The West Indian Road pit, central Nova Scotia: key to the Early Cretaceous Chaswood Formation[1]

Jean-Philippe Gobeil, Georgia Pe-Piper, and David J.W. Piper

Abstract: The West Indian Road pit is the only large outcrop in Nova Scotia of the Chaswood Formation, the terrestrial equivalent of the offshore Missisauga and Logan Canyon formations. It provides outcrop information on sedimentology, gravel petrology, and structures for a formation that is otherwise known from a few small overgrown pits and from boreholes. The Chaswood Formation in the pit is > 60 m thick and consists principally of sorted sand and gravel with three thinner clay units. Successions of sedimentary structures indicate deposition from a coarse-bedload river flowing to the east-southeast. Gravel consists principally of vein quartz, quartz arenite, and subarkose, together with minor igneous lithologies that can be matched to sources in the Cobequid Highlands to the north. Quartz arenite and subarkose appear derived from Carboniferous Horton Group. Single-crystal $^{40}Ar/^{39}Ar$ dates of detrital muscovite are a little older than the muscovite ages for the South Mountain batholith, interpreted to mean that the muscovite is second cycle from the Horton Group, which records the earliest unroofing of the batholith. The Chaswood Formation accumulated during progressive tectonic deformation along NNE-trending strike-slip faults in basement rocks, resulting in syn-sedimentary faulting and local unconformities. Sedimentation kept pace with the creation of accommodation. Unrelated younger deformation folded the Chaswood Formation at the pit into an east–west-trending syncline. The Early Cretaceous paleogeography of the Maritime Provinces is interpreted to have consisted of fault-bound horsts shedding coarse detritus surrounded by an interconnected series of basins that accumulated fluvial sands and gravels and overbank muds with well-developed paleosols.

Resumé : La carrière de West Indian Road est le seul endroit en Nouvelle-Écosse où l'on peut voir un grand affleurement de la Formation de Chaswood, l'équivalent terrestre des formations de Missisauga et de Logan Canyon au large. Cette carrière fournit des informations sur la sédimentologie, la pétrologie du gravier et les structures d'une formation que n'est connue autrement que par quelques petites fosses recouvertes de végétation et des trous de forage. Dans la carrière, la formation de Chaswood a une épaisseur de plus de 60 m et elle comprend surtout du sable et du gravier triés avec trois unités argileuses plus minces. La succession des structures sédimentaires indique une déposition à partir d'une rivière coulant vers le ESE et dont le lit est recouvert de granulats grossiers. Le gravier est principalement composé de quartz filonien, d'arénite quartzique et de subarkose, avec quelques lithologies ignées mineures qui peuvent être retracées à des sources dans les hautes terres de Cobequid vers le nord. L'arénite quartzique et la subarkose semblent provenir du Groupe Horton (Carbonifère). Les dates $^{40}Ar/^{39}Ar$ obtenues sur un cristal unique de muscovite détritique sont un peu plus anciennes que les âges de la muscovite du batholite de South Mountain, ce qui signifierait que la muscovite est du second cycle du Groupe de Horton, celui qui enregistre le retrait du toit le plus précoce du batholite. La Formation de Chaswood s'est accumulée durant une déformation tectonique progressive le long de failles décrochantes à direction NNE dans le socle rocheux; cela a donné des failles synsédimentaires et des discordances locales. La sédimentation a suivi la cadence de l'accommodation. À la fosse, une déformation plus récente a plissé la Formation de Chaswood en un synclinal à tendance est–ouest. La paléogéographie du Crétacé précoce des Provinces maritimes comprendrait des horsts, limités par des failles, d'où provient du matériel détritique; ces horsts sont entourés d'une série de bassins inter-reliés dans lesquels se sont accumulés des sables et des graviers fluviaux et des boues d'inondations présentant des paléosols bien développés.

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J.-P. Gobeil. Department of Earth Sciences, Dalhousie University, Halifax, NS B3H 3J4, Canada.
G. Pe-Piper.[2] Department of Geology, Saint Mary's University, Halifax, NS B3H 3C3, Canada.
D.J.W. Piper. Geological Survey of Canada (Atlantic), Bedford Institute of Oceanography, P.O. Box 1006, Dartmouth, NS B2Y 4A2, Canada.

[1]Geological Survey of Canada Contribution 2005320.
[2]Corresponding author (e-mail: gpiper@smu.ca).

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Introduction

The Chaswood Formation

Early Cretaceous sand(stone)s and mudstones in Nova Scotia and southern New Brunswick (Fig. 1A) form the Chaswood Formation, up to 200 m thick and are best preserved in a series of fault-bound basins in central Nova Scotia (Fig. 1B). Stea and Pullan (2001) defined a type section for the Chaswood Formation with three members from a series of boreholes south of Chaswood (Fig. 1B). The Chaswood Formation consists of a variety of terrestrial facies, principally fluvial sands and gravels with overbank kaolinitic mudstone with paleosols. The upper part of the formation is only loosely consolidated, but the lowest sandstones are well indurated. The middle part of the Chaswood Formation is of Aptian age (Davies et al. 1984; Wade and MacLean 1990), whereas Early Cretaceous biostratigraphic ages have been determined for some isolated deposits (Davies 1983; R. Fensome, personal communication, 2002). The Chaswood Formation is the proximal terrestrial equivalent of the thick deltaic and marine successions of the Missisauga and Logan Canyon formations offshore in the Scotian Basin. The Chaswood Formation thus preserves a record of the climatic conditions and sediment supply to these offshore formations, which are important reservoir rocks for oil and gas (Wade and MacLean 1990).

The West Indian Road pit

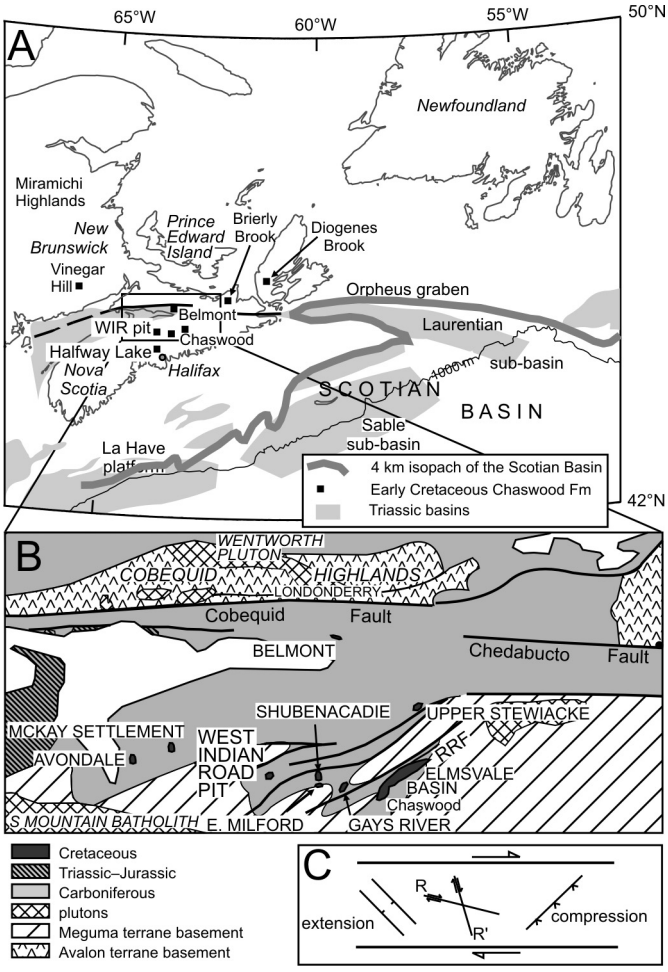
The West Indian Road pit is the only large outcrop of the Chaswood Formation in Nova Scotia. Therefore, it provides unique information on the sedimentology and structural geology of a formation that otherwise is known only from a few small overgrown pits, small deposits preserved in sinkholes in Carboniferous limestone and gypsum (Dickie 1986), and from boreholes and seismic reflection profiles (Stea and Pullan 2001; Pe-Piper et al. 2005*b*). The only other substantial outcrop of the formation is at Vinegar Hill in southern New Brunswick (Falcon-Lang et al. 2004), which is less informative in both sedimentology and structure.

The West Indian Road pit (Fig. 2) (also previously referred to as Brazil Lake or Grant Brook) occurs within a fault-bound basin in Carboniferous gypsum of the MacDonald Road Formation (Windsor Group) and was originally interpreted as a large sinkhole (Dickie 1986). The regular stratigraphic succession and tectonic tilting indicates that the deposit was originally more extensive and occupies its present position as a result of post-depositional faulting and folding into a syncline (Fig. 3B). The pit has been extensively exploited for silica sand and studied by Shaw Resources (Price 2000). When the pit was first developed, Stea and Fowler (1981) noted the presence of exotic pebbles and interpreted the deposits as fluvial in origin.

