The La Coulée Formation, a new post-Acadian continental clastic unit bearing groundwater calcretes, Gaspé Peninsula, Québec

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A 1 km^2 erosional remnant of the La Coulée Formation, a previously unrecognized stratigraphic unit, has been studied in the Percé area of the Gaspé Peninsula. It unconformably overlies folded Cambrian to Devonian rocks and is unconformably overlain by the mid-Carboniferous Bonaventure Formation. The erosional remnant includes the lowest 60 m of this newly identified formation of unknown thickness. Original sedimentary facies are limited to 50 m of breccia debris flows passing stratigraphically upward into 10 m of conglomeratic debris flows. Groundwater calcrete formation has partially or completely transformed the lowest 30 m of the sequence. The depositional environment is interpreted as being related to a proximal continental alluvial fan. The nearby presence of a saline body of water is inferred to account for thick and massive groundwater calcrete formation and water-saturated debris flows in a relatively arid climatic context. Most of the formation was eroded prior to deposition of the Bonaventure Formation. However, the basal groundwater calcretes were more widely preserved. They underlie the Bonaventure Formation in most of the Percé area and in the Saint-Elzéar area, close to a hundred kilometres to the southwest. Post-sedimentary faulting has affected both the La Coulée and Bonaventure formations.

La Formation de La Coulée, une unité stratigraphique nouvellement répertoriée, a été étudiée à l'intérieur d'une masse résiduelle de 1 km^2 dans la région de Percé en Gaspésie. La séquence recouvre en discordance des roches plissées du Dévonien Inférieur et elle est recouverte en discordance par la Formation de Bonaventure qui est attribuée au Carbonifère moyen. La masse résiduelle inclue les 60 premiers mètres de cette formation nouvellement identifiée et d'une épaisseur inconnue. Les faciès sédimentaires originels sont limités à cinquante mètres de coulées de débris bréchiques, passant à une dizaine de mètres de coulées de débris conglomératiques. La formation d'une calcrete phréatique affecte les premiers 30 mètres de la séquence, lesquels sont en partie ou complètement transformés. L'environnement sédimentaire est interprété comme étant lié à un cône de déjection continental dans sa partie proximale, mais la présence non-lointaine d'un plan d'eau salée est suggérée pour expliquer la formation de calcretes phréatiques épaisses et massives, ainsi que la saturation en eau des coulées de débris dans un contexte climatique relativement aride. La formation a presqu'entièrement été érodée avant que ne survienne la sédimentation de la Formation de Bonaventure. Toutefois, la base de calcrete a été plus largement préservée, ce qui fait qu'on la retrouve sous la Formation de Bonaventure presque partout dans la région de Percé ainsi que dans la région de Saint-Elzéar, à presqu'une centaine de kilomètres au sud-ouest. Des failles post-sédimentaires ont affecté à la fois la Formation de La Coulée et la Formation de Bonaventure.

INTRODUCTION

The Gaspé Peninsula of eastern Québec is located at the northwestern periphery of the Late Palaeozoic Maritimes Basin and its subbasins (Fig. 1a). Prior to this study, the record of post-Acadian (post-Middle Devonian) rocks in the Gaspé Peninsula included only two formations, namely the Bonaventure and Cannes-de-Roches formations (Fig. 1b). The post-Acadian stratigraphy of the Gaspé Peninsula, in which major hiatuses are recorded, has received much less attention than that of the Maritime Provinces over the last century (Table 1).

A 1 km^2 erosional remnant of a new stratigraphic unit has been identified in the Percé area. Resting unconformably on folded Cambrian to Devonian rocks, it is related to a post-Acadian sedimentation event. The lowermost section of this unit is occupied by a calcrete several metres in thickness. Two similar calcretes, underlying the Bonaventure Formation at other localities, were also identified. This paper provides a sedimentological and tectonostratigraphic analysis of the newly recognized unit, which we herein formally name the La Coulée Formation (Appendix 1).

GEOLOGICAL SETTING

The oldest rocks in the Percé area are the Murphy Creek and Corner-of-the-Beach formations, both of Cambrian age (Kindle 1942). They form a small inlier unconformably overlain by a sequence of Siluro-Devonian rocks that occupies most of the southern half of the Gaspé Peninsula. Both sets of rocks were involved in the mid-Devonian Acadian orogeny, which is related to the final closure of the Iapetus Ocean (Kent and Opdyke 1985; Briden *et al.* 1988; Kent and Keppie 1988).

The stratigraphic record of the Gaspé Peninsula (Table 1) currently does not account for the Late Devonian through early Visean extensional tectonics and thick clastic sedimentation, which occurred intermittently in the rest of southeastern Canada,

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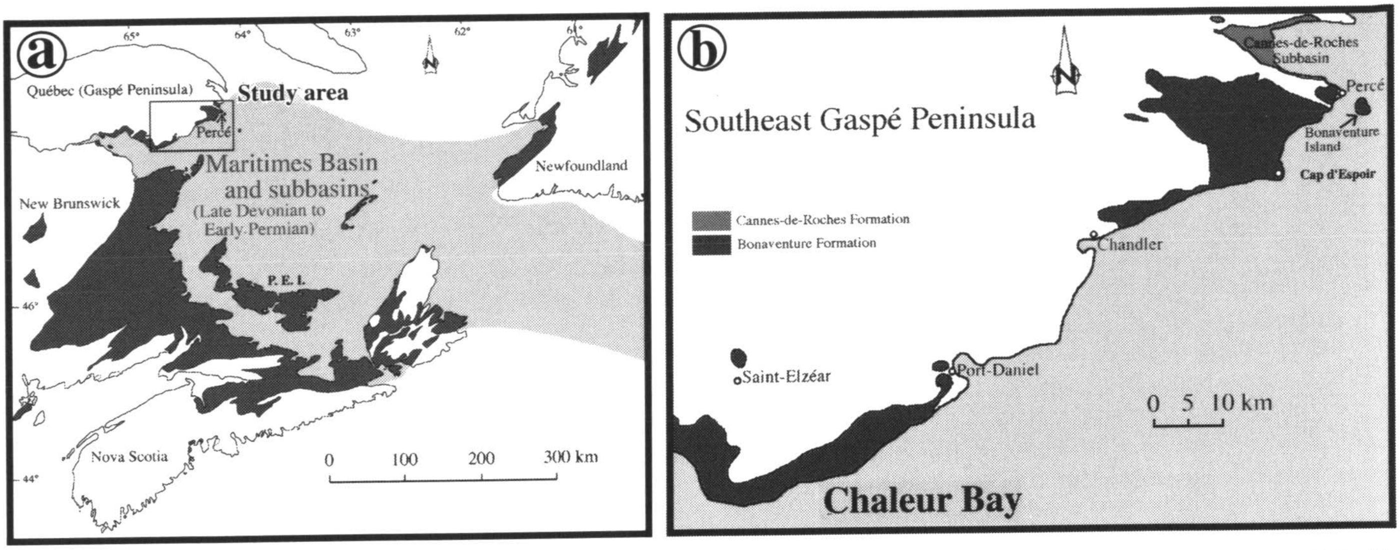

Fig. 1. The study area.(a) Position within the Late Palaeozoic Maritimes Basin of southeastern Canada (modified from Gibling *et al.* 1992). (b) Carboniferous formations of southeast Gaspé Peninsula (modified from Brisebois *et al.* 1992).

Table 1. Comparative post-Acadian stratigraphy of the Maritime provinces and the Gaspé Peninsula. The generalized environment (from several authors) is indicated for each group. Each major group has equivalent units (not shown) elsewhere within the Maritime provinces and in Newfoundland (time scale after Harland *et al.* 1990).

Period	sub-	Epoch	Stage	Ma	Maritime Provinces	Gaspé Peninsula
Carboniferous	Penn.	Westphalian	A		Riversdale, Cumberland and Morian groups (Passive alluvial plain sedimentation) ~~~~	? ? ? ?
Carboniferous	Mississippian	Namurian		323	Canso, Mabou and Hopewell groups (Strike-slip fault-related sedimentation)	Bonaventure and Cannes-de-Roches formations (Dip-slip (?) fault-related sedimentation) ?
Carboniferous	Mississippian	Visean		333	Windsor Group (Epicontinental marine sedimentation) **Windsorian Transgression** ~~~~	
Carboniferous	Mississippian	Tournaisian		350	Horton Group, upper sequences (Massive clastic sedimentation in extensional basins) ~~~~	? ? ? ?
Devonian		Late	Famennian	363		
Devonian		Late	Frasnian	367	Horton Group, lower sequences (Massive clastic sedimentation in extensional basins) ~~~~	Miguasha Group (Intermontane molasse and fossiliferous shales) ~~~~
Devonian		Middle	Givetian	377	Acadian orogeny	
Devonian		Middle	Eifelian	381		
				386		

~~~~ Compressive to transpressive deformation episode

and to which the Horton Group and equivalent units are related. There is also no record of the mid-Visean transgression that deposited the Windsor Group limestones and evaporites in New Brunswick, Nova Scotia and Québec (in the Magdalen Islands), and the Codroy Group limestones and evaporites in Newfoundland.

Prior to this study, the Bonaventure and Cannes-de-Roches formations (Fig. 1b and Table 1) were regarded as the first records of post-Acadian sedimentation after the synorogenic, Frasnian Miguasha Group (Brideaux and Radforth 1970). Although the stratigraphic relationship between the Bonaventure and Cannes-de-Roches formations is not clear, they are considered as probably synchronous (Rust 1981; Rust *et al.* 1989). Only the upper member of the Cannes-de-Roches Formation is unoxidized and has provided spores for dating. Hacquebard (1972) suggested an early Namurian age for the spores, whereas Barss (in Rust 1981) suggested a mid- to late Visean age. Both formations are interpreted as the product of fault-related continental clastic sedimentation in two distinct Carboniferous palaeovalleys (Rust 1981; Zaitlin and Rust 1983).

Few attempts have been made to correlate the post-Acadian sequences of eastern Québec with the well-established stratigraphy of the Maritime provinces. Howie and Barss (1975) considered the Miguasha Group to be a Horton Group
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equivalent. They correlated the Bonaventure and Cannes-de-Roches formations with the Canso-Riversdale groups based on their age (early Namurian, Hacquebard 1972) and their nonmarine nature. Van de Poll (1995) considered the Bonaventure as a Windsor-Canso groups equivalent, and the Cannes-de-Roches as a Canso-Riversdale groups equivalent.

