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Geochronology in Support of the Alberta Table of Formations: Rhenium-Osmium Isotope Dating of Selected Devonian and Jurassic Core Samples from Central and Northern Alberta



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Abstract

The 2015 version of the Alberta Table of Formations published by the Alberta Geological Survey (AGS) is the reference stratigraphic chart for the province of Alberta. This chart is used as an important tool for resource industries, academia, government, and the public to identify Alberta's geological units and understand their stratigraphic relationships. The AGS chart conforms to the current naming practices of the North American Stratigraphic Code, and was scaled in time based upon chronostratigraphic divisions following the International Stratigraphic Chart of the International Union of Geological Sciences (IUGS) International Commission on Stratigraphy, version 2015/01. As our understanding of stratigraphic relationships evolves, and with advancements in analytical techniques for absolute dating, the AGS—the custodian of the stratigraphic chart of the province—updates the Alberta Table of Formations as necessary.

Current detailed stratigraphic work at the AGS is combined with an effort to resolving uncertainties regarding the age and stratigraphic position of a number of stratigraphic units based on precise isotope dating. Recent advances in dating organic-rich shales using the rhenium-osmium (Re-Os) isotope system has allowed us to attempt dating important hydrocarbon source rocks in the Western Canada Sedimentary Basin. This report presents the results of Re-Os geochronology on 11 organic-rich and radiogenic shale samples from Devonian and Jurassic formations. The samples were collected from selected shale intervals from core hosted by the Alberta Energy Regulator Core Research Centre in Calgary. Analyses were performed at the Crustal Re-Os Geochronology Laboratory at the University of Alberta.

A sample from the Middle Devonian Keg River Formation yielded an errorchron of 389 ± 15 Ma, which is consistent with the inferred late Eifelian / early Givetian age of this unit. From the Upper Devonian (Frasnian) shale succession we analyzed two samples from the Duvernay Formation and one from the equivalent Muskwa Formation. A precise Re-Os isochron age of 376.0 ± 2.4 Ma for the Muskwa Formation is younger than the previously inferred minimum age of the Muskwa/Duvernay shales. From the Jurassic Fernie Formation, we analyzed five samples from the Gordondale Member and two samples from the Poker Chip Shale Member. Samples from the Gordondale Member yielded three errochrons of 175 ± 18 Ma, 181.2 ± 5.8 Ma, and 184 ± 14 Ma, which are in the expected time interval for the deposition of the lower Fernie Formation, and a precise isochron age of 192.0 ± 1.4 Ma, which represents the best estimate so far for the beginning of Jurassic marine transgression at the dated locality in northwestern Alberta. Two samples from the Poker Chip Shale Member Chip Shale Member yielded an errorchron of 184 ± 12 Ma and a reliable isochron age of 182.5 ± 2.5 Ma, which constrains the initiation of Poker Chip Shale deposition to the earliest Toarcian at this location.

1 Introduction

On behalf of the Alberta Energy Regulator (AER), the Alberta Geological Survey (AGS) published in 2015 an updated version of the Alberta Table of Formations (Alberta Geological Survey, 2015), an important reference tool for resource industries, academia, government, and the public to identify and name geological rock formations in Alberta. Besides being the most accurate and extensive update of Alberta rock units compiled to date, the 2015 version brings the Alberta Table of Formations into better alignment with the current naming practices of the North American Stratigraphic Code (North American Commission on Stratigraphic Nomenclature, 2005), which is the international scientific guide to categorizing and naming rock formations.

The Alberta Table of Formations includes eight columns, which represent generalizations of stratigraphic columns in different regions of Alberta, and typical stratigraphic relationships established across the province (Alberta Geological Survey, 2015). The primary sources for local and regional stratigraphic relationships in the Alberta portion of the Western Canada Sedimentary Basin (WCSB) consist of subsurface mapping by AGS specialists, in part reflected by the compilation map AGS Map 600 (Prior et al., 2013), and field observations in the Alberta portion of the Rocky Mountains and Foothills included in the compilation map AGS Map 560 (Pană and Elgr, 2013). The vertical axis of the AGS stratigraphic chart was scaled in time based upon chronostratigraphic divisions, with the absolute age of division boundaries in millions of years, following the International Chronostratigraphic Chart (version 2015/01) of the International Commission on Stratigraphy (ICS) (Cohen et al., 2013, updated; ICS, 2015).

The Alberta Table of Formations (Alberta Geological Survey, 2015) includes uncertainties regarding the age and stratigraphic position of a number of stratigraphic units. In an attempt to resolve some of these uncertainties, this report presents the results of rhenium-osmium (Re-Os) dating of selected shales from Devonian and Jurassic formations. The samples were collected from core hosted by the AER Core Research Centre in Calgary, the analytical work was performed at the University of Alberta, and the results were compared with the most recent version of the International Chronostratigraphic Chart (version 2017/02; ICS, 2017).