Purpose of this study

This study took advantage of the excellent outcrops in the West Indian Road pit, together with boreholes drilled by Shaw Resources, to understand the lithostratigraphy, sedimentology, detrital petrology, and structural deformation of the Chaswood Formation at this locality. Some aspects of the Chaswood Formation cannot be interpreted from the many available boreholes. Sand and gravel recovery is poor in boreholes and insufficient gravel is available to assess provenance. Borehole sections do not show large-scale sedimentary structures or paleocurrent indicators, and rarely intersect tectonic structures. Therefore, the study of this single well-exposed pit provides unique information applicable to other parts of the Chaswood Formation.

Fig. 1. (A) Location map of the Chaswood Formation in the southern Maritime Provinces. WIR, West Indian Road. (B) detail of central Nova Scotia, showing location of the West Indian Road pit. RRF, Rutherford Road fault. (C) secondary deformation associated with a master dextral strike-slip fault (from Woodcock and Schubert 1994).



Methods

The West Indian Road pit was mapped, stratigraphic sections were measured and correlated with adjacent sections by tracing individual beds, and well-located samples were collected. Details are given in Gobeil (2002). The older pit faces are obscured by wash-down of till, with good outcrops restricted to gullies, and in addition the dipping strata on many of the pit walls made tracing individual beds over distances of more than 10 m difficult. Paleocurrents were measured by excavating three-dimensional (3-D) sections of sedimentary structures. Grain size was determined by sieving. Heavy minerals were separated using sodium polytungstate (SG = 2.86 g cm^{-3}). Representative heavy minerals and pebbles were studied in petrographic thin sections, with identifications

Fig. 2. General geology of the West Indian Road pit, showing late faults, location of boreholes and measured sections, and location of figures. Outline of pit and location of boreholes from Price (2000).

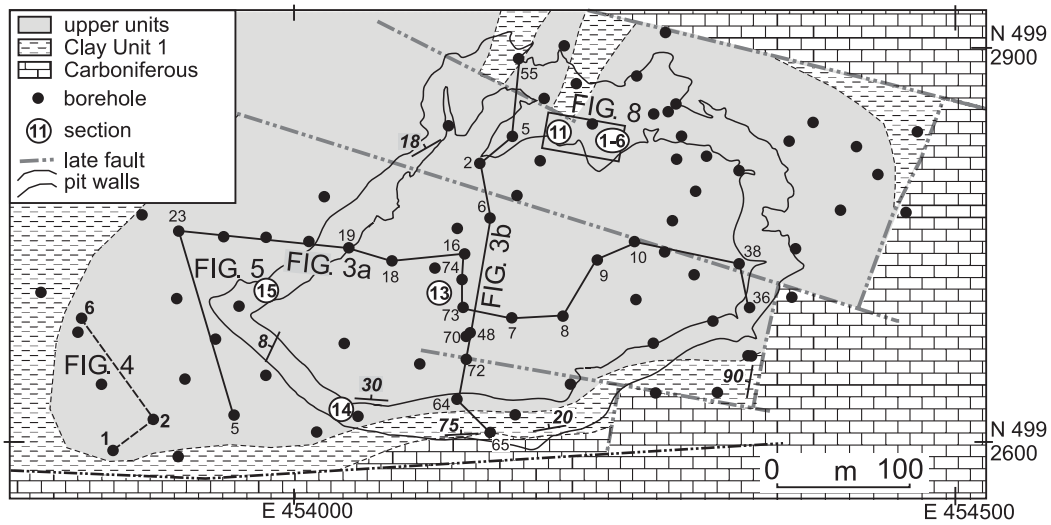
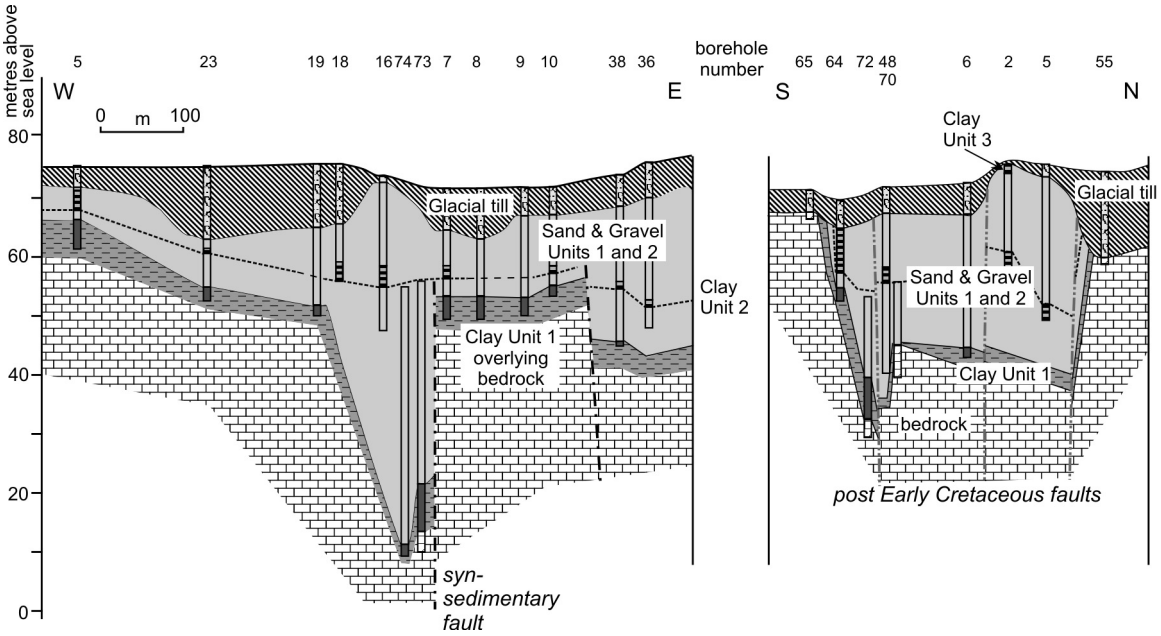


Fig. 3. Cross sections of the West Indian Road pit interpreted between boreholes described by Price (2000). Location in Fig. 2.

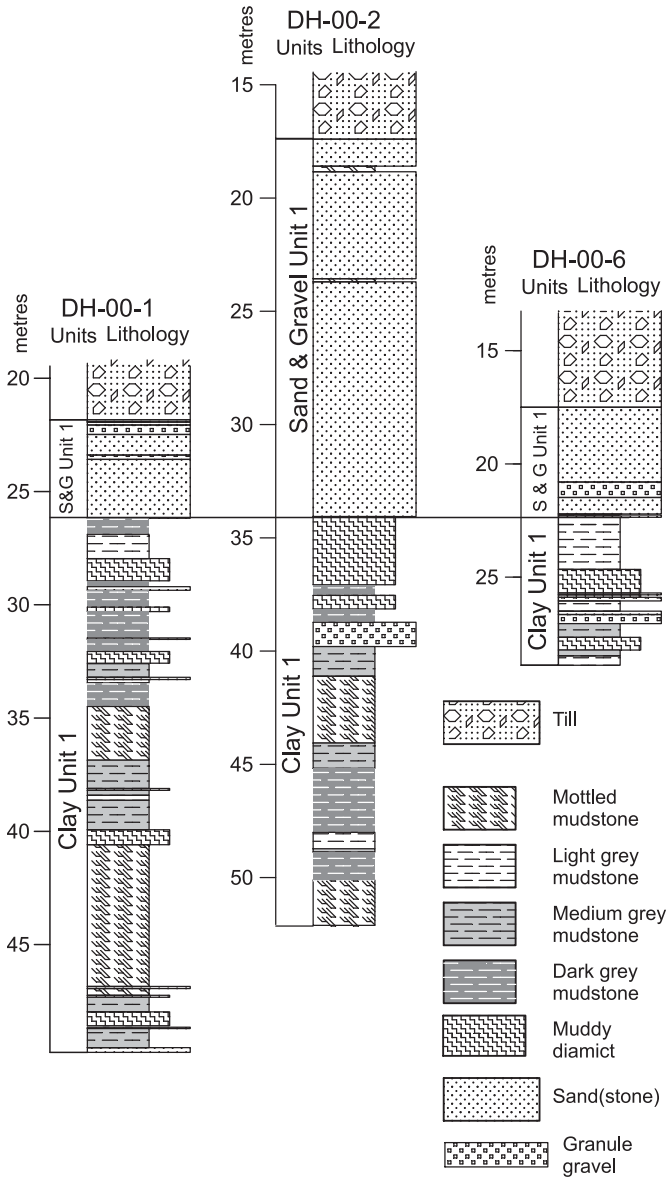


confirmed by electron microprobe analyses. Pebbles were counted in four large samples, each with >1000 pebbles, two from each of the main sand and gravel units. Less emphasis was placed on heavy minerals, because they are well known from boreholes in the Chaswood Formation (e.g., Pe-Piper et al. 2004, 2005*a*), and relative abundance of different minerals was only estimated. Methods for single-grain muscovite geochronology are described by Hicks et al. (1999).