SEDIMENTOLOGY OF THE LA COULÉE FORMATION IN THE MONT SAINTE-ANNE SEQUENCE

An ~60 m thick sequence has been observed at numerous outcrops on the northern side of Mont Sainte-Anne, which overlooks the village of Percé. The best outcrops are located in a deep gully occupied by a creek with waterfalls. The creek is unnamed but its main waterfall is named La Coulée. It is therefore referred to as the La Coulée Creek, and the newly identified formation over which it flows is referred to as the La Coulée Formation. This unit has been divided into three main facies (Fig. 2a), as defined below. The only exposure of the unconformable contact between the Mont Sainte-Anne sequence of the La Coulée Formation and the underlying basement is located at the 10 m-high La Coulée waterfall (Figs. 2b, 3), a vertical section located a few hundred metres west of Percé.

The basement consists of subvertical green mudstone (strike 275°, dip 80°) mapped as the Early Devonian Indian Point Formation by Kirkwood (1989). The overlying La Coulée Formation rests on this basement with a 60° angular unconformity. It is poorly stratified and the 'beds' dip gently towards the south-southwest (strike 295°, dip 20°).

Groundwater calcrete facies (0–11 metres)

The contact of the La Coulée Formation with the basement shows a sharp passage from brecciated green mudstone in the basement, with only minor calcite infiltrations (Fig. 3a), to mature calcrete with a few silicified, fossiliferous limestone clasts of ~1 cm maximum diameter (Fig. 3c). The lowermost 2 m of the section also include abundant intraclasts of calcrete (Fig. 3d).

Between 2.0 and 2.5 m, non-calcrete clasts are larger and more abundant but are still floating in a calcrete matrix. Sparse clasts of calcareous sandstone and calcareous mudstone of up to 10 cm maximum diameter are overlain by several large biocalcilutite blocks of up to 40 cm maximum diameter, all of the same lithology and parallel to bedding.

The 2.5 – 5 m interval is mainly occupied by brecciated calcrete, analogous to that of the 0 – 2 m interval (Fig. 3d), with only a few sparse clasts of sparsely fossiliferous microsparite.

The uppermost 1 m of the section is mainly pure calcrete, but two large tabular clasts of biosparudite (Fig. 3e) were observed, the largest being ~1 m in maximum diameter. They are dominated by bryozoans, brachiopods, crinoids, echinoderms and ostracodes. Correlation with regional basement rocks could not be determined but the conodont genus *Icriodus* (Fig. 3e) loosely constrains the age of the biosparudite between Late Silurian (Pridolian) and Late Devonian (Famennian) (Clark *et al.* 1981). Many discontinuous laminar structures and ooids are present in this upper part of the outcrop.

Numerous outcrops can be observed for 500 m upstream from the La Coulée waterfall. The slope of the creek bed is steeper than the dip of the La Coulée Formation for the first 250 m upstream and, thus, the outcrops represent progressively higher stratigraphic levels (Fig. 2b). The creek then becomes less steep and cuts back into lower stratigraphic levels. It is estimated that the base of the highest outcrop upstream represents approximately the same stratigraphic level as at the top of the waterfall, although the calcrete facies masks any original stratification and only allows imprecise correlation.

The lowest stratigraphic levels exposed upstream from the waterfall (6–11 m) are occupied by a stratiform calcrete where all features of the host sediment have been destroyed (Fig. 4a, b). The calcrete is mainly characterized by structureless microsparite; however, numerous ooids and discontinuous laminar structures can here again be observed.

According to Wright and Tucker (1991), the only calcretes known to exceed 3 metres in thickness are 'groundwater calcretes'. The calcrete developed in the La Coulée Formation is therefore regarded as the non-pedogenic product of groundwater circulation.

Local silicification is typical of groundwater calcretes (Arakel and McConchie 1982; Jacobson *et al.* 1988; Arakel *et al.* 1989; Wright and Tucker 1991) and is most probably responsible for the preservation of the limestone clasts. Figure 3e indicates how siliceous calcrete clasts observed throughout the calcrete are formed directly from the host sediment by mineral replacement. A siliceous coating formed *in situ* protects the clast from further mineral replacement.

Abundant intraclasts of calcrete are also typical of groundwater calcretes (Mann and Horwitz 1979; Arakel and McConchie 1982; Arakel *et al.* 1989; Wright and Tucker 1991), although brecciation also appears in pedogenic forms but is then usually root-induced (Wright and Tucker 1991).

The discontinuous laminar structures do not correspond to any of the three types of laminar calcretes defined by Wright *et al.* (1988), namely (1) the 'surficial laminar calcretes', formed at the bedrock-atmosphere interface, (2) the 'pedogenic laminar calcretes', usually formed over hardpans in soils, and (3) the 'capillary rise-zone laminar calcretes', forming a continuous horizon immediately over the water table. They correspond most closely to the 'ribbon-like geometries' described by Wright and Tucker (1991) for groundwater calcretes, which they interpret as the product of lateral shifts of groundwater flow in response to the profile becoming progressively plugged by cementation. Being associated with ooids, they were probably formed in the vadose zone. Peryt (1983) referred to such ooids as 'vadoids'.

Grey limestone breccia facies (11–50 m)

The 11 to 30 m stratigraphic levels are occupied by very poorly sorted grey limestone breccia with a calcretized matrix. It is only at about the 30 m stratigraphic level that the original sedimentary matrix is unaffected by calcrete replacement (Fig. 4c, d). This facies is rather uniform, with sporadic more conglomeratic intervals within the next 20 m, up to the 50 m stratigraphic level, based on outcrops along various roads across Mont Sainte-Anne.

Only limestone clasts were recognized. The finest fraction of the matrix contains sparse goethite and marcasite, which gives

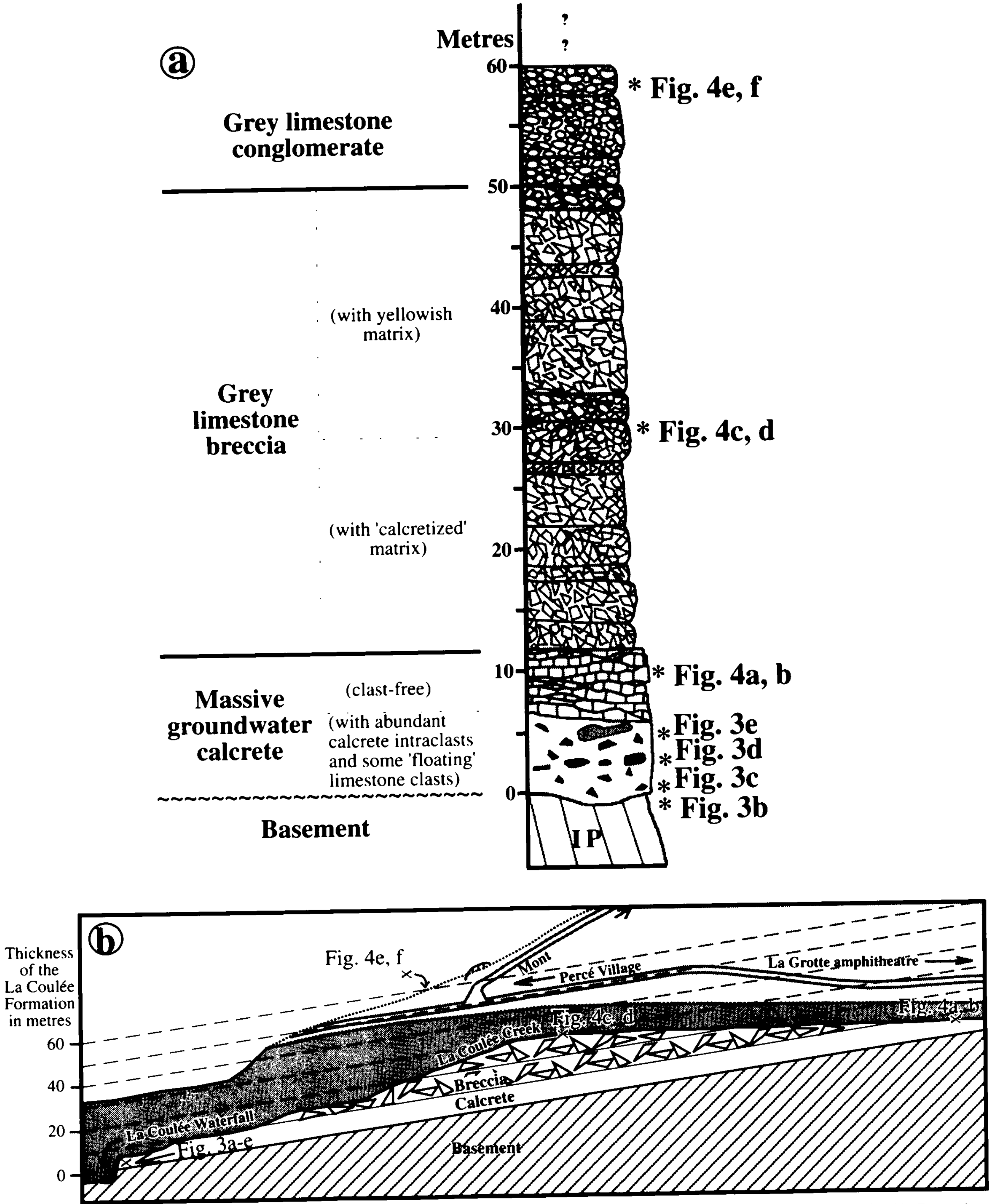

Fig. 2. 60 m remnant sequence of the La Coulée Formation at Mont Sainte-Anne. (a) Composite stratigraphic column of the La Coulée Formation in the Mont Sainte-Anne sequence showing the three main facies. The basement is the Indian Point Formation (IP) of Early Devonian age. The stratigraphic levels (asterisks) of Figures 3b-e and 4b-f are shown. (b) Schematic cross-section along La Coulée Creek (with locations of Figures 3a-e and 4a-f).