1.1 Scientific Basis for Re-Os Analysis

Eleven samples of shales from key horizons in the WCSB were collected at the AER Core Research Centre (<u>Table 1</u>). After initial testing of the rhenium (Re) contents in all samples, eight of them were selected for Re-Os geochronology using the isochron method. Devonian samples were collected from the Keg River Formation (Elk Point Group) laminites, and from the bituminous, highly radioactive shales of the Duvernay and Muskwa formations (Woodbend Group). From the lower Jurassic strata, samples were collected from the black shales of the Gordondale and Poker Chip Shale members of the Fernie Formation. The locations of the examined wells are shown in <u>Figure 1</u> and photos of the sampled core are included in <u>Appendix 1</u>.

Sample ID	UWI	Depth (m)	Stratigraphic unit	Description	Core #	Box #	Diameter (inch)	Length (cm)	Gamma Ray (cps)
19201	07-31-079-10W6	1557.35–1557.54	Gordondale Member	near Baldonnel/ Gordondale contact	2	3 of 6	3 7/8	19	195
19202	07-31-079-10W6	1555.82–1556.04	Gordondale Member	higher up from Baldonnel/Gordondale contact	2	2	3 7/8	22	285
19203	07-31-079-10W6	1537.15–1537.28	Poker Chip Shale Member	basal Poker Chip Shale, above unconformity	1	1 of 13	3 7/8	13	170
19204	07-31-079-10W6	1537.86–1538.11	Gordondale Member	upper Gordondale below unconformity	1	2 of 13	3 7/8	25	240
19205	13-28-073-21W5	1193.04–1193.28	Gordondale Member	basal Gordondale above Triassic strata	2	15 of 17	4	24	273
19206	13-28-073-21W5	1169.38–1169.62	Gordondale Member	upper Gordondale at contact with Poker Chip Shale	1	9 of 16	4	24	260
19207	13-28-073-21W5	1168.50–1168.70	Poker Chip Shale Member	basal Poker Chip Shale	1	8 of 16	4	19	220
15951	09-25-039-06W6	3258.15-3258.38	Duvernay Formation	middle Duvernay	2	2	3 7/8	23	200
15952	15-20-095-20W4	1169.68–1170.56	Keg River Formation	Keg River laminites	5	9	4	7	130
15953	02/10-27-057-21W4	1155.49–1155.66	Duvernay Formation	Duvernay at Redwater Reef	3	11	3 7/8	17	130
15954	01-19-105-05W6	1599.80–1600.00	Muskwa Formation	Muskwa in northwestern Alberta	1	19	3 7/8	20	200

Table 1. WCSB shale samples collected for Re-Os geochronology. Samples highlighted in bold have been found to contain the appropriate Re and Os isotope concentrations and ratios to be processed further.



Figure 1. Sample locations.

2 Stratigraphic Relationships and Previous Age Constraints

Due to the limited applicability of the Re-Os analytical technique to only organic-rich, commonly radioactive shale samples, we have only examined and sampled selected stratigraphic intervals. We present the stratigraphic relationships of the sampled formations that are relevant to our geochronological study, in the context of their group depositional history, as described in the Geological Atlas of the Western Canada Sedimentary Basin (Mossop and Shetsen, 1994) available on the AGS website (http://ags.aer.ca/reports/atlas-of-the-western-canada-sedimentary-basin.htm [May 2018]).

2.1 Middle and Upper Devonian Stratigraphy

2.1.1 Keg River Formation

The Keg River Formation is part of the Middle Devonian Elk Point Group (Figure 2), which was deposited in an intracratonic basin with paleotopographic sub-basins separated by highlands (Meijer Drees, 1994). Above a major erosional unconformity, the lower part of the Elk Point succession onlaps an irregular surface of considerable relief. In the northern Alberta sub-basin, the Elk Point succession directly overlies Precambrian crystalline basement, suggesting that this region was deeply eroded before the onset of Devonian deposition, whereas in southern Alberta, it overlies Cambrian clastics and carbonates.

The outline of the paleotopographic basins and the amount of paleotopographic relief are well constrained by the Elk Point isopachs because the upper boundary of the Elk Point Group is a relatively flat surface. Elk Point isopach maps are affected by salt dissolution and collapse of the overlying Beaverhill Lake Group strata to the northeast near the Canadian Shield (e.g., Hauck et al., 2017).

The sub-Headless and the sub-Watt Mountain unconformities, and the regional distribution pattern of the dominant lithologies within the basin, suggest that the Elk Point Group includes three complete depositional sequences and the basal part of a fourth one (Meijer Drees, 1988, 1990; Moore, 1988; Morrow and Geldsetzer, 1988). Each depositional sequence is composed of marginal clastics, redbeds, anhydritic carbonates, and fossiliferous carbonates, and some of the sequences include extensive evaporites.

