that followed the westward gradient inherited from the underlying slope. The continuously fed rippled sandstones settled out from thick flows that spilled over the channel banks and were thus only slightly deflected from a westward course. On the other hand, beds of FA I and FA II would have been deposited from flows con-

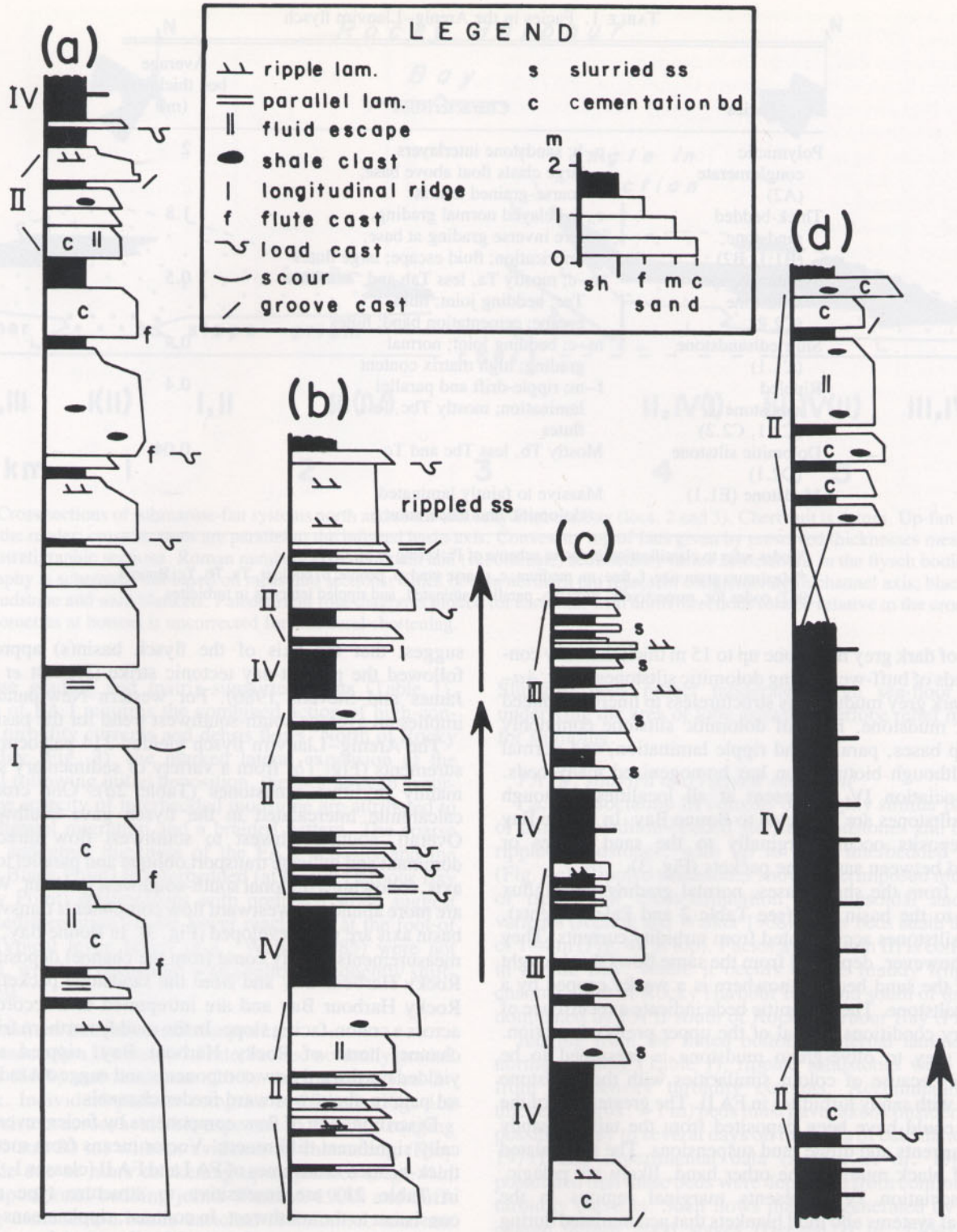

FIG. 4. Representative measured sections showing bedding style and facies associations described in text. Roman numbers to left of sections refer to facies associations. Arrows to right of sections (*b*) and (*d*) indicate thickening-up trends. bd, band; sh, shale; ss, sandstone. (*a*) FA I passing up to FA II and IV in a thinning-up trend; channel fill north of Rocky Harbour Bay (loc. 2, Fig. 1*b*). (*b*) Packets of FA II separated by FA IV; note 1.8 m thick rippled sandstone near top; northern channel margin north of Rocky Harbour Bay (loc. 2, Fig. 1*b*). (*c*) Intervals of FA III separated by FA IV; central sector in depositional system south of Rocky Harbour Bay (loc. 3, Fig. 1*b*). (*d*) Thick unit of FA IV, with dolomitic siltstone beds (black protruding lines) and FA II sandstone packets above and below; central sector in depositional system south of Rocky Harbour Bay (loc. 3, Fig. 1*b*).

