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A MIDDLE CAMBRIAN MASS-KILL RECORDED IN THE PENGUIN COVE FORMATION, WESTERN NEWFOUNDLAND

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ABSTRACT

A large (~80 x 40 x 20 cm), loose block of the Penguin Cove Formation in the North Brook Anticline of western Newfoundland is host to an unusual layer, crowded with complete specimens of the Middle Cambrian dorypygid trilobite Kootenia. *At least forty individuals were counted in a 32 x 19 cm area on the block; most of these vary in length from 3.6 to 4.2 cm. The block came from a nearby outcrop of heterolithic, largely unfossiliferous, thinly bedded succession of mudstone, shale, siltstone and sandstone with a few beds of hummocky sandstone, rare limestone laminae and a cluster of thrombolitic dolostone mounds.*

Trilobite remains typically are preserved as incomplete, disarticulated molts or fragments. Consequently, these complete, articulated trilobites represent a death assemblage. The mass mortality possibly occurred because of oxygen-deprivation, caused most likely by either a catastrophic release of toxic gas from the sea floor, or the trilobites' chance entry into a massive body of anoxic water, or exposure to fresh water brought to the shelf during fluvial input onto the shelf. Most of the Kootenia *on the large block are of similar size, indicating that they probably were of about the same age. This suggests that, like some modern day shrimp,* Kootenia *may have lived in 'schools'.*

The trilobites indicate that the rocks of North Brook – those in the immediate vicinity of the block, at least – were deformed by pure shear (irrational or coaxial strain); the principal strain Y'/X' ratio is between 0.67 and 0.68.

INTRODUCTION

A large, loose block of the Penguin Cove Formation (Plate 1), rich in complete trilobites, was discovered during 1:50 000 geological mapping. It was found close to a short section of the formation in the river bed and banks of North Brook, northwest of the community of Gallants, in the Harrys River (NTS 12B/09) map area by two of the co-authors (Knight and Brake) during the summer of 2005 (Figure 1; Plate 2). The block, measuring 80 x 40 x 20 cm thick, was retrieved by helicopter this past summer. It is now housed in the Natural History Annex of The Rooms Provincial Museum (St. John's); sample designation NFM F-657.

The section on North Brook (405802 E 5395345 N 150 m to 405945E 5395523N 153 m) lies in the hanging wall, *i.e.*, on the north side, of a well-exposed, high-angle fault that strikes 245° and dips to the northwest at 65°. The fault obliquely crosses the river bed at this locality (Plate 2), its trace picked out by a number of salmon pools and narrow rock-lined chutes and gullies that channel the river's flow between gravel bars. Nearby outcrops, upstream of the section, consist of 5 m cliffs of well-bedded quartz arenite, and exposures that display the contact of the top of the Hawke Bay Formation (Labrador Group), with the overlying March Point Formation (Port au Port Group). The section consists of siliciclastic rocks that are characteristic of the Penguin Cove Formation. This, coupled with the metre-thick units of bedded quartz arenite characteristic of the Hawke Bay Formation in a nearby outcrop, suggests that the North Brook Anticline hosts the transition from the Hawke Bay Formation to the west and northwest to the Penguin Cove Formation (Figure 2) to the southeast as discussed by Knight (2003).

THE PENGUIN COVE FORMATION

The section (Figure 3) in which the trilobite block was found is nearly 20 m thick. The base and top of the section are not exposed. The section consists of a number of coarsening-upward, metre-scale sequences that generally consist of mudstone, siltstone and sandstone (Plate 3). Shale occurs

Plate 1. *Block of Penguin Cove Formation (NFM F-657) containing abundant articulated* Kootenia*, from North Brook (off Harrys River), near Gallants, western Newfoundland (Lens cap for scale). A photographic illusion makes the trilobites appear as casts; they actually are molds.*

Plate 2. *Trace of the fault (traced by dashed line) along the North Brook river bed. Section was measured to the left. Fault (arrow) is visible through the shallow water in the foreground.*

below the mudstone in the topmost interval of the section. The base of the sequences is generally sharp on the top of the underlying cycle. The mudstone units are generally dark grey, micaceous, silty and up to 1.6 m thick. Although they appear massive, some joint surfaces hint at a vague internal stratification including very thin siltstone beds normally grading up into mudstone. Pyrite is common in the mudstones. Centimetre-thick lenses, laminae and thin beds of very fine-grained sandstones are common and increase in number upward. The sandstone beds are generally <1 to 2 cm thick and internally laminated. Sparse, simple, tubular, trace fossils locally decorate the base of the sandstones.

