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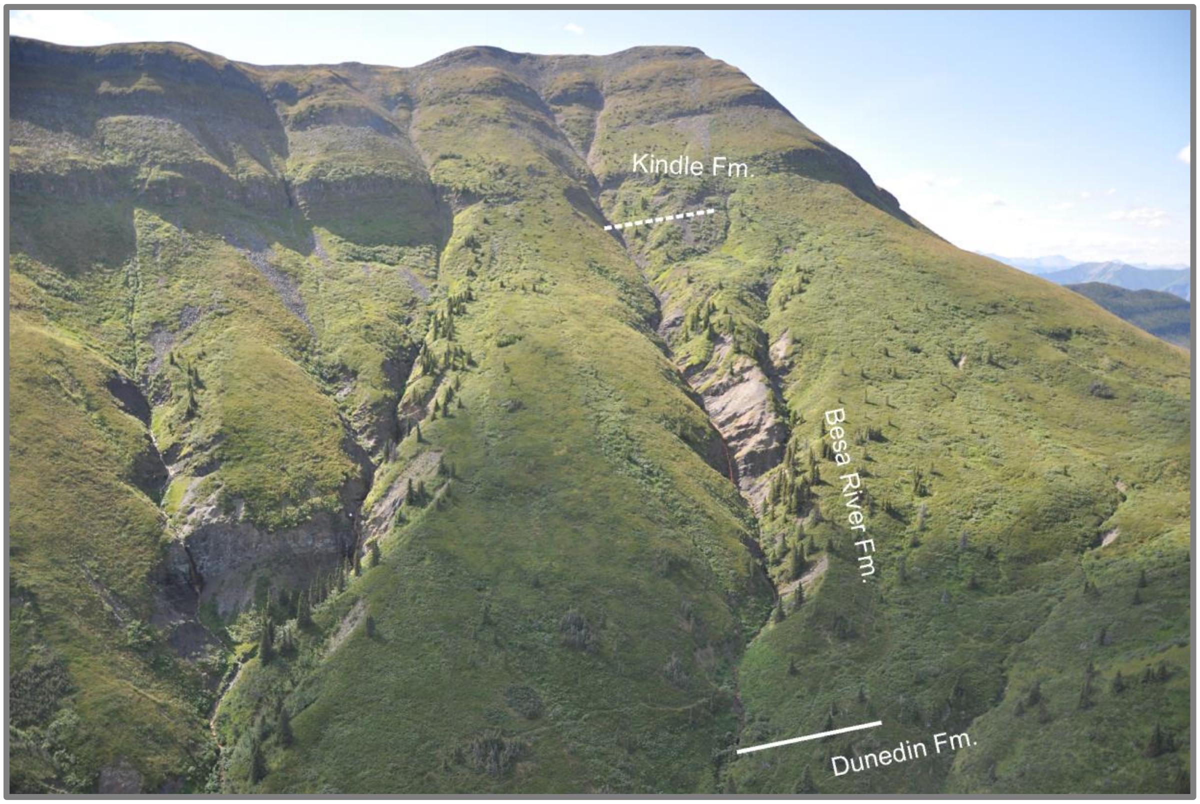

Reference surface and subsurface sections of the Besa River Formation, Liard Basin, British Columbia

P. Kabanov, B.C. Richards, Hyun Suk Lee, P. Thapa, H.M. King, and A. Mort

2019

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P. Kabanov[1], B.C. Richards[1], Hyun Suk Lee[2], P. Thapa[1], H.M. King[1], and A. Mort[1]

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Publications in this series have not been edited; they are released as submitted by the authors

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Title page photo: Stone Mountain section, airborne photo, courtesy of Filippo Ferri

ABSTRACT

The Middle Devonian to Upper Mississippian Besa River Formation (currently being elevated to a group by other authors) is a thick (300-1000 m) gas-prone succession of organic-rich basinal shales, bedded chert, and fine-grained limestone widely preserved in the Liard Basin of British Columbia, Yukon Territory, and Northwest Territories. The Besa River contains a major frontier shale-gas prospect in the Famennian to lower Tournaisian Exshaw Member and underlying informal Patry unit. The internal stratigraphic framework of the Besa River is poorly known and warrants intensive study because of its substantial economic significance. This report provides illustrated descriptions, lithologs, and spectral gamma surveys of one outcrop and three cored sections of the Besa River in the Liard Basin of B.C. and in the adjacent western part of the Horn River Basin. This study is part of the joint activity of Geological Survey of Canada, Korea Institute of Geoscience and Mineral Resources (KIGAM), and Filippo Ferri of B.C. Ministry of Natural Gas Development.

RÉSUMÉ

La formation de Besa River, agée du Dévonien moyen au Mississippien supérieur (actuellement sous considération d’érection au statut de groupe par d’autres auteurs) est une séquence épaisse (300-1000 m) de schistes de bassin, de chert lamellaire et de calcaire à grain fin riches en matières organiques, largement préservés dans le bassin de la Liard en Colombie-Britannique, au Yukon et dans les Territoires du Nord-Ouest. La Formation de Besa River renferme un important potentiel de gaz de schiste dans le Membre d’Exshaw (Famennien au Tournaisien inférieur) et l’unité sous-jacente informelle de Patry. Le cadre stratigraphique interne de la Formation de Besa River est peu défini et mérite une étude approfondie en raison de son importance économique. Ce rapport fournit des descriptions illustrées, des coupes lithologiques et des levés gamma spectraux d'un affleurement et de trois sections carottées de la Formation de Besa River dans le bassin de la Liard et du côté adjacent du bassin de Horn River. Cette étude fait partie d'une activité conjointe de la Commission géologique du Canada, de l'Institut coréen de géosciences et des ressources minérales (KIGAM) et de Filippo Ferri du ministère du Développement du gaz naturel de la Colombie-Britannique.

1. INTRODUCTION

This report compiles unpublished descriptions and spectral gamma surveys (SGR) from one outcrop section and two cored subsurface stratigraphic sections of the Besa River Formation in the Liard Basin in northeastern British Columbia (Figs. 1.1 and 1.2). The authors measured and sampled the sections between October 2017 and December 2018 (Table 1.1). These materials were acquired in the field in the northern Rocky Mountains and at the British Columbia Oil and Gas Commission core and sample facility in Fort Saint John. Descriptions are supplemented with photographs and retain much of the author's original wording and drafting. Figure 1.1 illustrates the lithostratigraphic relationships of the Besa River Formation and its principal constituent units. Numerous mapping and stratigraphic studies including those of Pelzer (1966), Bamber and Mamet (1978), Richards (1989), Switzer et al. (1994), and Richards et al. (1994) established the stratigraphic relationships of the Besa River to successions east of the Liard Basin, underlying Middle Devonian formations, and overlying Mississippian formations. Recent updates on lithostratigraphic characterization of the Besa River succession (Ferri et al. 2011, 2012, 2013, and 2015) include recognition of the Patry member (Ferri et al., 2015) and a proposal to formally elevate the Besa River Formation to a group. In addition, Ferri and Reyes (2019) recommended that the party member be elevated to the status of a formation. Much of the stratigraphic nomenclature used in this report is of a preliminary nature based largely on the work of Ferri et al. (2011, 2012, 2013, 2015, and 2019). Units within the Exshaw Member and the status of Patry unit have yet to be formalized.

Section	Scientist's code	Visit date	Station base		Station top		UTM Zone	Elevation base/ measured depth from KB (m)	Elevation top/ measured depth from KB(m)
			UTM NAD 83 (Easting, Northing)		UTM NAD 83 (Easting, Northing)				
Nexen Energy Dunedin A-38-b/94-n-8	--	Oct 2017	430591.74	6571735.04	457700	6422250	10v	3907	4075
Chevron Woodside HZ La Jolie B-3-K 94-O-12	18RAH1 18KOA05	Feb 26-Mar 09, 2018	455691.3	6614657.3	455691.3	6614657.3	10v	4265	4576
Stone Mountain (lower Besa River)	18KOA01	Aug 12-16, 2018	0386997	6523901			10N	1443	
Stone Mountain (lower Besa River)	18KOA02	Aug 12-16, 2018	0386976	6523902	0386963	6523895	10N	1440	1456
	18KOA03	Aug 12-16, 2018	0386963	6523895	0386893	6523913	10N	1456	1477
	18KOA04	Aug 12-16, 2018	0386876	6523936	0386789	6523944	10N	1504	

Table 1.1. Summary of measured stratigraphic sections

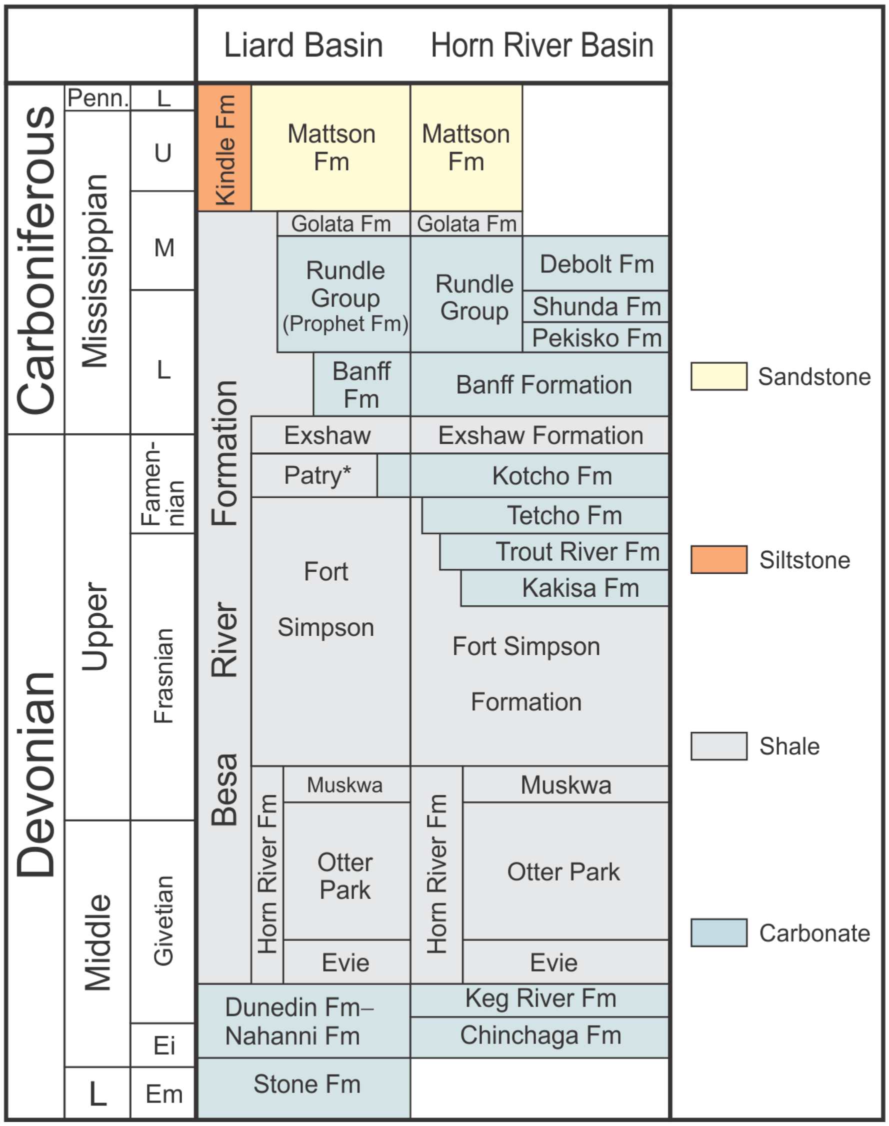

Figure 1.1. Mid-Late Paleozoic stratigraphic chart for northeast British Columbia showing relationships between lithostratigraphic units within the platformal and basinal successions of Liard and Horn River basins. Note that the Besa River can be elevated to a group in the eastern part of the study area but not in the western outcrop belt of the Rocky Mountains where the succession appears monotonous. L – Lower; M – Middle; U – Upper; Em – Emsian; Ei – Eifelian; Fa – Famennian. *Patry is an informal unit of member (Ferri et al., 2015) or formation rank (Ferri and Reyes, 2019)

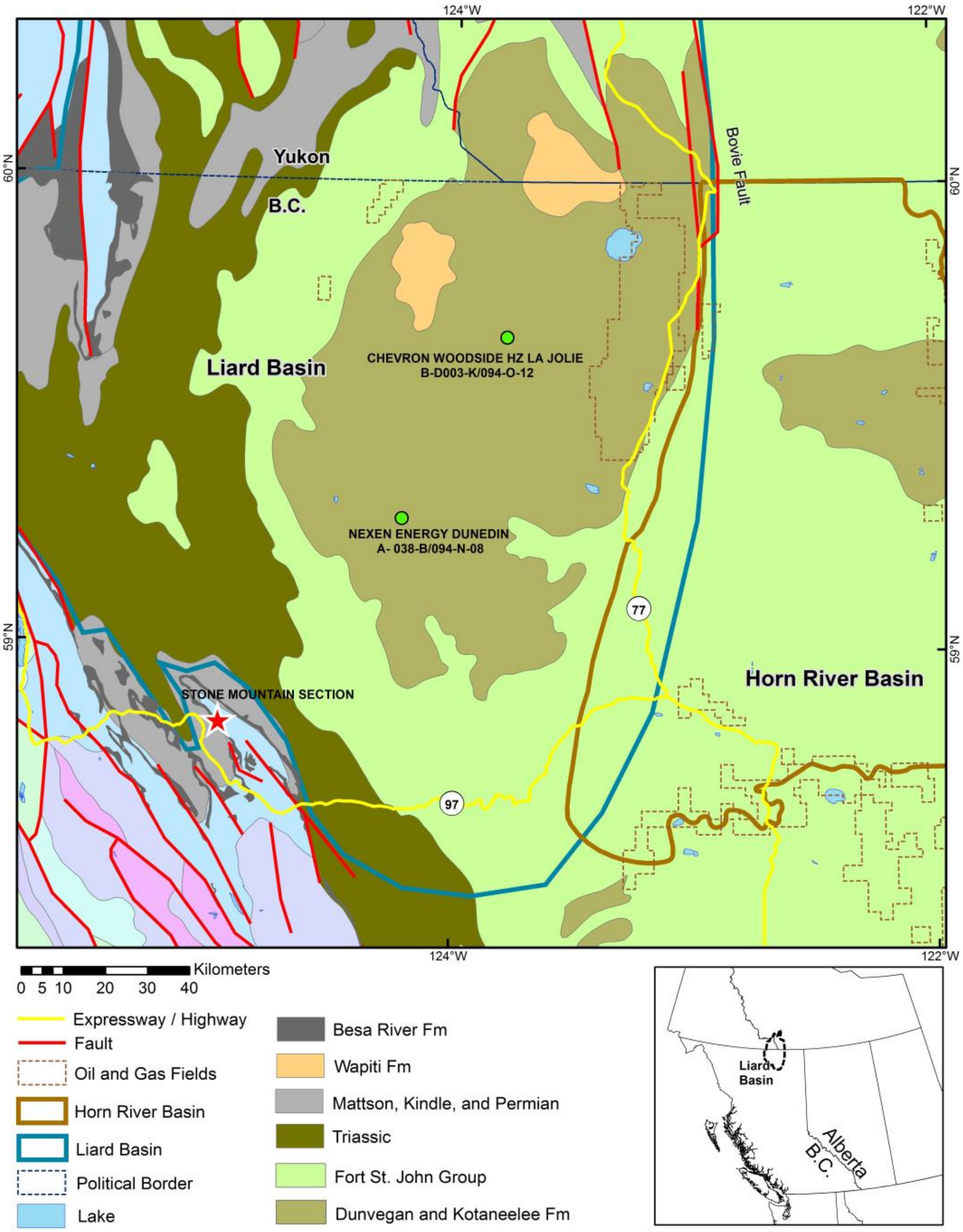

Figure 1.2. Measured stratigraphic sections on the simplified bedrock map, based on GIS project from (BC Geological Survey, 2012); see Ferri et al. (2011, 2015) and McMechan et al. (2012) for additional information.

2. Stone Mountain Section (lower part)

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The name Stone Mountain section (Table 1.1 and Figure. 1.2) refers to one of the best exposed stratigraphic sections of the Besa River (Fig. 2.1; Ferri et al., 2012; Ferri and Reyes, 2019). During the field program of 2011, the field work at the Stone Mountain section included a spectral gamma-ray (SGR) survey with RS-230 spectrometer at 1.0 m stratigraphic intervals, compilation of a detailed section description, and chip-sampling through 2.0 m intervals (Ferri et al., 2011, 2012a). The SGR reading time was set on 2.0 min (Ferri et al., 2011). The GSC-KIGAM team revisited this section in 2018. Three full days of work at the outcrop allowed us to measure the lower (approximating the Horn River – Muskwa) and the upper (Exshaw and lower Banff equivalents) within the Besa River section. Both parts were surveyed with RS-230 BGO tool. Stratigraphic spacing of SGR survey was at 0.5 m intervals and samples were collected at one-meter intervals or less thereby providing a higher resolution for subsurface correlation and geochemical signals. During the 2018 field study, signal acquisition time was two minutes except for a 20 m interval in the lower part of the 18KOA-04 section. A 1.5 minute acquisition time was used for the later interval (Appendix 1). Data for the upper part of the section comprising correlatives of the Exshaw and lower Banff (called 18RAH2) are not included herein.

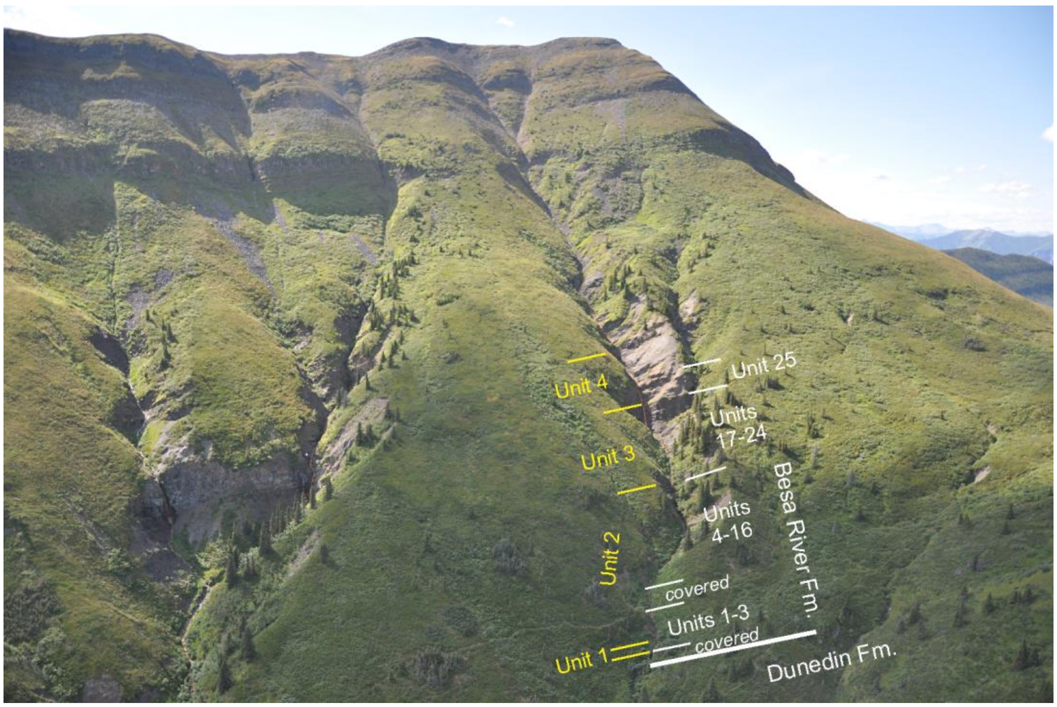

Figure 2.1. Airborne photo (courtesy of F. Ferri) with interpreted descriptive units from 2011 (yellow) and 2018 (white).

In 2018, the lower part of the Stone Mountain section was measured by P. Kabanov and surveyed with SGR tool by H.M. King. Stratal orientation information is reported in Table 2.1. Multipurpose "geochemical" samples, 100-200 g each, were collected with 1.0 m spacing by Hyun Suk Lee and P. Kabanov. Five large (>1.0 kg) samples with carbonate material were collected for conodonts (Fig. 2.2). The station number appears as 18KOA-0X and refers to the base of each of the four continuous sections in the gully. SGR-based correlation of sections from 2011 and 2018 indicates that meterages mismatch by about 10% (Fig. 2.2). The SGR proxies on Figure 2.2 are calculated from K, U, and Th signals:

$$SGR[gAPI] = 8 \times U[ppm] + 4 \times Th[ppm] + 16 \times K[\%] \quad (1)$$

$$U_n = U[ppm] / K[\%] \quad (2)$$

The equation (1) is widely used as an approximation to the total GR response (Ellis & Singer, 2007). Likewise, in the mnemonics of borehole spectralogs, KTH is the uranium-stripped SGR characterizing siliciclastic input (Ellis & Singer, 2007). The U_n is the proxy for authigenic uranium enrichment that mimics Al-normalized U based on strong linear covariation of Al and K in ICP elemental data (Fig. 2.3; Kabanov, 2019). Equation (2) omits slope as being provenance-specific and varying between sedimentary basins and sometimes between different stratigraphic units in one basin.

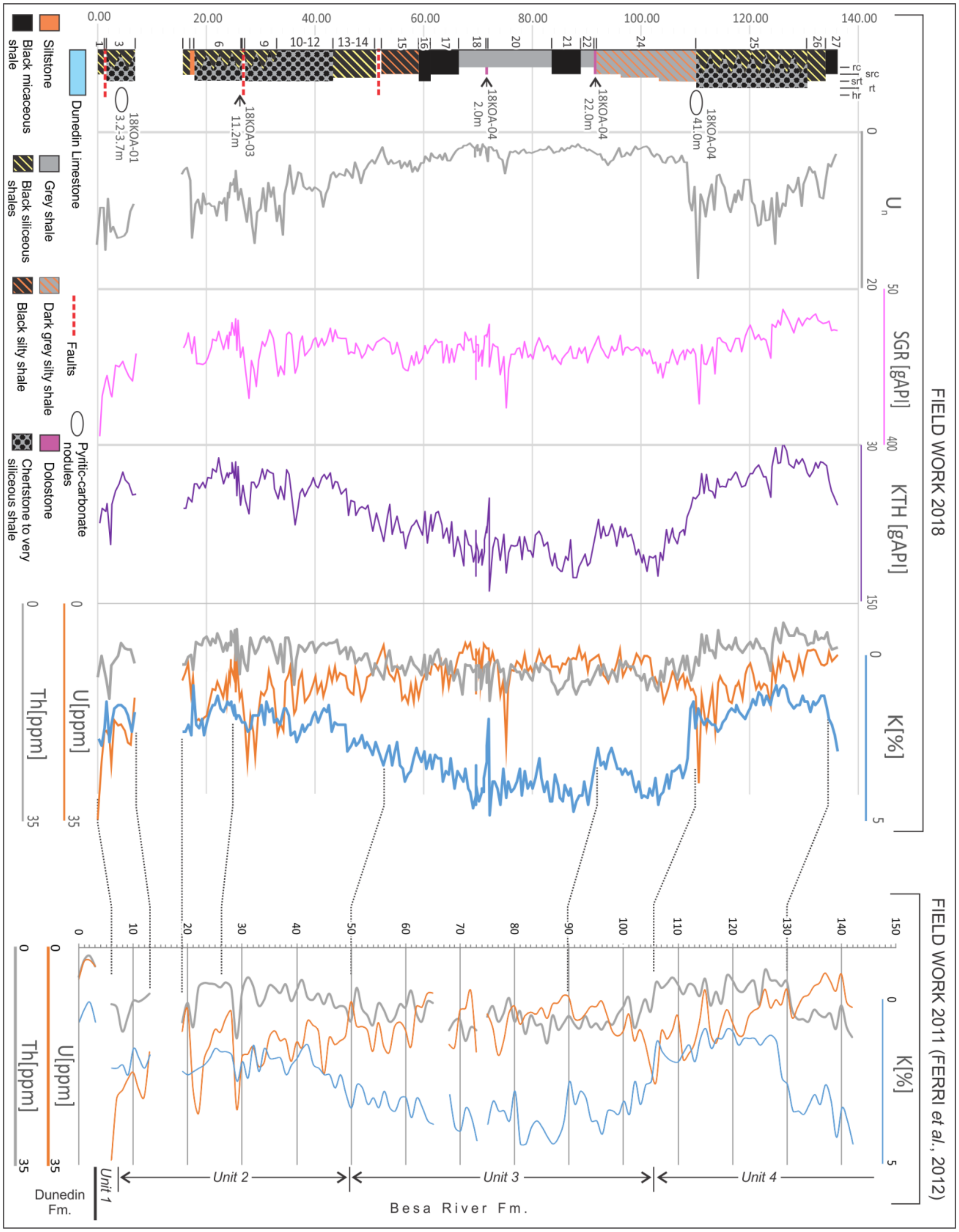

Figure 2.2. Stone Mountain section: SGR proxies, litholog, position of samples for conodonts, and correlation with same section measured in 2011 (Ferri et al., 2012b). Outcrop aspect: rc = recessive, src = semi-recessive, srt = semi-resistant, rt = resistant, hr = hard cliff-forming rock (*e.g.*, limestone, well-cemented sandstone)

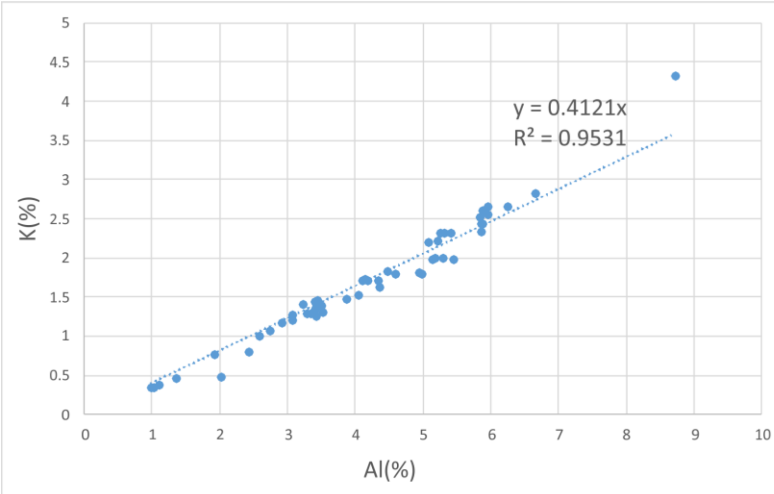

Figure 2.3. Al-K cross-plot, 52 ICP elemental data points from the Lower Besa River (Evie-Muskwa) interval of Beaver B-019-K/094-N-16 and ECA (Joint Venture) # 1 C-010-E/094-N-07 wells. Information on stratigraphic position of samples is available in McMechan et al. (2015).