Locally, the carbonate deposits of the Elk Point Group contain age-diagnostic corals, brachiopods, conodonts, and ostracods (Craig et al., 1967; Fuller and Pollock, 1972; Pedder, 1975; Norris and Uyeno, 1983; Norris et al., 1982; Braun et al., 1988). However, the lowest sandstones, redbeds, and Lotsberg salt deposits in the northern and central Alberta sub-basins are nonfossiliferous and are assumed to be Lower Devonian (Meijer Drees, 1980; Wardlaw and Watson, 1966).

The regional distribution of the lower Elk Point redbed and evaporitic facies suggests deposition in a tectonically stable, continental environment. The redbeds may represent the shoreline deposits of a salt water lake, and the evaporites the nearshore deposits of a partly or completely desiccated lake.

The carbonates of the Ernestina Lake Formation were deposited during the onset of early Middle Devonian sea incursion of these continental sub-basins from the north. The early Middle Devonian age of this formation and its equivalents to the north is based on ostracods and a coral (van Hees, 1956; Norris, 1963; Rice, 1967).

Communication of the central and northern Alberta sub-basins to the open sea became restricted, and deposition of the Cold Lake Formation salt in the central and northern Alberta sub-basin indicates excessive evaporation in a continental environment (Wardlaw and Watson, 1966).

After a fall in relative sea level with associated regression and minor erosion to the north (the sub-Headless unconformity in the District of Mackenzie), the sea invaded the Elk Point Basin for a third time during the early Middle Devonian. Transgressive deposits are widely distributed and extend southeastwards across Alberta into the Williston Basin. In Alberta, this event is recorded by evaporitic carbonates (upper Chinchaga) and nearshore clastics or redbeds (Contact Rapids Formation in Alberta and Ashern Formation in Saskatchewan). The upper, regressive part of this assemblage includes the fossiliferous, shallow-marine carbonates of the Keg River Formation and equivalent Winnipegosis Formation (in Saskatchewan).

We sampled bituminous laminites, also known as the bituminous marker (Chow et al., 1995) of the Keg River Formation in the La Crete sub-basin in northeastern Alberta. The laminites are a metre-thick succession of black shales and lesser carbonates deposited coevally with ramp carbonates of the lower part of the Keg River Formation (Chow et al., 1995).



Figure 2. Stratigraphic relationships of the sampled Keg River, Duvernay, and Muskwa formations (modified from Alberta Geological Survey, 2015). Sampled stratigraphic units are highlighted in red.

Based on a combination of brachiopod and conodont biostratigraphy, Norris (1973) suggested a late Eifelian age for the lower portion of the Keg River Formation, and an early Givetian age for the upper portion. Johnson et al. (1985) placed the lower Keg River Formation within the late Eifelian *kockelianus* Zone and the upper Keg River Formation within the latest Eifelian to earliest Givetian *ensensis* and Givetian lower *varcus* zones.

The presence of the widely distributed, fossiliferous carbonate Keg River Formation in the middle part of the Elk Point Group indicates relative sea-level rise that deposited open-marine carbonates. Continued relative sea-level rise segregated the interior basin into several bank complexes and intraplatform "basins". The regional distribution of the reefal carbonates, peritidal carbonates, nodular anhydrite, salt and redbed deposits in the upper Elk Point succession suggests a marine influence and a periodic connection with the sea to the north.

During the late Middle Devonian transgression, the reef mounds at the entrance of the Elk Point Basin amalgamated with inter-reef deposits to form the Presqu'ile Barrier in the north, which limited flow of sea water to the southeast where conditions became restricted. Anhydrite and salt of the Muskeg and Prairie Evaporite formations, respectively, accumulated in the supratidal flats, coastal lagoons, and ephemeral lakes southeast of the barrier. Several major cycles of flooding and desiccation led to partial dissolution of previously deposited evaporites and the accumulation of potash salts, especially to within the Williston Basin (e.g., Corrigan, 1975). Reef growth along the seaward (northwestern) edge of the Presqu'ile Barrier established itself at a lower level and prograded seaward to form the biostromal and associated deposits of the Sulphur Point Formation (Meijer Drees, 1988).

Regional regression and emergence during the mid-Givetian is recorded by the sub-Watt Mountain unconformity. Overlying the unconformity is the widely distributed thin, green or reddish brown shale of the Watt Mountain Formation, which represents the initial phase of the subsequent late Givetian to early Frasnian transgression. Windblown deposits of green and reddish brown silt and siliceous clay are present in the First Red Bed unit (in Saskatchewan) and the upper part of the Watt Mountain Formation. Sandy deposits around the Peace River Arch were reworked into nearshore, deltaic, and lagoonal sediments of the Gilwood Member of the Watt Mountain Formation (Jansa and Fischbuch, 1974) (Figure 2).

