AER/AGS Open File Report 2015-04

Alberta Energy Regulator

Outcrops of the Upper Devonian Moberly Member (Waterways Formation) on the Athabasca River West of Fort McMurray, Alberta (NTS 74D)

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Outcrops of the Upper Devonian Moberly Member (Waterways Formation) on the Athabasca River West of Fort McMurray, Alberta (NTS 74D)

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July 2015

ISBN 978-1-4601-0141-4

Schneider, C.L., Leighton, L.R., Forcino, F.L. and Grobe, M. (2015): Outcrops of the Upper Devonian Moberly Member (Waterways Formation) on the Athabasca River West of Fort McMurray, Alberta (NTS 74D); Alberta Energy Regulator, AER/AGS Open File Report 2015-04, 40 p.

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Published July 2015 by:
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Acknowledgements

We thank Steve Russell for jet boat transportation to outcrops along the Athabasca River. Tyler Hauck (AGS) reviewed the draft report and provided helpful comments. We also thank Tyla Willet and Aaron Dalton for the editing and proofreading of this report.

Abstract

Joint fieldwork completed by Alberta Geological Survey geologists and University of Alberta paleontologists over the summers of 2010–2012 resulted in the description and correlation of Moberly Member (Waterways Formation, Devonian) outcrops along the Athabasca River. This report contains the first published descriptions of five outcrops of the Moberly Member along the Athabasca River west of Fort McMurray, which were examined in the summer of 2011. Outcrops include those between Mountain Rapids and Cascade Rapids and capture the lower portion of the Moberly Member. The lower units of the exposed section tend to be fossiliferous, argillaceous, and generally bioturbated. The upper units were *Thalassinoides*-burrowed and less fossiliferous, although mostly remain argillaceous.

1 Introduction

A team of AGS and University of Alberta geologists visited the Moberly Member outcrops on the Athabasca River west of Fort McMurray to investigate the stratigraphy and paleoecology of Moberly Member (Waterways Formation) outcrops (Figure 1). Outcrops occur sporadically along the river and often are associated with rapids caused by exposed limestone beds in the river. Above some outcrops, thick McMurray Formation oil sand forms large cliffs.

The Devonian outcrops west of Fort McMurray along the Athabasca River remain undescribed in the published literature, although Cotterill and Hamilton (1995) included illustrations of some outcrops in their regional cross-sections. Herein, we present descriptions and a composite section for six outcrops examined between Mountain Rapids and Cascade Rapids during the late summer of 2011 (Figure 2).

Descriptions of Moberly Member outcrops within the Town of Fort McMurray are presented in Schneider et al. (2013); those of outcrops further north within Township 90 in Schneider et al. (2015a) and townships 91–93 in Schneider et al. (2015b). As a reference, unit 10 of this report is stratigraphically equivalent to unit 14 at the Water Treatment Plant locality and unit 4 at the Athabasca River Bridge locality of Schneider et al. (2013), and the biostromal units 4 of Schneider et al. (2015a) and 6 of Schneider et al. (2015b).

2 Background

The Waterways Formation was named by Warren (1933) for the limestone outcrops along the Athabasca River in the Fort McMurray area. Crickmay (1957) split the Waterways Formation into 5 members: the basal Firebag shale, the Calumet limestone, the Christina shale, the Moberly limestone, and the Mildred shale and limestone. Outcrops in the Fort McMurray area fall within the Moberly Member, as do most of the outcrops north of Fort McMurray along the Athabasca River and those along the Clearwater River between Fort McMurray and the Christina River.

Norris (1963) described most of the Moberly Member outcrops along the Athabasca and Clearwater rivers in the Fort McMurray area, but did not visit the outcrops along the Athabasca River west of Fort McMurray. According to his descriptions, the Moberly Member ranges from nodular, argillaceous limestone to a regionally extensive biostromal unit containing abundant stromatoporoids.

Cotteril and Hamilton (1995) included illustrations of outcrop sections from the Athabasca River west of Fort McMurray in their cross-section “D”, but did not describe outcrops beyond what was included in illustrated sections. Cotterill and Hamilton did not correlate beds between outcrops but did tie their outcrops to the Bear Biltmore No. 1 core (7-11-87-17W4). None of their outcrop locations coincide with those described in this report, although their section HC 94-43 is located across the river from the *Thalassinoides* outcrop described later on in section 6 (Figure 1).

Eccles and Pana (2003) also visited outcrops along the Athabasca River west of Fort McMurray, focusing on the potential for Mississippi Valley-type deposits in Moberly Member limestone. They suggested that dark brown, Fe-stained blotches in the limestone indicated mineralization by hydrothermal events, and that the most pervasive alteration occurred in the Devonian outcrops along the Athabasca River west of Fort McMurray.

Eccles and Pana (2003) reported a dominant joint set trending 240°, a secondary north-trending joint set, and possible faults from a locality near Cascade Rapids. One north-trending tensional fracture at

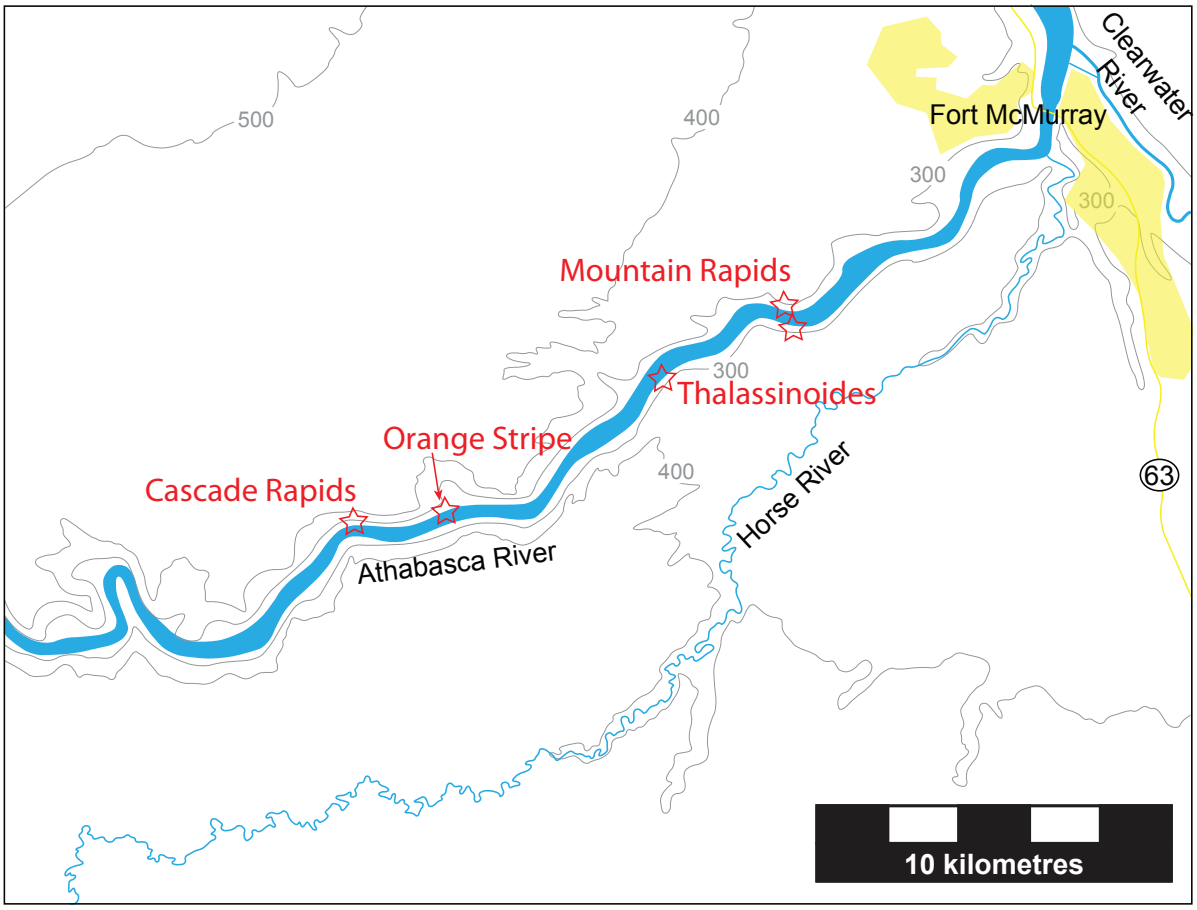

Figure 1. Map of outcrops examined along the Athabasca River west of Fort McMurray.

