Wabamun, Bakken-Equivalent Exshaw, and Banff Formations in Core, Cuttings, and Outcrops from Southern Alberta*

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Abstract

The Exshaw and lower Banff display a tripartite gamma ray character and lithologies similar to those of the stratigraphic equivalent Bakken in the Williston Basin and the Sappington in Montana, hence the name "Alberta (Basin) Bakken." The "Bakken" name holds promise of a ubiquitous (tight) oil play. The Alberta Bakken term was initially reserved for the shales of the Exshaw and Banff and the medial Exshaw dolomitic siltstone, but it has recently been expanded to include the underlying Stettler, Big Valley, and the overlying Banff formations.

The Stettler and Banff formations have historic production from vertical wells in the area. The best producer 10-30-008-23W4 has no core over the reservoir interval, but cuttings show 12 to 15m of porous micro-sucrosic dolomite reservoir in the Stettler and, in contrast, dense dolomitic siltstone with sporadic microporosity in the medial Exshaw siltstone. The 10-30 Stettler production of almost 250.000 barrels of oil since 1979 is used by industry for production forecasting (type curves) as a comparison to the Bakken. Cuttings and thin sections from the 10-30 "type Bakken producer" were compared in terms of lithology, thicknesses, and textures to surrounding wells and outcrops in the mountains. Outcrop and cores demonstrate that the Stettler reservoir is widespread yet not continuous.

Thus far, reservoir character of the Exshaw dolo-siltstone appears to compare poorly to the producing sweet spots of Bakken dolo-siltstone in the Williston Basin (6-9% Ø and 0.05 mD). This means that either the right facies has not been found (yet) or it does not exist in the Southern Alberta Basin.

Introduction

During the last several years, the "Alberta Bakken" of Zaitlin et al. (2010) (that we are displaying at the core conference) has received much attention, including major land sales, farm-ins, and horizontal drilling. The "Alberta Bakken" of southern Alberta has been expanded to "The

Alberta Bakken Petroleum System," to include the upper Stettler Formation and overlying Big Valley Formation of the Famennian Wabamun Group, the upper Famennian to lower Tournaisian Exshaw Formation, and the basal black-shale unit of the Lower Mississippian Banff Formation. The interval has been informally called the "Alberta Bakken" because the upper part of the succession (Exshaw and overlying black-shale unit of the Banff) collectively resembles the correlative upper Famennian to Lower Mississippian Bakken Formation in the Williston Basin region of southern Saskatchewan, southwestern Manitoba, North Dakota, and South Dakota (MacQueen and Sandberg, 1970). The arbitrary boundary separating the Exshaw and Bakken coincides with the Mesozoic expression of the Sweetgrass/ Bow Island Arch (Richards et al., 1994). The Exshaw also is equivalent to the Sappington Member of the Three Forks Formation in north-central Montana, and the arbitrary boundary separating the Exshaw and Sappington in that region lies along the Scapegoat-Bannatyne Anticline (Smith and Gilmour, 1979). The Exshaw and Bakken formations are underlain by either the Big Valley or the upper part of the underlying Stettler. The Sappington is underlain by the Trident and Logan Gulch members of the Three Forks Formation (Macqueen and Sandberg, 1970). Both the Sappington and Bakken are overlain by the Lodgepole Formation, which is lithologically and stratigraphically equivalent to most of the Banff Formation.

In the study area, the exploration history for the "Alberta Bakken" started in 2010. In contrast, in eastern Montana and North Dakota, the exploration history for the Bakken Formation commenced with the drilling of vertical wells through the formation, starting in the 1950s and followed with drilling into the upper Bakken black shale source rock in the late 1980s and early 1990s. Since 2000, the emphasis has been on horizontal drilling within the middle Bakken siltstone-sandstone member in the Williston Basin.

During the present study, we investigated the samples and cores from about 20 wells that penetrate the "Alberta Bakken", in southern Alberta between the Rocky Mountain Foothills and the Sweetgrass Arch. The study area extends from the Vulcan Low in the north (Twp 17 to 20) to the Canada-United States border in the south. The type well (10-30-008-23W4) for production analyses in the region produces from the upper part of the Stettler Formation immediately below the Big Valley Formation. Some early production (1953) from the Bakken play in the USA also occurred from immediately below the Bakken Formation from silty dolostone to dolomitic siltstone in the Three Forks Formation and the Sanish Sandstone (Carlson and Anderson, 1959).

We investigated the cuttings from the 10-30 well, the type well for production, and from several other boreholes and compared them with borehole cores from the study area and the Cordilleran outcrops of the units comprising the "Alberta Bakken". The purpose of the investigation was to compare thicknesses, facies, and microtextures between wells to determine if it is possible to relate those parameters to production and, furthermore, to determine the reservoir potential of the Exshaw siltstone member and components of the Alberta Bakken Petroleum System within the upper part of the underlying Wabamun Group.

Regional Geologic Setting

Deposition of the "Alberta Bakken" occurred on eastern margin of Montania and a tectonically active component of the western cratonic platform. The region lay north of the Carboniferous Central Montana Trough and east of the Antler Foreland Basin and its northern extension, the Prophet Trough (Figure 1). Deposition of the succession occurred on Ancestral North America during a time of transition from either a passive or relatively quiescent southwestern continental margin to one with an active contractional belt and ensialic arc magmatism (Richards et al., 2002, 1993). Whatever the underlying cause of the Famennian to Early Mississippian reorganization, it was in part coincident with the compressional Antler Orogeny of the western United States. Because of reactivation of the margin, many tectonic elements that prevailed during the Early Paleozoic were succeeded by elements that persisted through the Late Paleozoic. The Carboniferous tectonic features started to develop during Exshaw deposition in the latest Famennian, but were not clearly established until deposition of the overlying Mississippian Banff Formation and Rundle Group.

Early Famennian to Early Late Famennian Tectonic Elements

During most of the Famennian when the Wabamun Group was being deposited, the principal tectonic elements in the southwestern part of the Western Canada Sedimentary Basin (WCSB) were the cratonic platform, Peace River Arch, and Alberta Trough (Douglas et al., 1970; Morrow and Geldsetzer, 1988). A contractional belt that was episodically uplifted and magmatically active from the latest Devonian into the Early Mississippian was starting to develop along the southwestern side of the WCSB (Smith and Gehrels, 1992; Smith et al., 1993; Richards et al., 2002). The Famennian cratonic platform was a broad stable region dominated by shallow-marine environments, where carbonate-ramp deposition prevailed. Water depths increased southwestward, and slope environments were established along the southwestern edge of the cratonic platform and in the Alberta Trough. In the south, the cratonic platform was differentiated into the Alberta and Hay River shelves, separated by the Peace River Arch (Morrow and Geldsetzer, 1988).

A subaerially exposed topographically positive belt resulting from an early phase of the Cariboo Orogeny lay along the western side of the Alberta Trough. In the southern Cordillera, remnants of this positive belt are preserved in the pericratonic Kootenay Terrane and on the Windermere High of Reesor (1973) to the east. The Windermere High was a long-lived, northwest-trending Early Paleozoic feature that

In southernmost Canada and northern Montana, the Famennian expression of the western cratonic platform included a strongly positive area on the site of the Cambrian landmass Montania of Deiss (1941). The latter landmass, coincident with the southwestern part of the Medicine Hat Block (Ross and Stephenson 1989), extended westward to the southern margin of the Windermere High. On extensive parts of Montania, Tournaisian strata of the Banff Formation unconformably overlie either the Morro Member or the overlying lower Costigan Member of the Palliser Formation and their coeval correlatives in the Wabamun Group to the east. The presence of the unconformity and absence of the upper Costigan/Big Valley and overlying Exshaw suggests parts of Montania were at least episodically subaerially exposed into the early Tournaisian (Mississippian) as an island or islands (Figure 1).

Latest Famennian and Mississippian Tectonic Elements

During the latest Famennian and Mississippian, the principal tectonic elements along the northwest margin of ancestral North America and in the WCSB were the Prophet Trough, western rim of the Prophet Trough (includes the Cariboo Orogenic Belt and remnants of Windermere High), the Peace River Embayment, and cratonic platform, which included the intracratonic Williston Basin (Richards et al., 1993). The pericratonic Prophet Trough had a history dominated by extension, as indicated by the widespread occurrence of Carboniferous normal faults; however, the initial expression of the trough apparently developed in the foreland of an ensialic arc or continental margin volcanic-plutonic belt resulting largely from latest Devonian to Early Mississippian plate convergence and eastward-directed subduction (Richards et al., 1993; Ferri, 1997). Another important element was the extensional Slide Mountain Basin (represented by the Slide Mountain Terrane), which developed between the Mississippian expression of the western rim of Prophet Trough and a west-facing volcanic arc represented by the pericratonic Kootenay Terrane and the Quesnel Terrane of Wheeler et al. (1988). Most of the region where the Exshaw and its eastern correlatives in the Bakken Formation are preserved in southern Alberta and southeastern Saskatchewan was a drowned shelf developed on the vast carbonate ramp comprising the Wabamun Group and its correlatives in the Three Forks Group and Palliser Formation (Figure 2). During deposition of the Tournaisian to lower Viséan Banff Formation, the Canadian component of Montania and adjacent southern cratonic platform (Madison Shelf) subsided substantially and became occupied by relatively deep-water (below storm-wave base) slope and anoxic basin settings

Palliser Assemblage - Lithostratigraphy of Palliser Formation and Wabamun Group

The Famennian of the WCSB is a thick carbonate-dominated succession widely preserved on the Interior Platform from Manitoba into the southwestern District of Mackenzie and in the eastern Cordillera. The succession, which also extends into Montana, includes several formations, and their regional stratigraphy has commonly been discussed in terms of an assemblage called the "Palliser assemblage" (Morrow and Geldsetzer, 1988; Richards et al., 2009). Only the upper part of this succession, the upper Stettler Formation and overlying Big Valley Formation (Wonfor and Andrichuk, 1956) of the Wabamun Group are to be examined during the core conference. The purpose of the underlying discussion is to place these units into their regional stratigraphic and depositional contexts. The upper Stettler is a coeval correlative of the lower Costigan Member of the Palliser Formation, whereas the Big Valley is a coeval correlative of the upper transgressive unit of the Costigan. The Palliser assemblage generally overlies Frasnian strata and underlies the Banff assemblage (uppermost Famennian and Tournaisian) of Richards et al. (1994). In the Rocky Mountain Front Ranges of southern Alberta and toward the east, the assemblage is generally bounded by minor unconformities. The Palliser assemblage comprises a thick, lower T-R sequence that contains several subsequences (see Peterhänsel and Pratt, 2008) and is overlain by the initial transgressive deposits (Big Valley and upper Costigan) of a composite T-R sequence that contains the Devonian/Carboniferous boundary and includes the Exshaw Formation. Deposition started in the southwest with argillaceous carbonates, siltstone, and sandstone (Sassenach and Alexo formations) and expanded eastward onto the southern Alberta Shelf (Graminia Formation). In the northwest, these initial deposits started to onlap remnants of the Peace River Arch. Continued transgression, accompanied by carbonate and evaporite deposition formed a vast carbonate ramp that prograded westward and extended from Manitoba into District of Mackenzie.