The mudstones are overlain by thin- to-medium bedded, coarsening-upward, silty mudstone–sandstone couplets and by thin-bedded siltstones and very fine-grained sandstones intercalated, on a cm-scale, with dark grey shales (Plates 3 and 4). The sandstones generally increase in importance upward in some units, continue to be laminated and are, locally, convoluted. Tops of beds have small, mostly straight, ripple marks (wavelength = 11 cm, amplitude = 1 cm) whose crests generally trend south-southwest (Plate 5). Bedding-parallel, tubular burrows and other sediment-feeding, burrow traces decorate the sandstones, and synaeresis cracks cut intervening shale interbeds (Plate 6). Dis-

Plate 3. *Thin-bedded mudstone and sandstone capped by sandstone (arrow).*

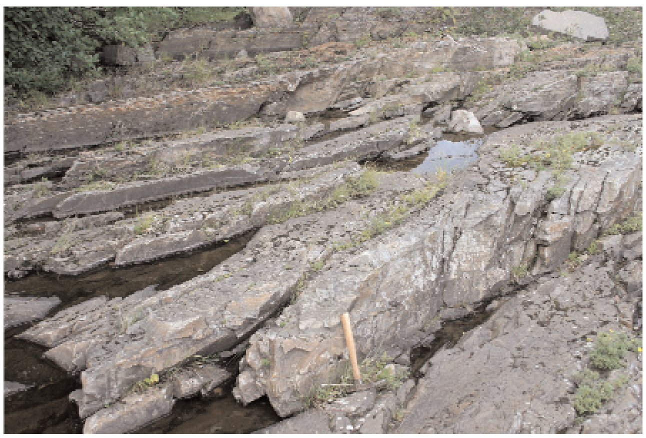

Plate 4. *Thin-bedded sandstone and mudstone. Unit that contained the trilobite block. Hammer is 33.5 cm long.*

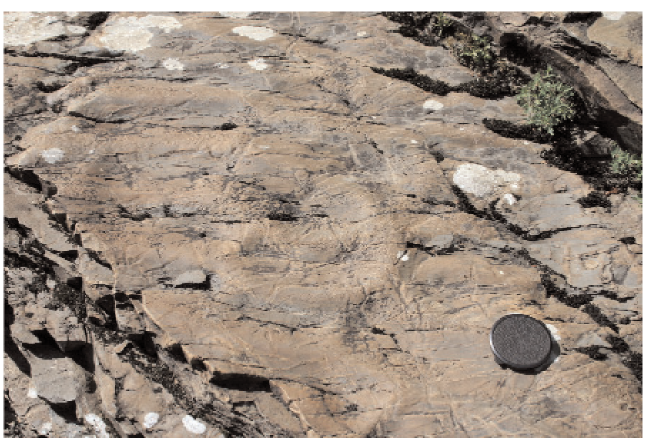

Plate 5. *Ripple marks ornamented by tubular traces and local patches of wrinkle marks. Lens cap 6 cm across.*

lodged blocks of the thin-bedded sandstone and mudstone facies carry trilobite traces including small *Rusophycus* (Plate 6). The trilobite block comes from this facies, which also contains hyolithids.

Plate 6. *Trilobite scratch marks, burrows and scattered synaeresis cracks (arrow; possibly controlled by burrows) on an overturned thin-bedded sandstone block. Lens cap 6 cm across.*

Plate 7. *Scour-based (dashed line) bed of hummocky cross-stratification underlain by and overlain by thin-bedded sandstone and shale. Lens cap is 6 cm across.*

The thicker beds of sandstone, 20 to 180 cm thick, are grey to off-white and very fine grained; the thinner sandstone beds, 15 to 30 cm thick, are separated by partings and thin beds of shale. The sandstone beds have either a sharp planar base or a basal scour (Plates 3 and 7). Internally, they can be structureless, thinly stratified and laminated, or display hummocky cross-stratification and lamination. The top of the massive bed is convoluted suggesting that dewatering may have destroyed the internal fabric. It is overlain by more of the intercalated shale and thin-bedded sandstone facies. A number of sandstone beds have smooth hummocky tops and most of the sandstones pinch and swell, and may pinch out over tens of metres along the outcrop.

The shale interval at the top of the formation is characterized by 1.7 m of dark grey and black shale and numerous thin beds of laminated very fine-grained sandstone. It is overlain by 2.55 m of mudstone and intercalated thin-bed-