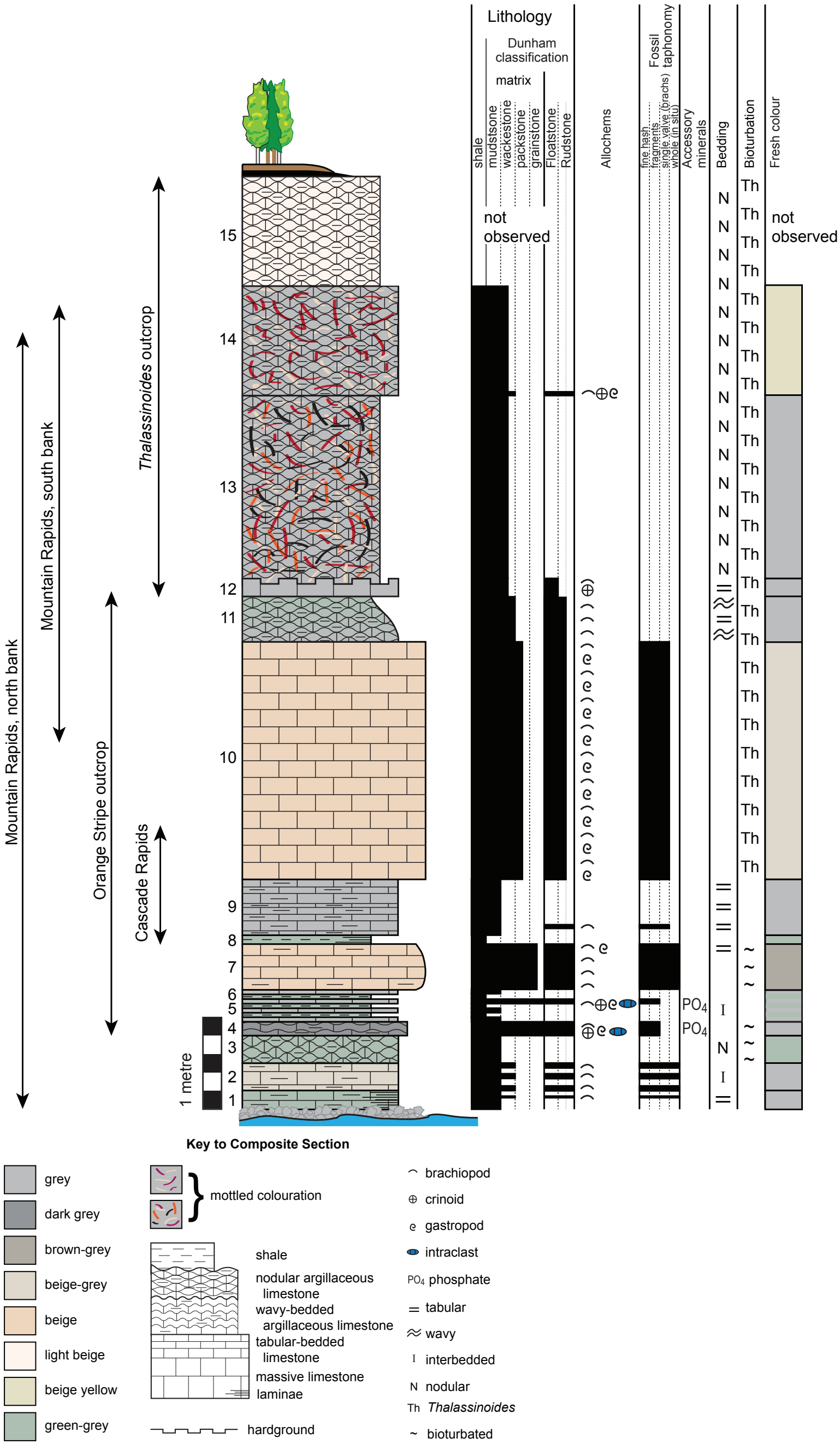

Figure 2. Composite section for the outcrops along the Athabasca River west of Fort McMurray described in this report. Units 1 through 11 are based on observations of the Mountain Rapids, north bank outcrop. Units 12 through 15 are based on observations from the *Thalassinoides* outcrop.

this locality contained disseminated to massive pyrite and highly altered rubble. They also reported that fractures at the base of the section contain greenish-grey clay, which they attributed to fault gouge.

Subsurface dissolution of halite within the Middle Devonian Prairie Evaporite Formation in the Fort McMurray area resulted in the subsidence, folding, and faulting of overlying strata (e.g., Norris, 1963, 1973). Halite dissolution is greatest east of the study area, where resulting deformation and collapse of post-Prairie Evaporite Devonian strata is also more extensive.

3 Composite Section, Mountain Rapids to Cascade Rapids, Athabasca River

Outcrops along the Athabasca River between Mountain Rapids and Cascade Rapids are correlatable, mainly based on the presence of a thick, resistant unit of *Thalassinoides*-burrowed floatstone (unit 10) and the nature of beds above and below this unit. Beds above unit 10 are also heavily bioturbated with *Thalassinoides* burrow networks, but beds below unit 10, although bioturbated, do not always contain distinctive burrows. Furthermore, beds below unit 10 are generally more fossiliferous.

Between Mountain Rapids and Cascade Rapids, the deformation observed at individual outcrops is minimal to nonexistent. Only the outcrop on the north bank of Mountain Rapids is gently folded into a north-south trending anticline. However, deformation is apparent at Mountain and Cascade Rapids when correlating strata from the opposite banks of the river. At Mountain Rapids, the south bank outcrop is stratigraphically higher (approx. 3 m) than that of the north bank, suggesting a small fault or a southward-plunging anticline between the two outcrops. At Cascade Rapids, the relationship is reversed relative to that of Mountain Rapids outcrops, in which the limestone beds along the south bank are stratigraphically lower (approx. 1 m) than that of the north bank.

A composite section for the region is mostly derived from the north bank outcrop at Mountain Rapids, because the section is the most complete at this locality (Figure 2). Units above unit 10 in the composite section are derived from other localities in the study area, as the upper units were inaccessible at Mountain Rapids.

3.1 Paleoenvironmental Interpretation

Most of the strata described in this report were deposited on the shallow shelf below fair-weather wave base. Some rudstone and coquina units, such as those in units 2, 4, 5 and 9, may be tempestites from storm events, indicating that deposition occurred at least intermittently above storm wave base. The presence of pervasive *Thalassinoides* burrow networks in many of the upper units (10 and higher) also suggests deposition on the shallow shelf.

Laminated lime mudstone and shale in the lower portions of the section, particularly in units 1 and 2, had little to no macrobiotic activity within the sediment. Rudstone tempestites associated with these beds could have formed in either deep water or shallow, restricted shelf settings; the transport of shells into either paleoenvironment is possible. Upsection in units 4 and 5, however, phosphatized intraclasts suggest ripped-up hardgrounds, which likely formed in the deeper shelf environment. Thus, the lower units (e.g., units 1 through 5) of this section were likely deposited on the deeper shelf near storm wave base.

4 Mountain Rapids, North Bank, Athabasca River

4.1 Locality Description and Access

UTM Zone 12, 467652E, 6281297N (NAD83)

The upstream end of the outcrop on the north bank of the Athabasca River begins at Mountain Rapids and extends downstream for approximately 250 metres. Across the river on the south bank, another, smaller limestone cliff outcrops in the trees lining the river bank.

At the rapids, the outcrop forms a steep cliff along the river's edge. The top surface of the outcrop has eroded into a gently sloping surface in the downstream direction. The uppermost beds remain intact only near the rapids and are truncated by erosion downstream. Because of the sheer cliff face along the rapids, the upper beds are inaccessible and can only be observed from below. A gentle anticline causes a nearly imperceptible westward dip to the upstream end of the outcrop. The exposure of the lowermost beds occurs in the axis near the downstream, eastern end of the outcrop.

This outcrop is easily accessed by jet boat, and may be accessible by helicopter during low river level to a grassy point bar downstream of the outcrop.

4.2 Stratigraphy

Description began at the eastern end of the outcrop where the lowermost beds are exposed. Numbers correspond to unit numbers of the composite section for the Athabasca River west of Fort McMurray (Figure 2). From the base to the top, the accessible beds include:

- Unit 1 (20 cm): recessive, green-grey weathering, grey, 1 to 1.5 cm tabular bedded, nodular weathering, argillaceous lime mudstone with green-grey calcareous shale partings between beds. Beds are laminated; laminae colours alternate between dark grey, grey, and blue grey and are laterally discontinuous. A 2 cm thick *Eleutherokomma* and atrypide brachiopod rudstone in a wackestone matrix occurs 8 cm below the top of the unit (Figures 3 and 4).
- Unit 2 (30 cm): recessive, 2 to 10 cm interbeds of (1) green-grey weathering, grey, laminated, argillaceous lime mudstone and (2) beige-grey weathering, grey, crinoid and brachiopod rudstone in a wackestone matrix. Measurements of individual beds from the base of the unit are: 11 cm rudstone, 3 cm laminated lime mudstone, 1 cm rudstone (also containing <0.5 cm, blue-grey, phosphatised intraclasts), 5 cm rudstone, 4 cm laminated lime mudstone, 2 cm rudstone, 3 cm rudstone, and 4 cm rudstone (Figures 3 and 4).
- Unit 3 (27 cm): recessive, green-grey weathering and fresh, centimetre-scale nodular, argillaceous lime mudstone. Green-grey calcareous shale partings anastomose around the nodules (Figures 3 and 4).
- Unit 4 (16 cm): slightly resistant, dark grey weathering, grey, up to 6 cm wavy bedded, crinoid, gastropod, brachiopod and intraclastic rudstone in a grainstone matrix. Intraclasts are concentrated in the lower half of the unit, are phosphatised, and are dark grey to black (Figures 3, 5, and 6).
- Unit 5 (26 cm): recessive, interbedded green-grey weathering and fresh, calcareous shale beds up to 1 cm thick, grey weathering and fresh, argillaceous lime mudstone beds up to 2.5 cm thick. Lime mudstone beds comprise 66% of the unit. The top of the unit is a 2 cm thick rudstone similar to that of unit 4 (Figures 3, 5, 7, and 8).
- Unit 6 (11 cm): recessive, interbedded shale and lime mudstone beds as in unit 5, except that lime mudstone beds are up to 1 cm thick and shale beds are up to 0.5 cm thick (Figures 3, 5, 7, and 8).
- Unit 7 (50 cm): resistant, beige weathering with red and orange siderite staining, brown-grey, massive, bioturbated brachiopod rudstone in a packstone to grainstone matrix. The basal 5 cm and