Deposition on a ramp (Figure 3), rather than a platform, is indicated by the lack of either extensive reefs or grainstone belts characteristic of the shelf margin on platforms. On the ramp, red beds, with evaporites and paleosols, were deposited in the east (Torquay Formation of Saskatchewan). An evaporite belt lay in southern Alberta (Stettler Formation), and a broad central belt of carbonates and subordinate evaporites extended westward to the edge of the cratonic platform and into the Alberta Trough (Palliser, Wabamun and Stettler formations).

Palliser Formation

Regional Stratigraphy

Carbonate-ramp lithofacies of the Famennian Palliser Formation (Beach, 1943) are widely distributed in the southern and central Rocky Mountains of western Canada and are locally exposed in the western Rocky Mountain Foothills of southern Alberta. East of the Rocky

Mountains and southwestern foothills of Alberta, subsurface correlatives of the Palliser are included in the Wabamun Group. In the Bow Valley region west of Calgary, the thickness of the Palliser ranges from 300 m at Jura Creek by Exshaw to nearly 400 m at Mount Rundle near Banff. At its type section on the north side of Lake Minnewanka at Devils Gap, the Palliser is about 255 m thick (Meijer Drees and Johnston, 1994). In the eastern Rocky Mountains of southwestern Alberta, the Palliser Formation generally overlies the recessive siltstone and silty dolostone of the lower Famennian Alexo Formation. The Palliser-Alexo boundary is commonly sharp and may be locally erosional. Most of the Palliser Formation of southwestern Alberta passes northeastward into the Stettler Formation but the uppermost Palliser (upper Costigan Member) passes northeastward into the Big Valley Formation. The Palliser Formation is abruptly and generally unconformably overlain by the Exshaw Formation in most of the southern Rocky Mountains, but on Montania in southwest Alberta and southeast British Columbia, the Exshaw is only locally preserved and the Lower Mississippian Banff Formation unconformably overlies the Palliser in most areas.

Members

De Wit and McLaren (1950) divided the Palliser into the Morro and overlying Costigan members (Figure 2). The Morrow is a thick-bedded cliff former dominated by burrow-mottled lime wackestone and packstone of neritic origin, whereas the lower Costigan is dominated by laminated to medium-bedded, peritidal dolostone and subordinate limestone. The Morro and most of the Costigan are coeval correlatives of the subsurface Stettler Formation. However, the upper 5.8 to 8.1 meters of the type Costigan on the north side of Lake Minnewanka (Meijer Drees and Johnston, 1994) is an unconformity-based, skeletal limestone unit that is correlative with the subsurface Big Valley Formation and is widely exposed in the Front Ranges of southwestern Alberta (Richards et al., 2002, Johnston et al., 2010).

Morro Member

The Morro Member, dominated by burrow-mottled lime wackestone and packstone of neritic origin, is 220-m thick at its type section on the north side of Lake Minnewanka at Devils Gap (Meijer Drees and Johnston, 1994). At its stratotype, the member comprises two main units. The lower one (34.44 m thick) is dominated by medium to dark grey dolostone that is either massive or locally burrow-mottled, but breccias and beds showing laminae are locally present. Most of the well bedded upper part of the member (185.9 m thick at the stratotype) is dominated by medium- to thick-bedded, burrow-mottled, intraclast-peloid lime wackestone and packstone locally containing abundant brachiopods and pelmatozoan ossicles. Small carbonate mounds containing tabular stromatoporoids are locally present in the upper part of the member. Toward the southwest (basinward), the lower dolostone-dominated unit of the Morro thins and passes into the upper unit.

Lower Costigan Member

The lower part of the Costigan Member is thinner bedded and less resistant than the Morro Member and comprises several thin T-R sequences. Lower parts of the sequences in the eastern Front Ranges generally overlie undulatory erosion surfaces and commonly comprise fossiliferous, intraclast-peloid lime wackestone to grainstone. Upper parts of most sequences in the east include fenestral cryptalgal boundstone, stromatolitic cryptalgal boundstone, algal wackestone, carbonate breccias, and planar- to wavy-laminated dolostone. Between the eastern and western Front Ranges, a basinward facies change from eastern peritidal lithofacies to open-marine neritic facies occurs in the lower Costigan. Western occurrences of the lower Costigan comprise lime floatstone and skeletal lime wackestone to packstone containing abundant brachiopods and pelmatozoan ossicles. The basal deposits in the sharp-based TR sequences of the eastern Costigan record transgressions and deposition in shallow-neritic to intertidal environments (Richards and Higgins, 1988). Overlying lithofacies in the sequences record minor regressions and deposition in lagoons and intertidal to supratidal, restricted, ramp environments.

Upper Costigan Member

In the eastern Front Ranges of southwest Alberta, the upper Costigan Member is a thin transgressive unit that overlies an undulatory unconformity and comprises dolomitic, cherty, skeletal lime wackestone and packstone, with subordinate lime rudstone, grainstone, and dolostone (Richards and Higgins, 1988; Johnston et al., 2010), showing 10 to 20 cm or more of erosional relief.. Marine erosion (transgressive ravinement), preceded by regional subaerial exposure, produced the unconformity. The upper Costigan commonly fines upward and shows evidence of bioturbation and common development of bored hard grounds. The main allochems are pelmatozoan ossicles, bryozoans, and intraclasts, but scattered brachiopods and large nautiloids are moderately common at some localities. The characteristics of the deposits record sedimentation in shoreline to neritic shelf (middle ramp) settings. The upper Costigan represents the initial transgressive deposits of a composite T-R sequence that contains the Devonian/Carboniferous boundary and includes the Big Valley and overlying Exshaw Formation (Richards et al., 2002).

Stettler Formation

The upper Famennian Stettler Formation of Wonfor and Andrichuk (1956) contains the main producing horizon in the "Alberta Bakken play" discussed by Zaitlin et al. (2010). In the study area, the Stettler overlies the Crowfoot Formation, which spans the Frasnian-Famennian boundary and is unconformably overlain by the Famennian Big Valley Formation in the southeast (see Figure 5C) and the Exshaw Formation in the west (Figure 5D). Toward the Sweetgrass Arch and the Saskatchewan border, the Stettler passes into the Torquay Formation. Halbertsma and Meijer Drees (1987) divided the Stettler Formation in central Alberta into several informal members, and these were correlated into southern Alberta by Halbertsma (1994). The upper Stettler in the study area appears to be assignable to the upper part of his Cardinal Lake Member.

The producing horizon in the upper Stettler is about 2 to 15 meters thick and dominated by thin-bedded to planar- and wavy-laminated dolostone and limestone of restricted, ramp aspect (Figure 4C). Evaporite solution - collapse breccias that resulted from dissolution of evaporites during periods of late Famennian subaerial exposure and erosion prior to deposition of the Big Valley and Exshaw are commonly present (see Figure 11). In most cores, fine- to medium-crystalline sucrosic dolostone predominates (see Figures 8 and 10), but oncolitic algal lime wackestone and packstone are commonly present in the upper part of the interval. The thin-bedded to laminated productive horizon gradationally overlies the anhydrite-dominated lithofacies that constitute most of the Stettler. Underlying deposits in Stettler are dominated by nodular anhydrite, but the nodules are commonly encased in laminated dolostone of peritidal aspect. The upper Stettler is generally slightly more silty and argillaceous than the underlying anhydrite-dominant component of the formation, and on gamma-ray logs it commonly displays a more serrated log profile.

Big Valley Formation

The Famennian Big Valley Formation of the Wabamun Group is a thin but widely developed unit of marine carbonates and shale that is correlative with the upper Costigan Member and extends from southeastern Saskatchewan to the north side of the Peace River Arch in northwestern Alberta (Halbertsma, 1994). It is, however, absent in a broad northwest-trending belt on the western part of the Interior Platform in southwestern Alberta and in the easternmost Cordillera of southwestern Alberta from Montana to about township 31 north (Johnston et al., 2010). The unit also extends into central Montana but is called the Trident Member of the Three Forks Formation south of the border (Sandberg et al., 1988). At its type section in the Gulf Rumsey No. 6-30 borehole at 6-30-033-20W4 near the town of Big Valley in southern Alberta, the Big Valley is 13.6 m thick (Wonfor and Andrichuk, 1956). The unit attains a maximum thickness of about 30 m at a depocentre in the vicinity of its type section and another section in southwestern Saskatchewan. The formation occurs in most of the eastern part of the study area east of about range 20W5 but is generally less than 3 m thick and thickens eastward. The Big Valley and its equivalents are absent on most of Montania in the eastern Cordillera.

The Big Valley unconformably overlies the peritidal carbonates and evaporites of the upper Stettler Formation and is unconformably overlain by the black-shale member of the upper Famennian to lower Tournaisian Exshaw Formation. A thin (2 to 10 cm thick) carbonate lithoclast breccia is generally present at the Stettler-Big Valley (Figure 5C) and a thin (2 to 10 cm thick) bed of pyritic and phosphatic conglomeratic sandstone to breccia constitutes the base of the overlying Exshaw (Figure 5B,D). In the study area greenish-grey, slightly dolomitic skeletal limestone with subordinate laminae and thin beds of calcareous shale to marlstone and mudstone constitute the Big Valley Formation (Figures 4D and 5B). The proportions of shale, marlstone, and mudstone tend to decrease upward and westward, whereas that of clean limestone increases. The formation is thin- to medium-bedded, with nodular and lenticular bedding being common. Skeletal and peloid-skeletal lime rudstone and floatstone grading into lime wackestone and packstone are the predominant limestones, but beds of peloid-skeletal grainstone occur, and the limestone tends to become more texturally mature toward the formation's top. Crinoid ossicles and brachiopods are the main allochems; other major components are peloids, oncolites, bryozoans, and calcareous algae. Much of the limestone and marlstone is conspicuously (stylo)nodular, with nodules being encased by argillaceous laminae. Small-scale cross laminae are the most common primary sedimentary structures. The poorly sorted nature of the Big Valley, the presence of abundant relatively complete macrofossils, and common presence of abundant oncolites and calcareous algae indicates most of the unit was deposited in low-energy neritic settings that were below fair-weather wave base but within the photic zone. Cross-laminated deposits in its lower part and grainstone near the top suggest deposition above fair weather wave base but in relatively low-energy shelf settings. Overall, the Big Valley records a regional transgression followed by a short-lived regression prior to the major deepening recorded by the overlying lower Exshaw. The regression is recorded by upward shallowing at some localities, westward truncation of the Big Valley below the Exshaw of the study area, and the common presence of a breccia to sandy conglomeratic lag in the basal Exshaw (Richards et al., 2002, p. 172-173).