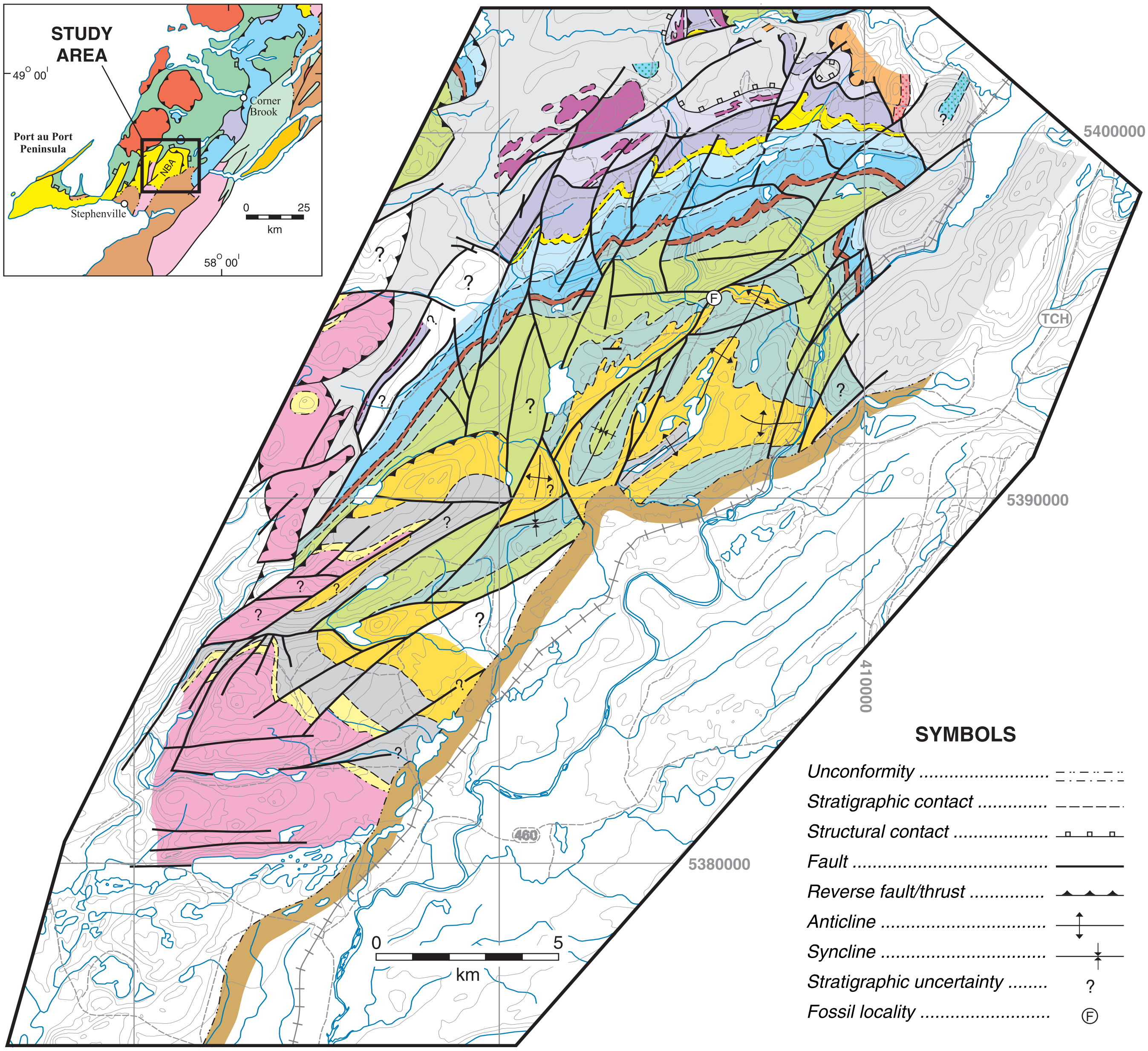

Figure 1. *Geological map of the Northern Brook Anticline, showing the location of the Penguin Cove Formation fossil site (modified from Knight, 2003).*

ded sandstone lenses. A very thin (<1 cm) skeletal limestone bed containing hyolithids, inarticulate brachiopods and rare trilobite fragments (Knight sample K08-059-2; Figure 3) occurs at the base of the shale. Hyolithids and trilobite pieces are also present on the top of sand beds, in the shale interval, and have also been found in the uppermost mudstones, where they are associated with phosphate. Compacted sandstone dykes cut this upper succession of shale and mudstone, the dykes trending south-southwest (Plate 8). This interval is also host to a cluster of decametre-sized, thrombolitic, microbial mounds (Plate 9) that are dolomitized and have trapped fine-grained, siliciclastic detritus. The mounds appear to lie in a deformed bed of shale and dolomitic thin-bedded sandstone.

The heterolithic succession described above are likely the deposits of a restricted, shelf setting, where features such as lenticular hummocky sandstones, suggest infrequent storm events punctuated by alternating mud and very fine-grained sand deposition. The latter are consistently found as thin-laminated sheets suggesting distinct high-flow, bottom-current events such as those associated with a fluvial input into a marine shale setting. Synaeresis cracks probably imply fluctuating salinity conditions and possibly the influx

LEGEND

Quaternary gravels and peats overlying Pennsylvanian sedimentary rocks

Undivided slate terranes including mostly broken Goose Tickle Group and elements of mélange, Green Point Formation, Irishtown Formation, and Weasel group

Weasel group?

