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Structural and stratigraphic history of the southern domain of the Indian Mountain Deformed Zone, southeastern New Brunswick, Canada: Tournaisian (Lower Carboniferous) tectonic ‘pop-up’ and collapse

Histoire structurale et stratigraphique du domaine méridional de la zone déformée du mont Indian, dans le sud-est du Nouveau-Brunswick, au Canada soulèvement et effondrement tectonique du Tournaisien (Carbonifère inférieur)

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Article abstract

The southern domain of the Indian Mountain Deformed Zone (IMDZ) in southeastern New Brunswick marks a major right-lateral strike-slip fault belt active during late Tournaisian (Lower Carboniferous) sedimentation. The rocks of the Sussex Group, representing a depositional cycle from subsidence to basin inversion, occupy this zone and lie unconformable on crystalline basement, the latter representing a partially exhumed portion of the adjacent (to the south) buried Westmorland uplift. Deformation is related to early reverse faults/thrusts, later strike-slip faults. and latest normal faults. The Gorge Fault zone in the southern domain of the IMDZ demonstrates many essential features of the entire zone. The offset of The Gorge Fault zone increases to the east. In the west it forms a blind thrust and asymmetric anticline whereas in the east it expands into a reverse fault/thrust complex. A progressive evolution from reverse faults/thrusts to strike-slip fault movement resulted in a tectonic pop-up, culminating in gravitational collapse along normal faults with listric profiles that flatten out within 100–200 metres of the present erosion surface. Megabreccias formed during deposition of the Sussex Group are contemporary with reverse fault/thrusts. The geometry of the various faults is best explained by progressive deformation within an overall right-lateral strike-slip regime under general shear, with early formed features rotating both congruently and incongruently to the main IMDZ boundaries. Further complexity is a consequence of many reverse faults/thrusts and normal faults occurring close to a free surface and the latter a response to gravitational instability of the pop-up structure controlled by topography. A revised stratigraphy for the Sussex Group in the Indian Mountain Deformed Zone and its interpretation is integral to constructing the structural history. Two units, Stilesville Formation and Briggs Cross Formation, are formally defined here.

Structural and stratigraphic history of the southern domain of the Indian Mountain Deformed Zone, southeastern New Brunswick, Canada: Tournaisian (Lower Carboniferous) tectonic 'pop-up' and collapse

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ABSTRACT

The southern domain of the Indian Mountain Deformed Zone (IMDZ) in southeastern New Brunswick marks a major right-lateral strike-slip fault belt active during late Tournaisian (Lower Carboniferous) sedimentation. The rocks of the Sussex Group, representing a depositional cycle from subsidence to basin inversion, occupy this zone and lie unconformable on crystalline basement, the latter representing a partially exhumed portion of the adjacent (to the south) buried Westmorland uplift. Deformation is related to early reverse faults/thrusts, later strike-slip faults. and latest normal faults. The Gorge Fault zone in the southern domain of the IMDZ demonstrates many essential features of the entire zone. The offset of The Gorge Fault zone increases to the east. In the west it forms a blind thrust and asymmetric anticline whereas in the east it expands into a reverse fault/thrust complex. A progressive evolution from reverse faults/thrusts to strike-slip fault movement resulted in a tectonic pop-up, culminating in gravitational collapse along normal faults with listric profiles that flatten out within 100–200 metres of the present erosion surface. Megabreccias formed during deposition of the Sussex Group are contemporary with reverse fault/thrusts. The geometry of the various faults is best explained by progressive deformation within an overall right-lateral strike-slip regime under general shear, with early formed features rotating both congruently and incongruently to the main IMDZ boundaries. Further complexity is a consequence of many reverse faults/thrusts and normal faults occurring close to a free surface and the latter a response to gravitational instability of the pop-up structure controlled by topography. A revised stratigraphy for the Sussex Group in the Indian Mountain Deformed Zone and its interpretation is integral to constructing the structural history. Two units, Stilesville Formation and Briggs Cross Formation, are formally defined here.

RÉSUMÉ

Le domaine méridional de la zone déformée du mont Indian (ZDMI) dans le sud-est du Nouveau-Brunswick correspond à une ceinture de décrochement dextre active au cours de la sédimentation du Tournaisien tardif (Carbonifère inférieur). Les roches du groupe de Sussex, qui représentent un cycle sédimentaire d'un affaissement à une inversion du bassin, occupent cette zone et reposent de façon discordante sur un socle cristallin, ce dernier constituant une partie exhumée du soulèvement de Westmorland adjacent (au sud) enfoui. La déformation est apparentée à des failles inverses/chevauchements, à des décrochements ultérieurs et aux failles normales les plus récentes. La zone de la faille Gorge dans le domaine méridional de la ZDMI recèle nombre de caractéristiques essentielles de l'ensemble de la zone. Le décalage de la zone de la faille Gorge augmente à l'est. Dans l'ouest, la zone forme un chevauchement aveugle et un pli anticlinal asymétrique, alors que dans l'est, elle s'élargit en un complexe de failles inverses/chevauchements. Une évolution progressive des failles inverses/chevauchements à un mouvement de coulissage a produit un soulèvement tectonique culminant en un effondrement gravitationnel le long de failles normales aux profils listriques qui s'aplanissent à moins de 100 à 200 m de la surface d'érosion présente. Des mégabrèches s'étant formées durant le dépôt du groupe de Sussex sont du même âge que les failles inverses/chevauchements. La structure géométrique des diverses failles est principalement liée à la déformation progressive à l'intérieur d'un régime de failles dextres subissant un cisaillement général, dont les caractéristiques

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les plus anciennes décrivent une rotation congruente et incongruente par rapport aux principales limites de la ZDMI. La complexité supplémentaire est attribuable à nombre de failles inverses/chevauchements et failles normales présents à proximité de la surface libre et ces dernières résultent d'une instabilité gravitationnelle de la structure de soulèvement régie par la topographie. Une stratigraphie révisée du groupe de Sussex dans la zone déformée du mont Indian et son interprétation font partie intégrante de l'élaboration de l'histoire structurale. Deux unités, les formations de Stilesville et de Briggs Cross, sont formellement définies aux présentes.

[*Traduit par la redaction*]

INTRODUCTION

The Lower Carboniferous sedimentary rocks of New Brunswick comprise deposits filling the southwestern part of the post-orogenic Maritimes Basin, a successor basin to the Acadian phase of the Appalachian orogen (Fig. 1; Williams 1974, see also St. Peter and Johnson 2009 and references therein). The 'Maritimes Basin' is a 'basin complex' lying on basement that is a tectonic collage of Appalachian terranes assembled during Silurian to middle Devonian (Fyffe and Fricker 1987; van Staal and Barr 2012). This collage continued to adjust along orogen-parallel faults until latest-Carboniferous to Permian time, marking the interaction of the Meguma terrane with the rest of the Appalachian collage during much of the Carboniferous, and its final docking in the Alleghenian (late Carboniferous–early Permian) orogenic phase (Waldron *et al.* 2015). The various depositional cycles preserved in the Maritimes Basin record a history of repeated subsidence and basin inversion, reflecting the way in which the basin complex formed over a basement still subject to overall right-lateral strike-slip tectonism and varying regimes of transpression and transtension (St. Peter 1993). Such complex histories have been recorded in other post-orogenic successor basins (see for instance Coward *et al.* 1989 on the Orcadian Basin and Allen *et al.* 1991, 1995 on the Junggar Basin).

The Indian Mountain Deformed Zone (IMDZ) exposed north and west of Moncton, New Brunswick (Fig. 2), contains Lower Carboniferous (Tournaisian) sedimentary rocks deposited during two subsidence-inversion cycles: the older Horton Group and younger Sussex Group (Fig. 3). The IMDZ is bounded on the north by the Smith Creek Fault, and on the south by the Berry Mills Fault—each of which marks the limit of exposed Lower Carboniferous rocks, which are buried to north and south beneath younger Carboniferous formations (Fig. 2; St. Peter 2006) filling respectively the Cocagne Subbasin and Moncton Subbasin (Figs. 1, 2). The two faults are members of a family of east-north-

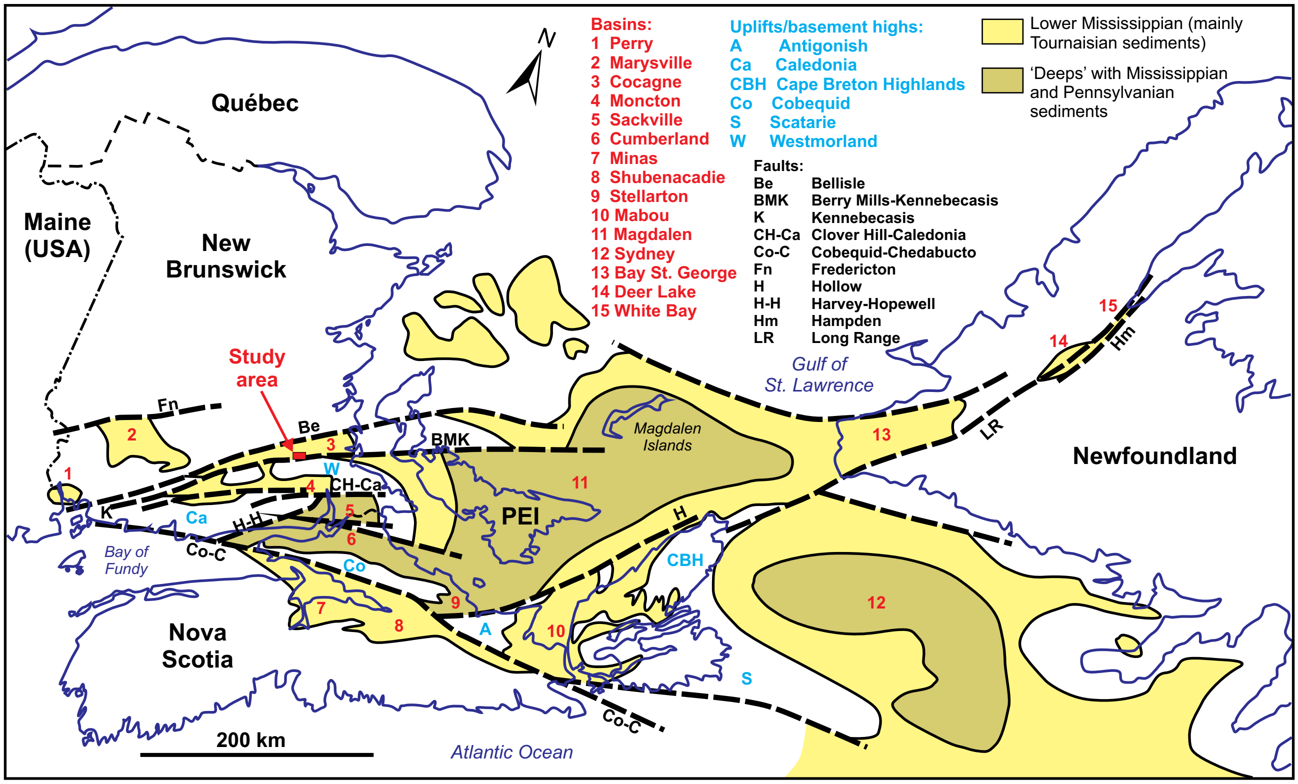


Figure 1. Location of the Indian Mountain Deformed Zone in the Maritimes Basin complex, eastern Canada, after St. Peter and Johnson 2009 (and references therein).

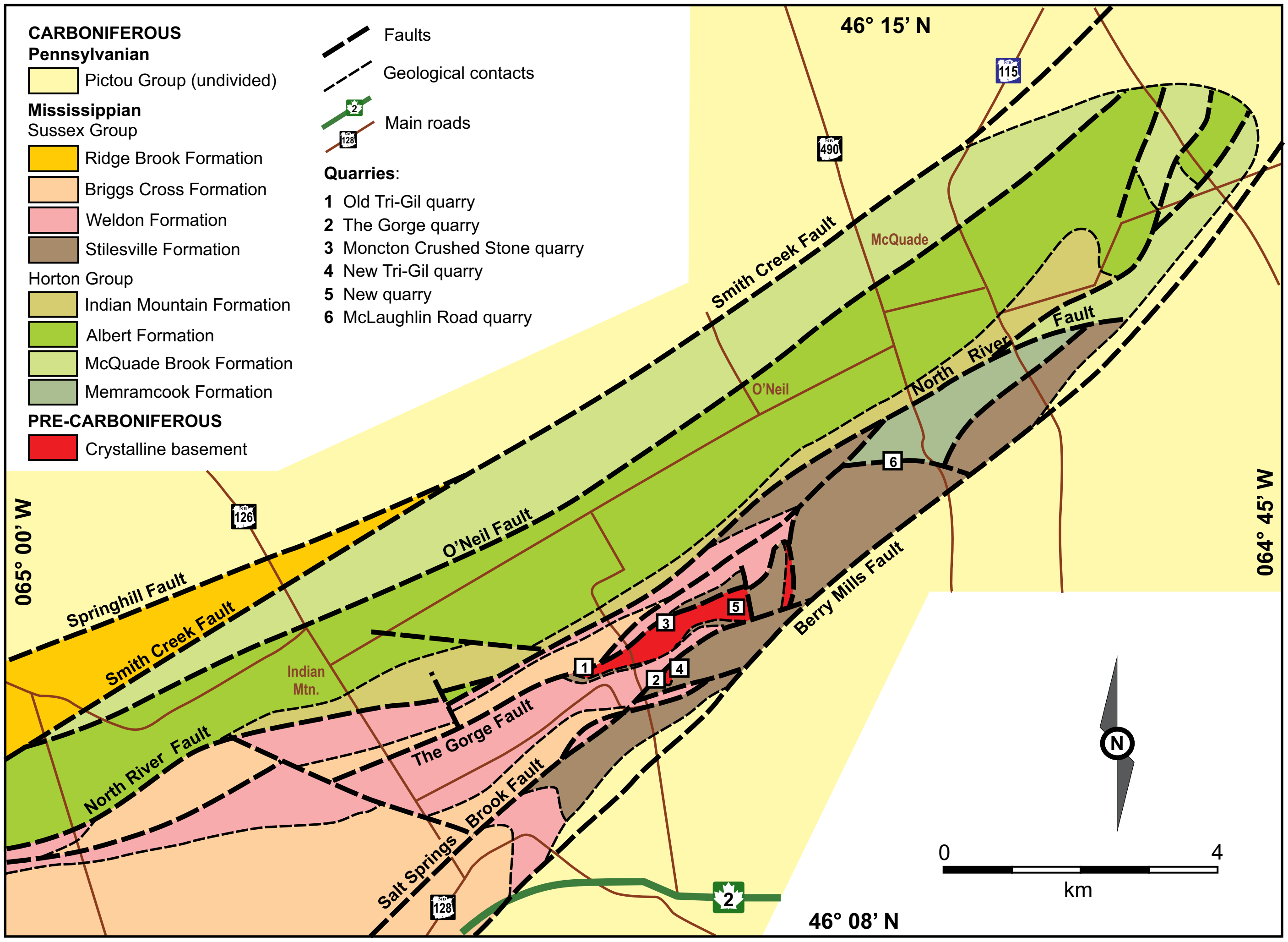


Figure 2. Geological map showing the distribution of Tournaisian (Lower Carboniferous) rocks in the Indian Mountain Deformed Zone (IMDZ), southeastern New Brunswick (after Park and St. Peter 2009). IMDZ is separated by the North River Fault into a northern and southern domain. Also shown are quarries cited in the text. The new quarry has been expanded considerably since 2009 and subsequent mapping by three of the authors (AFP, SJH and MJS) since 2010 is unpublished.

east-trending structures in southern New Brunswick, that are related to the post-Acadian orogen-parallel strike-slip faults that dominate the Appalachians of the Canadian Maritime provinces (Figs. 1, 2, 4; see St. Peter and Johnson 2009, and references therein; Waldron *et al.* 2015).

The IMDZ separates the Cocagne subbasin from the Moncton subbasin (Fig. 1), both of which contain a hydrocarbon play related to the Tournaisian Horton Group (specifically the oil shale source rock of the Frederick Brook Member in the Albert Formation). The evolution of this play is intrinsically connected to the tectonic development of the large strike-slip faults that traverse the Maritimes Basin, and the IMDZ and its contained faults, specifically the North River, Smith Creek, The Gorge, and Berry Mills faults; the latter two are related to the Kennebecasis Fault, a major strike-slip structure that can be traced to the southwest for over 100 km (Fig. 1). The importance of the IMDZ derives from the fact that it is the only example within the Maritimes Basin of one of these fault zones bringing pre-Carboniferous rocks to the surface, and where numerous stone quarries furnish excellent exposure. Other examples are known along the Clover Hill Fault southwest of Sussex and at Jordan Mountain, north of Sussex (related to the Kennebecasis Fault) but are not well exposed (Fig. 1). The results of detailed mapping of structure in the IMDZ can be contrasted with the way these strike-slip zones elsewhere within the Maritimes Basin can be imaged only on seismic reflection profiles.