stricted by channels that curved to the south-southwest (to the left) as they aproached the basin axis—hence the range of west to south-southwest paleocurrent trends. Note that sole marks and ripples (rippled division of Bouma sequence, Table 1) from beds of lithic sandstone give parallel paleoflow directions. This may evidence thin flows in which the dilute portions are also confined by the shallow channels or strongly entrained by the denser cores.

TABLE 2. Summary of paleocurrent data for the Arenig–Llanvirn flysch

(*a*) Measured sedimentary structures (314 measurements)

Flutes	21%
Ripples	21%
Grooves	19%
Parting lineations and sheeted fluid escape structures	17%
Longitudinal ridges	11%
Imbrication	7%
Medium-scale cross sets	3%
Prod casts and oriented graptolites	1%

(*b*) Measurements from depositional systems north and south of Rocky Harbour Bay

		North		South	
Class	Sedimentary structure	Number of measurements N	Vector mean G	Number of measurements N	Vector mean G
1	Flutes	11	244	26	234
2	Grooves, longitudinal ridges	21	233	73	229
3	Imbrication, parting lineations, fluid escape	12	258	34	231
4	Ripples from rippled sandstone	12	269	21	250
5	Ripples from dolomitic siltstone	4	273	12	265
6	Ripples from lithic wackes	5	254	13	234
Total		65	249	179	236

(*c*) Tests for difference of means between classes 1 + 2 (G_a) and classes 4 + 5 (G_b)

Null hypothesis H_0: $G_a = G_b$ rejected	5% level (north)	1% level (south)

Submarine-fan systems

The reconstruction of the flysch depositional system north of Rocky Harbour Bay (Fig. 3) shows conglomeratic deposits occupying a narrow axial zone followed by more extensive braided-channel deposits that appear to pass laterally into areas of sand-lobe and mud accumulation. The conglomeratic but apparently nonerosive nature of this channel complex suggests a position at the foot of the slope. This channel complex is approximately as wide as that of the braided inner fan valley on Navy fan (Normark 1978) but lacks the abundant levee deposits. It is also similar in width and in lithofacies to the unleveed, braided, upper middle fan channel complex described by Walker (1975) from the Capistrano Formation, except for a generally coarser grain size.

Exposures south of Rocky Harbour Bay (Fig. 3) are attributed to a separate depositional system characterized by transverse flow components, poorly preserved channel-fill deposits, and an overall asymmetric facies arrangement, with proximal to distal transition toward the south.

The sand-rich nature of these two depositional systems, the radial dispersal of sand, and the spatial arrangement of facies are consistent with the radial submarine-fan model (Stow *et al.* 1984). The channel complex (FA I) would have developed on the inner to middle fan regions and fed sand lobes (FA II) on the middle fan region where slurried and rippled sand beds (FA III) accumulated in interlobe and lobe-fringe positions. The fan north of Rocky Harbour Bay is generally coarser grained and characterized by more proximal facies than the fan south of Rocky Harbour Bay. Along the main line of cross section (NNW–SSE) in Fig. 3, the thickness of preflysch deposits separating the flysch from the chert is similar under both fans. This suggests that their paleotopographic positions were approximately the same relative to the basin axis and that the lithological contrast is mainly due to differences in the shelf and slope feeder systems.

The convex-up tops of these two fan bodies (Fig. 3) may crudely reflect their original morphology. Quite likely their plan shape was highly asymmetric due to the south-southwest basin gradient and topographic constrictions, so the outer fan deposits, which are not exposed, possibly formed elongated bodies flanking the inner slope. The fans grew at the foot of the orogen and were not perched in slope troughs because the preflysch section lacks evidence of having been overridden by the orogen before flysch sedimentation (see stratigraphic reconstructions in González-Bonorino 1979; James and Stevens 1986; James *et al.* 1987).