HUMBER ARM ALLOCHTHON

Irishtown Formation

Summerside Formation

AUTOCHTHON

GOOSE TICKLE GROUP

American Tickle Formation

Daniels Harbour Member +/- Table Cove and Black Cove formations

TABLE HEAD GROUP

Table Cove Formation

Table Point Formation

ST. GEORGE GROUP

Aguathuna Formation

Catoche Formation

Boat Harbour Formation

Watts Bight Formation

PORT AU PORT GROUP

Berry Head Formation

Petit Jardin Formation

March Point Formation

LABRADOR GROUP

Hawke Bay/Penguin Cove formations

Forteau Formation

Bradore Formation

GRENVILLIAN BASEMENT

Granite and gneiss

Figure 1. *Legend.*

of freshwater that would cause clays to flocculate and mud to shrink (Collinson and Thompson, 1989; Demicco and Hardie, 1994). The presence of thrombolitic mounds at the top of the section suggests that the shelf was shallowing close to sea level with time, although the deformed nature of the enclosing thin-bedded clastic sediments may imply a slump on the shelf carried the mounds into the section. The poor fauna of hyolithids, phosphatic brachiopods and the

Plate 8. *Compacted sandstone dykes cutting grey shale near top of the measured North Brook section. Lens cap is 6 cm across.*

Plate 9. M*icrobial mound (lens cap) in a dolostone, surrounded by deformed, rusty weathering, shale and dolomitic siltstone. Lens cap 6 cm across.*

scattered trilobite parts (likely swept into place), and the simple tubular trace fossils in the thin sandstones, suggesting a sediment-feeding, soft-bodied fauna and the dolomitized, microbial, thrombolite mounds all suggest that bottom conditions mostly were not suitable for all but a few, most tolerant organisms.

PALEONTOLOGICAL SIGNIFICANCE OF THE BLOCK

CORRELATION

Boyce *et al.* (2007a, b, 2008) identified the trilobites on the block as belonging to the genus *Kootenia* Walcott, 1889. In western Newfoundland, *Kootenia cloudensis* Howell, 1943 is present in the upper part of the Middle Cambrian Bridge Cove Member of the Hawke Bay Formation and the basal part of the overlying March Point Formation (Knight

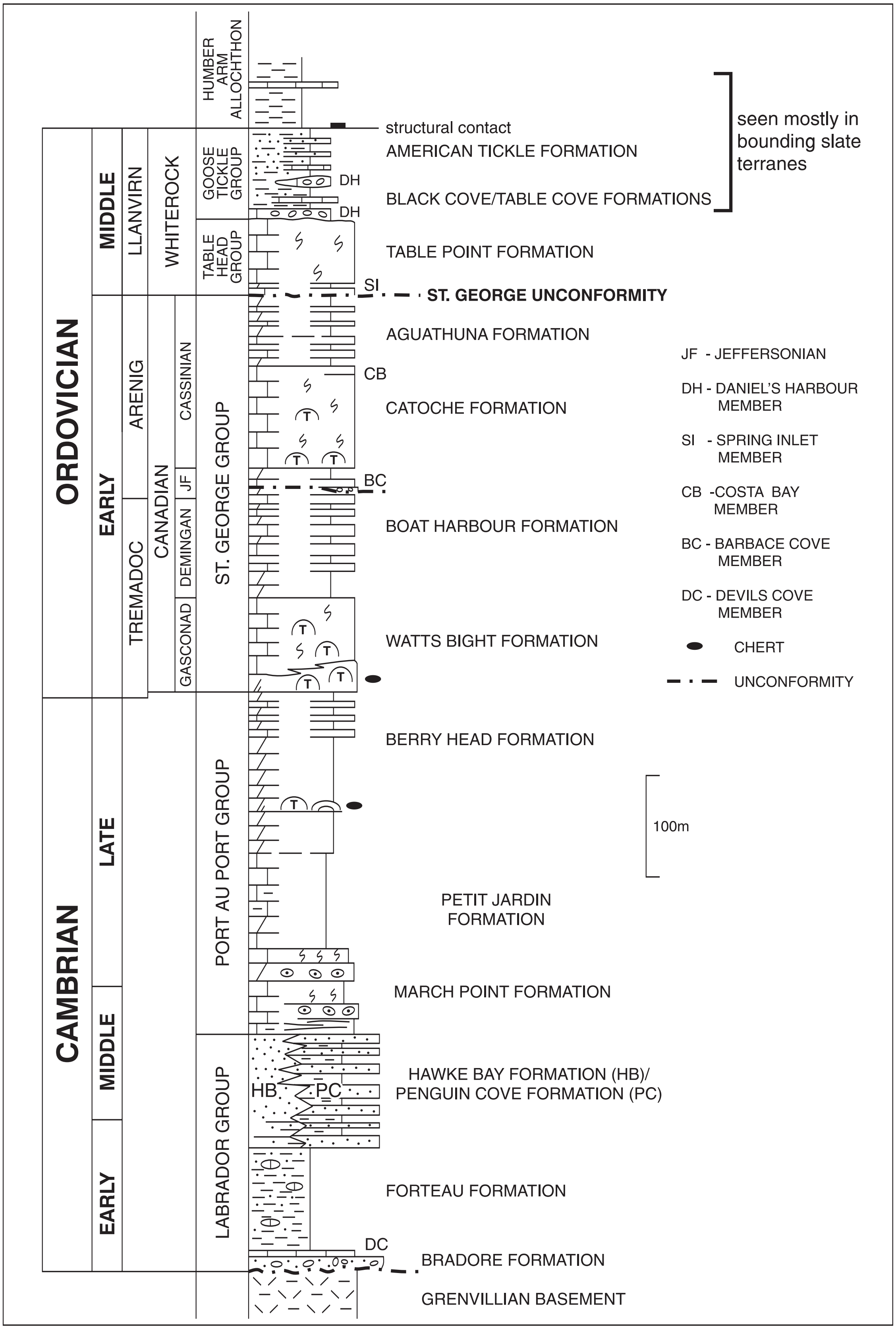

Figure 2. *Stratigraphy of the Cambrian–Ordovician shelf rocks in the Northern Brook Anticline.*

