Cap-Chat Mélange, Quebec Appalachians: a folded polyphase deformation zone recording the building and collapse of the Taconian orogenic wedge

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Abstract: The Cap-Ch Mélange occurs in a fairly continuous belt along the south shore of the St. Lawrence River. The mélange consists mostly of disrupted rocks of the Rivière Ouelle Formation with a lesser contribution of overlying flysch units. The mélange includes packages of sediments, tens of metres to several hundreds of metres thick, characterized by a well preserved internal stratigraphy resting on strongly deformed belts that are up to several tens of metres thick.

The Cap-Chat Mélange recorded early (D_1) and late (D_3) regional tectonic events. The more chaotic aspect of some part of the Cap-Chat Mélange compared with the rest of the external Humber Zone is mainly attributed to the superimposition of a D_2 tectonic event that is poorly documented outside the mélange. D_2 structures include both layer-extensional (block disruption along shear zones and faults) and layer-contractional (folds) features that are interpreted to record the collapse of the Taconian orogenic wedge.

Résumé : Le Mélange de Cap-Chat forme une bande relativement ininterrompue le long de la rive sud du fleuve Saint-Laurent et est constitué principalement de roches démembrées de la Formation de Rivière Ouelle, avec une contribution moindre des unités de flysch sus-jacentes. Le mélange comprend des ensembles de roches sédimentaires à stratigraphie interne bien conservée d'une épaisseur variant de quelques dizaines à plusieurs centaines de mètres, qui reposent sur des bandes de roches très déformées dont l'épaisseur peut atteindre plusieurs dizaines de mètres.

Le Mélange de Cap-Chat conserve les traces d'épisodes tectoniques régionaux, l'un précoce (D_1) et l'autre tardif (D_3). L'aspect plus chaotique de certaines parties du Mélange de Cap-Chat, comparativement au reste de la Zone de Humber externe, est attribué principalement aux effets superposés d'un épisode tectonique D_2, qui est peu documenté à l'extérieur du Mélange. Les structures D_2 témoignent d'une déformation à la fois en extension (fragmentation en blocs le long de zones de cisaillements et de failles) et en compression (plis) dans un plan parallèle au litage. Les structures D_2 sont interprétées comme témoignant l'effondrement du prisme orogénique taconique.

INTRODUCTION

Mélanges are found in key geodynamic settings such as orogenic fronts and subduction zones (Kusky et al., 1997; Ujiie, 2002; Fukui and Kano, 2007; among others); however, mapping of such geological assemblages is usually arduous and many are mapped as chaotic units. This paper presents evidence that beyond the general complexity of Mélange units, geological observations may still contribute to unravelling their tectonic history and depicting the relative role of soft sediments (submarine mass wasting) and tectonic processes in the genesis of Mélanges.

This paper focuses on the Cap-Chat Mélange, a map unit that outcrops in the frontal part of the Quebec Appalachians. Detailed structural observations are reported and a preliminary interpretation is proposed.

GEOLOGICAL SETTING

The Cap-Chat Mélange outcrops discontinuously along the south shore of the St. Lawrence River from Métis-sur-Mer to Marsoui (Slivitzky et al. (1991); Cousineau (1998); Brisebois and Nadeau (2003); Fig. 1). It belongs to the frontal units of the Humber Zone which includes early Paleozoic rocks deposited on the paleomargin of Laurentia, reworked by Paleozoic orogenesis (Williams, 1979).

The external Humber Zone (St-Julien and Hubert, 1975; Tremblay and Pinet, 1994), which structurally overlies the autochthonous rocks of St. Lawrence Platform, has been interpreted to represent a typical north-directed foreland fold-and-thrust belt formed during the Ordovician Taconian Orogeny (St-Julien and Hubert, 1975). The imprint of younger structural events has been documented on the basis of fieldwork (Lynch, 1998) and seismic studies (Sandford and Grant, 1990; Pinet et al., in press). The external Humber Zone includes Cambrian to Middle Ordovician rift and passive margin slope and rise sedimentary rocks (Québec Supergroup, Lavoie et al. (2003)) and Middle to Late Ordovician synorogenic flysch deposits (Hiscott, 1995).

The rift and passive margin succession consists mainly of siliciclastic rock-dominated Cambrian (with a minor amount of mafic volcanic rocks) and mixed siliciclastic and carbonate Ordovician strata with a few conglomeratic horizons (*see* Lavoie et al. (2003) for a review). Regionally, the succession is divided into three broad stratigraphic packages, with from the bottom to the top: the (?)Lower to Middle Cambrian Orignal Formation, the Upper Cambrian to lowermost Ordovician Trois-Pistoles Group, and the Lower to early-Middle Ordovician Rivière Ouelle Formation. Flysch deposits are early-Middle to Late Ordovician and include the Tourelle, Deslandes, and Cloridorme formations (Hiscott, 1995). In the Rivière-du-Loup area, the oldest flysch unit (Tourelle Formation) lies in stratigraphic contact with the Rivière Ouelle Formation (Vallières, 1984).