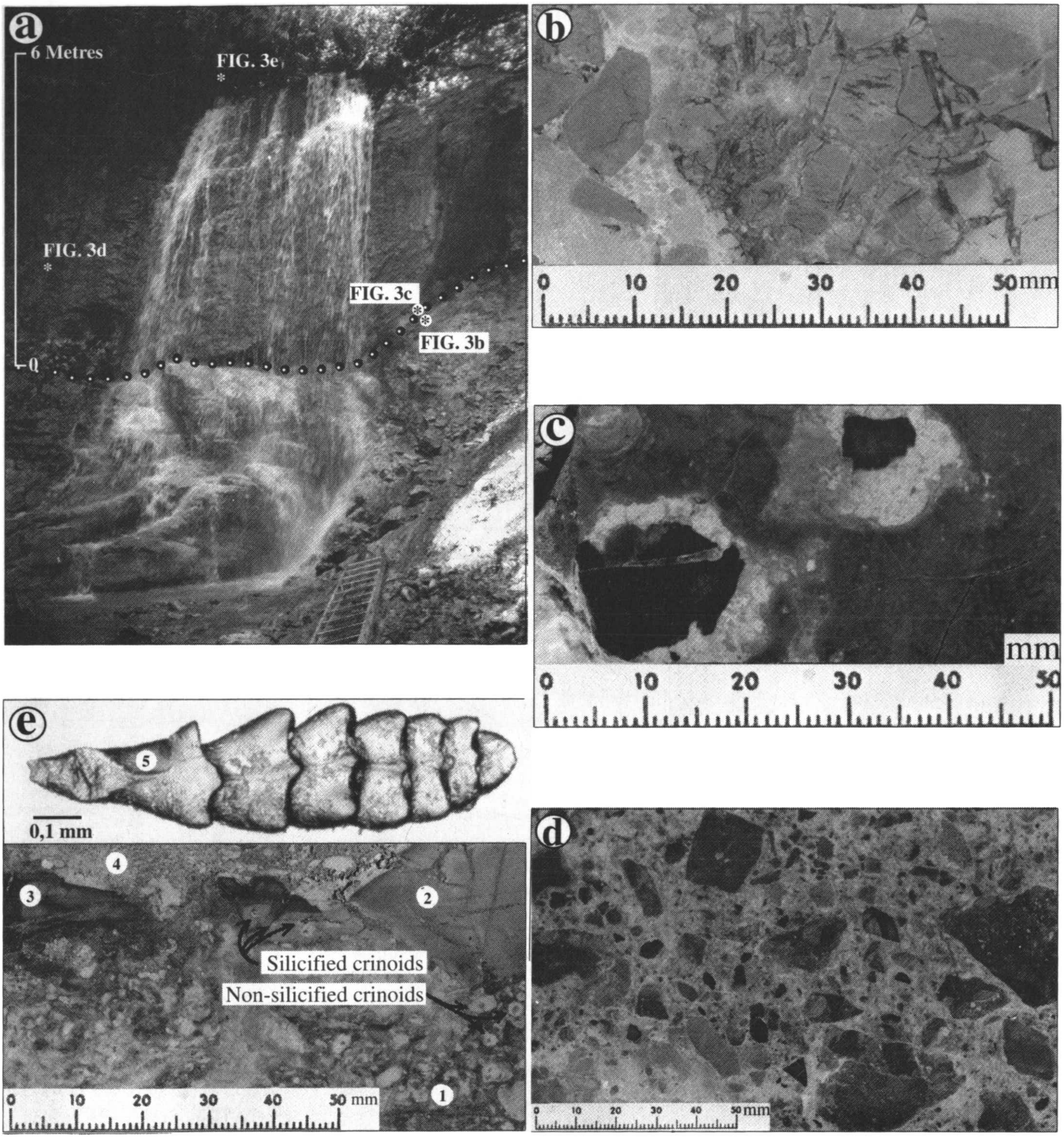

Fig. 3. The La Coulée waterfall section. (a) General view of the La Coulée waterfall. Dotted line indicates the irregular contact between the La Coulée Formation and the underlying basement. The locations of Figs. 3b-e are shown. (b) Basement green mudstone, brecciated at the contact with the La Coulée Formation. (c) Calcrete with silicified (dark) fossiliferous limestone clasts. (d) Brecciated calcrete, the most common facies throughout the 6 m-thick section. The smaller, darker clasts are silicified. (e) Biocalcirudite (1) with silicified zones (2) and (3) that seem to represent concentrations of silica-rich elements from (1). (4) is the surrounding calcrete matrix. (5) is conodont genus *Icriodus* (Royal Ontario Museum [Palaeobiology], #53514). Composition of: (1) 98% calcite, 1.45% silica, 0.13% K-feldspar; (2) 57.21% calcite, 36.57% silica, 6.22% K-feldspar; (3) 3.33% calcite, 75.45% silica, 10.61% K-feldspar; (4) 84.83% calcite, 13.34% silica, 1.83% K-feldspar.

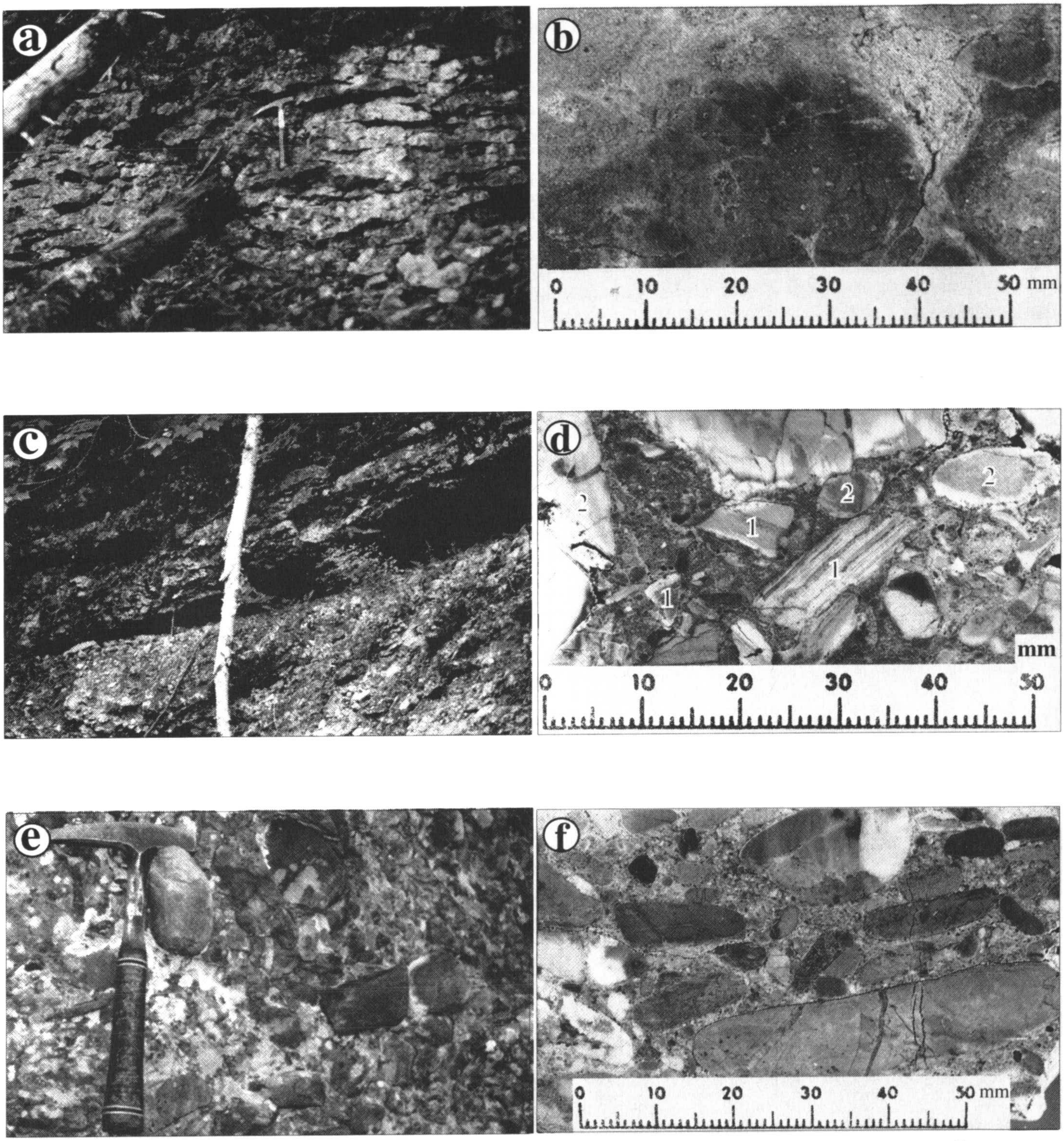

Fig. 4. Main facies of the La Coulée Formation from stratigraphic level 6 to 60 m. (a) Clast-free calcrete. It has a lenticular to stratiform structure but (b) has entirely been affected by mineral replacement. (c) Sheet-like beds of limestone breccia. (d) Examples of angular to very angular clasts (1) associated with sub-rounded clasts (2). The fine fraction of the matrix is mainly composed of kaolinite with small amounts of goethite, marcasite (which gives it a yellowish colour) and some titanium oxides. (e) Limestone conglomerate with an overall chaotic debris flow structure. The conglomerates are polymodal and matrix- to clast-supported. (f) The clasts have high roundness but low sphericity. As the photo illustrates, numerous clasts are aligned parallel-to-flow, revealing a certain degree of organization during emplacement.

the matrix a yellowish colour, but no hematite. Based on X-ray diffractometry, kaolinite forms 8–10% of the matrix, which suggests deep weathering under relatively warm and humid conditions.

For a given stratigraphic level, clasts become smaller south-southwest upstream along La Coulée Creek. Close to the waterfall, abundant clasts of more than 50 cm maximum diameter can be found, whereas 500 m upstream, they rarely exceed 10 cm. Clasts exceeding 5 cm diameter are usually sub-angular to sub-rounded while smaller clasts range from very angular to sub-rounded (Fig. 4d).

We interpret the grey to yellowish-grey breccia forming the 30–50 m stratigraphic levels as a succession of several mud-poor debris flows. The wide lateral extent of the beds, the lack of erosional bases and the tendency for large clasts to be flat-lying, all suggest laminar rather than turbulent ("floating plug") flow (Enos 1977). The lack of fine mud implies that water was abundant when the flows were initiated (Wells 1984; Nemec and Steel 1984).

Grey limestone conglomerate facies (50–60 m)

A 5 m thick by 10 m wide outcrop of massive grey to greenish-grey limestone conglomerate is exposed on the eastern flank of Mont Sainte-Anne (Fig. 4e, f) and represents the 55–60 m stratigraphic level of the La Coulée Formation. The unit therefore has a minimum thickness of approximately 60 m (see composite column, Fig. 2a); extrapolation of the extra 5 m of conglomerate underlying the uppermost 5 m thick section was made from small outcrops on the road that leads to the summit of Mont Sainte-Anne.

The conglomerate is neither well sorted nor well packed (matrix- to clast-supported) and is poorly imbricated. It ranges between the Gmg (matrix-supported gravel) and the Gci (clast-supported gravel) facies of Miall (1996). It does not show clear internal stratification (planar or cross-bedding) or interbeds of sandstone or gravely sandstone, which would reveal flow variations and vertical aggradation. The sandy to granular matrix lacks fine silt and clay. The clasts, mainly limestone with sporadic calcareous sandstone and calcareous mudstone, are sub-rounded but generally have low sphericity. They are mainly blade-shaped. Some of the larger casts are oriented vertically, although surrounded by smaller fractions (Fig. 4e). The above-mentioned traits pertain more to debris flow than to fluvial or sheet flood environments (Miall 1977, 1996; Wasson 1977; Ethridge and Wescott 1984; Harvey 1984; Kleinspehn *et al.* 1984; Nemec and Steel 1984).