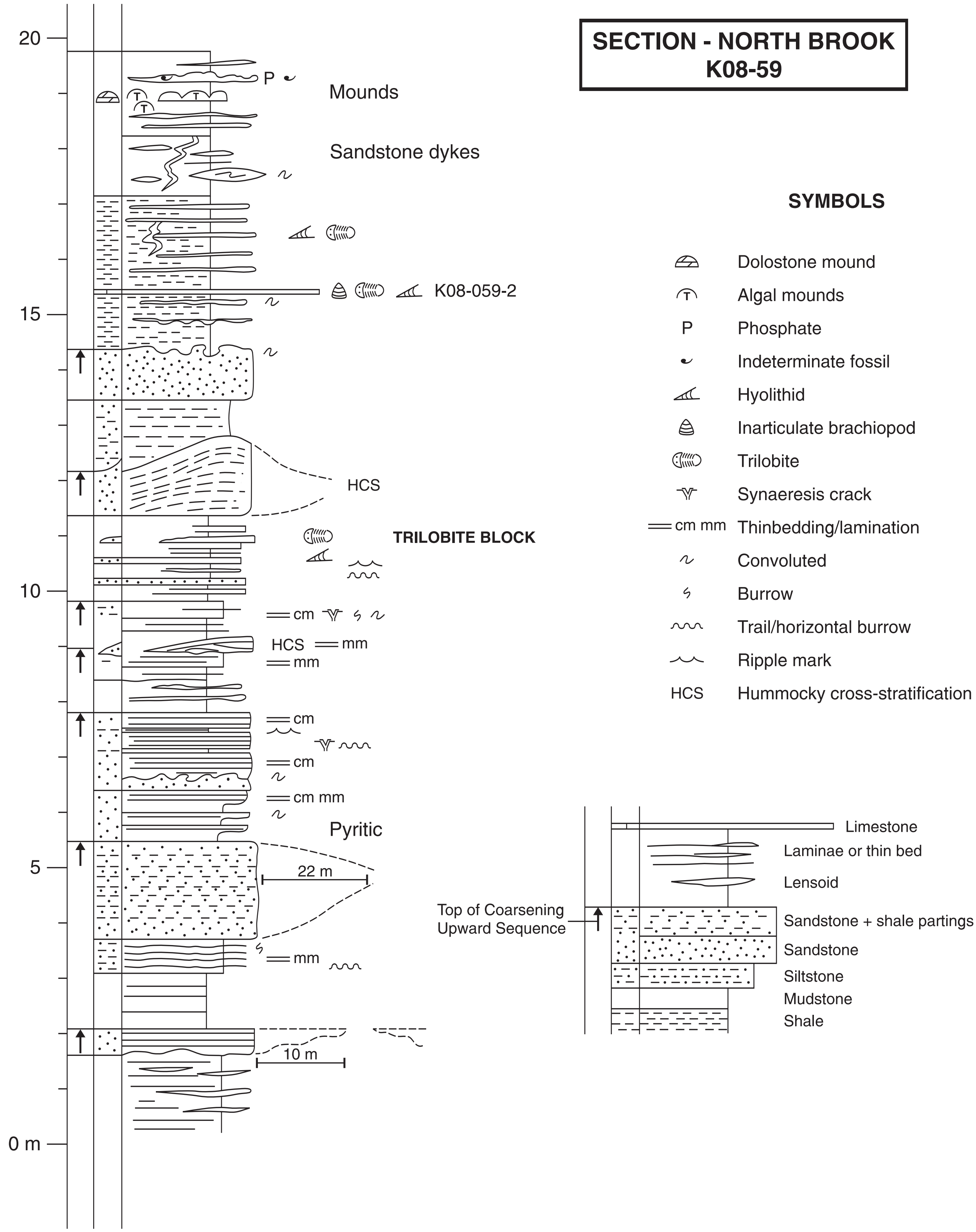

Figure 3. *Detailed graphic log of the section on North Brook, K08-59 (mapped in 2005 as K05-69D to 59F).*

and Boyce, 1987) suggesting that the block comes from the upper part of the Penguin Cove Formation in the North Brook Anticline.

CLASSIFICATION

Melzak and Westrop (1994, page 975) consider the genus *Kootenia* to be a junior synonym of *Olenoides* Meek, 1877 and suggest that Bonnia Walcott, 1916 may also be a synonym of *Olenoides*. In a review of the systematic literature, Boyce (1987; unpublished data, 2008) found references to at least 37 species of *Bonnia*, 75 species of *Kootenia*, and 41 species of *Olenoides*. This suggests, at the very least, that the three genera have been oversplit and that Melzak and Westrop (1994) may therefore be correct in their assessment. However, this question is beyond the scope of this report and must await further study.