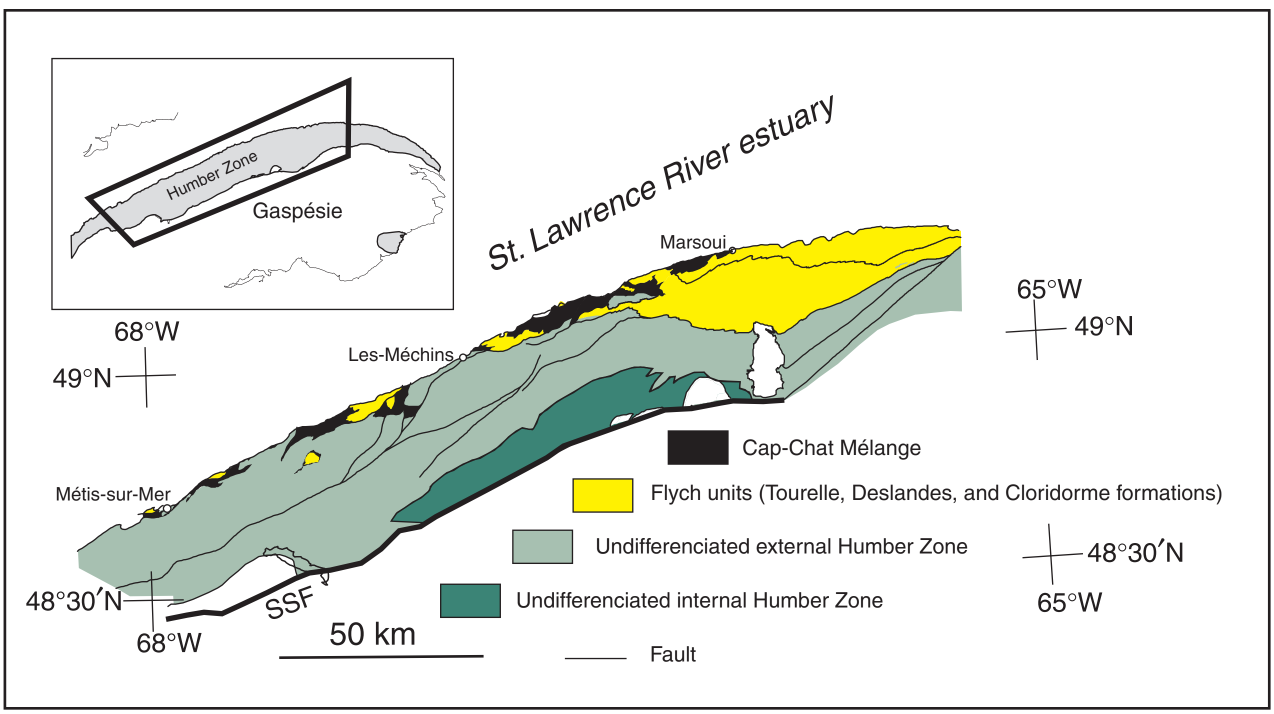

Figure 1. Geological map of the Humber Zone in the western Quebec Appalachians (*modified from* Brisebois and Nadeau, 2003). SSF = Shickshock-Sud Fault.

DESCRIPTION

The term ‘Mélange’ is used herein in a purely descriptive sense. It indicates ‘a mappable, internally fragmented and mixed rock body containing a variety of blocks, commonly in a pervasively deformed matrix’ (Silver and Beutner, 1980). In this study, the author used the term Cap-Chat Mélange because it is a widely accepted term; however, as a whole, it is best described as a stratally disrupted sequence or a broken formation (Raymond, 1984), because detailed mapping (at the 1:25 000 scale or larger) would probably allow to differentiate rock units within the Cap-Chat Mélange.

The Cap-Chat Mélange outcrops in a fairly continuous belt that extends 175 km along strike (Fig. 1). On compilation maps (Slivitsky et al., 1991; Brisebois and Nadeau, 2003) the Mélange belt varies in width from 0 to 4.5 km.

The chaotic aspect of the Cap-Chat Mélange varies significantly from one outcrop to another. The Mélange contains tens of metres to several hundreds of metres thick packages of very weakly deformed beds with well preserved internal stratigraphy, resting on strongly deformed belts that are up to tens of metres thick.

As noted by Cousineau (1998), the Mélange consists mostly of disrupted rocks of the Rivière Ouelle Formation with lesser contribution of the overlying flysch units (Tourelle and Deslandes formations). The assignation of rocks that comprise the Cap-Chat Mélange to the Rivière Ouelle Formation is based on the typical association of varicoloured mudstone-rich intervals, fine-grained calcarenite, limestone pebble conglomerate, ribbon limestone, and centimetre- to metre-thick beds of sandstone. The only evidence for rocks older than the Rivière Ouelle Formation (such as the Orignal Formation, Cousineau (1998)) is located near the fault zones that mark the contact between the Cap-Chat Mélange and surrounding sedimentary units.

In outcrop, deformed belts correspond to elongated blocks in fine-grained rocks. The deformation style of the Mélange is mainly controlled by the mechanical competency of rock units. Fine-grained rocks (mudstone and fine-grained siltstone) have deformed rather ductily and are often characterized by a phacoidal to slaty cleavage and diffuse stratal disruption. More competent units such as sandstone, calcarenite, and conglomerate have deformed rather brittly and stratal disruption is associated with discrete shear zones and/or faults. Blocks exhibit an angular shape with elongated necks and subrounded clasts are notably absent. Blocks are typically elongated with a length/width ratio averaging about five.

Evidence of fluid involvement in the Cap-Chat Mélange includes calcite and/or quartz veins and calcite on brittle fault planes.

STRUCTURAL GEOLOGY

Multiple deformation events are recognized in the Cap-Chat Mélange. Several generations of small-scale structures (D_0, D_1, D_2, D_3, and D_4) have been identified on the basis of crosscutting relationships and structural style. Preliminary investigation of geological units adjacent to the Cap-Chat Mélange indicates that most of deformation events (in particular D_1 and D_3) were of regional extent and that variations in the intensity of specific structures may be attributed to an inhomogeneous strain distribution during the development of the regional deformation.