2.1.2 Muskwa and Duvernay Formations

Extensive deposits of the Duvernay and Muskwa formations in the subsurface and at least the lower part of the Perdrix Formation in the deformed belt represent the maximum transgressive stage of the Upper Devonian (Frasnian) Woodbend Group (Figure 2) (Switzer et al., 1994). This interval was recorded throughout the WCSB, beyond those of the underlying Majeau Lake and Cooking Lake formations (Figure 3). The Muskwa and Duvernay formations are the basinal, organic-rich mudrock and shale equivalents of the Woodbend Group carbonate platforms and reefs (Cooking Lake, Leduc, and Grosmont formations) (Switzer et al., 1994; Wong et al., 2017).

The Duvernay Formation was deposited in two sub-basins termed the East and West Shale basins that are separated by the Rimbey-Meadowbrook Leduc reef trend which formed along the western edge of the Cooking Lake Platform (Stoakes, 1980). In the West Shale Basin the Duvernay mostly overlies the Majeau Lake Formation and comprises highly radioactive, bituminous, clay-rich and siliceous shales, along with a middle carbonate that thins towards the west where the Duvernay directly overlies calcareous shale of the Waterways Formation or carbonates of the Swan Hills Formation (Wendte et al., 1998). In the East Shale Basin the Duvernay overlies the Cooking Lake Formation carbonate platform and is mainly composed of clay-rich shale and lime mudstone (Stoakes and Creaney, 1985). The Duvernay deposits are synchronous with middle Leduc reef growth, and signal a profound change in the stratification and oxygenation of basinal waters. The same sequence of strata occurs parallel to the Grosmont carbonate shelf edge north of the Peace River-Athabasca Arch and transitions northwestwards



Figure 3. Schematic cross-section showing stages of reef, shelf, and basin-fill development within Woodbend and Winterburn chronostratigraphic intervals in the WCSB (modified from Switzer et al., 1994).

into the highly radioactive, organic-rich shales of the Muskwa Formation with which the Duvernay Formation appears to be largely equivalent (Switzer et al., 1994).

The Muskwa Formation in northwestern Alberta overlies Waterways Formation calcareous shales or Slave Point Formation bank carbonates, where the Waterways Formation is absent (Oldale and Munday, 1994; Switzer et al., 1994). In the Cordova Embayment and Horn River Basin of northeastern British Columbia, Muskwa strata overly calcareous shale of the Otter Park Member and are assigned as a member to the Horn River Formation (Williams, 1983; Oldale and Munday, 1994).

The Duvernay and Muskwa formations are overlain by, and in their upper parts are possibly equivalent to, the generally westward advancing basin-filling shales of the Ireton and Fort Simpson formations, respectively (Switzer et al., 1994).

Biostratigraphic control (mainly conodonts) and regional correlations constrain deposition of the Duvernay Formation to between uppermost Montagne Noir (MN) conodont zone MN 5 and lowermost MN 11 (McLean and Klapper, 1998; Wong et al., 2017), spanning an age range of approximately 3 Ma (from 379.5 Ma to 376.5 Ma; Becker et al., 2012; Wong et al., 2017). As a result of the westward-advancing increased siliciclastic input, deposition of the organic-rich Duvernay shale appears to have ceased earlier in the East Shale Basin than in the West Shale Basin (Wong et al., 2017).

No conodont biostratigraphic data appear to be available for the Muskwa Formation in northern Alberta. McLean and Klapper (1998) report conodonts from the Otter Park Member (underlying the Muskwa black shales) in northeastern British Columbia diagnostic of conodont zones MN 2 to 4. A conodont fossil identified as "probable *Mesotaxis asymmetrica*" from the Muskwa Formation in northeastern British Columbia at a location where it directly overlies Slave Point Formation bank carbonates is taken as tentative evidence that the Muskwa could range at least has high as conodont zone MN 6 (McLean and Klapper, 1998). Regional correlations of the Muskwa Formation black shale as the toe-of-slope basinal deposits in front of the westward advancing clinoforming fine siliciclastics of the Waterways, Hay River, and lower Fort Simpson formations, and as the stratigraphic equivalent of upper Horn River Formation strata in the southern District of McKenzie (Williams, 1977, McLean and Klapper, 1998; Morrow, 2012) suggest that the Muskwa Formation may have been deposited within the range of conodont zones MN 5 to at least MN 10 (McLean and Klapper, 1998), corresponding to a similar age range as that of the Duvernay Formation.