Lithostratigraphy of Exshaw Formation

Distribution and Thickness

The upper Famennian to lower Tournaisian Exshaw Formation (Warren, 1937; Macqueen and Sandberg, 1970), comprising black shale and chert conformably overlain by silty dolostone, siltstone, sandstone and limestone, occurs in most of the western Interior Plains from southern Alberta into the southwestern District of Mackenzie. It also extends into central Montana but becomes called the "Sappington Member" of the Three Forks Formation south of the Scapegoat-Bannatyne Anticline at about 48°N (Macqueen and Sandberg, 1970; Sandberg et al., 1988). In the eastern Cordillera, it is generally present from 49°00'N to 52°30'N, but from 52°30'N into east-central British Columbia, it occurs only locally because of uplift and subaerial erosion prior to deposition of the overlying Tournaisian Banff Formation (Richards et al., 1994; Savoy et al., 1999).

The Exshaw Formation is equivalent to, and was deposited contemporaneously with, the lower and middle members of the Bakken Formation, widely preserved in the Williston Basin region east of the Sweetgrass Arch. The Exshaw differs from the Bakken by lacking the upper blackshale member of the latter. The dark grey- to black-shale unit that overlies the upper member of the Exshaw in the study area is included in the Banff Formation. East of the Sweetgrass Arch, the Bakken is overlain by the Mississippian Lodgepole Formation, a correlative of the Banff.

The Exshaw, 47 m thick in the Rocky Mountain Front Ranges at its stratotype near Exshaw Alberta (Richards and Higgins, 1988), is generally from 7 to 50 m thick but is commonly less than 2 m thick in the study area and elsewhere on both the cratonic platform and in the eastern Cordillera. The formation attains its greatest thickness at a depocentre near the type section and at a second one in the southeastern part of the Peace River Embayment. Numerous local differences in thickness occur and resulted from syndepositional block faulting, post-depositional erosion prior to deposition of the Banff Formation (Caplan and Bustin, 1998), and subsidence related to evaporite dissolution in underlying Devonian formations. In the study area, the Exshaw thickens toward the east and the Sweetgrass Arch.

In most areas, including southern Alberta, the Exshaw disconformably overlies the upper Famennian Palliser Formation and Wabamun Group (Macqueen and Sandberg, 1970; Caplan and Bustin, 1998; Richards et al., 2002), but its basal contact is at least locally conformable in the Rocky Mountains of east-central British Columbia (Richards and Higgins, 1988; Richards et al., 2002) and is gradational over extensive areas in the Peace River Embayment (Johnston and Meijer Drees, 1993). The disconformity is indicated by the common occurrence of sedimentary breccias and conglomeratic sandstone lying on the sharp undulatory basal contact of the Exshaw. Widespread erosion prior to Exshaw deposition is also recorded by: sub-Exshaw and sub-Bakken westward beveling of the Big Valley Formation from western Saskatchewan (Christopher, 1961) to western Alberta, the widespread presence of phosphatic breccias and conglomeratic sandstone lag deposits at the base of the Bakken Formation, the varied age of deposits immediately below the Exshaw (Meijer Drees and Johnston, 1996; Savoy et al., 1999; Johnston et al., 2010) and the local presence of hard grounds below the Exshaw.

At its stratotype and at numerous other localities in the southern Canadian Rocky Mountains, the formation disconformably overlies neritic ramp carbonates of the upper Costigan Member of the Palliser Formation. That disconformity appears to be a relatively minor one resulting largely from submarine erosion (Richards and Higgins, 1988; Richards et al., 2002) during a major flooding event. However, over an extensive region on the western part of the interior platform and on Montania in the eastern Cordillera, such as at the Crowsnest Lake section, the upper Costigan and its equivalent, the Big Valley Formation, are absent, and the Exshaw unconformably overlies older strata, such as the Morro Member of the Palliser and upper Cardinal Lake Member of the Stettler Formation. At the latter localities, a substantial hiatus spanning several conodont zones is noted, and subaerial exposure was likely.

Throughout the WCSB, the Exshaw is overlain by shale and carbonates of the Tournaisian Banff Formation (Macqueen and Sandberg, 1970; Savoy et al., 1999). As shown on the regional cross sections of Richards et al. (1994) and on the correlation chart used by Richards et al., (2002), the nature and biostratigraphic position of the Exshaw-Banff contact is quite variable. On Montania in the western part of the study area the Exshaw occurs as thin erosional remnants below the Banff (Figure1). North of Montania in the foothills and Rocky Mountains of western Alberta, the contact is abrupt and erosional at many eastern localities but becomes gradational west of the eastern Front Ranges. On the cratonic platform of the study area, the contact is also erosional, but in the Interior Plains of central Alberta (north of study area), the Exshaw-Banff contact is commonly gradational and difficult to pick in the subsurface because the upper member of the Exshaw is not typically developed. At locations where the Exshaw-Banff contact is unconformable, a thin (2 to 5 cm thick) conglomeratic and phosphatic sandstone unit, resembling that of the basal Exshaw, is commonly present at the base of the Banff and is generally overlain by a thin, dark grey to black shale unit resembling the upper Bakken Formation.

Members of Exshaw Formation

From the Peace River Embayment southward, the Exshaw generally comprises a lower, shale- and chert-dominated member gradationally overlain by an upper member comprising silty to sandy carbonates with subordinate dolomitic to calcareous siltstone, sandstone, and shale. However, the upper member is either not typically developed (Figure 3 of Meijer Drees and Johnston, 1996; column 2 in Figure 2 of Richards et al., 2002) or has been removed by pre-Banff erosion over extensive areas on the Interior Platform of central Alberta (Caplan and Bustin, 1998; Johnston et al., 2010). At the Exshaw type section on Jura Creek, the lower shale-dominated member is 9.3 m thick, and the upper member is 37.5 m thick (Richards et al., 2002).

Lower Member

Three rock units constitute the lower member of the Exshaw Formation at its type section and are extensively developed from southern Alberta into the Peace River Embayment. At the type section, the lower member comprises a 1- to 6-cm-thick, basal bed of conglomeratic sandstone to breccia; a 6.9 m thick middle interval of noncalcareous to slightly calcareous, brownish-black, siliceous shale and chert; and an upper 2.4-mthick unit of calcareous brownish-black fossiliferous shale. The upper calcareous to fossiliferous shale unit is somewhat less widely developed than the lower siliceous shale and grades into dark-grey to greenish-grey calcareous and noncalcareous shale in much of the subsurface east of the Rocky Mountains. In the Crowsnest Lake section the upper shale unit appears to constitute all but the basal 17 cm of the lower member. Crystal tuff, bentonite and associated arkosic sandstone are widely preserved in this member but are most abundant in the siliceous black-shale unit. Deposits of the lower member, particularly those of the siliceous shale and chert unit, are characterized by high levels of radioactivity as recorded by gamma-ray logs from borehole sections. The black siliceous shale and associated chert in the lower member of the Exshaw, and its correlative in the Bakken Formation, record deposition in relatively deep water basin and drowned-shelf settings (Savoy, 1992; Richards et al 2002). Deposition of the lower member occurred in the anaerobic to dysaerobic zones and generally below storm wave base, but probably at water depths of less than 300 m (Richards et al., 2002; Caplan and Bustin, 1998).

Upper Member

Silty fine- to medium-crystalline dolostone with subordinate dolomitic, sandy siltstone and silty to argillaceous lime mudstone constitute most of the upper Exshaw from southern Alberta into the Peace River Embayment of east-central British Columbia. Oolitic lime grainstone and cross-laminated sandstone deposits are extensively preserved in the upper part of this member in the southeastern part of the Peace River Embayment. In the Rocky Mountains of east-central British Columbia, the upper member is dominated by volcanic arkose but contains beds of tuffaceous shale and sandy skeletal lime grainstone and packstone.

In the Rocky Mountains of southwestern Alberta, primary sedimentary structures other than subplanar bedding and hummocky cross stratification are rare in the medium- to thick-bedded upper member. To the east, small- to medium-scale cross-laminae are common in exposures at some foothills localities. Additionally, some core from the upper Exshaw of southeastern Peace River Embayment shows horizontal stratification of probable beach origin and abundant small- to medium-scale wave- and current-formed cross laminae. The trace fossils *Scalarituba* sp., *Helminthopsis* sp. and *Helminthoidea* sp. are conspicuous in the upper member at most outcrops in the southern Rocky Mountains and in some core from subsurface sections in the study area. Scattered macrofossils (mainly brachiopods and pelmatozoan ossicles) are generally present but seldom abundant.

The upper Exshaw records shallowing, regression, and deposition in aerobic to dysaerobic environments at moderate- to shallow-water depths (Richards and Higgins, 1988; Savoy, 1992). In the southern Rockies and the study area, most of this member was probably deposited below storm wave base in middle- to inner-shelf settings. Such deposition is suggested by the fine-grained, dark-coloured deposits, the presence of a trace fossil assemblage dominated by grazing traces, and the apparent absence of wave- and current-formed structures. Components of the upper member in the foothills and southeastern part of the Peace River Embayment region were deposited in shallow-marine environments (above fair-weather wave base to intertidal) as indicated by the local presence of ooid and skeletal lime grainstone, horizontally stratified sandstone, and small- to medium-scale cross laminae of wave- and storm origin (Richards et al., 2002; Caplan and Bustin, 1998)

Sequence Stratigraphy

The Exshaw Formation constitutes most of a regionally developed composite T-R sequence called the Exshaw-Bakken sequence by Richards (1989) and Richards et al. (2002), which includes the upper transgressive unit of the Costigan Member and its subsurface correlative, the Big Valley Formation. Over wide areas, the sequence contains two higher order T-R sequences: 1) the Big Valley / upper Costigan and 2) the Exshaw. Over extensive areas of the WCSB, the Big Valley / upper Costigan interval records a significant regression and period of erosion prior to the transgression that resulted in deposition of the lower Exshaw (Richards et al., 2002). Where the contact between the Big Valley / upper Costigan and the Exshaw is gradational (Rockies of east-central British Columbia and the southern part of the Peace River Embayment) evidence for a regression subsequent to Big Valley deposition is lacking, and the transgression that started with deposition of the Big Valley culminated during deposition of the lower Exshaw. In parts of the WCSB that lack the Big Valley and upper Costigan, the Exshaw-Bakken sequence is represented by the Exshaw only.