D_0 structures

In several localities, folded intervals bounded by homoclinal beds have been interpreted as slumps. Among the characteristics that argue for such an interpretation are the lacks of well defined shear zones at the boundaries of folded intervals and of fractures and/or incipient cleavage in the hinge zones of folds.

Early deformation is also recorded by the intrusion of clastic dykes that may be hundreds of metres long (Hiscott, 1979) and by the intrusion of mud into the sandstone blocks along planar surfaces.

D_1 structures

The most obvious structures associated with the D_1 deformation event are isoclinal folds. In deformed belts, D_1 folds are oblique to, and are truncated by, the later D_2 shear zones (Fig. 2, 3). In such cases, rootless isoclinal folds, usually with an ambiguous asymmetry, are common and have various fold axis orientations in the same outcrop. Isoclinal folds have a ductile style with thinning of flanks and thickening of hinge zones. In most cases, if not all, the curvature of the fold axis may be attributed to later tectonic events.

Half-wavelength of the D_1 folds ranges from 1 m to over 100 m. A tectonic origin for these folds is often suggested by an incipient crenulation cleavage and/or by radially distributed calcite-filled fractures that converge toward the hinge zones, indicating that rock units were already consolidated during the deformation.

Faults characterized by north- to northwest-directed sense of motion have been attributed to the D_1 deformation event. Despite subsequent deformation, a clear gradient from rocks lacking internal deformation to highly sheared rocks is usually associated with these 0.1 m to 10 m thick fault zones.

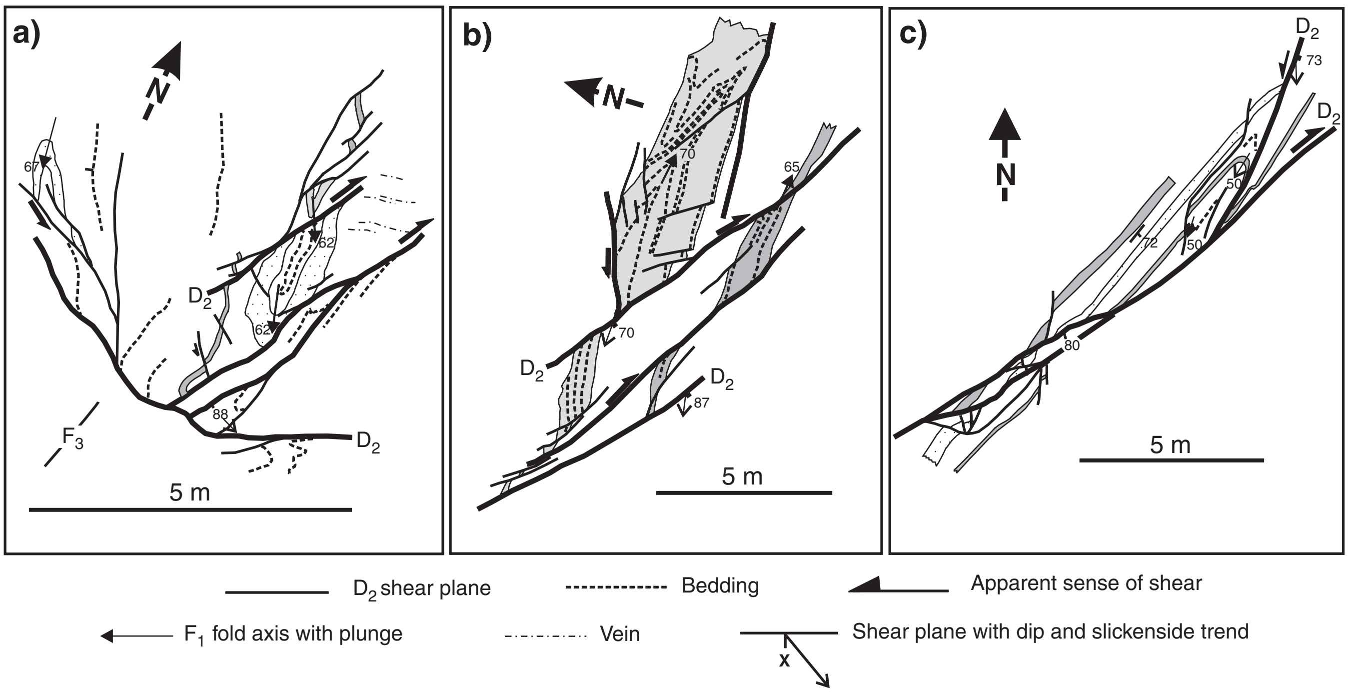

Figure 2. Field sketches of deformation pattern within the Cap-Chat Mélange. All plan views. Grey and stippled patterns have no lithological significance and are used to enhance marker beds.