The rocks and structures of the IMDZ were first comprehensively reviewed by Gussow (1953, see references therein for older workers), who identified the major east-north-east-trending faults. More detail was added by Leger and Williams (1986) who recognized the importance of reverse faults, including thrusts. A major remapping of the zone and detailed stratigraphic and structural analysis and reinterpre-

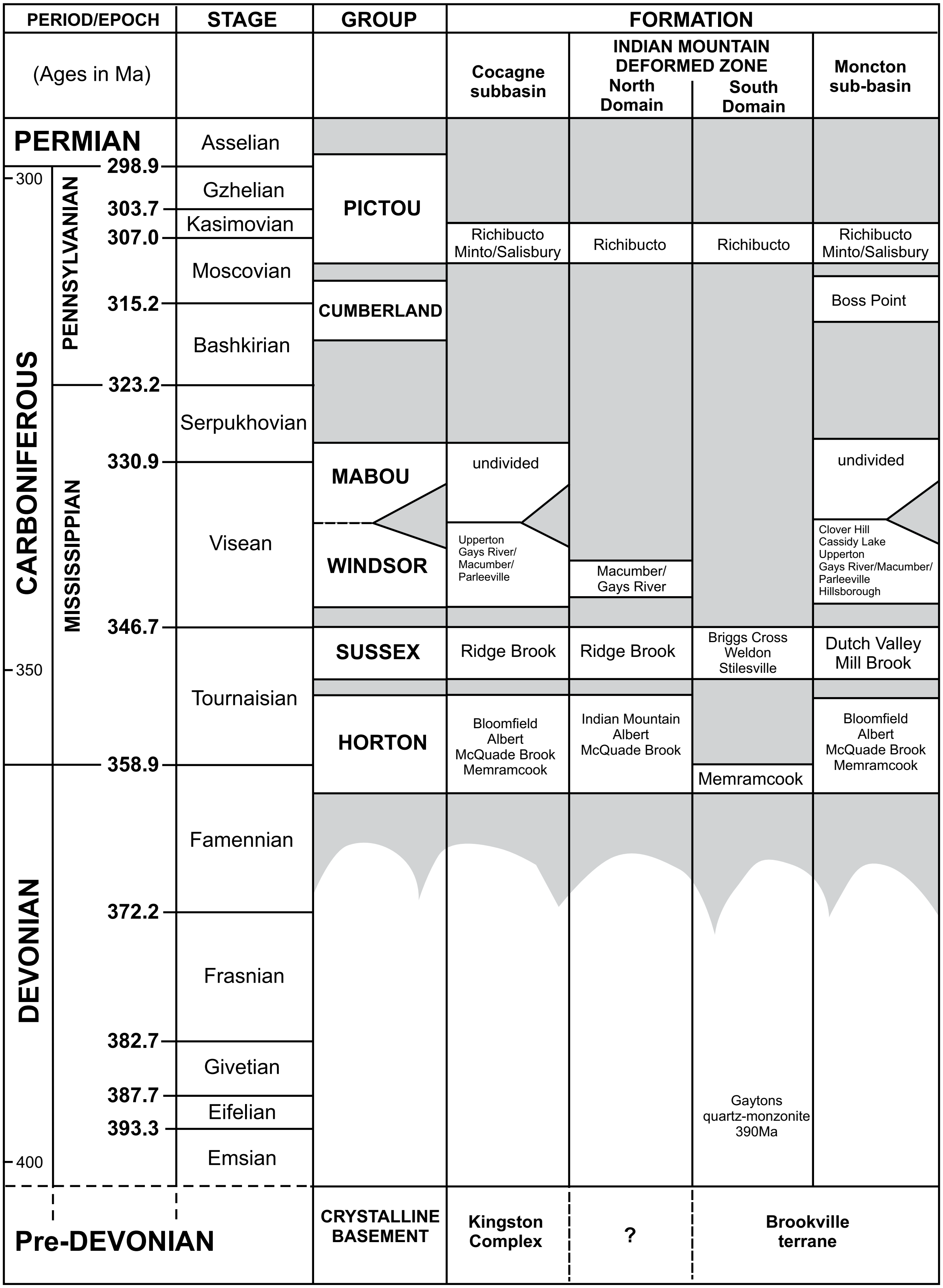


Figure 3. Stratigraphy of the northern and southern domains of the Indian Mountain Deformed Zone and the adjacent Lower Carboniferous subbasins (after Park and St. Peter 2009; St. Peter and Johnson 2009). Ages are from Cohen *et al.* (2013; revised 2023).

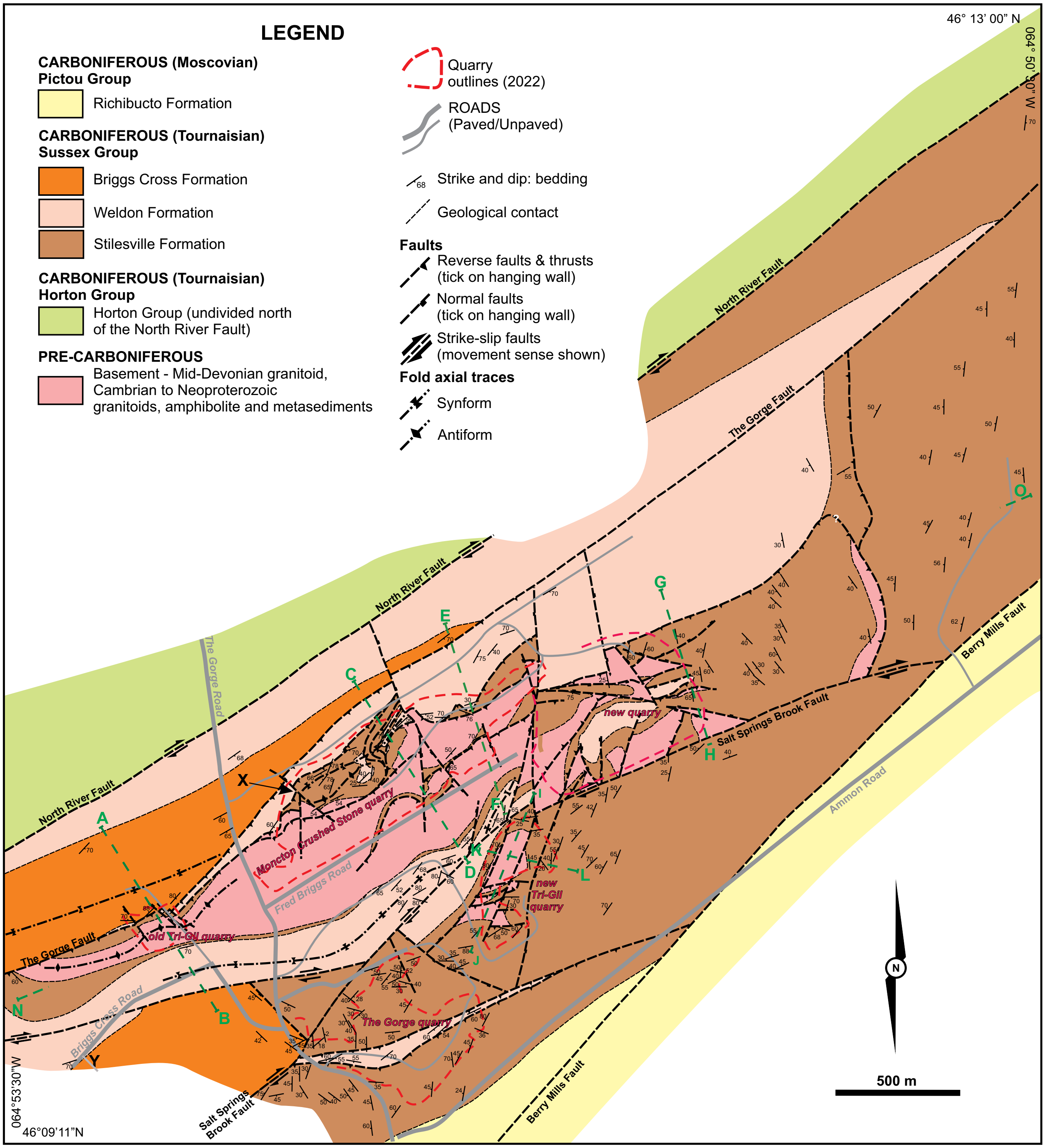


Figure 4. Detailed geological map of the area around The Gorge in the IMDZ showing structures discussed in the text and cited quarry locations (after Park and St. Peter 2009 and on-going mapping of the active and expanding new quarry). X and Y indicate the location of type sections for the Stilesville and Briggs Cross formations (see Appendix; Figs. 19, 20). Cross sections on lines A-B to G-H are illustrated on Figure 14, I-J and K-L are on Figure 11b, and N-O is on Figure 16.

tation were published by Park and St. Peter (2009, see Figs. 3, 4) and subsequent mapping in an expanded new quarry has been carried on by three of us (AFP, SJH and MRS) until 2022. Within the IMDZ a major subdivision is apparent, marked by the North River Fault (Fig. 4; Park and St. Peter 2009). This fundamental structure separates two domains of Lower Carboniferous rocks with radically different stratigraphic and structural histories. The domains were juxtaposed after deposition of the upper Tournaisian Sussex Group, and prior to the deposition of the Moscovian to Gzhelian Pictou Group (cf. Figs. 3, 4; see Park and St. Peter 2009 for details). Lower Carboniferous rocks in the northern domain lie on an unexposed basement presumed to be either the Silurian Kingston Group, or the Neoproterozoic–Lower Paleozoic Gander terrane(s) that underlies most of the platform of central New Brunswick (Fig. 3; Barr *et al.* 2002a; Fyffe *et al.* 2011). The Carboniferous rocks in the northern domain include both the Horton and Sussex groups within the exhumed Cocagne Subbasin (Figs. 1, 2). The oldest sedimentary units exposed here are coarse- to fine-grained red-buff sandstone and shale of the McQuade Brook Formation (Figs. 2, 3), overlain by grey shale, dolomitic marlstone, and minor sandstone and ironstone of the Albert Formation, and finally greenish to red and buff sandstone and shale, with minor ironstone, of the Indian Mountain Formation. These three units comprise the Horton Group. These rocks are folded and locally carry pencil cleavage or slaty cleavage. They are overlain with marked angular unconformity by the red pebbly sandstone and conglomerate of the Ridge Brook Formation, the representative of the Sussex Group north of the IMDZ. These younger rocks show none of the deformation noted in the underlying Horton Group.

The southern domain of the IMDZ has affinities with the largely buried Westmorland uplift (Figs. 1, 2)—a basement comprising the Brookville terrane: a late Neoproterozoic–Cambrian terrane containing a Tonian anorthosite complex, metasedimentary rocks of the Cryogenian Green Head Group, and a suite of late Ediacaran to Cambrian granitoid intrusions (White and Barr 1996; White *et al.* 2002; Miller *et al.* 2018). This terrane was also intruded by Devonian (Eifelian) plutons (Barr *et al.* 2002b, 2007). The overlying lower Carboniferous rocks consist of Horton and Sussex Group sedimentary formations with affinities to the Moncton Subbasin to the south (Figs. 1, 2, 3; 'Subbasin' here alludes to separate depocentres forming part of the Maritime Basin complex). Carboniferous cover to the Westmorland uplift reflects a complex history. Along the southern margin, which is partly fault-bound (St. Peter and Johnson 2009), Tournaisian formations overlap from the south and thin northwards. Locally Windsor Group and Cumberland Group overstep directly onto pre-Carboniferous basement. Though no post-Tournaisian pre-Moscovian units occur in the exposed IMDZ, some seismic reflection and borehole data suggest Windsor Group carbonate-evaporite lie in the subsurface immediately south of the Berry Mills Fault near the eastern part of the exposed IMDZ (St. Peter and Johnson 2009; Park and St. Peter 2009).

This contribution discusses the stratigraphy and structural history of the southern domain: the IMDZ south of the North River Fault. Details of the entire zone, its structure and stratigraphy are covered comprehensively in Park and St. Peter (2009; see also St. Peter 2006; St. Peter and Johnson 2009).

GEOLOGY OF THE SOUTHERN DOMAIN OF THE IMDZ

Basement rocks

Crystalline basement rocks forming part of the Westmorland uplift are exposed in the central part of the IMDZ, mainly in quarries around The Gorge (Fig. 4). They are preserved in a series of thrust slices and otherwise fault-bounded blocks. They consist of dioritic to granitic intrusions with screens and xenoliths of metasedimentary rocks typical of the Brookville terrane identified further west in southern New Brunswick (White and Barr 1996). The metasedimentary rocks are correlated with the Neoproterozoic Green Head Group, and one of the dioritic plutons exposed in the Moncton Crushed Stone quarry has been dated at 542 ± 2 Ma (U–Pb zircon; White *et al.* 2002), suggesting that it is related to the Ediacaran–Cambrian Golden Grove suite seen to the east near Saint John (Eby and Currie 1996; White *et al.* 2002). The basement rocks have also been intruded by a porphyritic quartz monzonite, which is locally foliated. Park and St. Peter (2009) correlated this lithology with the Gaytons quartz monzonite exposed 20 km east of Moncton, which has a Middle Devonian (Eifelian) U–Pb zircon age of 390.6 ± 1.0 Ma (Barr *et al.* 2007).

Tournaisian sedimentary rocks

Tournaisian sedimentary rocks in this area are subdivided into a lower Horton Group and an upper Sussex Group. For more details of this stratigraphy, including type sections and palynology see St. Peter (2006), Park and St. Peter (2009), and St. Peter and Johnson (2009) (Figs. 3, 4; Appendix).

Horton Group

The exposed Horton Group in the southern domain of the IMDZ consists solely of the Memramcook Formation. It is exposed in a triangular-shaped fault-bounded wedge lying to the east and northeast of the McLaughlin Road quarry (Fig. 2). The formation is dominated by pink to grey, coarse polymictic conglomerate (Fig. 5a) with lesser interbeds of grey siltstone and shale (Fig. 5b). In the type section on the Memramcook River near Gaytons (St. Peter and Johnson 2009), which lies about 25 km southeast of the McLaughlin Road quarry (St. Peter and Johnson 2009), conglomerate beds of the Memramcook Formation carry clasts of the Gaytons quartz monzonite with its distinctive red feldspar phenocrysts; however, in the McLaughlin Road quarry and the rest of the outcrops in the southern domain of the IMDZ, such monzonite clasts are not common. Within this southern domain of the IMDZ the finer-grained siltstone and shale in the Memramcook Formation carry a distinctive slaty cleavage.

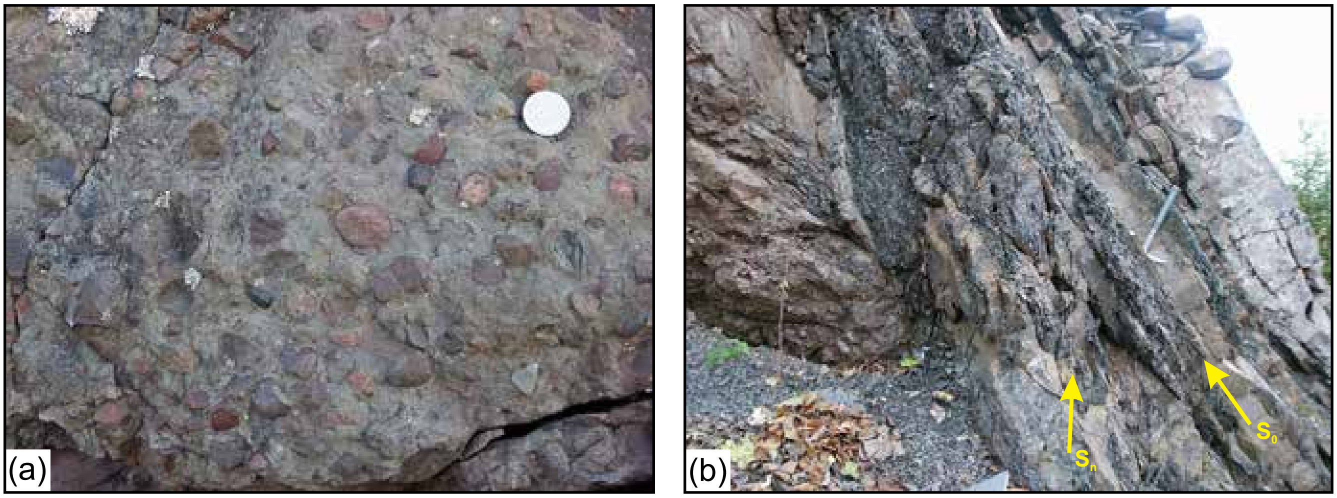


Figure 5. (a) Detail of the conglomerate of the Memramcook Formation in the McLaughlin Road quarry (see Fig. 2 for location). Coin = 2.8 cm diameter. (b) Sandstone, siltstone and shale layers in Memramcook Formation with slaty cleavage (arrow), McLaughlin Road quarry (see Fig. 2). Hammer for scale.

Sussex Group

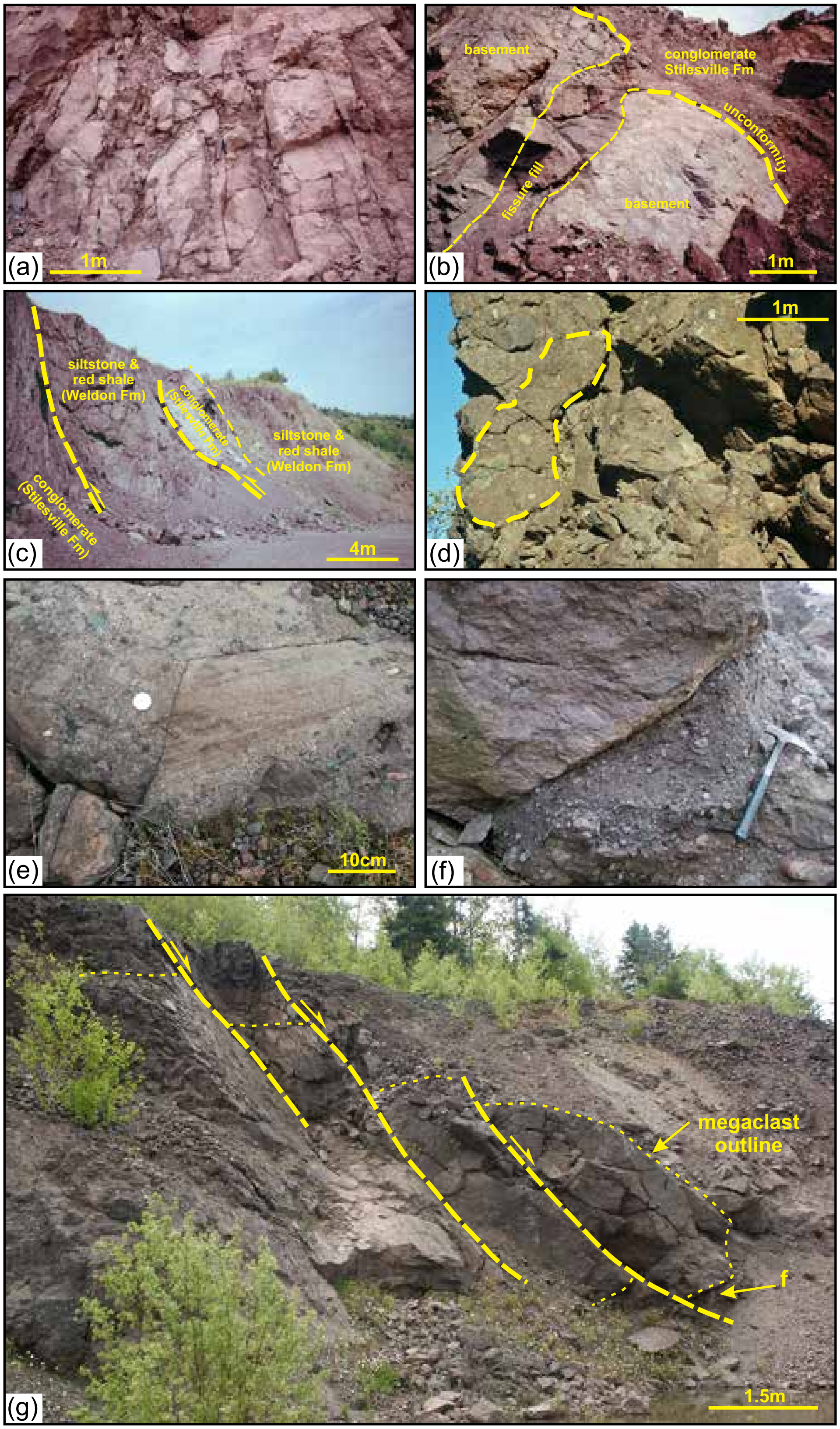
Rocks of the Sussex Group in the study area make up most the outcrop of the southern domain of the IMDZ (Fig. 4), where they are subdivided into three formations: a lowermost Stilesville Formation, a middle Weldon Formation, and an upper Briggs Cross Formation (Figs. 2, 3, 4). Details of the stratigraphy and late Tournaisian palynology of the formations in the Sussex Group, and regional lateral facies relationships among its formations in the IMDZ and the Moncton Subbasin, are provided in Park and St. Peter (2009) and St. Peter and Johnson (2009). The formal definitions of the Stilesville and Briggs Cross formations and their type sections are presented in the Appendix.