2.2 Lower Fernie Stratigraphy

Seven of our samples were taken from the Gordondale and Poker Chip Shale members of the Fernie Formation (Figure 4) which represents most of the Jurassic rocks in Alberta. These units, sampled in the subsurface, are also exposed in the front ranges and foothills of the Rocky Mountains, and are ubiquitous in the subsurface of the western prairies. The Fernie Formation is dominated by marine, shaly facies, and entirely so in its lower parts in northwestern Alberta. In west-central and southwestern Alberta, the Lower Jurassic sequences are relatively thin and contain a prominent platformal limestone and chert unit (Nordegg Member), and widespread, variably phosphatic, organic-rich shales, with siltstones and sandstones (Poulton et al., 1994). For comparison, we briefly describe the units south of 54°N latitude first (Figure 1).



Figure 4. Stratigraphic relationships of the sampled Gordondale and Poker Chip Shale members (modified from Alberta Geological Survey, 2015). Sampled stratigraphic units are highlighted in red.

2.2.1 Lower Fernie Stratigraphy South of 54°N Latitude

In the central segment of the Alberta Rocky Mountains, Foothills, and eastwards in the subsurface of the Alberta Plains, the lowest unit of the Jurassic is the Nordegg Member, comprising a thin, highly radioactive shaly marker unit with a thin basal grit layer at its base, followed by conspicuously banded limestones and cherts with a blocky log signature. These lithologies vary through dolomites and increasing amounts of sandstone into near-shore facies to the east near its subcrop edge. It contains the Late Pliensbachian ammonite Amaltheus (Frebold, 1966), and U-Pb zircon-dated bentonites (185.25-187.21 Ma) in its western outcrops (Poulton et al., 2017). The Red Deer Member is the western calcareous siltstone and mudstone facies equivalent of the Nordegg Member, bordering it on its west side, and also characterized by Amaltheus (e.g., Them et al., 2017a). It contains bentonites that provided U-Pb zircon dates of 185.49 and 188.58 Ma (Nordegg and slightly older ages) in its type area at Bighorn Creek (Them et al., 2017b). A thin, phosphatic-pebble bearing, basal Jurassic sandstone beneath the Red Deer Member at Bighorn Creek contains Late Sinemurian ammonites (Hall et al., 2004). The shaly Red Deer Member is apparently continuous northward with the lithologically similar Gordondale Member (described in the next section) which borders the Nordegg carbonate platform/ramp to its north (Asgar-Deen et al., 2004), and with an unnamed lower Fernie phosphatic shale and limestone unit in southwestern Alberta (MacDonald, 1987; Poulton and Aitken, 1989). This latter unit has Early Sinemurian ammonites (Frebold, 1957) and a U-Pb zircon age of 186.21 Ma, within the age ranges for the Nordegg and Red Deer members, i.e., Pliensbachian (Poulton et al., 2017).

In southwestern Alberta, the basal Fernie unit is a thin (up to 10 cm) grit layer, or a basal sandstone or heterogeneous and poorly sorted breccia up to 60 cm thick. The oldest beds of the Fernie Formation in southwestern Alberta, representing the easterly-younging transgression above the sub-Jurassic unconformity, vary in age from Early Sinemurian to Toarcian judging by occasional ammonite occurrences in either the basal unit or the immediately overlying shaly unit. Detrital zircons from this diachronous unit yielded latest Triassic to Sinemurian maximum depositional ages (MDA of ca. 211 Ma and 192 Ma, Pană et al., 2017). The Lower Jurassic units overlie Upper Triassic strata paraconformably at MacLeod River (Gibson and Poulton, 1994), Lower Triassic strata to the south with regional unconformity in the front ranges at Bighorn Creek and in southwestern Alberta, and Carboniferous strata to the east in the west-central Alberta subsurface to the eastern Crowsnest Pass area.

These various Pliensbachian units are overlain by the Toarcian (and uppermost Pliensbachian, locally at least) Poker Chip Shale Member black shale. Westerly thickening to more than 50 m is suggested by the outcrop data in southwestern Alberta, perhaps partly related to westward shaling out of underlying Nordegg carbonates and overlying Rock Creek sandstones. West of Edmonton, upper parts of the Poker Chip Shale Member comprise western shalier equivalents of the overlying lower Rock Creek Member sandstones in the subsurface farther east.

The Poker Chip Shale is apparently associated with a global transgression, and in western Alberta is regionally consistent, contrasting with the other more localized lithologic units above and below it. Where it overlies the distinctive cherty limestone of the Nordegg Member in west-central Alberta, the age of the base of the Poker Chip Shale Member is relatively well constrained in the Prairie Creek Quarry by a MDA of ca. 186.5 Ma for the limonitic sandstone near its base and a ca. 185.25 Ma bentonite layer in the underlying upper Nordegg Member (Pană et al., 2017; Poulton et al., 2017). At the Prairie Creek Quarry, the lower Poker Chip Shale contains a latest Pliensbachian ammonite, but regionally the unit is characterized by Toarcian ammonites (Pană et al., in press). It contains, in its lower part, a geochemical and extinction record that contributes to our knowledge of a major volcanic event (T-OAE or "Jenkyns Event") associated with the opening of the South Atlantic Ocean, and the global effects of such an event (Them et al., 2017a,b).