Comparison of Cuttings, Core, and Outcrop in Relation to Stratigraphy, Depositional Facies, and Production

Bakken, Exshaw, and Sappington

Within the Alberta Bakken Petroleum System, the upper part of the Stettler Formation has the best potential for hydrocarbon reservoirs, and they are of a conventional nature. The overlying limestone-dominant Big Valley Formation has negligible potential but the dolomitic siltstone unit of the Exshaw Formation appears to have some unproven potential as an unconventional play. The upper Exshaw dolo-siltstone is, however, a relatively poor target because in the east it is thin (Johnston et. al., 2010), and it has very low levels of porosity and permeability. In contrast, most of the correlative middle member of the Bakken Formation in the Williston Basin region of southern Canada and the northern USA is a prolific producer from both conventional and unconventional reservoirs. The reservoir lithofacies in the middle Bakken varies from a conventional Darcy-permeable sandstone play in Saskatchewan and Manitoba to a micro-Darcy unconventional play in eastern Montana and the central part of the Williston Basin in North Dakota (Walker et al., 2006). The reservoir character of the unconventional Bakken play of North Dakota and eastern Montana pale in comparison to the ubiquitously highly porous and permeable siltstones and sandstones in the Bakken of Saskatchewan and Manitoba, but it obviously is a commercially viable target. However, the 6 to 9% of visible porosity and 0.05- 0.07 millidarcys of permeability in the unconventional play in Montana and western North Dakota compare favorably to the barely visible microporosity in the dolomitic siltstone of the upper Exshaw. The contribution of the two shales to Bakken production in Montana and Dakota is not known, but rumored to be 20% (Sonnenberg, 2010).

The 10-30-008-23W4 Type Well

The cuttings of the 10-30-008-23W4 well, the best producer in the Alberta Bakken play were investigated (Figure 6). This well had a three-month initial production of 348 bbl/day and has produced 250,000 barrels of oil since 1979. The production of 10-30 is used to construct "a type production curve" for comparison to other wells in the Bakken. In this type well, the Exshaw siltstone member is a tightly cemented mixture of pyrite, dolomite, and detrital quartz and feldspar. During drilling, the siltstone chips from the type well broke flat with low surface relief, which is a telltale sign that the rock contains few mechanical discontinuities such as pores (Figure 7); 2208-2211m sample vial). A low value of microporosity is sporadically observed between the silt-size particles in a small proportion of the cuttings. A substantially more porous zone is present in the upper part of the underlying Stettler Formation, as revealed by a cursory look at a tray of vials containing cuttings from the "Alberta Bakken" interval in the type well. The cuttings show a brown-stained zone in the vials from the depths of 2225 and 2240m (Figure 6). The brown zone (about 15m thick) consists of relatively pure, finely crystalline, porous dolomite (Figure 8). In contrast to samples from the overlying Exshaw siltstone, the dolomite possesses 10-15% visible porosity and good matrix permeability (estimated at 1-50millidarcys). Additional fractures, although not observed in samples from the dolostone, could improve on those values. Thin sections made from the cuttings derived from the Stettler interval (red dots on vials in Figure 6) demonstrate that ghosts of fine- to medium-grained peloidal grainstone were preserved during transformation from limestone to sucrosic dolostone (Figures 9 and 10). The sucrosic dolostone from the upper Stettler in the 10-30-008-23W4 borehole generally shows a larger crystal size than that typical of Archie IIA micro-sucrosic dolomudstones (2-10 m) observed in laminated peritidal dolomudstones in core from other wells in the play. The 10-30 peloidal dolograinstones were likely derived from a higher energy facies then the laminated dolomudstones that predominate in the interval. Variable amounts of anhydrite cement may occlude porosity (Figure 10B) and increase in volume toward the underlying anhydrite-dominated component of the Stettler.

Comparison of Cuttings to Core and Outcrop

At Turtle Mountain, surface location 08-25-007-04W5, in the eastern Rocky Mountain Front Ranges about 160km or 11 Townships to the west of the type producer 10-30 well, an outcrop of the Famennian Palliser Formation, overlies a splay of the Turtle Mountain thrust and underlies a continuous succession of relatively undeformed strata extending from the lower Banff Formation through the Rundle Group and into the Pennsylvanian. The upper Palliser shows intraclast breccia, tepee structures and planar-laminated to cross-laminated dolostone similar to that described from the type section of the lower Costigan Member of the Palliser on the north side of Lake Minnewanka by Meijer Drees and Johnston, (1993, 1994). As stated above, the lithofacies in the lower Costigan differ substantially from the skeletal wackestone to floatstone of the upper Costigan and its coeval correlative, the limestone-dominated Big Valley Formation of Wonfor and Andrichuk (1956). Similar to the cuttings in the 10-30 well, the outcrop samples show the presence of 10-15% porosity and millidarcy permeability. Micropermeametry on suitable surfaces yielded millidarcys of permeability (Monahan 2010, personal communication), which match the empirical values of permeability for the observed 100-200 m crystal size at the given porosity Lucia (1983). Furthermore, when using the white card technique (Dravis, 1991), fine- and medium-size peloids stand-out despite complete dolomitization (Figure 9B, from Langenberg and Hartel, 2010). The two photomicrographs in Figure 9 were taken at the same magnification and show similar size peloidal ghosts in completely recrystallized dolostone. A low porous domain was chosen in order to observe the original peloidal grainstone fabric (Figure 9B). This porous dolomite texture, although obliterated in places by shear associated with thrusting, has been observed over a distance of about 500 meters in more or less continuous outcrop.

In contrast, the 06-30 core, located in the same township approximately 500m away from the 10-30, shows 25m of restricted dolostones to limestones, above the lower Stettler anhydrites. Most of the core is in an unfavorable reservoir facies, like evaporite solution breccias (Figure 11) and restricted but nondolomitized lime mudstones. The oil stained reservoir has mostly developed in a more restricted peritidal dolomudstone in which, at certain levels, anhydrite cement has occluded the porosity and decimated permeability. As far as it is feasible to compare core to cuttings in variable carbonates, the 06-30 core compares poorly to the reservoir character of the nearby 10-30 cuttings.

The best reservoir is developed in fine- to medium-grained dolomitize, "clean," peloidal grainstones (Figures 8, 9, and 10C,D). Laminated, peritidal, restricted, microcrystalline dolomudstones, wackestones, and packstones are porous but less permeable (Figure 10A,B), and intraclast breccias, silty argillaceous evaporite-solution collapse breccias, undolomitized restricted lime mudstones and cemented lime grainstones all make poor reservoirs. Anhydrite cementation obviously ruins the reservoir, and evaporite dissolution or meteoric leaching of exposed carbonates *may* improve the reservoir. The reservoir of the upper Stettler has developed in few specific carbonate facies, and is inhomogeneous on a variety of scales. The reservoir is widespread because it can be observed over distances of 100s of kilometers in the mountains and the deep basin (even in the Three Forks); it can be followed for 500m in outcrop and almost disappears between wells less than a kilometer apart. This locally low-permeability reservoir appears to be a prime candidate for horizontal wells, but due to lateral facies and thickness variations, the reservoir distribution is likely not ubiquitous.

The wildcard in this play is late stage hydrothermal dolomite, which has created spectacular reservoir on the Peace River Arch area (Packard et al., 2001), albeit in a thicker target zone.

Tectonics, Accommodation Space, and Erosion

Another similarity between outcrop and subsurface is the thickness or thinness as a result of nondeposition or erosion (Figure 11B). The various fragments at the contacts (Figure 5) indicate that after Stettler, Big Valley and Exshaw times there were periods of nondeposition or erosion. Isopachs of the Big Valley Formation, for example, suggest that it was eroded in the vicinity of the 5^{th} meridian (Johnston et al., 2010). In Jura Creek, west of Calgary, there is a thick section of Exshaw shale (~10m) and siltstone (~40m) exposed, while in the Crowsnest Pass they total a few meters combined. In some core as little as 1 foot, 6 inches each of Exshaw shale and silt are observed (Figure 11B). Topography must have had a major influence on accommodation space, sediment thickness, facies, and erosion.

Although meters of relief, as derived from thickness variations in formations between wells kilometers apart allow for much assumption and interpretation, it has been suggested by means of seismic profiles that basement blocks with subvertical faults, underlying the stratigraphy, have influenced sedimentation and erosion patterns (Eaton et al., 1995). In southern Alberta the relationship between sea level and heterogeneous basement subsidence is thought to have influenced sedimentation patterns in a similarly low-accommodation setting during the Cretaceous (Zaitlin et al., 2002). On a much larger scale the Peace River and Central Montana arches inverted in Famennian-Tournasian times, to form the Peace River Embayment and Central Montana Trough, respectively (Figure 1). Because we have not seen detailed seismic in the basin, we can only guess about the tectonic influence on reservoir development and isopach maps through facies development and erosion, but the permeability-challenged shales, dolo-siltstones and even the dolomites, stand to have benefitted from late stage, Laramide fracturing associated with reactivation of basement faults (Eaton et al., 1995, Zaitlin et al., 2011), especially in combination with the effects of hydrocarbon-porepressure- related fracturing during kerogen maturation of the source rock. Open fractures with hydrocarbon-coated surfaces are regularly observed (Gatenby and Staniland, 2011).

Conclusions

The Alberta Bakken Petroleum System consists of 4 components: the Stettler Formation, the Exshaw and Banff shales and the medial Exshaw siltstone. In southern Alberta the lower part of the Stettler is composed of anhydrite and lesser dolomite. There is commonly a gradual transition from anhydrite to cream-to-tan laminated micro-sucrosic dolomites of the upper Stettler Formation. The contact with the overlying green-grey fossiliferous argillaceous limestones of the Big Valley is generally more abrupt. Oil production flows from the pervasively oil stained, restricted-marine dolomites of the Stettler Formation. The very fine-crystalline and consequently low-permeable, yet very porous Stettler dolomudstones present a suitable target for horizontal drilling and hydraulic fracturing.

The bioclast limestones of the Big Valley are not porous, and either thin or eroded in a major portion of the study area. In outcrop the bioclast limestone in the upper part of the Costigan correlates with Big Valley, whereas the lower Costigan is an intraclast stromatolitic dolostone (Meijer Drees and Johnston, 1993) similar to the restricted-marine dolostones of the Upper Stettler.