The Stilesville Formation (Figs. 2, 3, 4) consists mainly of polymictic conglomerate/breccia ranging from coarse to very coarse (at its coarsest clasts exceed 10 m diameter), interbedded with minor arkose, red siltstone and mudstone (Fig. 6a). Minor grey mudstone intervals contain plant detritus and late Tournaisian spores (Park and St. Peter 2009). The conglomerates are almost entirely derived from local basement and include the distinctive Middle Devonian Gaytons quartz monzonite with its large phenocrysts (2–4 cm) of red alkali feldspar (Barr *et al.* 2007). Other distinctive clasts include brown sandstone and shale from the Horton Group. This unit lies unconformably on the crystalline basement, and the contact is usually marked by a paleosol and fissure-fillings which can extend over 50 m below the unconformity. Part of this rotted zone includes megabreccia of basement rocks where blocks of granitoid rock are separated by fissures of conglomerate and argillic material in a three-dimensional network (Fig. 6b). The paleosol is usually marked by a zone of argillic alteration in the crystalline basement, and silcretes occur locally. Some of these silcretes contain opaline silica (showing little or no crystal structure in XRD analysis and being isotropic in thin section) implying that they have never been subjected to temperatures above 100°C or been deeply buried. The formation varies in thickness from less than 2 m to a maximum of around 250 m, and variations are controlled by paleo-topography on the unconformity. The sequence fines upward. The Stilesville Formation is interpreted as fanglomerate bodies marginal to the uplifted block of Westmorland uplift in the IMDZ. The megabreccias along the unconformity represent collapsed granitic tors.

One megabreccia unit within the Stilesville Formation is exposed in the McLaughlin Road quarry (Fig. 6d, e, f, g). The matrix is a pebble to cobble conglomerate with a friable arkosic matrix containing megaclasts up to 10 m in diameter consisting of indurated conglomerate identical to the underlying Memramcook Formation (Fig. 6d, f, g). There are also boulder-sized clasts of cleaved grey siltstone from the same source and blocks of feldspathic sandstone with abundant red alkali feldspar (Fig. 6e). These sandstone blocks have a striking resemblance to feldspathic and arkosic sandstones from the basal part of the Stilesville Formation exposed in the Moncton Crushed Stone quarry, and contrast markedly with the local Memramcook Formation sandstone with its paucity of red alkali feldspar debris.

The McLaughlin Road quarry megabreccia is not in the basal part of the Stilesville Formation. The unconformity with crystalline basement and the paleosol zone is not exposed here, nor are the bedded, coarse-grained feldspathic and arkosic sandstones seen farther west. The Weldon Formation that overlies the Stilesville Formation in the Moncton Crushed Stone quarry is also absent hereabouts and is seen to thin within the IMDZ toward the east. To the west of the McLaughlin Road quarry there is evidence of thrusts thickening the Stilesville Formation, so in the absence of the Weldon Formation marker it is difficult to judge just how high in the Stilesville succession this megabreccia unit lies. If the blocks of feldspathic sandstone are recycled from the basal part of the Stilesville Formation already indurated, then the position is well above the unconformity.

The Weldon Formation (Figs. 2, 3, 4) consists mainly of red, green, and grey mudstone, with minor interbeds of red or grey-green sandstone (Fig. 6c), brown shale and limestone. Its base interfingers with the upper part of the Stilesville Formation in the study area (Fig. 2). To the south and west of the study area it laterally interfingers with and is



overlain by the more typical red shale, siltstone, and sandstone of the Weldon Formation (Park and St. Peter 2009). The grey-green component of the Weldon Formation typically contains abundant evidence of deposition under arid conditions, such as desiccation cracks, and some of the limestone layers are nodular with characteristics of caliche. St. Peter (2006) and Park and St. Peter (2009) correlated this entire unit with the Gautreau Formation seen to the south in the Moncton Subbasin where evaporite and limestone are important (gypsum-anhydrite, halite, glauberite, and epsomite (St. Peter 2006). The Gautreau Formation was originally included in the Horton Group but was redefined as part of the Sussex Group by St. Peter and Johnson (2009); however, a recent restudy of the type area involving three of the authors (AFP, SJH and MJS, see also Macrae *et al.* 2017) considerably revised this correlation in the light of new palynology and newly acquired seismic reflection data. The grey-green assemblages in the Weldon Formation are now interpreted as distinct facies within this unit, also representing desiccated intervals in a lacustrine succession. The Weldon Formation is interpreted as a lake or lake margin succession subjected to repeated desiccation.

The Briggs Cross Formation consists largely of upward coarsening conglomerate, ranging from pebble to very coarse boulder. These rocks are interbedded with sandstone and shale. Most units are red-brown but some greenish mudstones with plant debris are present. Most clasts derive from the Westmorland uplift but are not as dominated by the Gaytons quartz monzonite as those of the Stilesville Formation. Clasts of Horton Group sandstone and shale are a minor component. This formation is also interpreted as fanglomerate marginal to the Westmorland uplift. Its total thickness is unknown, but at least 300 m are present beneath the sub-Moscovian unconformity that truncates the top of the Tournaisian section.

Younger Carboniferous rocks

The Viséan to Serpukhovian rocks of the Windsor and Mabou groups do not occur anywhere within the IMDZ. They occur to the southwest, where they outcrop around Havelock, and to the south in the Moncton area where they are known from outcrop and boreholes and have been interpreted in seismic reflection profiles (St. Peter 2006; St. Peter and Johnson 2009).

Only one outcrop of the sub-Moscovian unconformity and the overlying Moscovian to Gzhelian Pictou Group lies on the southern domain of the IMDZ north of the Berry Mills Fault (along the Ammon Road at GPS N 46˚ 52' 40", W 065˚ 52' 40"). These rocks are grey feldspathic micaceous sandstone and interfingered micaceous red mudstone of the upper Moscovian–Gzhelian Richibucto Formation (Pictou Group, Figs. 3, 4). The sub-Pictou Group distinctive grey-green conglomerate and sandstone of the Boss Point Formation (Bashkirian Cumberland Group) are not seen locally but are extensively preserved to the south and southeast in the Moncton and Sackville subbasins.

Faults

North River Fault

The North River Fault separates the northern and southern domains of the IMDZ (Figs. 2, 4, for details see Park and St. Peter 2009). Along most of its length it is a vertical structure, but locally dips steeply (75–80°) southward. All movement indicators seen at outcrop indicate right-lateral strike-slip motion. As the fault juxtaposes two domains of Tournaisian rocks and exits the eastern end of the exposed IMDZ without any offset on the sub-Moscovian unconformity (Fig. 4), its movement can be constrained only as post-Tournaisian and pre-Moscovian. The broad zone of deformation along the trace of this fault, 50 m wide in places, and incorporating wedges of Sussex and Horton Group rocks 50 m wide and several hundred metres long, indicate that it is the most fundamental structure within the IMDZ.

Salt Springs Brook Fault

The Salt Springs Brook Fault (Figs. 2, 4) lies parallel to the Berry Mills Fault, and can be traced from north of Petitcodiac into the exposed IMDZ at The Gorge, a distance of 40 km. At The Gorge it splits into several splays – at least three – two of which are eventually truncated by the Berry Mills Fault and one turns northeast into The Gorge Fault. It is generally a vertical structure. Where movement indicators are present, they are largely consistent with right-lateral strike-slip offset. Some left-lateral indicators occur in The

Figure 6. (previous page) (a) Thickly bedded coarse sandstone and conglomerate of the Stilesville Formation, east end of the Moncton Crushed Stone quarry (Fig. 2). (b) Fissure in crystalline basement filled with conglomerate of the Stilesville Formation extending down from the nonconformity seen near the top of the face. West end of Moncton Crushed Stone quarry (Fig. 2). (c) Thrust interlayering of Stilesville and Weldon formations. Central north side of Moncton Crushed Stone quarry (Fig. 2). (d) Megabreccia within the Stilesville Formation, with outline of one conglomerate megaclast (recycled indurated Memramcook Formation) highlighted. McLaughlin Road quarry (Fig. 2). (e) Clast of indurated conglomerate (Memramcook Formation with Horton Group sandstone clasts) in Stilesville Formation, McLaughlin Road quarry (Fig. 2). (f) Detail of 'g' showing boundary between an indurated conglomerate megaclast (Memramcook Formation) and the more friable conglomerate (Stilesville Formation) matrix. Hammer for scale. (g) Megaclast of indurated conglomerate (Memramcook Formation) in the Stilesville Formation, McLaughlin Road quarry (Fig. 2). The megaclast outline is highlighted, and it is offset by late normal faults (see text).

Gorge quarry (Figs. 2, 4) where south-trending splays also show top to the northeast reverse dip-slip motion. Locally the exposed fault zone contains dip-slip slickenlines.

In The Gorge area, where splays of the Salt Springs Brook Fault swing toward the northeast, they typically show reverse offset, with the fault planes inclined to the west and hanging walls moved to the northeast or east. Their dips remain steep (>60°). These observations are inconsistent with overall right-lateral movement sense if these structures were instantaneously related; however, evidence in The Gorge quarry suggests that strike-slip motion post-dated reverse fault movement. Similarly, in the old Tri-Gil quarry (Fig. 2), horizontal slickenlines consistently overprint down-dip slickenlines.

In The Gorge area a dramatic difference in thickness of the Stilesville Formation occurs across this fault, and similar but smaller changes in thickness are seen in the Weldon Formation. Both units more than double in thickness from north to south, implying that this fault exercised some control on topography during Sussex Group deposition.

The Gorge Fault and related structures

The largest and best exposed of the structures in the southern domain of the IMDZ is The Gorge Fault (Fig. 4), best exposed in the old Tri-Gil quarry (Figs. 4, 7). It was analysed by Leger and Williams (1986) who recognized both dip-slip (thrust) and strike-slip elements of offset. The Gorge Fault dips southward generally at an angle around 40 to 50°, and in several localities crystalline basement rocks lie in the hanging wall beneath Stilesville Formation. The footwall is generally comprised of rocks of the Sussex Group—mainly Briggs Cross Formation, but locally Weldon and Stilesville formations are also present (Fig. 4).

Tracing The Gorge Fault to the east of Gorge Road through the Moncton Crushed Stone quarry and farther east has proven problematic, and most interpretations published to date (Park and St. Peter 2009; St. Peter and Johnson 2009) show its continuation north of the Moncton Crushed Stone quarry with Stilesville Formation or basement in its hanging wall, and Weldon or Briggs Cross Formation in the footwall (Fig. 4). The problem has hinged on deciding which, if any, of several thrust faults exposed in the Moncton Crushed Stone quarry east of Gorge Road could be correlated with the single structure seen in the old Tri-Gil quarry to the west.

The trace of The Gorge Fault through the old Tri-Gil quarry is offset by a series of small north-northwest trending cross faults (Fig. 7). Offset on these vertical cross faults appears to be predominantly dip-slip; thus, the trace of The Gorge Fault is divided into a series of panels which expose different levels of the larger and earlier reverse structure (Figs. 7, 8, 9a, b and d). The hanging wall is crystalline basement overlain by Stilesville Formation which includes a megabreccia associated with the basal Sussex Group paleosol. These rocks are overlain by red shale and sandstone (including a quartz-pebble conglomerate) of the Weldon Formation, which are in turn overlain by red-brown conglomerate and minor grey shale of the Briggs Cross Formation. These units of the hanging wall are disposed about an open anticline overturned to the north, such that at the north end of the quarry the Weldon and Briggs Cross formations are vertical or slightly overturned and younging north (Figs. 7, 8), whereas at the south end of the quarry they dip gently south and young to the south.

In the footwall the exposed rocks in the old Tri-Gil quarry are mainly red-brown conglomerates of the Briggs Cross Formation, dipping steeply south or vertical, and younging north (Fig. 7). They represent beds overturned on the southern limb of a syncline, the axis of which lies about 150 m north of the quarry (Fig. 4). To the west Weldon Formation is present beneath these conglomerates (Fig. 2) but is not seen in the footwall in the quarry.

Between cross-faults in the central segment of the quarry, basement and Stilesville Formation megabreccia occur in both footwall and hanging wall of a single plane of The Gorge Fault (Fig. 9b, c), with wedges of Weldon Formation smeared along the fault (Fig. 8). This is the deepest level of the fault exposed (Figs. 7, 8). In the west face of the quarry basement and megabreccia of the Stilesville Formation in the hanging wall overlies red-brown conglomerate of the Briggs Cross Formation in the footwall, and intervening Weldon Formation is preserved as red shaly gouge with red sandstone knockers along the fault plane (Fig. 9a). This area represents an intermediate level (Figs. 7, 8) of The Gorge Fault. Along the east side of the quarry the highest levels are exposed, with a remnant of the vertical, northward-younging Stilesville-Weldon succession preserved in the hanging wall, overlying a thick, overturned Briggs Cross Formation section preserved in the footwall (Fig. 9d). Critically, where the plane of The Gorge Fault rises above the level of basement and Stilesville megabreccia in the hanging wall, the fault plane splits into an array of splays with no clear 'main fault' (Figs. 8, 9d).

In the Moncton Crushed Stone quarry to the northeast, no single trace of The Gorge Fault remains. Instead, basement rocks and the Stilesville, Weldon, and Briggs Cross formations are juxtaposed along thrusts and reverse faults that are largely splays of the main structure. The overall form seen in cross section across the entire Moncton Crushed Stone quarry north of an unnamed structure running along the southern edge of the pits is of a severely disrupted anticline overturned toward the north. This feature suggests that The Gorge Fault dies out upward along splays into an anticline—thus the present erosion level represents the exhumation of what was originally a blind thrust/reverse fault.

In the old Tri-Gil Quarry it is common for the east-northeast faults, including The Gorge Fault and its splays, to carry conspicuous sub-horizontal slickenlines (Fig. 9c). Where down-dip slickenlines are also present the sub-horizontal set overprints. Motion sense in the sub-horizontal set is invariably right-lateral. Movement history here evolved from being reverse structures with dip-slip movement top-to-the-north, into strike-slip motion with a right-lateral sense.

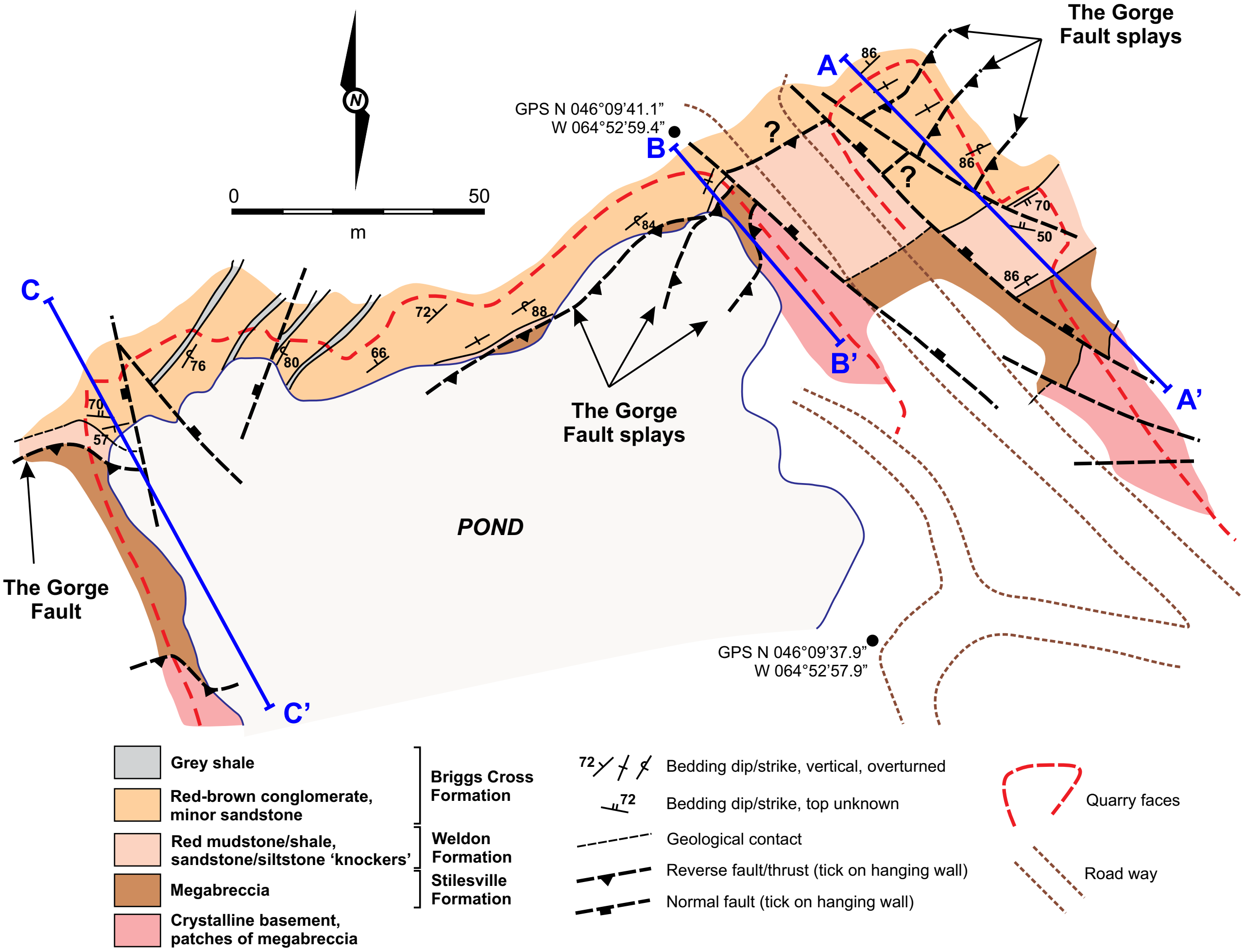


Figure 7. Geological map of the old Tri-Gil quarry (Fig. 4), after Park and St. Peter 2009 (their fig. 27) with various depths along The Gorge Fault preserved in normal fault-bounded panels. Sections A-A', B-B' and C-C' were used to construct the composite section in Figure 8.

Both occurred before The Gorge Fault was segmented by the north-northwest-trending cross faults (Fig. 7).