Field station at section base	Lat (field station), NAD83	Long (field station), NAD83	Meterage from base of 18KOA-01	Stratal dip Azimuth/dip deg	Magnetic declination (mid-August 2018)	Uncorrected azimuth	corrected azimuth
18KOA-001	58° 50' 24.4" N	124° 57' 28.84" W	4	264/12	19	245	264
18KOA-003	58° 50' 24.18" N	124° 57' 30.92" W	23.5-25.5	244/34	19	225	244
18KOA-003	58° 50' 24.18" N	124° 57' 30.92" W	23.5-25.5	234/30	19	215	234
18KOA-003	58° 50' 24.18" N	124° 57' 30.92" W	23.5-25.5	228/27	19	209	228
18KOA-003	58° 50' 24.18" N	124° 57' 30.92" W	23.5-25.5	234/28	19	215	234
18KOA-003	58° 50' 24.18" N	124° 57' 30.92" W	27	249/20	19	230	249
18KOA-003	58° 50' 24.18" N	124° 57' 30.92" W	33	228/29	19	209	228
18KOA-003	58° 50' 24.18" N	124° 57' 30.92" W	34	214/24	19	195	214
18KOA-003	58° 50' 24.18" N	124° 57' 30.92" W	35	222/24	19	203	222
18KOA-003	58° 50' 24.18" N	124° 57' 30.92" W	42.8	219/35	19	200	219
18KOA-003	58° 50' 24.18" N	124° 57' 30.92" W	43	229/34	19	210	229
18KOA-003	58° 50' 24.18" N	124° 57' 30.92" W	48	233/32	19	214	233
18KOA-003	58° 50' 24.18" N	124° 57' 30.92" W	50	234/25	19	215	234
18KOA-003	58° 50' 24.18" N	124° 57' 30.92" W	52	219/21	19	200	219
18KOA-003	58° 50' 24.18" N	124° 57' 30.92" W	59	234/30	19	215	234
18KOA-004	58° 50' 25.4" N	124° 57' 36.43" W	70	234/27	19	215	234
18KOA-004	58° 50' 25.4" N	124° 57' 36.43" W	124.5	234/28	19	215	234

Table 2.1. Stratal dip azimuth and angle information

18KOA-01

Base: 0386997 N, 6523901 E Top: not measured Alt:1443 m

A cliff of semi-resistant mudrock exposed in ~5-8 m above the stratigraphically uppermost exposure of the Dunedin limestone (Fig. 2.4). A bedrock rib of hard calcareous black mudrock exposed in the vegetated gully in ~1-2 m above the cliff of Dunedin limestone is considered to occur very close to the base of the Besa River shale.

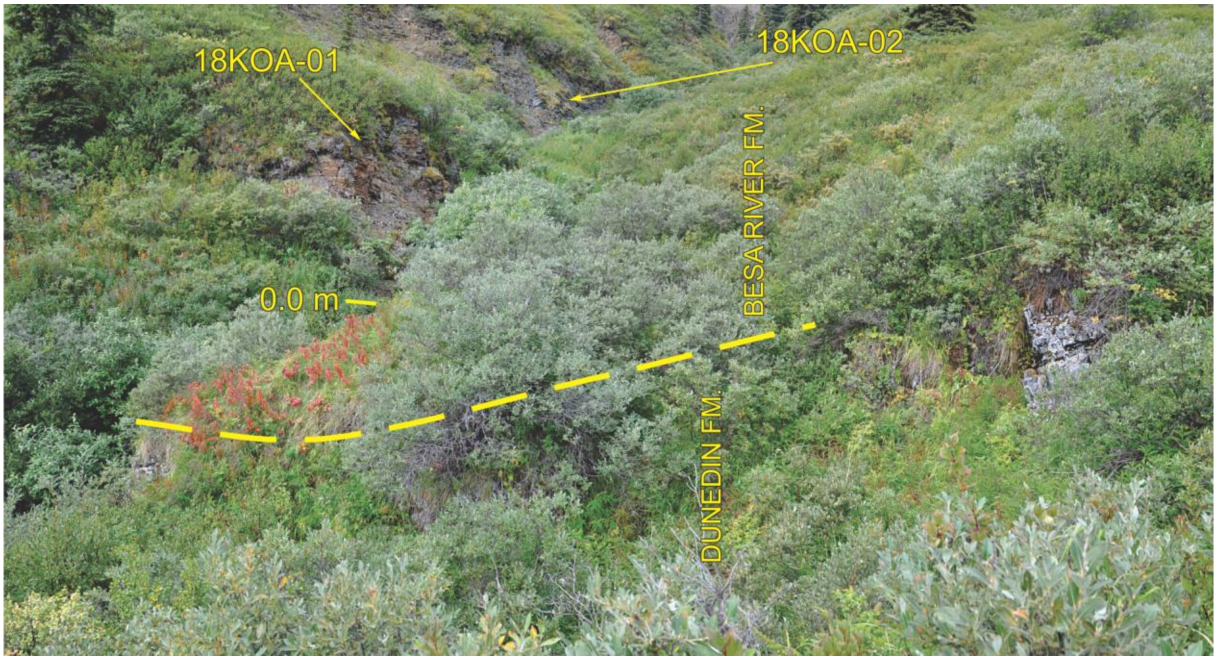

Figure 2.4. Approximate base of the Besa River Formation in Stone Mountain section (dashed line); the base of bedrock exposure at station 18KOA-01 is a zero m datum.

1. 0.0-1.3 m. Shale: black to dark grey, medium-hard, partly papery, semi-recessive, fissile, weathering in small (1.0 cm) flakes; weathered surfaces are dull rusty.

2. 1.3-1.45 m. Shale: softer than below and very recessive, deeply caving in the middle, may represent a fault plane.

3. 1.45-7.0 m. Mudrock: siliceous, semi-resistant, laminated, dark grey to black; pelitomorphic with minor silty shale and muddy siltstone lithology. Distinct rhythmicity: 2-4 cm thick beds of muddy cherts are interbedded with hard fissile platy shale. Thickness of chert-shale couplets varies between 4 and 6 cm. Cherts split along characteristic conchoid fractures. Rare large (20-30) very weathered pyritic-carbonate nodules at 3.2-3.65 m; pyrite is almost entirely converted into rusty crusts (Fig. 2.5).

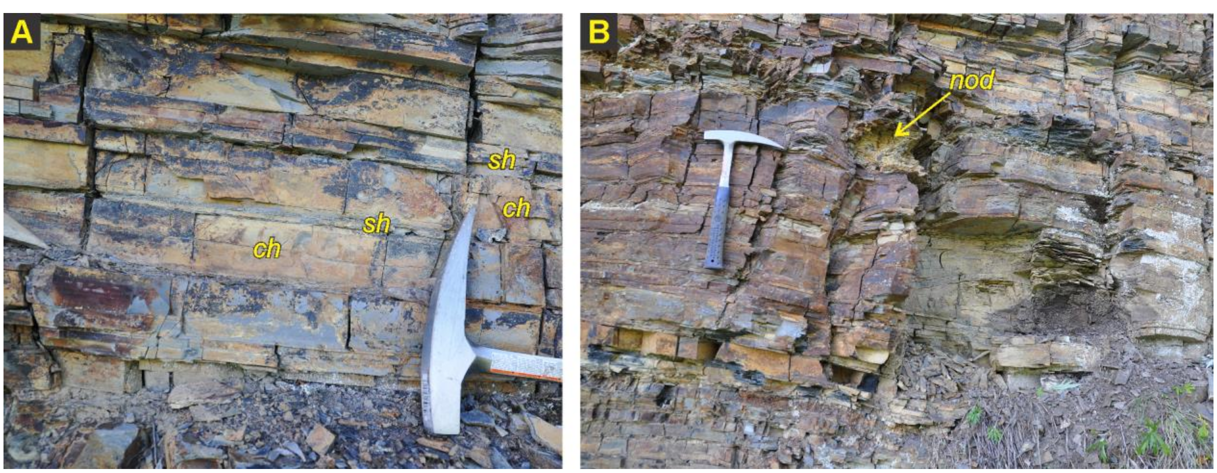

Figure 2.5. Stone Mountain section, 18KOA-01: (A) Alternation of chertstone (ch) and shale (sh) in unit 3; (B) weathered nodule of authigenic carbonate (*nod*) in unit 3 (3.4 m from the base). Hammer handle is 32 cm.

18KOA-02

Base: 0386976 N, 6523902 E Top: 0386963 N, 6523895 E Alt: 1456 m

Sections 18KOA-01 and 18KOA-02 occur on the right slope of the gully (looking downstream) and are separated by 8-9 m of covered slightly receding interval (Fig. 2.6). Dual meterage counts from the base of 18KOA-01 and (the base of 18KOA-02).

4. 15.5-16.9 (0.0-1.4) m. Shale: hard, siliceous, homogeneous, semi-recessive, black on fresh cuts, subfissile, weathering ochre (Fig. 2.7A). The shale is silty; minor admixture of very fine-grained sand in some beds.

5. 16.9-17.9 (1.4-2.4) m. Siltstone: soft and semi-recessive, dark brownish grey on fresh cuts, platy, homogeneous; minor interbeds of very fine-grained sandstone and silty shale.

6. 17.9-25.6 (2.4-10.1) m. Chertstone/mudrock: semi-resistant to resistant, low-contrast rhythmic alternation of laminated muddy chertstones and siliceous platy shales. Gentle synsedimentary folding (slumping structures) at 20.5 m and 14.5-14.7 m (Fig. 2.7B).

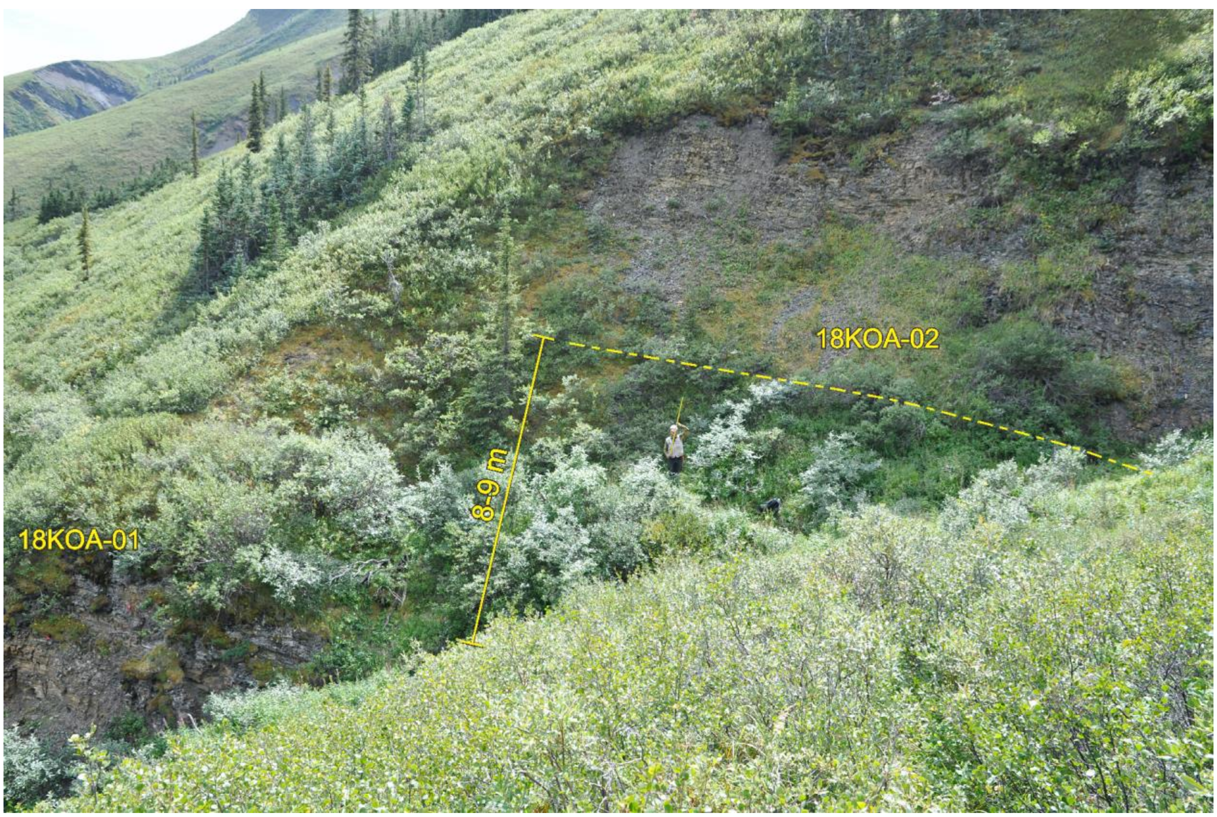

Figure 2.6. Stone Mountain section. Covered interval between sections 18KOA-001 and 18KOA-002.

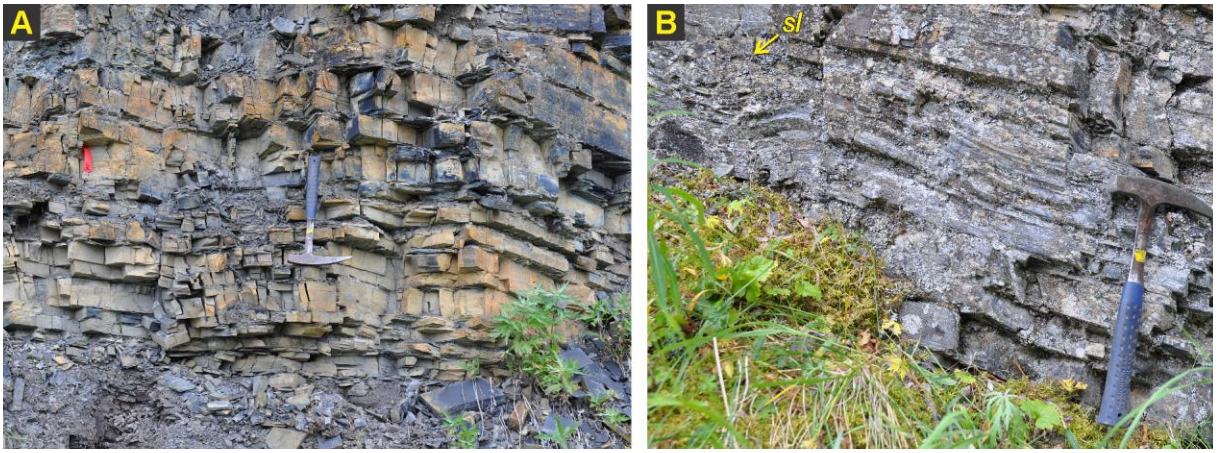

Figure 2.7. Stone Mountain section, 18KOA-02: (A) Outcrop aspect of the unit 4; (B) A gentle slumping fold (*sl*) at 20.5 m.

18KOA-03

Base: 0386963 N, 6523895 E Top: 0386893 N, 6523913 E Alt: 1477 m

The section starts at the left slope of the gully opposite the top of Section 18KOA-02. The poorly exposed lower 15 m of 18KOA-03 were cleaned with the shovel (Fig. 2.8). Middle part continues in the gully bed, and the upper part (61.4-71.8 m) was measured in a cliff on the right bank. The stratigraphic overlap between 18KOA-02 and 18KOA-03 is 2-3 m.

Figure 2.8. Stone Mountain section, 18KOA-03: Trench exposure of the section base. The red pogo stick is 1.0 m.

6. 23.5-26.85 (8.0-11.35) m. Continuation of the unit exposed at 17.9-25.6 m of 18KOA-02. Siliceous shale in low-contrast interbedding with muddy cherts (Fig. 2.9); pyrite is moderately abundant inside non-weathered rock, occurs as dispersed "dust". Very weathered rusty carbonate nodules at 26.7 (11.2) m.

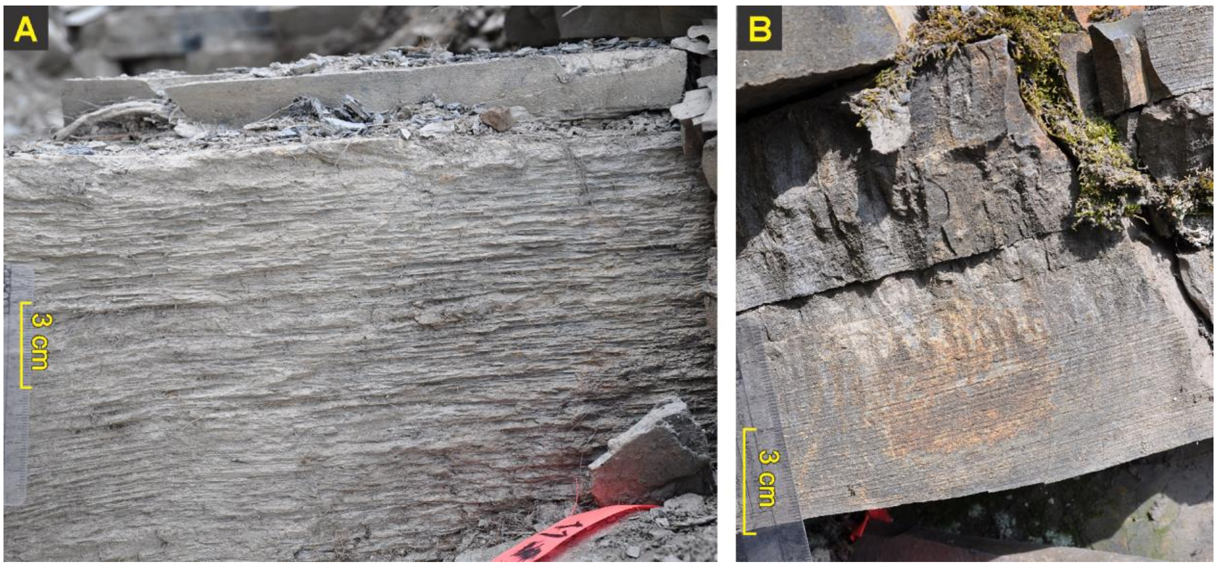

Figure 2.9. Stone Mountain section, 18KOA-03: Sedimentary lamination on weathered surfaces of vertical fractures, cherty mudrocks of unit 6.

7. 26.85-27.0 (11.35-11.5) m. Shale: fissile, black, hard, with one or several beds of poorly preserved tentaculitids and possibly other types of carbonate grains.

8. 27.0-27.8 (11.5-12.30) m. Weathered very recessive interval: soft extensively slickensided black shale, no bedrock preserved in the middle. Interpretation: strike-slip fault.

9. 27.8-33.0 (12.30-17.5) m. Siliceous shale as below 27.0 m: low-contrast alternation of more siliceous (chertstones) and less siliceous, more fissile intervals (shales). Chery intervals are black, massive on fresh cuts, rich in evenly dispersed "pyrite dust"; overall pyrite content seems to grow upward in the upper 2 m of the interval. Gentle synsedimentary slumping fold at 14.5 m.

10. 33.0-34.0 (17.5-18.5) m. Chertstone: hard, very pyritic (evenly dispersed "pyrite dust"). Distinct bedding: 10-15 cm thick competent chertstone beds are separated by thinner interbeds of hard platy shale.

11. 34-36.5 (18.5-21.0) m. Alternation of chertstone and shale forming a low resistant rib (Fig. 2.10): low-contrast alternation forming 5-7 cm couplets; overall less pyritic than at 33.0-34.0 m; pyrite occurs as pyrite dust and streaks. Meter-scale slumping structures at about 20.0 m.

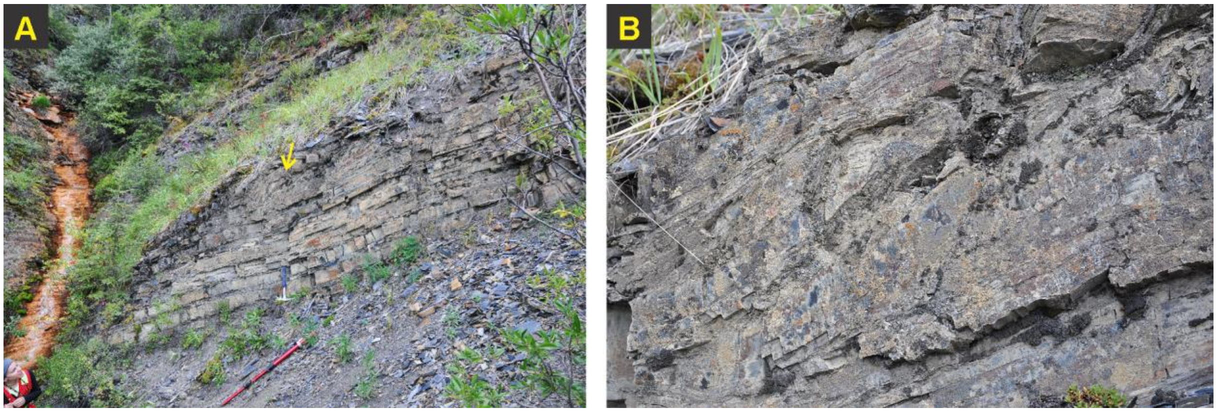

Figure 2.10. Stone Mountain section, 18KOA-03: (A) A resistant rib of cherty mudrocks at 34.0-36.0 m (unit 11); (B) Close-up at the area arrowed on (A) showing slumping structures with roll in the middle.

12. 36.5-43.8 (21.0-28.3) m. Chertstone: medium-bedded (4-10 cm) black cherty mudrocks and chertstones with thin interbeds of fissile shale (Fig. 2.11). Regularly spaced (4-6 mm) pyritic streaks and laminae are frequently seen on fresh cuts.

13. 43.8-48 (28.3-32.5) m. Shale: hard, black, fissile, weathers darker ochre than below; distinct from the chertstones below by prevailing fissile rocks and lowered pyrite content. Minor very poorly differentiated more competent cherty beds.

14. 48-51 (32.5-35.5) m. Shale: low-contrast alternation of fissile shales and harder cherty mudrocks forming 10-20 cm thick rhythms. Distinct from 43.8-48 m by increased pyrite content in the form of pyritic streaks and dust.

51.0-52.1 (35.5-36.6) m. Vegetated fault plane.

15. 52.1-59.0 (36.6-43.5) m. Shale: very fissile, very dark grey on fresh cuts, hard, platy, silty (micaceous), homogeneous, with minor siltstones; distinct from units 13 and 14 by lack of hard cherty interbeds; weathers dull rusty and greenish.

16. 59.0-61.4 (43.5-45.9) m. Shale; black, pelitomorphic; low-contrast, 15-25 cm thick alternation of fissile hard shales as below and subfissile hard mudrocks with local conchoid fracturing; pyrite content is relatively low; moderate yellow powdery weathering - jarosite?

Units 15-16 are cliff forming (Figs. 2.12B and 2.13A).

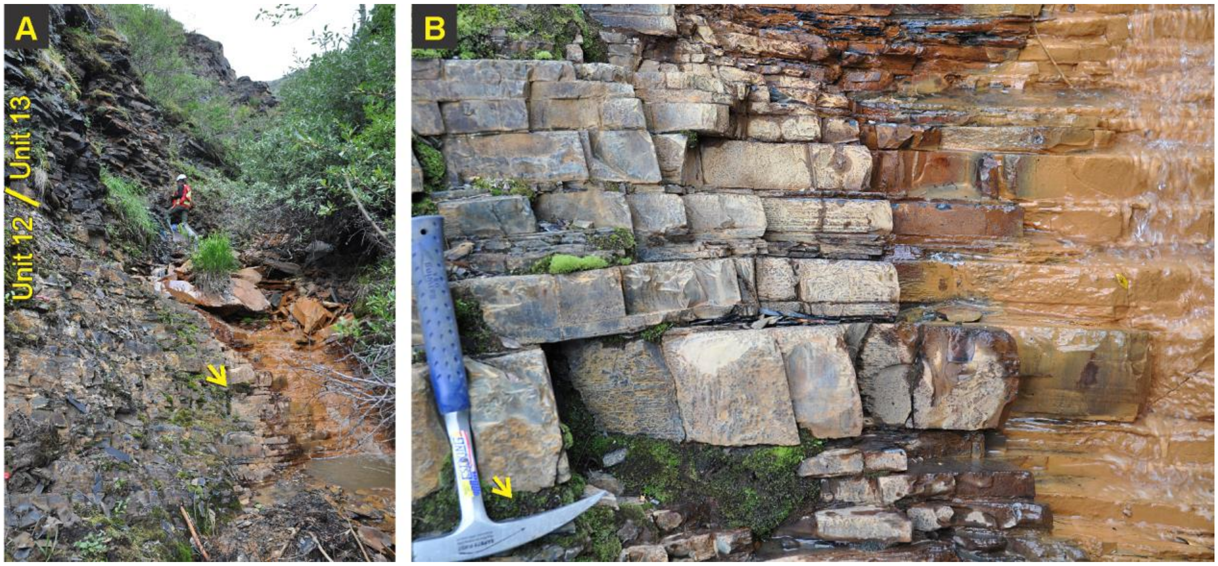

Figure 2.11. Stone Mountain section, 18KOA-03: (A) Contact of hard chertstones of unit 12 and overlying fissile shales; (B) Aspect of bedded chertstones in the creek bed. Arrows in (A) and (B) point at the same spot.