The submarine-fan interpretation is tentatively extended to the more poorly exposed flysch deposits at Martin Point, Black Point, and Rocky Point. Flysch deposits at each of localities 1 through 5 are inferred as representing separate depositional systems because of the presence at all localities of coarse-grained FA I sediments attributed to feeder channels. Five or more submarine fans may have become operative in the Newfoundland segment of the Taconic foredeep in middle Arenigian to early Llanvirnian time. The young mountainous relief on the Taconic Orogen would have been drained by short rivers with small drainage basins, conditions favouring high sediment yields (Milliman and Meade 1983). A great relief in the source area and a narrow coastal plain favour development of numerous rivers debouching directly onto the shelf. A modern analogy may be the Peru coastline, cut by 35 major (mappable at scale 1 : 7 000 000) rivers, giving an average spacing of 50 km (minimum 10 km). With a narrow shelf and frequent seismic activity, such river systems may deliver abundant sand to submarine fans at the foot of the orogen, as

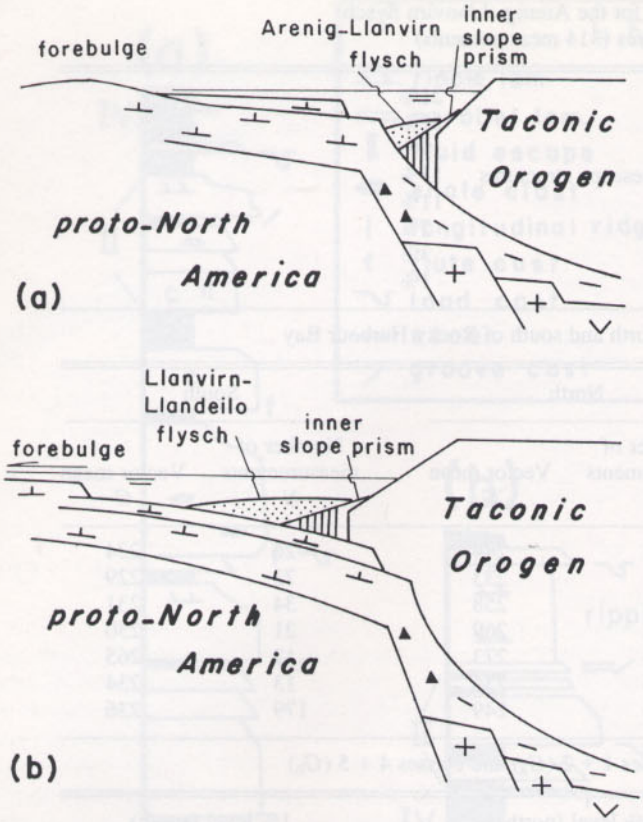

FIG. 5. Highly schematic reconstructions of the structural settings for Ordovician flysch in west-central Newfoundland (partly based on Stevens 1970; Williams 1975; Marillier *et al.* 1989). (*a*) A thin, Arenig–Llanvirn flysch occupied a narrow, underfilled foredeep flanked by an outer, passive-margin slope and an inner orogen slope. Minor foundering and platform recession took place at this stage. Note that the Taconic Orogen has just begun to surmount thicker crust. (*b*) A thicker, Llanvirn–Llandeilo flysch overlay the foundered platform. Deep subsidence, carbonate-bank recession, and inland migration of the forebulge took place as the Taconic Orogen succeeded in surmounting the buried shelf.

occurs in the southern reaches of the modern Chile trench (Thornburg and Kulm 1987). Sporadic river floods could feed long-lived turbidity currents that deposit thick, rippled sandstones on the fans.

A possible analog for Arenig–Llanvirn flysch sedimentation in the Newfoundland Taconic foredeep is found in the Maestrichtian submarine-fan systems of the Great Valley Sequence in California, described by Cherven (1983). Cherven mapped eight fans over a distance of approximately 100 km along the basin axis. The fans were fed from deltas across a narrow (commonly less than 5 km wide) slope and accumulated in a narrow trough in water depths of the order of 200–300 m. Fan thickness ranges from 30 to 250 m, and they are less than 10 km wide in their proximal portions. Applying Cherven's reconstruction to the Newfoundland flysch, the two closely spaced fans located north and south of Rocky Harbour Bay may have been successively fed from a single delta following fluvial-channel avulsion.

Discussion

Four main points are considered here: (*i*) evidence for an easterly provenance of muds in the uppermost preflysch section; (*ii*) time of initial emergence of the Taconic Orogen; (*iii*) regional dispersal of Arenig–Llanvirn sand; and (*iv*) evolution of the foreland basin and its sediment fill.