2.2.2 Lower Fernie Stratigraphy North of 54°N Latitude

North of about 54°N latitude, the Fernie Formation is entirely shaly, except in the far northwest where eastern lower representatives of the uppermost Jurassic Monteith sandstones extend (Kukulski et al., 2013) and a glauconitic Upper Jurassic sandstone is present (Lackie, 1958). The Nordegg Member platform/ramp carbonates and the more westerly shaly Red Deer Member of west-central Alberta are replaced to their north by the radioactive, phosphatic, organic-rich shale with platy limestone of the Gordondale Member (Asgar-Deen et al., 2004). The Gordondale Member is an important hydrocarbon source/reservoir rock and consists of dark brown, finely laminated, organic-rich, phosphatic, highly radioactive, calcitic mudstones, calcilutites, and fine-grained calcarenites. Ammonites and coccoliths indicate its age as Hettangian to Late Toarcian, and it contains abundant fish fragments, pectinoid bivalves, *Ostrea*, belemnoids, and radiolarians (Asgar-Deen et al., 2004).

The Gordondale Member is primarily correlative with the Pliensbachian Nordegg Member cherty carbonate facies and the Red Deer Member (Asgar-Deen et al., 2003) in west-central Alberta, but it also includes strata as old as Hettangian in northwestern Alberta (Hall et al., 2000) and northeastern British Columbia (Tozer, 1982; Poulton et al., 1990; Hall and Pitaru, 2004), as well as possibly lower parts of the Toarcian calcitic mudstones that may be alternatively assigned to the Poker Chip Shale Member in the Alberta Foothills outcrop belt (e.g., Asgar-Deen et al., 2003, 2004).

The Gordondale Member reaches a maximum thickness of approximately 40 m in the subsurface of northwestern Alberta. An offset to the east of this NNW-SSE-oriented depocentre compared with that of the Nordegg Member to its south may be related to the difficulty in recognizing the boundary with the overlying Poker Chip Shale, and compensated by the more westerly maximum thickness of the latter (compare figures 18.19 and 18.20 in Poulton et al., 1994). The abrupt eastward thinning is largely or entirely related to erosion at the sub-Cretaceous unconformity.

Together, the Nordegg, Red Deer, and Gordondale members thin westwards from a maximum thickness exceeding 50 m in the subsurface west of Edmonton (Poulton et al., 1994). This observation, and geochemical data from wells in northwestern Alberta suggesting the input of meteoric water from western sources and deposition in a silled basin (Riediger and Coniglio, 1992) led to the suggestion of an Early Jurassic backbulge depozone environment (McCartney et al., 2010).

The overlying, mainly Toarcian Poker Chip Shale Member is a fissile, black or greenish shale with siltstone and sandstone units. The Poker Chip Shale Member exhibits gradual northward thickening to more than 55 m south of Peace River townsite, but it is unclear how much of this is related to confusion with the underlying Gordondale Member shale, from which it is difficult to distinguish (e.g., Asgar-Deen et al., 2003, 2004) in many areas.

The glauconitic sandstone above the Poker Chip Shale in the Peace River area, previously reported as the Rock Creek Member (Lackie, 1958; Meloche, 2011, see his figure 1 [intraslope basin 2] and figure 2), contains Late Jurassic palynomorphs (Poulton et al., 1990) and is a northern correlative of the Niton Member or the Green Beds Member of west-central Alberta (Williams et al., 2013), overlying the Poker Chip Shale Member with regional unconformity. In adjacent northeastern British Columbia, a similar glauconitic sandstone in the same stratigraphic position has also produced Oxfordian–Kimmeridgian palynomorphs, and only questionable Middle Jurassic forms, and has been most recently referred to as a "Fernie sand" (Janicki and Balogun, 2015). The Aalenian to Lower Bajocian Rock Creek Member proper, or rather the northern of two major sandstone-siltstone lobes assigned to this member in west-central Alberta (its type section is in the southern lobe in southwestern Alberta: e.g., Poulton et al., 1994, figure. 18.21) overlies the Lower Jurassic shale succession in west-central Alberta. Its northern zero-edge coincides approximately with the northern limit of the underlying Nordegg carbonate facies.

3 Analytical Technique

Each of the 11 shale samples has been divided into 8–10 subsamples. Each subsample was ground to a fine powder using metal-free equipment, and tested for Re content. Following confirmation of adequate Re contents by semi-quantitative ICP-MS analysis, full Re-Os isotope analyses were undertaken. All Re-Os isotope analyses are carried out by the Carius tube dissolution method, followed by solvent extraction, ion exchange, and negative thermal ionization mass spectrometry as described by Selby and Creaser (2003) and Kendall et al. (2004). For all samples, Re is analyzed by a Faraday collector, and Os is analyzed by an electron multiplier detector. During analysis of Re and Os, isotopic analysis of Re and Os standards is carried out to ensure accuracy. All results were within the normal tolerances for Re and Os standards. Isochron regressions are calculated using the program Isoplot 3.0 (Ludwig, 2003) and all uncertainties are quoted at the 2σ level as produced by Isoplot. Any ages referred to herein use the value of $\lambda = 1.666 \times 10^{-11} a^{-1}$ (Smoliar et al., 1996) for the decay constant of ¹⁸⁷Re.