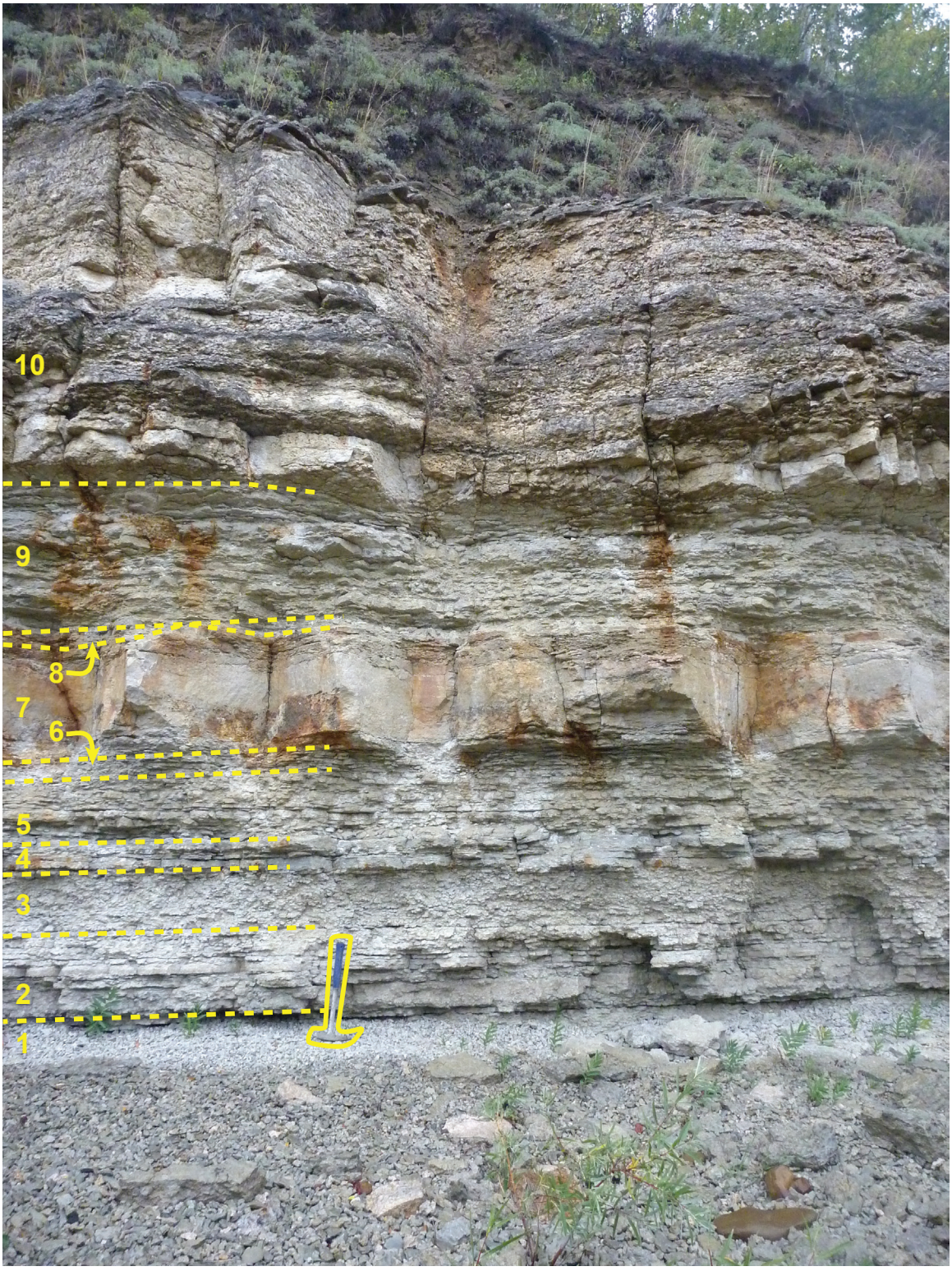

Figure 3. The outcrop in the axis of the anticline at Mountain Rapids, north bank on the Athabasca River west of Fort McMurray. The outlined rock hammer provides scale. The talus slope changes from light grey (dry) near the outcrop to dark grey away from the outcrop (wet) because of rain, not lithology or weathering.

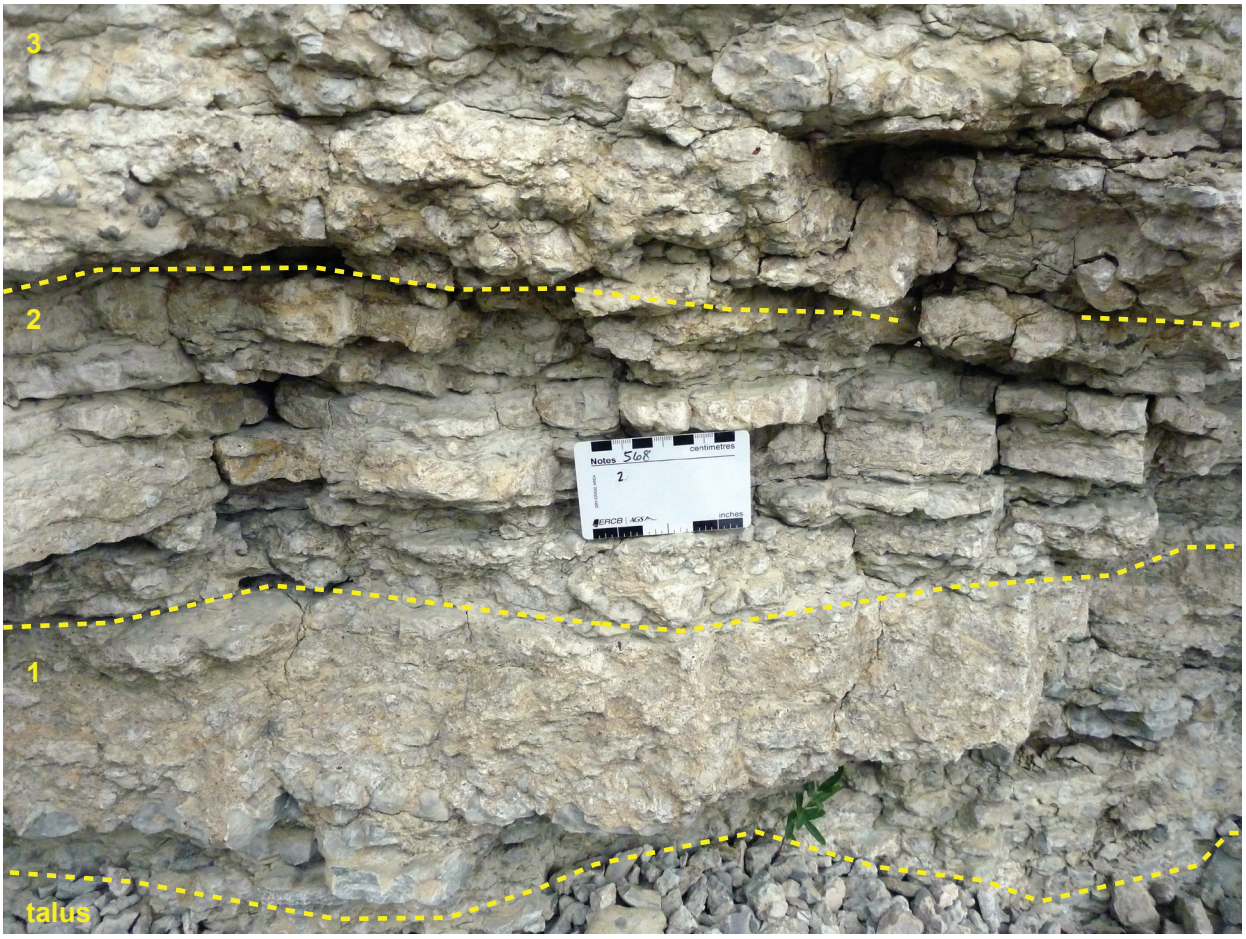

Figure 4. Units 1 through 3 at the Mountain Rapids, north bank outcrop along the Athabasca River west of Fort McMurray. Bedding contacts between units are planar; perceived waviness of the contacts on the photo arises from the camera angle, bedding plane exposure at the top of unit 1 and the base of unit 3, and slumping.

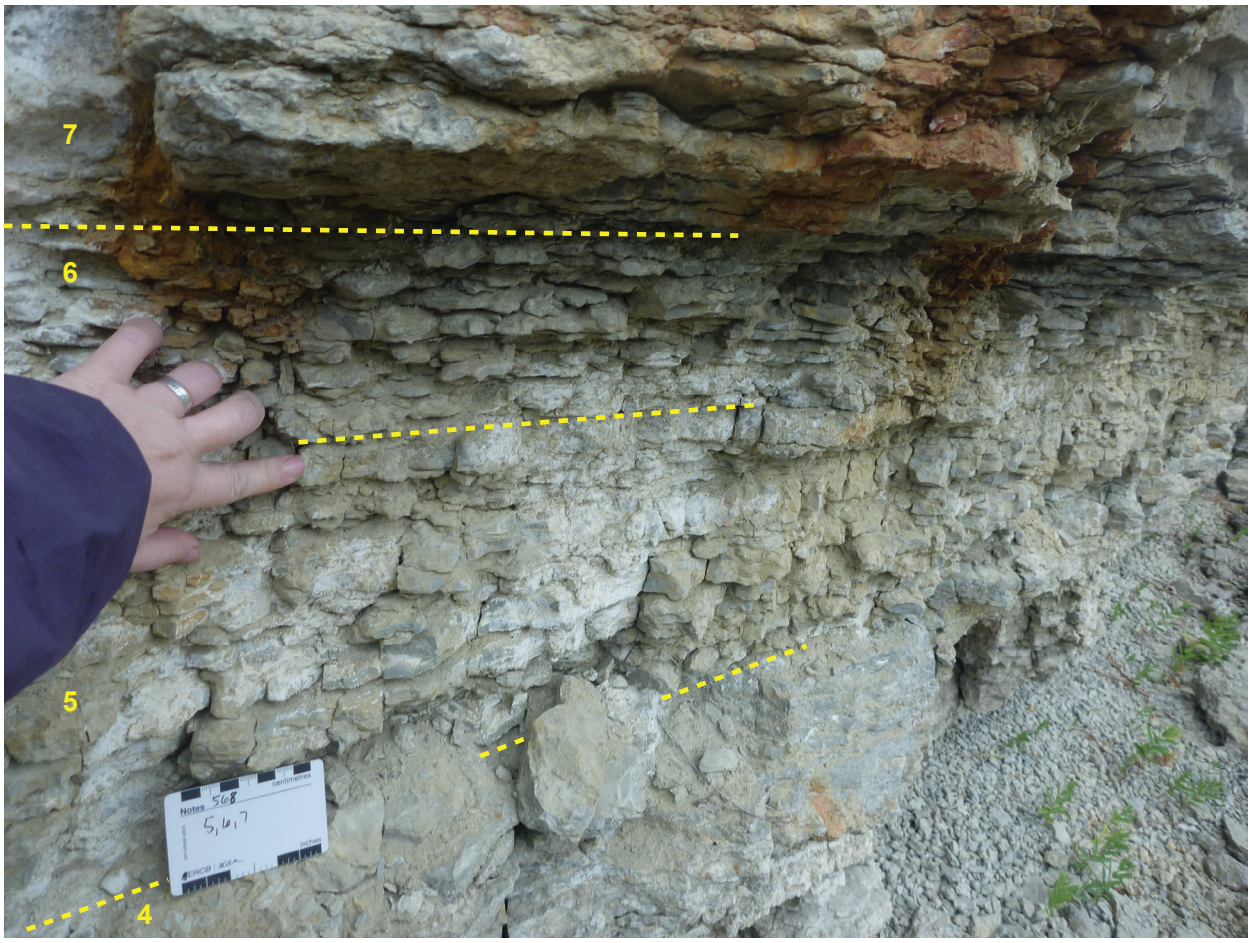

Figure 5. Units 4 through 7 at the Mountain Rapids, north bank outcrop along the Athabasca River west of Fort McMurray. The photographer is pointing to the topmost bed of unit 5.