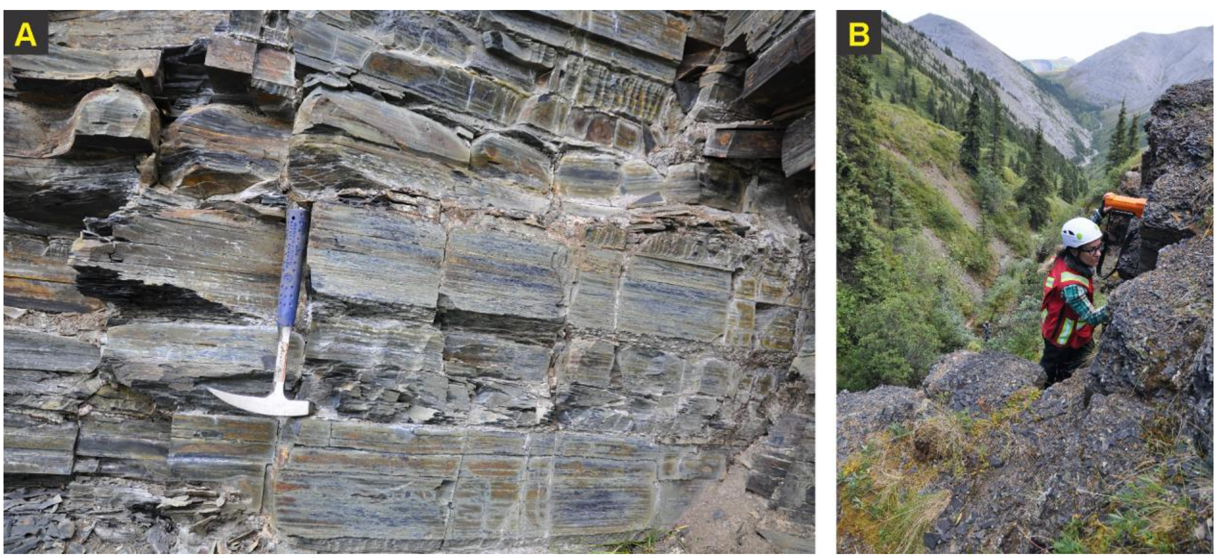

Figure 2.12. Stone Mountain section, 18KOA-03: (A) Outcrop aspect of Unit 15; (B) Acquisition of SGR data from unit 16 near the cliff top.

17. 61.4-66.5 (45.9-51.0) m. Shale: black to very dark grey, silty and locally pelitomorphic, very fissile, in the base harder and weathering in large plates, upward becomes softer, more recessive and weathering into small plates and chips.

18. 66.5-71.5 (51.0-56.0) m. Shale: dark grey, fissile, soft and recessive, with brick smell when crushed, weathers in small (≤ 2 cm) plates. This interval was shoveled in a trench.

19. 71.5-71.8 (56.0-56.3) m. Dolomitic marl (or argillaceous dolostone): soft, dark brownish grey, very finely crystalline, weathered in soap bar shaped nodules; grades in the upper one-half into soft dark grey shale. Hard dolostone occupies only the lower 10-15 cm at this location.

Figure 2.13. Stone Mountain section: (A) Top of section 18KOA-03 viewed from the opposite slope of the gully; the unit 18 is measured in two shoveled trenches (above and to the right of the person); dolostone location at 71.5-71.8 is arrowed. (B) Hard black shale of unit 16 at 45.0-45.4 m.

18KOA-04

Base: 0386876 N, 6523936 E Top: 0386789 N, 6523944 E Alt: not recorded

Section starts on the left bank of the creek. Sections are correlated by the dolostone found at 56.0 m of 18KOA-03 and 2.0 m of 18KOA-04. The lower part (0-22 m) is affected by pervasive sheering pattern occurring at low angle to sedimentary lamination. Dual meterage counts from the base of 18KOA-01 and (the base of 18KOA-04).

18. 69.5-71.5 (0.0-2.0) m. Shale: dark grey, silty, fissile, homogeneous, soft and rusty on weathering surfaces.

19. 71.5-71.75 (2.0-2.25 m). Dolostone: very finely crystalline, argillaceous and originally pyritic, weathers in soft blocky nodules that are separated by very soft (earthy) limonitic joints. Grading to overlying and underlying shales (Fig. 2.14).

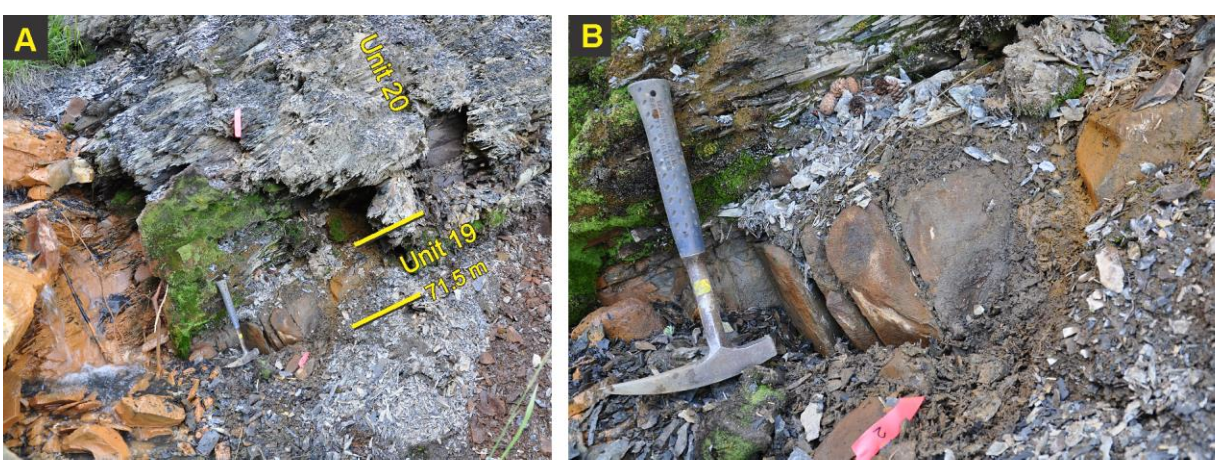

Figure 2.14. Stone Mountain section, 18KOA-04: (A) Units 19-20; (B) the close-up at the dolostone of unit 19.

20. 71.75-83.5 (2.25-14.0) m. Shale: dark grey, fissile, homogeneous, partly silty. Sedimentary lamination is mostly unrecognizable under the overprint of the shearing pattern and fissility. Rare laminae of heterolithic siltstone in the basal 1.0 m. A poorly preserved slumping fold in the base. Pyrite content is medium to low, appears as “pyrite dust” on fresh cuts of non-weathered chips.

21. 83.5-88.5 (14.0-19.0) m. Shale: black to very dark grey, very fissile, slightly harder than below; weathers in thin (< 1 mm) plates that are ≤ 1.5 cm across. Moderate pyrite content (“pyrite dust”). The shearing pattern as in the unit 20 (Fig. 2.15).

Figure 2.15. Stone Mountain section, 18KOA-04, unit 21 at 84.5 m. Shearing pattern overprints sedimentary lamination with tendency to produce false bedding planes.

22. 88.5-91.3 (19.0-21.8) m. Shale: dark grey, soft, fissile, recessive. This interval was concealed under the scree and required shoveling.

23. 91.3-91.8 (21.8-22.3) m. Dolostone: argillaceous, soft, very finely crystalline (texture resembling sandstone), fractured and weathered dark brown; interbeds with shale.

24. 91.8-110.5 (22.3-41.0) m. Silty shale and siltstone: Homogeneous, very fissile, dark grey, relatively hard and thin-platy, semi-resistant and wall forming.

25. 110.5-130.5 (41.0-61.0) m. Alternation of shale, cherty mudrock and chertstone: hard, resistant (capping the waterfall), pelitomorphic to silty, black, with rare admixture of very fine-grained sand; Pyrite content is hard to estimate from the weathered outcrop. Characterized by decameter scale synsedimentary slumping folds and rolls developed in the entire unit (Figs. 2.16, 2.17, and 2.19A). Elliptical weathered rusty carbonate nodules are encountered in the base (Fig. 2.18).

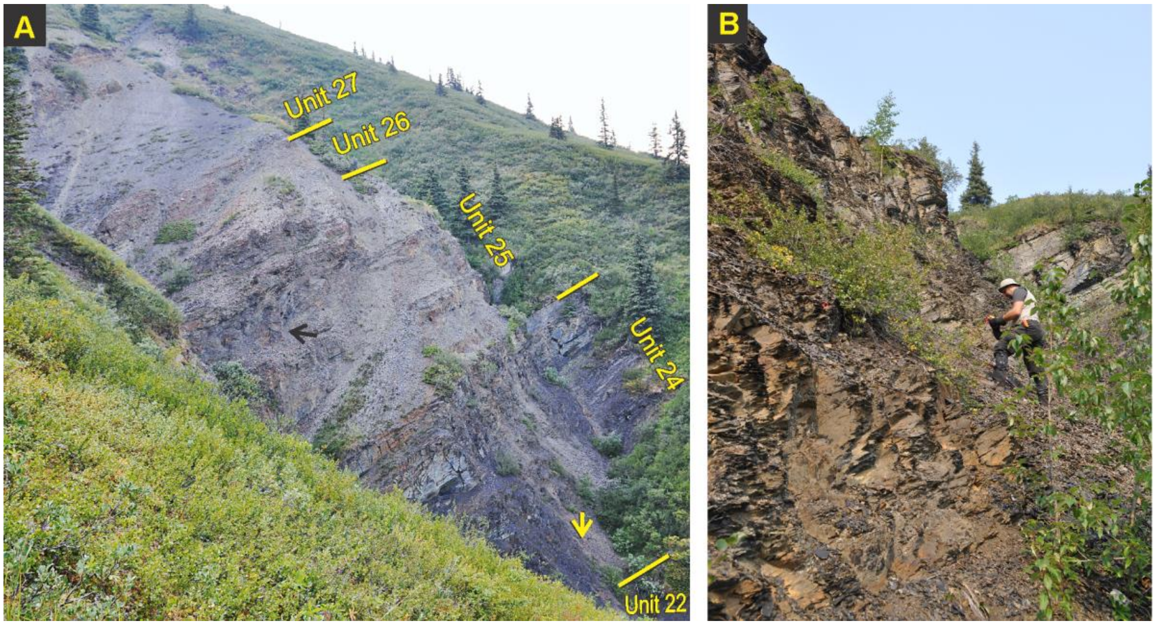

Figure 2.16. Stone Mountain section, 18KOA-04: (A) Units 22-27 viewed from the opposite slope of the gully; black arrow points at large-scale slumping structures in the unit 25; yellow arrow points at the position of the person on (B); (B) sheared, semi-resistant, wall-forming aspect of unit 24.

26. 130.5-133.9 (61.0-64.4) m. Shale/mudrock: black, hard, siliceous, semi-resistant, weathering deep rusty. Low-contrast alternation of harder cherty mudrocks with some feathery surfaces and more fissile shales.

27. 133.9-136.0 (64.4-67.0) m. Shale: Black to dark grey, very fissile, weathering brown. Non-disturbed sedimentary lamination is distinct in the base and mostly obscure in the upper part. Contact with the underlying mudrock is very gradational. Grades upward into a very recessive interval of the fissile shale (Fig. 2.19).

Description from August 2018 stops at 137.0 m.

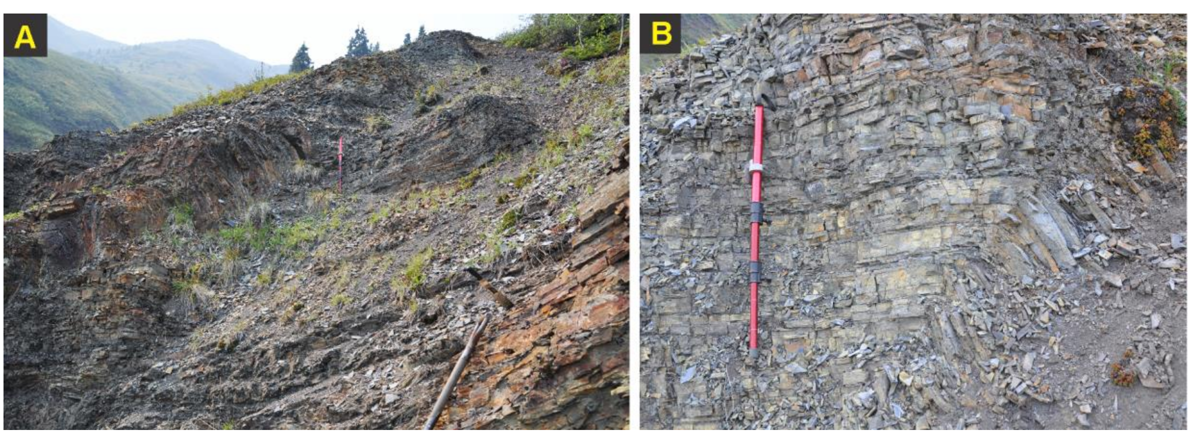

Figure 2.17. Stone Mountain section, 18KOA-04: large-scale synsedimentary folds in the upper part of unit 25. Pogo stick is 1.0 m.

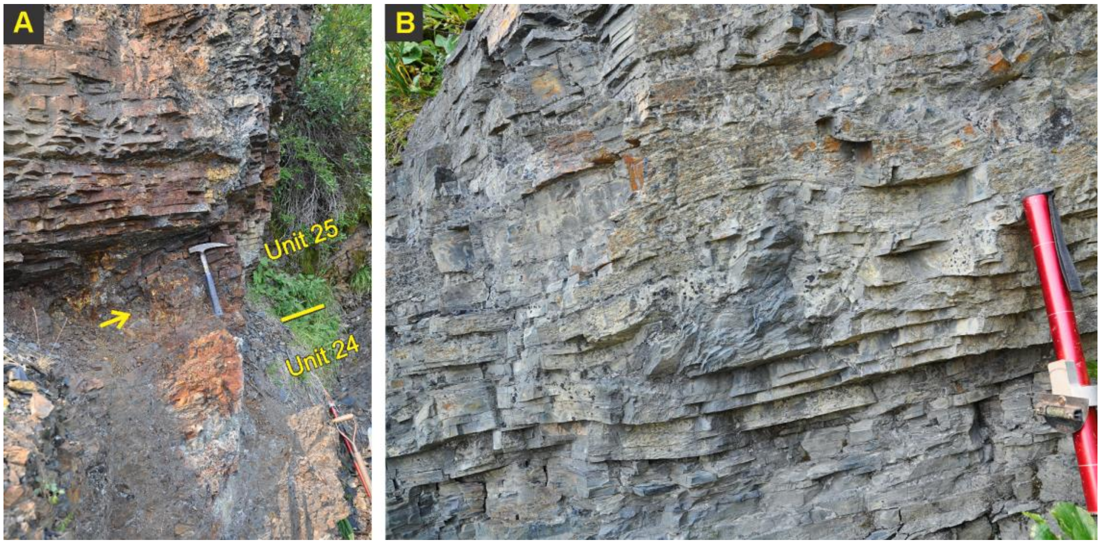

Figure 2.18. Stone Mountain section, 18KOA-04: (A) Contact of units 24 and 25 in a side gully; caved limonite-carbonate nodule is arrowed. (B) Slumping structure with convolute folding in the base of unit 25.

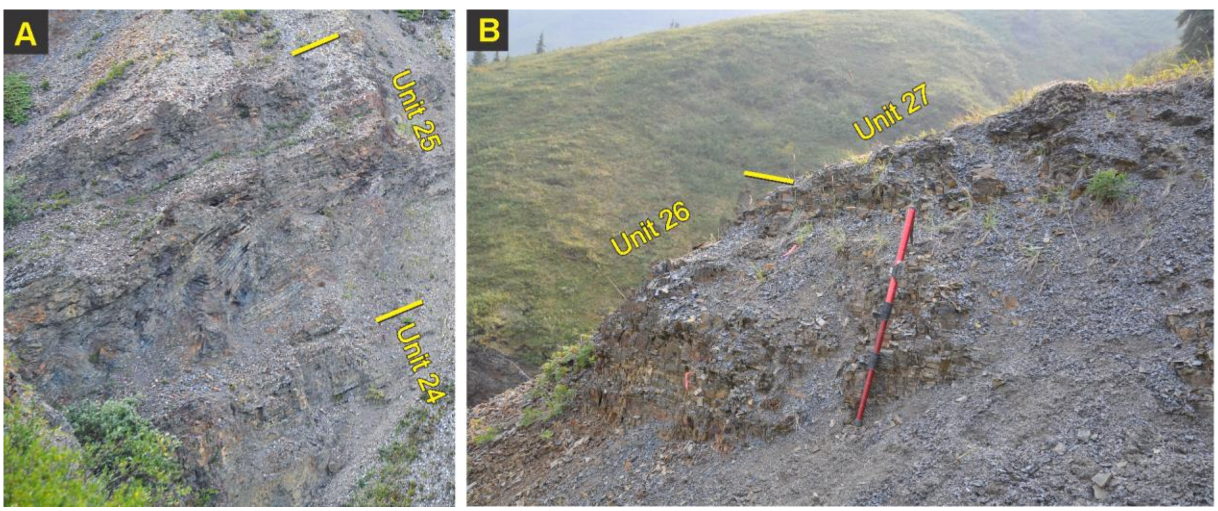

Figure 2.19. Stone Mountain section, 18KOA-04: (A) Zoom at the slumping folds of the unit 25 from the opposite (right) slope of the gully; note that overlying and underlying strata are not co-folded; (B) Transition to the recessive unit 27 in top of the measured section. Pogo stick is 1.0 m.

3. Chevron Woodside La Jolie B-3-K 94-O-12, WA29749 (measured by B.C. Richards)

The core was studied and sampled in Fort Saint John from February 27 to March 9, 2017 and December 3 to December 7, 2018. The description is illustrated with digital photographs of dry core surfaces, in difference to imagery of water-sprayed surfaces of the same core placed in Chapter 4 of this report. All measurements in core description are in metres.

Summary of unit tops based on gamma-ray logs and lithology

Top Exshaw Member (top upper radioactive unit) in Besa River Formation: 4197.8 m

Base upper radioactive unit of Exshaw: 4209.01 m

Base "upper Exshaw" and top lower radioactive unit of Exshaw: 4337.8 m

Base lower radioactive unit of Exshaw and top Patry interval in Besa River Formation: 4371.7 m

Base Patry unit and top Fort Simpson Member of Besa River: 4477.7 m

The core description starts in the "upper Exshaw" below the upper radioactive unit of the Exshaw Member and continues down into the upper Fort Simpson Member. Preliminary interpretations are included with the descriptions of some units.

The preliminary core descriptions given below for the Chevron Woodside La Jolie B-3-K 94-O-12 are based solely on observations made at the BC Oil and Gas Commission's core and sample facility in Fort Saint John between February 27 and March 9, 2018 and December 3 to December 7, 2018. The descriptions do not include data derived from the study of petrographic thin sections, X-ray diffraction analyses, and geochemical analyses. The stratigraphic nomenclature used in the core description is also of a preliminary nature. In the Chevron Woodside La Jolie B-3-K 94-O-12, the Exshaw Member is near its western depositional limit and is difficult to differentiate from the overlying Banff Member of the Besa River Formation. Further basinward, it cannot be differentiated from underlying and overlying strata using basic lithological criteria. Following Ferri et al. (2015), we have divided the Exshaw into informal lower and upper units. The interval called the upper Exshaw herein does not resemble the upper Exshaw at its type section on Jura Creek in southwest Alberta (see Richards et al., 2002) but the lower unit is similar to the black-shale member in the type Exshaw and elsewhere in the Rocky Mountains.

In the Chevron Woodside La Jolie B-3-K, we place the top of the Exshaw Formation of Ferri et al. (2015) at the top of its upper radioactive unit at 4197.8 m. The base of the upper radioactive unit of the upper Exshaw lies at 4209.01 m. The base of the upper Exshaw of Ferri et al. (2015) and top of the lower radioactive unit lies at 4337.8 m. The lower Exshaw contains an interval (4349.58 to 4371.7 m) that is transitional between the typical black-shale and chert lithofacies of the Exshaw and underlying calcareous mud rocks of the Patry member. Based on lithological observations from the core, the base of the Exshaw and top of the informal Patry unit could be placed at the thick laminae to thin beds of limestone that appear at 4,349.58 m. Another potential level for the base of the Exshaw, based on the gamma-ray log and lithological considerations, lies at 4371.7 m and is the one used herein. In the interval between 4,349.58 and 4,371.7 m, the gamma-ray log shows several anomalously high radioactive intervals characteristic of the lower Exshaw in the southwestern part of the Western Canada Sedimentary Basin (WCSB). Although the core in the interval contains some thin limestone beds, black siliceous mud rocks characteristic of the lower Exshaw predominate. A bed of volcanic ash, common in the lower Exshaw but not in underlying upper Famennian strata in western Canada, occurs as well.

Ferri et al. (2015) applied the name Patry member to the shale-dominant unit that underlies the Exshaw Member in the eastern to central Liard Basin, the region penetrated by the Chevron Woodside La Jolie B-3K borehole. They demonstrated that the Party is a basinal correlative of the shale-dominated, Famennian Kotcho Formation in the eastern Liard Basin and Horn River Basin further eastward. The name Party member has not been formalized and it is not clear that the unit can be differentiated from the underlying shale-dominated succession in the Fort Simpson using lithological criteria alone. It has, however, a relatively distinct gamma-ray signature and is somewhat more radioactive than underlying strata in the Fort Simpson Member of the Besa River. Following Ferri et al. (2015), we have placed the base of the Party at the base of a prominent radioactive marker in our well sections. On the gamma-ray log for the Chevron Woodside La Jolie B-3-K, the base of the radioactive interval marking the base of the Patry lies at 4,477.7 m. The contact does not coincide with a significant lithological change in the core. In this borehole at the depth of the cored interval, the measured depths (MD) below the Kelly bushing differ substantially from the true vertical depths and the deviation increases with depth. In the core description, only the measured depths are used.

Core 1: 4265.00 – 4283.00 m; 16 boxes, recovery 17.70 m

Core 2: 4283.00 - 4310.00 m; 22 boxes, recovery 26.78 m

Core 3: 4310 – 4337 m; 22 boxes, recovery 26.61 m

Core 4: 4337.00 – 4356.0 m; 16 boxes, recovery 19.3 m

Core 5: 4356.50 – 4367.00 m; 8 boxes, recovery 8.7 m

Core 6: 4367.20 – 4394.46 m; 24 boxes recovery 27.26 m

Core 7: 4394.46 – 4421.73 m; 24 boxes, recovery 27.27 m

Core 8: 4421.73 – 4449.00 m; 23 boxes, recovery 27.27 m

Core 9: 4449.00 – 4476.50 m; 23 boxes, recovery 27.44 m

Core 10: 4476.5 – 4494.00 m; 14 boxes, recovery 17.6 m

Core 11: 4494.00 – 4521.50 m; 23 boxes, recovery 27.28 m

Core 12: 4521.5 – 4549.00 m; 23 boxes, recovery 27.49 m

Core 13: 4549.00 – 4576.00 m; 23 boxes, recovery 29.94m

Unit 1 of section: 4265.00 to 4293.19 m

In core 1 and upper part core 2; in "upper Exshaw" of Ferri et al. (2015) well below the upper radioactive unit.

Top of unit was not cored; base is gradational.

Lithology: greyish-black to black siliceous mudstone and subordinate shale, shows faint horizontal laminae, thin bedded to very thinly laminated, laminae prominent where pyritic, poor fissility, hard and siliceous (cherty), noncalcareous but may be slightly dolomitic (Fig. 3.1). No body fossils, trace fossils or evidence of bioturbation. Black, very thin laminae lie between the slightly lighter (greyish black) beds and laminae.

- A lighter-coloured interval lies at 4282.61 – 4282.65 m; interval tuffaceous and very sandy, well indurated, and pyritic. Base tuffaceous interval sharp, top gradational through 5 mm. Greyish-black shale below sandy band swells when wet and is tuffaceous.

- Bentonitic volcanic tuff lamina present at 4282.685 – 4282.694 m; light brownish grey, expands rapidly when wet. Top and base bentonite lamina sharp; only 1 mm of black shale at base and that lies above 5 cm thick rubble zone lacking bentonite (Fig. 3.3).

- Tuffaceous bed with pyrite present at 4284.68 – 4284.76 m (Fig. 3.2). Bed normally graded; lower 5 mm of volcanic tuff sandy. Above sandy tuff, grey, swelling mudstone occurs to 4284.736 m.

- At 4284.736 to 4284.69 m, deposits very pyritic; pyrite accentuates thin laminae. Lamina comprising swelling mudstone at 4284.674 - 4284.69 m; 1 mm thick pyrite lamina at top.

- Interval showing very thin, medium-grey laminae occurs at 4276.36 – 4276.43 m. A slightly lighter medium-grey interval occurs at 4273.78 – 4273.96 m and contains disseminated pyrite; pyrite accentuates the thin laminae.

- Locally distinctly laminated as at 4273.75 - 4274.6 m. The distinctly laminated intervals tend to be more pyritic than mudstone that lacks pyrite.

Pyrite: Main intervals with pyrite laminae and nodules: a) pyrite nodule with irregular margins at 4276.94 - 4276.975 m, about 95% pyrite; b) pyrite laminae at 4277.57 – 4277.59 m, 30% pyrite; c) pyrite lamina at 4278 – 4278.035 m, 80 % pyrite; d) pyrite lamina 4279.215 – 4279.25 m, 20% pyrite; e) conspicuous pyrite lamina at 4280.65 – 4286.69 m, about 10% to 15% pyrite.

Interpretations: Anoxic basin lithofacies comprising distal turbidites and hemipelagic laminae. Closely resembles lithofacies in the lower member of the Exshaw Formation in southwest Alberta. Unit records several episodes of influx of tuffaceous volcanics that settled through the water column within the Liard Basin.