The entire 5 m high section is massive. Two small lenses of laminated sandstone, at different levels, are the only indication that the section does not represent only one single depositional event. One of them has partially crumbled under the subsequent debris flow. We interpret these two lenses, which are 4 and 10 cm in maximum thickness, as surficial run-off subsequent to debris flows. A high frequency of debris flows would prevent sufficient consolidation between two events and explain the lack of demarcation between flows.

The overall structure of the conglomerate is chaotic but flat-lying clasts are locally abundant (Fig. 4f). A tendency for such 'parallel-to-flow' fabric is reported for many debris flows (Fischer 1971; Heward 1978; Lewis *et al.* 1980; Nemec and Steel 1984; Wells 1984) and is associated with laminar flows (Enos 1977). Flows of the La Coulée conglomerate were probably water-rich to compensate for the mud-poor matrix and to explain the fabric (Nemec and Steel 1984; Wells 1984).

PERCÉ-BEACH CALCRETE

The sea-cliff directly south of Percé, less than 2 km from the La Coulée waterfall, exposes the unconformable contact between the Carboniferous Bonaventure Formation and the underlying Matapedia Group limestone basement. A basal limestone unit up to 5 m thick, first reported by Kirkwood (1989), separates the red clastics of the Bonaventure Formation from the basement (Fig. 5a–c). This limestone unit has been interpreted as a massive pedogenic calcrete (P.A. Bourque, personal communication, 1998). However, based on its thickness, abundance of silica, absence of soil profile and plant-induced features, and on current classifications (Wright and Tucker 1991), we interpret it as a non-pedogenic groundwater calcrete.

The Percé-Beach calcrete apparently differs from the basal calcrete of La Coulée Creek in that it is not covered by the rest of the La Coulée Formation but by red clastic rocks of the seemingly conformable Bonaventure Formation. However, a probable continuation of the same basal calcrete, 4 km away, shows a stepped topography (i.e., the surface shows a succession of step-like levels) under the Bonaventure Formation on the northern tip of Bonaventure Island (where dense guano cover prevents it from being documented by photography), revealing an erosional discontinuity. This discontinuity suggests that the basal groundwater calcrete formed prior to deposition of the Bonaventure Formation. The latter formation would not, therefore, be its host sediment.

We propose that the calcrete underlying the Bonaventure Formation at Percé-Beach is an erosional remnant of the La Coulée Formation. In more dissected regions, groundwater calcretes commonly cap mesas, thus revealing their high resistance to erosion (Mann and Horwitz 1979). Being more resistant to erosion than the rest of the overlying La Coulée Formation, it was therefore more widely preserved during pre-Bonaventure erosion.

Large calcrete clasts up to 70 cm maximum diameter are found in sandy to microconglomeratic matrix within the Bonaventure Formation (Fig. 6a, b) on the south side of Cap d'Espoir (Fig. 1b), approximately 15 km from Percé. The palaeosurface underlying the Bonaventure Formation in this area is very irregular and these large pieces are most likely derived from local palaeorelief. This supports the hypothesis that the erosional remnants of the calcrete base had a larger extent than the rest of the La Coulée Formation and that it is not necessary to account for the sporadic presence of thick groundwater calcretes underlying the Bonaventure Formation (Fig. 7a) by hypothesizing a second groundwater calcrete formation event.

TECTONOSTRATIGRAPHIC SETTING OF THE LA COULÉE FORMATION IN THE PERCÉ AREA

The La Coulée Formation is limited by faults along its

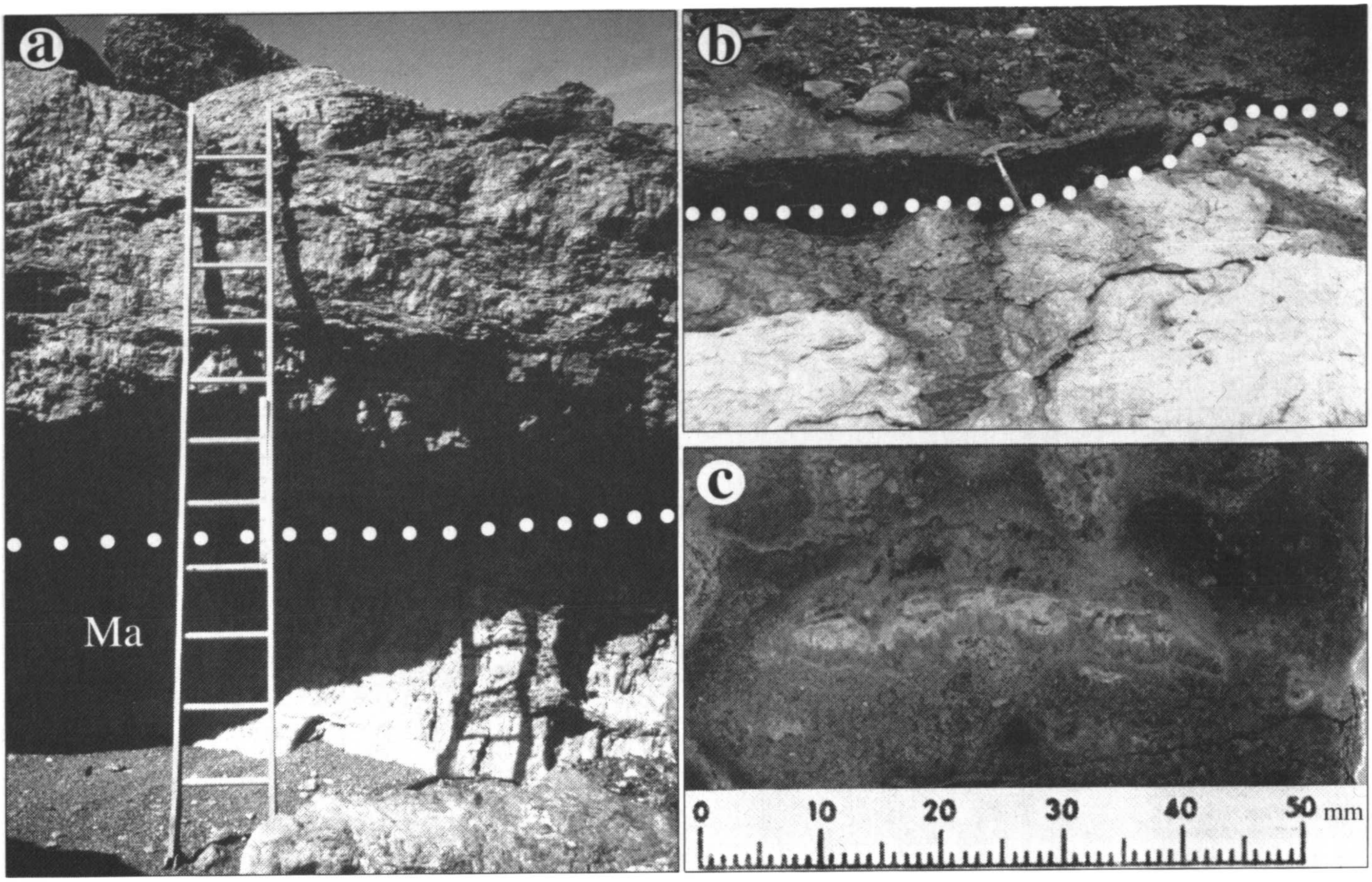

Fig. 5. The Percé-Beach calcrete. (a) Underlain by the Matapedia Limestone (Ma). Dotted line marks contact between the calcrete and the basement. (b) Sharp but seemingly conformable contact between the calcrete and the overlying red clastics of the Bonaventure Formation. (c) Clast-free calcrete with vadoids and laminated structures.

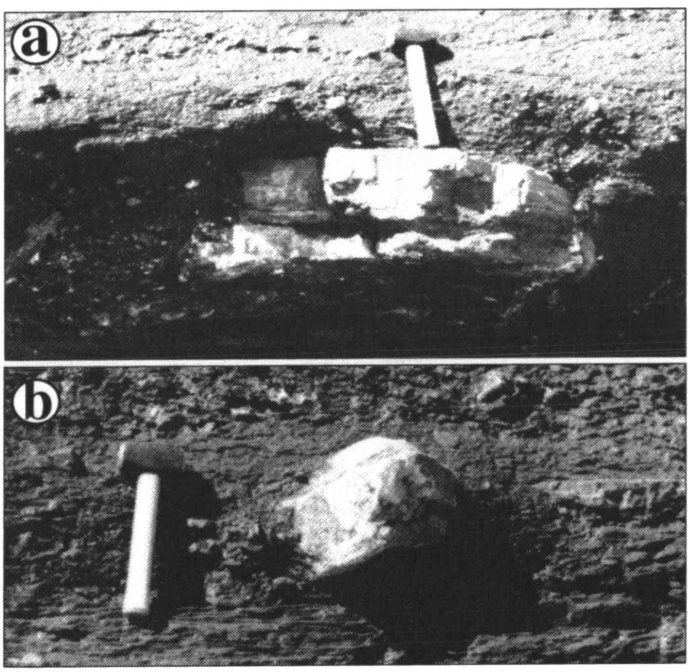

Fig. 6. Large calcrete clasts lodged in (a) micro-conglomeratic and (b) sandy matrix of the Bonaventure Formation on the south side of Cap d'Espoir.

northern and southern margins (Fig. 7b, c). The previously unidentified southern fault, here referred to as the Mont Sainte-Anne Fault, cuts across Mont Sainte-Anne, leading to the juxtaposition of the grey limestone breccia and conglomerate of the La Coulée Formation and the red sandstone and conglomerate of the Bonaventure Formation. The latter may be traced in nearly continuous outcrops along the creeks of the area and on the Mont Sainte-Anne cliffs, from Percé-Beach to the top of the hill, indicating a minimum thickness of 350 m (Fig. 7a).

The two formations differ not only in terms of colour, structure, stratigraphy and stratigraphic position, but also in terms of clast composition: as was mentioned above, all gravel in the La Coulée Formation conglomerate is composed of clasts of limestone, calcareous mudstone or calcareous sandstone, whereas these lithologies comprise between 65% and 80% of the Bonaventure Formation conglomerates at Percé (based on three petrographic counts). The Bonaventure Formation conglomerates are readily distinguished from those of the La Coulée Formation by the presence of 10–20% of rounded quartz pebbles. Most conglomeratic beds of the Bonaventure Formation, at all locations, also include sparse but highly visible red jasper pebbles.