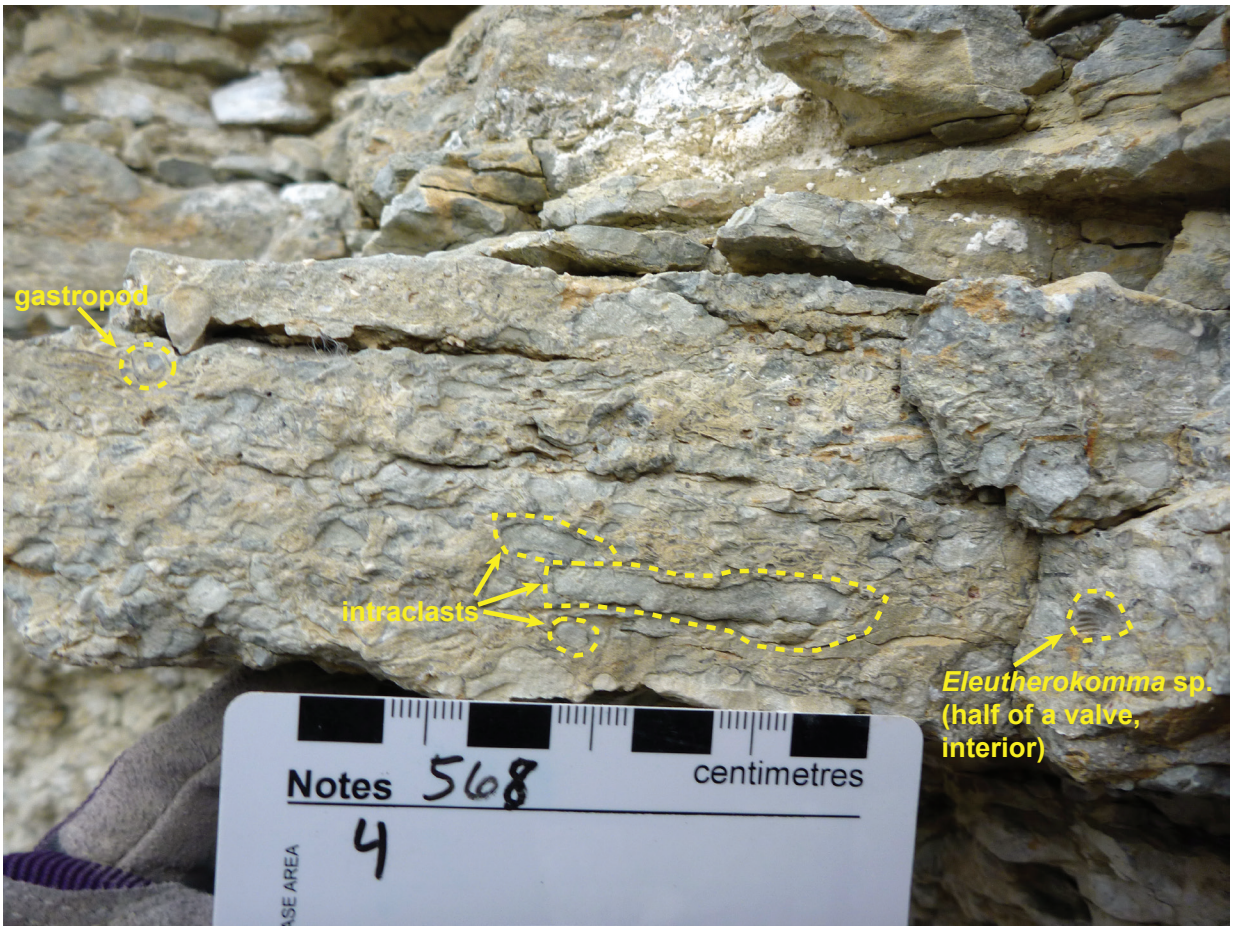

Figure 6. Close-up of unit 4 at the Mountain Rapids, north bank outcrop along the Athabasca River west of Fort McMurray. A few examples of the many allochems in this limestone bed have been outlined and labelled on the photograph.

Figure 7. Units 5 through 11 at the Mountain Rapids, north bank outcrop along the Athabasca River west of Fort McMurray. The outcrop in this photograph is overlain by alluvium.

Figure 8. Units 5 through 13 near the upstream end of the Mountain Rapids, north bank outcrop along the Athabasca River west of Fort McMurray. The rapids can be seen between the boat and the outcrop as a thin white line in the river.

top 15 cm are slightly recessive and argillaceous. The top 15 cm is tabular bedded and contains *Radiatrypa*, *Praewaagenoconcha*, and athyride brachiopods, and gastropods. Some brachiopods in this bed are moldic (Figures 3, 5, 7, 8, and 9).

- Unit 8 (9 cm): recessive, green-grey weathering and fresh, laminated, calcareous shale (Figures 3, 7, and 8);
- Unit 9 (61 cm): recessive, grey weathering and fresh, up to 3 cm tabular-bedded, argillaceous lime mudstone with up to 0.5 cm thick, green-grey, calcareous shale partings to interbeds. Thickness of shale interbeds decreases upwards to become millimetre-scale partings. A grey, 3 cm thick, brachiopod rudstone occurs 10 cm above the base of the unit, in which single-valve brachiopods are concave down, shingled, and tightly packed (Figures 3, 7, and 8).
- Unit 10 (260 cm): resistant, beige weathering, beige-grey, *Thalassinoides*-burrowed, massive, gastropod and brachiopod floatstone to rudstone in a wackestone matrix. Intermittent 7 to 10 cm thick beds are slightly argillaceous, contain *Thalassinoides* burrows in which burrow fill has been preferentially weathered and occurs at 35 cm, 60 cm, 100 cm, 125 cm, 140 cm, 161 cm, 212 cm, and 244 cm above the base of the unit (Figures 3, 7, 8, and 10).

The upper beds are inaccessible and were described at a distance from the river level. Thicknesses are estimated based on the thickness of unit 10:

- Unit 11 (~50 cm): recessive, grey weathering becoming green-grey upsection, nodular limestone. Nodules become smaller in the upper 15 cm. The unit becomes increasingly recessive upwards, grading from the resistant nature of unit 10 to a deep recess beneath unit 12 (Figures 7 and 8).
- Unit 12 (~20 cm): resistant, beige weathering with reddish siderite staining, limestone in three beds of approximately 5, 10, and 5 cm thickness each (Figure 8).
- Unit 13 (~200 cm): recessive, grey to green-grey weathering, nodular limestone (Figure 8).
- Unit 14 (~100 cm): resistant, beige weathering, massive limestone with a distinct parting 15 to 20 cm above the base of the unit.

4.3 Sub-Cretaceous Unconformity

Where observed above unit 10, the limestone whitens below the erosional surface of the sub-Cretaceous unconformity. The face of the limestone is moderately siderite-stained. At one location above unit 10, from base to top, strata and sediments that overly the Devonian limestone include:

- 5 cm of brown shale;
- 10 cm of McMurray Formation oil sand containing clasts of Devonian limestone up to 5 cm in diameter;
- 25 cm of beige limestone that is nodular bedded to rubbly; and
- soil.

In other locations, the sub-Cretaceous unconformity has been eroded and the limestone is overlain by channel alluvium (Figure 7).

Where unit 14 is the topmost limestone, the eroded surface is overlain by a thin soil, as seen from the river bank.

4.4 Structure and Karst

Viewed at the outcrop, bedding orientation appears to be flat-lying. Viewed from across the river, the outcrop forms the western limb of a gentle anticline, in which the axis is located near the downstream end of the outcrop.

Figure 9. Close-up of the rudstone of unit 7 at the Mountain Rapids, north bank outcrop along the Athabasca River west of Fort McMurray. Examples of the fossils within the rudstone are outlined and labelled.

Figure 10. Close-up of unit 10 at the Mountain Rapids, north bank outcrop along the Athabasca River west of Fort McMurray.

Vertical joints occur every 5 to 15 m. These joints are vertical fractures up to several centimetres wide and are easily seen from a distance, as they are associated with slightly recessive, erosional indentations in the cliff face.

Although the top surface of the outcrop was eroded, pre-Cretaceous karstification was minimal and possibly restricted to nodules of limestone within a post-Devonian matrix and decalcification, as described above.

5 Mountain Rapids, South Bank, Athabasca River

5.1 Locality Description and Access

UTM Zone 12, 467617E, 6280913N (NAD83)

This outcrop is a limestone cliff recessed into the trees along the south bank of the river, opposite the north-bank outcrop at Mountain Rapids and slightly downstream of the rapids. Beds of this outcrop appear flat-lying and are equivalent to some of the upper units that are not accessible at the outcrop across the river.

This outcrop is easily accessible by jet boat, although submerged rocks can present hazards during low water level. The upper beds of the cliff can be reached through a short scramble through a slump at the upstream end of the outcrop.