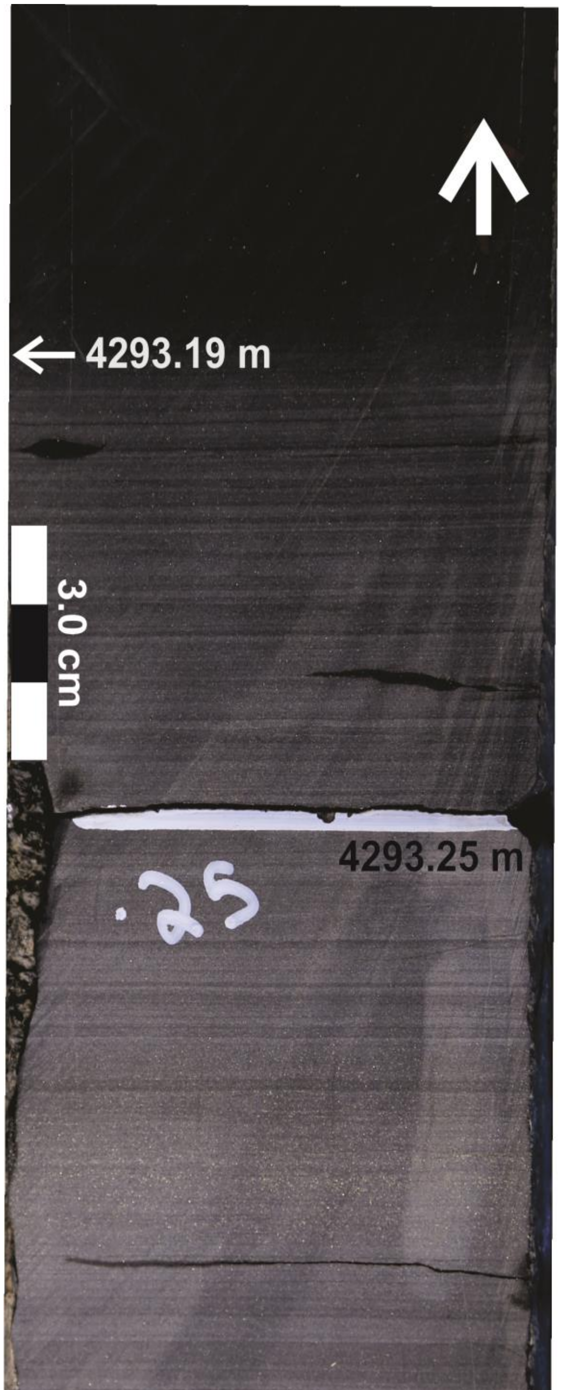

Fig. 3.1. Contact between units 1 and 2 of upper Exshaw at 4293.19 m showing characteristics of units. Unit 1 comprises greyish-black, cherty mudstone to chert showing faint, thin, horizontal laminae. Unit 2 is medium-grey, pyritic, cherty mudstone to chert showing prominent, very thin, horizontal laminae.

Fig. 3.2. Characteristic lithofacies of unit 1 of upper Exshaw near 4284.75 m. Medial part core shows laminated, pyritic, siliceous mudstone overlying greyish-black shale comprising swelling clays. Upper and lower parts of interval shown are medium-grey, siliceous, mudstone to chert showing faint horizontal laminae.

Fig. 3.3. Bottom of core shows upper part of thin, volcanic tuff bed between 4282.685 and 4282.695 m (black arrow indicates top) in unit 1 of "upper Exshaw". Medium-grey shale containing swelling clays overlies tuff. Arrow indicating 4282.61 m level is near top of light-grey, sandy, pyritic interval that may be tuffaceous. Core above 4282.61 m shows characteristic cherty mudstone of unit 1.

Fig. 3.4. Characteristic deposits in unit 3 of upper Exshaw at 4308.02 m (upper white arrow) and below. Core comprises cherty, greyish-black, mudstone to chert with thin- to very thin, horizontal laminae. Pyrite nodule and lamina near base of core. The thin laminae are bundled forming thin beds that tend to become darker upward.

Unit 2 of section: 4293.19 – 4293.38 m

In core 2 and "in upper Exshaw".

Top and base of interval are gradational.

Lithology: Medium-grey, hard siliceous mudstone with prominent very thin laminae; not fissile, may be dolomitic, noncalcareous; slightly pyritic (2 – 5%). A lighter grey than deposits above and below.

Interpretations: This is a basinal lithofacies deposited in the Liard Basin under anoxic deep-water conditions.

Unit 3 of section: 4293.38 – 4327.05 m

In core 2 and "in upper Exshaw".

Top and base of unit are sharp.

Lithology: Unit closely resembles unit 1 and has a uniform aspect. Comprises laminated to thin-bedded siliceous mudstone grading into shale (Fig. 3.4). The laminae and bed boundaries are indistinct; beds mainly 10 to 15 mm thick. Thin, black-shale partings occur between the slightly more resistant beds and lamina. Beds and laminae show poorly-defined normal grading. Laminae and thin beds are slightly more prominent than in unit 1. Unit remains essentially the same down to box 22 and bottom of core 2. Deposits appear to be silty and siliceous. Some widely separated lighter bands that are more thinly laminated (Fig. 3.5). Laminae more distinct than in core 1. Laminae become better defined below 4297.42 m. Where laminae better defined, core splits into thinner layers (more fissile). Non-calcareous to slightly calcareous; intervals with lighter laminae most calcareous. Slightly lighter band with prominent very thin laminae at 4316.93 – 4317.165 m. Another slightly lighter band with very thin planar laminae at 4318.81 – 4319.12 m. At 4297.40 m to about 4303.75 m in core #2 deposits break up more into thin layers (more fissile); basically a black shale in this interval. Below 4303.75 m, core less fissile, shows bundling of lamina to form thin beds. No body fossils, trace fossils, or evidence for bioturbation

Pyrite: Unit moderately pyritic with main pyrite occurrences at: a) pyrite band 4295.50 – 4295.52 m, 30 – 40 % pyrite here; b) pyrite band 4297.74 – 4297.73 m, 20% pyrite; c) pyrite nodule 4302.18 – 4302.20 m; d) pyrite band 4306.57 – 4306.58 m; e) pyrite nodule 4308.15 – 4308.16 m; f) pyrite band 4315.18 – 4315.19 m; g) pyrite band 4316.35 – 4316.40 m; h) pyrite band 4319.09 m; i) pyrite band 4322.80 – 4322.81 m.

Interpretation: This is an anoxic basin lithofacies comprising distal turbidites and hemipelagic deposits. Lithofacies are characteristic of those in the lower member of the Exshaw in its type section in Alberta.

Unit 4: 4327.055 – 4327.24 m

In core 3 in "upper Exshaw".

Top and base of unit sharp.

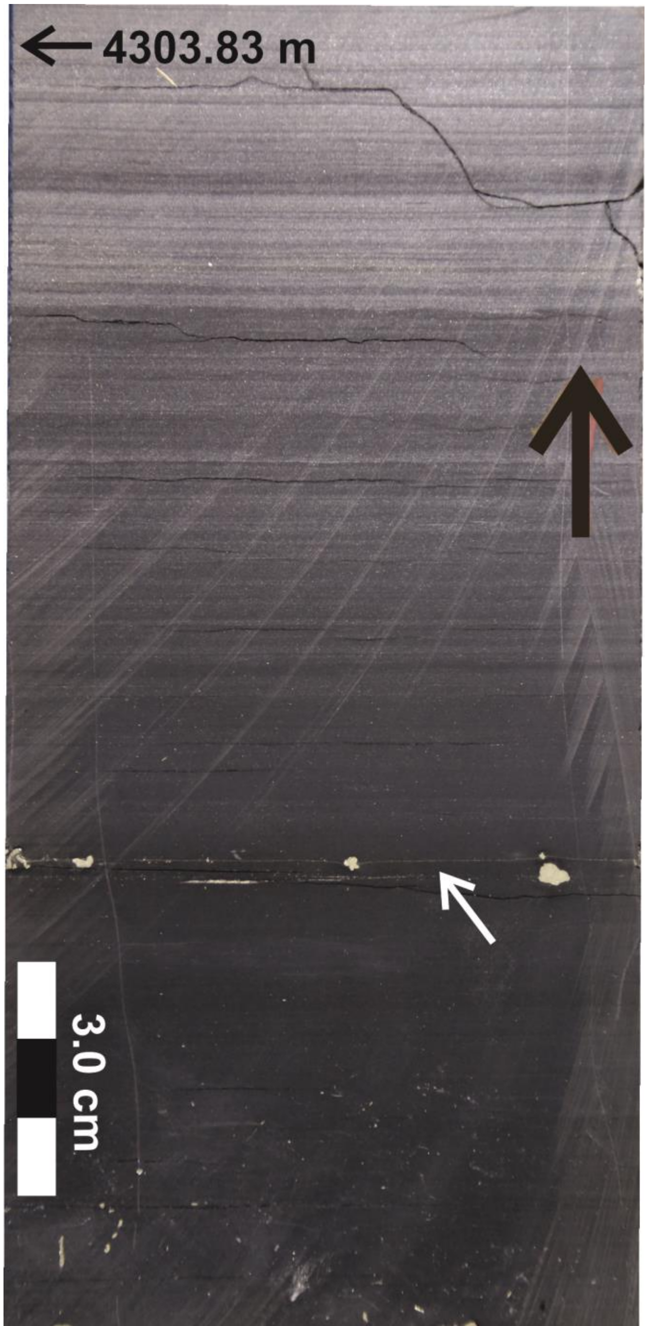

Fig. 3.5. Characteristic lithofacies of unit 3 in "upper Exshaw" at 4303.83 m and below. Greyish-black, cherty mudstone to chert showing indistinct, horizontal laminae dominate unit 3 (below white arrow) but some light- to medium-light-grey intervals showing well-defined, very thin, horizontal laminae occur (above white arrow). Pyrite occurs as small nodules at level of white arrow and as disseminated crystals and framboids.

Lithology: Prominent tuffaceous interval; thinly planar laminated; upper 6 mm slightly pyritic with 5% pyrite; becomes lighter down and is lightest at 4327.08 – 4327.245 m. This volcanic tuff contains visible sand grains. Unit is well indurated and not friable like typical tuff; may be dolomitic.

Unit 5: 4327.24 - 4346.65 m

In cores 3 and 4 from "upper Exshaw" and lower radioactive unit of Exshaw; contact at 4337.8 m on gamma-ray log.

Top of the unit sharp, base gradational.

Lithology: Laminated to very thin bedded, siliceous mudstone (Fig. 3.6) grading into shale; unit resembles units 1 and 3. Laminae and bed boundaries not clearly defined; thin black-shale partings occur between the slightly more resistant beds and lamina. Beds and laminae show poorly-defined grading. Laminae and thin beds are slightly more prominent than in unit 1. Beds mainly 10 to 15 mm thick; some widely separated lighter bands that are more thinly laminated. Unit remains essentially the same down to bottom of unit. Unit is silty and siliceous; slightly pyritic with pyrite bands as indicated below. Slightly lighter grey interval at 4333.45 – 4333.60 m with locally prominent light-grey very thin laminae. Lacks burrows, macroscopic body fossils, and bioturbated intervals.

- The thin beds locally contain silver-grey, crystalline masses that are less than 5 mm across. Masses appear at 4337.91 m and continue to 4338.72 m; composition uncertain, maybe sulphides, barite, or carbonate. Not seen elsewhere in section. Deposits in interval laminated to thin bedded like rest of unit 5; resistant beds and laminae are separated by slightly darker shale partings.

- Thin volcanic tuff bed at 4337.33 – 4337.36 m in core 4 (Fig. 3.6). Top tuff sharp, base not seen (removed or in rubble). Volcanic tuff medium brownish grey and shows diffuse internal partings. A slightly lighter coloured bed lies above tuff at 4337.27 – 4337.31 m and may be tuffaceous. The tuff is sandy.

- Volcanic tuff lamina at 4340.675 – 4340.68 m (about 4 – 5 mm thick); base sharp; top sharp.
- Concretion at 4341.89 – 4341.95 m; concretion slightly calcareous, internally thinly laminated.
- Prominently laminated interval at 4293.19 – 4293.38 m; slightly lighter grey than rest of unit.
- Bottom of unit marks base of typical lower Exshaw black shale and chert lithofacies.

Pyrite: Main intervals with pyrite laminae and nodules in unit: a) pyrite nodule at 4328.79 – 4328.81 m; b) pyrite nodule at 4334.25 – 4334.27 m; c) pyrite band at 4338.22 – 4338.24 m; d) 3 mm thick pyrite lamina at 4339.13 m.

Unit 6: 4346.65 – 4349.58 m

In core 4 and lower radioactive unit of Exshaw Member.

Top of unit gradational, base of unit is sharp.

Lithology: Unit of greyish-black silty to siliceous shale and mudstone. At this depth, succession becomes prominently thinly planar laminated (Fig. 3.7) like underlying Patry unit of Ferri et al. (2015). Laminae become more prominent downward and the shale to mudstone more fissile. The prominent very thin laminae continue down to 4347.76 m. At 4347.76 – 4348.295 m, unit becomes darker (black) and not so prominently laminated. Prominent, thin laminae occur again at 4348.295 – 4349.75 m (Fig. 3.7). At 4349.75 – 4349.58 m, deposits become darker (greyish black) and laminae not prominent but interval is fissile. At 4349.58 m, laminae become very prominent again. The clearly laminated intervals contain medium-light-grey, thin calcareous laminae. No macroscopic body fossils, trace fossils or bioturbated intervals observed.

Interpretations: This is a basinal lithofacies comprising hemipelagic laminae deposited in a deep-water anoxic setting within the Liard Basin. Deposits in unit 6 resemble those in much of the underlying Patry and appear to represent a transitional lithofacies between the Exshaw and Party.

Fig. 3.7. Unit 6 in lower radioactive unit of Exshaw showing characteristics of lithofacies transitional between lower Exshaw and underlying informal Patry interval. Comprises greyish-black, cherty mudstone to chert with numerous very thin, light-grey, calcareous laminae. Laminae bundled forming thin beds that become darker upward.

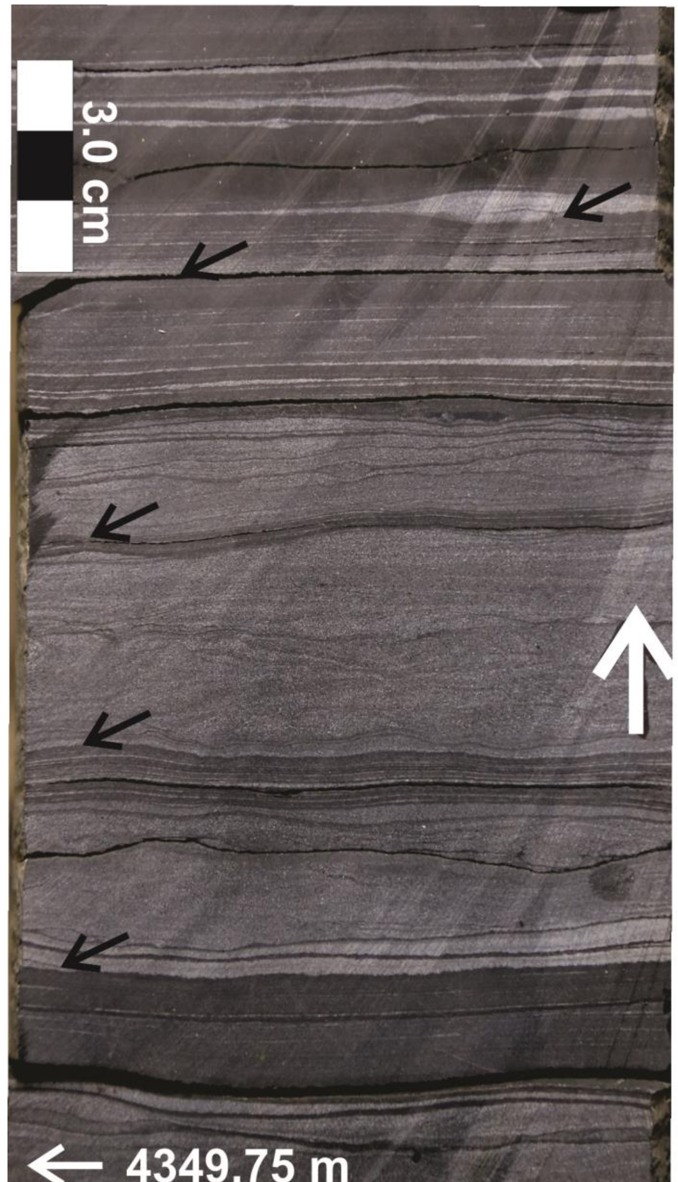

Fig. 3.8. Unit 7 in lower radioactive unit of Exshaw Member in Besa River Formation. Comprises turbidites (C-DE sequences) consisting of siliceous limestone passing upward into greyish-black siliceous mudstone to chert. Thicker turbidites in lower part of core show small-scale cross laminae and intervals with soft-sediment deformation. Black arrows point to bases of turbidites.

Unit 7: 4349.58 – 4350.97 m

In core 4 and lower radioactive unit of Exshaw Member in the Besa River.

Top unit sharp, base gradational.

Lithology: Unit of medium-grey siliceous limestone turbidites and black shale (Fig. 3.8). Records a marked change in lithofacies with appearance of distal calci-turbidites at top of unit. Unit thin bedded to thin laminated. Beds and thick laminae normally graded (CDE and DE turbidites). Black-shale partings occur between the thin beds and laminae. Mainly very thin bedded with thickest beds 2.5 to 3 cm thick. Becomes darker and thinner laminated downward. Black-shale partings mainly 2 to 3 mm thick. Bases of some beds and thick laminae show load casts and flame structures. Thin-shelled brachiopods occur in lower parts of some turbidites.

Interpretations: This is not a typical Exshaw lithofacies and its top could be used to define the base of the Exshaw Member. However, at exposures in the Rockies of east-central British Columbia, and in the subsurface of the Peace River Embayment, Richards et al. (2002, figs. 7, 9) reported tuffaceous limestone in the transition zone between the limestone of the Famennian Palliser Formation and overlying black shale member of the Exshaw and included them in the lower Exshaw. Elsewhere in the Liard Basin, Ferri et al. (2015) also placed the thin-bedded limestone and associated black, siliceous mudstone in the lower Exshaw.

Unit 7 is of lower-slope to basin-margin aspect and represents a distal lithofacies of the carbonate ramp succession preserved in the Famennian Kotcho Formation and Wabamun Group east and southeast of the borehole location.

Unit 8: 4350.97 – 4352.49 m

In core 4 and lower radioactive unit of Exshaw Member in Besa River.

Top unit gradational, base sharp.

Lithology: Siliceous (cherty), greyish-black to black shale and mudstone. Uniform in aspect; diffuse laminae dominate unit but prominent thin laminae locally prominent. Lacks the prominent, alternating light-grey and greyish-black very thin calcareous laminae of unit 6.

Interpretations: Lithofacies are characteristic of the lower Exshaw elsewhere in the WCSB and record deposition in a deep-water setting in the eastern Liard Basin.

Unit 9: 4352.49 – 4352.69 m

In core 4 and lower radioactive unit of Exshaw Member in Besa River.

Top unit sharp, base gradational.

Lithology: Unit of thin-bedded to laminated, medium-grey limestone turbidites and black shale resembling unit 7. Laminae and thin beds very prominent because of thin calcareous turbidites. Pyrite replaced bed at base 4352.65 - 4352.69. Calcareous and not a typical Exshaw lithofacies.

Interpretations: Lithofacies in this unit are not characteristic of the lower Exshaw in most of the WCSB but Richards et al. (2002) observed them in the Peace River Embayment and Rockies of east-central British Columbia. Unit 9 is of lower-slope to basin-margin aspect and represents a distal lithofacies of the carbonate ramp succession preserved in the Famennian Kotcho Formation and Wabamun Group east and southeast of the borehole location.

Unit 10: 4352.69 – 4353.02 m

In core 4 and lower radioactive unit of Exshaw Member in Besa River.

Top unit gradational, base sharp.

Lithology: Siliceous (cherty) black shale to mudstone; noncalcareous to slightly calcareous. Deposits appear relatively massive because the prominent thin, medium-grey beds and laminae of unit above are lacking. Black-shale intervals separate the slightly lighter grey intervals and define thin beds. Pyrite accentuates some very thin laminae. No evidence of bioturbation.

Interpretations: Lithofacies are characteristic of the lower Exshaw elsewhere in the WCSB.

Unit 11: 4353.02 – 4354.16 m

In core 4 and lower radioactive unit of Exshaw Member in Besa River.

Top unit sharp, base gradational.

Lithology: Conspicuously thinly laminated to thin bedded, dark grey to greyish-black, siliceous shale and mudstone grading into siliceous limestone. Thin, medium-grey, calcareous laminae and thin beds alternate with black laminae. Beds and thick laminae internally thinly planar laminated. Some beds and thick laminae show normal grading and are turbidites. Load casts at bases some beds.

Interpretations: Lithofacies are characteristic of deposits in Patry unit of Horn River Basin but interval is included in the lower radioactive unit of the Exshaw because several units (14, 16, 17, and 19) comprising typical lower Exshaw lithofacies occur lower in the section.

Unit 12: 4354.16 – 4354.25 m

In core 4 and lower radioactive unit of Exshaw Member in Besa River.

Top unit gradational, base sharp.

Lithology: Thin black interval of siliceous (cherty) shale to mudstone; thin bedded to thin laminated.

Unit 13: 4354.25 – 4354.751 m

In core 4 and lower radioactive unit of Exshaw Member in Besa River.

Top unit sharp, base gradational.

Lithology: Unit of conspicuously thin-laminated to thin-bedded calciturbidites and siliceous shale to mudstone. Becomes darker down; lighter (medium to dark grey) thin beds and laminae are separated by siliceous black shale laminae. Upper 0.14 m of unit medium dark grey and dominated by thin-bedded to laminated, distal, calcareous turbidites. Lower part of unit (21 cm) very thinly planar laminated and comprising alternating black and subordinate medium-grey laminae. A typical Patry facies. Thin beds show sharp bases, small-scale cross laminae, very thin laminae and poorly-defined normal grading.

Interpretations: Lithofacies in unit resemble those that predominate in the Patry.

Unit 14: 4354.751 – 4360.13 m

Cores 4 and 5 in lower radioactive unit of Exshaw Member in Besa River Formation.

Top unit gradational, base gradational.

Lithology: Greyish-black, siliceous shale and mudstone; lacks prominent light and dark laminae of unit 13. Thin bedded to laminated; poor fissility and core holds together well. Noncalcareous to slightly calcareous; no evidence of bioturbation.

Interpretations: Unit 14 comprises black, siliceous lithofacies characteristic of the lower Exshaw elsewhere in the WCSB; therefore, it warrants inclusion in the Exshaw.

Unit 15: 4360.13 – 4360.30 m

In core 5 and lower radioactive unit of Exshaw Member in Besa River.

Top unit gradational; base not seen and is in rubble zone preserved in bags.

Lithology: Shale to siliceous mudstone; shows prominent very thin laminae. Black and very thin, medium grey calcareous laminae alternate; fissile. No evidence of bioturbation, becomes darker downward.

Unit 16: 4360.30 – 4363.16

In core 5 and lower radioactive unit of Exshaw Member in Besa River.

Top unit not seen (rubble zone in bags); base of unit is rubble zone at top of underlying volcanic tuff.

Lithology: Dark-grey to greyish black siliceous mudstone. Laminae not obvious; shows diffuse thin beds and laminae.

- Pyrite replaces part of bed at 4361.735 – 4361.75 m.

- Rubble interval at base contains volcanic ash.

Interpretations: Unit 16 comprises black, lithofacies characteristic of the lower Exshaw elsewhere in the WCSB; therefore, unit warrants assignment to the Exshaw.

Unit 17 4363.33 to 4363.37 m.

In core 5 and lower radioactive unit of Exshaw Member in Besa River.

Top unit not seen, base sharp.

Lithology: Thin bed of light-brownish-grey volcanic tuff. Tuff at least 3 to 4 cm thick; upper part tuff preserved in overlying rubble zone. Lower part (about 1 cm thick) preserved at top underlying core.

Interpretations: These deposits are best included in the Exshaw instead of the upper Patry interval. In the WCSB, late Famennian beds and laminae of volcanic ash normally occur only in the Exshaw Formation and not the underlying succession.

Unit 18: 4363.37 – 4369.60 m

In lower part core 5 and upper part of core 6; in lower radioactive unit of Exshaw Member in Besa River.

Top unit sharp, base gradational.

Lithology: Distinctly thinly planar laminated siliceous shale and mudstone; medium dark grey with subordinate (about 5 to 10% of interval) light- to medium-grey laminae; slightly lighter grey than typical lithofacies in lower Exshaw; slightly calcareous with lighter grey laminae most calcareous; slightly pyritic.

Interpretations: These are distal turbidites and hemipelagites deposited in a deep-water setting in the eastern Liard Basin.

Unit 19: 4369.60 – 4371.7 m

In core 6 and lower radioactive unit of Exshaw Member in Besa River.

Top unit gradational, base gradational.

Lithology: Very thinly laminated, siliceous, greyish-black shale to mudstone; similar to unit 18 but medium- to light-grey calcareous laminae less abundant; this is a dark band in the lower Exshaw. Slightly calcareous and pyritic.

Interpretations: Unit 19 comprises black, siliceous lithofacies characteristic of the lower Exshaw elsewhere in the WCSB. The base of the unit marks the base of the Exshaw Member in this borehole section.

Unit 20: 4371.7 – 4372.48 m

In core 6 and Patry interval of Besa River.

Top unit gradational, base gradational.

Lithology: Siliceous to calcareous shale and mudstone; contains abundant (10 to 15% of interval) medium-grey laminae that separate the greyish-black to black laminae. Interval becomes darker downward; no evidence of bioturbation. Medium-grey laminae most calcareous. This is a light-coloured interval in Patry.

Interpretations: Unit comprises hemipelagic deposits of basinal aspect. Top of unit marks base of Exshaw Member. In most of WCSB, base of Exshaw is erosional but in this section evidence for erosion is lacking.

Unit 21: 4372.48 – 4375.06 m

In core 6 and Patry interval in Besa River.

Top unit gradational, base gradational.

Lithology: Thinly planar laminated, greyish-black shale and mudstone; lacks the abundant very thin medium grey calcareous laminae of unit 20 and forms dark interval in Patry. Slightly calcareous and pyritic; no trace fossils, macroscopic body fossils or evidence of bioturbation.