CAUSE OF MASS KILL

At least forty *Kootenia* specimens, most of them from 3.6 to 4.2 cm in length, occur in a 32 x 19 cm section on the block (Plate 1). Since trilobite remains typically are preserved as incomplete, disarticulated molts or fragments, complete, articulated trilobites normally represent dead individuals. The trilobites on the block – all lying on their backs, typical of trilobite mass kills (D.M. Rudkin, personal communication, 2008) – represent a death assemblage.

Mass mortality could have been caused by:

1. Rapid burial. This is considered unlikely because the trilobites would be in a variety of orientations and attitudes, as is observed in the Burgess Shale.
2. Oxygen deprivation. This would be more likely should there have been a catastrophic release of toxic gas from the sea floor or if the trilobites inadvertently entered an existing mass of anoxic water or the latter shifted, catastrophically smothering the trilobites. Pyrite in the surrounding mudstones suggests oxygen-poor, reducing conditions were common.
3. Mating-related stress. This is doubtful, because a smaller block from the same locality contains larger cranidia and pygidia, indicating that *Kootenia* had a longer lifespan; in other words, if this *Kootenia* species only mated once during its life, you would not expect specimens bigger than those on the block
4. Stranding of the individuals in a supratidal pool after a storm surge. The heterolithic succession of lenticular hummocky sandstones and thin-laminated sheets of alternating mud and very fine sand, however, suggests that the sediments were deposited on a shelf rather than in a tidal-flat setting.
5. Exposure to fresh water due to a fluvial influence into a marine setting. The presence of synaeresis cracks and the low number and diversity of skeletal and burrowing faunas may support this idea.

In summary, possibilities 2 and 5 are regarded as the most likely.

MODE OF LIFE

Most of the *Kootenia* on the large block are of a similar size (Plate 1). This probably indicates that the trilobites were all about the same age and suggests that, like some modern day shrimp, the Cambrian crustaceans may have lived in 'schools'.

STRUCTURAL SIGNIFICANCE OF THE BLOCK

Pure shear involves irrotational or coaxial strain where the orientations of the principal strain axes, X and Z, do not change during deformation. In contrast, simple shear involves rotational or non-coaxial strain and the principal strains rotate during deformation (Figure 4).

Two *Kootenia* specimens that are on the block lie perpendicular to each other (Plate 10A). One has been lengthened and the other has been shortened. Lines that were perpendicular before deformation remain perpendicular (Plates 10B and 10C). This means that the trilobites are parallel to the principal strain axes as shown in the brachiopod example of Figure 5; this is a textbook example of pure shear (Park, 1989).

Using the formula $Y'/X' = \sqrt{(y_1 y_2 / x_1 x_2)}$, the principal strain Y'/X' ratio for this part of North Brook Anticline is calculated as being between 0.67 and 0.68 (Figure 6). Plates 10B and 10C show the trilobites before and after retro-deformation.

CONCLUSIONS

The mass mortality indicated by the abundant, complete, upside down *Kootenia* on the block was most likely caused by oxygen-deprivation. This may have happened because there was a catastrophic release of toxic gas from the sea floor or the trilobites inadvertently ventured into a massive body of anoxic water or were exposed to fresh water because of fluvial input to the shelf. The unimodal size of the trilobite population suggests that these animals may have lived in bottom-dwelling schools, making them vulnerable to mass-mortality events.

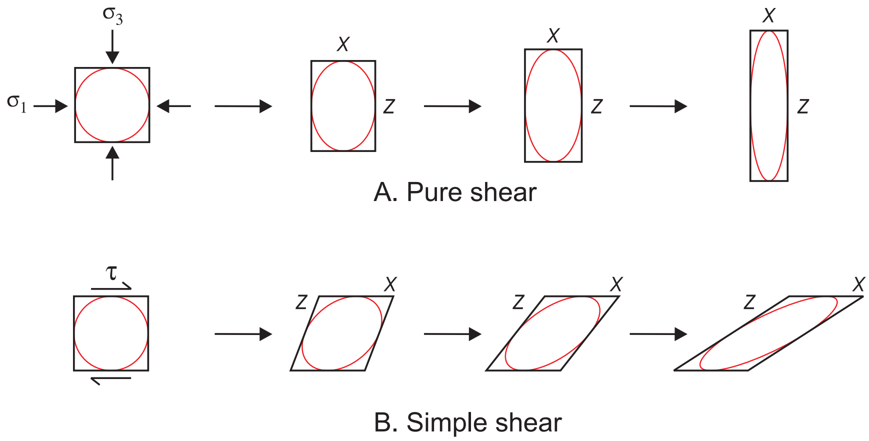

Figure 4. *Pure shear vs. simple shear (from Park,1989, page 40, Figure 6.7). Pure shear (above), involves irrotational or coaxial strain; the orientations of the principal strains X and Z do not change during deformation. In contrast, simple shear (below) involves rotational or non-coaxial strain; the principal strains rotate during deformation.*