5.2 Stratigraphy

This outcrop contains the upper beds (units 10 to 14) of the outcrop across the river on the north bank. The measurement of unit 13 was approximated because of slumping at the base of the unit and problems with accessibility. The base of the outcrop is covered by talus. From base to top, the outcrop contains:

- Units 10 through 12 (278 cm): recessive becoming resistant, beige weathering, beige-grey, tabular to wavy-bedded, argillaceous, *Thalassinoides*-burrowed, brachiopod floatstone in a wackestone matrix. The base is a grey, 3 cm thick, brachiopod rudstone, which occurs as a resistant bed protruding from the talus of the river bank. The top of the unit is covered with slumped nodules of the overlying unit (Figure 11);
- Unit 13 (200 cm): recessive, beige weathering, grey, *Thalassinoides*-burrowed, argillaceous lime mudstone to wackestone (Figure 11); and
- Unit 14 (165 cm): resistant, weathers beige and reddish-pink mottled, beige-grey, 1 to 5 cm nodular bedded, *Thalassinoides*-burrowed, argillaceous lime mudstone (Figures 11 and 12).

5.3 Sub-Cretaceous Unconformity

At this locality, the sub-Cretaceous unconformity has been eroded and the top of the outcrop is overlain by a thin layer of soil.

5.4 Structure and Karst

The beds of this outcrop are flat-lying. Joints occur every 5 to 10 m and, as in the outcrop on the north bank of the river, are easily recognized by a slight, erosional recession in the cliff face. No karst features were observed at this outcrop.

Figure 11. The outcrop at Mountain Rapids, south bank, along the Athabasca River west of Fort McMurray. The photograph is of the western end of the outcrop downstream of Mountain Rapids.

Figure 12. Unit 14 at the top of the Mountain Rapids, south bank outcrop along the Athabasca River west of Fort McMurray. The unit is 165 cm thick from lowermost exposure to the topmost exposed bed at this location.

6 *Thalassinoides* Outcrop

6.1 Locality Description and Access

UTM Zone 12, 463608E, 6279313N (NAD83)

This outcrop is striking in its mottled black, brown, red, orange, and tan beds (Figure 13). Differential weathering of *Thalassinoides* burrow networks resulted in the mottled colour on the surface of the rock, hence the informal name of the outcrop. The brightest colouration occurs where the limestone is proximal to a mound of oil sand, presumably the result of heating of the outcrop surface and the viscous flow of bitumen-rich McMurray Formation sand (see Cascade Falls outcrop, section 8, below).

Also conspicuous are the small caves and scallops associated with enlarged joints, which during high water level may be submerged (Figure 14). The outcrop extends into the water without a talus slope, so joints and caves can be traced beneath the water level.

This outcrop is accessible by jet boat, but abundant submerged rocks make landing difficult. At the time of the September 2011 visit, the rocks at water level were very slick; take care if walking along the river bank.

6.2 Stratigraphy

- Unit 12 (40 cm): resistant, grey weathering and fresh, tabular bedded, 1 to 3 cm nodular weathering, *Thalassinoides*-burrowed, argillaceous crinoid and brachiopod floatstone in a lime mudstone to wackestone matrix (Figure 14). The top of the unit contains a 5 cm thick, black to brown-grey, fragmental fossil wackestone with a capping hardground.
- Unit 13 (207 cm): recessive, weathers grey mottled with black, red, maroon and/or orange, grey, 1 to 3 cm nodular weathering, *Thalassinoides*-burrowed, argillaceous lime mudstone to wackestone (Figures 14 and 15). Nodules appear to form from the weathering of burrows. The lower 50 cm is slightly more resistant. The unit becomes increasingly argillaceous in the top 20 cm, where nodules become 1 cm and smaller in diameter.
- Unit 14 (115 cm): resistant, weathers grey mottled with red and beige, beige-yellow, up to 10 cm nodular bedded, *Thalassinoides*-burrowed lime mudstone to wackestone (Figure 15). The base is a beige weathering and fresh, variably 3 to 10 cm thick, crinoid, gastropod, and brachiopod rudstone in a wackestone matrix.

The uppermost unit was inaccessible and was observed from below:

- Unit 15 (~120 cm): recessive, light beige and nodular weathering, *Thalassinoides*-bioturbated, argillaceous limestone. The top of the unit is weathered and exposed or is covered by slumped oil sand (Figure 15).

6.3 Sub-Cretaceous Unconformity

Oil sand is slumped and previously flowed along the top of the limestone (Figures 15 and 16). Where the oil sand has been eroded from the contact, the mottled colouration is strong and reaches the highest variety of shades of orange, red, and black (Figure 13). The topmost limestone bed at the contact is often well-cemented and heavily stained orange to maroon, darkening upward to a very deep red and smooth texture on the top surface (Figure 17). Bitumen and McMurray Formation sand flowed into fractures, joints, and caves in the outcrop during a previous interval of heating (Figure 14).

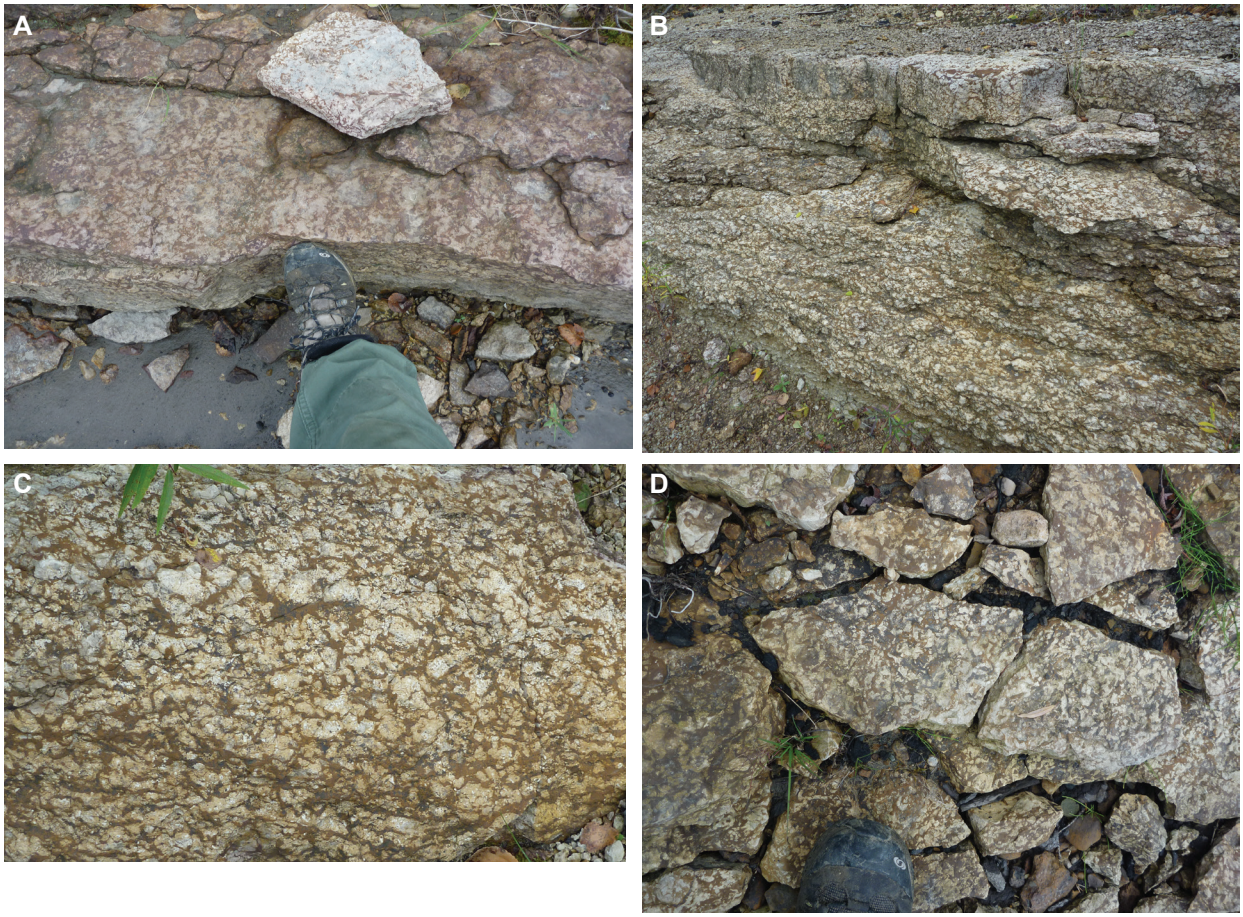

Figure 13. Variation in the mottled colouration arising from *Thalassinoides* bioturbation at the *Thalassinoides* outcrop along the Athabasca River west of Fort McMurray. The outcrop in figures A and B are in situ, figure C is float originating from the outcrop, and figure D shows in situ but fractured beds.