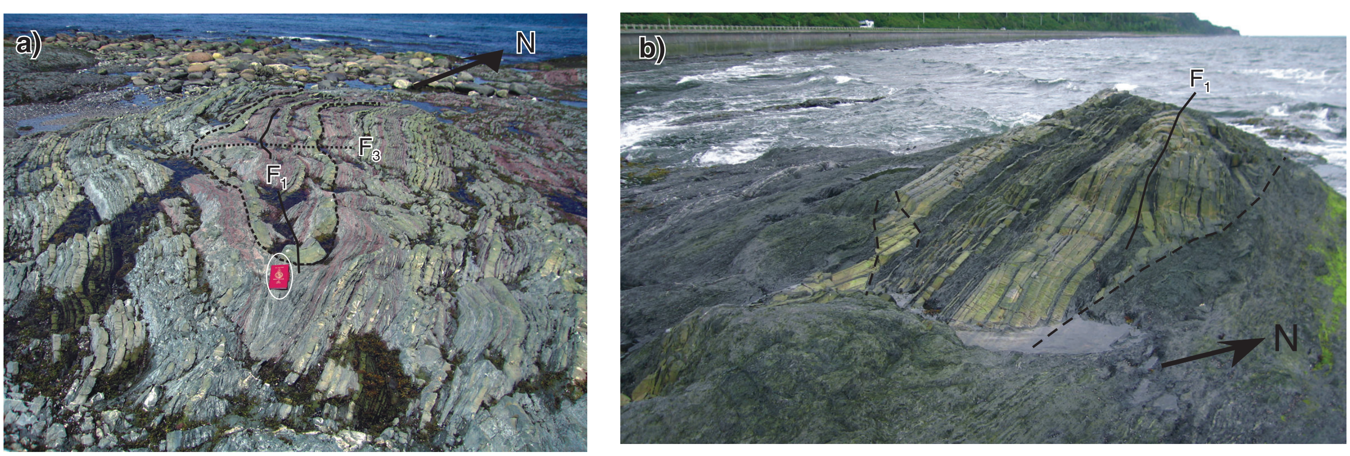

Figure 3. D_1 structures. **a)** Isoclinal F_1 fold. Note the superimposition of an F_3 open fold; scale is indicated by a note book (20 cm long). **b)** Rootless isoclinal F_1 fold. D_2 shear zones are indicated by dashed lines. The near view is approximately 5 m wide.

D_2 structures

D_2 structures found in the Cap-Chat Mélange may be divided in two groups: those that contract the bedding plane and those that extend it. This division avoids the reference to a contractional or extensional stress regime that implicitly refers to a paleohorizontal plane that may be difficult to determine considering the polyphase structural history and the probable rotation of bedding during deformation.

D_2 structures result from a highly inhomogeneous strain distribution and account for various stages of bedding disruption. In the studied localities, a complete transition exists from narrow D_2 deformation zones with a scaly fabric bounding 100 m long blocks with a homoclinal internal geometry to a pervasive scaly anastomosing D_2 fabric with disconnected centimetre to metre blocks. D_2 structures are common and more easily identifiable in sedimentary intervals including centimetre- to decimetre-thick, relatively competent layers and mudstone interbeds. These structures are difficult to characterize in more homogeneous fine-grained intervals and correspond to discrete shear zones in thickly bedded intervals (>2 m).

Layer-extensional structures

Structures recording layer-parallel extension correspond to shear zones and faults that are typically millimetres to decimetres in thickness and exhibit an anastomosed geometry (Fig. 2, 4). Competent beds are offset by D_2 south-dipping shear surfaces leading to a typically lozenge-shaped block geometry (Fig. 4). The fine-grained sediments adjacent to the blocks show evidence of brittle and brittle-ductile deformation such as slickenside on fault planes, dragging, fault-zone fragmentation, and scaly cleavage.

The numerous evidences of rotated fragments and the asymmetric fragment shape indicate that the strain path during layer extension was noncoaxial and associated with simple shearing.

In several cases the reactivation of inherited D_1 deformation zones by D_2 shear zones and faults can be demonstrated. Such reactivation is well displayed in an outcrop located along Highway 132, approximately 2.2 km to the west of Marsoui (Fig. 5; *see also* Lynch (1998)). In this outcrop, calcareous sandstone beds are in thrust contact with a mudstone-rich unit. Some segments of this major D_1 thrust are reactivated by D_2 structures, whereas others are cut by them (Fig. 5).

Layer-contractional structures

At the outcrop scale, D_2 contractional structures correspond to asymmetric folds, with a typical wavelength of 0.1 m to 2 m (Fig. 6). These folds have axes that show considerable variations of their plunge from 20° to 80°. F_2 folds exhibit a clear structural vergence toward the south to southeast and are generally located in the hanging wall of D_2 extensional shear zones and/or faults.

Relationship between layer-contractional and layer-extensional structures

The geometrical relationship between folds and shear zones and the consistency on their kinematic (slickenside and sense of drag versus asymmetry of folds) suggest that they formed during the same increment of deformation (Fig. 7).

The variable response of rock intervals to the D_2 deformation event depending on their mechanical competency is schematically illustrated on Figure 7. Mudstone-rich intervals including relatively thin competent beds (grey surface on Fig. 7) commonly exhibit zones where layer-extensional structures predominate over layer-contractional structures or the reverse. This strain partitioning between layer-extensional and layer-contractional deformation occurs in 1 m to 100 m zones and results in a variable thickness of mudstone-rich intervals (Fig. 7). Thickly bedded intervals with few mudstone interbeds (stippled patterns on Fig. 7) lack evidence of D_2 folding and are characterized by discrete layer-extensional shear zones and faults. As shown on Figure 7, surface balancing of the sedimentary intervals involved in the Cap-Chat Mélange is ensured by the structural thickening (folding) and thinning (pinching) of mudstone-rich intervals.