Stratigraphy

The lithostratigraphic section in the West Indian Road pit, from outcrop and boreholes (Fig. 3), is several tens of metres thick. At the base, Clay Unit 1 is typically 3–10 m thick (Fig. 3) resting unconformably on the MacDonald Road Formation, but reaches thicknesses of 23 m at the western end of the pit (Fig. 4). It consists principally of dark grey clay, with some interbedded mottled brown, pink, red, purple and green clay and thin sand and gravel beds. The overlying Sand & Gravel Unit 1 is known mostly from boreholes and is generally 3–7 m thick, but locally reaches thicknesses of 45 m. It consists of gravel and sand, commonly in fining-upward successions. Clay Unit 2 is 0.5–3.6 m, thickening systematically to the northeastern part of the pit. In places, it is disrupted by sand injection (Fig. 5) and was not identified in all boreholes. Sand & Gravel Unit 2 is typically 15 m thick and consists of cross-bedded pebbly sand and lesser gravel (Figs. 6, 7), with local erosional unconformities (Fig. 8), at which undeformed strata discordantly overlie strata showing structural deformation. Clay Unit 3 is a 0.5 to

Fig. 4. Descriptive logs of boreholes in Clay Unit 1 and Sand & Gravel (S&G) Unit 1 to the southwest of the pit. Location in Fig. 2.



1.2 m thick pink clay bed found throughout the pit. It is overlain locally by thin sediments of Sand & Gravel Unit 3 and then unconformably by glacial till.

Structural deformation

Two different phases of deformation are recognised in the West Indian Road pit: (1) deformation synchronous with deposition and (2) later folding and faulting that created the present syncline. The syn-sedimentary deformation is seen most clearly in Clay Unit 2, which is folded into two anticlines (Fig. 9), one with a faulted margin on its eastern side, against which Sand & Gravel Unit 2 onlaps with local unconformities (Fig. 8). At unconformity I in Fig. 8, faulted sands (Fig. 10) are overlain disconformably with onlap by gravel and sand that lack faults but are folded together with the unconformity to dips of >50° at the margin of the anticline (Fig. 8). Unconformity II erosionally truncates the folded unconformity I and is overlain by a thick gravel bed. All this sand and gravel is within Sand & Gravel Unit 2, and the unconformities cannot be distinguished from normal erosional bedding contacts more than a few metres from the margin of the anticline. Below unconformity I, bedding is tilted to subvertical, and subhorizontal shear zones predominate (Fig. 10). This style of faulting is consistent with strike-slip faulting under a low vertical confining stress. Both the anticlines and the fault zone strike north-northeast.

Rapid variations in thickness of the Chaswood Formation in the West Indian Road pit are also suggestive of syn-sedimentary faulting creating accommodation. Clay Unit 2 lies at an elevation of about 60 m (above sea level), except at the northen and southern margins of the pit, where it has been tilted and uplifted (Fig. 3). Beneath this marker, Sand & Gravel Unit 1 is commonly 2–7 m thick over much of the pit, except in three depocentres (Fig. 9). In a narrow NNE-trending zone across the centre of the pit, proven thicknesses of Sand & Gravel Unit 1 in places exceed 30 m (Figs. 3*a*, 9). This depocentre is parallel to the syn-sedimentary faults (Fig. 9). In the east of the pit, Sand & Gravel Unit 1 is 10 m thick in borehole 38 and Clay Unit 2 has dropped to about 55 m elevation in this and nearby boreholes (Fig. 3*a*). Locally, there are also thick sands and gravels southeast of the pit, where Clay Unit 1 is also much thicker (e.g., 23 m in borehole 1, Fig. 4) than proven thicknesses elsewhere in the pit (e.g., 7–8 m in boreholes 72, 73, Fig. 3). There are insufficient boreholes to define the trends of the eastern and southwestern depocentres.

Late deformation folded the Chaswood Formation into an east–west-trending syncline, with subvertical dips close to bounding east–west- or WNW–ESE-trending faults (Figs. 2, 3*b*). These faults have a large normal component of displacement. The Chaswood Formation is also faulted against Carboniferous basement at the eastern end of the pit by NNE-trending faults (Fig. 2), which parallel the Early Cretaceous syn-sedimentary faults and may be reactivated structures. The age of this late faulting is unknown.

Sedimentology

Field observations of sand and gravel facies

The following sand and gravel facies are recognised (Table 1). Massive to horizontally laminated gravel (**Gm**) beds form the base of fining-upward successions, in places forming amalgamated beds up to 1.5 m thick. Clasts may be either pebble or granule size. Massive graded gravel (**Gms**) beds are 0.5–0.8 m thick, generally with an erosive base with a pebble lag. Trough cross-bedded gravel (**Gt**) occurs in multiple sets 0.3–0.5 m thick interbedded with other types of gravel deposit. Planar cross-bedded gravel (**Gp**) forms single sets 0.4–2.1 m thick. Crudely cross-bedded sand with an erosional scoured base (**Se**) forms beds up to 0.8 m thick, with a pebble–granule lag at the base. In places, this facies passes laterally into massive sand (**Ss**) with broad, shallow scours and, in some beds, normal grading. Planar cross-bedded sand (**Sp**) forms single sets 0.2–0.7 m thick. Trough cross-bedded sand beds (**St**) occur in multiple sets 0.2–1 m thick, commonly with granule lags at the base of sets. They pass up into hori-

Fig. 5. Annotated photograph of sand injection structures in Clay Unit 2. Location in Fig. 2. Spade for scale. S&G, Sand & Gravel.

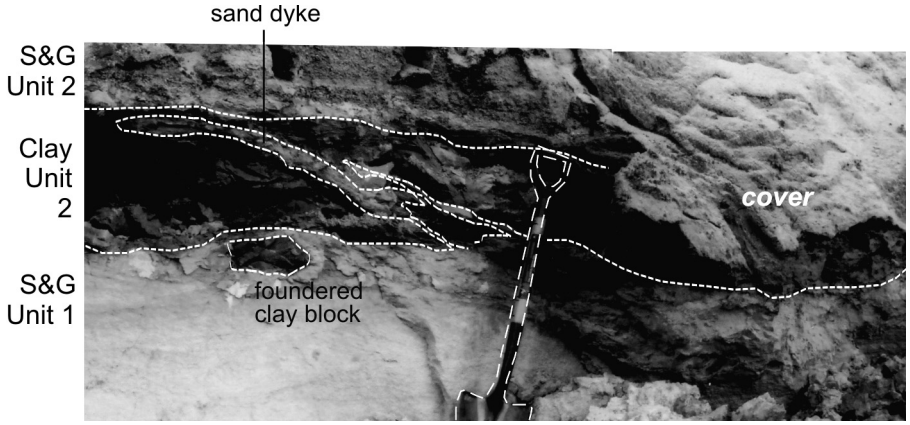


Fig. 6. Measured sections from Sand & Gravel Unit 2 in the northeastern part of the West Indian Road pit. Location in Fig. 2. Lithology code in Table 1. Sections are located in relative stratigraphic position.