Unit 22: 4375.06 – 4375.67 m

In core 6 and Patry interval in Besa River.

Top unit gradational, base gradational.

Lithology: Thin-laminated shale and mudstone; laminae more prominent than in unit 21; abundant (10 to 15% of unit) very thin medium-grey laminae separate the greyish-black laminae; slightly calcareous; no evidence of bioturbation; unit becomes darker downward and forms light interval in Patry.

Interpretations: These are hemipelagites or distal DE turbidites.

Unit 23: 4375.67 – 4383.10 m

In core 6 and Patry interval in Besa River.

Top unit gradational, base gradational.

Lithology: Thinly planar laminated shale and mudstone but laminae indistinct. Mainly greyish black but contains about 5% very thin, medium-grey laminae. Forms a dark interval. Slightly calcareous with medium-grey laminae most calcareous. Laminae not clearly graded; no evidence of bioturbation.

Interpretations: Unit comprises basinal hemipelagic deposits to distal DE turbidites.

Unit 24: 4383.10 – 4384.01 m

In core 6 and Patry interval in Besa River

Top unit gradational, base gradational.

Lithology: Very thinly laminated shale to mudstone; comprises greyish-black laminae separated by medium-grey laminae (10 to 15% of unit); forms light interval in Patry. Slightly calcareous and pyritic; no trace fossils observed.

Interpretations: These are distal turbidites and hemipelagic deposits.

Unit 25: 4384.01 – 4385.85 m

In core 6 and Patry interval in Besa River.

Top unit gradational, base gradational.

Lithology: This is a dark thinly laminated unit of shale to mudstone; mainly greyish black and lacks the abundant medium-grey laminae of unit 24. Slightly calcareous; some thin pyrite bands; no trace fossils or bioturbated intervals. Interval 4384.01 – 4384.50 is sealed in plastic and not cut.

Unit 26: 4385.85 – 4387.34 m

In core 6 and Patry interval in Besa River.

Top unit gradational, base gradational.

Lithology: Very thinly planar laminated shale and mudstone; medium-grey laminae (10 to 15% of unit) alternate with greyish-black laminae. Slightly calcareous with lighter laminae most calcareous. Medium-grey laminae more common than in unit above; no visible bioturbation or trace fossils. The very thin laminae are commonly grouped forming thin beds in which lighter laminae become less abundant upward (resembles subtle normal grading).

Slightly pyritic with pyrite replacing some light calcareous laminae.

Interpretations: These are distal turbidites to hemipelagic laminae deposited in a deep-water basin seting.

Unit 27: 4387.34 – 4394.46 m

In core 6 and Patry interval in Besa River.

Top unit gradational, base sharp.

Lithology: Greyish-black mudstone to shale; a dark unit with a few medium-grey laminae; interval extends to bottom of core 6. Thinly planar laminated but laminae not distinct. Slightly calcareous; calcareous deposits are the very thin lighter grey laminae. No visible trace fossils or bioturbated intervals.

Unit 28: 4394.46 – 4394.585 m

In core 7 and Patry interval in Besa River.

Top unit sharp, base gradational.

Lithology: Conspicuous, light-coloured unit comprising very thin planar to slightly wavy medium-grey laminae and subordinate medium-dark-grey laminae. Very calcareous and may grade into limestone.

Unit 29: 4394.585- 4407.98 m

In core 7 and Patry interval in Besa River.

Top unit gradational, base gradational.

Lithology: A dark unit of shale to mudstone containing negligible light laminae (2-5%); uniformly dark grey to greyish black and monotonous; darkest down to 4399.06 m. Unit very thinly planar laminated; slightly calcareous with medium-grey laminae most calcareous. Interval with many medium grey very thin laminae at 4400.07 – 4400.10 m. Shale moderately fissile. Pyrite: Some pyrite laminae; pyrite band at 4398.52 (4 mm thick, 70 – 80% pyrite); pyrite band at 4404.90 -4404.905 m; pyrite band 4406.71 – 4406.715 m.

Interpretations: This is a deep-water basin facies comprising hemipelagic deposits to distal turbidites.

Unit 30: 4407.98 – 4453.70 m

In cores 7, 8, and 9; Patry interval in Besa River.

Top unit gradational, base gradational.

Lithology: Thinly planar laminated shale to mudstone; shows moderate fissility. Unit lighter grey than unit above and the very thin planar laminae are more prominent. About 15 to 20% light calcareous laminae separate the greyish black noncalcareous to slightly calcareous laminae. Unit becomes slightly more calcareous downward. Unit of is of uniform aspect and monotonous. No trace fossils or bioturbated areas. Unit becomes slightly darker down below 4453.0 m. Some thick laminae show subtle normal grading.

Pyrite: Pyrite nodule at 4417.45 – 4417.46 m; prominent pyrite band at 4421.88-4421.90 m; pyrite nodule at 4440.54 – 4440.57 m.

Interpretations: Unit of basinal deposits, hemipelagic deposits to distal turbidites.

Unit 31: 4453.70 – 4459.13 m

In core 9 and Patry interval in Besa River.

Top unit gradational, base gradational.

Thinly planar laminated shale. Shale mainly greyish black but includes medium-grey laminae (5 to 10% of unit). Deposits in unit are similar to those in unit 30 but are darker because of a lower proportion of medium-grey laminae. Contains some lighter grey more calcareous intervals but these constitute less than 5% of unit. Slightly calcareous; good fissility; no trace fossils or bioturbated areas.

Unit 32: 4459.13 – 4461.83 m

In core 9 and Patry interval in Besa River.

Top unit gradational, base gradational.

Lithology: Thinly planar laminated to thin-bedded shale. Shale mainly greyish black but includes abundant medium-grey laminae (10 to 40% of unit). A similar lithofacies to unit 31 but is a lighter grey because of a higher proportion of medium-grey laminae; becomes darker down. Moderate to good fissility. The medium-grey laminae are calcareous and grade into limestone. Laminae commonly grouped into thin beds that show subtle normal grading and become darker upward. Lower calcareous parts some beds show small-scale cross laminae. No trace fossils or bioturbated areas seen; negligible pyrite.

Interpretations: This is a basinal lithofacies comprising distal turbidites and hemipelagic deposits. Presence of carbonate turbidites indicates deposition in lower-slope to basin-floor settings basinward of the Famennian carbonate-ramp deposits that occur east of the Horn River Basin.

Unit 33: 4461.83 – 4469.84

In core 9 and Patry interval in Besa River.

Top unit gradational, base gradational.

Lithology: Thinly planar laminated shale; comprises greyish-black laminae alternating with medium grey laminae; lithofacies similar to that of unit 32 but slightly darker because of lower proportion of medium-grey laminae (5 to 10% of unit). Becomes slightly darker downward. Some slightly lighter intervals as at 4463.60 – 4464.0 m and these have about 10 to 15% light laminae. Greyish-black laminae only slightly calcareous. Laminae commonly bundled forming thick laminae to thin beds; these become darker and less calcareous upward and show subtle normal grading. No trace fossils or bioturbated areas.

Pyrite: Slightly pyritic with laminae and nodules; pyrite mass at 4462.2 – 4462.265 m; pyrite lens at 4467.55 – 4467.575 m.

Interpretations: This is a basinal lithofacies comprising distal turbidites and hemipelagic deposits.

Unit 34: 4469.84 – 4476.14 m

In core 9 and lower deposits of Patry interval in Besa River.

Top unit gradational, base gradational.

Lithology: Thinly planar laminated shale, similar to unit above but slightly darker. Contains 5 to 10% calcareous, medium-grey laminae; most laminae are greyish black. Some dark intervals as at 4474.94 – 4474.96 m. Laminae commonly bundled forming thick laminae to thin beds. Shale is moderately fissile. No trace fossils or bioturbated areas.

Unit 35: 4476.14 – 4490.06

In core 10; comprises lower part Patry interval and upper part Fort Simpson Member in Besa River Formation.

Top unit gradational, base gradational.

Lithology: Thinly planar laminated shale. A slightly lighter grey interval than unit 34. Comprises very thin, greyish-black laminae alternating with medium grey laminae (7 to 20% of unit). Laminae bundled to form thin (1 to 2 cm) graded beds that become darker upward. Unit is of uniform aspect but becomes slightly darker downward starting at about 4487.5 m. Slightly calcareous, no trace fossils or bioturbated areas.

Pyrite: Locally with abundant pyrite as bands, framboids and scattered crystals. Pyrite band at 4476.37 – 4476.405 m; pyrite rich interval above at 4476.31 – 4476.34 m, pyrite crystals/framboids partly replaced laminae at 4476.91 – 4476.97 m.

Interpretations: On the gamma-ray log, the base of the radioactive interval marking the base of the Patry interval lies at 4477.5 m. The contact does not coincide with a significant lithologic change in the core. This is a basinal lithofacies comprising distal turbidites and hemipelagic deposits.

Unit 36: 4490.06 – 4490.20 m

In core 10 and Fort Simpson Member of Besa River.

Top unit gradational, base gradational.

Lithology: Greyish-black very thinly laminated shale. This is a thin, dark interval in Fort Simpson with less than 2% calcareous, medium-grey shale laminae. Noncalcareous to slightly calcareous; no trace fossils or bioturbated intervals.

Interpretations: A basinal lithofacies comprising hemipelagic and turbiditic deposits.

Unit 37: 4490.20 – 4506.75 m

In cores 10 and 11 in Fort Simpson Member of Besa River.

Top unit gradational, base gradational.

Lithology: Very thinly laminated shale to mudstone. A typical Patry lithofacies with abundant light- to medium-grey, very thin, calcareous laminae alternating with greyish-black laminae. Laminae tend to be bundled into thin beds that are 1 to 2 cm thick; some of these show subtle normal grading and become darker upward. Core holds together well and does not break up in core box into thin layers; more like a mudstone than a fissile shale. Slightly calcareous although light laminae are common. No trace fossils or bioturbated areas seen.

Pyrite: Finely disseminated pyrite crystals/framboids and pyrite laminae common.

Unit 38: 4506.75 – 4532.25 m

In cores 11 and 12 in Fort Simpson Member of Besa River.

Top unit gradational, base sharp and marked by appearance of deformed deposits.

Lithology: Laminated, greyish-black to dark-grey siliceous mudstone and shale. Although very thinly laminated, laminae not prominent unless core is wet or laminae partly replaced by pyrite crystals. Lacks the prominent medium- to light-grey calcareous laminae of unit 37. Unit becomes darker and more siliceous (cherty) downward; noncalcareous to slightly calcareous; no visible bioturbation. Laminae tend to be bundled forming thin beds; beds lack obvious grading. Deposits hard and at least in part chert.

Pyrite: Mainly slightly pyritic but locally with abundant pyrite (>10%) as disseminated crystals that partly replace some laminae; good example at 4511.20 to 4511.25 m. Prominent pyrite-rich interval at 4531.61 to 4531.622 m.

Interpretations: A basinal lithofacies of hemipelagic and turbiditic deposits.

Unit 39: 4532.25 – 4543.65 m

In core 12 and Fort Simpson Member in Besa River.

Top unit abrupt and marked by appearance of syndepositional deformation, base gradational.

Greyish-black shale and mudstone. Unit has several intervals showing soft-sediment deformation. Above and below deformed intervals, laminae generally flatten out becoming thin and sub horizontal. Ten main deformed intervals and intervening relatively undeformed intervals observed. 1) Deformation at 4532.25 to 4533.48 m. Below 4533.48 m, laminae become thin and prominent again but are inclined at 15 to 20 degrees. 2) Prominent deformation at 4535.52 to 4535.75 m. Below 4535.75 m, laminae level out to depth of 4536.25 m. 3) Soft-sediment deformation at 4536.25 to 4536.5 m; below 4536.5 laminae level out to depth of 4536.75 m. 4) Prominent disrupted band at 4536.75 to 4537.0 m. Below latter deformation, laminae thin and level out or are gently inclined until 4537.44 m. 5) Deformed zone with prominently inclined thin laminae (25^{O} to 30^{O}) at 4537.44 to 4537.90 m. Below 4537.90 m, laminae become subhorizontal until 4538.85 m. 6) Sediment strongly disrupted from 4538.85 to 4539.18 m. Laminae are subhorizontal at 4539.18 to 4539.37 m. 7) From 4539.37 to 4540.07 m, deposits strongly disrupted but become subhorizontal from 4540.07 to 4540.50 m. 8) Deposits deformed from 4540.50 to 4540.87 m. Core not slabbed from 4540.87 to 4541.40 m. From 4541.40 to 4541.73 m, deposits horizontally laminated. 9) Deposits disrupted from 4541.73 to 4543.08 m; from 4543.08 – 4543.50 m, laminae and thin beds level out below deformation. 10) Deposits from 4543.50 to 4543.65 m show prominent deformation.

Unit slightly calcareous to noncalcareous; slightly pyritic with disseminated crystals and pyrite lens. No trace fossils or bioturbated intervals observed.

Interpretations: This is a basin lithofacies. Deformed intervals are submarine slump deposits that developed on a low-gradient slope in the Famennian expression of the Horn River Basin.

Unit 40: 4543.65 – 4555.26

In cores 12 and 13 and Fort Simpson Member in Besa River.

Top unit abrupt and marks end of deformation, base sharp at prominent colour change.

Lithology: Thin-bedded to thin-laminated shale and mudstone; bed boundaries planar to slightly undulatory. Mainly dark grey but contains some (2-5%) medium- to light-grey laminae. Laminae less prominent than in units 38 and above and tend to be thicker. Unit contains some thin intervals showing minor soft-sediment deformation. Slightly calcareous to noncalcareous; contains scattered small brachiopods (not common) and scattered ostracodes; well-preserved observed goniatite at 4557.07 m; no trace fossils or bioturbated intervals observed.

Pyrite common as small masses 55 mm or more across in lower part, pyrite becomes less abundant downward.

Interpretations: This lithofacies is of basinal aspect and comprises hemipelagic deposits. Some syndepositional slump deposits also occur. Deposits expand rapidly when wet indicating presence of smectite or expandable mixed-layer clays.

Unit 41: 4555.26 – 4560.22 m

In core 13 and Fort Simpson Member in Besa River Formation.

Top abrupt and marked by appearance of dark-greenish-grey to medium-grey laminae and lenses, base gradational.

Lithology: Laminated to thin-bedded shale and mudstone; medium-dark grey to greenish-grey. Deposits expand rapidly when wet. Prominent soft-sediment deformation at 4555.60 to 4555.66 m (Fig. 3.9). In parts of unit, laminae were disrupted by burrowing and deposits are massive to burrow mottled. Laminae commonly grouped forming thin beds that become darker upward and resemble turbidites with subtle grading. Intraclasts occur at bases some beds.

Slightly pyritic and calcareous.

Interpretations: This lithofacies is of basinal aspect and contains beds resembling distal turbidites and disrupted hemipelagic deposits.

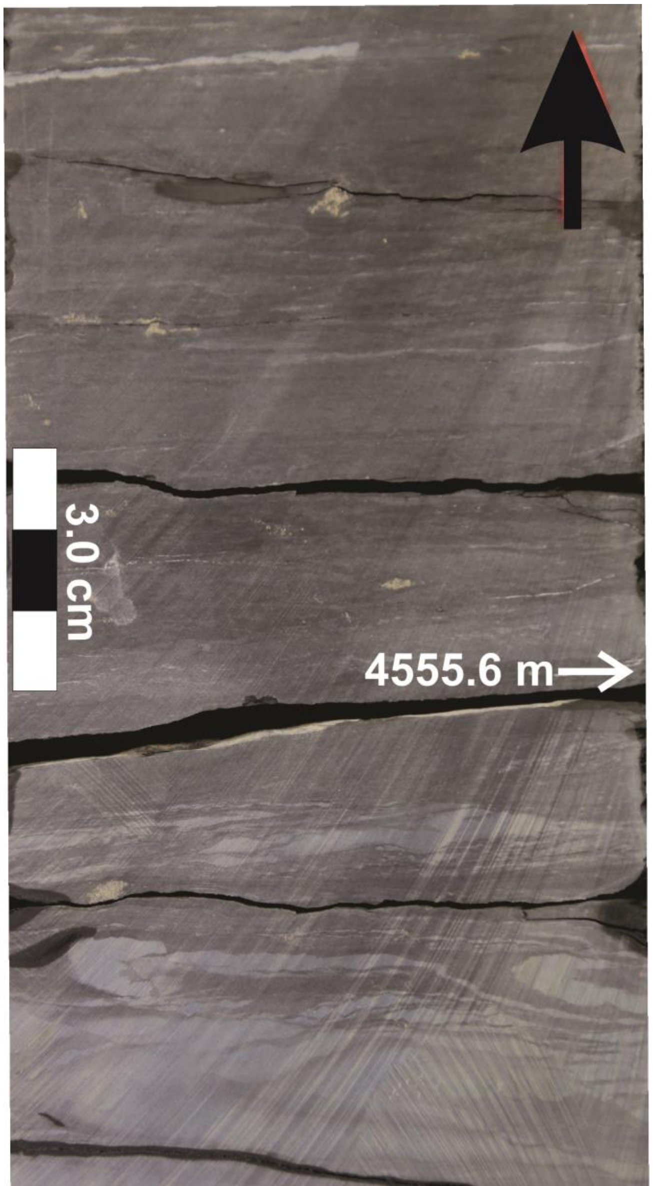

Fig. 3.9. Unit 41 in Fort Simpson Member showing soft-sediment deformation (convoluted laminae) below 4555.6 m. Deposits are pyritic, calcareous mudstone. Laminae above 4555.6 m are discontinuous because of slumping.

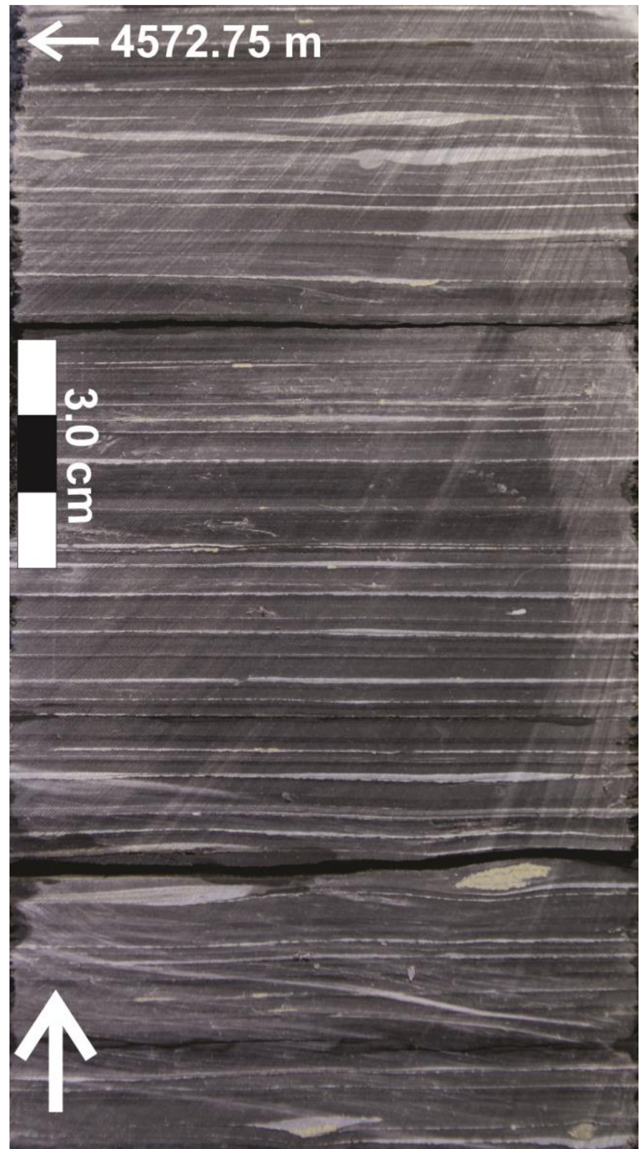

Fig. 3.10. Unit 43 showing lithofacies within upper part of Fort Simpson (top Ft. Simpson at 4477.5 m). Comprises light- to medium-grey, calcareous, thin laminae and noncalcareous, dark-grey to greyish-black, thin laminae. Thin laminae are bundled forming thin beds to thick laminae that commonly become darker upward and resemble distal turbidites and hemipelagic deposits.

Unit 42: 4560.22 – 4568.30 m

In core 13 and Fort Simpson Member in Besa River Formation.

Top unit gradational and marked by end of abundant light-greenish-grey beds and laminae, base gradational.

Lithology: Thinly planar laminated shale and mudstone; shows greyish-black, very thin laminae and subordinate medium-grey laminae (5% of unit); resembles laminated deposits in unit 37 and above. Some laminae contain swelling clays, but most of core hard and may be siliceous; slightly calcareous.

Pyrite: Slightly pyritic with local pyrite masses in lower part of unit.

Interpretations: This lithofacies is of basinal aspect.

Unit 43: 4568.30 – 4575.85 m

In core 13 and Fort Simpson Member in Besa River Formation.

Top unit gradational and marked by appearance of abundant very thin, medium- to light-grey laminae; base unit not seen (at bottom of cored interval).

Lithology: Laminated calcareous shale and mudstone (Fig. 3.10) like dominant deposits in Patry interval. Deposits medium dark grey to light grey. Calcareous, becomes more calcareous down as light laminae become more common; margins of core become friable when wet indicating presence of abundant swelling clay in core. Many thick laminae and thin beds show subtle normal grading and become darker upward. Bases some thin beds and thick laminae show load casts overlain by lenses of calcareous deposits (grade into limestone) showing small-scale cross laminae. Laminae were not disrupted by burrowing and no megascopic body fossils observed. Nodule-like mass occurs at 5470.61 – 4570.81 m (very calcareous); deposits above mass deformed from 4570.51 to nodule; nodule shows deformed internal laminae. Another very calcareous band or nodule present at 4573.31 to 4573.38 m; calcareous band or nodule at 4574.85 – 4574.92.

Pyrite: Slightly pyritic (2 to 5%) with pyrite as very thin laminae, small nodules, and disseminated crystals.

Interpretations: This lithofacies is of basinal aspect and comprises distal turbidites and hemipelagic deposits.

4. Chevron Woodside La Jolie B-3-K 94-O-12, WA29749 (measured by P. Kabanov)

The continuously cored section at 4265.0-4576.0 m MD was measured and imaged by P. Kabanov on February 27 – March 08, 2018 (Figs. 4.1-4.16). Core recovery information, list of samples, and provisionary stratigraphic subdivision is given above in the description of B.C. Richards.

BESA RIVER FORMATION

4265.0-4268.0 Mudrock: black hard homogeneous argillaceous poorly sorted siltstone with abundant "pyrite dust", rare pyritic streaks and very rare pyrite laminae and small nodules. Cherty component in the matrix is probably high. Lamination is faint, as minor differences in grain size. Core comes in 5-25 cm long cylinders broken with subhorizontal conchoidal surfaces. Minor clay shows in dirty smearing under water spray. No fossils.

4268.0-4291.0 Mudrock: hard brownish black subfissile, similar to 4265.0-4268.0 m but slightly finer grained, slightly more argillaceous and smears more intensely under water (Fig. 4.1A). Abundant and evenly dispersed "pyrite dust". Bedding planes are smooth; an interval of hard and less argillaceous mudrock with conchoid bedding planes at 4275.95-4276.60 m. More frequent small (> 1 cm) pyrite-marcasite nodules below 4283.0 m. Rare 5-12 cm thick carbonate-impregnated intervals (Fig. 4.1B). Several bentonitic shale seams (Fig. 4.1C).

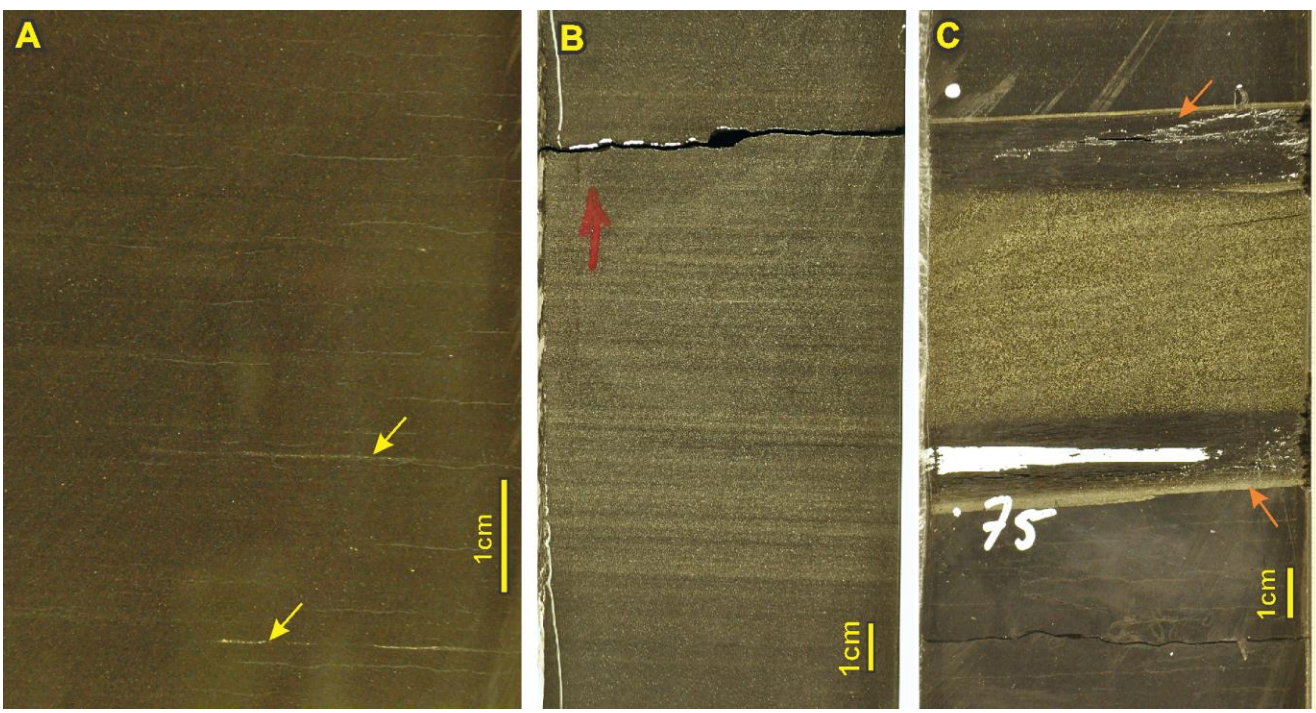

Fig. 4.1. Mudrock and bentonite seam at 4268.0-4291.0 m. (A) background mudrock facies with faint non-disturbed lamination, pyritic streaks are arrowed, 4275.35 m. (B) Carbonate-impregnated interval at 4273.80 m. (C) Pyritized bentonite layer with arrows at its top and base, 4284.75 m. Close-up photos here and below are made under water spray.