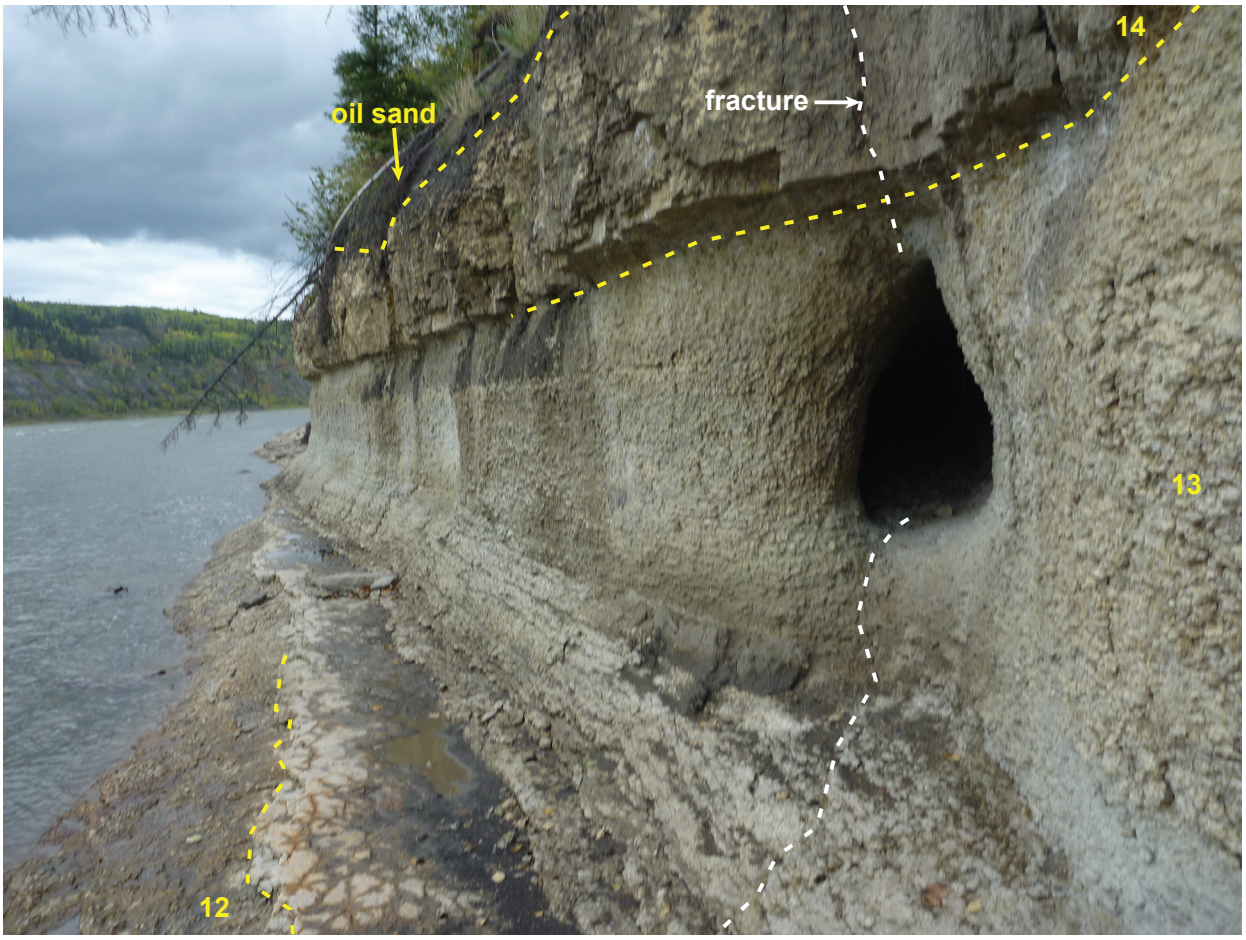

Figure 14. A small cave expanded along a vertical fracture (joint) in the *Thalassinoides* outcrop along the Athabasca River west of Fort McMurray. The cave is approximately 1 m deep. The top of the outcrop is overlain by McMurray Formation oil sand.

Figure 15. The measured section at the *Thalassinoides* outcrop along the Athabasca River west of Fort McMurray. Note the small mound of bitumen and McMurray Formation sand that previously flowed from the base of the fracture in the outcrop. McMurray Formation oil sand overlies the outcrop.

Figure 16. The contact between the Devonian Moberly Member and the overlying Cretaceous McMurray Formation oil sand at the *Thalassinoides* outcrop along the Athabasca River west of Fort McMurray. The oil sand was previously heated and flowed viscously over the limestone.

Figure 17. The exposed sub-Cretaceous unconformity (deep maroon beds) at the *Thalassinoides* outcrop along the Athabasca River west of Fort McMurray. The view is from above. The black object on the outcrop at the bottom of the photograph is the photographer's boot, for scale.

6.4 Structure and Karst

Vertical joints are common in this outcrop. Some are enlarged into shallow scallops or small caves, none of which are large enough for entrance (Figures 14 and 15).

7 Orange Stripe Outcrop

7.1 Locality Description and Access

UTM Zone 12, 456083E, 6274778N (NAD83)

This outcrop forms a limestone cliff along the north bank of the river below a sloping forest. The face and fractures of unit 10 give the outcrop an appearance of orange stripes on beige-grey rock, hence the informal name of the outcrop (Figure 18). A talus bank makes the outcrop accessible, but during the field visit, only the lower beds could be observed; the upper beds were out of reach.

Red-orange hematite and siderite stains on the outcrop are often associated with fractures and joints in the outcrop. Some float blocks on the river bank are also stained red-orange.

This outcrop can be accessed by jet boat, but submerged rocks during low water level make access difficult; engaging an experienced jet boat operator is advisable.

7.2 Stratigraphy

The base of the outcrop is covered by talus. From base to top, the outcrop contains:

- Unit 4 (5 cm exposed): resistant, dark grey weathering, grey, wavy bedded, crinoid, gastropod and brachiopod rudstone in a grainstone matrix (Figure 19).
- Units 5 and 6 (35 cm): recessive, green-grey weathering and fresh, calcareous shale up to 0.5 cm thick interbedded with grey weathering and fresh, argillaceous lime mudstone up to 1 cm thick. A 3 to 5 cm thick brachiopod and crinoid rudstone occurs at 12 cm above the base (Figure 19).
- Unit 7 (38 cm): resistant, beige weathering, brown-grey, massive, bioturbated brachiopod rudstone in a packstone matrix. The top 15 cm are slightly recessive, argillaceous, and tabular bedded and contain *Radiatrypa*, *Praewaagenoconcha*, athyride brachiopods and gastropods. Partings occur at 10 and 22 cm above the base (Figures 19 and 20).
- Unit 8, not observed.
- Unit 9 (43 cm): recessive, grey weathering and fresh, up to 2 cm tabular to slightly wavy-bedded, argillaceous lime mudstone with up to 0.5 cm thick, green-grey, calcareous shale partings. The thickness of interbeds decreases upwards to become millimetre-scale partings. Crinoid and brachiopod rudstone beds up to 4 cm thick occur in the lower half of the unit (Figures 19 and 20).
- Unit 10 (195 cm): resistant, beige weathering, beige-grey, *Thalassinoides*-burrowed, massive to bedded, gastropod and brachiopod floatstone to rudstone in a wackestone matrix (Figures 19 through 24). Gastropod, brachiopod, and crinoid rudstone beds occur at 20 cm and 100 cm below the top of the unit and are underlain by hardgrounds. *Thalassinoides* burrow networks terminate along firmground to hardground surfaces (Figures 21 and 22), which are usually overlain by slightly recessive limestone. High-resolution stratigraphy of this unit includes, from base to top:
  - 12 cm: rudstone of shingled brachiopod shells.
  - 8 cm: slightly recessive, argillaceous and bioturbated brachiopod floatstone.
  - 20 cm: nodular weathering, slightly argillaceous, *Thalassinoides*-burrowed brachiopod floatstone.

Figure 18. Photo of the vertical orange-stained stripes on the beige-grey Moberly Member at the Orange Stripe outcrop, north bank of the Athabasca River, west of Fort McMurray.

Figure 19. Units 4 through 11 at the Orange Stripe outcrop, Moberly Member, north bank of the Athabasca River, west of Fort McMurray.

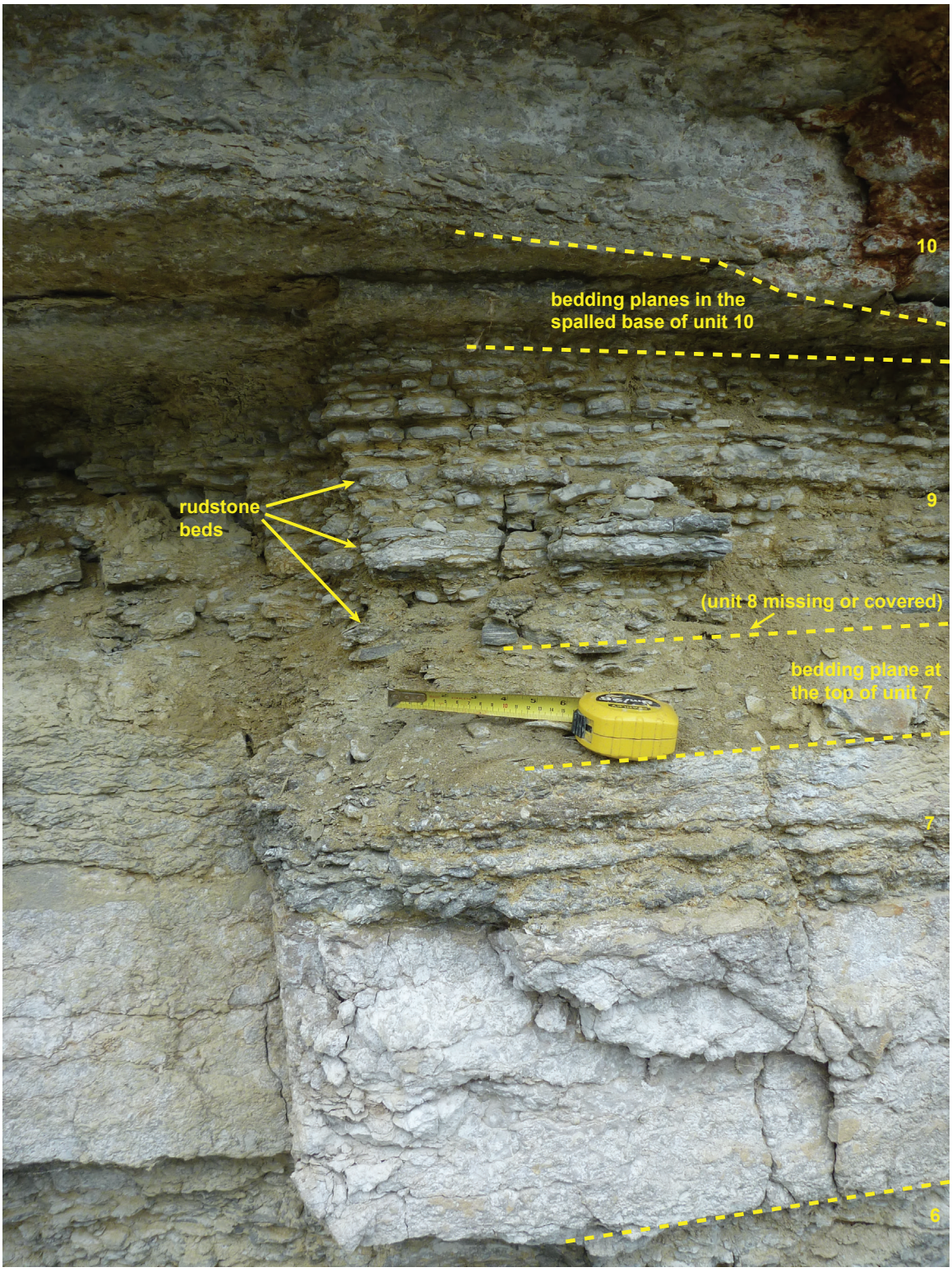

Figure 20. The top of unit 6 through the base of unit 10, Moberly Member, north bank of the Athabasca River, west of Fort McMurray. The thin shale of unit 8 was not observed at this outcrop.