4 Results

A summary of Re-Os analytical results is included in <u>Table 2</u>. We report the measured ranges of Re and Os concentrations, and the ratios of ¹⁸⁷Re/¹⁸⁸Os and ¹⁸⁷Os/¹⁸⁸Os. Re-Os regression of the data in sample 19201 from the Gordondale Member and in samples 15951 and 15953 from the Duvernay Formation failed to yield an isochron. Sample 15952 from the Keg River Formation (<u>Figure 5a</u>), samples 19202, 19204, and 19206 from the Gordondale Member, and sample 19203 from the Poker Chip Shale Member (<u>Figure 6</u>), yielded errorchrons (a straight line cannot be fitted to the data points within the limits of analytical error) with ages in the expected ranges but with relatively large errors. Relatively precise isochron ages were produced for sample 15954 from the Muskwa Formation (<u>Figure 5b</u>), sample 19205 from the Gordondale Member, and sample 19207 from the Poker Chip Shale Member (<u>Figure 6</u>). These ages allow us to constrain the timing of deposition within a few million years.

Core sample 15954 was taken from the Muskwa Formation in well 01-19-105-05W6 at a depth interval of 1599.8 m to 1600.0 m, near the base of the Muskwa where it overlies the Beaverhill Lake Group (Figure 5b). Subsampling of the core yielded a Re-Os isochron with an age of 376.0 ± 2.4 Ma. This age is younger than the age of the Muskwa and correlative Duvernay formations as shown on the Alberta Table of Formations (Alberta Geological Survey, 2015), but rather falls within the time span assigned to the overlying Ireton and Fort Simpson formations. This age places this Muskwa Formation sample into the middle of conodont zone MN 11 on the correlation table between Devonian chronostratigraphy and marine biostratigraphy in Becker et al. (2012, figure 22.10), slightly younger than what has been so far documented or suggested for the Muskwa or Duvernay formations. A maximum age within the analytical error limits of 378.4 Ma (corresponding to conodont zone MN 7) is still younger than the current representation of the Muskwa Formation in the Alberta Table of Formations (Figure 2).

The two samples from the Lower Jurassic strata, which produced meaningful Re-Os ages come from a well (13-28-073-21W5) that lies south of the eastern end of cross-section B-B' (Asgar-Deen et al., 2003) and the middle portion of cross-section V-V' (Asgar-Deen et al., 2004) but it was not discussed in their definition of the Gordondale Member. In that area, the boundary between the Gordondale and the overlying Poker Chip Shale is particularly difficult to recognize and was questionably located within the Toarcian by Asgar-Deen et al. (2004). This decision may have been influenced by the Late Toarcian age assigned to a small and poorly preserved ammonite fragment that is here considered to be questionable.

Sample ID	UWI	Depth (m)	Stratigraphic Unit	Re (pbb)	Os (ppt)	¹⁸⁷ Re/ ¹⁸⁸ Os	¹⁸⁷ Os/ ¹⁸⁸ Os	Errorchron/ Isochron age (Ma)
19201	07-31-079-10W6	1557.35–1557.54	Gordondale Member	20–60	200-800	400–600	1.8–2.0	N/A
19202	07-31-079-10W6	1555.82–1556.04	Gordondale Member	240–600	3800–6000	380–590	1.5–2.1	175 ±18
19203	07-31-079-10W6	1537.15–1537.28	Poker Chip Shale Member	90–240	500–1250	900–1600	3.5–5.2	184 ±12
19204	07-31-079-10W6	1537.86–1538.11	Gordondale Member	250–500	1600–2500	880–1970	3.1–5.2	181.2 ±5.8
19205	13-28-073-21W5	1193.04–1193.28	Gordondale Member	128–145	900–1200	770–1130	2.9–4.1	192 ±1.4
19206	13-28-073-21W5	1169.38–1169.62	Gordondale	160–280	790–1360	1600–2000	5.3–6.2	184 ±14
19207	13-28-073-21W5	1168.50–1168.70	Poker Chip Shale Member	90–100	600–730	930–1120	3.0–3.8	182 ±2.5
15951	09-25-039-06W6	3258.15–3258.38	Duvernay Formation	10–130	300–500	120–180	1.1–2.0	N/A
15952	15-20-095-20W4	1169.68–1170.56	Keg River Formation	70–330	1600–4500	150–620	1.2–4.22	389 ±15
15953	02/10-27-057-21W4	1155.49–1155.66	Duvernay Formation	18–21	700–800	140–160	1.24–1.32	N/A
15954	01-19-105-05W6	1599.80–1600.00	Muskwa Formation	75–150	1400–2200	220–730	1.8–4.9	376.0 ±2.4

Table 2. Summary of Re-Os geochronology analyses from selected organic shales of WCSB. Ages in bold are isochrons (analytical data points fit a straight line within the limits of analytical error).