4291.0-4293.20 Mudrock: similar to 4268.0-4291.0 but pelitomorphic and with more distinct fissility. Lamination here is distinct, expressed in 1-3 mm thick rhythms composed of alternating competent mudrocks (cherts) and flaky receding shales.

4293.20-4293.35 Dolomitic (?) mudrock to dolostone: very hard finely crystalline distinctly laminated interval; original sedimentary texture is obliterated (recrystallized), may have represented a graded bed of vf/g calcarenite-calcisiltite.

4293.35-4297.25 Mudrock: identical to 4291.0-4293.20 m (Fig. 4.2A).

4297.25-4315.75 Mudrock: similar to the above but more fissile (Fig. 4.2B,C). Lamination is distinct, in the form of 1-3 mm thick rhythms/couplets as above. The interval looks generally less pyritized than above. Pyrite mostly as "pyrite dust", some intervals of mm-sized nodules. Rare 0.5-1.0 mm thick lenticles of vf/g sandstone in the base. Sand-sized grains are likely a mixture of Radiolaria and siliciclastics. Base by gradual increase in grain size to siltstone.

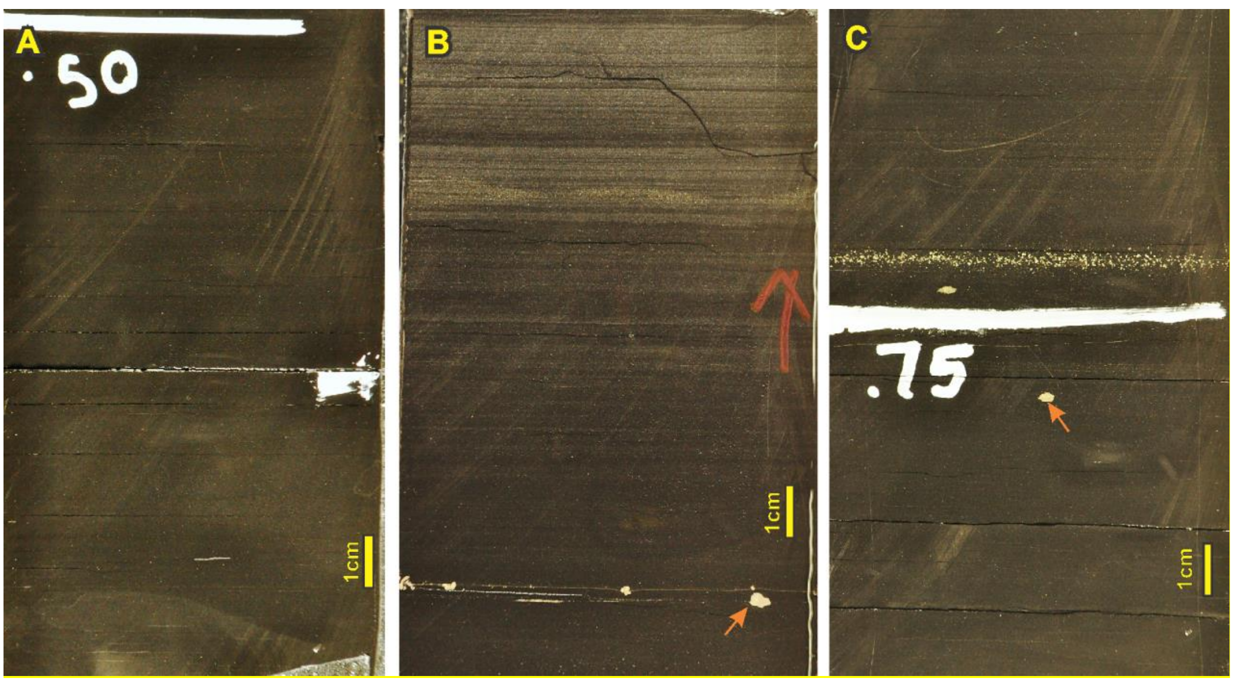

Fig. 4.2. Mudrocks at 4293.0-4334.50 m: (A) 4294.50 m; (B) 4303.85 m, with carbonate-rich interval in top; (C) 4311.75 m; arrows point at mm-sized FeS_2 nodules.

4315.75-4334.50 Mudrock: black, hard, with almost no clay-indicative smearing; slight variation between silty mudstone and siltstone, probably very cherty (Fig. 4.3); bedding planes are planar, some of them finely stylolitized. Frequent 1-2 cm thick graded beds with granular texture of vf/g to f/g sandstone. Grain composition to be clarified with petrographic study: whitish grains include spherical forms (radiolarians?) and subangular forms (quartz?) (Fig. 4.3A). Abundant tiny pyrite inclusions. Rare organic-walled acritarchs and similarly rare small pyritized sponge spicules on bedding planes.

4334.50-4339.50 Mudrock: black, hard, platy, siliceous silty shale to siltstone with rare radiolaria-rich laminae; pyrite mostly as dispersed "dust". Distinct from 4315.75-4334.50 m by horizons of small (1-5 mm) nodules looking like sulphide mineralization (Fig. 4.5).

4337.33-4337.37 Shale: pale brownish grey, soft and fissile, with numerous sand-sized mafic grains, identified as bentonite.

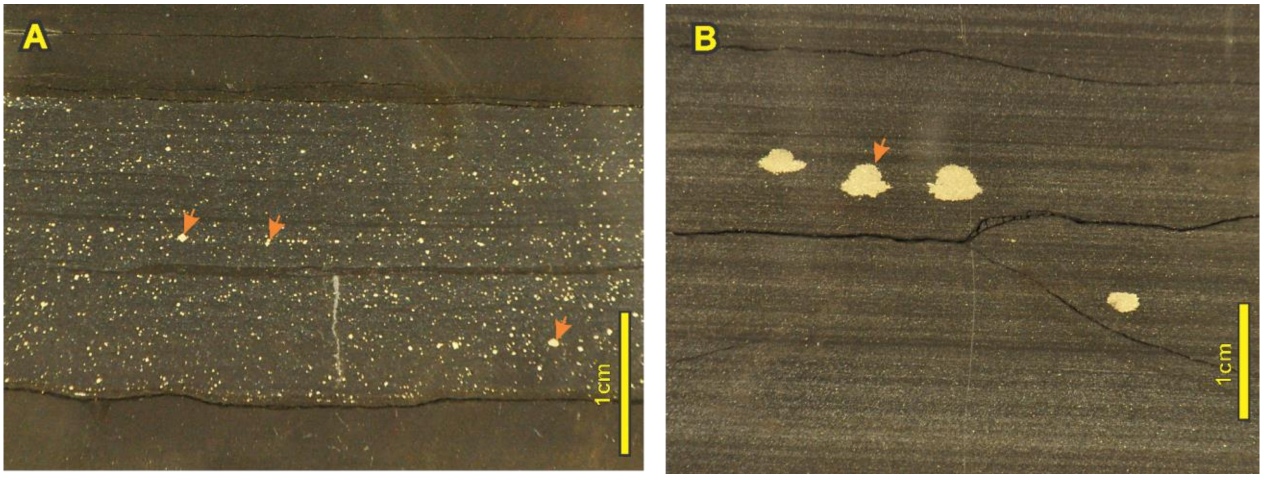

Fig. 4.3. Siliceous pyritic mudrocks at 4315.75-4334.50 m: (A) A lamina of Radiolaria-rich arenitic chert at 4322.85 m, note numerous sand-sized pyrite inclusions; (B) Siltstone at 4316.95 m. Some crystals and aggregates (small nodules) of authigenic FeS_2 are arrowed.

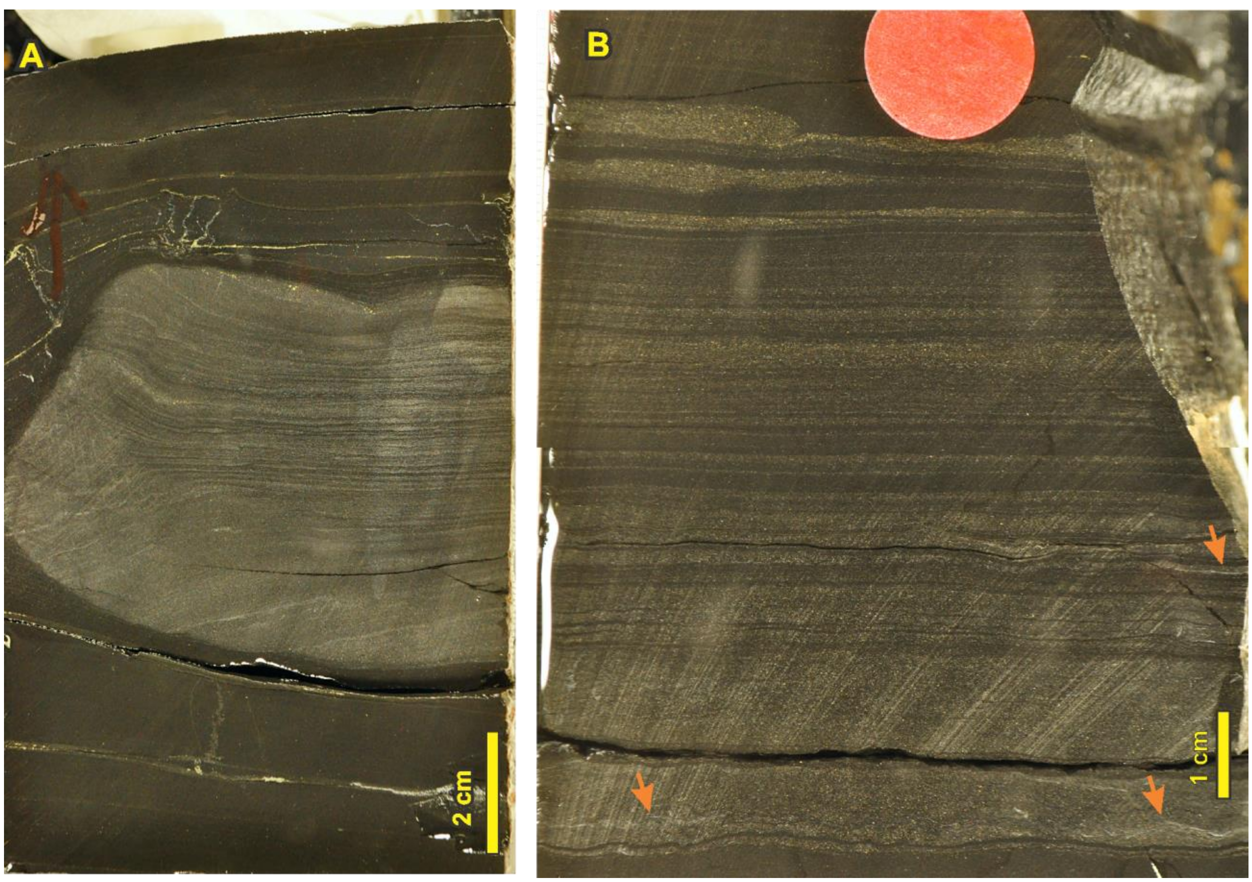

Fig. 4.4. (A) Calcareous nodule at 4341.90. (B) Graded bed of laminar fine-grained limestone at 4354.15 m; thin coquinas of brachiopod and ostracod(?) shells are arrowed.

4339.50-4345.00 Mudrock: black, cherty, hard, platy, with 1-5 cm thick massive intervals; changes granulometrically from silty shale to siltstone; a large (core diameter) calcareous nodule a 4341.85 m (Fig. 4.4A). Rare radiolaritic layers. Rare thin (< 1.0 mm) calcareous lenticles and laminae appear in the section below 4342.0 m. Many upright tensile fractures, sometimes feathery, some lined with whitish cement.

4345.00-4355.10 Mudrock-limestone alternation: microlaminated calciturbiditic facies with graded laminae (Fig. 4.4B); basal concentrates are calcisiltites and f/g (rarely m/g) calcarenites; rare thin-shelled brachiopod coquinas; calcareous beds are relatively thick (0.1-3.0 mm) and frequently bundled into cm-thick intervals; flame structures, channel cuts. Top and base gradational.

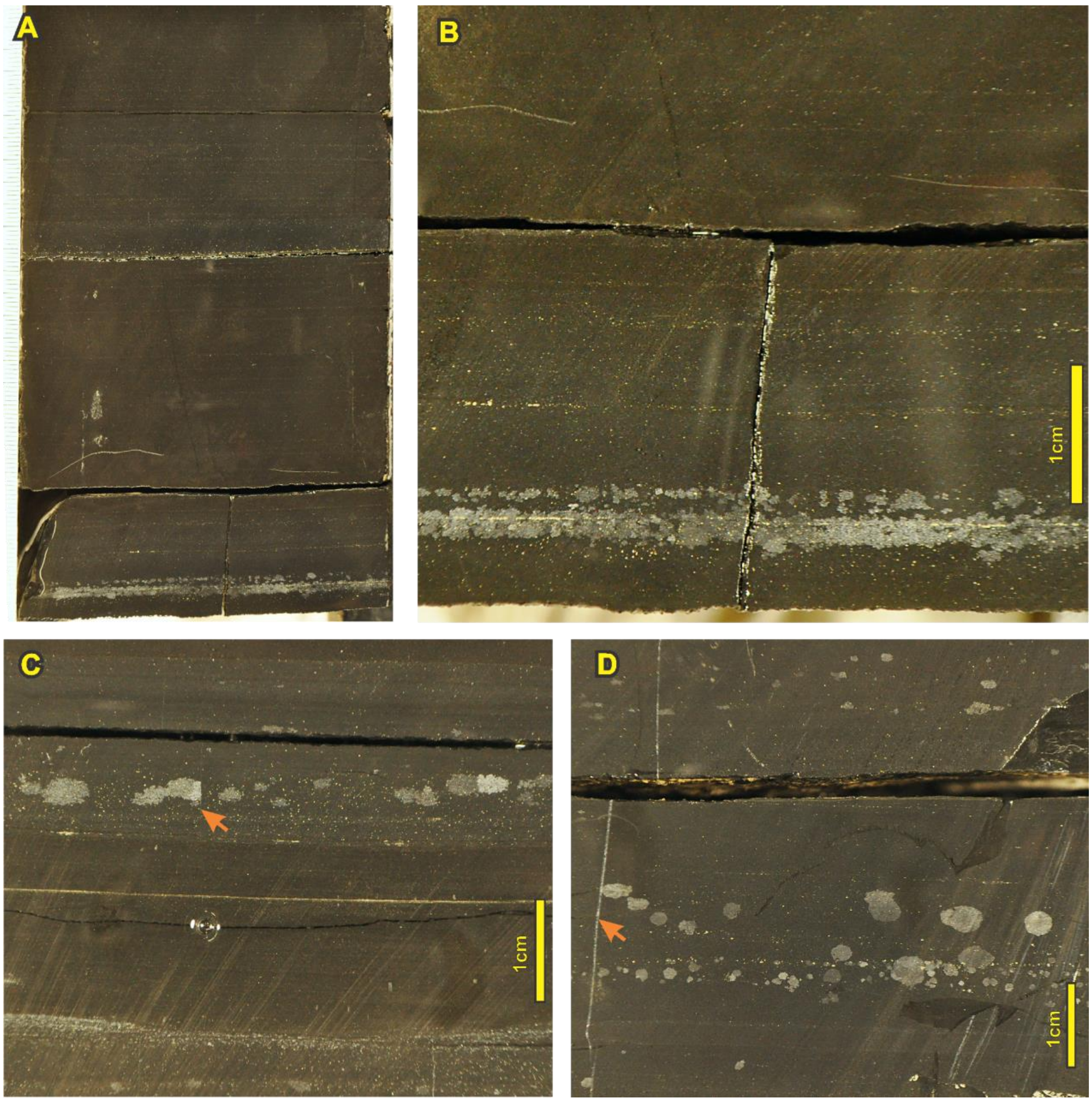

Fig. 4.5. Mineral aggregates at 4334.50-4339.50 m: (A, B) 4338.10 m, (B) is zoom at the mineral horizon in base of (A); (C) 4334.65 m; (D) 4338.65 m. Fractures structurally related to mineral aggregates (possible vents) are arrowed.

4355.10-4359.50 Mudrock: black, homogeneous, subfissile, jointed in "hockey pucks", weakly to moderately calcareous from intervening calcisiltite-calcilutite beds. Bundled calcareous-noncalcareous mudrock laminae are very thin (0.1-1.0 mm). Evenly dispersed pyrite dust, frequent pyrite streaks.

4359.50-4360.50 Mudrock with limestone laminae: recurrence of rhythmic facies like at 4345.00-4355.10 m with thin (<1 mm) calcisiltitic basal concentrates.

4360.50-4362.45 Calcareous mudrock: black, homogeneous, very similar to 4355.00-4359.50 m.

4362.45-4363.0 Mudrock: massive, hard, pyritic (mostly evenly dispersed "pyrite dust"), non-calcareous silty shale to siltstone with rare calcisiltitic horizons.

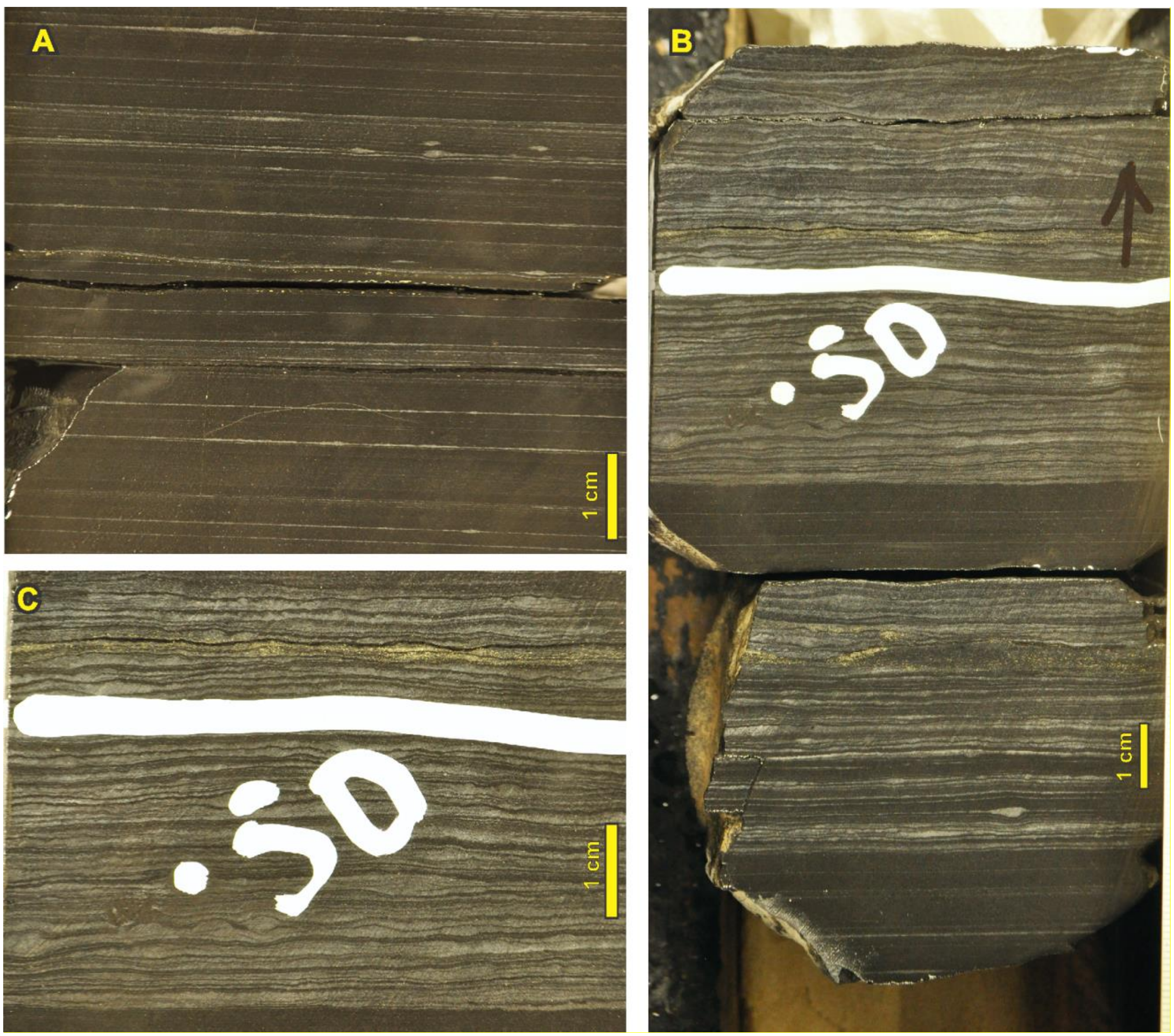

Fig. 4.6. (A) Mudrock with calcisiltite laminae at 4375.40 m. (B, C) Limestone at 4394.4-4394.6, (C) is X 1.5 zoom of the upper calcarenite-calcisiltite rhythm on (B).

4363.0-4394.4 Mudrock: black, laminated, calcareous, hard silty mudrock to muddy siltstone with regular thin (<0.3 mm) calcisiltitic laminae defining graded micro-rhythms (Fig. 4.6). The rock is subfissile, jointed in “hockey pucks”. Vertical shear surfaces and some upright conchoid fracturing at less calcareous intervals. The interval is mostly hard and not smearing under water spray; few thin (about 0.1 mm) clay-enriched laminae flaking off under water spray. Lower ~3.5 m contain minor intervals of slightly more smearing and thinner bedded mudrocks.

4394.4-4394.6 Limestone: argillaceous, laminar and flaser, dark steel gray, defined by closely spaced recrystallized calcisiltite-calcarenite laminae.

4394.6-4419.25 Mudrock: calcareous, platy silty mudrock to siltstone, dark grey due to development of very thin (about 0.1 mm and less) calcisiltitic laminae; the interval is very simlar to 4363.0-4394.4 m. Rare oblate pyritic nodules.

4419.25-4459.1 Siltstone: dark grey, muddy, platy, very calcareous and distinctly microlaminar. Lamination is defined by thin (0.05-0.5 mm) calcisiltite-mudrock couplets, by contrast in color can be called the heterolithic lamination (Fig. 4.7). The interval becomes slightly less pyritic than above. Rare pyritic nodules (Fig. 4.7A).

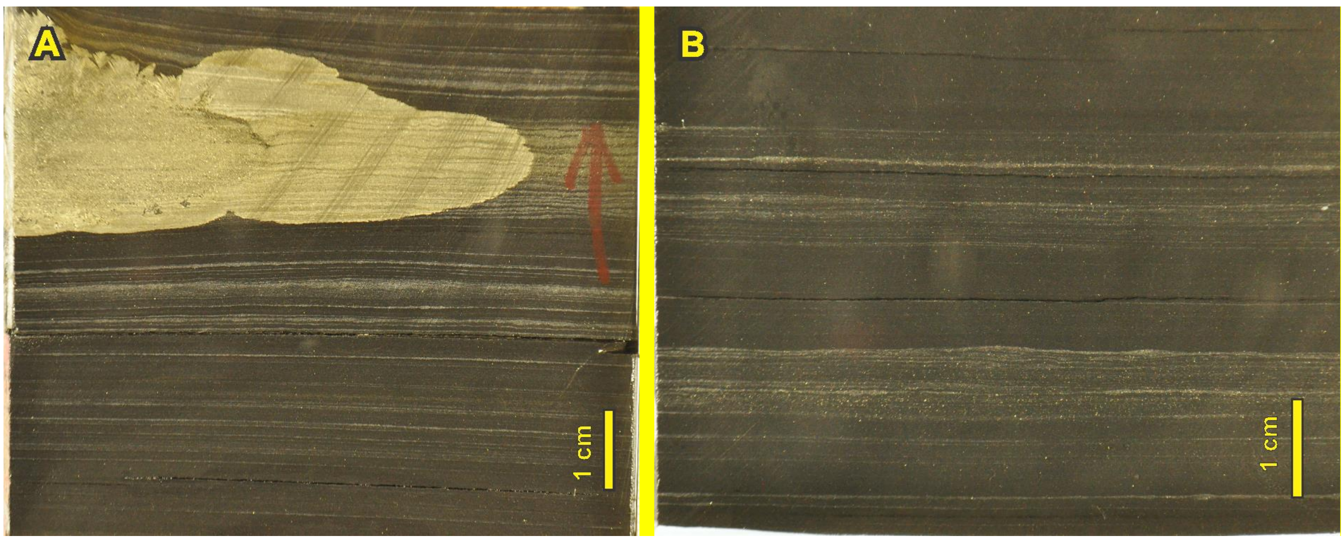

Fig. 4.7. Calcareous siltstones: (A) at 4421.95 with large pyrite nodule; (B) at 4419.50

4459.1-4461.2 Siltstone-limestone alternation: low-contrast alternation of more calcareous (limestones) and less calcareous (siltstones) intervals. The interval is very similar to the above but more calcareous.

4461.2-4505.0 Siltstone to minor sandstone: dark grey, muddy, platy, moderately micaceous, very calcareous and microlaminar (Fig. 4.8). Lamination is defined by thin (0.05-0.5 mm) couplets of pale grey calcisiltite and dark grey to black muddy siltstone (Fig. 4.8). Most of the interval is not smearing under water spray due to paucity of clays. Receding shale laminae are rare and very thin (≤ 0.1 mm). Average grain size fluctuates between siltstone and vf/g sandstone. Some coarser grained calcisiltite laminae are f/g calcarenites. Pyrite is a minor component (less than above). Gradation to underlying interval is flagged with growing pyrite content.