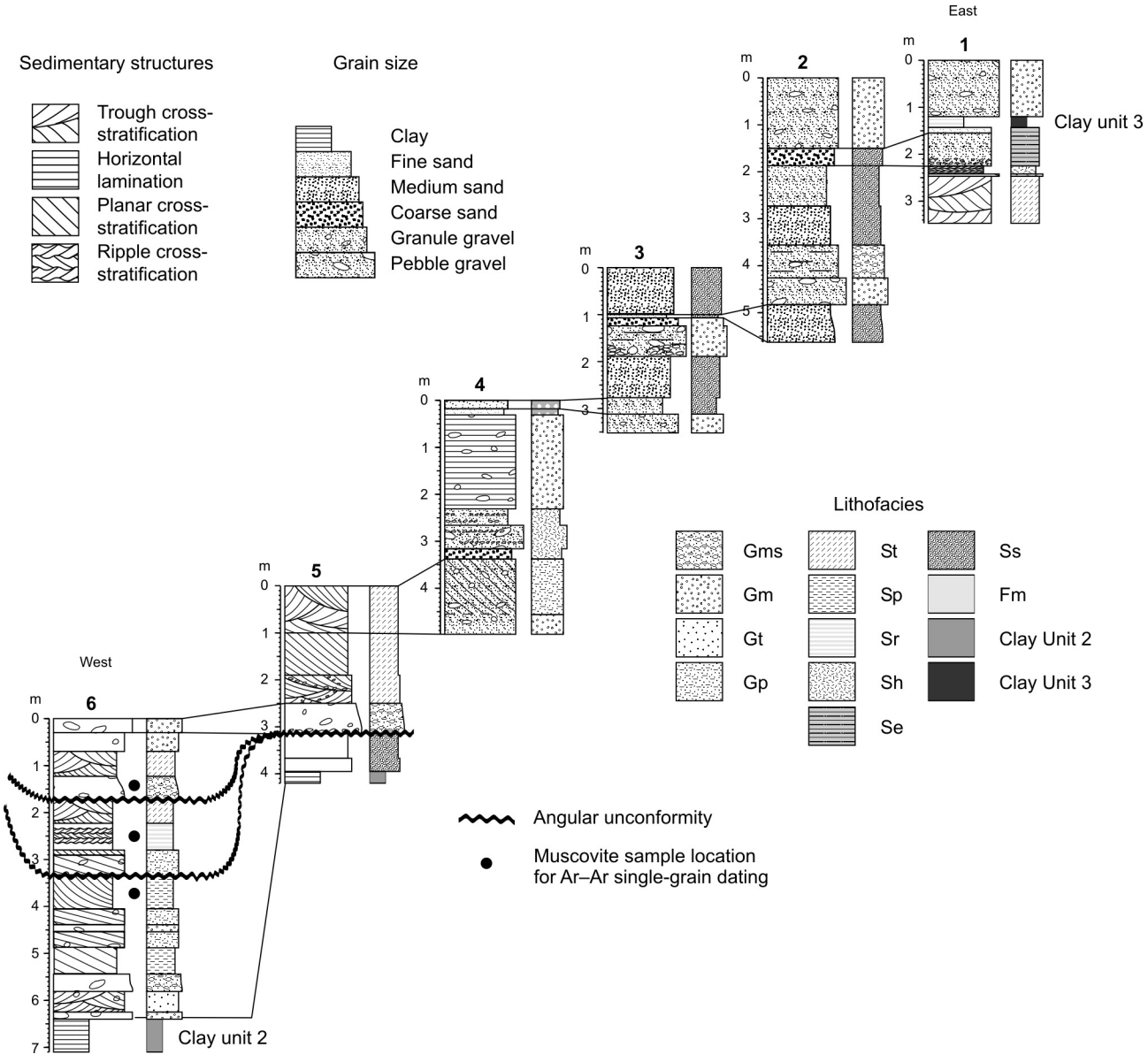
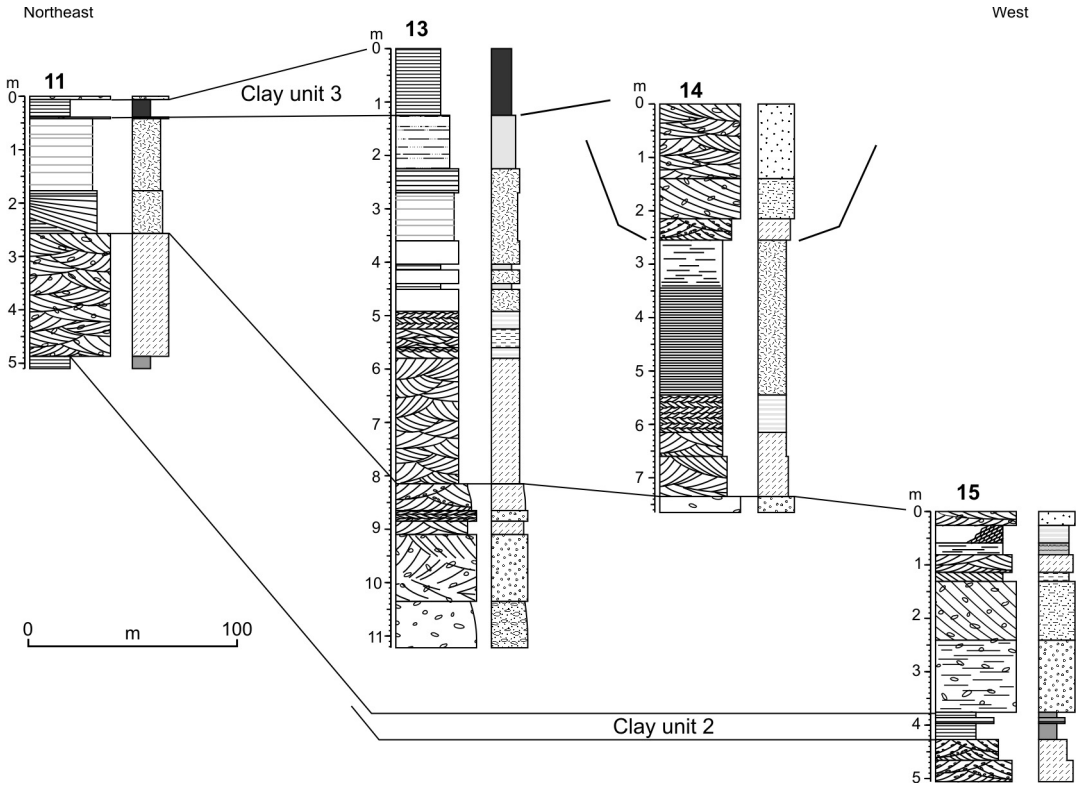


Fig. 7. Measured sections from the central and western part of the West Indian Road pit. Locations in Fig. 2. Legend as in Fig. 6.



zontally laminated sand beds (**Sh**) and then into thin ripple cross-laminated sand (**Sr**).

Within the lower part of Sand & Gravel Unit 2 (Fig. 6), several metre-scale fining-upward successions are developed with gravel facies (**Gm**, **Gms**, or **Gp**) at the base, passing up into **Sp** or **St**. In the upper part of the unit, the most common succession is **Gm** → **Sh.** Paleocurrents in the Sand & Gravel units, determined principally from facies **Gt** and **St**, are unimodal to the east-southeast (Fig. 11).

Groups of beds can be correlated over distances of hundreds of metres by their relationship to the Clay units (Figs. 3, 7), but single beds can only rarely be traced laterally for distances of more than 10–20 m. Prominent channels were not recognised; visible erosional surfaces at the bases of beds have relief of only 1 m although lateral correlation between measured sections shows variation in thickness of groups of beds of several metres (Fig. 7).

Field observations of clay units

Clay Unit 3 is typically 0.5 m thick. It is pink, appears structureless, and continuous throughout the pit (except where removed by Quaternary erosion). Clay Unit 2 is pale to medium grey, with the uppermost 0.1–0.3 m being pink with purplish mottling. In places, apparently bioturbated silt laminae are present. The unit shows sand injection structures consisting of dykes, 10–50 mm wide, that cut locally fractured or brecciated clay (Fig. 5). These structures are widespread, outcropping at both ends of the pit. The base of the clay bed has rounded clay load casts within the underlying sand.

Clay Unit 1 is principally a dark grey clay, locally with lignite and charcoal. In places, the clays show red, purple, or green mottling. Some clays have planar silt laminae. Where thickest in the southwest of the pit, clays are interbedded with thin beds of sand and of granule gravel and beds of muddy diamict 0.5–3 m thick (Fig. 4). The diamict includes subangular pebbles of vein quartz and decimetre-size folded and faulted clasts of clay.

Grain-size distribution

Grain-size distributions of both sand and gravel (Fig. 12) are moderate to well sorted, generally with both a coarse and a fine tail. Following Kuhnle (1992) and Sengupta et al. (1998), these distributions result from three main transport processes. The main log-normal population that shows a similar slope for all fine-grained sandy facies and facies **Gp**, but with a different modal size, probably moved in saltation and was deposited during flow rate diminution. A fine tail of similar slope is present in every facies and is interpreted as trapped suspended sediment. Most sediments also show a coarser log-normal population (or coarse tail), probably resulting from true bedload transport.

Detrital petrology

Pebbles were visually separated into about 20 lithologic types (Fig. 13). Most pebbles are quartz-rich lithologies, either vein quartz, quartz arenite, or subarkose. Pebbles are subrounded to well rounded, with low to moderate sphericity. The quartz arenite and subarkose pebbles contain detrital resistant heavy minerals, including zircon and tourmaline. In addition, however, there are deeply weathered "exotic" pebbles, including numerous mafic igneous rocks, originally gabbro or diorite. Some pebbles consist of hornblende largely altered

Fig. 8. Photograph and cross section of anticline in Clay Unit 2 and Sand & Gravel Unit 2, with a faulted eastern limb (detail shown in Fig. 10). Unconformity I truncates faulted sand and was itself tilted before being cut by Unconformity II. Gravel and sand above both unconformities are also part of Sand & Gravel Unit 2 (detailed log in Fig. 6).