Other reverse faults

The reverse faults and thrust faults seen in the Moncton Crushed Stone quarry main pit are all south-dipping structures, some of which juxtapose slices of basement rocks in their hanging walls over Sussex Group in their footwalls. More generally, they carry Stilesville Formation in hanging walls, over Weldon Formation in footwalls. In most of these structures, offset appears to be much less (30–40 m at most, generally 20 m) than in the main outcrop of The Gorge Fault where it is a single structure (50–100 m)—consistent with the entire structure dying out upward into splays. Where faulted slices contain basement rocks the unconformity can be traced through the entire quarry (Fig. 4). Very marked strain partitioning is also a feature of the deformed Sussex Group rocks in the Moncton Crushed Stone quarry, especially in the Weldon Formation, where highly sheared mudstone can be juxtaposed within metres of mudstone in which primary features like desiccation cracks and trace fossils are preserved without any strain other than minor fault planes (Fig. 10a).

Movement indicators are abundant in the Moncton Crushed Stone quarry, especially where the coarse conglomerates of the Stilesville Formation override the mudstones of the Weldon Formation. They are everywhere dip-slip, either directly down-dip, or steeply inclined and oblique toward the southwest. The most common indicators are large grooves in mudstone related to boulders in the overlying conglomerate (Fig. 10b). Mudstone is generally very deformed along these grooves, but in a plastic fashion with no brittle fracturing—implying that the mudstone was not completely dewatered at the time. The grooves are interpreted as rheoplasts.

Along the southern edge of the Moncton Crushed Stone quarry an un-named fault forms a steep structure that is either vertical or dipping to the south between 75 and 80° (Fig. 4). In the deep benches of the quarry basement rocks form both walls, but in the higher benches wedges of Stilesville Formation are preserved. In these wedges the paleosol

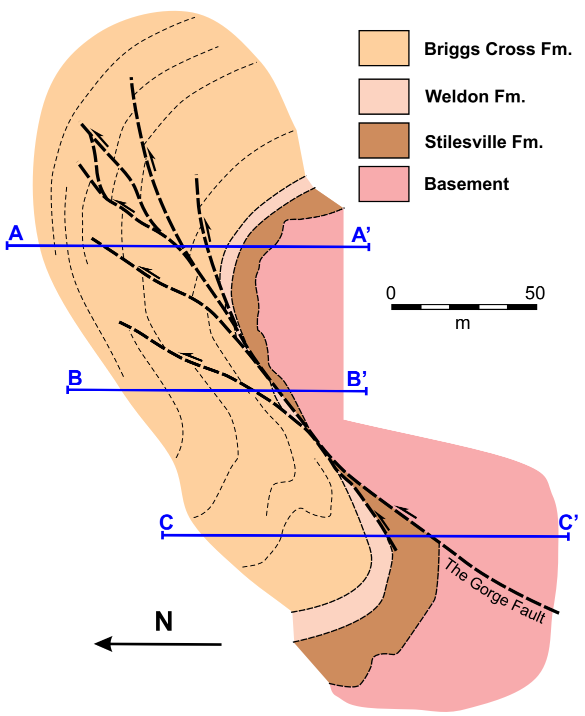


Figure 8. Composite section through The Gorge Fault as seen in the old Tri-Gil quarry (Fig. 4). See Figure 7 for the location of sections A-A', B-B' and C-C'.

and unconformity with the basement are intact along their northern edges, whereas their southern margins are marked by fault gouge (Fig. 4). The Stilesville Formation here is usually a pebble to cobble conglomerate or feldspathic sandstone and is tightly folded. The relationship of this fault to The Gorge Fault to the north cannot be demonstrated in outcrop, but movement indicators consistently show south-side-up. Using the displacement of the sub-Stilesville unconformity, offset along this fault must be at least 100 m.

Thrusts and reverse faults occur south of these large quarries; an example in The Gorge quarry shows hanging wall Stilesville Formation over footwall Weldon Formation. This fault can be traced into the splays of the Salt Springs Brook Fault. To the northeast in the new Tri-Gil quarry the basement-Stilesville Formation unconformity is repeated three times in a series of thrust imbricates, all dipping south with movement top-to-the-north (Fig. 11a, b). In the same quarry, a southward-directed thrust also carries basement in the hanging wall over Stilesville Formation in the footwall (Fig. 11a).

East of the Moncton Crushed Stone quarry thrust relationships become more complex (Fig. 4). The pattern of basement in hanging walls over Sussex Group in footwalls remains, but the direction of thrust orientation and movement is more variable. At least two thrusts dip west, with kinematic indicators showing movement to the east. One of these thrusts, east of the quarries, carries a narrow wedge of basement in the hanging wall. In the new quarry east of the Moncton Crushed Stone quarry, a south-directed thrust (dipping northward) offsets a north-directed (south dipping) thrust (Figs. 4, 11c).

Fault-related folding

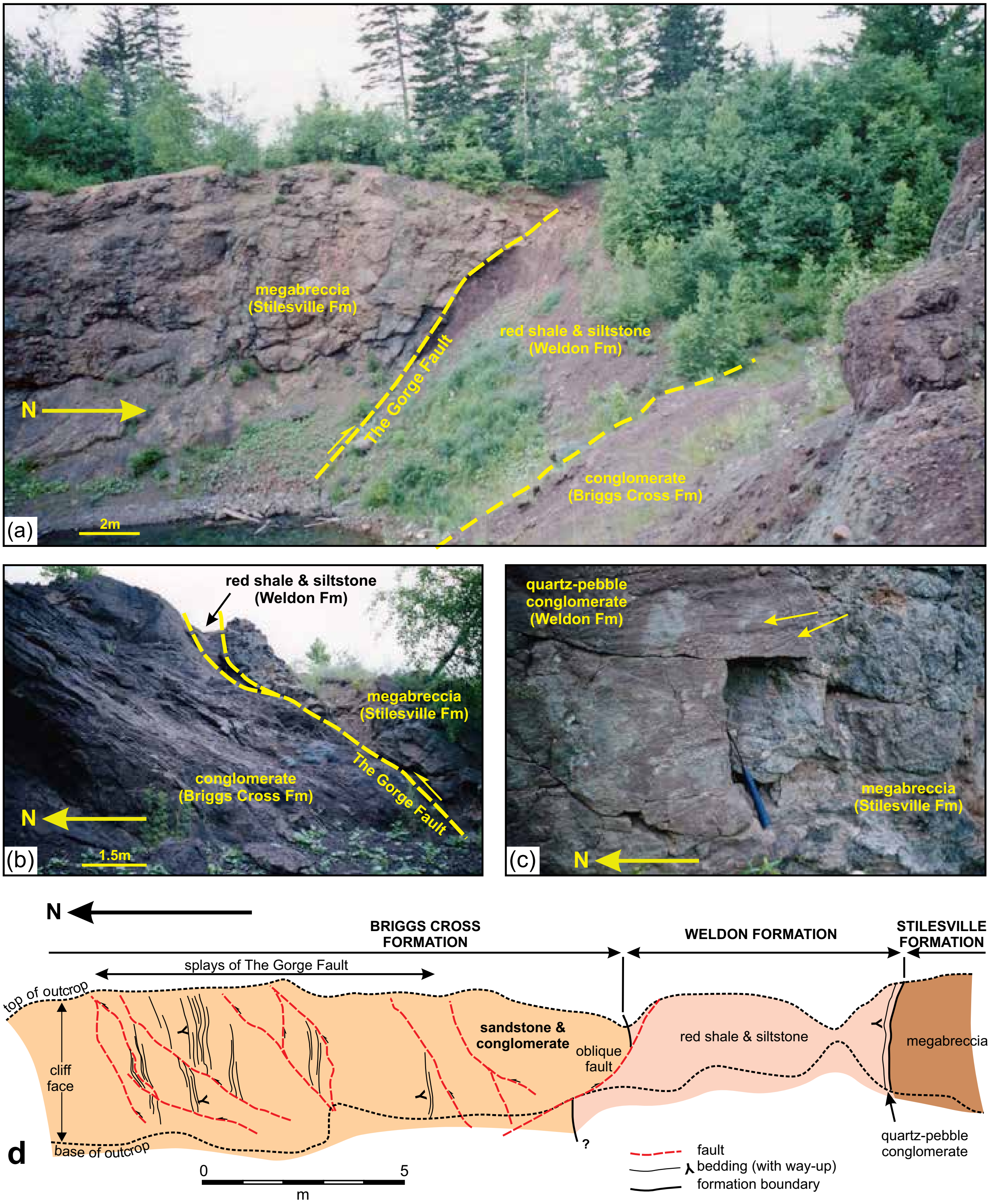
The largest scale fault-related folding exposed (rather than mapped) is the overturned anticline-syncline pair at the old Tri-Gil quarry, with the anticline in the hanging wall of The Gorge Fault (Figs. 4, 7). Traced eastward The Gorge Fault splays and dies out into this structure in the manner of a blind thrust. Other hanging wall anticlines on a smaller scale are seen in the Moncton Crushed Stone quarry. Some folds there are very tight, almost isoclinal in profile (Fig. 12a). Like many of the small-scale structures associated with these thrusts the style of deformation is plastic, with the more 'competent' sandstones showing little or no brittle fracturing accommodating the deformation (Fig. 12a, b). In siltstone and shale of both the Stilesville and Weldon formations these small-scale folds commonly have strongly curvilinear hinge-lines, and at least one example from the central part of the Moncton Crushed Stone quarry is a true sheath fold, in which the hinge rotates through more than 120° in the axial plane (Fig. 12c, d).

At the northwest corner of the Moncton Crushed Stone quarry these early thrust-related folds are refolded by a very steeply plunging (ca. 75° E) fold pair, forming a z-fold related to an unexposed strike-slip fault that lies to the north of the quarry. This is the only major left-lateral strike-slip structure seen in the southern domain of the IMDZ with an unambiguous relationship to the reverse faults. Significantly, it is later than the thrusts. Clear left-lateral indicators and thrusts in The Gorge quarry are related to the Salt Springs Brook Fault, but the important refolding or cross-cutting relationships are not preserved. These folds also display a lot of brittle accommodation of deformation in their tight hinges, with the more competent sandstone being extensively fractured. Unfortunately, limited exposure does not permit elucidation of the relationship between this strike-slip fault

Figure 9. (next page) (a) West end of the old Tri-Gil quarry approximately section C-C' from Figures 8 and 9, where Stilesville Formation megabreccia is in the hanging wall of a reverse fault/thrust (The Gorge Fault), and Weldon Formation and Briggs Cross Formation occur in the footwall. (b) Eastern wall above the pond in the old Tri-Gil quarry (Fig. 8) approximating to the section B-B'. Stilesville Formation megabreccia is in the hanging wall of The Gorge Fault and overturned Briggs Cross Formation conglomerate in the footwall. A wedge of Weldon Formation (red mudstone) is preserved in the fault zone at the top of the face. (c) Detail of the top of the Stilesville Formation (a pebble conglomerate) at the right end of Figure 9d showing horizontal slickenside lineations (arrows). Hammer for scale. (d) Sketch of the eastern face of the old Tri-Gil quarry (Fig. 7) from a photomosaic. The Gorge Fault here has dispersed into several splays approximately at the level of section A-A' in Figures 7 and 8.

and the later normal faults that offset the earlier thrusts. By analogy with the North River Fault, it is assumed to be a relatively late feature.

Minor folds exposed along Gorge Road near the entrance to The Gorge quarry in Sussex Group rocks (mainly Weldon Formation) generally show the same vergence as the



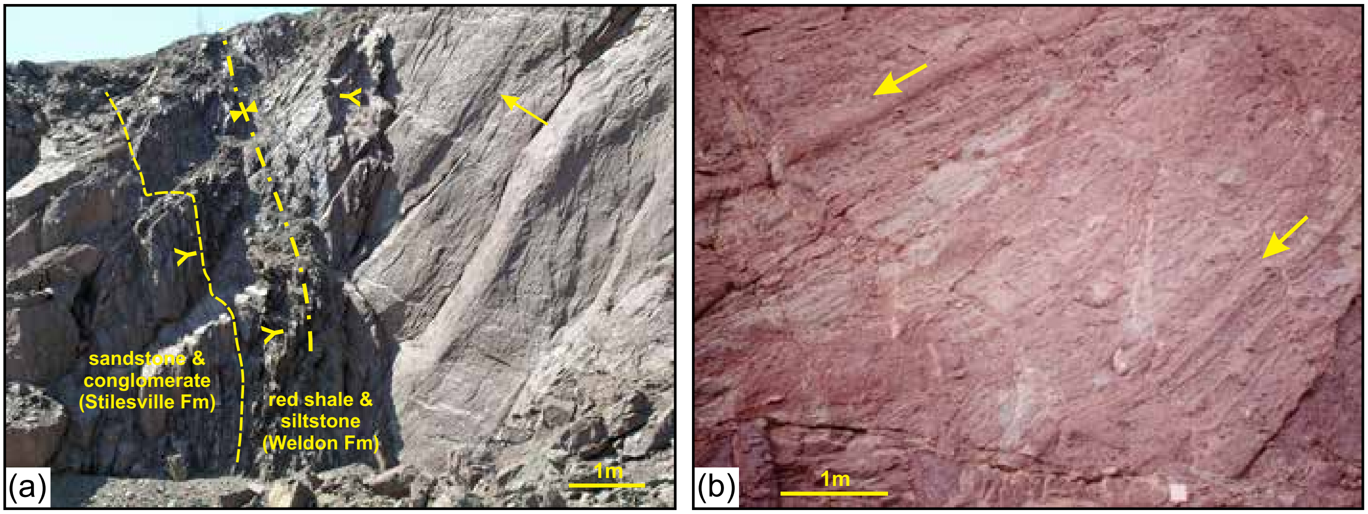


Figure 10. (a) Highly sheared mudstone of the Weldon Formation in a tightly folded enclave (synclinal keel) within Stilesville Formation. The arrow indicates a bedding plane with preserved desiccation cracks illustrating the partitioning of deformation. West end of the Moncton Crushed Stone quarry (Fig. 2). (b) Rheoplastic grooves and ridges (arrows) on a bedding plane between coarse conglomerate and mudstone within the Stilesville Formation, central north side of the Moncton Crushed Stone quarry (Fig. 2).

reverse faults/thrusts, i.e., south over north (Fig. 13a). There are exceptions, including an asymmetric conjugate pair related to a reverse-sense minor fault verging southward (Fig. 13b, c), and an overprinted pair of folds with an early set with northward vergence, overprinted by a southward vergent structure (Fig. 13d). In the same location, there are also examples of folds overprinting layers displaying earlier extensional boudinage (Fig. 13e)—the overprinting folds showing north-over-south vergence, or both northward and southward vergence (Fig. 13f).

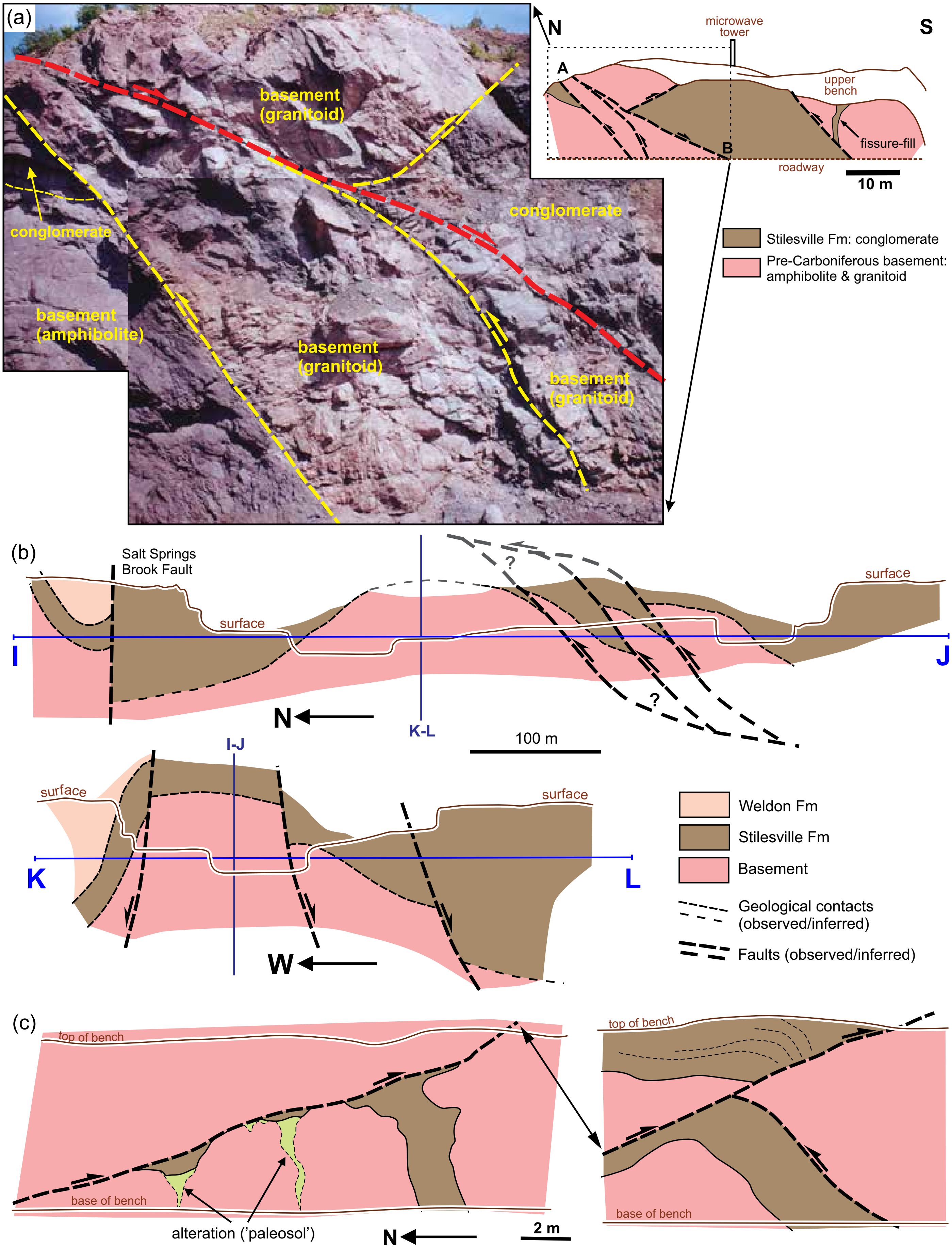
Normal faults

Normal faults in the southern domain of the IMDZ generally trend northward or northwestward, and include the cross faults already mentioned in the old Tri-Gil quarry offsetting the trace of The Gorge Fault. These are a distinct sub-group of near-vertical structures. The other sub-group of normal faults share the same overall trend, but show a more varied range of dips, between 30 and 75°. Significantly, neither sub-group appears to significantly offset the trace of the North River Fault, suggesting that they are unique to the southern domain, and pre-date this fundamental structure. A second distinct subgroup of normal faults trend closer to east-west and dip both north and south. Most of these are seen in the new quarry and McLaughlin Road quarry.