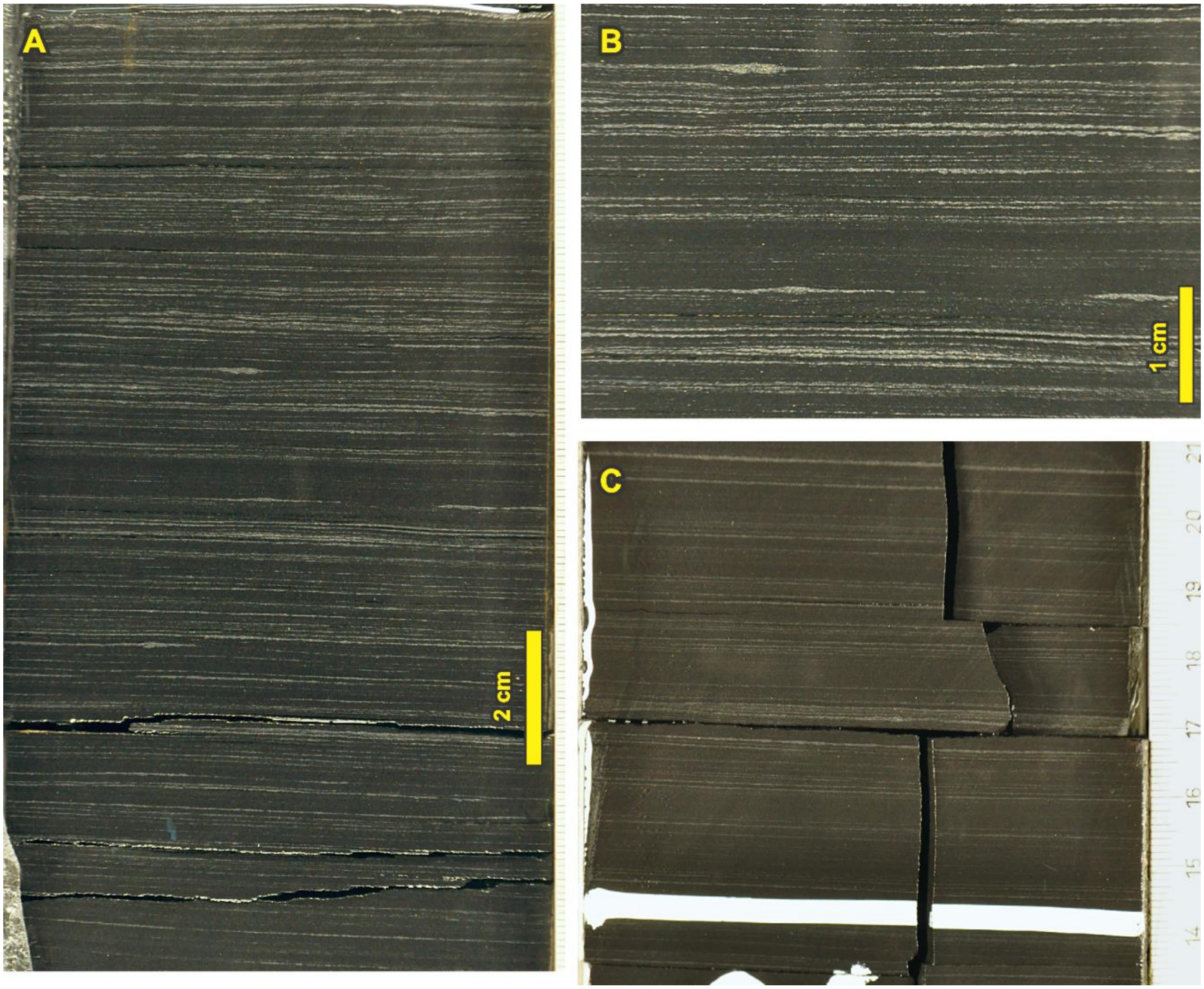

Fig. 4.8. (A, B) Typical facies at 4461.2-4505.0, (B) is the zoom of the middle area in (A). (C) Fractured calcareous siltstone at 4474.25m.

4505.0-4524.0 Siltstone: very dark grey, moderately calcareous (less than above), finer grained (silt only, no major sand-sized lithologies), with thinner and less frequent calcisiltite laminae, with abundant “pyrite dust”. Calcisiltite laminae are locally pyritized. The interval becomes more fissile downward.

4524.0-4529.80 Siltstone: very dark grey and similar to 4505.0-4524.0 m but non-calcareous with rare very thin (≤ 0.1 mm) whitish laminae of calcisiltite and vf/g calcarenite. Significant pyrite development (pyrite dust and thin streaks or pyritized coarser-grained laminae). Lithology varies mostly between silty shale and siltstone. Some bedding planes bear pyritized sponge spicules. Minor fine coaly detritus.

4529.80-4532.10 Silty mudrock: black, pyritic, hard, laminated, with moderate smearing underwater indicating slightly increased clay content. The rock is rich in “pyrite dust” and occasional intervals of enhanced pyritization.

4532.10-4538.5 Siltstone: muddy and partly interlaminated with shale, hard, monolithic to subfissile, dark brownish grey to black, pyritic, with weak dirty smearing; the interval is distinct by inclined lamination and large-scale convolute slumping fabrics in the upper part (Fig. 4.9). Base sharp, at the discontinuity underlain by paler colored mudrock with burrows (Fig. 4.10).

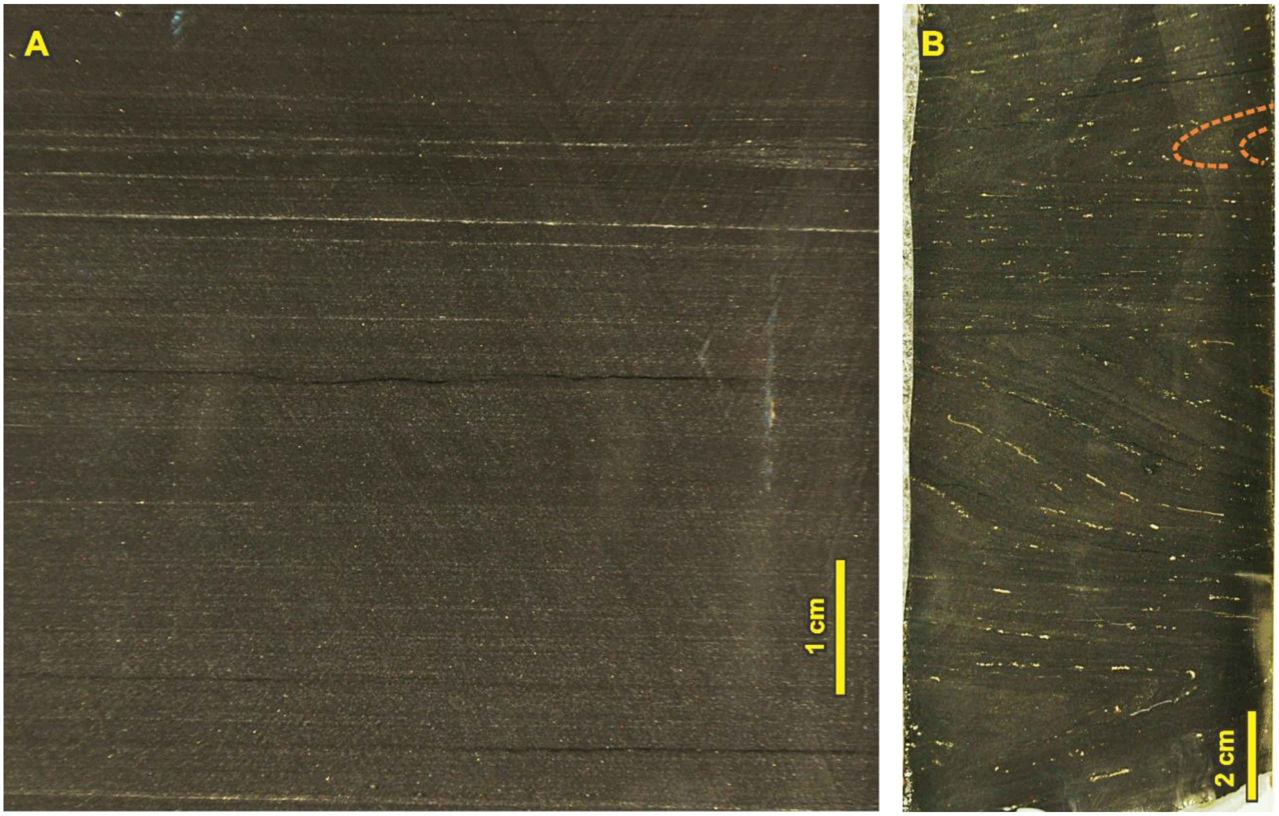

Fig. 4.9. Siltstones and mudrocks at 4532.10-4538.5: (A) 4526.20 m; (B) Slumping fabric at 4533.40, convolute folding is partly traced.

4538.50-4541.50 Mudrock: dark grey, subfissile to fissile silty shale with some interval of sandy shale; moderate amount of "pyrite dust", rare horizons of small pyrite nodules and almost no pyrite streaks. Distinct from the above by presence of lamination-masking burrowing patterns. BI (bioturbation index *sensu* Taylor et al., 2003) is 2-3. Inclined laminar sets and convolute slumping forms are common (Fig. 4.11).

4541.50-4543.50 Mudrock: dark grey fissile silty and partly sandy shale, similar to 4538.50-4541.50 but with preserved thin (0.3-0.1 mm) lamination composed of harder (silt-rich?) and flaky receding clay-rich couplets. Burrowing patterns are rare, BI 1-2. Inclined laminar sets, oblique shearing planes and some slickensides are present (Fig. 4.12A). Minor coaly detrius and rare ostracods on fissility planes.

4543.50-4547.2 Mudrock: grey homogeneous silty shale, lamination is rare, burrowing patterns are obscure or unrecognizable probably due to homogeneity. Barely discernible nodularity is present as an expression of minor early diagenetic impregnation with a cementing non-calcareous material, most likely siderite. Small ostracods on bedding planes. Intraclasts of darker mudrocks are present.

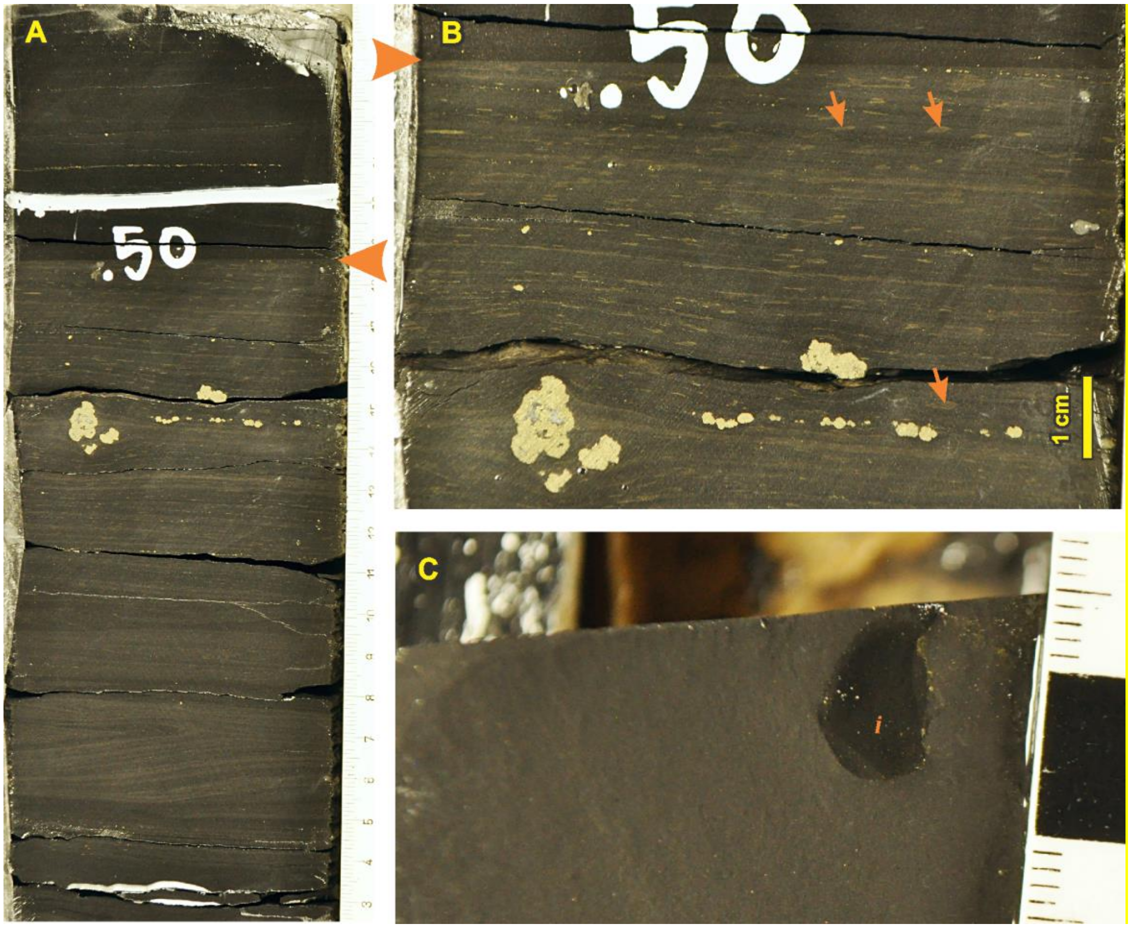

Fig. 4.10. (A, B) Sedimentary discontinuity at 4538.10 m (large arrows); small arrows point at planar trace fossils (pascichnia). (C) an intraclast of black shale (*i*) in grey bioturbated shale, fissility plane, 4547.0 m.

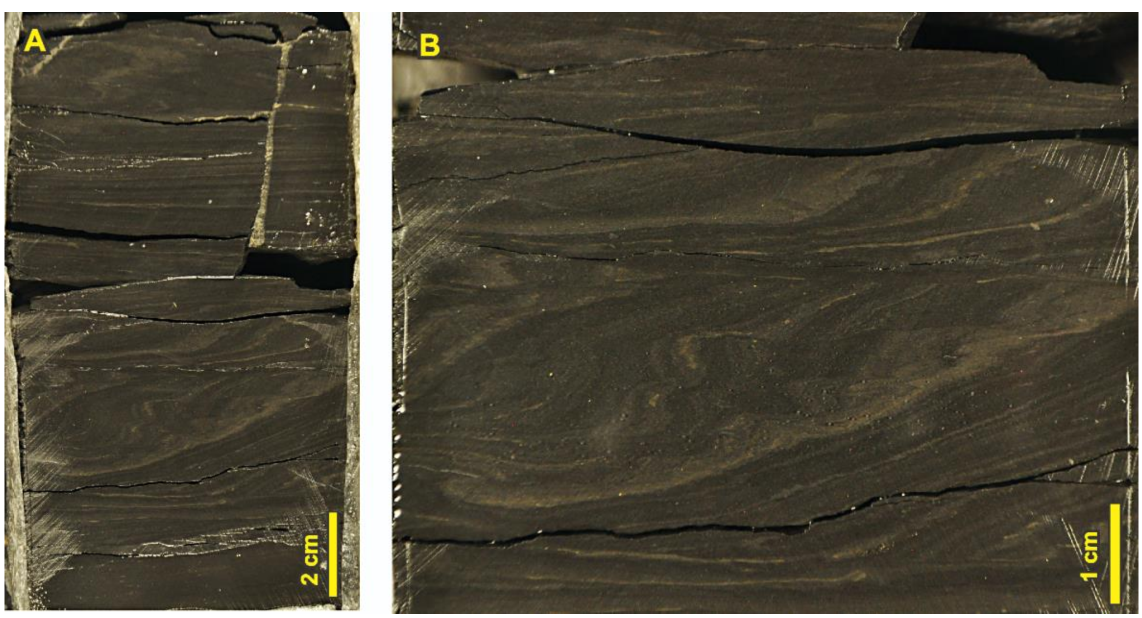

Fig. 4.11. Convolute slumping fabric at 4539.10 m, successive zoom-ins.

4547.2-4549.50 Mudrock: grey laminated shale; lamination is thick (0.5-10.0 mm), defined by normally graded bedding of silty and sandy mudrocks in base and pelitomorphic shales in top (Fig. 4.12B-D). Some coarser grained beds are weakly impregnated with pelitomorphic siderite. Rare pyritized patches; overall pyrite content is low. 4549.50-4553.20 Mudrock: grey pelitomorphic to silty shale; alternation of homogeneous and crudely laminar intervals similar to lamination at 4547.2-4549.50 m; BI is probably around 2. Rudimentary nodularity in the upper part of interval.

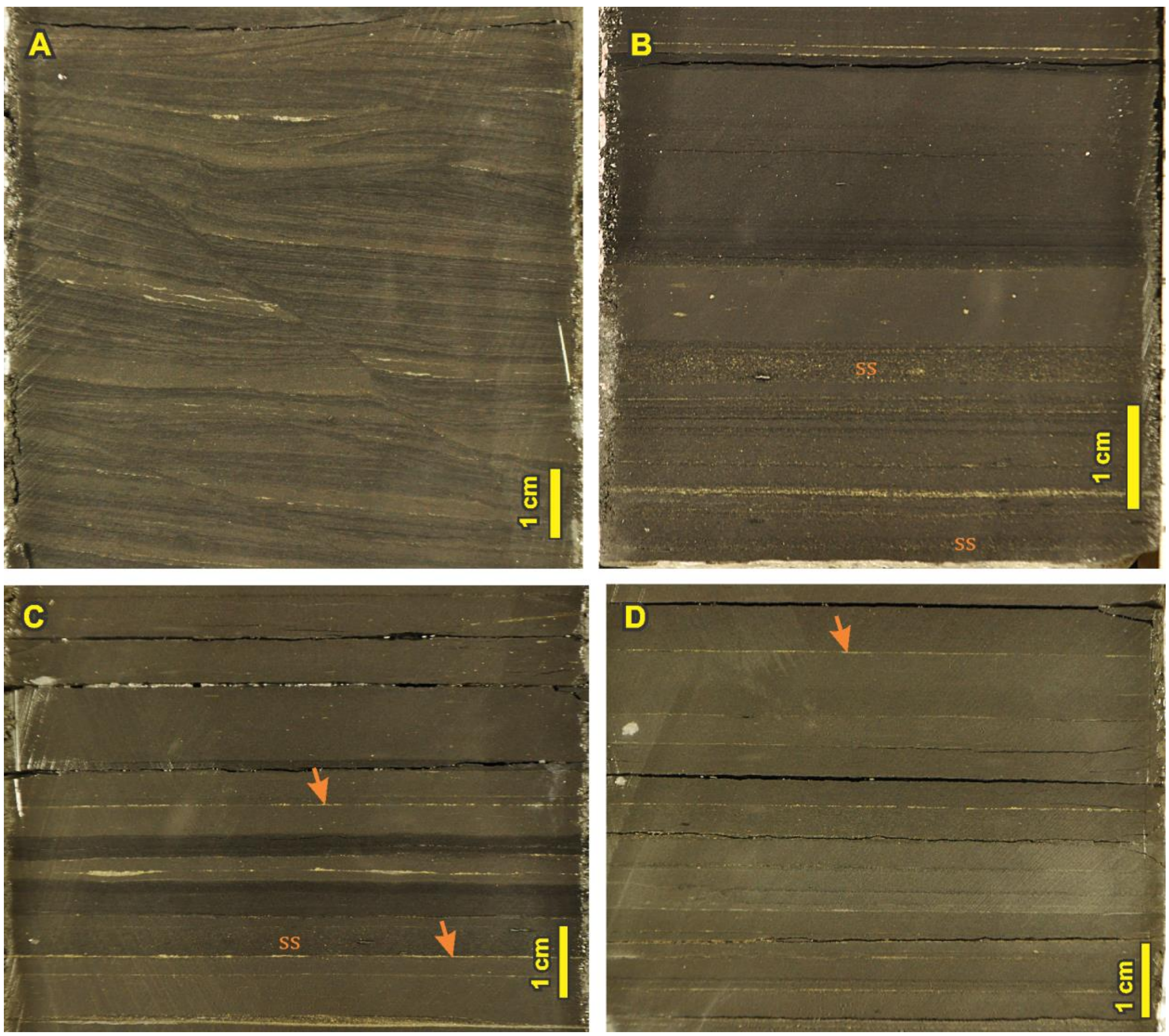

Fig. 4.12. (A) Shear plane in a fabric of ductile deformation, 4542.5 m. (B-D) Character of lamination in grey mudrocks at 4547.2-4549.50 m: (B) 4549.45 m; (C, D) 4547.70 m; pyritic laminae are arrowed; (*ss*) are sandstone intercalations.

4553.20-4555.10 Mudrock: dark grey, crudely laminar clay-rich shale; lamination as above. Thick (0.5-3.0 cm) homogeneous intervals are paler colored and likely finely bioturbated, they alternate with rhythmically laminated intervals which are prevailing at this interval. Distinct feature: bedding-parallel horizons of cone-in-cone coarsely crystalline carbonate ("beef" carbonate layers; Cobbold et al., 2013) similar to those in the Bluefish Member of Mackenzie Plain area (Mackenzie, 1972; Ihsan et al., 1993) but less fizzing in HCl (Fig. 4.13). XRD and structural examination is required to confirm mineral composition.

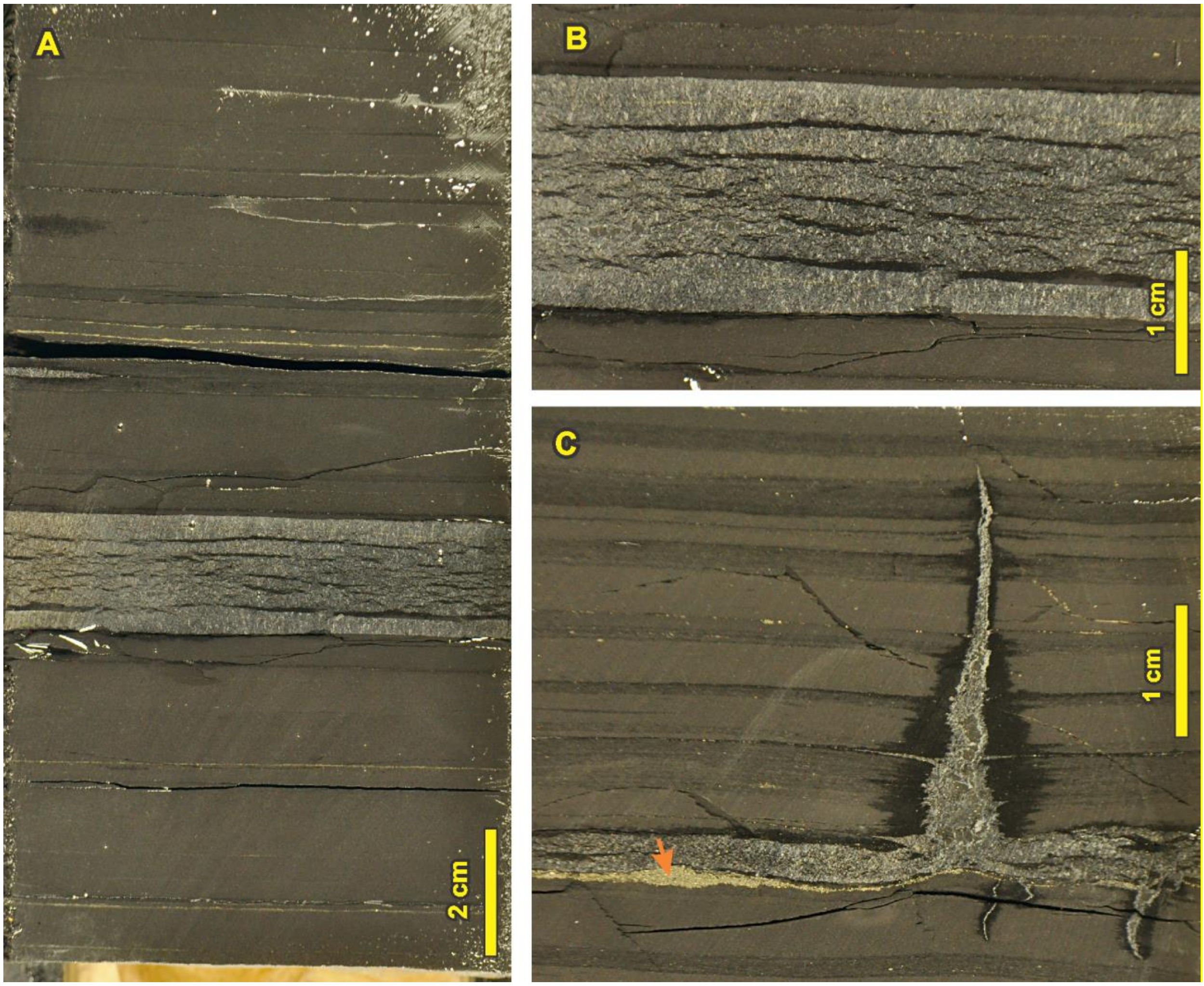

Fig. 4.13. (A, B) Beef carbonate layer at 4553.35, (B) is X2 zoom of (A). (C) Polymineral vein (tensile crack fill?) funneling upward from a thin beef carbonate layer; pyrite lenticle is arrowed; 4554.90 m

4555.10-4560.30 Mudrock: grey, crudely laminated (0.1-1.0 cm), sideritic shale; siderite occur as flattened nodules and selective impregnations of laminae (Fig. 4.14). Gently inclined laminar sets are present. The upper one-half is more bioturbated with decimeter-scale thoroughly mixed intervals (BI 3-4); the lower one-half is more laminated (BI ~2). Siderite mineralogy is subject to confirmation with XRD.

4560.30-4564.75 Mudrock: dark grey to grey, slightly harder and more monolithic than above, sandy and silty at many intervals with minor muddy vf/g sandstones; mostly bioturbated (BI 3-4); siderites are not expressed morphologically. Weakly calcareous laminae appear near the base flagging transition to underlying facies.