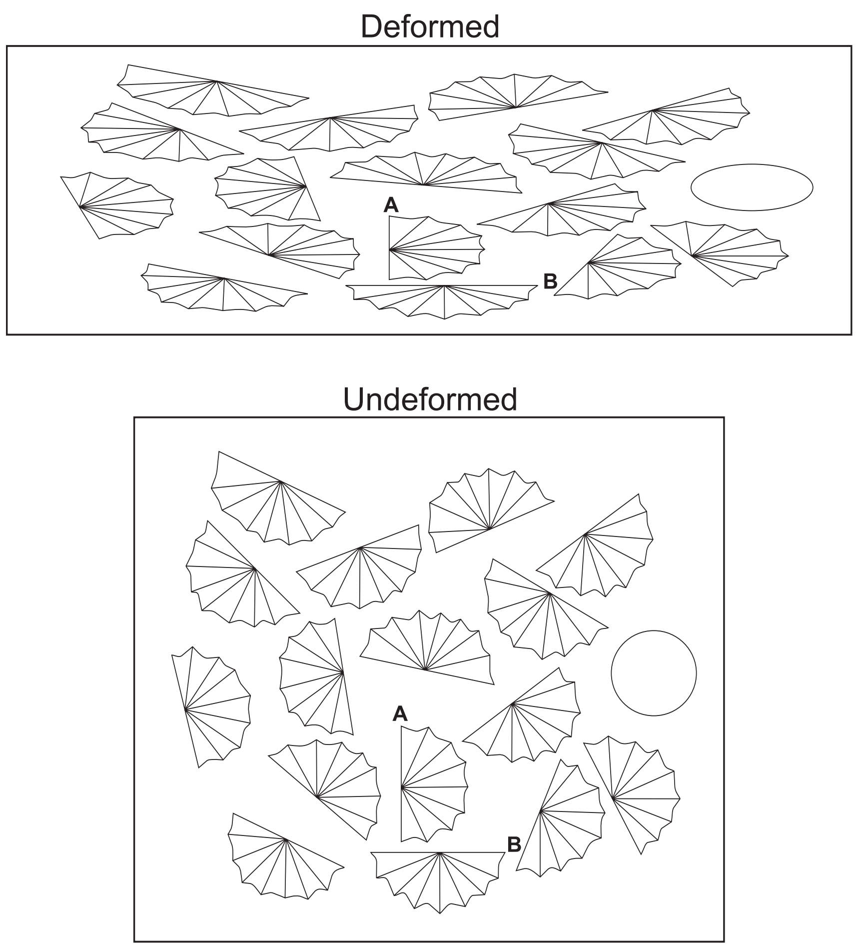

Figure 5. *Identification of pure shear using brachiopod fossils. The principal strain axes may be determined by specimens A and B, in which two originally perpendicular lines remain perpendicular after deformation. Modified from Hobbs* et al. *(1976, page 51, Figure 1.23).*