An Arenigian slope prism flanking the Taconic Orogen

The muddy preflysch strata did not yield useful paleocurrent measurements, and thus their provenance must be established by indirect arguments. The quartzose turbidites in the uppermost preflysch section indicate input from the Taconic Orogen and thus a provenance and paleoslope reversal. In Bonne Bay the appearance of these sandstones is accompanied by an enrichment in dolostone, suggesting a connection between influx of dolomitic mud and emergence of the orogen. This is supported by the chert fragments in the dolostone, which were probably derived from preflysch strata uprooted by the rising orogen. In addition, the scoured bases in the uppermost dolostone beds indicate greater flow turbulence, and probably flow velocity, and suggest an increase in sea-floor gradient that is more reasonably attributed to growth of the orogen than to changes tied to foundering and recession of the craton platform (James *et al.* 1987). These arguments support a provenance from the Taconic Orogen for at least part of the argillaceous and lime mud in the uppermost preflysch section.

Active carbonate banks may have developed on the orogen (Stevens 1970) and shed dolomitic mud before massive flysch sedimentation. Dolomite formation may have been aided by the addition to the pore waters of magnesium freed during diagenetic alteration of volcanic debris from the orogen (Suchecki *et al.* 1977).

Inferences from the reconstruction of the fan systems in Bonne Bay and the conformable relationship between the flysch and preflysch beds suggest that this mud accreted into an inner slope sedimentary prism resting on, and interbedded with, outer slope deposits derived from the craton. Along the southern shore of Rocky Harbour Bay is exposed an eastward-thickening wedge of sediment underlying the flysch (Fig. 3). Sheared mudstone and broken beds are common, and these exposures have been mapped entirely with the Middle Ordovician Rocky Harbour Mélange (Williams *et al.* 1985). From east to west, approximately along bed strike, facies in this unit change from dolomitic mudstones, with numerous intercalated quartzose turbidites showing basal lags of coarse sand, to dolomitic mudstones, ribbon limestones, limestone breccias, and chert in disrupted beds. It is suggested that part of these deposits are correlative with the preflysch section and that the eastward thickening was partly inherited from the preflysch inner slope prism.

Emergence above sea level of the Taconic Orogen

By the end of the Arenigian, voluminous flysch sedimentation was under way (James and Stevens 1986; James *et al.* 1987). The Taconic Orogen must have been of considerable height at that time. A base-level fall (Hiscott *et al.* 1986) would have released detritus previously eroded and stored on the shelf but could not have created the topographic relief necessary for the production of the abundant sand and gravel in the flysch. Now, assuming that initial emergence of the orogen is recorded by the older quartz turbidites in the preflysch section and by the rapid increase in dolostone content, emergence may have started at about the middle to late Arenigian boundary (estimated from data in James and Stevens 1986; James *et al.* 1987).

Regional flysch dispersal

In the Newfoundland – Gaspé Peninsula Arenig–Llanvirn flysch belt about one dozen separate fan systems have been

mapped, with a spacing of about 5–100 km (Fig. 1*a*). Reconstructions for the preflysch basin in Cow Head – Bonne Bay (James and Stevens 1986; James *et al.* 1987) and for the fan systems in Bonne Bay suggest that the Arenig–Llanvirn flysch in Newfoundland accumulated in a narrow foredeep between the orogen and a receding platform edge. In contrast, correlative fans in Gaspé Peninsula filled basins on the lower reaches of a craton-facing structural slope moulded on the preflysch beds (Hiscott *et al.* 1986), perhaps partly veneered with mass-wastage deposits. Despite their different structural setting, these fans are similar in size and sedimentary facies. It is possible that the latter fan characteristics were governed more by the nature of the feeder systems than by the structural setting.

The Arenig–Llanvirn flysch deposits in Newfoundland lie on the northern flank of the St. Lawrence recess (Thomas 1977) (Fig. 1*a*). Thomas proposed that promontories served as sediment sources to the clastic wedges that accumulated in adjacent reentrants. He also noted that as the clastic wedges began to fill the basins, paleocurrent directions changed from longitudinal to transverse toward the craton.

Hiscott *et al.* (1986) compiled paleocurrent data for allochthonous and autochthonous flysch in Newfoundland – Gaspé Peninsula and showed that regional sediment transport was from the St. Lawrence recess into the Quebec salient (Fig. 1*a*). Their data for Newfoundland was scarce and did not include the Arenig–Llanvirn flysch. Paleocurrent measurements presented above reveal a strong south-southwest longitudinal flow component in both the allochthonous and autochthonous flysch (Fig. 1*b*) and support their conclusion. A high subsidence/sedimentation ratio would maintain a basin floor sloping toward the orogen and the basin axis leaning against the seaward slope, thus constricting sediment dispersal to longitudinal directions. Note that the Newfoundland salient (Fig. 1*a*) has no effect on flysch dispersal, despite its proximity to the studied exposures. A change to transverse flow in the younger flysch, as found by Thomas (1977), is not generally apparent. However, upper Middle Ordovician autochthonous flysch in southwest Quebec (marked × in Fig. 1*a*) (Belt and Bussières 1981) flowed mainly transverse to the foredeep.