As the production history of horizontal wells drilled directly into the shale source rock in the Williston Basin suggests, horizontal drilling of the Exshaw shale may not be viable in our study area, as well. A higher permeability medial siltstone pipeline may be required. The Exshaw siltstone, alias the “Alberta Bakken” portion of the Alberta Bakken Petroleum System, looks similar in log character and mineralogy to the Bakken siltstones of Montana and Dakota but displays poorer porosity and permeability. This may mean that either we have not as yet drilled the right facies or that the medial siltstone is not an economic reservoir here.

The Banff has not been thoroughly investigated here, but there is historic production in the area from five vertical wells that produced between 1000 to 30,000 barrels cumulative between 1977 and 1984 (Bryden, 2011), and bitumen-lined fractures have been observed in core (e.g., Gatenby and Staniland, 2011) and drill cuttings.

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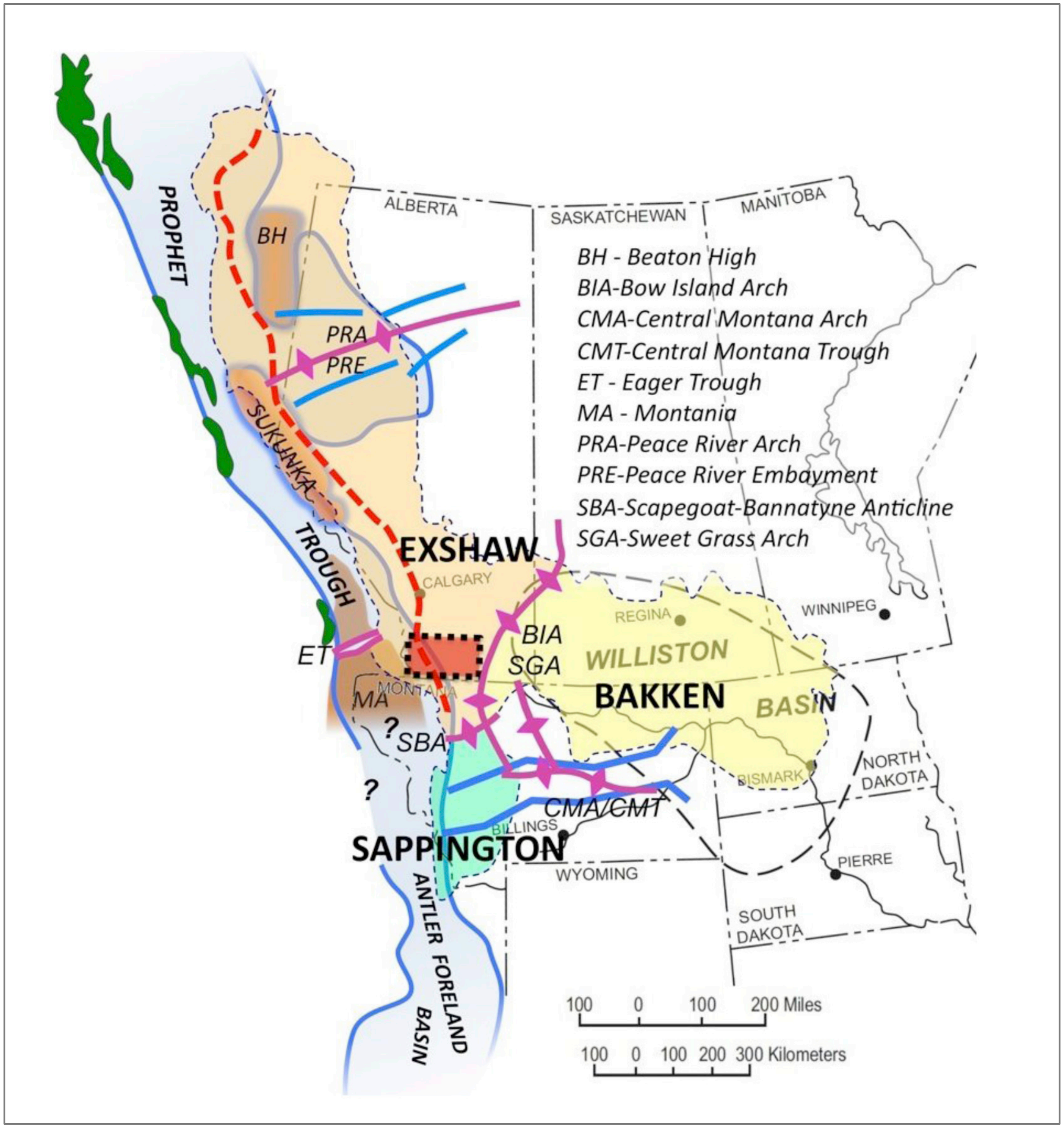

Figure 1. Schematic map showing the distribution of Bakken, Exshaw, and Sappington with some major tectonic elements; in purple are Famennian elements (which tend to be positive features) and in blue Carboniferous elements (which tend to be inverted negative features) (from Smith and Gilmour 1979, Morrow and Geldsetzer, 1988, Pitman et al., 2001, Wheeler et al., 1988; Richards et al., 1994).

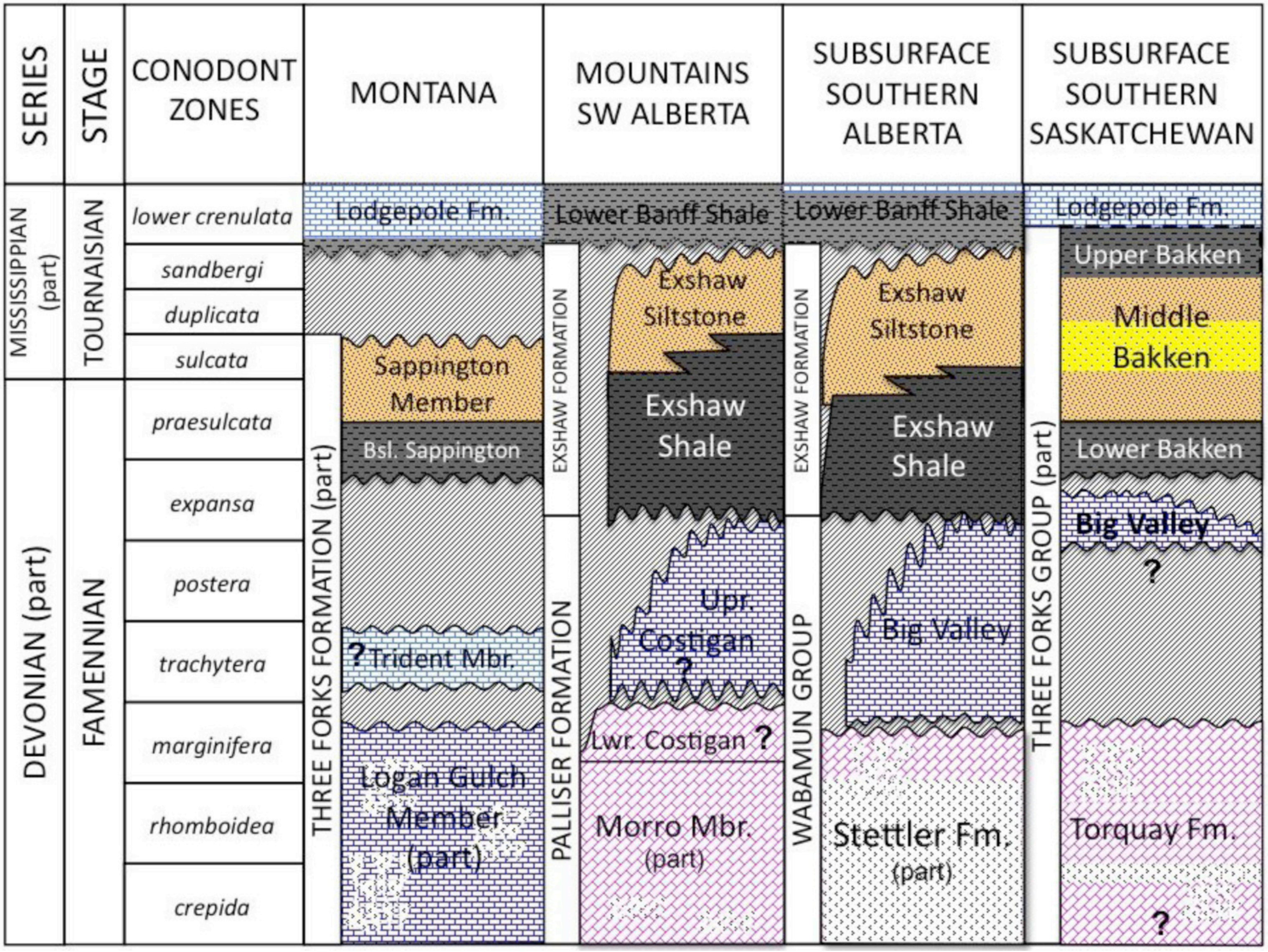

Figure 2. Schematic stratigraphic chart of the Stettler to Lower Banff formations in Montana, Alberta, and Saskatchewan, with data from: Sandberg et al. (1972, 1988), Savoy and Harris (1993), Meijer Drees and Johnston (1996), Savoy et al. (1999), Richards et al. (2002), and Johnston et al. (2010).