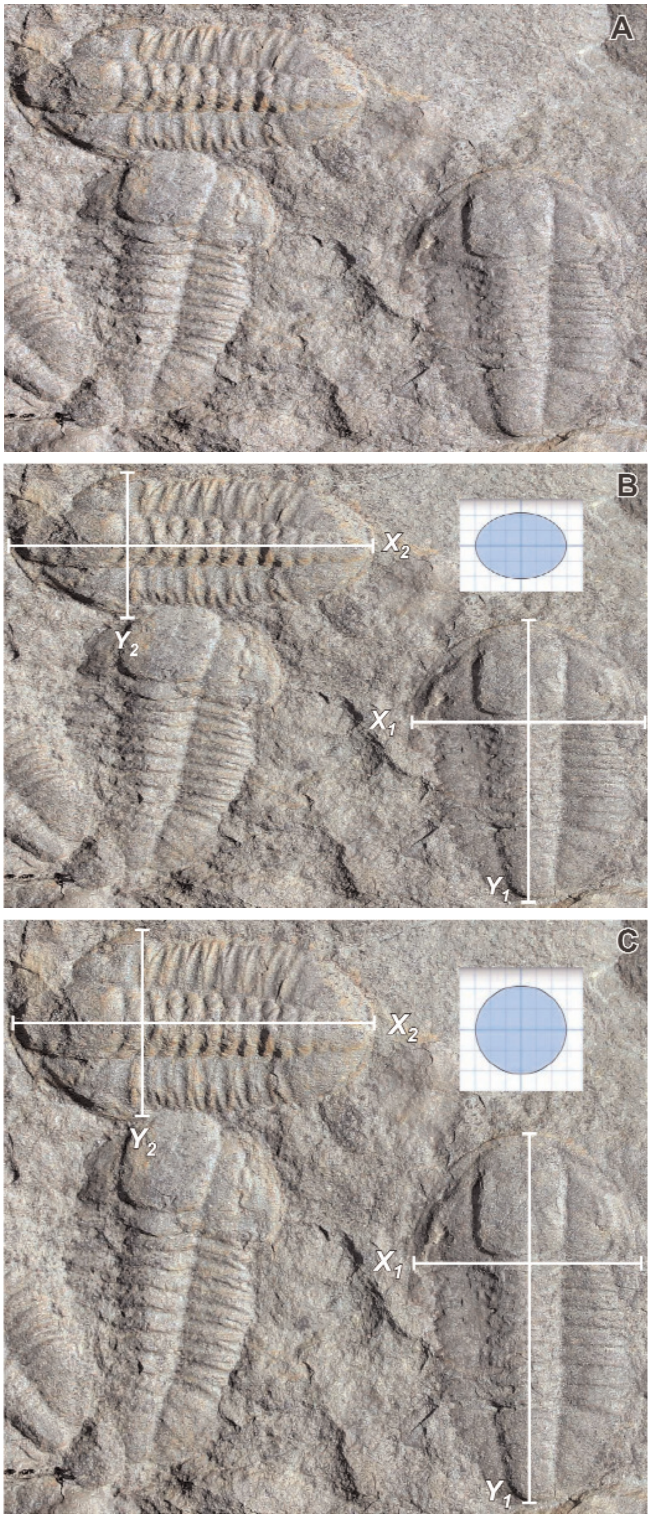

Plate 10. *A) Close-up of three articulated* Kootenia *from the block, Plate 1. Two individuals are at right angles to each other, and parallel to the principal strain axes. The top left trilobite has been lengthened, that on the right has been shortened. B) Specimens of Plate 10A with pre-retro-deformation axes and strain ellipse added, as in Figure 6. C) Kootenia specimens after retrodeformation.*

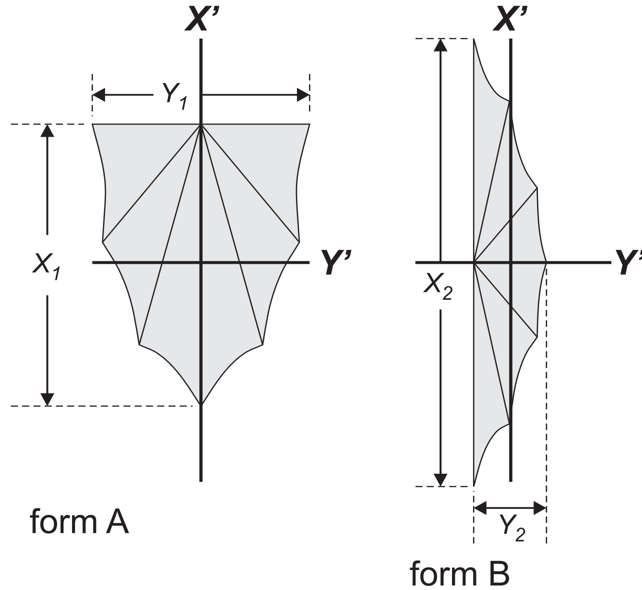

Figure 6. *Determining the principal strain ratio in two dimensions, using short and long fossil shapes (articulate brachiopods) lacking angular shear strain. If the lengths of the short and long forms are x_1 and x_2, respectively, and the widths are y_1 and y_2, then the strain ratio $Y'/X' = \sqrt{(y_1y_2/x_1x_2)}$. Modified from Park (1989, page 55, Figure 8.6).*

The trilobites indicate that the rocks on North Brook Anticline were deformed by pure shear (irrotational or coaxial strain); the principal strain Y'/X' ratio for this part of North Brook is calculated as being between 0.67 and 0.68.

ACKNOWLEDGMENTS

Josh Manning and Devon Seymour did the hard work moving the block into the helicopter, which was piloted by Derek Newhook (Canadian Helicopters). The specimens illustrated in this report are housed in the Natural History Annex of the Rooms Provincial Museum (NFM), St. John's; Mr. Randy Batten (Natural History Collections Manager) provided the specimen numbers. Dr. W. Lawson Dickson critically reviewed the first draft of the manuscript.

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APPENDIX

Fossil Horizons in the Penguin Cove Formation, North Brook (off Harrys River), near Gallants, NTS 12B/09 (Harrys River), UTM Zone 21

The datum for the fossil sites is NAD27. "2007F" = samples collected by W.D. Boyce. "K-2005" = samples collected by I. Knight. The UTM coordinates and the altitude are shown in metres as indicated by GPS.

2008F002
Loose block. 405882E, 5395456N, 151 m.

Arthropoda–Trilobita
Kootenia sp. undet. – 40+ articulated specimens

2008F002A
Outcrop. 405924E, 5395477N.

Brachiopoda–Inarticulata
Gen. et sp. undet.
Hyolithida
Gen. et sp. undet.

2008F002B
Outcrop. 405934E, 5395487N, 162 m.

possible trace fossils (not collected)

2008F002C
Float. No UTM coordinates were measured.

Hyolithida
Gen. et sp. undet.

2008F003
Outcrop. 405908E, 5395483N, 156 m.

Arthropoda–Trilobita
Kootenia sp. undet.