D_3 structures

The most obvious D_3 structures correspond to F_3 open folds with wavelengths varying between 5 m to more than 100 m (Fig. 8). An S_3 axial-planar cleavage trending 040° to 060° is locally associated with F_3 folds. F_3 folds plunge steeply toward the south to southeast, indicating that the bedding surfaces were relatively steep before the D_3 tectonic event. Despite their relatively simple geometry, F_3 folds account for major changes from one outcrop to another in the trend of the bedding and of previous structures.

D_4 structures

D_4 structures correspond to brittle fault planes that may be continuous for up to hundreds of metres or more. These faults, which record predominant strike-slip motion, are characterized by a planar geometry and clear-cut F_3 folds.

Significance of stratal disruption during D_2 deformation

In the Cap-Chat Mélange, D_2 cataclasis and shearing is an important deformation process in the formation of isolated blocks. Cataclasis has been reported in gravity-driven slide

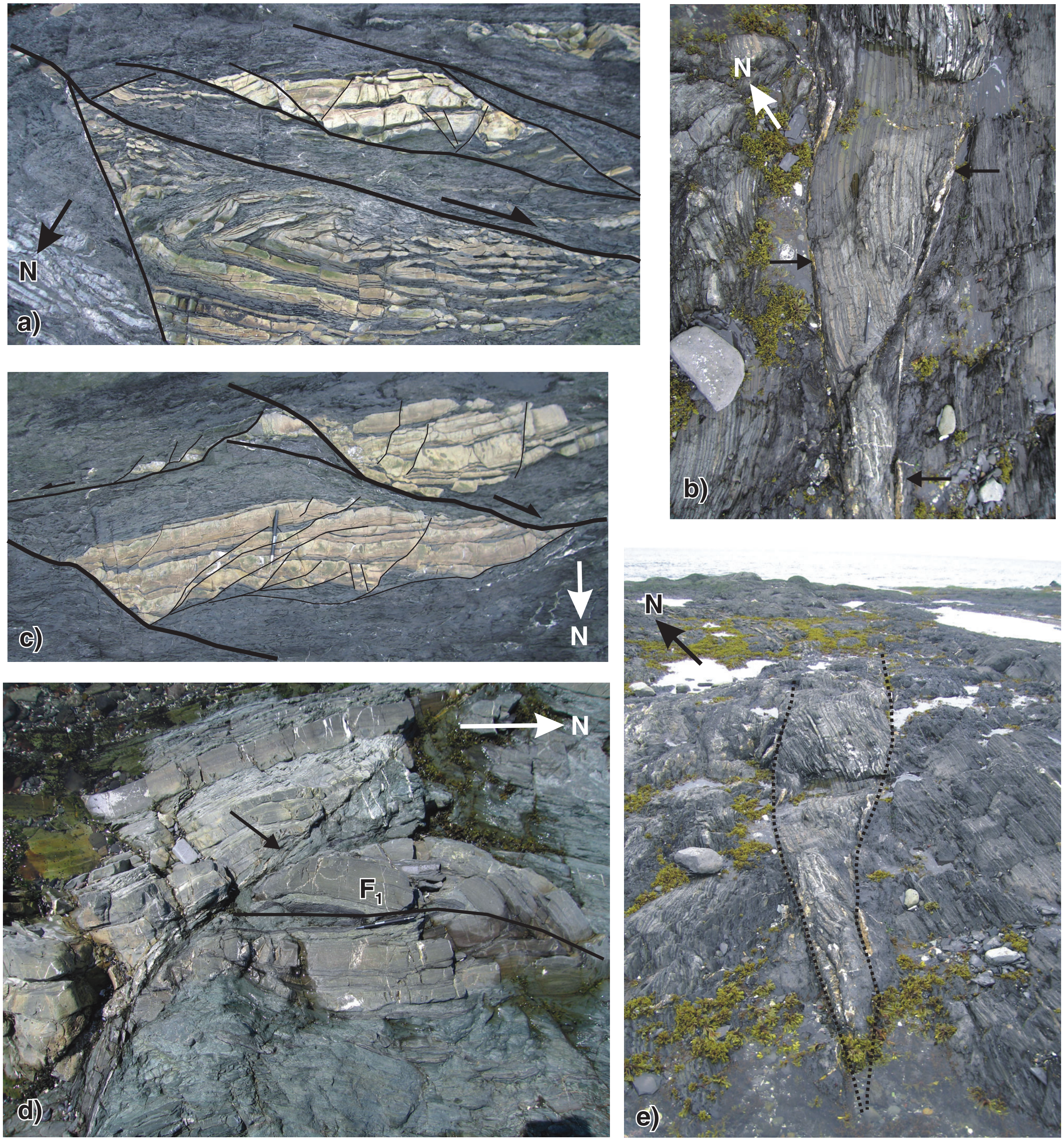

Figure 4. D_2 layer-extensional structures. **a)** Plan view of a D_2 shear zone cutting a F_1 fold. Note the anastomosed geometry of D_2 structures and the second-order antithetic faults. The view is approximately 1 m wide. **b)** Faults bounded lozenge-shaped block. Note the presence of a calcite infill along fault planes (arrows). The view is approximately 2 m long. **c)** Isolated blocks bounded by D_2 shear zones. Note the presence of second-order antithetic faults. The view is approximately 0.8 m wide. **d)** F_1 fold truncated by a D_2 fault (black arrow). The view is approximately 1 m wide. **e)** Block bounded by D_2 shear zone. The near view is approximately 2 m wide. Note the lozenge shape of the block.