Figure 5. Core sample positions (red stars) for a) Keg River Formation (well 15-20-095-20W4, 1169.68–1170.56 m depth) and b) Muskwa Formation (well 01-19-105-05W6, 1599.80–1600.00 m depth).

13-28-073-21W5



Figure 6. Core sample positions (red stars) for the Gordondale and Poker Chip Shale members (well 13-28-073-21W5, 1193.04–1193.28 m and 1168.50–1168.70 m depth, respectively. Log type abbreviations: GR = gamma ray, PE = photoelectric, RESD = deep resistivity, RHOB = density, SP = spontaneous potential, SFL = spherically focused log.

The Gordondale core sample 19205 was collected at a depth interval of 1193.04 m to 1193.28 m, just above the unconformable contact with the underlying Triassic strata (Figure 6). Along the 24 cm of sampled core, 5 subsamples produced 5 analytical data points that define a Re-Os isochron with an age of 192 ± 1.4 Ma. This age for the near-basal Gordondale shale, places the sample into the Late Sinemurian approximately, is similar to that of the basal Fernie unit in several localities in the southwestern Alberta Rocky Mountains (Poulton et al., 1994), and indicates a depositional gap of more than 10 Ma at the sub-Jurassic unconformity, which is dated as 201.3 Ma according to the International Chronostratigraphic Chart (ICS, 2017). The Jurassic transgression was diachronous, younger toward the east onto the craton;

it apparently started in the earliest Jurassic (Hettangian) in northeastern British Columbia and northwestern Alberta, but did not reach this well locality until the Late Sinemurian, and then successively later eastward, through the Middle and Late Jurassic.

Core sample 19207 was collected from the base of the Poker Chip Shale Member over a length of 20 cm between the depths of 1168.50 m and 1168.70 m (Figure 6). Subsampling of the core yielded seven data points that define a Re-Os isochron with an age of 182 ± 2.5 Ma.

The age of 182.5 ± 2.5 Ma is near the Pliensbachian-Toarcian boundary at 182.7 Ma (ICS, 2017), and is consistent with an Early Toarcian, but locally latest Pliensbachian, age of the lower Poker Chip Shale regionally.

5 Conclusions

Eleven samples of core were selected from organic-rich, radiogenic shales of the WCSB. The Re-Os 389 ± 15 Ma errorchron obtained from the Keg River Formation sample corresponds to a latest Eifelian age, but the analytical error is too large to add a valuable constraint to the stratigraphically/paleontologically inferred late Eifelian to early Givetian age of this formation. The precise Re-Os isochron age of 376.0 ± 2.4 Ma for the Muskwa Formation is younger than the previously inferred age interval of the Muskwa Formation, and requires adjustments to the Alberta Table of Formation (Alberta Geological Survey, 2015). The Gordondale Member samples yielded three errorchrons of 175 ± 18 Ma, 181.2 ± 5.8 Ma, and 184 ± 14 Ma and a precise isochron of 192.0 ± 1.4 Ma which fall in the previously inferred age interval of this formation. This isochron age of 184 ± 12 Ma, and a good isochron age of 182.5 ± 2.5 Ma. The reliable isochron age constrains the initiation of Poker Chip Shale deposition to earliest Toarcian at this locality.

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Appendix 1 – Core Photographs of Core Sampled for Re-Os Isotope Dating









Plate 1. Photographs of Devonian cores sampled for Re-Os dating: a) sample ID 15951, Duvernay Formation; b) sample 15952, Keg River Formation; c) sample ID 15953, Duvernay Formation; d) sample ID 15954, Muskwa Formation. For detailed sample information and analysis results, see Tables 1 and 2, respectively.

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Plate 2. Photographs of Jurassic cores sampled for Re-Os dating: a) sample ID 19201, Gordondale Member; b) sample ID 19202, Gordondale Member; c) sample ID 19203, Pokerchip Shale Member; d) sample ID 19204, Gordondale Member. For detailed sample information and analysis results, see Tables 1 and 2, respectively.

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Plate 3. Photographs of Jurassic cores sampled for Re-Os dating: a) sample ID 19205, Gordondale Member; b) sample ID 19206, Gordondale Member; sample 19207, Poker Chip Shale Member. For detailed sample information and analysis results, see Tables 1 and 2, respectively.

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