At the coast, the Mont Sainte-Anne Fault (Fig. 7b, c) separates the Cambrian Murphy Creek Formation from the Bonaventure Formation (Fig. 8, cross-section E–F). Further west, just north of the La Grotte amphitheatre, the fault separates the

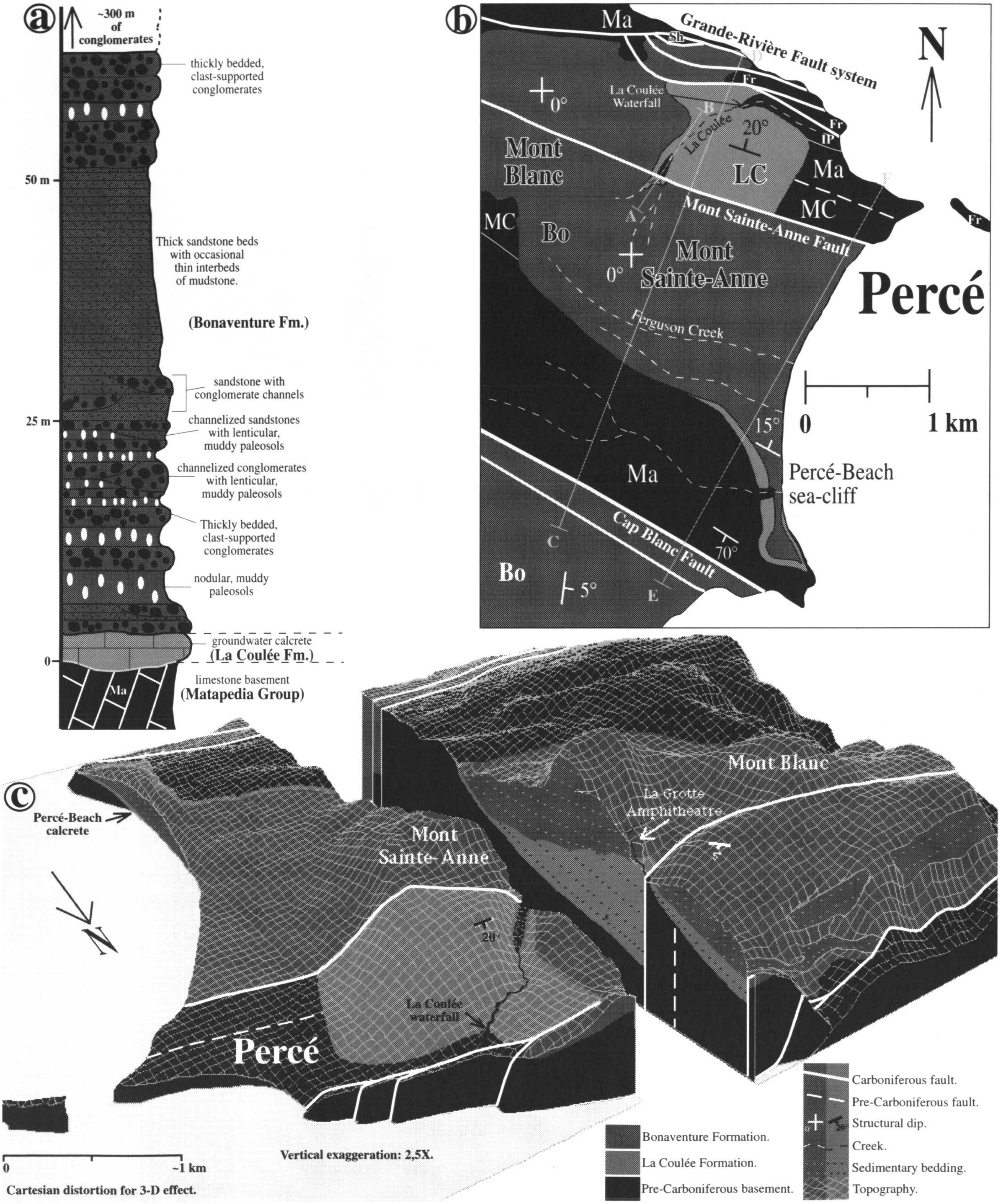

Fig. 7. Geology of the Percé area. (a) Cumulative column of the Bonaventure Formation in the Percé region. Detailed section measured on the Percé-Beach sea-cliff and extrapolations of the remaining upper conglomeratic beds are from Ferguson Creek outcrops (see Figure 7b) and Mont Sainte-Anne cliffs. (b) Outline geological map (modified from Kirkwood 1989). Cross-sections A-B, C-D and E-F shown on Fig. 8. MC=Murphy Creek Fm. (Cambrian); Ma=Matapedia Gp. (Ordovician–Silurian); IP=Indian Point Fm. (Early Devonian); Fr=Forillon Fm. (Early Devonian); Sh=Shiphead Fm. (Early Devonian); LC=La Coulée Fm. (Late Devonian or Mississippian); Bo=Bonaventure Fm. (Mississippian). (c) Block Diagram.

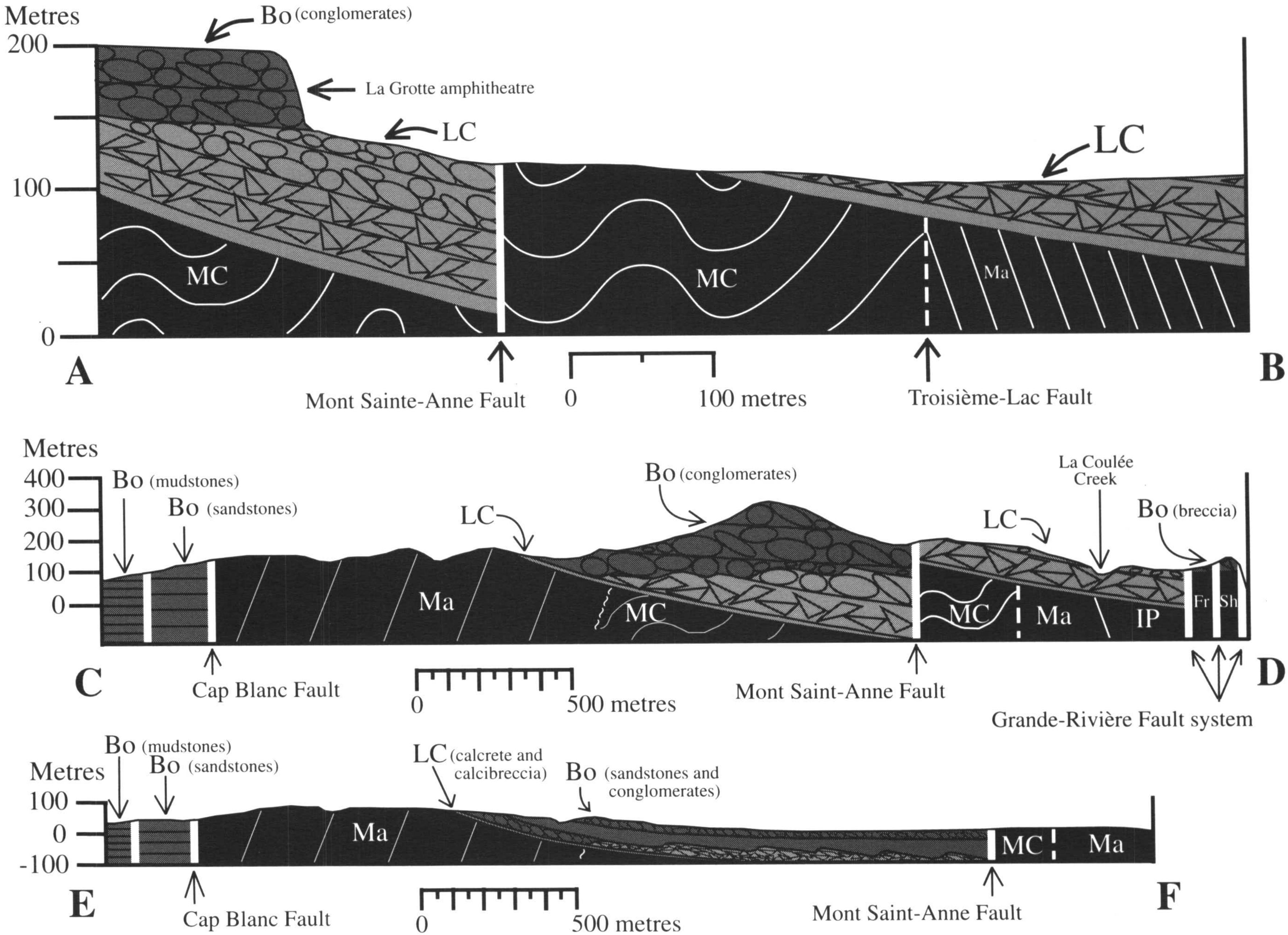

Fig. 8. Cross-sections A–B, C–D and E–F. MC=Murphy Creek Fm. (Cambrian); Ma=Matapedia Gp. (Ordovician to Silurian); IP=Indian Point Fm. (Early Devonian); Fr=Forillon Fm. (Early Devonian); Sh=Shiphead Fm. (Early Devonian); LC=La Coulée Fm. (Late Devonian or Mississippian); Bo=Bonaventure Fm. (Mississippian).

calcrete base of the La Coulée Formation from its conglomeratic upper beds (Fig. 8, cross-section A–B). It then cuts through the Bonaventure Formation on the northern side of Mont Blanc (Fig. 7b, c).

The Mont Saint-Anne Fault is well defined on air photos but outcrops are not preserved along the fault line. It has an important dip-slip component, but being paralleled by a series of Carboniferous strike-slip faults (research in progress), it is assumed to be an oblique fault.

At the base of the La Grotte amphitheatre, south of the Mont Saint-Anne Fault, a 15° angular unconformity between the Bonaventure Formation and conglomerate of the underlying La Coulée Formation can be observed (Fig. 8, cross-section A–B). North of the fault, this unconformity has not been documented but is inferred to the west.

Finally, the grey limestone breccia of the La Coulée Formation is separated from the red breccia of the Bonaventure Formation by a splay of a northern fault system (Fig. 8, cross-section C–D), previously unidentified, which is most probably the eastern extension of the east-west trending Grande-Rivière Fault system attributed to the Acadian deformation (Béland *et al.* 1981 Malo and Béland 1989; Malo *et al. 1*992, 1995; Malo and Kirkwood 1995; Kirkwood *et al.* 1995).

SAINT-ELZÉAR CALCRETE

Close to a hundred kilometres southwest of Percé (Fig. 1b), the village of Saint-Elzéar is situated on an exhumed Carboniferous palaeosurface interpreted as the product of marine erosion (Jutras 1995; Jutras and Schroeder 1999). It is a key area as a residual hill of Bonaventure Formation red clastics lies on the hypothetical wave-cut platform just 1 km away from an exhumed Carboniferous coastal-cliff that locally marks the maximum extent of the postulated Carboniferous paleomarine invasion (Fig. 9).

The base of the hill was investigated in detail in an attempt to find some sedimentological evidence for this proposed transgressive event. A 10–12 m thick, flat-lying calcrete base was identified (Fig. 10a–c) overlying the steeply dipping green mudstones mapped as the Silurian Weir Formation (Bourque and Lachambre 1980). This calcrete is also interpreted as non-pedogenic because it largely exceeds 3 m in thickness. Like the calcretes of La Coulée Creek and Percé-Beach, it is lying directly on relatively fresh basement (the direct contact is not exposed but has been confirmed by excavation), which also indicates that it was not formed within a soil profile.