The largest group of normal faults offset the earlier reverse faults/thrusts (Fig. 12e) and they are variably dipping both eastward and westward, and generally display some degree of curvature where enough relief is present in their exposure – such as the 50 m vertical relief in the Moncton Crushed Stone quarry, where one such fault dips east at around 65° at the top of the highest bench, but has curved to a dip around 45° in the quarry floor. Other examples, such as those in the McLaughlin Road quarry, show similar curvature in a 10 m vertical section (Figs. 4, 6g). Such faults, exposed in the new Tri-Gil quarry, are associated with dramatic changes in thickness of the Stilesville Formation, implying that some are partly growth faults active during part of the deposition of this unit (Figs. 4, 11b). The visible curvature also suggests they are listric and flatten out at shallow depth—perhaps within 200 m of the current surface.

Where cross-cutting relationships can be established, most these normal faults offset the thrust faults, as is clearly seen in outcrop at the west end of the Moncton Crushed Stone quarry, and in the new Tri-Gil quarry (Figs. 11a, b, 12e).

Figure 11. (next page) (a) East face of the new Tri-Gil quarry (photomosaic and synoptic sketch) showing north- and south-dipping thrust faults offset by a later normal fault. The thrust faults trend nearly perpendicular to the face, whereas the normal fault is a steep structure only slightly oblique to the face. See Figure 4 for location details. (b) A north-south (I-J) and east-west (K-L) section through the new Tri-Gil quarry showing the south- dipping thrust faults and the variation in thickness of the Stilesville Formation across a basement high. See Figure 4 for location of the lines of section. (c) Sketch of two parallel bench walls in the new quarry (see Fig. 4 for location) showing a north-dipping thrust offsetting a south dipping-thrust. The bench walls are almost parallel to movement directions on both thrusts.


(a)
basement (granitoid)
conglomerate
basement (amphibolite)
basement (granitoid)
conglomerate
basement (granitoid)
N
microwave tower
S
A
upper bench
fissure-fill
B
roadway
10 m
Stilesville Fm: conglomerate
Pre-Carboniferous basement: amphibolite & granitoid
(b)
Salt Springs Brook Fault
surface
surface
?
?
I
J
N
K-L
100 m
I-J
surface
surface
K
L
W
Weldon Fm
Stilesville Fm
Basement
Geological contacts (observed/inferred)
Faults (observed/inferred)
(c)
top of bench
base of bench
alteration ('paleosol')
N
2 m
top of bench
base of bench

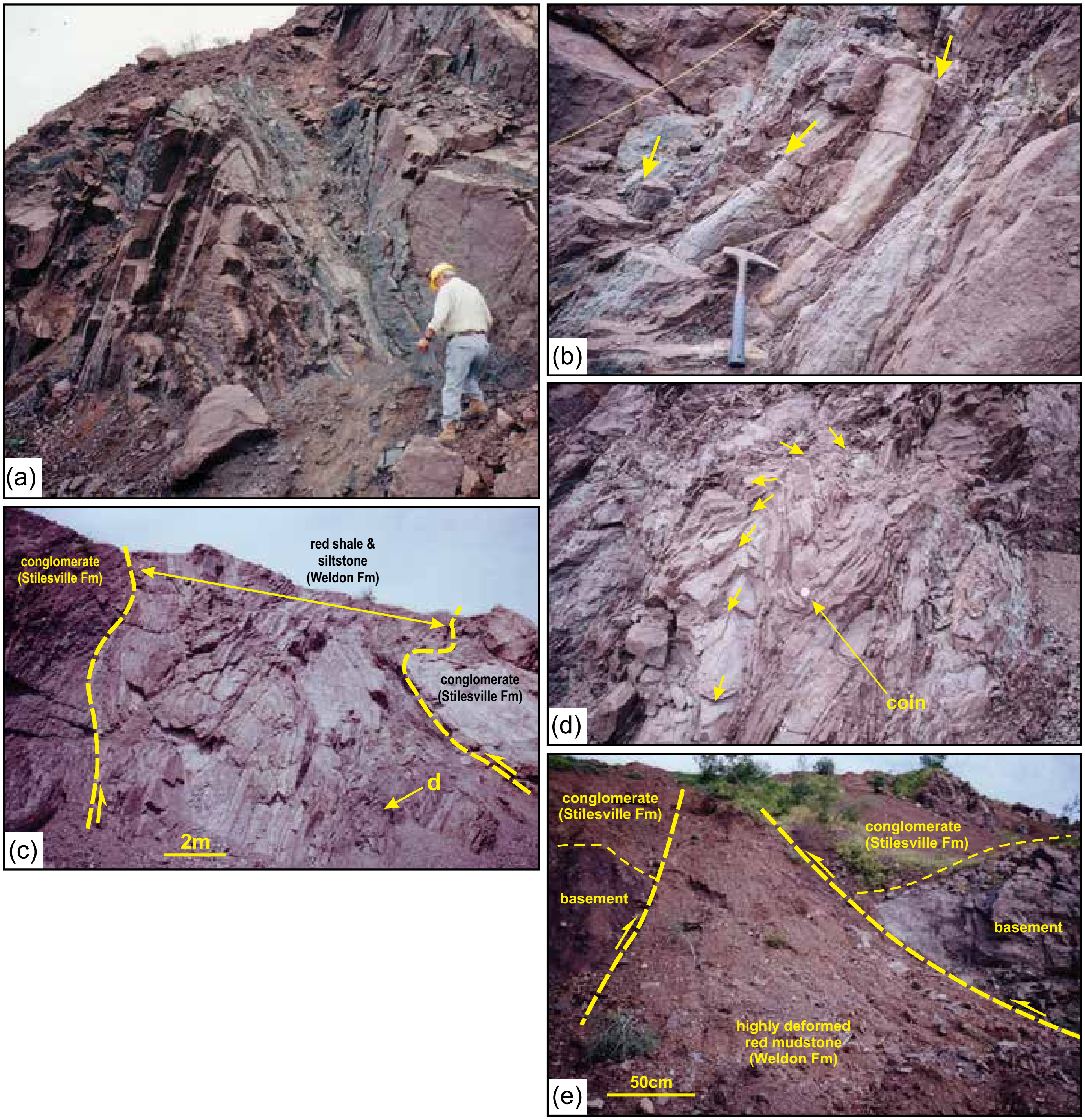


Figure 12. (a) Early fold in pebbly sandstone and mudstone of the Stilesville Formation. The face cuts a very oblique section through this fold which is almost isoclinal. Note the lack of fractures in the sandstone layers at the fold hinge. West end of the Moncton Crushed Stone quarry (Fig. 4). One of the authors for scale = 1.75 m. (b) Hinges of early folds of sandstone between mudstone layers (Stilesville Formation), west end of the Moncton Crushed Stone quarry. Hammer for scale. (c) North-central wall of Moncton Crushed Stone quarry with conglomerate of the Stilesville Formation interlayered by thrusting over mudstone/siltstone of the Weldon Formation, with thrust-related folds. Arrow shows location of Figure 12d. (d) Sheath fold in finely interlayered siltstone/mudstone of the Weldon Formation, arrows showing the plunge of the fold axis on each folded layer. See Figure 12c for location of the feature. Coin = 2.3 cm diameter. (e) Normal fault offsetting earlier thrust fault. West end of the Moncton Crushed Stone quarry (Fig. 4).

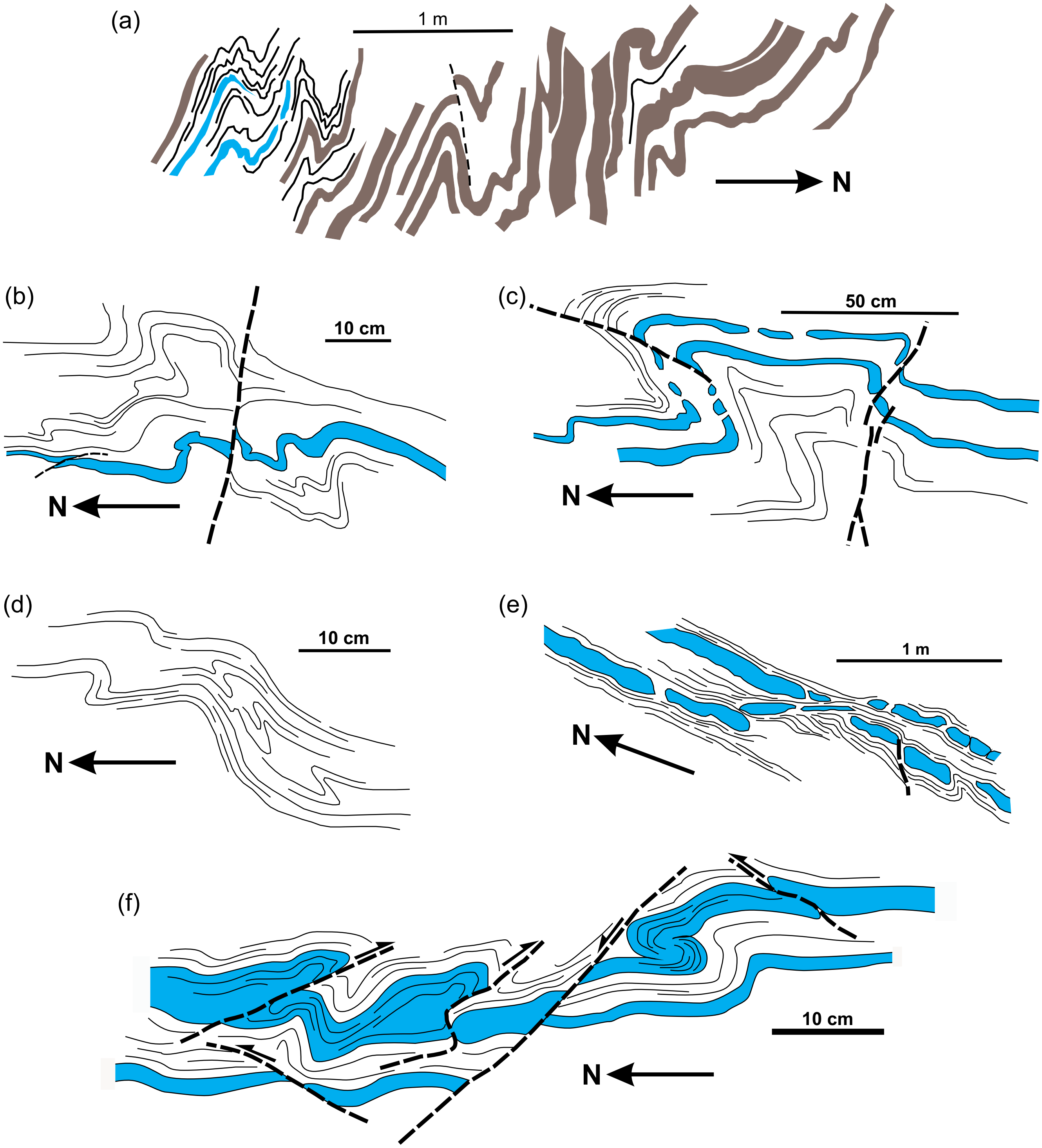


Figure 13. (a) Folded shale (no colour) with layers of limestone (blue) and sandstone (brown) of the Weldon Formation. Ditch alongside Gorge Road south of Fred Briggs Road (Fig. 4). Fold axes within 30° perpendicular to plane of sketch. (b) Limestone layers (blue) in grey-green shale of the Weldon Formation near the entrance to The Gorge quarry, Gorge Road (Fig. 4). Sketch profile is perpendicular to fold axes. (c) Conjugate folds and faults affecting limestone layers (blue) in grey-green shale of the Weldon Formation near the entrance to The Gorge quarry, Gorge Road (Fig. 4). Fold axes perpendicular to plane of sketch. (d) Fold overprinting in grey-green shale (south vergence overprinting north vergence) of the Weldon Formation near entrance to The Gorge quarry, Gorge Road (Fig. 4). Fold axes perpendicular to plane of sketch. (e) Limestone layers (blue) in grey-green shale of the Weldon Formation showing boudinage and layer-parallel extension. Ditch on Gorge Road near The Gorge quarry entrance (Fig. 4). (f) Limestone layers (grey) in grey-green shale of the Weldon Formation showing folds, boudinage and minor faults with both north and south vergence, near the entrance to The Gorge quarry, Gorge Road (Fig. 4). Fold axes are perpendicular to plane of sketch.

Megabreccias

Megabreccias were found in two stratigraphic positions in the southern domain of the IMDZ, one widespread throughout the domain is related to the paleosol at the base of the Stilesville Formation whereas the other lies within the Stilesville Formation and is restricted to one location—the McLaughlin Road quarry in the eastern part of the southern domain of the IMDZ (Fig. 2).

The megabreccia at the base of the Stilesville Formation is everywhere developed in crystalline basement rocks and takes the form of intersecting fissure-fills of arkose and conglomerate criss-crossing crystalline material, with or without extensive argillic alteration. This feature can extend 50 m below the unconformity at the base of the Sussex Group. It is most conspicuous in the central and western part of the Moncton Crushed Stone quarry, and in the northern part of The Gorge quarry, where it resembles tor-formation and tor-collapse in a zone where the overlying Stilesville Formation is thinner than usual—possibly representing a paleo-topographic high. Elsewhere, the basement blocks in the megabreccia are chaotically disposed in an arkosic or conglomeratic matrix, for instance in the old Tri-Gil quarry, The Gorge quarry, or along Gorge Road. This type of megabreccia grades into coarse boulder conglomerate. Crucially, the mega-clasts and boulders are all composed of local basement lithologies, dominated by the red-feldspar phenocryst-bearing Gaytons quartz monzonite, whereas the pebbly or sandy material contains abundant red-feldspar clasts.

The megabreccia within the Stilesville Formation is seen only in the McLaughlin Road quarry (Fig. 6d, e, f, g), juxtaposed by a fault with the Memramcook Formation (Fig. 2), a conglomeratic unit with intervals of grey siltstone-shale carrying a spaced slaty cleavage (Fig. 5b). The blocks in this megabreccia include basement lithologies and conglomerate and cleaved siltstone-shale of the Memramcook Formation. The coarse sand matrix of the Memramcook Formation is not as dominated by the red feldspars as is the Stilesville Formation unit, and critically, there are also boulders of red feldspar-dominated sandstone-conglomerate resembling indurated basal Stilesville Formation seen in the Moncton Crushed Stone quarry to the west (Fig. 6e, f). These fragments have angular to sub-rounded shapes and were evidently well-lithified prior to erosion and transport into this megabreccia. Local basement and Horton Group rock types are clearly contributing to this megabreccia, but there is also the possibility that indurated sandstone from the basal Stilesville Formation was being recycled here as well.

At least one thrust lies west of the McLaughlin Road quarry carrying basement and Stilesville Formation in the hanging wall over-riding Stilesville Formation in the footwall. This megabreccia and its location show that these thrusts were exhuming basement, Memramcook Formation, and the lowest part of Sussex Group rocks for erosion, but that the thrusts were in part over-riding their own debris.

STRUCTURAL HISTORY OF THE SOUTHERN DOMAIN OF THE IMDZ

The rapid lateral variations in thickness displayed by all three units of the Sussex Group suggests paleo-topographic control, and the large changes in thickness in the Stilesville and Weldon formations across the Salt Springs Brook Fault imply that some of this paleo-topography was fault-controlled, and specifically that some of the strike-slip faults were active during all stages of deposition.

The thrusts are in part related to the strike-slip movement, especially those thrusts seen in The Gorge quarry that are splays of the Salt Springs Brook Fault. All the thrusts seen in outcrop have fold structures related to them, which in the finer-grained lithologies and sandstone display plastic characteristics in all the Sussex Group rocks implying deformation before these sediments were fully dewatered. Folds of more competent sandstones can be tight or even isoclinal with no brittle fractures accommodating deformation in folds that are too tight to be produced by layer-parallel slip alone (Fig. 12a; Ramsay 1974; Tanner 1989). Other ‘soft sediment’ or rheoplastic features, consistent with deformation prior to complete dewatering, are the grooved lineation on conglomerate-mudstone boundaries (Fig. 10b) where slip has occurred either along thrusts or alongside layer-parallel slip within larger fold limbs.

The megabreccia within the Stilesville Formation exposed in the McLaughlin Road quarry, interpreted as debris from an exhumed hanging wall incorporated into a footwall of a thrust(s) east of the Moncton Crushed Stone quarry, suggests that thrust movement was contemporary with (latest?) Stilesville deposition. This interpretation is consistent with deformation of Stilesville and Weldon sediments soon after they were deposited. However, a corollary of this observation is that some Stilesville Formation lithologies (notably some of the conglomerates with arkose matrix) lithified very rapidly. The presence of silcretes in the lower part of the Stilesville Formation is consistent with this scenario. The nearest exposed thrust to these outcrops lies 300 m to the southwest along the ridge above Ammon Road (Fig. 4), and this structure carries Stilesville Formation in its hanging wall, with a wedge of crystalline basement. The fault that is exposed in the McLaughlin Road quarry juxtaposes the Stilesville Formation megabreccia with conglomerate and sandstone-siltstone of the Memramcook Formation. It is a south-southwest-dipping normal fault, downthrown on the south side, and belongs to the late set of normal faults related to the collapse of the IMDZ pop-up.