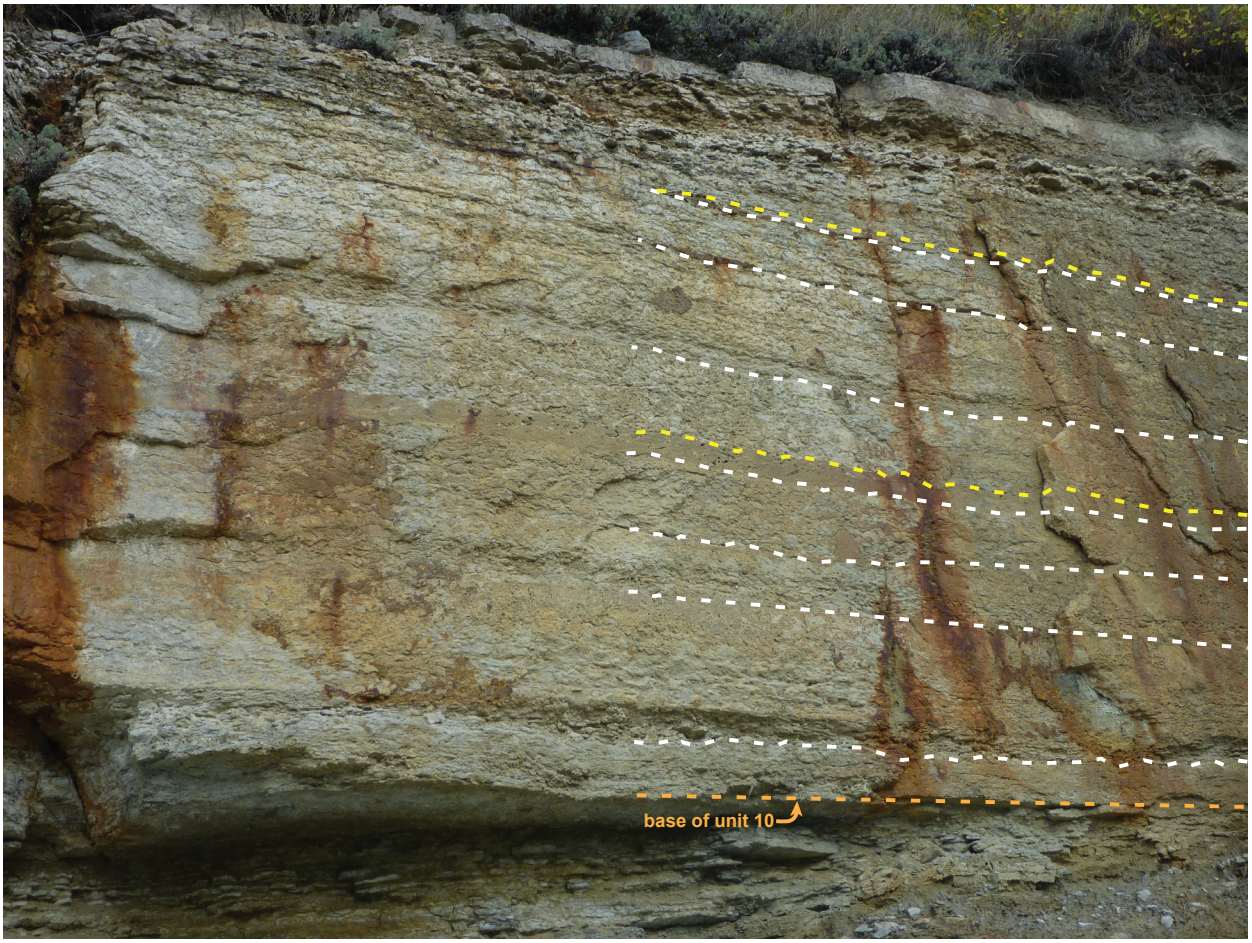

Figure 21. Unit 10 at the Orange Stripe outcrop, Moberly Member, north bank of the Athabasca River, west of Fort McMurray. White dashed lines are burrow termination surfaces and possible firmgrounds or hardgrounds. Yellow dashed lines are burrow termination surfaces and confirmed hardgrounds (evidence of boring, mineralization). The orange dashed line is the base of the unit.

Figure 22. Close-up of a hardground in unit 10, Orange Stripe outcrop, Moberly Member, north bank of the Athabasca River, west of Fort McMurray.

Figure 23. Stromatoporoid in subunit 10g, Orange Stripe outcrop, Moberly Member, north bank of the Athabasca River, west of Fort McMurray.

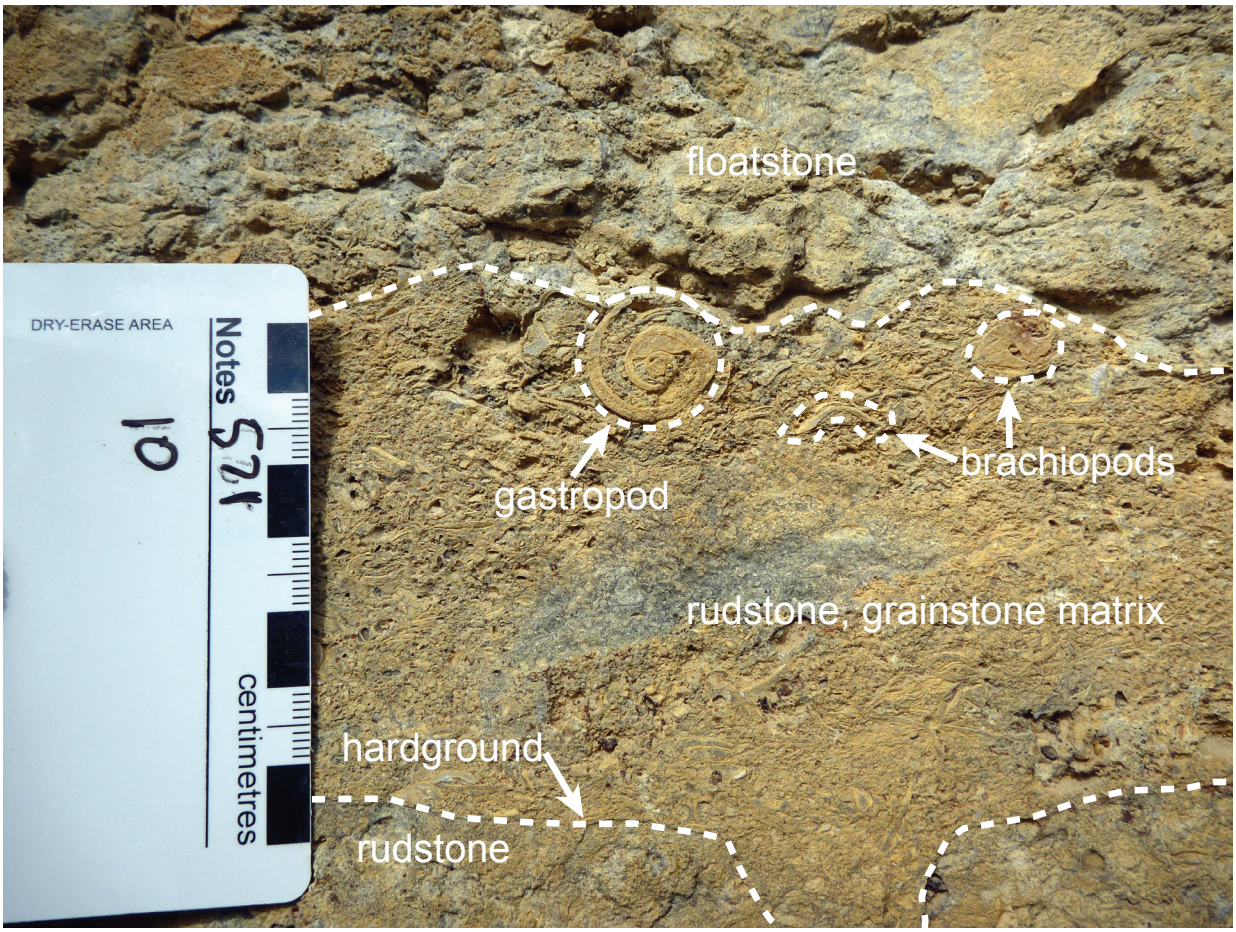

Figure 24. Unit 10h, Orange Stripe outcrop, Moberly Member, north bank of the Athabasca River, west of Fort McMurray.