The calcrete is stratiform and gives an impression of sedimentary bedding. It has, however, been subject to thorough mineral replacement and displacement. The result is a very mature calcrete, composed of more than 98% calcite, which has entirely obscured the nature of the host sediment.

Apparent conformity of the calcrete with the overlying Bonaventure Formation is denied by the fact that a small outcrop on the north side of Duval River (Fig. 10a), less than 500 m from the exposure of groundwater calcrete, shows red clastics lying directly on the mudstone basement. Such an abrupt discontinuity is best explained by erosion prior to deposition of the Bonaventure Formation.

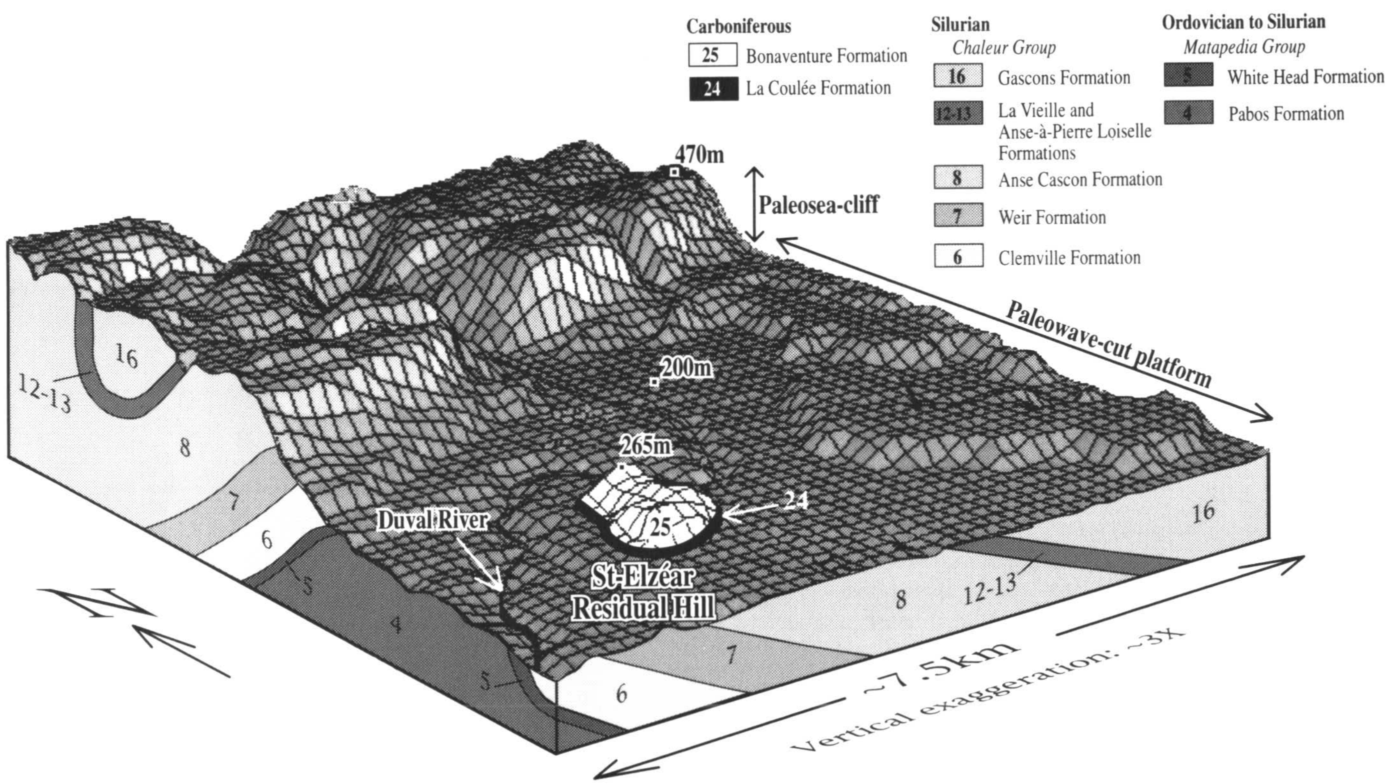

Fig. 9. 3-D geology and topography of the Saint-Elzéar area (modified from Jutras and Schroeder 1999), based on geological mapping by Bourque and Lachambre (1981) and Brisebois *et al.* (1992).

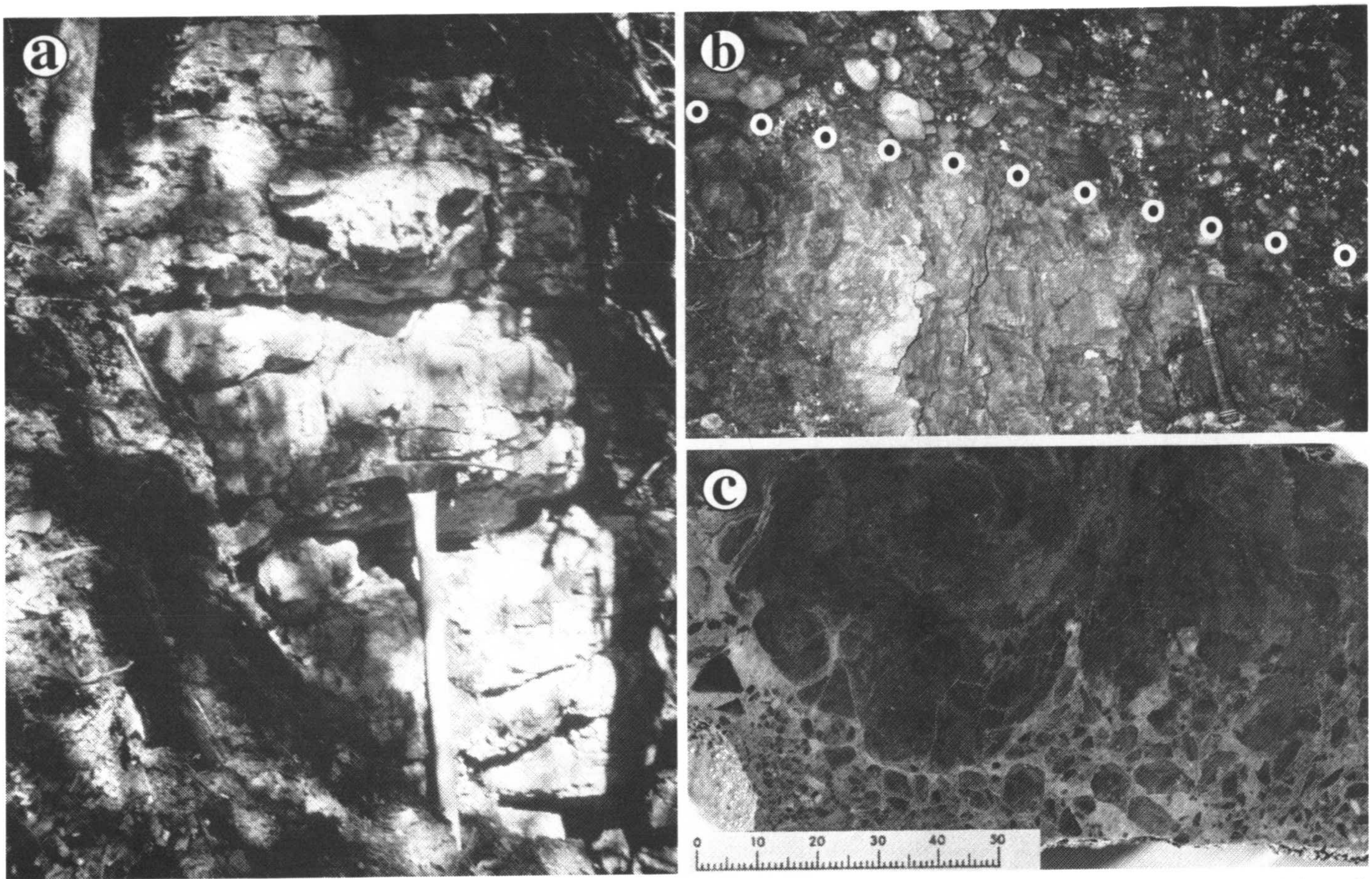

Fig. 10. The Saint-Elzéar calcrete. (a) Stratiform structure. (b) Sharp but seemingly conformable contact between the calcrete and the overlying red clastics of the Bonaventure Formation. (c) Mature calcrete with brecciated horizons.

GEOCHEMISTRY OF THE LA COULÉE CREEK, PERCÉ-BEACH, AND SAINT-ELZÉAR CALCRETES

Stable isotopes

Insufficient work has been done on the stable isotopes of groundwater calcretes to derive solid palaeoenvironmental conclusions (Wright and Tucker 1991). Stable isotope data for the brecciated calcrete facies of the La Coulée waterfall section clearly shows the difference between the marine-water-precipitated limestone of the clasts in the host sediment and the meteoric-water-precipitated, invading calcrete (Fig. 11a). Going up the calcrete profile, heavier values for both C and O are typical and related to a higher evaporation rate in the upper part of the profile (Drever *et al.* 1987).

Stable isotopes for the three calcretes (Fig. 11b) suggest a similar environment. The three calcretes tend to have lower delta ^{18}O values than those reported for the arid climate groundwater calcretes of Central Australia (Jacobson *et al.* 1988), which would reflect a less arid climate. More constrained values for the Saint-Elzéar calcrete may reflect its higher maturity which, as mentioned above, is also suggested by its structure and composition.

General constitution and rare earth elements

The three calcretes are mineralogically similar. They consist of >90% calcite except in areas were silica is concentrated. They have similar REE distribution patterns (Fig. 12) that show the typical negative anomaly of Ce in marine environments (Elderfield *et al.* 1981). Because both the La Coulée and the Bonaventure clastics are dominated by marine limestone clasts, this does not preclude the possibility, in all three cases, that the

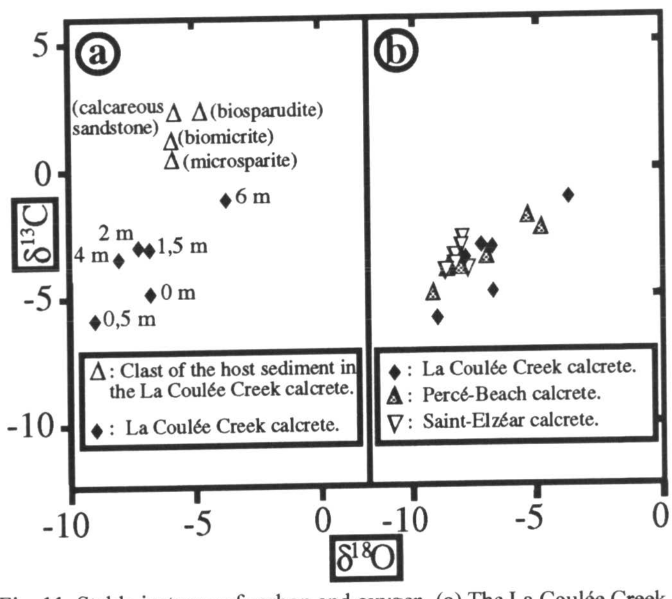

Fig. 11. Stable isotopes of carbon and oxygen. (a) The La Coulée Creek calcrete versus remaining limestone clasts of the host sediment at the level of the waterfall. (b) Stable isotopic range of the three studied calcretes.