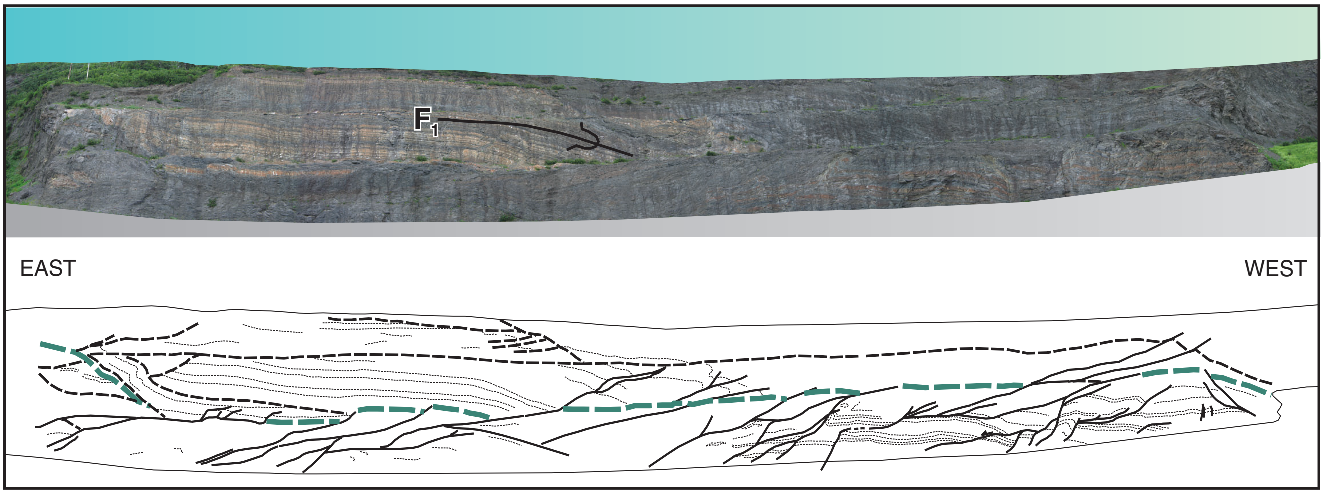

Figure 5. a) Panoramic view and **b)** interpretation of an outcrop located along Highway 132, 2.2 km to the west of Marsoui. The outcrop is approximately 250 m long. A major D_1 thrust fault (green dashed line) puts in contact calcareous sandstone with a mudstone-rich unit in the eastern part of the outcrop. Other D_1 thrust faults are indicated by dashed lines. Segments of D_1 thrusts are locally reactivated by D_2 layer-extensional faults (full line), whereas others are cut by D_2 structures.

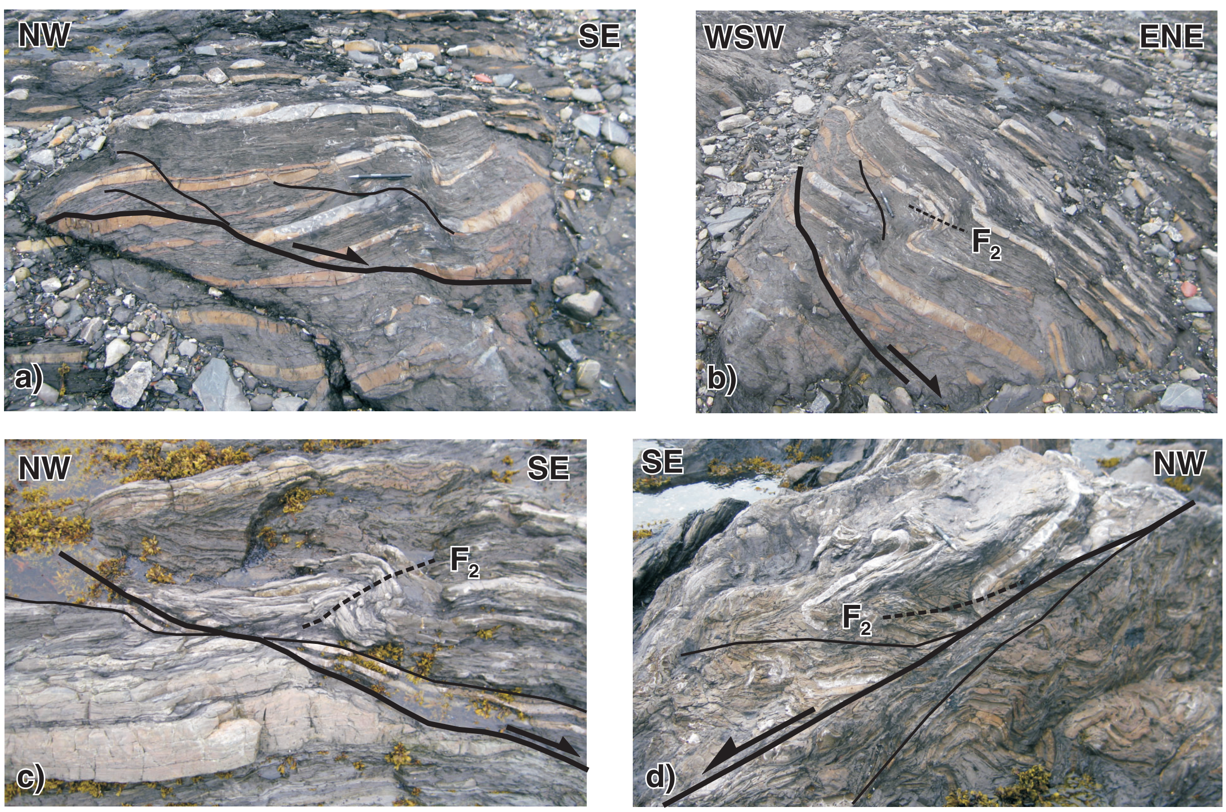

Figure 6. D_2 layer-contractional structures. **a)**, **b)** Two nearly perpendicular views of the same outcrop. The fold (F_2, axis: 048°) is associated with a layer-extensional shear. Field of view for both Figures 6a and 6b is approximately 1 m. **c)** Southeast-verging fold associated with a fault that limits a lozenge-shape block. The view is approximately 1 m long. **d)** Southeast-verging fold associated with a southeast-dipping fault. The view is approximately 2 m long.