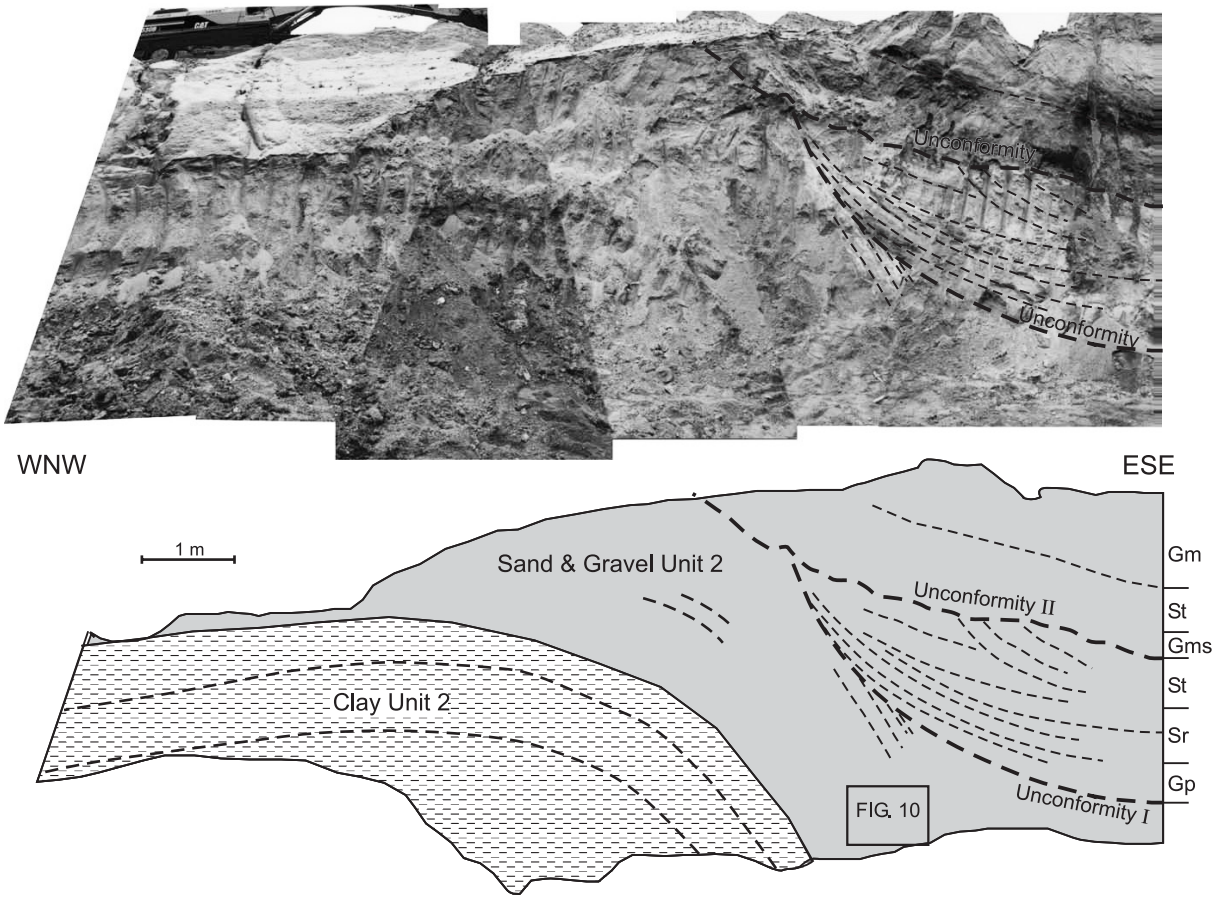
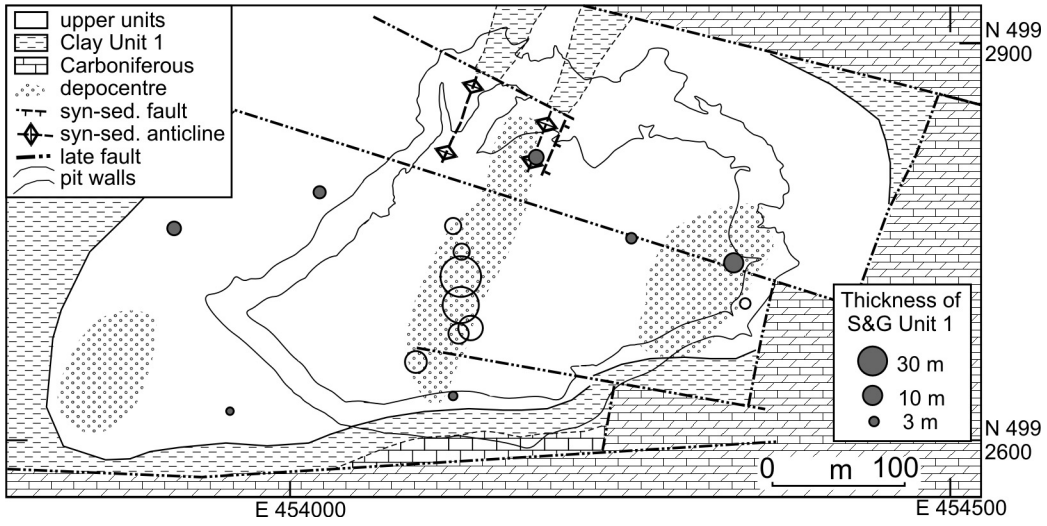


Fig. 9. Generalized geology of the West Indian Road pit, showing syn-sedimentary (syn-sed.) faults and depocentres where Clay Unit 1 and (or) Sand & Gravel Unit 1 are unusually thick. For fuller explanation of recognition of depocentres, see text. Also shows boreholes that give a stratigraphic thickness for Sand & Gravel (S&G) Unit 1; open symbols indicate minimum value.



to actinolite, plagioclase, ilmenite, and K-feldspar; others consist principally of epidote, chlorite, and feldspar. Other exotic pebbles include pink granite and both porphyritic and recrystallized rhyolite. Pebbles also include clasts of pebbly sandstone with a cement of opaque iron oxide (probably ilmenite) and fractured vein quartz with ilmenite filling the fractures. No systematic differences in pebble petrology could be detected between Sand & Gravel units 1 and 2. No pebbles

Fig. 10. Detail of highly faulted, steeply dipping sands in Sand & Gravel Unit 2, which are unconformably overlain by undeformed gravel shown in Fig. 8. f, small, subhorizontal fault.