- 8 cm: resistant, brachiopod floatstone to rudstone with a burrow network terminus and hardground at the top of the bed.
- 10 cm: nodular weathering, slightly argillaceous, *Thalassinoides*-burrowed brachiopod floatstone.
- 8 cm: resistant, brachiopod floatstone to rudstone with a burrow network terminus and hardground at the top of the bed.
- 23 cm: nodular weathering, slightly argillaceous, brachiopod, bulbous stromatoporoid, and gastropod rudstone with a hardground at the top of the bed (Figure 23).
- 10 cm: resistant, brachiopod, bulbous stromatoporoid, and gastropod rudstone in a grainstone matrix (Figure 24).
- 20 cm: nodular weathering, slightly argillaceous, *Thalassinoides*-burrowed brachiopod floatstone;
- 7 cm: resistant, brachiopod floatstone to rudstone with a burrow network terminus at the top of the bed.
- 28 cm: nodular weathering, slightly argillaceous, *Thalassinoides*-burrowed brachiopod floatstone.
- 5 cm: resistant, brachiopod floatstone to rudstone with a burrow network terminus at the top of the bed.

The overlying remainder of unit 10 could not be closely observed.

The following units were inaccessible, and could only be observed from the river bank:

- Unit 11 (~30 cm): recessive, grey becoming green-grey, nodular limestone. Nodules become smaller in the upper 20 cm (Figure 19).
- Unit 12 (~20 cm): resistant, massive, grey limestone with a parting approximately 8 cm above the base of the unit.

7.3 Sub-Cretaceous Unconformity

At the upstream end of the outcrop, units 7 and 8 are truncated by erosion. The outcrop is overlain by soil and dense forest, so the contact between the Devonian strata and the McMurray Formation was not observed.

7.4 Structure and Karst

The limestone surrounding joints and smaller fractures in unit 3 is orange to red with iron and siderite staining. Most fractures are filled with pyrite (Figure 25). Joints are vertical to near vertical.

8 Cascade Rapids, North Bank

UTM Zone 12, 454093E, 6274341N (NAD83)

8.1 Locality Description and Access

This outcrop forms the half-metre-high falls at Cascade Rapids and lines the banks of the river downstream of the rapids (Figures 26 and 27). On the north bank, the Moberly Member forms a wide bench when the water level is sufficiently low. On the south bank, the Moberly Member forms a vertical face at the river, but does not exceed 1 m in height.

Outcrops throughout the region often have a pinkish to maroon tint, which is distinct from the hematite and siderite rinds and stains that are associated with fractures and the pre-Cretaceous unconformity. At this outcrop, we examined a campfire ring, in which the limestone surface beneath and surrounding

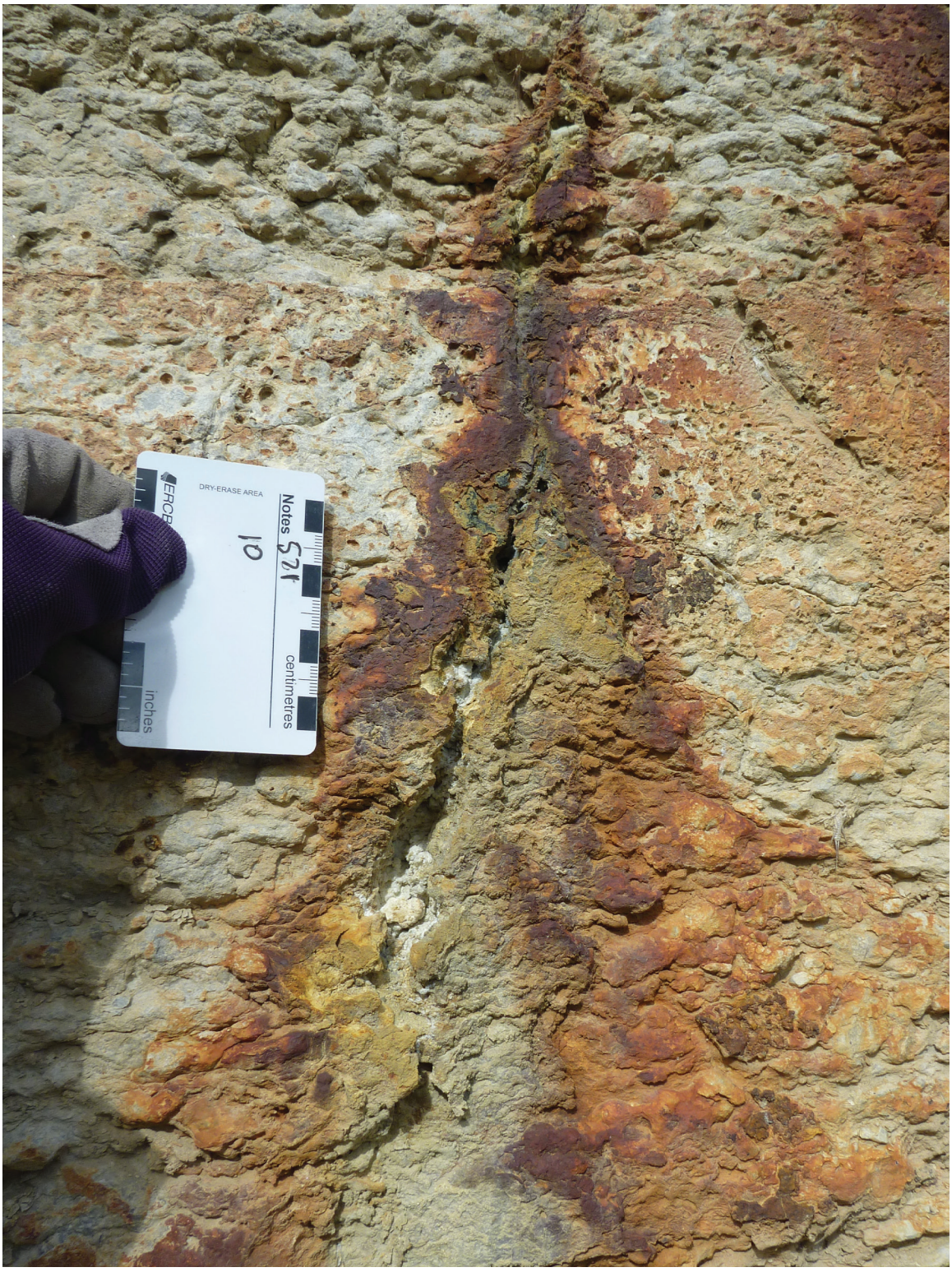

Figure 25. Pyrite fill in a fracture at the Orange Stripe outcrop, Moberly Member, north bank of the Athabasca River, west of Fort McMurray.

Figure 26. Cascade Rapids, flowing over the Moberly Member limestone, Athabasca River west of Fort McMurray.

Figure 27. Moberly Member, south bank of the Athabasca River, west of and adjacent to Cascade Rapids. View is downstream.

the fire ring was the same pinkish-red colour seen at other outcrops in the region. This pinkish-red tinge extended beneath the rock surface for at least a centimetre (further depth could not be tested) and extended out from the centre of the fire ring in a radius of approximately a half-metre. Burrow networks and fossils within this ring of pinkish-red colour were of a deeper red than the surrounding rock. The limestone, fossils, and burrows outside of the pinkish-red area were the typical greyish to beige colour of weathered Moberly Member limestone.

This outcrop is easily accessible by jet boat to the falls and either bank. Observations of the Moberly Member are best undertaken at the north bank, where access by helicopter on the wide bench of limestone is possible.

8.2 Stratigraphy

The falls at Cascade Rapids tumble over a limestone bed equivalent to unit 8 at the Mountain Rapids north bank locality. The south bank of the river, observed from the jet boat, contained beds equivalent to units 5 through 7, units 8 and 9, and the bottom of unit 10 (Figure 27). The south bank benched limestone contains unit 10 at the surface; units 8 and 9 can be seen in the surface water of the river. From base (observable depth in the river) to top, the limestone bench on the north bank contains:

- Units 8 and 9 (~20 cm; at and below water level during the time of measurement): recessive, blue-grey weathering, calcareous shale beds up to 1 cm thick interbedded with grey weathering and fresh, argillaceous lime mudstone up to 2 cm thick. The proportion of lime mudstone to shale is less than that of the Mountain Rapids north bank outcrop.
- Unit 10 (~50 cm; forming the limestone bench): resistant, grey-beige weathering, 10 to 20 cm bedded, bioturbated, crinoid, brachiopod and gastropod rudstone (Figures 28 and 29). Some of the beds have a grey, argillaceous crust that contains *Planolites* burrows (Figure 30).

8.3 Sub-Cretaceous Unconformity

The top of the outcrop is exposed as a bench in the north bank or under the falls; otherwise, the limestone is covered by soil and the sub-Cretaceous unconformity has been eroded.

8.4 Structure

Closed, vertical to near-vertical fractures cut through the entire outcrop. The dominant joint direction is northeast-southwest at 45°. The secondary joint trend is nearly east-west at 115°. Joints in the dominant trend are spaced every 50 to 75 cm.

9 Conclusion

Devonian outcrops along the Athabasca River west of Fort McMurray capture the lower Moberly Member of the Waterways Formation. Beds of these outcrops are generally argillaceous limestone and bioturbated, with greater evidence of *Thalassinoides* bioturbation in units 10 and higher than in the lower units. Unit 10, which here is a *Thalassinoides*-burrowed, brachiopod-rich floatstone to rudstone containing crinoids, gastropods, and sparse stromatoporoids, is likely stratigraphically equivalent to the biostromal unit 37 of Norris (1963) based on the presence of stromatoporoids in Norris's description and in unit 10 at the Mountain Rapids north bank locality, and at the water treatment plant outcrop in Fort McMurray (unit 14 of Schneider et al., 2013, Water Treatment Plant locality).

Figure 28. Wide bench created by the lower beds of unit 10, Cascade Rapids north bank, Athabasca River west of Fort McMurray. View is upstream. The rapids are a thin white line seen on the distal edge of the river.

Figure 29. Wide bench created by the lower beds of unit 10, Cascade Rapids north bank, Athabasca River west of Fort McMurray. View is downstream.

Figure 30. Top surface of a bed in unit 10, Cascade Rapids north bank, Athabasca River west of Fort McMurray. Note the burrow networks in the surface, best seen to the left of the boot where water has filled the burrows proximal to the puddle (brown). The fracture running from upper left to lower center of the photo follows the northeast-southwest trend.

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