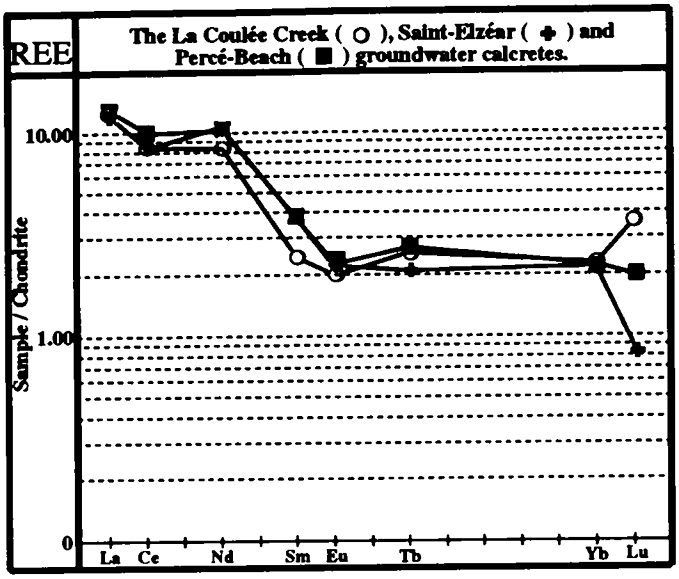

Fig. 12. Rare earth element distribution pattern in the three studied groundwater calcretes.

host sediment is a continental clastic. For the Saint-Elzéar and Percé-Beach calcretes, where no clasts were found to indicate that the host sediment is clastic, the Ce anomaly does, however, exclude the possibility that a lacustrine or palustrine phase preceded the continental clastic sedimentation event (such limestones can develop a very similar calcrete facies; Wright and Tucker 1991). What is not excluded is that the 10–12 m thick Saint-Elzéar calcrete, which rests on a surface interpreted as a Carboniferous wave-cut platform (Jutras and Schroeder 1999), could be masking the sedimentological record of a change from coastal-marine to continental environments.

DISCUSSION

Sedimentology

The Saint-Elzéar, Percé-Beach and La Coulée Creek calcretes are similar in terms of composition, structure, stable isotopes, REE distribution and stratigraphic relationship, which suggests that they are lateral equivalents. We group them, along with the rest of the La Coulée Creek sequence, within the La Coulée Formation.

It should be kept in mind, however, that only the La Coulée Creek calcrete is demonstrably pre-Bonaventure, being included in a sequence unconformably overlain by the Bonaventure Formation. The existence of an apparent conformity between the Bonaventure Formation and the Percé-Beach calcrete is negated by the fact that the continuity of the same basal calcrete shows several metres of stepped topography underneath that formation on Bonaventure Island.

The calcrete outcrop at Saint-Elzéar is narrow and offers no direct evidence contrary to its apparent conformity apart from the fact that it is discontinuous. However, conformity would mean that it developed within the Bonaventure Formation. There are two major objections to this interpretation: (1) a very sharp contact is observed between the Bonaventure Formation clastics and the underlying calcretes at both Percé-Beach and Saint-Elzéar. This is unlikely to occur within the sediment where the calcretes are formed since they are influenced by fluctuations of the water table. For instance, the La Coulée Formation at Mont Sainte-Anne shows almost 20 m of incomplete calcrete formation above the mature, clast-free calcrete; and (2) the three groundwater calcretes here ascribed to the La Coulée Formation, including the one at Saint-Elzéar, are grey and free of iron oxides, which is not the case for the pedogenic calcretes observed sporadically throughout the Bonaventure Formation. It is very unlikely that any thick calcrete that had developed in red clastics would remove or replace all iron oxides, whether in oxidized or reduced form.

Attempts to date the La Coulée Formation through spore analysis have been unsuccessful. South of the Mont Sainte-Anne Fault, the formation is unconformably overlain by the Bonaventure Formation, which is ascribed to the mid-Carboniferous and is time-equivalent either to the Windsor Group or to the Hopewell and Canso groups. Being unconformable upon the pre-Acadian basement, the La Coulée Formation is therefore time-equivalent to either the Horton Group (Late Devonian to early Visean) or the Windsor Group (mid- to late Visean).

In the entire 60 m sequence of the La Coulée Formation at Mont Sainte-Anne, prior to the post-sedimentary calcrete formation, the omnipresence of coarse debris flow deposits, without interbedded decantation mud, suggests subaerial alluvial fan sedimentation. The size of the clasts, especially a 1 m-long biosparudite clast, suggests the close proximity of a fault, most likely the Grande-Rivière Fault system. The La Coulée waterfall, where the largest clasts are found, is the closest outcrop to the fault and is the only locality where an original sedimentary dip, although partly obscured by calcrete formation, can be observed. This sedimentary dip suggests that the source is to the north-northeast, thus crossing the Grande-Rivière Fault system.

For a given stratigraphic level, clasts fine away from the Grande-Rivière Fault system. The sedimentary dip also decreases gradually in that direction and becomes difficult to determine. The north-northeastward 20° dip, which is very consistent throughout the La Coulée Formation at Mont Sainte-Anne, is structural. It is probably slightly underestimated since its direction is opposite to that of the sedimentary dip, which is towards the south-southwest.

The alluvial fan that formed the La Coulée Formation was not very steep: the sedimentary dip quickly becomes negligible away from the fault, although the sediments remain quite coarse. It is also non-channelized and the beds are more sheet-like than lenticular. The paucity of mud, the lack of lateral variation, the absence of a strong sedimentary dip, as well as the internal structure of the debris flows, all suggest an abundance of water in the sedimentation process. Some reduction in the conglomerates, some alteration to kaolinite in the breccia and the absence of red coloration also suggest a water-rich environment.

Paradoxically, the absence of organic remains and the development of groundwater calcretes suggest that the climate was relatively arid. Locally, more abundant water supply can be found internally by passive saturation from an adjacent water reservoir (Nemec and Steel 1984). The La Coulée Formation can be regarded, therefore, as having evolved under a somewhat arid climate, with perhaps a higher water table than the typical

Carboniferous red clastic sequences of southeastern Canada.

A high water table would bring about rapid saturation during rainfalls and would favour debris flows; however, the effective drainage that occurs within coarse clastics would not allow much water retention and would have thus prevented vegetation from developing if the climate was sufficiently arid. A high water table would also narrow the vertical zone in which oxidation can occur and, with a high sedimentation rate, could possibly prevent red hematite from developing, even under a relatively arid climate. According to Miall (1996), the level of the water table is more important than climate in controlling colour differences amid continental clastics.

The Mont Sainte-Anne erosional remnant of the La Coulée Formation includes only the proximal reaches of the fan and does not enable us to arrive at any conclusions regarding the outer reaches. It is therefore not possible to determine whether the fan was connected to a lake, a sea or an alluvial plain. However, a fan-delta model would partly explain some of the non-arid features of the La Coulée Formation and perhaps even the extensive calcretization that has affected it: since groundwater calcretes tend to develop in drainage systems where the water table is very close to the surface, their formation usually occurs in proximity to a body of water, very often close to salt lakes and playas, in the groundwater discharge zone where fresh and saline waters mix (Mann and Horwitz 1979; Arakel and McConchie 1982; Jacobson *et al.* 1988; Arakel *et al.* 1989).

The Percé region is just outside the zero isopach of the Windsor Group according to Howie and Barss (1975) (Fig. 13). As both the stratigraphic and the geographic positions of the La Coulée Formation make it a Windsor Group candidate, and since it is underlain by a surface interpreted as being related to marine erosion processes in the Saint-Elzéar region, the proximity of a contemporaneous or abandoned arm of the Windsor Sea is possible.

We propose that small water bodies, resembling playa-lake extensions, were the most likely proximal environment when groundwater calcrete formation occurred. Such environments are commonly present in the peripheral environments of the Windsor Group (P. Giles, personal communication, 1998). However, the La Coulée Formation does not resemble the facies either of the Windsor Group or of any other Late Palaeozoic formation of Atlantic Canada described in the literature. Solid correlation remains to be made.

Quaternary groundwater calcretes are abundantly recorded in Australia where they are laterally associated with gypsum-rich playa-sequences (Mann and Horwitz 1979; Arakel and McConchie 1982; Jacobson *et al.* 1988; Arakel *et al.* 1989). If evaporite patches remain, they would most probably be under Chaleur Bay or under the thick Bonaventure Formation sequence that extends south-southwest of the Cap Blanc Fault (Fig. 7b, c). However, groundwater calcretes have not been sufficiently studied outside Australia to discriminate regional versus general features and, thus, the presence of a groundwater calcrete does not automatically imply the proximity of gypsum deposits.

Some pre-Quaternary continental clastics cemented by calcite of groundwater origin have been reported (Kalliokosky 1986; Thériault and Desrochers 1993; Kalliokosky and Welch 1985; Tandon and Gibling 1997; Chandler 1998). However, to our knowledge, this is the first pre-Quaternary record of thick

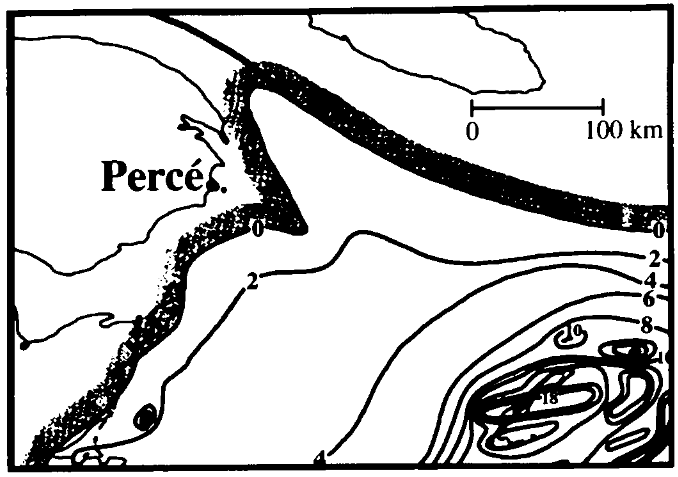

Fig. 13. Isopach map of the Windsor Group in thousands of feet (modified from Howie and Barss 1975).