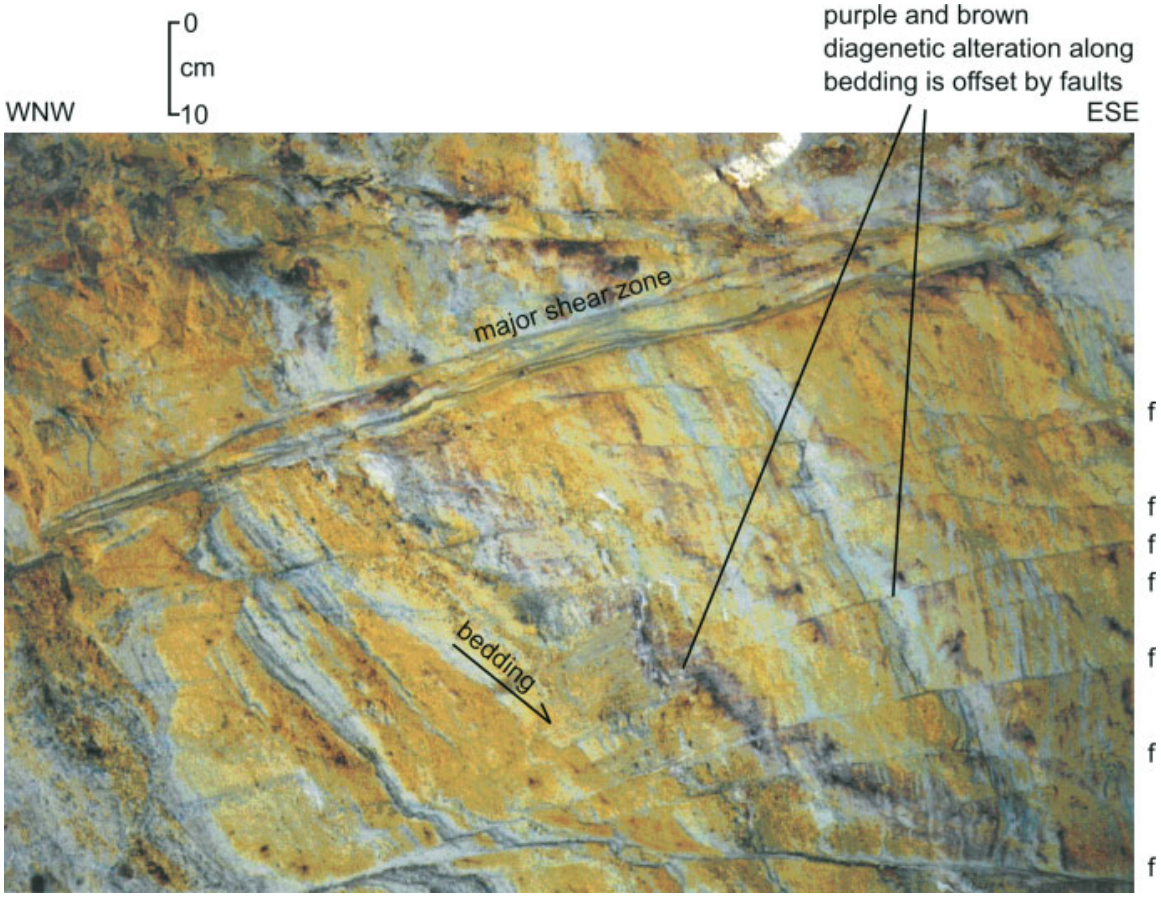


Table 1. Lithofacies present in the West Indian Road pit (after Miall 1978).

Facies code	Description
Gms	Massive graded gravel
Gm	Massive to horizontally bedded gravel
Gt	Trough cross-bedded gravel
Gp	Planar cross-bedded gravel
St	Trough cross-bedded sand
Sp	Planar cross-bedded sand
Sr	Ripple cross-laminated sand
Sh	Horizontally laminated sand
Se	Crudely cross-bedded sand, erosional base
Ss	Massive sand with broad shallow scours
Fm	Massive mud

of the distinctive Meguma Group metasediments have been found.

In Clay Unit 1, the pebbles consist only of vein quartz and quartz arenites resembling Horton Group sandstones. These clays contain predominant reworked Carboniferous palynomorphs (R. Fensome, personal communication, 2002).

Sand grains are predominantly of subangular quartz, with a few percent of mica and traces of heavy minerals. Heavy minerals have been analysed from Sand & Gravel Unit 2, where they are concentrated as lags along foresets in cross-stratified sands. The dominant heavy minerals are ilmenite and its alteration products (cf. Pe-Piper et al. 2005*d*), rutile, zircon, and tourmaline, with lesser staurolite, andalusite, monazite, and cassiterite. This assemblage is similar to that found in nearby boreholes at Shubenacadie and in the Elmsvale basin (Fig. 1B) (Pe-Piper et al. 2004, 2005*a*).

Single-crystal $^{40}Ar/^{39}Ar$ age determinations have been made on detrital muscovite from three samples in the West Indian Road pit (Fig. 14). The ages are a little older than the muscovite ages for the South Mountain batholith determined by Carruzzo (2003), but the mean of 374 Ma is within the range of precise U–Pb ages for the batholith and its satellite plutons, as summarized by Kontak et al. (2004).

Discussion

The sedimentary environment

The sand–gravel facies are characteristic of deposition in coarse-grained bedload rivers (e.g., as summarized by Collinson 1996; Lunt et al. 2004). In Sand & Gravel Unit 2 in the northeast part of the pit, there is a repetitive sequence of erosion surfaces overlain by gravel facies (**Gm**, **Gt**, **Gms**) that pass up into cross-bedded sands (**Sp** or **St**). Two of the erosion surfaces correspond to the local unconformities in Fig. 8. Individual facies can be interpreted, but lateral relationships are rarely seen. Facies **Gm** and **Gms** probably developed in longitudinal bars under high flood conditions,

Fig. 11. Paleocurrents from the West Indian Road pit determined from trough cross-bedding (black) and planar cross-bedding (grey) principally from Sand & Gravel Unit 2.

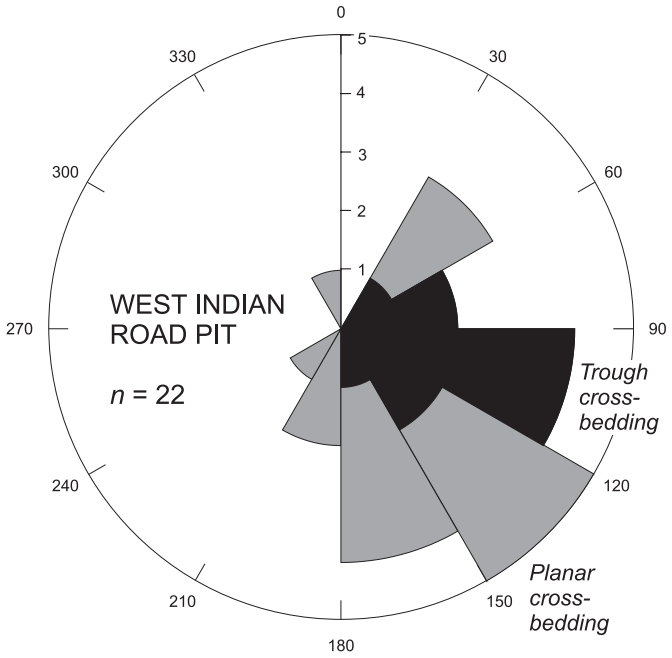
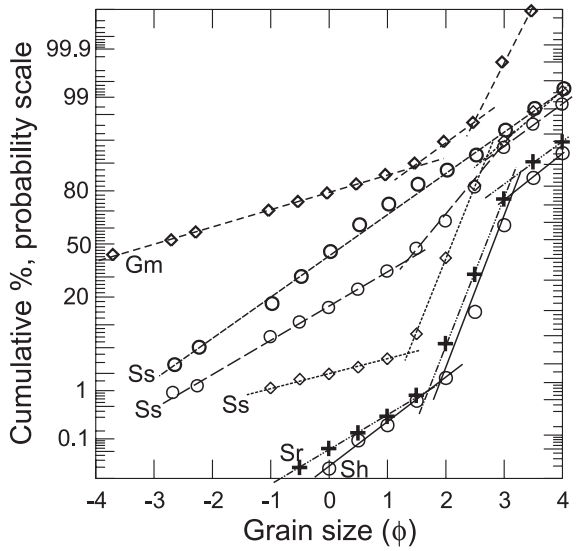


Fig. 12. Representative grain-size analyses from the West Indian Road pit plotted on a probability scale. Grain size determined by sieving. Facies codes refer to Table 1.



with erosive bases and pebble lags representing channel erosion, whereas planar cross-bedded facies **Gp** and **Sp** are developed at bar margins (e.g., Miall 1977). Trough cross-bedded sands (**St**), in places, are seen to occupy metre-deep channels (e.g., Fig. 8). Rippled sands (**Sr**), interpreted as deposited during low-water stages (Smith 1971), may overlie any of the other facies. In the upper part of Sand & Gravel Unit 2, the lithofacies are principally massive gravel (**Gm**) overlain by horizontally bedded or trough cross-bedded sands (**Ss**, **Sh, St)** (sections 1–4, Fig. 6), with a 2.5 m deep inferred channel in section 14 (Fig. 7) of trough cross-bedded fine

Fig. 13. Example of detrital petrology of gravel fraction from one sample from Sand & Gravel Unit 2, West Indian Road pit.