The early reverse fault/thrusts largely belong to that set of structures related to The Gorge Fault, and along its strike, from west to east, this feature varies from a partly breached asymmetric anticline/blind thrust, to a feature best termed an inclined ‘positive flower structure’ (Fig. 14). Within the quarries some 50 m relief shows that these faults, even the thrusts, root into reverse faults that are generally steeper than 65° toward the south. Construction of a truly balanced section is not possible because stratigraphic units do not

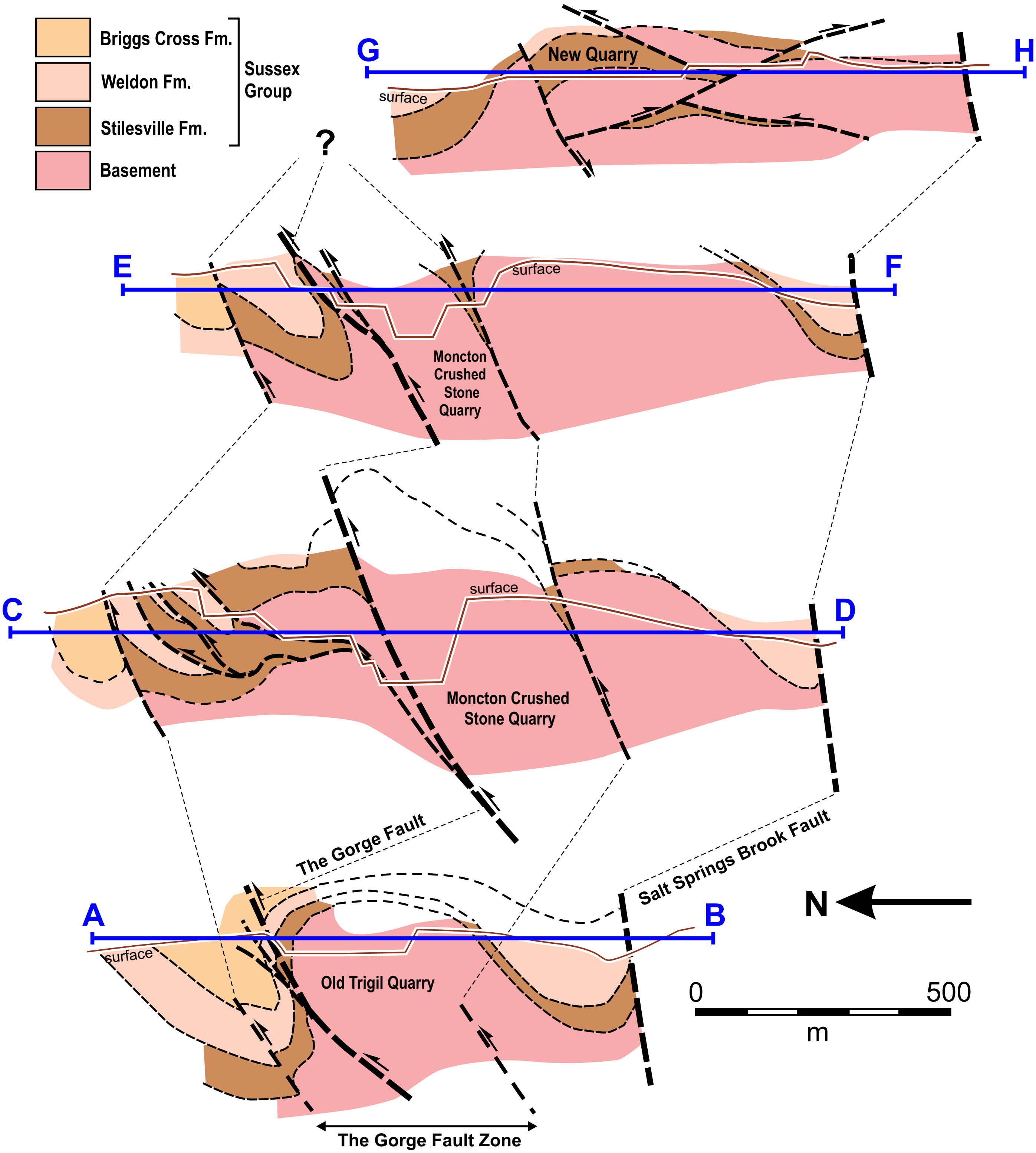


Figure 14. Serial geological cross sections through The Gorge Fault and related structures from the old Tri-Gil quarry, Moncton Crushed Stone quarry and new quarry. In section G-H some normal faults are omitted for clarity. See Figure 4 for lines of section A-B, C-D, E-F, G-H and locations.

have uniform thickness, and movement indicators show enough diversity of direction to negate the idea that any one vertical section even approximates to plane strain. However, using the Stilesville-basement unconformity as a marker there is at least 200 m cumulative displacement along the thrusts (Fig. 15a). In contrast, there is clearly nowhere near

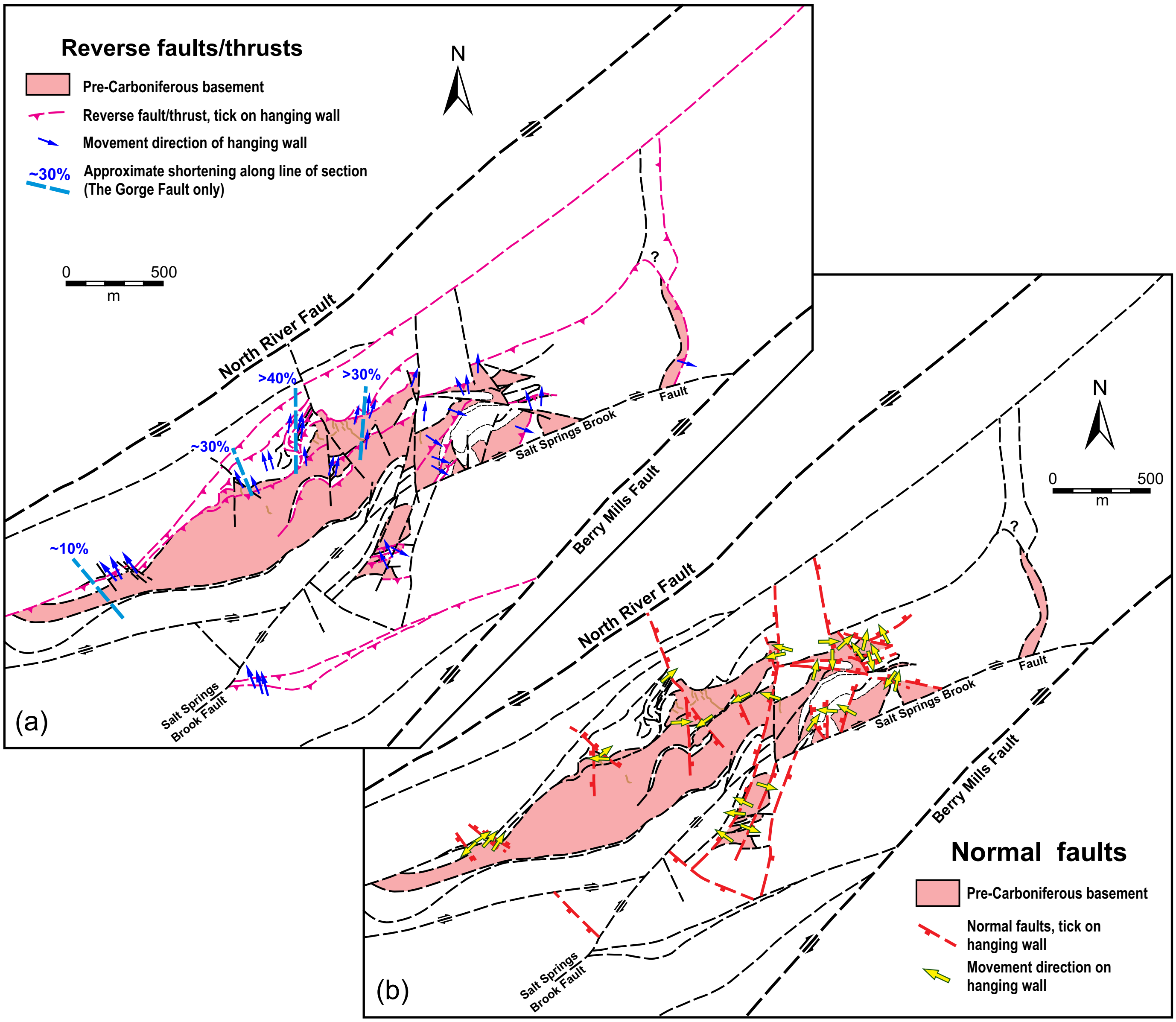


Figure 15. (a) Map showing major reverse faults/thrusts in The Gorge area with movement indicators and direction, plus estimates of shortening along selected lines of section (cf. Fig. 14). (b) Map showing major normal faults between The Gorge area quarries with movement indicators and directions (cf. Figs. 4 and 16).

this vertical displacement across The Gorge Fault zone in total (Figs. 8, 14, 15a). One way to accommodate this geometry is to have The Gorge Fault flatten out into a shallower southward-dipping structure within 500 m of the present surface. The outcropping steep reverse faults become ramps on this larger structure. Unfortunately, neither borehole nor seismic reflection data are available to provide control on this hypothesis, and other faults in this area where such controls do exist show no sign of becoming shallower-dipping with depth. Interpreting the entire zone as an asymmetric positive flower structure is probably the most realistic alternative.

Thrusts that have moved toward the south and even east, such as those seen in the new quarry, on the ridge 100 m to the east, and in the new Tri-Gil quarry are interpreted here as back-thrusts on the main structures (Fig. 14). The spread of movement directions observed is consistent with these fault blocks moving at shallow depth toward a free surface (Fig. 15a).

The relationship of thrusts to the right-lateral Salt Springs Brook Fault (Fig. 4), a fault whose earliest movements exerted some control on paleo-topography from Stilesville Formation deposition onwards, indicates deformation was ongoing throughout Sussex Group deposition. The general geometry of thrust movement is not only consistent with right-lateral transpression, but also upward movement of the southern domain of the IMDZ toward a free surface. Again, shallow tectonic levels are preserved here, a fact supported by the preservation of opaline silica in some Stilesville Formation silcretes.

Whenever sub-horizontal movement indicators are present on faults that also preserve evidence of steep reverse movement, such as those seen in the old Tri-Gil quarry especially, the strike-slip component overprints the reverse dip-slip component. Furthermore, the faults showing strike-slip movement are offset by later normal dip-slip faults. There is a general evolution from early south-over-north thrusting (with movement directions splayed from north-northwest to east-northeast, plus back-thrusts and one example of an eastward motion, (Figs. 14, 15a, b), to a right-lateral strike-slip motion. This motion was followed by normal faulting within the overall right-lateral strike slip regime (Fig. 15a).

Normal faults that offset the thrusts are generally shallowly flattening listric structures, and some seem to have influenced Sussex Group deposition. They were contemporary with latest Sussex Group deposition. If the thrusts represent uplift of part of the southern domain of the IMDZ during Sussex Group deposition, then the normal faults represent gravity collapse along faults at the end of Sussex Group deposition (Fig. 16). Some of the listric structures may flatten out within 200 m of the present surface and may have been controlled as landslide scars by paleo-topography rather than being a tectonic expression of transpression or transtension.

The normal faults of the listric sub-group, and the steep cross faults are all terminated against the trace of the North River Fault (Fig. 4), indicating that this fundamental structure juxtaposed the two domains of the IMDZ in their present configuration after these faults formed. The North River Fault is a pre-Moscovian structure, so by implication, the thrusts and listric normal faults of the southern domain of the IMDZ must be earlier still. This is an uppermost time constraint. The interpretation offered here is that most of the fault motion, especially on the thrusts and reverse faults of the southern domain of the IMDZ, occurred during deposition of the Sussex Group whereas the later normal faults postdated deposition of most, if not all, of Briggs Cross Formation. The IMDZ was related to right-lateral

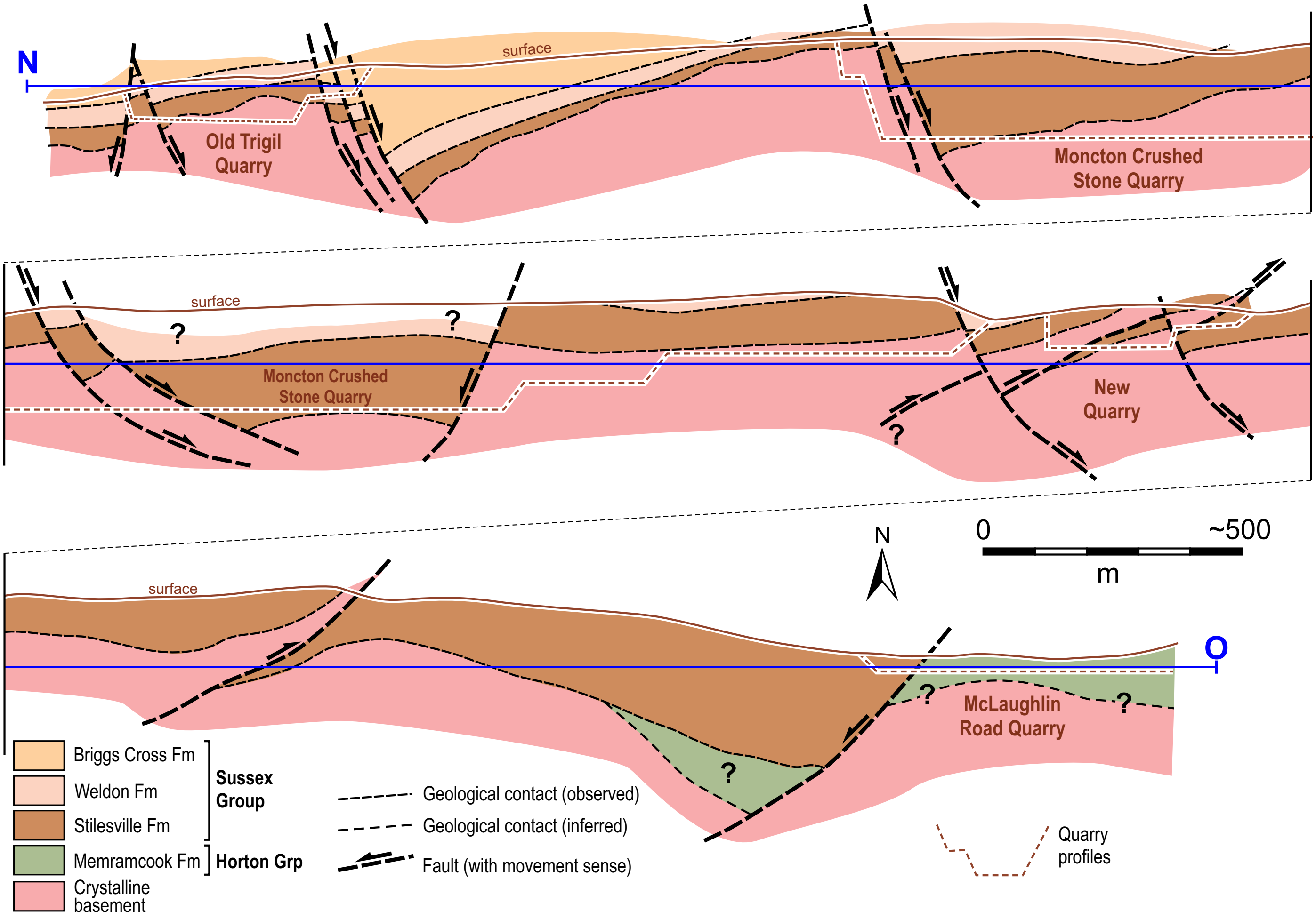


Figure 16. Semi-schematic longitudinal geological cross section through the southern domain of the IMDZ illustrating the major normal faults at a high angle to the length of the zone (see Fig. 4 for approximate line of section N-O, with the section extended to include the McLaughin Road quarry, Fig. 2).

strike-slip and represents a 'pop-up' structure in a zone of overall transpression, shedding debris at a free surface. This pop-up also underwent gravity collapse. In contrast, fault-control of deposition in the lower part of the Sussex Group may represent transtension under the same movement regime, with local accommodation of thick Stilesville successions. Transpression seems to have resumed during Stilesville deposition permitting the formation of megabreccia recycling Memramcook material and possible indurated early Stilesville sediments. The very presence of the Weldon Formation in the southern domain of the IMDZ, an evaporite-bearing desiccated lacustrine facies from the basin centre, constrains how much uplift could occur prior to the deposition of the Briggs Cross Formation.

SCHEMATIC ANALYSIS

The relationship of strain to a high-strain zone with right-lateral strike-slip and transpression is illustrated in Figure 17(a–e). Under the usual simplification of simple shear, the principal stretching axes (PSA_s and PSA_e for shortening and extension) are shown oblique to the zone boundaries and related to the instantaneous strain ellipsoid (in plan view, see Lister and Williams 1983; Passchier 1986, 1987). Material lines are parallel to the zone boundaries and the eigen vectors (along which there is no rotational strain; vorticity = 0) are parallel to the material lines. Progressive deformation beyond instantaneous strain sees all markers not initially parallel to material lines rotate congruently to the boundary motion (clockwise in this case) toward being parallel with the zone itself (Ramsay 1980; Ramsay and Graham 1970). In a shallow zone where brittle and semi-ductile processes predominate over ductile, faults will initially propagate at a high angle to the PSA_s, extensional at high angles to PSA_e, and reverse faults/thrusts at high angles to PSA_s (Fig. 17c, cf. Price and Cosgrove 1990, Chapter 6; Sylvester 1988; Woodcock and Schubert 1994). Again, if progressive strain is permitted beyond the instantaneous case, these faults, non-parallel to the material lines, must rotate. Later faults will relate to the position of the instantaneous ellipsoid (and PSA_s) and offset earlier rotated structures. Critically, all rotation is congruent with the boundary conditions.

In transpression some shortening must be occurring across the high strain zone, so conditions are not adequately described by the special cases of simple shear or pure shear (Fig. 17a–d). General shear is the more realistic model (Fig. 17e). Here the instantaneous ellipsoid and PSAs have the same position as in the simple shear case, but the material lines relate to the eigen vectors (a_1 and a_2 in Fig. 17e). As they are no longer parallel to the boundaries (as in simple shear), or parallel to the PSAs (as in pure shear) the resulting patterns of passive markers are more complex (Lister and Williams 1983; Passchier 1986). The acute angle between the eigen vectors (angle α in Fig. 17e) is inversely proportional to strain rate, so for high strain rates α may approach 0, and conditions approximate to simple shear. The domain defined by this acute angle permits rotation that is incongruent with the overall sense of the zone boundaries. Faults (extensional and compressional) will still form at high angles to the instantaneous position of the PSA_s, but their subsequent rotation will depend on their relationship to the eigen vectors, and at times this rotation may be anticlockwise in a right-lateral strike slip high strain zone. A further complication is that strain rate will vary in zones where the boundaries are non-parallel (for instance show dilatant and constrictive curvature), and as the strain rate varies, so does the angle α (and hence the position of the eigen vectors), and the relative areas of the domains in the acute angle between the eigen vectors. This will influence the amount of congruent and incongruent rotation in the same zone through time. On a large and extreme scale, this permits the same location along a high-strain zone to experience sequentially transpression and transtension or vice versa. Locally this may permit the formation of dilatant zones in overall transpression, and possibly localized zones where incongruent rotation is more common.

One final complication occurs in shallow, brittle, or semi-ductile high-strain zones in the upper crust close to a free surface. During transpression some of the material in the high-strain zone will move toward this free surface as 'pop-ups' or 'escape structures'—the simple case illustrated in Figure 17f for a vertical high-strain zone under transpression is a crudely symmetrical positive flower structure, with steep faults near the centre and lower angle reverse structures to either side. If the deep high-strain zone is not vertical, the resulting positive flower structure loses the symmetry and 'back-faults' and 'back-thrusts' are second order to reverse faults and thrusts reflecting the geometry of the deeper zone (Fig. 17g). Note that in both cases these faults will initiate oblique to the boundaries at high angles to the PSA_s, but with more scatter. This initial scatter will only be increased by subsequent rotation.

As the pop-up welt grows its internal strain will be controlled by load rather than conditions in the underlying high-strain zone (the instantaneous ellipsoid will have vertical PSA_s, horizontal PSA_e, and an oblate form). Any extensional faults formed by the gravitational collapse of the pop-up will be controlled by topography rather than conditions in the underlying high-strain zone (Fig. 17h). They are the failure surfaces of large landslides and should have the listric form of rotational slides flattening out near to or at a shallow depth beneath the base of the pop-up welt.