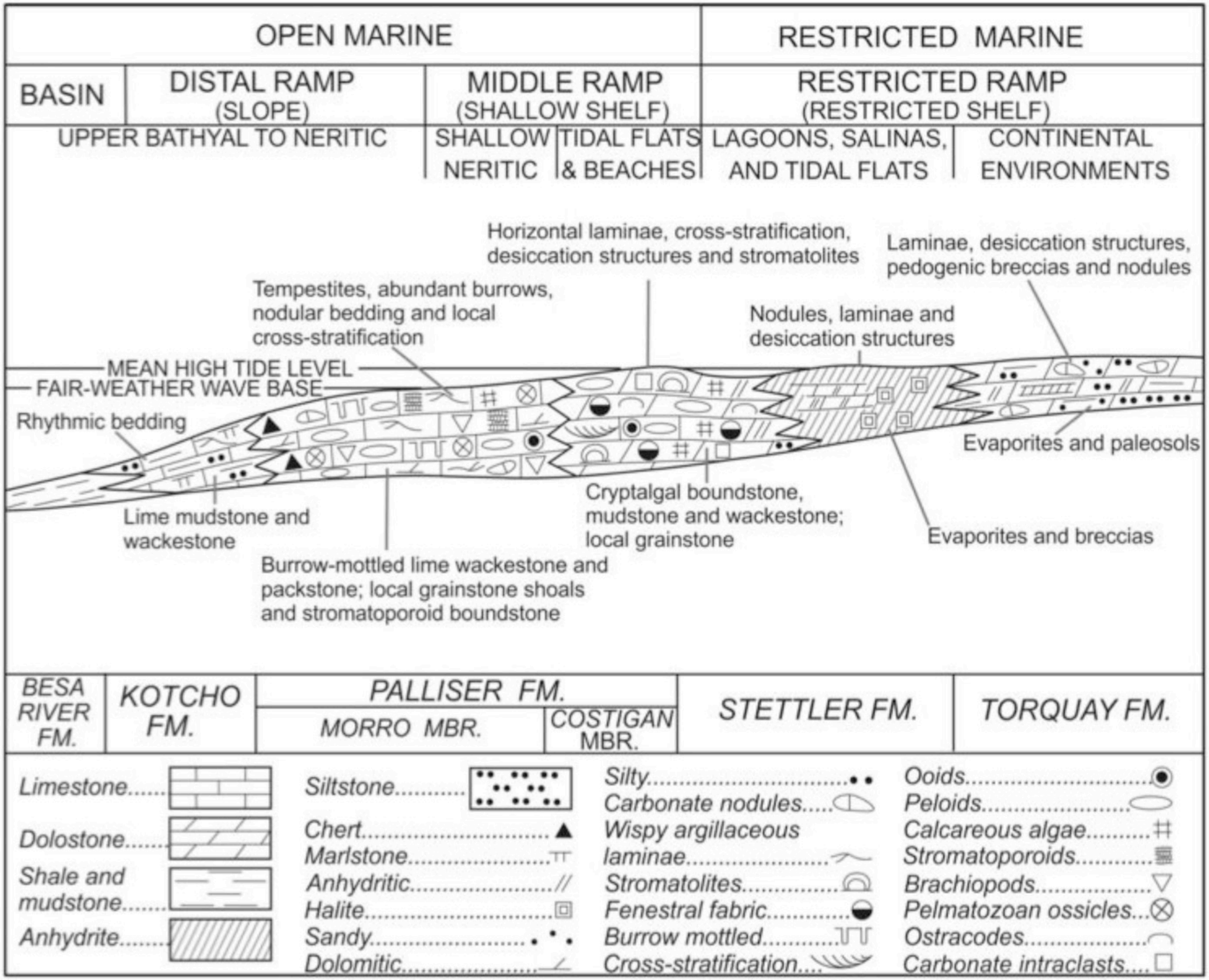

Figure 3. Carbonate ramp model: Generalized depositional model of a Famennian carbonate ramp (from Richards et al., 1991).

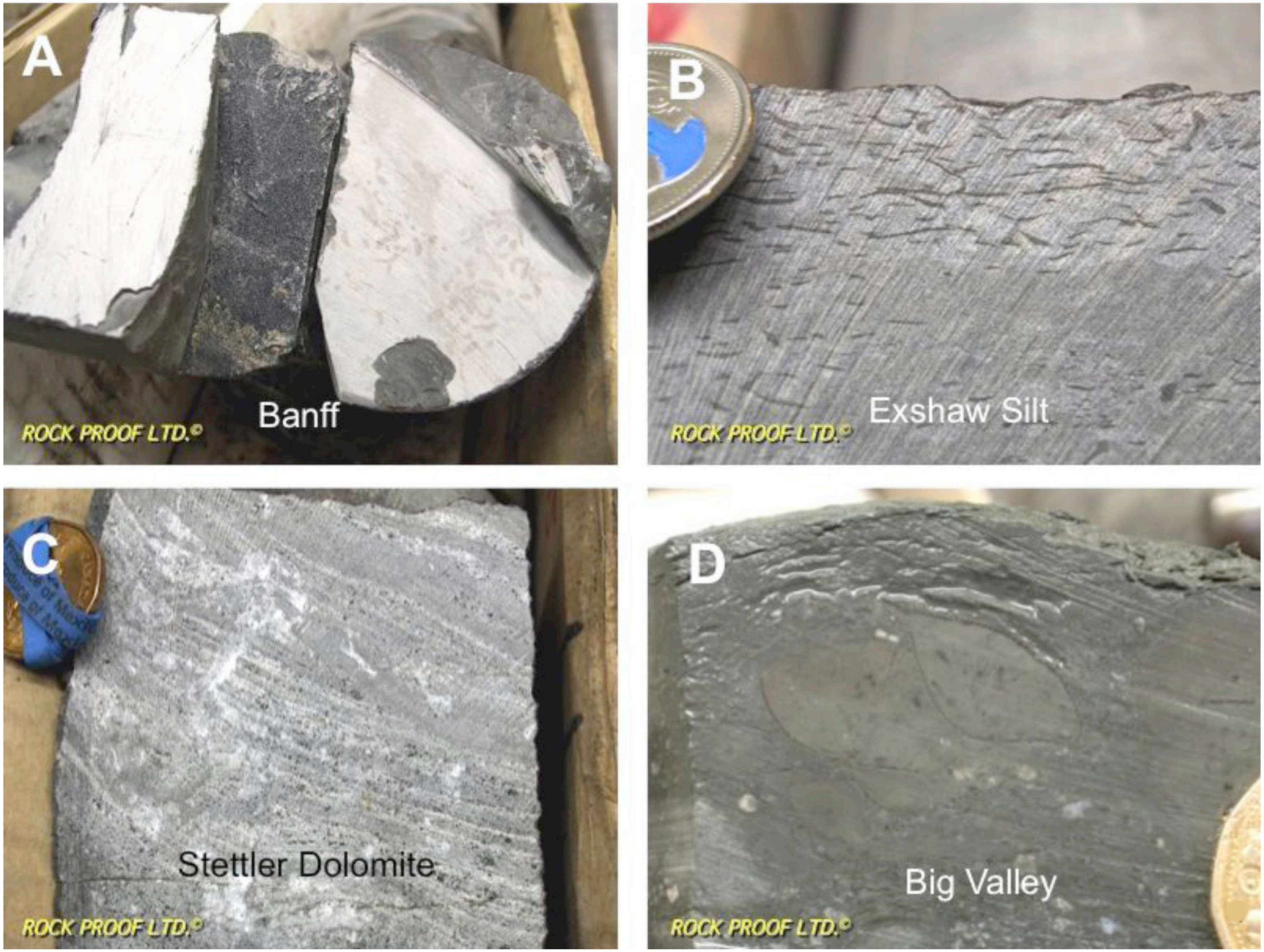

Figure 4. Core fragments with typical lithofacies characteristics as displayed by: A) burrowed and fractured Banff, B) burrowed Exshaw siltstone, C) Stettler stromatolitic dolomite, and D) Big Valley argillaceous brachiopod-pelmatozoan limestone.

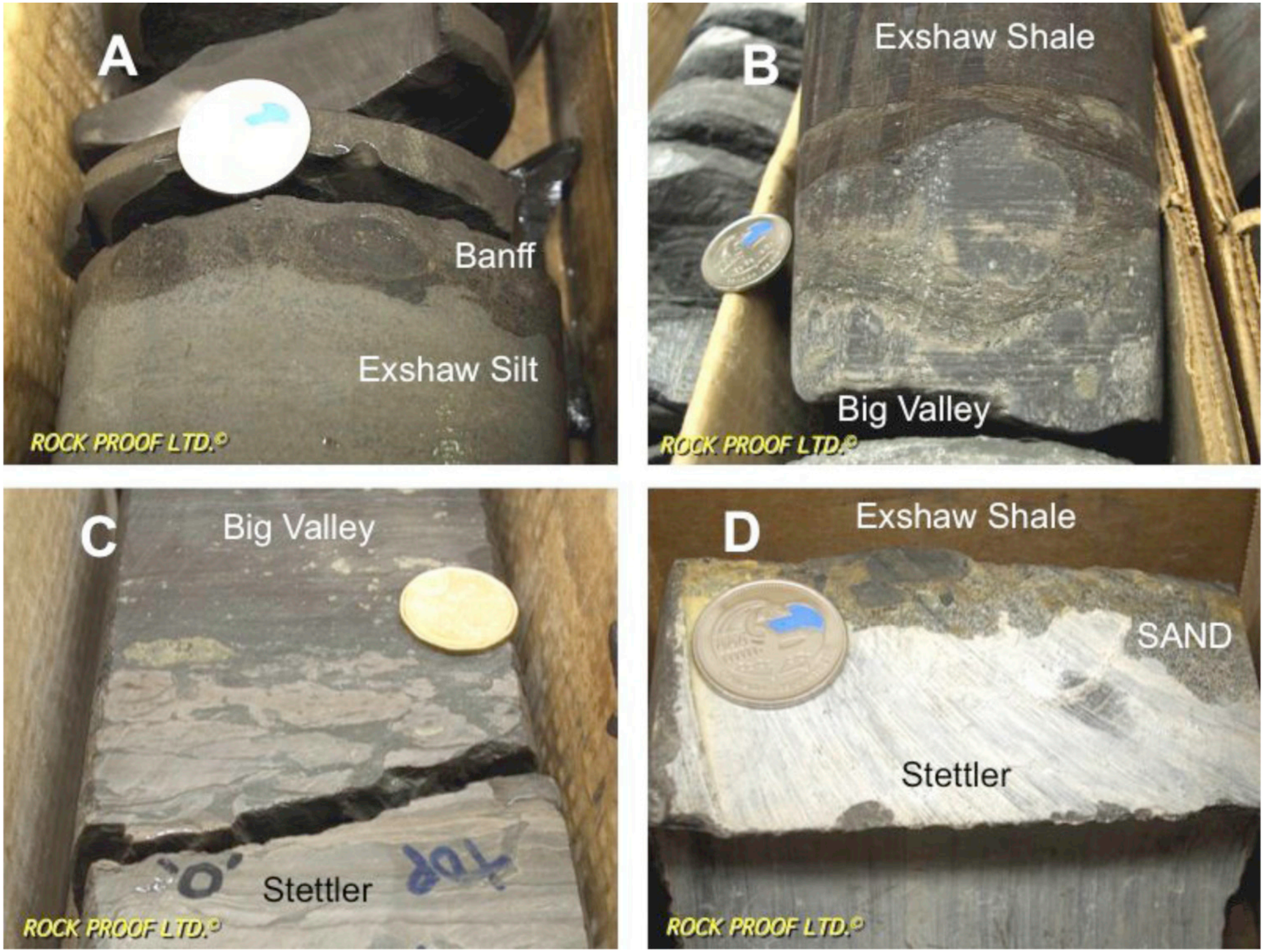

Figure 5. Various contacts between: A) Exshaw silt and Banff shale with cm-scale phosphatic clasts, B) Exshaw shale on top of argillaceous bioclastic Big Valley Limestone, C) Big Valley on top of Stettler with irregular shape cm-scale clasts, and D) Erosional contact between Exshaw pyritic conglomeratic sand lag and light colored restricted limestone of the Stettler (?).