blocks (Lucente and Pini, 2003) and thus cannot be used alone to infer a tectonic origin; however, several observations provide insights into the mode of formation of isolated blocks within the Cap-Chat Mélange:

- The Cap-Chat Mélange extends for 150 km along strike and pervasive shearing is recorded in belts that may exceed 100 m in width; such dimensions have been reported only for a few submarine landslides (McAdoo et al., 2000);
- Submarine slides are expected to exhibit a clear strain partition and consist primarily of a contractional zone at the toe and an extensional zone at the head (Lucente and Pini, 2003; among others); such a strain partition has been observed in the Cap-Chat Mélange at the 1 m to 100 m scale (Fig. 7), but not at the scale of typical submarine slide (>1 km);
- Beds were already lithified when subjected to layer-parallel extension; and
- Shear planes are commonly associated with calcite- and/or quartz-filled fault planes, suggesting that pressure and temperature conditions for the precipitation of these minerals was reached.

Most of the disruption of the Cap-Chat Mélange appears thus to be tectonic in origin, although early slumps are present.

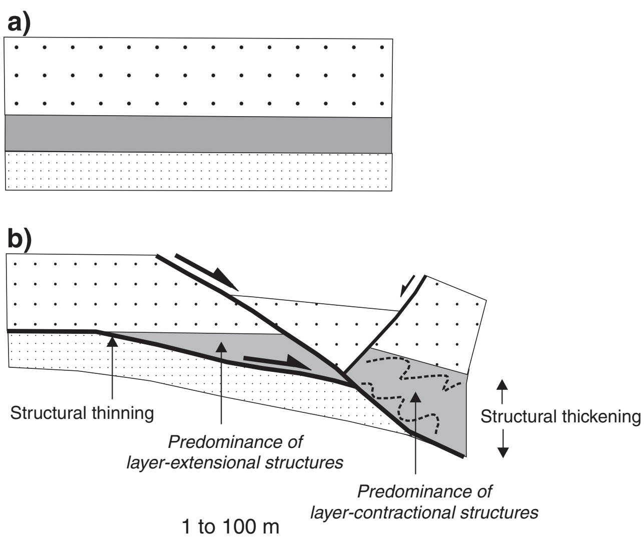

Figure 7. Schematic sketch illustrating the relationship between layer-contractional and layer-extensional structures and the variable response of rocks intervals to the D_2 deformation depending of their competency. Original layer and/or unit surfaces (sketch a) are kept constant after deformation (sketch b). The grey pattern corresponds to a mudstone-rich layer and/or interval including relatively thin competent beds. More competent layers and/or intervals are indicated by a stippled pattern.

Shear-sense indicators along D_2 shear zones and faults and the overall vergence of associated F_2 folds indicate hinterland-directed motion. Slip direction varies from one outcrop to the other. Restoration of the slip direction to its original trend is difficult because bedding was not horizontal prior to the formation of D_2 structures and shear-sense indicators have been obscured by tilting of shear planes during subsequent folding; however, as mentioned above, D_2 shear zones and faults in the studied outcrops exhibit an invariant geometrical relationship with the bedding. If the bedding is restored to a northeast trend (the structural grain of the

Figure 8. Typical open F_3 fold. View is 3 m wide.

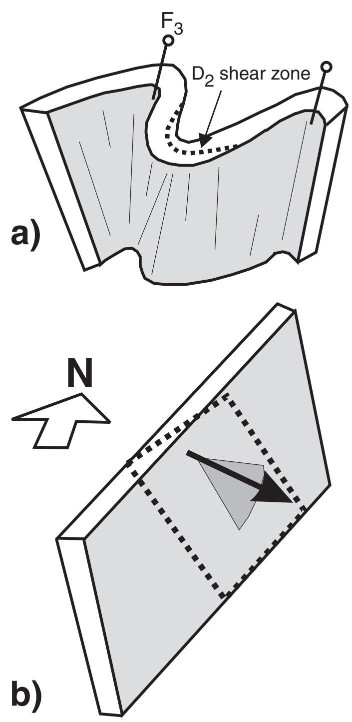

Figure 9. Retrodeformation of the D_3 tectonic event considering a northeast original trend for the precursor of Cap-Chat Mélange. Motion along D_2 shear zones ranges from south- to southeast-directed (grey cone). The black arrow represents the average direction of transport.

Quebec Appalachians; Fig. 9), mixed dextral and normal motion are recorded along east-northeast-directed shear zones and faults, whereas mixed sinistral-normal motion are recorded along second-order north-northwest shear zones and faults.

IMPLICATION FOR THE TACONIAN OROGENIC WEDGE

As noted by Cousineau (1998), the Cap-Chat Mélange exhibits soft-sediment deformation (sedimentary injections and slumps) that occurred soon after the deposition of the Rivière Ouelle and Tourelle formations; however, structural analysis indicates that much of the geometrical complexity of the Cap-Chat Mélange is related to several tectonic events.