DISCUSSION

A schematic model for the IMDZ as an asymmetric positive 'flower structure' or 'reverse fault/thrust complex' seen at the surface is the expression of a southerly, steeply dipping fundamental structure beneath, a local expression of a more regional strike-slip regime known to the southwest as the Kennebecasis Fault. The Berry Mills, The Gorge and

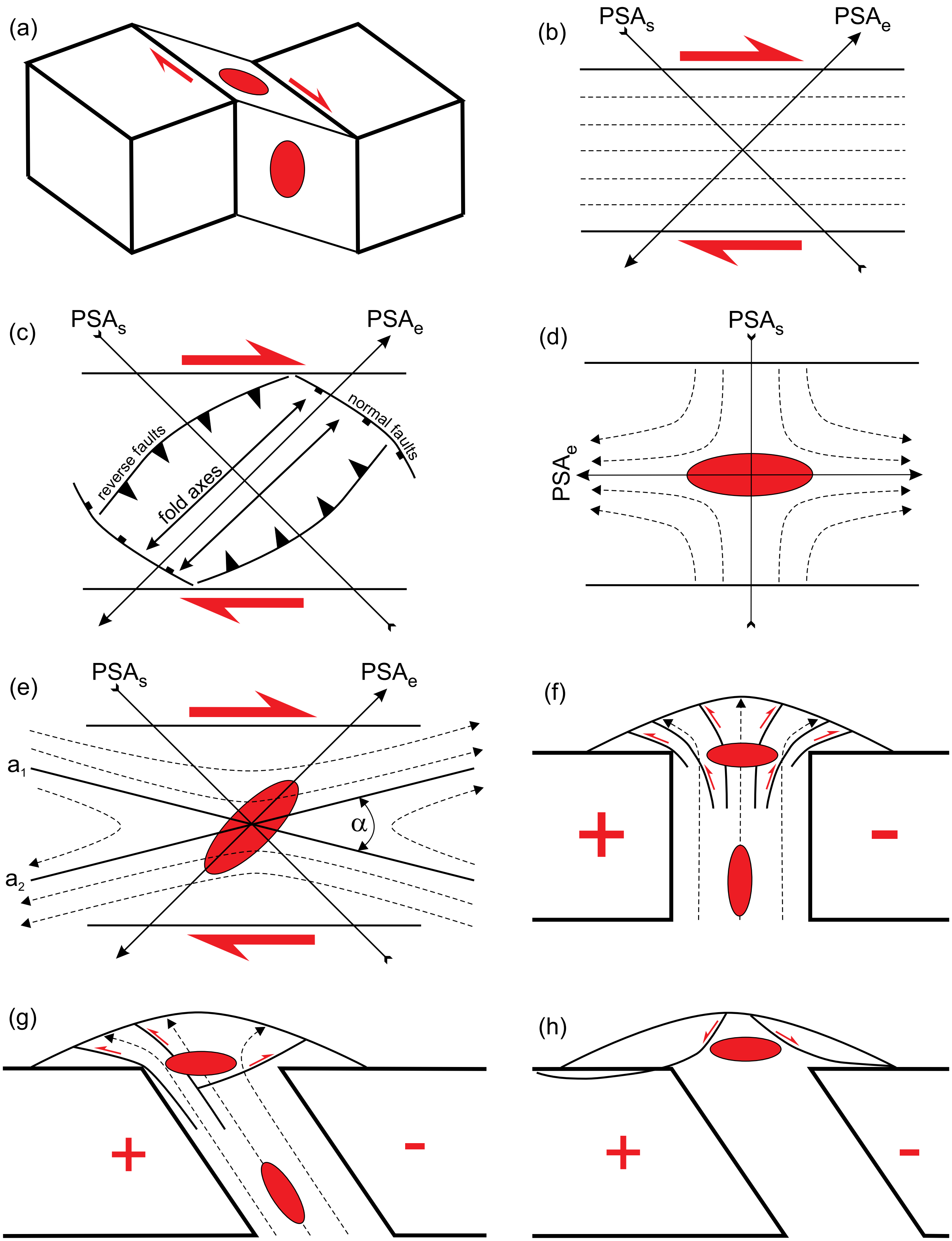


Figure 17. Schematic kinematics for a right-lateral strike-slip zone under transpression (a) for the special cases of simple shear (b, c), pure shear (d) and general shear (e). (f, g and h) Illustrate a pop-up welt developed above such a zone when the underlying zone is vertical (f), inclined (g) and finally after undergoing gravitational collapse (h). See text for details.

Salt Springs Brook faults are all splays of this fundamental structure. The North River Fault, on the other hand, is a splay of the Belleisle Fault to the northwest. The exposed major faults generally display early kinematic features related to dip-slip reverse motion, followed by later indicators of strike-slip right-lateral movement. These features are followed by dip-slip normal faults that cross cut and displace reverse and strike-slip features. The reverse faults/thrusts generally show a south-over-north asymmetry with a movement direction ranging from toward the northwest to northeast, and a minor group are clearly back-thrusts with hanging walls having moved to the south or southeast. The complexity of features related to The Gorge Fault (the best exposed structure within the southern domain of the IMDZ) illustrates this asymmetry and appear to relate to a deeper feature dipping toward the south or southeast. This characteristic is shared by the North River Fault that forms the northern boundary of this domain.

Rotation of early-formed features is well illustrated by the orientation of the lineations related to early dip-slip reverse movement on The Gorge Fault in the old Tri-Gil quarry through the Moncton Crushed Stone quarry. At the west end of the area the orientation of these lineations is plunging southeast, almost perpendicular to the trend of the fault. Through the Moncton Crushed Stone quarry to the east, this plunge changes gradually through a southern direction to southwest (a clockwise rotation along the zone, Fig. 15a). A more general scattering of movement directions on all thrusts and reverse faults, including the back thrusts in the new quarry and new Tri-Gil quarry is consistent with these features having formed close to a free surface. It is also consistent with the rocks of the Sussex Group never having been buried to any great depth seen in the survival of primary opaline silica in Stilesville Formation silcretes (Park and St. Peter 2009), and the low maturation indices seen in organic material from these units (MacIntosh and St. Peter 2005).

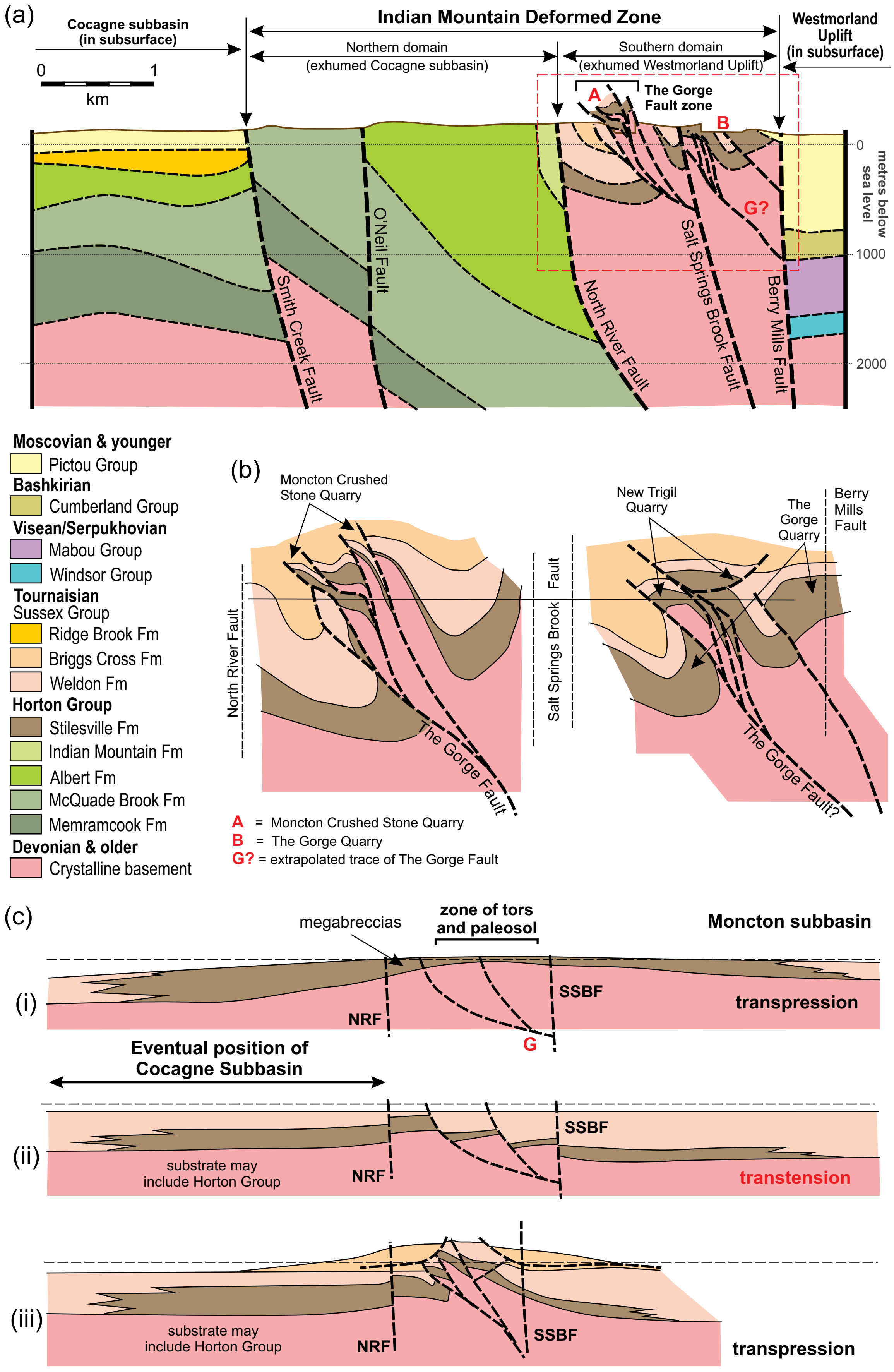
Folding related to faults generally mirrors this asymmetry, with northward vergence, but some folds, like the thrusts to which they are related, have southward vergence too. There are also examples of early formed structures related to extension parallel to bedding.

The present patterns displayed by these features make little sense when they are compared to the instantaneous strain ellipsoid consequent on right-lateral transpression across the IMDZ (using either the simple shear or general shear cases for reference). It is only when progressive deformation with rotation is considered, both congruent and incongruent to the overall sense of the zone under general shear, that the features become coherent. Further complications can be explained by the relationship of these faults to a free surface.

The pop-up of a welt above the IMDZ transpressional zone ended with collapse controlled by normal faults (Fig. 16). These faults occur all along the exposed IMDZ and are always later than (cross cutting and offsetting) the reverse faults and right-lateral strike-slip faults. Their orientation is generally highly oblique to the trend of the IMDZ, though there are important exceptions. Once again, their pattern is hard to explain in an instantaneous strain model but makes more sense when rotation is permitted (again congruent and incongruent to the sense of the zone as a whole), and they are considered to have formed close to a free surface. Where these faults can be observed with any vertical continuity, their planes curve indicating an overall listric form, flattening out at shallow depths, all less than 0.5 km below the present erosion surface, and most even shallower.

Figure 18 summarizes this history through the deposition of the Sussex Group. The present geological cross section (Fig. 18a) represents the complete assembling of the various components of the IMDZ (northern and southern domains), the reconfiguration of early components by later strike-slip fault motion perpendicular to the section, and the latest Carboniferous fault movements evident on the Smith Creek and Berry Mills faults that affect the Moscovian to Gzhelian Pictou Group. The strike-slip and post-Tournaisian elements are removed in Figure 18b, as are the late Tournaisian normal faults, in an attempt to reconstruct the configuration of the reverse fault/thrust geometry. Elements north of the North River Fault have been completely removed from the sections, and a reconstruction attempted for the strike-slip Salt Springs Brook Fault (Fig. 18b). This reconstruction has no reliable pining-points; instead, the north side of the

Figure 18. (next page) (a) Geological cross section of the IMDZ through the area of The Gorge quarries (approximately N-S), modified after St. Peter and Johnson (2009, their fig. 85) to correlate The Gorge Fault north of the Salt Springs Brook Fault as seen in the Moncton Crushed Stone quarry, with the thrust faults seen in the new Tri-Gil Quarry, which lies south of the Salt Springs Brook Fault. (b) Schematic reconstructions of The Gorge Fault thrusts based on the sections exposed in the Moncton Crushed Stone quarry (left) and new Tri-Gil and The Gorge quarries (right). Strike-slip faults perpendicular to the line of section and later normal faults in all orientations are omitted. (c) Evolution of the IMDZ through late Tournaisian time illustrated on a north-south section. Features north (left) of the North River Fault (NRF) are speculative, but probably represent an eastward extension of the Cocagne Subbasin now translated to the east-northeast. SSBF is the Salt Spring Brook Fault. (i) During deposition of the Stilesville Formation over a basement high established during the end-Horton Group inversion. Paleosol and tors are developed in the basement high prior to Stilesville Formation megabreccias and conglomerates draping the structure. (ii) Subsidence (transtension) permits the basin centre facies (Weldon Formation) to overstep the position of the IMDZ. Precursor structures to the Salt Spring Brook Fault and The Gorge Fault are suggested as accommodating subsidence. (iii) Uplift (transpression) during deposition of the Briggs Cross Formation (pop-up) with gravitational collapse along large landslide scars (shown schematically as most are not so orientated to the line of section).


(a)
Cocagne subbasin (in subsurface)
0
1
km
Indian Mountain Deformed Zone
Northern domain (exhumed Cocagne subbasin)
Southern domain (exhumed Westmorland Uplift)
Westmorland Uplift (in subsurface)
The Gorge Fault zone
A
B
G?
Smith Creek Fault
O'Neil Fault
North River Fault
Salt Springs Brook Fault
Berry Mills Fault
0
1000
2000
metres below sea level
Moscovian & younger
Pictou Group
Bashkirian
Cumberland Group
Visean/Serpukhovian
Mabou Group
Windsor Group
Tournaisian
Sussex Group
Ridge Brook Fm
Briggs Cross Fm
Weldon Fm
Horton Group
Stilesville Fm
Indian Mountain Fm
Albert Fm
McQuade Brook Fm
Memramcook Fm
Devonian & older
Crystalline basement
(b)
Moncton Crushed Stone Quarry
North River Fault
The Gorge Fault
Salt Springs Brook Fault
New Trigil Quarry
The Gorge Quarry
Berry Mills Fault
The Gorge Fault?
A = Moncton Crushed Stone Quarry
B = The Gorge Quarry
G? = extrapolated trace of The Gorge Fault
(c)
megabreccias
zone of tors and paleosol
Moncton subbasin
(i)
NRF
SSBF
G
transpression
Eventual position of Cocagne Subbasin
(ii)
SSBF
substrate may include Horton Group
NRF
transtension
(iii)
substrate may include Horton Group
NRF
SSBF
transpression

fault is pulled back west until the syncline lying north of The Gorge and new Tri-Gil quarries is restored. This restoration makes the thrusts seen in the new Tri-Gil quarry a possible continuation of The Gorge Fault zone traced through the Moncton Crushed Stone and new quarries to the north. Coincidentally, it brings the new Tri-Gil quarry thrusts close to the megabreccia within the Stilesville Formation seen in the McLaughlin Road quarry. Although not well constrained, the reconstruction is at least plausible. The Berry Mills Fault is removed by taking off the post-Tournaisian normal motion that is down to the south and does not consider any other component in the evidently longer history of this structure (seen to the WSW in the Sussex area, Wilson and White 2006; Wilson *et al.* 2006).

Figure 18c (i–iii) illustrates a schematic upper Tournaisian history for the southern domain of the IMDZ. The area north of the North River Fault is assumed to be part of the Cocagne Subbasin, but a part of this basin now translated to the east-northeast. At the end of the depositional cycle represented by the Horton Group (Fig. 18c, i) the northern end of the buried Westmorland uplift formed a topographic high created by the end-Horton basin inversion (Wilson and White 2006). This high is marked in the modern IMDZ by those areas of crystalline basement where the unconformity beneath the Stilesville Formation is marked by paleo-tors and a deep paleosol. The Stilesville Formation represents fanglomerates of debris from the main Westmorland uplift (east of the line of section) that were gradually burying this uplift. Out in the subbasins to north and south these fanglomerates interfinger into basin-centre facies represented by the Weldon Formation (St. Peter and Johnson 2009; Park *et al.* 2010). The basin-centre facies eventually overstep the IMDZ during a general subsidence (transtension?), preserved as the Weldon Formation in the IMDZ itself (Fig. 18c, ii). The role illustrated of the precursors to The Gorge and Salt Springs Brook faults is completely speculative. The final pop-up occurs during deposition of the upper part of the Sussex Group (transpression/end-Sussex basin inversion, Fig. 18c, iii), with the pop-up having enough topographic expression to become gravitationally unstable and undergo collapse through landslide.

The ultimate constraint on timing of the pop-up of the IMDZ is the overstepping of the unconformity beneath the Moscovian Richibucto Formation. However, the plastic nature of many of the structures in the Weldon and Stilesville formation sediments implies that these units had not fully dewatered. This characteristic, and the possibility that the megabreccias within the Stilesville Formation may relate directly to early thrusting, suggest that much of this deformation history occurred during the deposition of the Sussex Group. This makes the pop-up and collapse of the IMDZ a late Tournaisian event, culminating with the end-Tournaisian inversion known to affect the entire Moncton Subbasin (Wilson 2003, 2005; Wilson and White 2006; Park and St. Peter 2005; St. Peter and Johnson 2009). Though the initial pop-up welt underwent late Tournaisian collapse (around 347 Ma, Cohen *et al.* 2013, revised 2023), the IMDZ remained a positive feature for some time after. The Viséan–Serpukhovian Windsor and Mabou groups are preserved in the Moncton Subbasin immediately to the south and in the Cocagne Subbasin some 25 km to the west, but there is no suggestion that they ever covered the IMDZ in this area. Similarly, no Bashkirian Cumberland Group rocks cross the IMDZ. The overlap of the Moscovian–Gzhelian Pictou Group (around 315–300 Ma, Cohen *et al.* 2013, revised 2023) across the IMDZ at its eastern end represents the demise of the positive topographic feature created some 30 million years earlier.

CONCLUSIONS

1. A right-lateral strike-slip zone of progressive deformation preserved in the southern domain of the Indian Mountain Deformed Zone was active throughout the deposition of the late Tournaisian Sussex Group.
2. Some faults, such as the Salt Springs Brook Fault and The Gorge Fault, created topographic features marked by highly variable thicknesses of the Stilesville and Weldon formations, and zones of deep weathering and tor formation in pre-Carboniferous crystalline basement rocks. Tor collapse contributed to megabreccia at the base of the Stilesville Formation.
3. Early formed features such as fault planes, slickenlines, and layer-parallel rheoplasts show rotation during progressive deformation. A general shear model permits this rotation to be both congruent and incongruent with the overall right-lateral regime. Incongruent features can include left-lateral strike-slip faults.
4. The overall strike-slip regime was close enough to a free surface to allow vertical pop-up or escape structures on dip-slip reverse faults or thrusts. One such occurred during deposition of the Stilesville Formation forming a megabreccia within this unit. The main pop-up structures affect the entire Sussex Group, primarily along The Gorge Fault.
5. The final pop-up structures created an unstable topographic feature subject to gravity collapse. These features are preserved as listric normal faults shallowing out within 0.5 to 1.0 km of the current surface, representing landslides.
6. The overall form of the faults in the southern domain of the IMDZ is that of an asymmetric flower structure in which The Gorge, Salt Springs Brook, and Berry Mills faults are splays of the Kennebecasis Fault. This structure controls the features related to the end-Tournaisian basin inversion evident along the northwestern margin of the Moncton Subbasin.
7. The detail revealed in the extensive quarry exposures in the southern domain of the IMDZ serves as a caution when interpreting the other strike-slip faults in New Brunswick where exposure is limited and seismic reflection profiles are the only data available.