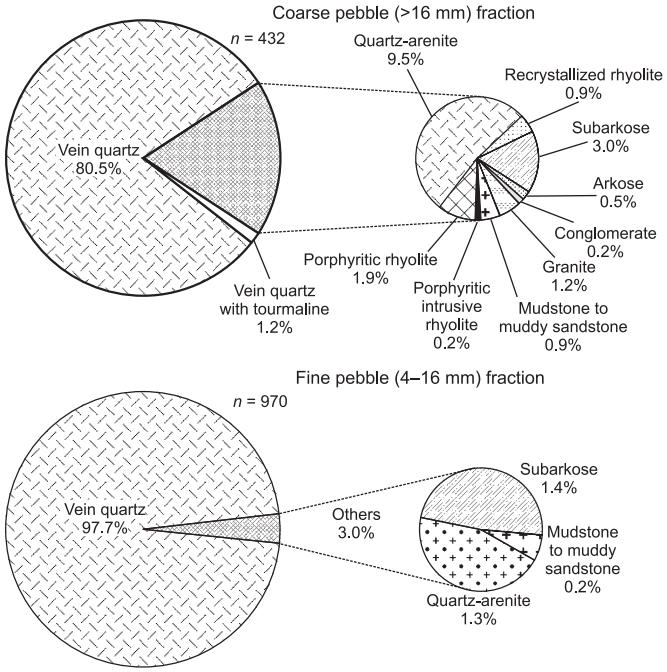
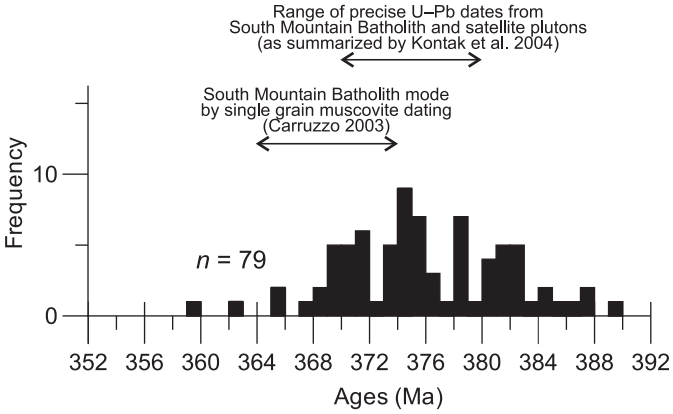


Fig. 14. Composite of single-grain muscovite dating from three samples from Sand & Gravel Unit 2. Also shows comparison with single-grain muscovite data from the South Mountain batholith (Carruzzo 2003) and U–Pb dating of the batholith (Kontak et al. 2004).



gravel (**Gt**). Thus deposition appears dominated by bars in the lower part of Sand & Gravel Unit 2 with a greater importance of channel deposition in the upper part of the unit. Paleocurrents in trough cross-bedded facies developed in channels are consistently to the east-southeast, with a much greater spread in planar cross-beds that typically develop at bar margins (Fig. 11). The width of individual channels is not well constrained, although observations near section 14 (Fig. 7) suggest a width of tens of metres, rather than metres or hundreds of metres, for the gravel fill at the top of Sand & Gravel Unit 2.

The clay facies are not well exposed in the pit and are better known in the Chaswood Formation from studies of boreholes (Stea and Pullan 2001; Pe-Piper et al. 2005*b*).

Boreholes show that Clay Unit 1 from the thicker development of the unit southwest from the pit (Fig. 4) includes muddy diamicts, sorted sands, and granule gravels, and predominantly dark clays with silt laminae. The latter lithology predominates in outcrops of the unit in the pit. The presence of pyrite nodules and preservation of lignite suggest water-logged gley soils and reducing conditions, as found elsewhere in the lower part of the Chaswood Formation (the "lignites" of Stea and Pullan 2001). Mottled clays are similar to paleosols (predominantly oxisols), known elsewhere from boreholes in the Chaswood Formation (Pe-Piper et al. 2005*b*). The thin sand and granule gravel beds (<0.65 m) suggest that fluvial channels were small. Mottled clays co-occur in the borehole sections with sand and gravel beds, but both are absent in the pit outcrops; this may indicate that mottled clays are a better drained levee facies associated with small fluvial channels. Pebbles in the diamict are of subangular vein quartz and show a wider range of grain size than the granule gravels, suggesting that the diamicts are more likely to be alluvial-fan debris flows than river bank collapses. The facies change to overlying Sand & Gravel Unit 1 is abrupt, with coarser grained gravels, thicker gravel and sand beds, the presence of exotic pebbles, and the absence of muds in Sand & Gravel Unit 1. This change suggests the arrival of larger river system in the area.

Clay Unit 2 reaches thicknesses of 3.6 m (Fig. 8) and consists of grey clay with silt laminae. It thus resembles medium grey clays known from boreholes elsewhere in the Chaswood Formation, for example from 148–156 m in borehole RR-97-23 in the Elmsvale Basin (Pe-Piper et al. 2005*b*). Similar beds at Shubenacadie have been interpreted as fluvial swamp deposits on the basis of biota (Eisnor 2002). The mottled pink-purple colour of the top 0.1–0.3 m is interpreted as a paleosol, by analogy with better developed paleosols in boreholes elsewhere in the Chaswood Formation (Stea and Pullan 2001; Pe-Piper et al. 2005*b*). The widespread sand injection in Clay Unit 2 (Fig. 5) is interpreted as resulting from liquefaction and deformation triggered by seismic shaking. The possibility that it represents erosional bank collapse was considered but rejected because of the lack of evidence for intermixed channel facies and the presence of foundered clay blocks.

Clay Unit 3 is much thinner than Clay Unit 2, typically 0.5 m, and although widespread may be absent over some bars (section 2, Fig. 6). Similar pink clay units are known from boreholes, with the pink colour interpreted as resulting from a paleosol (Stea and Pullan 2001; Pe-Piper et al. 2005*b*). The thickness and extent of the upper two Clay units suggest a total cessation of channelized river flow in the area of the present West Indian Road pit at those times.

Grain-size distribution is of limited value in environmental analysis and interpretation of transport processes (Miall 1996, pp. 18–19) and was carried out in this study principally to document sediment type. Compared with data from boreholes elsewhere in the lower part of the Chaswood Formation (Pe-Piper et al. 2005*c*), there is a lack of a diagenetic clay matrix within the West Indian Road pit gravels. In this regard, Sand & Gravel units 1 and 2 resemble sediments of the upper member of the Chaswood Formation defined by Stea and Pullan (2001).

Sediment provenance

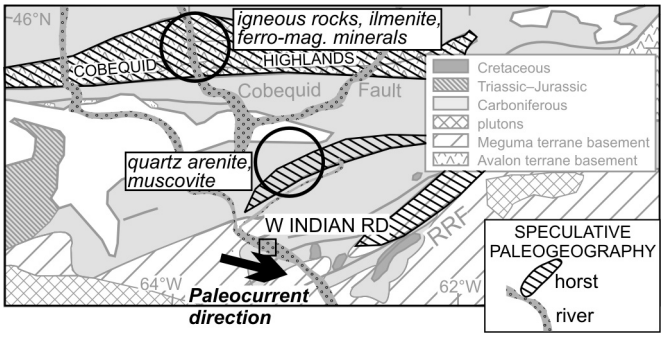
Regionally, deltaic and marine sediments correlative with the Chaswood Formation lie to the south and east of the West Indian Road pit (Fig. 1A) and the coarsest gravels (?most proximal facies) in the Chaswood Formation are found at the Vinegar Hill pit to the northwest. These paleoenvironmental observations suggest a regional paleogeographic gradient to the southeast, consistent with the local paleoflow direction to the east-southeast at the West Indian Road pit. While this does not preclude sources via tributary rivers from any direction, it suggests that the predominant source lay to the northwest.

The study of pebble and heavy mineral petrology confirms this interpretation because of the lack of any evidence for a direct source of sediment from the Meguma Group. Stea and Pullan (2001) noted that the magnetic susceptibility of the Chaswood Formation was inconsistent with a source from the local metasediments of the Meguma Group. No pebbles of Meguma Group or South Mountain batholith lithologies were found in the thousands of pebbles identified from the West Indian Road pit. This interpretation is supported by borehole studies at Shubenacadie that show that coarse lithic sand grains do not include Meguma Group lithologies (Pe-Piper et al. 2004).

Quartz arenite and subarkose pebbles petrographically resemble sandstones of the local Early Carboniferous Horton Group. Lower Paleozoic and Neoproterozoic (meta)sandstones in potential source areas to the northeast are more indurated, and younger Carboniferous sandstones are generally more friable, although they cannot be excluded as a source of pebbles. The radiometric dating of mica also suggests an important source from the Horton Group, which contains abundant micaceous sandstone. The Horton Group was deposited from the earliest unroofing detritus of the South Mountain batholith and its metamorphic aureole, and thus contains early cooled muscovite of similar age to the U–Pb ages for the plutons. In contrast, the present day exposed level of the South Mountain batholith would have cooled through the muscovite blocking temperature a little later, thus accounting for the younger mica ages found by Carruzzo (2003) from the batholith. Most younger Carboniferous sandstones have a more distant provenance, either from Namurian uplift of horsts in the Maritimes (Ryan et al. 1987) or from the Alleghenian orogen (Gibling et al. 1992), and reworking of large amounts of these sandstones should have yielded a much wider range of ages for detrital muscovite.