Figure 6. Tray of sample vials filled with drill cuttings from the 10-30-008-23W4 Kaiser Kipp well from between 2196 and 2256m (3m vials as opposed to 5m). Four to five vials have an obvious brown (oil-stained) color and cuttings with microporosity.

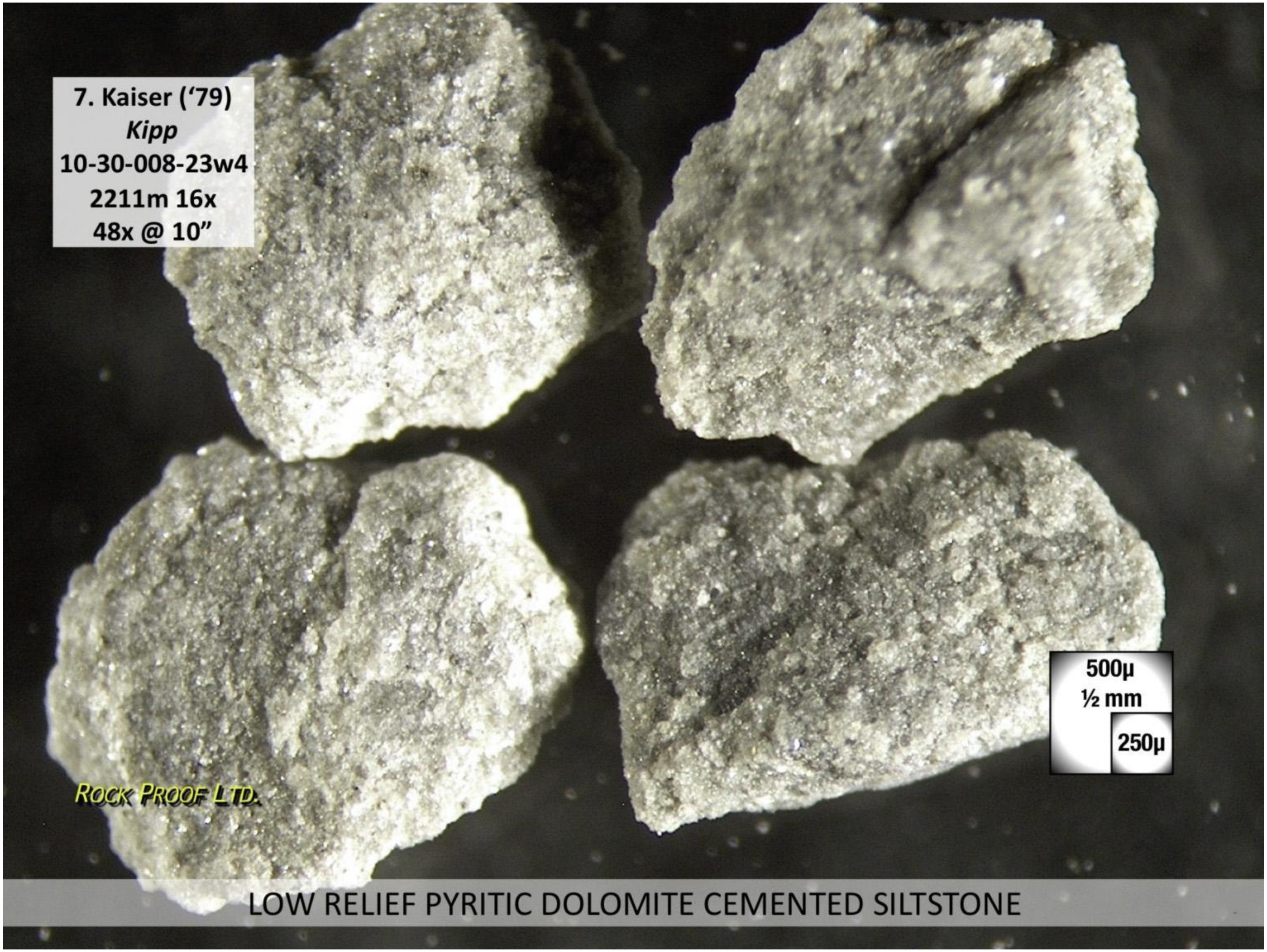

Figure 7. Four cuttings of tabular shape, light colored, pyritic dolomitic siltstone of Exhaw siltstone. At higher magnification they show low relief, suggesting the dolo-siltstone has low porosity and is strongly consolidated.

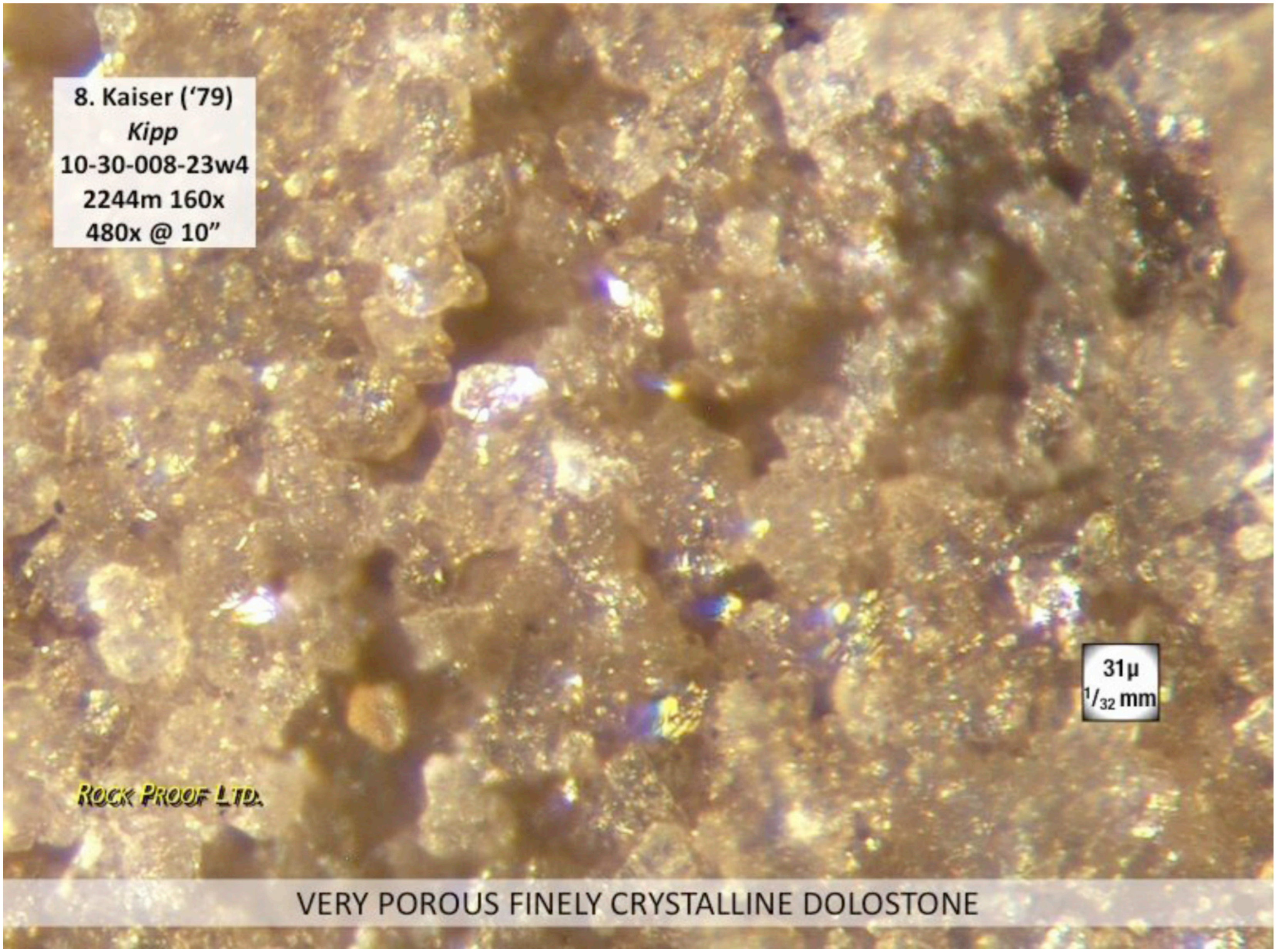

Figure 8. An example of highly porous and fairly permeable, finely crystalline dolostone in the 2244m sample from the 10-30-008-23W4 type producer.