D_1 structures found in the Cap-Chat Mélange are correlated with the main deformation event described in the external Humber Zone; however, F_1 folds within the Cap-Chat Mélange are generally characterized by tighter hinge zones than usual in the external Humber Zone. This characteristic may be related either to the rheological properties of the Rivière Ouelle Formation that may have reacted disharmonically to the deformation compared with surrounding and more competent units (which may have favoured internal deformation rather than large-scale folding and thrusting) and/or to higher strain within the Cap-Chat Mélange. On Figure 10a, D_1 structures of the Cap-Chat Mélange are tentatively interpreted as formed along a high-strain décollement level localized in the less competent unit of the sedimentary pile (Rivière Ouelle Formation).

Most of the structural complexity of the Cap-Chat Mélange is related to D_2 structures. As noted above, both layer-extensional and layer-contractional structures record hinterland-directed motion along mixed normal and strike-slip shear zones and faults. Except for a few high-angle brittle faults that are interpreted to have accommodated down-to-the-southeast normal motion (Lynch, 1998), such D_2 structures have not been described in the rest of the Humber Zone. This suggests that D_2 deformation was mostly localized along a pre-existing D_1 deformation zone, as locally demonstrated at the outcrop scale (Fig. 5). The age of the D_2 deformation event remains poorly constrained. It must postdate the deposition of the Cloridorme Formation (Caradocian), as D_1 structures are well preserved in this sedimentary unit (Lynch, 1998) and predate the formation of F_3 folds interpreted to be related to the Middle Devonian Acadian Orogeny (*see* below). This time range includes the Salinic event which is associated with normal faulting in the adjacent Gaspé belt (Bourque, 2001).

On Figure 10b, D_2 deformation is portrayed as occurring in a high-strain zone (precursor of Cap-Chat Mélange) and along brittle structures in its hanging wall. The collapse of the orogenic wedge may have been driven by an increase of the critical taper of the wedge either following D_1 deformation or due to the tilting of the frontal units in response to the propagation of the deformation toward the foreland. Such collapse (in association or not with shortening) allows the orogenic wedge to return to a normal thickness without much erosional denudation and contribute to the preservation of upper crustal sequences.

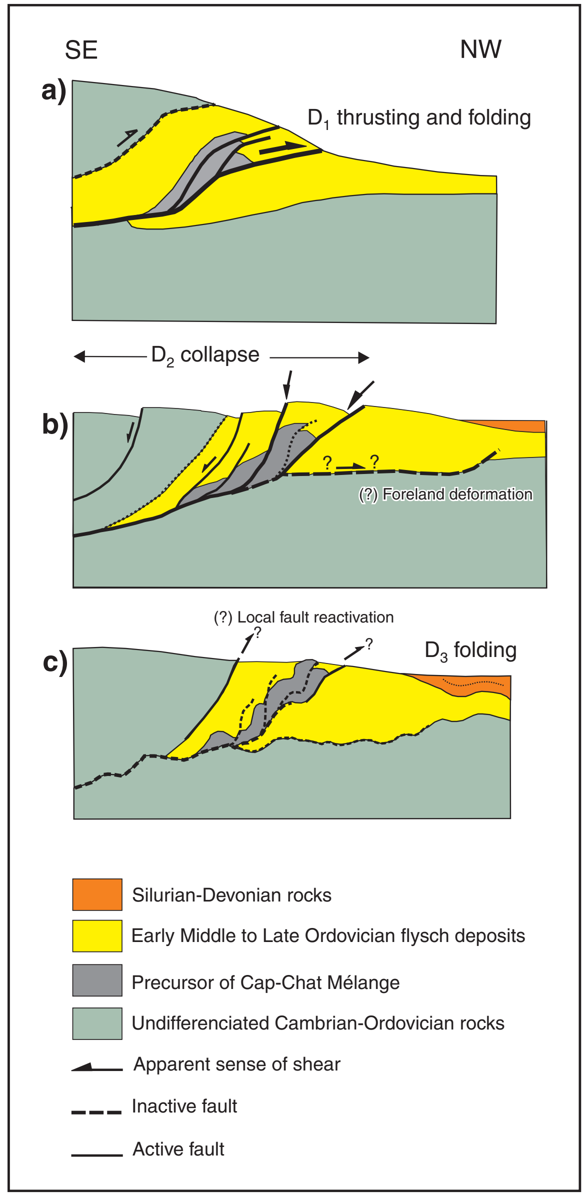

Figure 10. Interpretative model illustrating the evolution of the frontal part of the Appalachian tectonic wedge and the position of the Cap-Chat Mélange. **a)** D_1 deformation in the Cap-Chat Mélange occurs in a décollement zone localized in the less competent Rivière Ouelle Formation. **b)** D_2 deformation is mainly localized along the inherited D_1 deformation zone. Second-order brittle structures associated with the D_2 deformation event affected the whole tectonic prism. **c)** D_3 Acadian folding.

D_3 structures correspond mainly to open folds that exhibit a style similar to Acadian folds found in the Silurian-Devonian rocks of the Gaspé belt (Bourque et al., 1993). In the external Humber Zone, the imprint of Acadian deformation is generally considered as minimal; however, preliminary field investigation in the Bas-Saint-Laurent area indicate that D_3 structures have been underestimated probably due to the wavelength of F_3 folds that exceed the typical outcrop size.

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