Exotic pebbles can be correlated with Avalonian late Precambrian plutonic and metamorphic rocks and Carboniferous plutons and volcanic rocks of the Cobequid Highlands to the north (Fig. 15). The only sizeable local source of the hornblende gabbro–diorite clasts is from the earliest Carboniferous Wentworth Pluton of the Cobequid Highlands (Koukouvelas et al. 2002), 40 km to the north. Exotic clasts of pink granite and both porphyritic and recrystallized rhyolite could also be derived from the central part of the Cobequid Highlands (Pe-Piper and Piper 2003). Pebbles of quartz-rich lithologies with ilmenite veins can be matched to similar ilmenite veins in deformed Devonian–Carboniferous granites north of the Cobequid fault zone, for example, as illustrated by Pe-Piper et al. (1991, their fig. 3). Widespread

Fig. 15. Geological map of northern Nova Scotia showing potential sources for the sediments at the West Indian Road pit and a speculative distribution of horsts and main rivers.



iron mineralization is associated with the Wentworth Pluton, creating the important Londonderry siderite–hematite ore deposits (Fig. 1B). Ilmenite, which is the dominant heavy mineral at the West Indian Road pit, is a common accessory mineral throughout the Wentworth Pluton (Koukouvelas et al. 2002).

The study of heavy minerals at the West Indian Pit alone does not allow discrimination of sources. For example, staurolite might be derived directly from Meguma or Gander terrane metasediments or as a second cycle mineral from Carboniferous or even Triassic sandstones. The subangular character of many of the quartz grains suggests relatively short transport distances. The lack of feldspars in the sands suggests deep chemical weathering in the source areas (Stea et al. 1996), with the rare unstable clasts probably shed off active fault scarps, as discussed later in the text.

Structural evolution

The structural style of the syn-sedimentary faulting in the Chaswood Formation is typical of strike-slip faulting, with abrupt local rotation of beds and sediment thickness changes (e.g., Nilsen and Sylvester 1995). The principal faults are inferred to trend north-northeast, parallel to the anticlines (Fig. 9) and many secondary faults (Fig. 10).

Syn-sedimentary faulting within the Chaswood Formation can be related to secondary shear zones produced by the master Cobequid–Chedabucto fault. Pe-Piper and Piper (2004) argued that there was Early Cretaceous dextral slip on the Cobequid–Chedabucto–southwest Grand Banks fault that resulted in secondary reverse faulting on northeast-trending faults, such as imaged by seismic profiles along the Rutherford Road fault zone (Fig. 1B) (Stea and Pullan 2001; Piper et al. 2005). The initiation of Chaswood Formation deposition in the Cretaceous implies extensional basin formation. Under conditions of dextral slip on the Cobequid–Chedabucto fault, such basins would trend southeast (Fig. 1C), subparallel to the observed east-southeast paleocurrents in the West Indian Road pit (Fig. 11). Original basin margins have been obscured by younger faulting and erosion.

The younger deformation that created the east–west syncline and WNW–ESE-trending faults at the West Indian Road pit does not appear to be a continuation of the syn-sedimentary folding and faulting. The orientation of structures is quite different. Deformation on syn-sedimentary faults ended prior to latest Chaswood Formation deposition at the West Indian Road pit, as shown by the lack of deformation above unconformity II (Fig. 8) and the apparent lack of significant growth faulting from sediment thickness variations above Clay Unit 2 (Fig. 3). The termination of syn-depositional deformation prior to latest Chaswood Formation deformation has also been interpreted from seismic-reflection profiles in the Elmsvale basin (Piper et al. 2005). Neither in the Elmsvale basin nor at the West Indian Road pit is there any control on the age of the younger deformation. Pe-Piper and Piper (2004) argued that such deformation of the Chaswood Formation might correlate with Oligocene uplift on the eastern Scotian Shelf.

Paleogeographic evolution

Most of the Chaswood Formation is of similar lithologic character throughout the southern Maritime Provinces, comprising well sorted fluvial sand(stone) (locally gravelly) and overbank mudstones with paleosols and some lignite beds (Dickie 1986). The coarsest grained sediment are found at the Vinegar Hill pit in southern New Brunswick (Falcon-Lang et al. 2004), suggesting a northerly provenance. Early Cretaceous biostratigraphic ages were determined for the base of the Diogenes Brook deposit in Cape Breton Island (Davies 1983) and some isolated deposits in sinkholes in central Nova Scotia (R. Fensome, personal communication, 2004). Outliers of Middle and Upper Jurassic strata are not known in the Maritime Provinces, suggesting that the local or regional basin formation that allowed deposition to take place was tectonically initiated in the Early Cretaceous. In the offshore, mid to Late Jurassic shelf carbonate deposits of the Abenaki Formation pass landward and eastward into siliciclastic facies of the MicMac Formation. At the beginning of the Cretaceous, the predominantly siliciclastic sediments of the Missisauga Formation deltas spread over all but the westernmost Scotian Shelf and prograded seaward (Wade and MacLean 1990), indicating substantially increased supply of terrigenous sediment.

The earliest Chaswood Formation deposits at West Indian Road pit, Clay Unit 1, include small fluvial channel deposits and locally derived debris-flow deposits, suggesting deposition in a steep-sided local basin. Analogous local sediment supply to a confined basin is inferred for the oldest Chaswood Formation at Brierly Brook (Pe-Piper et al. 2005*c*). Overlying Sand & Gravel Unit 1 and younger strata contain clasts with a more distant provenance and are the deposits of a coarse bedload river system that deposited more widely over Nova Scotia than is represented by the present erosional remnants in outliers.

During deposition, there was ongoing tectonic deformation, resulting in the folding, faulting and local unconformities at the West Indian Road pit. Sedimentation kept pace with the creation of accommodation, so that local unconformities were overlain by further sand and gravel deposits, and the mean paleocurrent direction to the east-southeast was almost orthogonal to the most active syn-sedimentary faults. Similar patterns are seen in many modern actively deforming basins (e.g., Leeder and Jackson 1993). Syn-sedimentary deformation of Clay Unit 2 (Fig. 5) is interpreted as due to seismically induced liquefaction. The deformation of unconformities (Fig. 8) suggests that sediment accumulation may have taken place over a long period of time in the Early Cretaceous,

with most fluvial sediment bypassing and accumulation taking place only as accommodation was created. Cessation of coarse sediment supply during deposition of Clay Units 2 and 3 could have been the result of tectonic deformation temporarily diverting the river to a new course.

Horsts within the Maritime Provinces shed coarse-grained detritus, including quartz arenites from the Horton Group of central Nova Scotia and igneous rocks from the Cobequid Highlands. Regionally, detrital monazite from boreholes yield predominantly Ordovician ages, suggesting important sediment supply from rocks deformed in the Taconic orogeny in northern New Brunswick (Pe-Piper and MacKay 2005).

The West Indian Road pit has a higher proportion of sand and gravel facies (>90%) compared with other parts of the Chaswood Formation. Only the Vinegar Hill pit (Falcon-Lang et al. 2004) has a similarly high proportion of coarse-grained sediment. Diogenes Brook (Dickie 1986) and Belmont (Pe-Piper et al. 2005*c*) have about 70% sand; the eastern Elmsvale basin (Stea and Pullan 2001; Pe-Piper et al. 2005*b*) has as little as 10% sand. Grain-size analysis shows that gravel units at the West Indian Road pit are coarser grained than sand and gravel in the Chaswood type section (Stea and Pullan 2001) and the Shubenacadie outlier (Stea et al. 1996), suggesting that the West Indian Road pit lay on the principal drainage route from the northwest.

Conclusions

The importance of the West Indian Road pit lies in the information that it provides about sedimentology of the sand and gravel units, detrital petrology of pebbles, and syn-sedimentary structural deformation, none of which can be convincingly interpreted from boreholes. Sedimentology indicates deposition from a coarse bedload river that flowed to the east-southeast and cut only shallow channels but deposited sediment over a zone broader than the preserved 0.5 km wide deposit. The syn-sedimentary deformation in the pit provides outcrop evidence that the Chaswood Formation accumulated during progressive tectonic deformation along NNE-trending strike-slip faults in basement rocks, in contrast to previous interpretation of seismic-reflection profiles in the Elmsvale basin that deformation post-dated the Chaswood Formation (Stea and Pullan 2001). Sedimentation was limited by the creation of accommodation. Interpretations of provenance of the Chaswood Formation elsewhere, based only on heavy minerals from boreholes, are difficult because the minerals are diagnostic of multiple sources (Pe-Piper et al. 2005*a*). The petrology of rare exotic pebbles in the West Indian Pit demonstrates that there is no significant source from the Meguma terrane and that pebbles were derived from local sources in the Carboniferous of central Nova Scotia and in the Cobequid Highlands. The Early Cretaceous paleogeography of the Maritime Provinces consisted of fault-bound horsts shedding coarse detritus surrounded by an interconnected series of basins that accumulated fluvial sands and gravels and overbank muds with well-developed paleosols.

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