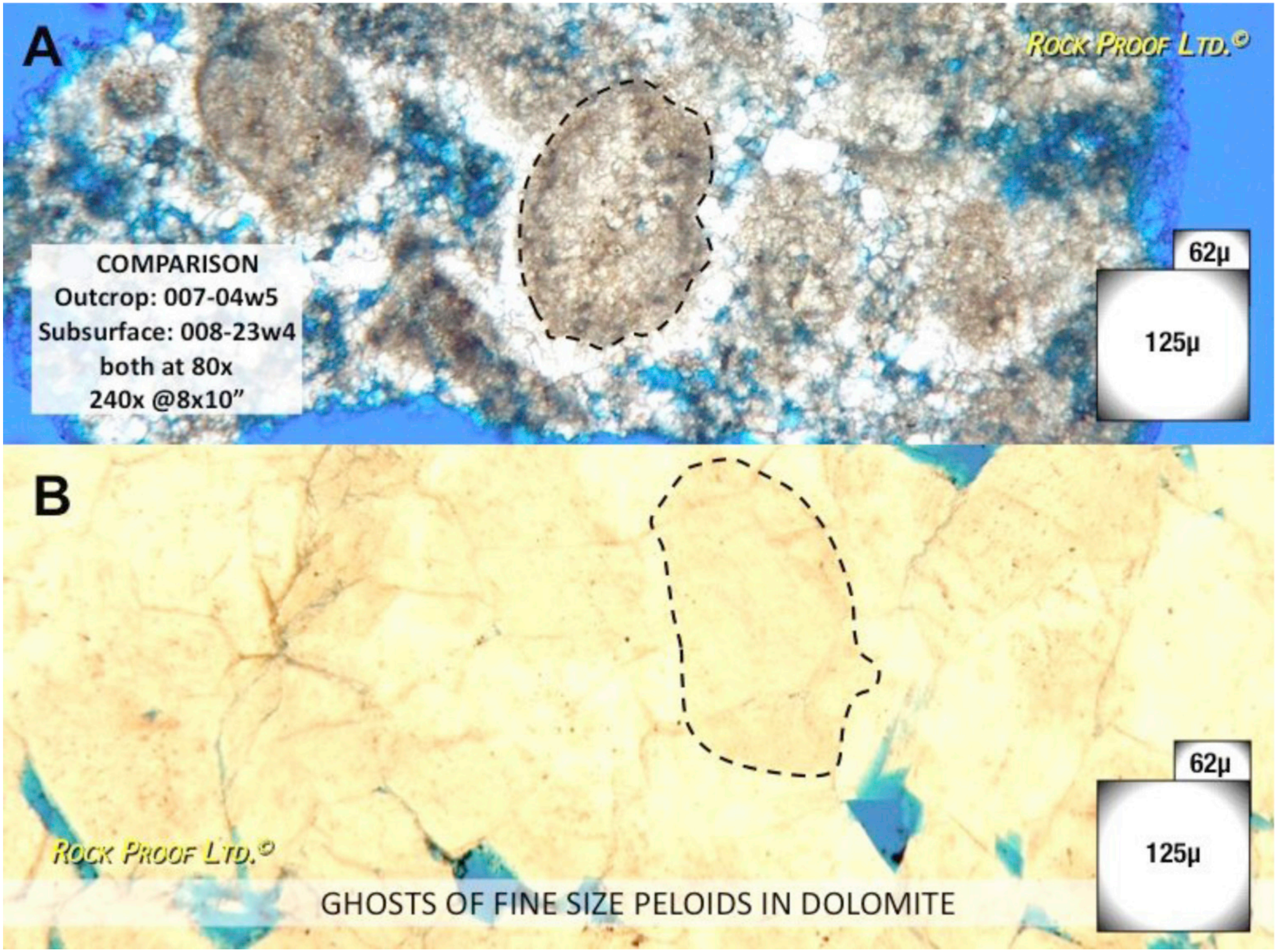

Figure 9. Comparison between two thin sections from the 10-30 well (top) and from outcrop on Turtle Mountain (bottom). Although the crystal sizes are different, both thin sections demonstrate that the dolomite precursor was a fine-grained packstone or grainstone with peloids of similar size and shape. Small amounts of black bitumen in the pore space of both samples.

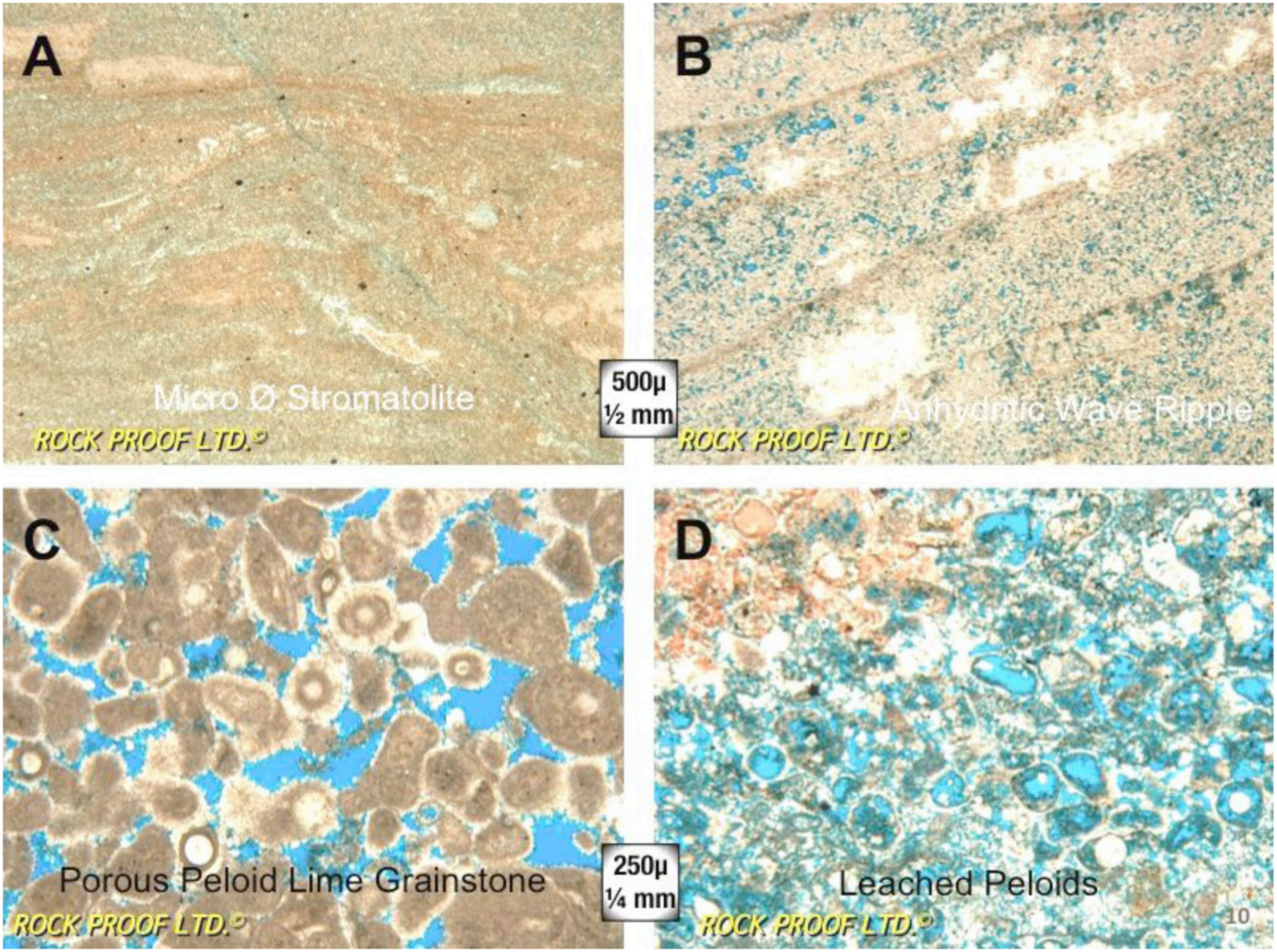

Figure 10. Various types of porosity in thin sections of restricted-marine carbonate facies: A) microporosity in stained calcareous stromatolitic dolostone, B) minor anhydrite cement in porous (oil-stained) wave-rippled dolomudstone, C) primary interganular porosity in calcisphere peloid lime grainstone, and D) porosity reversal in peloidal packstone to grainstone.

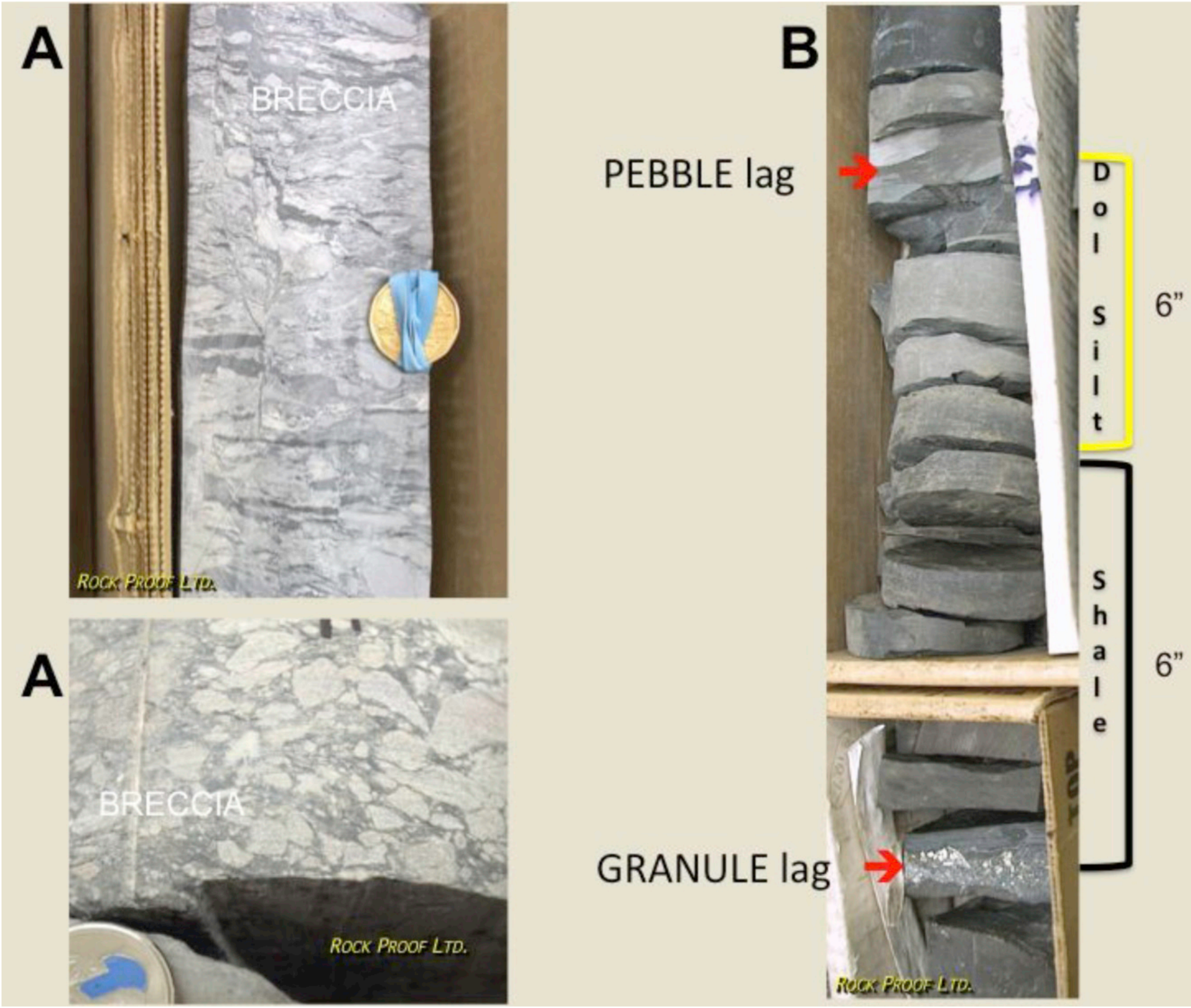

Figure 11. A, on the left: two examples of evaporite dissolution breccia, with porous clasts in a tight argillaceous matrix. B, on the right: an example of 15-cm-thick dark Exshaw shale between two lags (upper pebble lag above dolomitic siltstone; lower granule lag below shale). (According to gamma logs, this is likely not an artifact of lost core.)