In Newfoundland, the consistent average south-southwest flow suggests that the basin deepened down the flank of a St. Lawrence promontory. The greater thickness of the Mainland Sandstone flysch compared with the Norris Point formation flysch offers some support for this. Connection with the Quebec foredeep through an extensive axial channel (similar to the axis channel in the Chile trench; Thornburg and Kulm 1987) is, however, uncertain. Hiscott *et al.* (1986) found evidence for intrabasinal highs in the Quebec foredeep. A major transform fault, as postulated by Stockmal *et al.* (1987), south of Newfoundland would likely have caused sufficient topographic relief to pond longitudinal flows.

Evolution of the foreland basin

Widespread chert sedimentation in the foreland basin during the Arenigian reflects starved conditions (James and Stevens 1986). James and Stevens attributed this to a eustatic high sea-level stand. Alternatively, or in addition to eustasy, low mud influx may reflect mild flexural foundering of the carbonate platform coupled with nonemergence of the Taconic Orogen during early convergence. Starved basin conditions preceded flysch sedimentation in the Cenozoic Apennines (Pescatore and Senatore 1986) and in the upper Paleozoic Marathon Basin in the Ouachita Mountains (Wuellner *et al.* 1986).

During the late Arenigian the effects of the orogenic load were more strongly felt on the carbonate platform, causing fault-induced subsidence and collapse of the shelf edge (James and Stevens 1986; James *et al.* 1987) and growth of a flexural forebulge (Jacobi 1981). At this time the Taconic Orogen began to shed mud and some sand that accreted an inner slope prism. Voluminous flysch sedimentation started in the latest Arenigian. This may have been prematurely triggered by a eustatic fall in base level (Hiscott *et al.* 1986) and probably does not reflect a dramatic change in tectonic rates. Flysch accumulated on the slope region of the proto-North American margin (James and Stevens 1986), possibly a short distance seaward from the buried hingeline (Fig. 5*a*). The lack of structural deformation of preflysch strata previous to flysch arrival suggests a very slow advance of the orogenic front while the inner slope prism and flysch accumulated. A possible explanation for this is that the orogen had met the crustal ramp, and compressive stresses were mainly spent in thickening the crust. The orogenic load would have partly rested on attenuated continental crust, and downflexing of the thicker craton was not sufficiently fast to drown the carbonate shelf (Hiscott *et al.* 1986).

Later in the Llanvirnian, the orogen overthrust the platform, causing its rapid subsidence and a shift in flysch depocentres (Fig. 5*b*). Transition from the massive carbonates to the coarse-grained, thick-bedded Llanvirn–Llandeilo flysch occurs over several tens of metres stratigraphically. This is in contrast with the thin zones of interbedded flysch and preflysch deposits beneath the Arenig–Llanvirn flysch and may reflect differences in tectonic versus eustatic rates of base-level change. By the early Caradocian at least parts of the foredeep (loc. B, Fig. 1*b*) had become overfilled, and the Humber Arm allochthon had reached its final position.

This reconstruction implies that the Arenig–Llanvirn flysch originally accumulated near the eastern border of the Humber Zone (Fig. 1*a*) and was tectonically transported about 100 km to its present position. Bradley (1989), on the other hand, estimated the transport distance as 270 km. Using his model parameters, however, this estimate is excessive. At approximately the time when the Arenig–Llanvirn flysch was accumulating, the effect of a flexural forebulge rise was recorded in the cratonic platform sequence (Jacobi 1981; Bradley 1989). With Bradley's (1989, Fig. 4) model the orogenic front should have lain about 100 km away from the forebulge, a distance that agrees with the present estimate.

Conclusions

During the Early Ordovician the structural edifice of the Taconic Orogen in Newfoundland was assembled from slope-rise deposits of the former passive margin. While still regionally submerged, mass wastage and mud eroded from the orogen accreted an inner slope prism. Following widespread emergence of the Taconic Orogen, a thin Arenig–Llanvirn flysch accumulated as a series of small submarine fans along the lower reaches of the slope, a short distance seaward of the buried passive-margin shelf edge. As the orogen thickened and encroached upon the platform, flysch depocentres migrated toward the craton, and in Llanvirnian–Llandeilian times a thicker flysch covered the foundered shelf. Through time the setting and thickness of the flysch reflects the passage of the Taconic Orogen across the buried early Paleozoic passive margin and the changing nature of the underlying continental crust.

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