and mature groundwater calcretes, where not only cementation but also thorough mineral replacement and displacement have occurred.

In modern records, such massive groundwater calcretization appears to be systematically associated with the presence of salt (Mann and Horwitz 1979; Arakel and McConchie 1982; Jacobson *et al.* 1988; Arakel *et al.* 1989). Is mixing with saline water required for the development of such thick non-pedogenic 'hardpans'? The determination of such a relationship would be greatly facilitated by the establishment of a tighter nomenclature regarding the different types of groundwater calcretes.

Tectonics

The Grande-Rivière Fault system was probably active during the Acadian orogenic phase (Béland *et al.* 1981; Malo and Béland 1989; Malo *et al.* 1992, 1995; Malo and Kirkwood 1995; Kirkwood *et al.* 1995), which would explain why no green mudstone clasts of the underlying basement rocks have been found in the La Coulée Formation at Mont Sainte-Anne; they had already been displaced and were locally absent as source rocks when the fault system was reactivated during deposition of the La Coulée Formation.

The apparent layering of the different lithologies in the calcrete at La Coulée waterfall can also be explained by proximal, strike-slip fault-related sedimentation. The local Acadian folded strata generally have a very high dip, which would bring about rapid change of source rocks in a strike-slip context, unless the fault responsible for sedimentation of the La Coulée Formation was perfectly parallel to the tectonic grain, which was unlikely the case.

Dextral strike-slips have occurred in the Maritime provinces from mid-Visean through Westphalian B time (Ruitenberg and McCutcheon 1982; Bradley 1982; McCutcheon and Robinson 1987; Thomas and Schenk 1988). They are related to regional shear at the level of the Iapetan suture while the Theic Ocean, southern extension of the then-already-closed Iapetus (Kent and Opdyke 1985; Keppie 1985, 1992; Briden *et al.* 1988; Kent and Keppie 1988; Reed *et al.* 1993), was still in the process of closing (Arthaud and Matté 1977; Piqué 1981; Lefort and Van der Voo 1981; Russel and Smythe 1983; Haszeldine 1984; Kent and Opdyke 1985; Lefort *et al.* 1988). Hence, arguments for strike-slip movement being responsible for sedimentation of the La Coulée Formation are weak but contextual.

The 20° structural dip of the La Coulée Creek sequence, which is not shared with the Bonaventure Formation, tilts away from the Cap Blanc Fault (Fig. 7b, c). This fault separates the Bonaventure Formation from limestones of the Matapedia Group (Fig. 8, cross-sections C–D and E–F). It demonstrably affects the Bonaventure Formation but it may also have acted as a normal fault during the pre-Bonaventure uplift and erosion of the La Coulée Formation.

Extensional magmatic events of approximate Visean age have been reported for the Hog's Back (338 ± 10 Ma; De Römer 1974) and Vallières-de-Saint-Réal (338 ± 6 Ma; Larocque 1986) plutons of the north-central highlands of the Gaspé Peninsula. Many other similar highlands occupied by Devonian to Permian plutonic complexes are found throughout the Maritime provinces (Fyffe *et al.* 1981; Barr 1990; Fyffe and Barr 1986; Waldron *et al.* 1989; Pe-Piper 1991; Pe-Piper *et al.* 1991; McDonald *et al.* 1992; Piper *et al.* 1993; Kontak 1994). They are interpreted as horst structures induced by plutonic activity and would have served as intermittent sources for clastic sedimentation during Late Devonian and Mississipian times (St. Peter 1993). The uplift of the La Coulée Formation, prior to deposition of the Bonaventure Formation, could have been related to such extensional magmatic events.

Reactivation of the Grande-Rivière Fault system was probably responsible for deposition of the Bonaventure Formation, an event that buried the erosional remnants of the La Coulée Formation. Based on the presence of inversely graded conglomerate-filled channels which, they argued, suggests dip-slip rejuvenation, Rust *et al.* (1989) proposed that the Bonaventure Formation was the product of dip-slip related sedimentation. Reactivation of the fault system also occurred after deposition of the Bonaventure Formation and caused block displacements affecting both formations.

CONCLUSIONS

The grey clastic sequence on the northern side of Mont Sainte-Anne is the erosional remnant of an undated post-Acadian unit, the La Coulée Formation, which stratigraphically underlies the Bonaventure Formation, also undated but estimated as Visean in age (Rust *et al. 1*989; Brisebois *et al. 1*992). A strike-slip fault-related, continental alluvial fan environment is suggested by the sedimentological features of the La Coulée Formation.

The presence and nature of a thick groundwater calcrete at the base of the sequence, combined with structure, fabric, and matrix composition in alluvial fan deposits, suggest that the La Coulée Formation was connecting to a passive body of probably saline water under a relatively arid climate. In contrast, the alluvial fans of the Bonaventure Formation were connected to a deeply oxidized alluvial plain (Zaitlin and Rust 1983), suggesting an environment that was further from base level. It is unlikely that thick groundwater calcretes could have developed in such an environment, especially at the level of the alluvial fans.

The calcrete at Percé-Beach seems to be the continuation of the nearby La Coulée Creek calcrete and it is considered a thin erosional remnant of the La Coulée Formation. As massive groundwater calcretes are very rare in the stratigraphic record, and as they only seem to develop in very specific environmental settings, it is postulated that the calcrete at Saint-Elzéar, ~100 km away, is more or less synchronous with the similar groundwater calcretes of the Percé area. It notably maintains the same stratigraphic position, underneath the Bonaventure Formation. The Quaternary groundwater calcretes of Central Australia (Mann and Horwitz 1979; Arakel and McConchie 1982; Jacobson *et al.* 1988; Arakel *et al.* 1989) are an example of such a setting where massive groundwater calcretes develop almost simultaneously in various areas of the same region.

The Saint-Elzéar calcrete rests on a surface interpreted as having been carved by the Windsor Sea (Jutras and Schroeder 1999). This suggests that the calcrete post-dated maximum Windsor transgression. In this interpretation, the lower age limit of the La Coulée Formation would be mid-Visean because no Windsor Group limestones older than that are known (Howie and Barss 1975).

The La Coulée Formation is most easily pictured in the general subsidence context of the Windsor Group. It belongs to one of the numerous events of post-Acadian fault activity in southeastern Canada during the Late Palaeozoic.

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APPENDIX 1

La Coulée Formation

Authors: Jutras, P., Prichonnet, G., and von Bitter, P.H.

Age: Late Devonian or early to middle Carboniferous; possibly Visean.

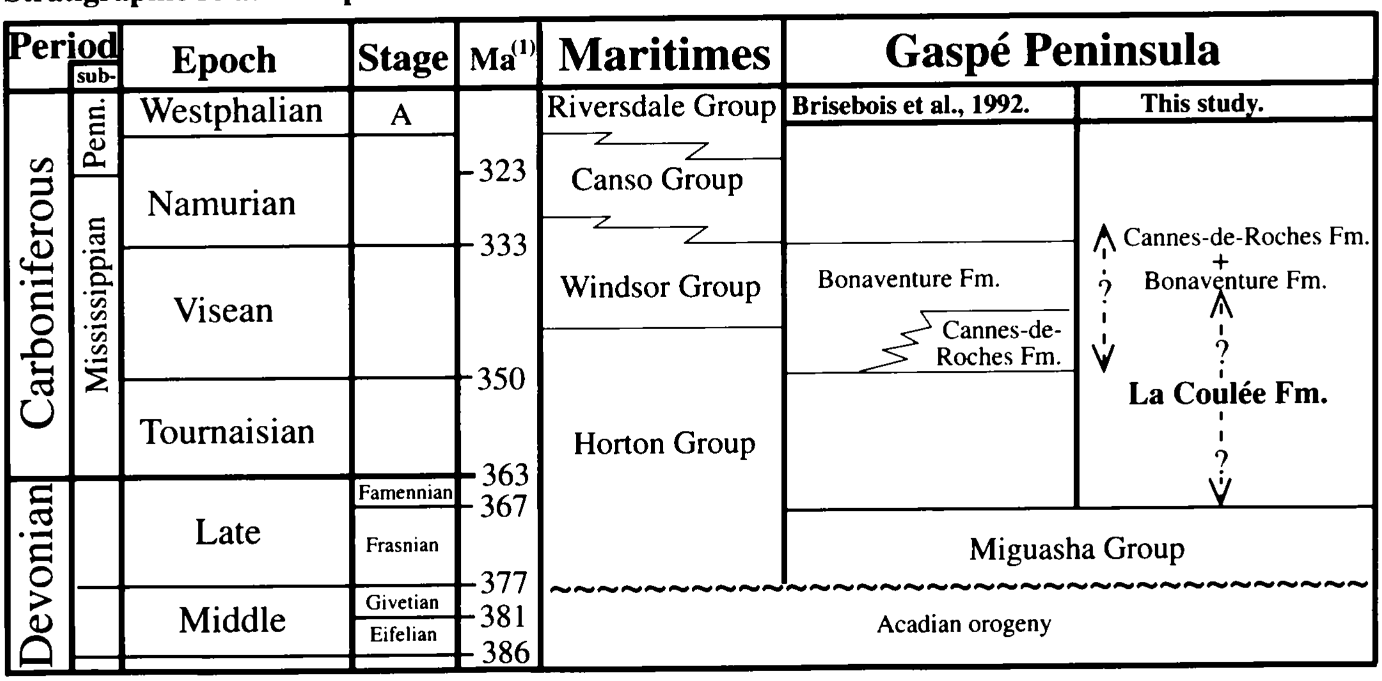
History: Mapped as Bonaventure Formation by Kirkwood (1989). Partially mapped as the Murphy Creek Formation (Cambrian) by Brisebois *et al.* (1992).

Minimum thickness: 60 m

Lithology:
- Groundwater calcrete base formed in limestone breccia (~10 m).
- Grey limestone breccia with calcrete matrix (~20 m) topped by the same breccia with yellowish-grey matrix (~20 m).
- Grey limestone conglomerate with 100% calcareous clasts (minimum thickness: 10 m).

Distribution: The thickest sequence is found on the northern side of Mont Sainte-Anne, west of the village of Percé. It can be followed upstream from the La Coulée Creek waterfall, which is located at 22A/09, 5376750m N., 406500m E. This erosional remnant covers approximately 1 km^2, as small part of which is separated by the Mont Sainte-Anne Fault. The stratigraphic level of the grey limestone conglomerate on the southern side of the fault is unknown but it corresponds to the same facies as that found in the continuous sequence on the northern side above the 50 m stratigraphic level. The calcrete base can be found underneath the Bonaventure Formation in several places around Percé and 990 km to the west-southwest at Saint-Elzéar (22A/03, 5340000m N, 321500m E).

Stratigraphic relationships:



[1] Time scale after Harland et al. 1990