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Editorial responsibility: Sandra M. Barr

APPENDIX

Definition of new stratigraphic units

The Sussex Group was introduced by St. Peter (2006) and St. Peter and Johnson (2009), for strata lying above the Horton Group and below the Windsor Group. The Sussex Group is separated from the older Horton Group by an angular unconformity throughout the Moncton Subbasin and overstep directly onto older basement in the Caledonia Highlands and in the Indian Mountain area. Predominantly a red bed succession, the group consists of the fine- to medium-grained rocks of the Weldon Formation (Norman 1941) that occur throughout the Moncton subbasin and Indian Mountain area, and the coarser red conglomerate units that are more localized around the subbasin margins. The red conglomerate units of the Sussex Group comprise the Millbrook Formation around Sussex, the Round Hill Formation around the northeastern part of the Caledonia Highlands, and the Stilesville, Briggs Cross and Ridge Brook formations in the Indian Mountain area (St. Peter 2006; Park and St. Peter 2009; St. Peter and Johnson 2009). Prior to their work the coarser conglomerate units in the Indian Mountain area were variously identified as proximal facies of the Moncton Group (Weldon and Hillsborough formations) or Horton Group (specifically Memramcock Formation, Gussow 1953). Park and St. Peter (2009) documented the interfingering of two conglomerate dominated formations (Stilesville and Briggs Cross formations, see below) with the Weldon Formation, revealed in the stone quarries around The Gorge (exposure not available when Gussow (1953) remapped the Indian Mountain area). This succession rests with non-conformity on crystalline basement. Unambiguous Memramcook Formation occurs in the McLaughlin Road quarry and to the east along the Shediac River, and along with green and brown sandstone from the Horton Group, occurs as clasts in Stilesville and Briggs Cross formation conglomerates.

The Hillsborough Formation is now included in the Windsor Group (St. Peter 2006; St.Peter and Johnson 2009). This unit lies with angular unconformity on the Sussex Group, throughout the Moncton Subbasin, and oversteps onto Horton Group rocks and the crystalline basement of the Caledonia Highlands. This unit does not occur in the Indian Mountain area.

Stilesville Formation (new name)

Authors: Stilesville Formation was introduced by Park and St. Peter (2009) for the lower of two predominantly conglomerate units comprising the main ridge of Indian Mountain and they defined type sections. These definitions and type sections were then used in the memoir produced by St. Peter and Johnson (2009). Both Park and St. Peter (2009) and St. Peter and Johnson (2009 were government publications and not peer-reviewed. These rocks had previously been considered part of the Memramcook Formation (Wright 1922; Norman 1941; Gussow 1953) owing to their close association with pre-Carboniferous basement inliers.

Type section: The type-section for the Stilesville Formation (Fig. 19) is designated in the (disused) northwest corner of the Moncton Crushed Stone quarry (GPS N46˚ 09' 58.6", W064˚ 52' 19.5", 'X' on Fig. 4); formerly Stilesville quarry, in the parish of the same name (Park and St. Peter 2009). This section consists of around 250 m of predominantly conglomerate/breccia with interbedded sandstone, siltstone and shale measured to the south and east of the GPS point. Though there is some evidence of disturbance by bedding-parallel faults, this measured section lies entirely in the footwall of the northern splay of The Gorge Fault.

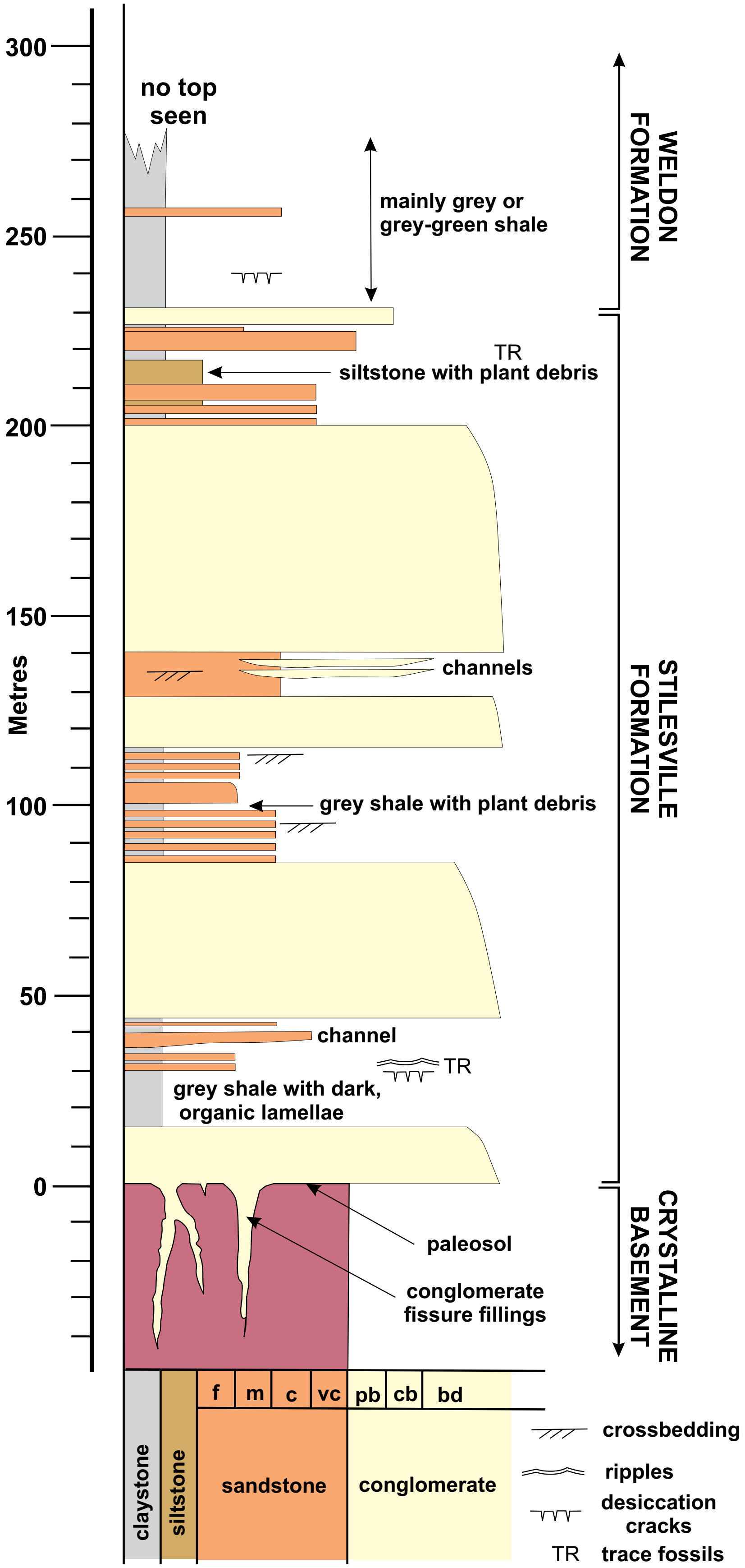

Figure 19. (previous page) Measured type section for the Stilesville Formation located in the northwest part (disused section) of the Moncton Crushed Stone quarry, Stilesville parish (see X on Fig. 4). From Park and St. Peter (2009).

Reference section: A comparable section is seen in the northern sector of The Gorge quarry (Fig. 4), where the lower half consists of megabreccia and paleo-tors. This is overlain by an upward-fining sequences of conglomerate/breccia and coarse sandstone. Interlayered red shales contain silcrete horizons. The overlying Weldon Formation is also present. As this is an active quarry exposure is constantly changing.

Definition and description: The Stilesville Formation is predominantly a red/brown or buff-coloured conglomerate/breccia with pebble to boulder grain-size, generally matrix-supported with a coarse arkosic matrix. Clasts are dominantly the distinctive monzonite derived from the Gaytons pluton exposed in the quarries along Highway 2 (Barr *et al.* 2002, 2007), or just the red K-feldspar from the same source. Overall, the sequence is upward fining. The conglomerate/breccia is highly indurated with a silica cement. Minor silcrete horizons have been identified preserved as opaline silica. This conglomerate/breccia is interbedded with red/brown to buff coloured medium- to coarse-grained arkose and feldspathic quartz arenite, red siltstone, red and grey-green shale. Grey-green shale may contain comminuted plant debris, and some shale horizons carry mud-cracks. Trace fossils include *Cruziana problematica*, *Rusophycus carbonarius*, and *Planolites* isp (Pickerill 1992).

Distribution and thickness: Thickness of the Stilesville Formation varies considerably, from 250 m at the type section to zero along the access road to the new Tri-Gil quarry. The unit appears to have been deposited on a surface with considerable relief. Thickness estimates greater than 500 m along the wooded ridges NE and SW of The Gorge are based on mapping and make no allowance for fault repetitions. Regionally the Stilesville Formation wedges out to the SW of Lutes Mountain.

Upper and lower boundaries: The Stilesville Formation lies with non-conformity on the granitoid crystalline basement of the Westmorland uplift, the contact marked by a paleosol seen as a zone of phyllic alteration between 0.5 and 3.0 m deep into the basement rocks. Locally, mainly in the The Gorge quarry, this phyllic alteration extends deep into granitoid basement defining core stones up to 20 m diameter. When these blocks are completely surrounded by alteration and conglomerate/breccia filled fissures varying degrees of relative movement are evident, suggesting a spectrum from relative undisturbed paleo-tors to completely disrupted megabreccia. Conglomerate/breccia fissure fills up to 2 m wide can extend as deep as 50 m below the nonconformity. The upper contact of the Stilesville Formation with the Weldon Formation is transitional and conformable. The boundary is set in the type section at the top of the last conglomerate/sandstone layer with conspicuous red feldspar or monzonite clasts.

Age: Three datable palynomorph assemblages have been recovered from grey mudstone layers within the Stilesville Formation (for details see Park and St. Peter 2009, using the biozonation of Hacquebard 1972; Utting 1987, 1989; Utting *et al.* 1989, 2010; Dolby in St. Peter and Johnson 2009). Spore Zone 4 -5, with possibly some from Zone 3b, are consistent with the Sussex Group elsewhere in New Brunswick, are indicated.

Depositional environment: Depositional environment of the Stilesville Formation is most probably marginal to a playa lake near the foot of a paleoscarp. The conglomerate/breccia layers represent debris flows occurring as sheet flood or smaller channelized events. The mobility of silica, general stability of feldspar clasts, presence of silcrete and the deep weathering of the basement suggest a seasonal (monsoonal?) semi-arid tropical climate with strongly alkaline groundwater.

Briggs Cross Formation (new name)

Authors: Briggs Cross Formation was introduced by Park and St. Peter (2009) for the upper of two predominantly conglomerate units comprising the main ridge of Indian Mountain. This publication included a type section, but as a New Brunswick Department of Natural Resources memoir, was not peer-reviewed. These rocks had previously been considered part of the Memramcook Formation (Wright 1922; Norman 1941; Gussow 1953) owing to their close association with pre-Carboniferous basement inliers.

Type section: The designated type section for the Briggs Cross Formation (Fig. 20) is a ditch and road cut along a private side-road south of Briggs Cross Road about 1 km southwest of The Gorge (between GPS N46˚ 09' 08", W064˚ 53' 19" and N46˚ 09' 11", W064˚ 53' 23", 'Y' on Fig. 4) exposing some 100 m of section from the base that is conformable on the underlying Weldon Formation (Park and St. Peter 2009).

Reference section: A reference section showing the lower boundary between Briggs Cross and Weldon formations is designated in the southern section of The Gorge quarry (Fig. 4). The section is disturbed by the Salt Springs Brook Fault and splays, but the Weldon/Briggs Cross Formation boundary is preserved. This quarry is active and hence the exposed section is constantly changing.

Definition and description: The Briggs Cross Formation is a red/brown to dark green polymictic pebble to boulder conglomerate interbedded with coarse to medium-grained feldspathic sandstone with minor siltstone and shale, the latter being both red and grey or grey-green. In the lower 10 to 15 m of the formation distinct upward fining cycles of conglomerate to shale are present, but above this conglomerate units are thicker, and the formation overall coarsens upward. Some of the grey-green shales in the lowest part of the formation contain comminuted plant debris. Overall polymictic, clast populations in the lowest conglomerate

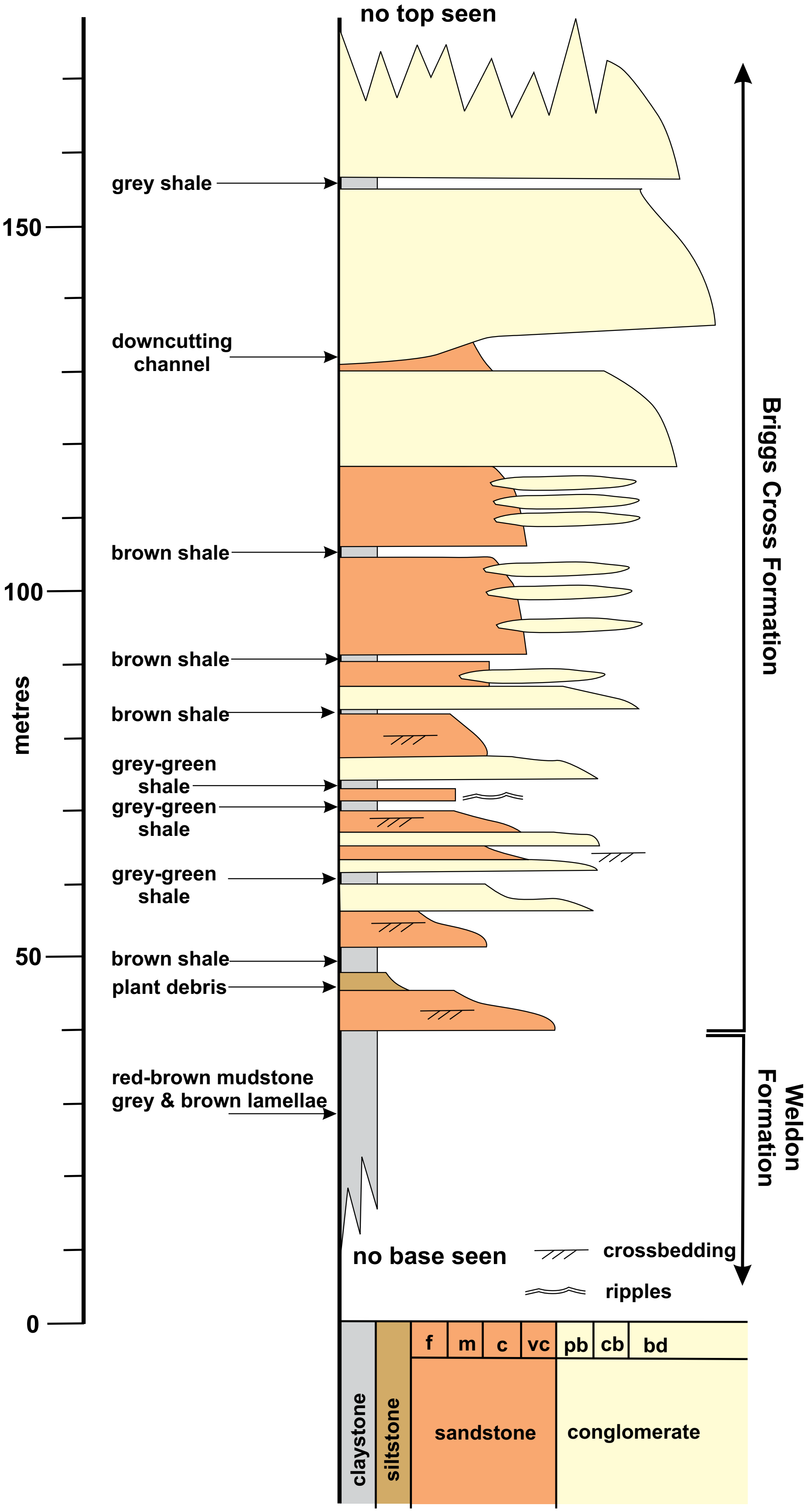

Figure 20. Measured type section for the Briggs Cross Formation located along a private road south of Briggs Cross Road to the west of the old Tri-Gil quarry (see Y on Fig. 4). From Park and St. Peter (2009).

layers are predominantly white vein quartz and granite, but over the first 2 m other lithologies, such as diorite, gabbro, schist, and a reddish-brown to grey sandstone become as important. Clasts are distinctly sub-rounded to rounded, and typically carry evidence of 'desert varnish'.

Distribution and thickness: Above the type section mapping indicates the Briggs Cross Formation constitutes most the ridge extending to the SW and south to the Salt Springs Fault. If there is no fault repetition this section must be at least 225 m thick, with most the outcrop in the coarser conglomerate. The Briggs Cross Formation is no longer present 40 km to the southwest.

Upper and lower boundaries: The lower boundary of the Briggs Cross Formation with the underlying Weldon Formation is taken to be the base of the first polymictic conglomerate in an otherwise transitional contact. The upper boundary is not seen anywhere in the Indian Mountain zone.

Age: Six palynomorph assemblages have been recovered from the Briggs Cross Formation, of which four yielded biostratigraphically significant forms (see Park and St. Peter 2009 for details, after Hacquebard 1972; Utting 1987, 1989; Utting *et al.* 1989, 2010; Dolby in St. Peter and Johnson 2009). The miospores all fall into Biozone 4 and 5 of the late Tournaisian, consistent with regional results from the Sussex Group. There is also evidence of miospore recycling from the lower Tournaisian Horton Group, consistent with the present of sandstone clasts from the Albert Formation.

Depositional environment: Depositional environment of the Briggs Cross Formation is one of high energy, rapid accumulation with little sorting. The wedge-shape of the unit, thickest adjacent to the exposed Westmorland uplift in the northeast, wedging to zero thickness to the SW, and clast lithologies indicate prograding fanglomerate(s) originating in this uplift and in part contemporary with the upper part of the playa lake/lake margin sequence preserved in the Weldon Formation. Desert varnish implies a strongly seasonal arid-semiarid environment.

Note: This paper is part of Special Series in "Atlantic Geoscience" in recognition of the geological career of Sandra M. Barr.