4564.75-4567.80 Mudrock to siltstone: dark grey, very calcareous and silty, pyritic, low-contrast alternation of muddy vf/g sandstones, siltstones, minor thin shales, and calcisiltites (Fig. 4.15).

Calcareousness increases downward in the upper 1.5 m. Bioturbation decreases from 2-3 near the top to non-existent in the main lower part. Amount of pyrite increases as well, mostly as "pyrite dust". Base is defined by entry of whitish calcisiltitic laminae and lenticles.

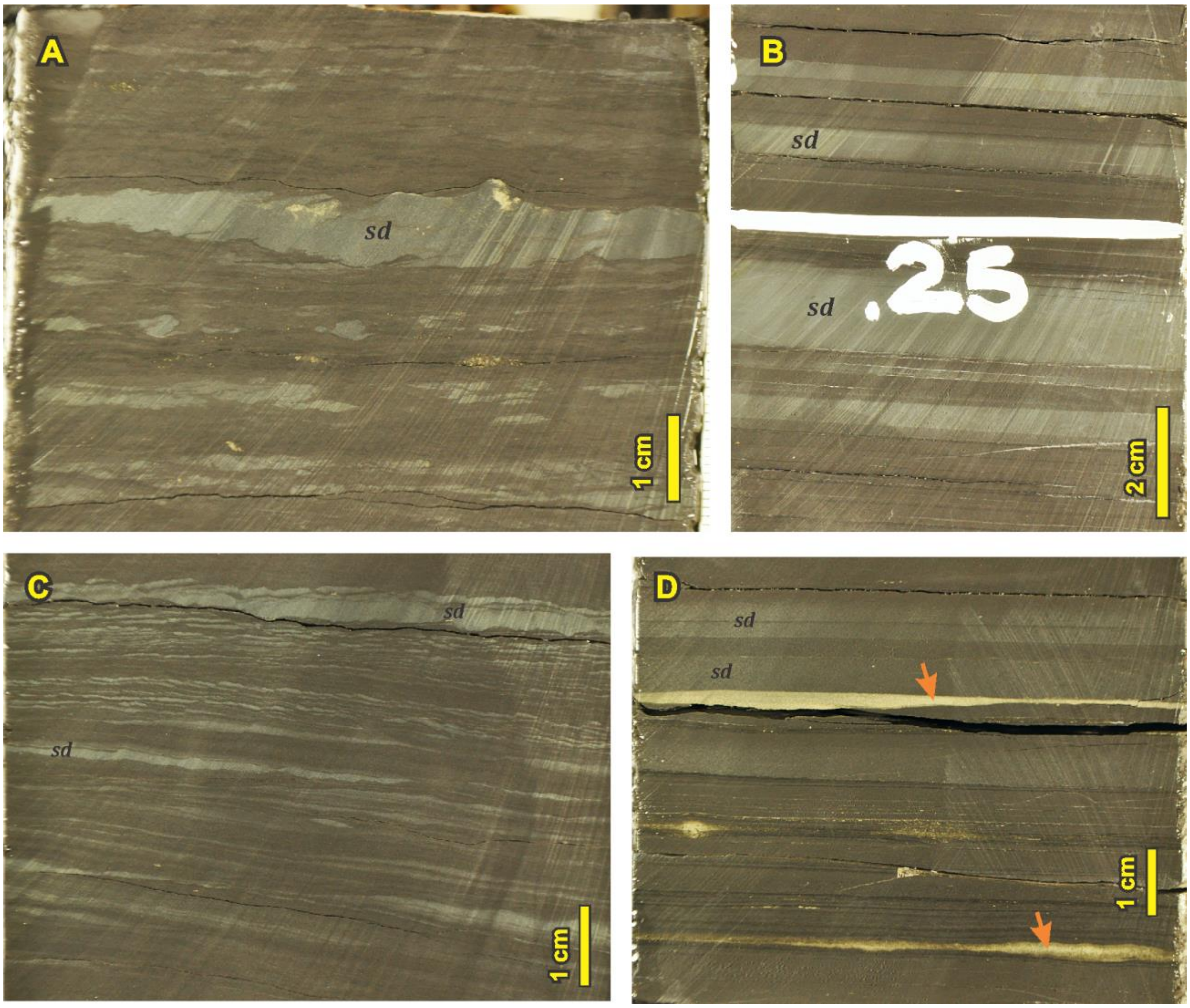

Fig. 4.14. Siderite impregnations and nodules (*sd*) in bioturbated to laminated mudrocks at 4555.10-4560.30 m: (A) 4555.40 m; (B) 4558.25 m; (C) 4557.75 m; (D) 4559.30 m. Note varying development of siderite impregnations from incipient (D) to hard nodules and plates (A, B). Pyritic laminae are arrowed.

4567.8-4576.0 Calcareous mudrock to siltstone: the mudrock is very dark grey, very calcareous and silty, moderately pyritic; lamination is distinct, emphasized by laminae of pale grey calcisiltite (Fig. 4.16). Calcareousness and abundance of calcisiltitic laminate increases to the bottom of the interval.

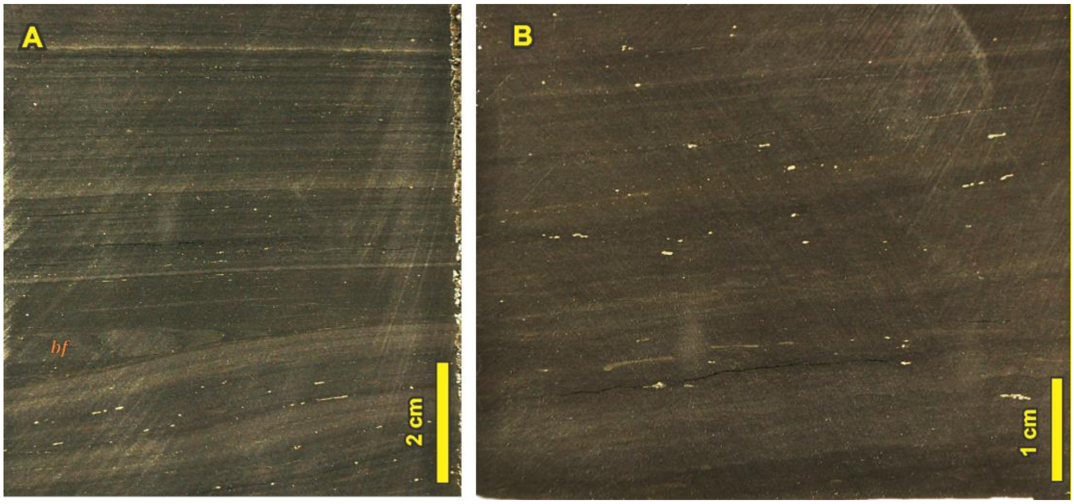

Fig. 4.15. Mudrocks at 4564.75-4567.80 m: (A) 4564.8 m, mostly laminated; (*bf*) is a trace fossil with subhorizontal backfill – *Zoophycos*?; (B) Homogeneous moderately bioturbated mudrock at 4567.25 m.

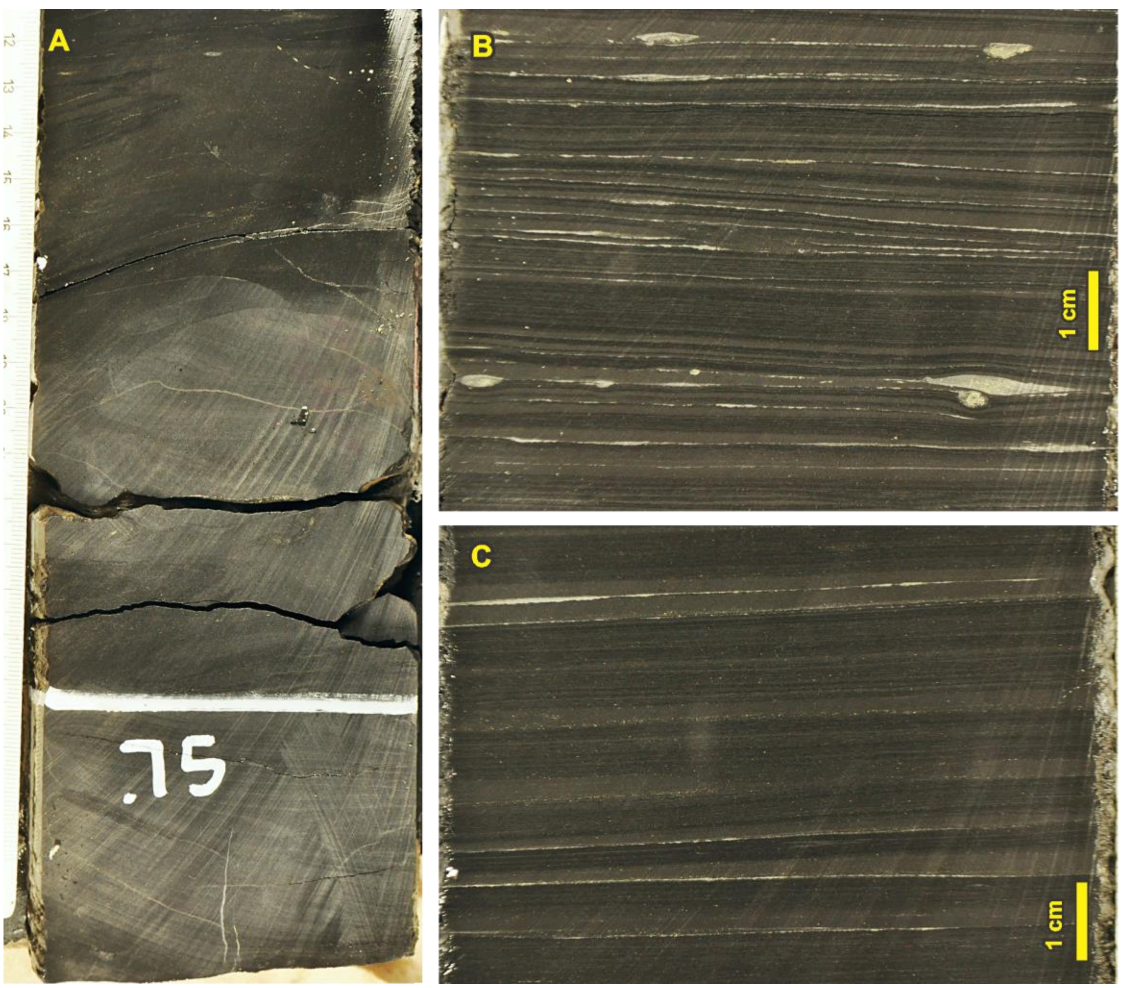

Fig. 4.16. Calcareous mudrocks and siltstones in core bottom (4565.0-4564.0 m): (A) large calcareous nodule with diffuse boundaries at 4570.75 m; (B) calcisiltite laminae and lenticular channel cuts at 4571.0 m; (C) rhythmic lamination with miner pyritized calcisiltite laminae, 4569.85 m.

5. Nexen Energy Dunedin A-38-B/94-N-8

Hyun Suk Lee

The Nexen Energy Dunedin a-38-b/94-n-8 well is located in the middle of Liard Basin (coordinates, 6571735.04N/430591.74E). Seven sedimentary facies are recognized in cores from 3907 m to 4075 m of the Nexen Energy Dunedin A-38-B/94-N-8 well. The sedimentary facies mainly consist of 4 mudstone facies, 2 siltstone to fine sandstone facies, and alternating mudstone and sandstone facies.

Homogeneous mudstone (Mh)

This facies represents homogeneous or faintly laminated, dark grey to black, and noncalcareous or calcareous mudstone (Fig. 5.1A). Partly silt-sized grains and calcite grains are dispersed. Nodular or layered pyrites are commonly interlayered. White discontinuous streaks are intercalated in part. Homogeneous mudstone beds are dominant in the upper part of core and relatively thinly intercalated in the lower part. This facies is frequently occurred with laminated mudstone and black laminated mudstone (facies Ml and Mlb, Fig. 5.2).

Laminated mudstone (Ml)

Laminated mudstone is represented by alternation of gray and dark gray parts (Fig. 5.1B). Gray part is coarser than dark gray part. A-few-mm thick horizontal and continuous laminae are common. Calcite streaks or veins formed abundantly along parted bedding due to calcite concretions. Normal grading partly was developed in gray part. This facies can be divided into thinly (Ml) and thickly laminated mudstone (Mlt) sub-lithofacies. This facies occurred dominantly in lower part of core with homogenous mudstone and black laminated mudstone with grain (facies Mh and Mlbg)

Black laminated mudstone (Mlb)

This facies is divided into two sub-lithofacies, black laminated mudstone (Mlb) with grains (Mlbg) (Fig. 5.1C). A-few-mm thick continuous black laminae are frequently intercalated within dark gray mudstone. Black laminae are usually finer in grain size than dark gray laminae. Grain-dispersed laminae are interlayered in some units, forming subdivision of lithofacies. Systematic trends either in bed thickness or intercalating interval are hard to be identified though laminae are commonly interlayered a few mm to 10 cm apart. This facies is abundant in the middle part of core and occurred with laminated mudstone (facies Ml, Fig. 5.2).

Papery-fractured mudstone (Mpf)

This facies represents papery fractured mudstone (Fig. 5.1E). Gray to dark grary mudstone beds are laminated and entirely fractured parallel to bedding. Grain size of mudstone is a little coarser than homogeneous and laminated mudstone. Fractures space a few mm to cm apart in vertical direction. This facies occurred in the lowermost part of core below homogenous mudstone (facies Mh, Fig. 5.2). Intercalating bioturbated fine sandstone beds (facies Fb) have sharp upper and lower boundaries. Laminated siltstone beds (facies Fl) are also interlayered. It shows sudden drop of TOC from 4 wt % to less than 1 wt% (Fig. 5.3).

Laminated siltstone (Fl)

Laminated siltstone is characterized by alternation of a-fww-mm thick coarse and fine laminae (Fig. 5.1H). Coarse laminae consist of bright gray siltstone whereas fine laminae are of dark gray mudstone. Massive or normally graded white grains (max. medium sand) are dispersed in some beds. Pyrite grains are abundant. This facies shows wide range from 5 mm to 80 cm in bed thickness. Bed boundaries are mostly sharp and flat but indistinct boundaries are also easily recognized. This facies are frequently intercalated in the upper and lower part of core but rare in the middle part (Fig. 5.2).

Bioturbated fine sandstone (Fb)

This facies represents calcareous fine sandstone to siltstone with massive or mottled texture (Fig. 5.1F). The bioturbation index is higher than 4. The lower and upper boundaries are sharp and flat. This facies occurred in the lowermost part of core and are intercalated within papery-fractured mudstone (facies Mpf).

Alternation of laminated fine sandstone and mudstone (Flm)

This facies is represented by thin alternation of laminated fine sandstone and laminated mudstone (facies Fl and Ml, Fig. 5.1F) with same ratio. Each lamina is a few mm in thickness. This alternation is overlain by homogeneous mudstone and underlain by laminated black mudstone (Fig. 5.2).

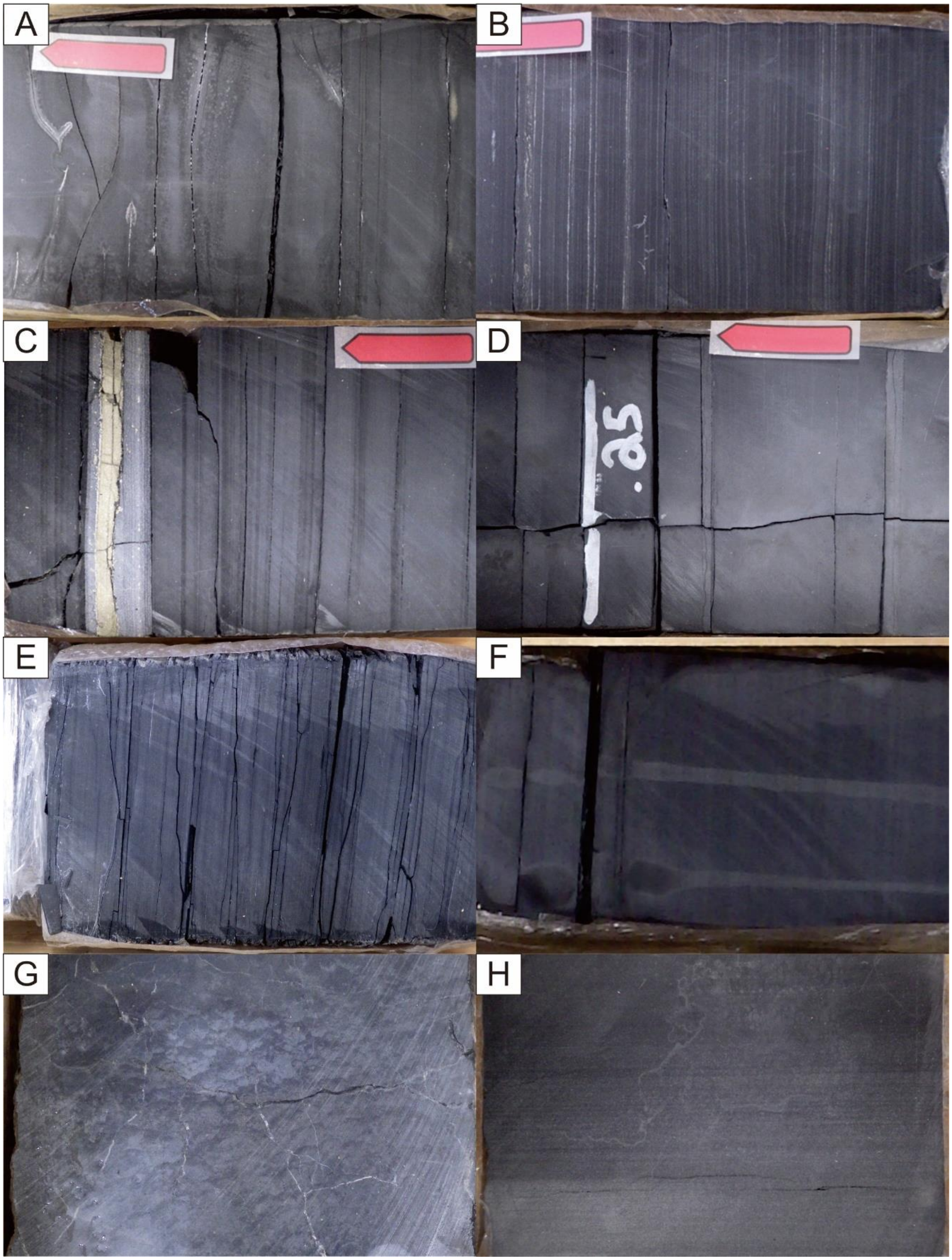

Figure 5.1. Photographs of sedimentary facies. A. Homogeneous mudstone (Mh), B. Laminated mudstone (Ml), C. Black laminated mudstone (Mlb), D. Black laminated mudstone with grains (Mlbd), E. Papery-fractured mudstone (Mpf), F. Alternation of laminated fine sandstone and siltstone (Flm). G. Bioturbated fine sandstone (Fb), H. Laminated siltstone (Fl). Core diameter as scale is 4 inch. Left side is upward (A-F).

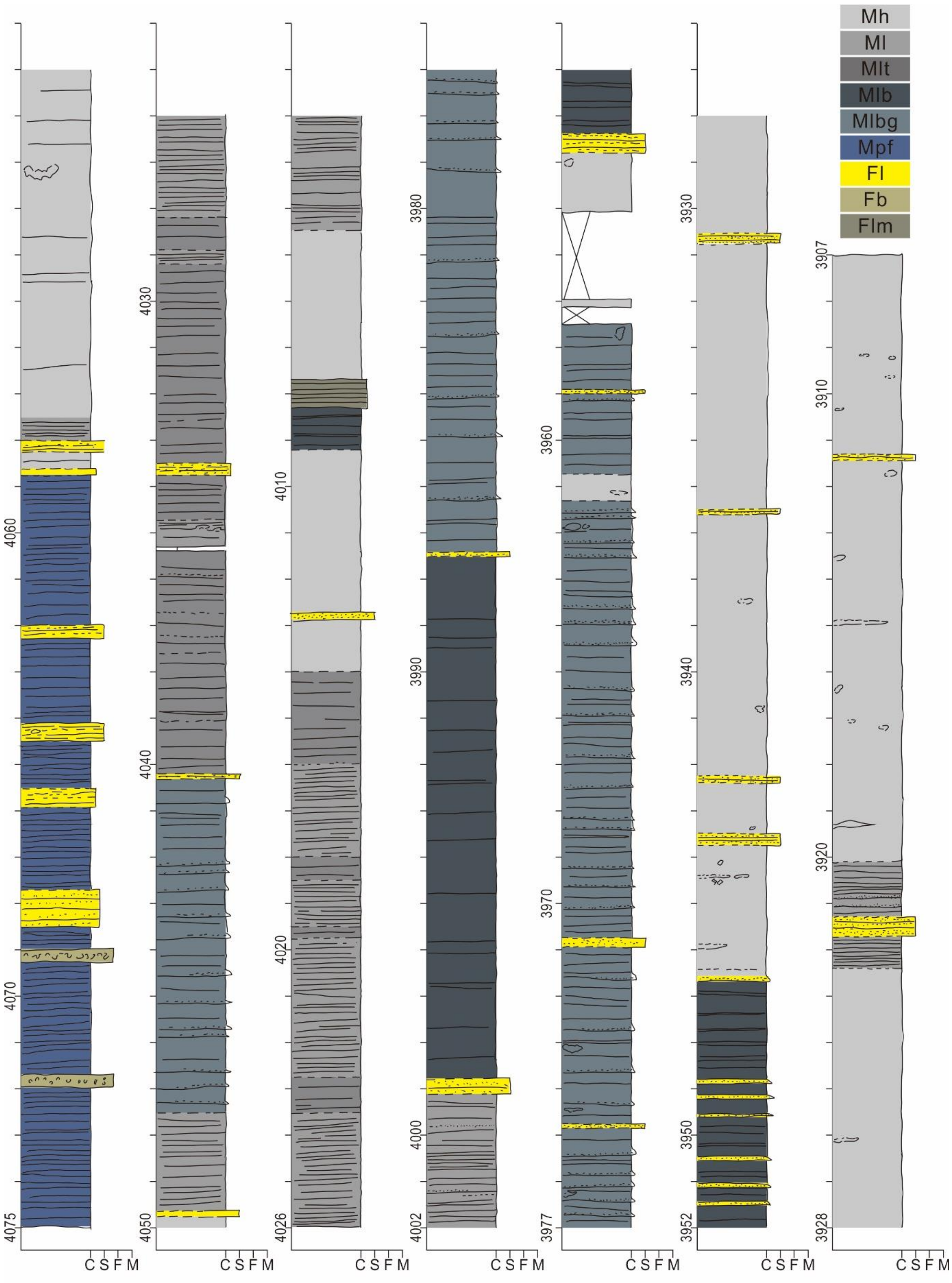

Figure 5.2. Columnar description of Nexen Energy Dunedin A-38-B/94-N-8 well. C: Claystone, S: Siltstone, F: Fine sandstone, M: Medium sandstone. See text for sedimentary facies code.

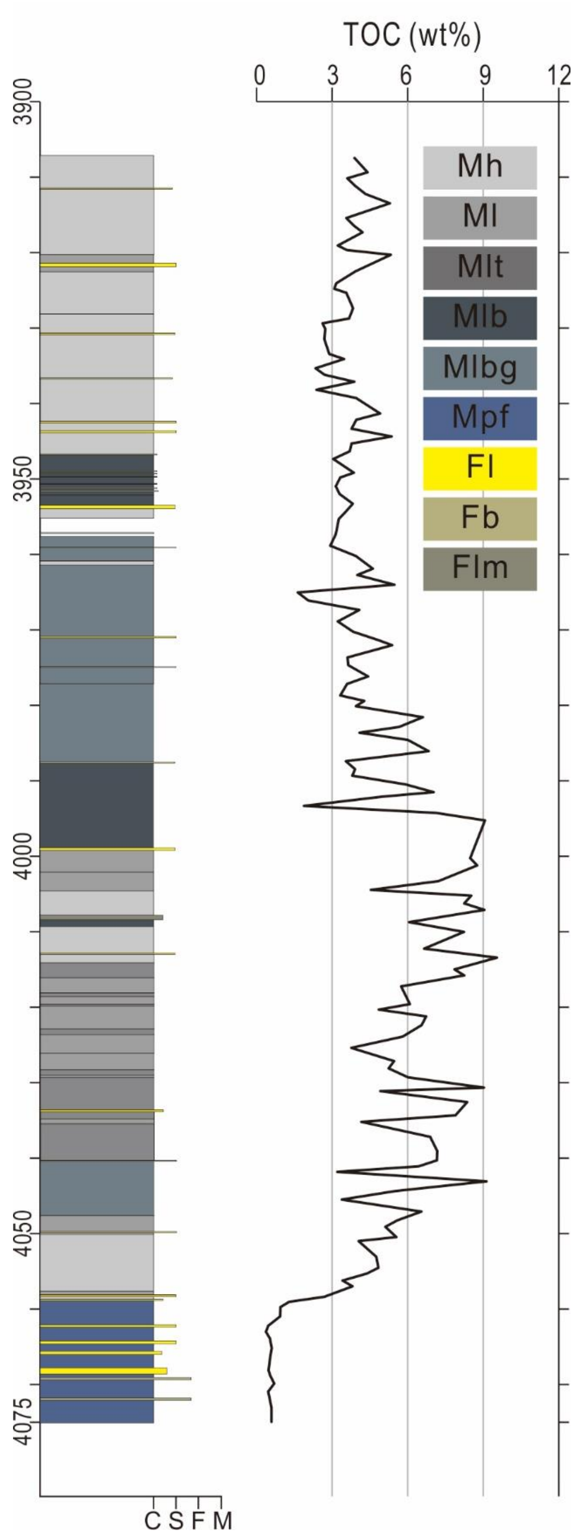

Figure 5.3. Vertical changes of lithofacies and TOC in studied well

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