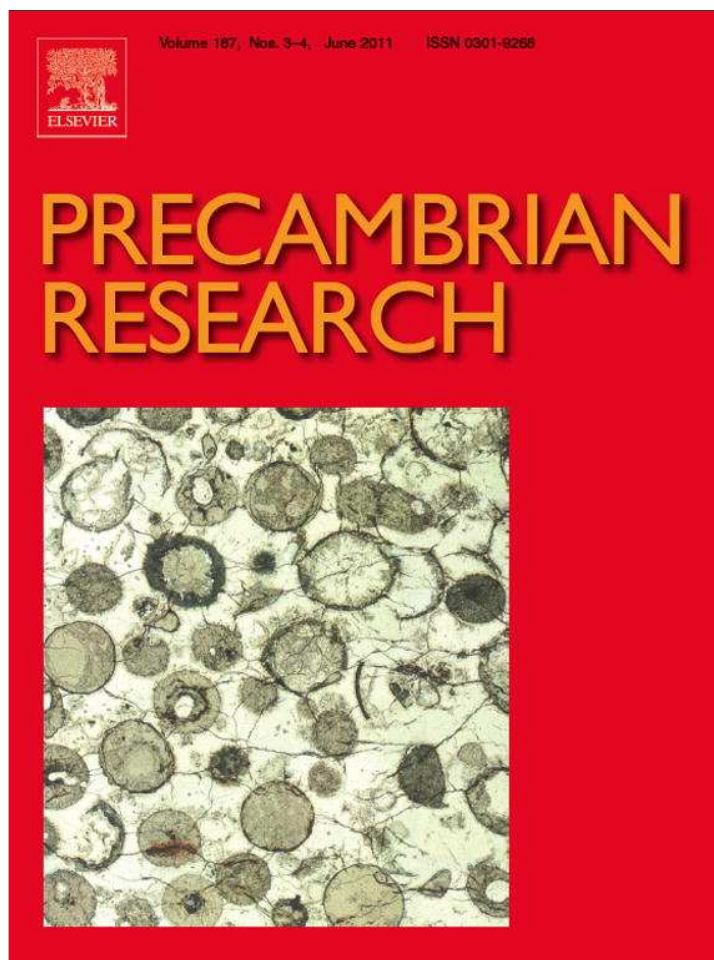




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Hydrogeology, sequence stratigraphy and diagenesis in the Paleoproterozoic western Thelon Basin: Influences on unconformity-related uranium mineralization

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ABSTRACT

The Paleoproterozoic (Statherian) Thelon Formation consists of unmetamorphosed sandstone and conglomerate that was deposited in the Thelon Basin, a continental basin in northern Canada. This study presents the first detailed sedimentological and sequence stratigraphic analysis of the expansive and under-studied western Thelon Basin, and its relation to uranium mineralizing processes in the vicinity of the Boomerang Lake unconformity-related U prospect.

Four lithofacies comprise the Thelon Formation in the western Thelon Basin, consisting of breccia, conglomerate, sandstone, and minor mudstone. These are grouped into four facies associations that represent deposition in alluvial fans and braided fluvial streams. Three stratigraphic sequences were identified based on the recognition of widespread surfaces that mark significant periods of subaerial exposure or changes in depositional environment. These unconformity-bounded sequences are composite in nature and can be subdivided into six high-frequency sequences (HFS). Low-accommodation and high-accommodation systems tracts are delineated, instead of the traditional systems tracts that are linked to changes in relative sea level, as no marine deposits are recognized in the Thelon Formation.

Two significant strataform paleohydrogeological units were distinguished in the Thelon Formation, based on the relative timing of key diagenetic events such as compaction, grain dissolution, and cementation. *Diagenetic aquicludes* became isolated from basinal fluid flow due to stylolite-catalyzed early diagenetic quartz cementation, and occlusion of secondary intergranular macroporosity by kaolinite and muscovite, and minor dickite during later peak diagenesis. *Diagenetic aquifers* conducted U-bearing basinal fluids throughout diagenesis and are marked by an abundance of peak diagenetic dickite. Sequence stratigraphic correlation indicates that *diagenetic aquicludes*, which were not effective at conducting U-bearing basinal fluids, overlie the unconformity at the Boomerang Lake prospect and extend along the entire strike length of a related exploration trend. In contrast, thick diagenetic aquifers lie approximately 10 km to the north of the Boomerang Lake prospect along a different exploration trend.

The western and eastern portions of the Thelon Basin experienced depositional environments and diagenetic conditions distinct from one another, suggesting that they were separate sub-basins. The western Thelon Basin contains fewer of the well-cemented facies that compartmentalized basinal fluid flow than the eastern Thelon Basin, and contains a kaolin-dominated diagenetic mineral assemblage rather than a muscovite-dominated assemblage that is common in the eastern Thelon Basin. In these regards, the western Thelon Basin evolved more similarly to the eastern portion of the Athabasca Basin, where thick, regional, kaolin-rich diagenetic aquifers were fluid conduits for the movement of the U-rich fluids that formed high-grade unconformity-related U deposits.

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1. Introduction

Predictions of rising nuclear fuel consumption and the realization of declining stockpiles in the early 2000's drove the price of uranium to the highest levels in 30 years, which revitalized uranium exploration and renewed interest in under-explored prospects. One of these is the Boomerang Lake U prospect in the western

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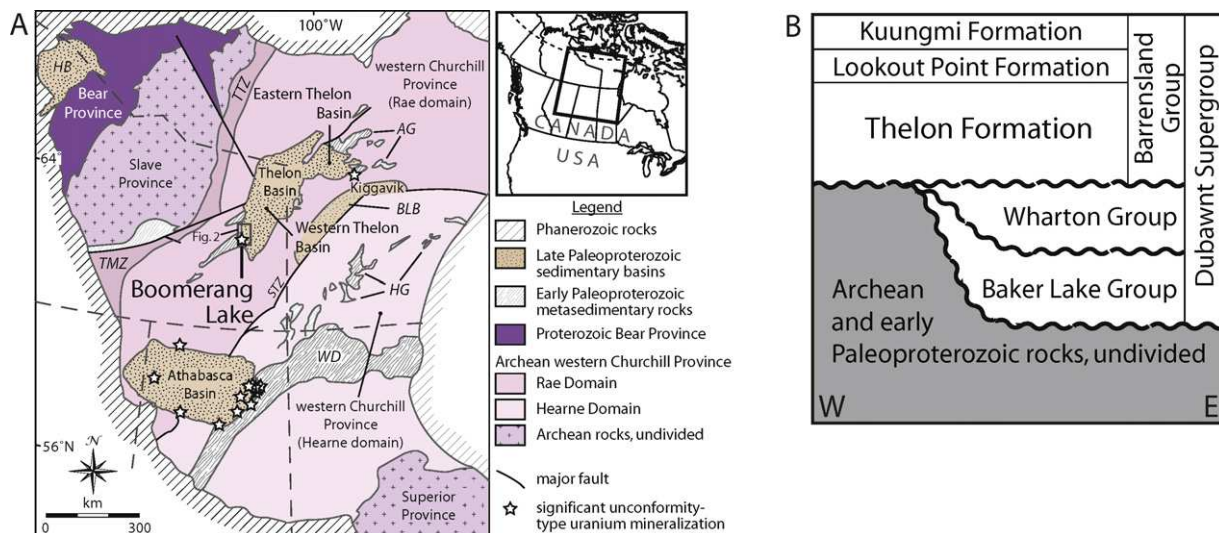


Fig. 1. A. Generalized geological map of the western Churchill Province, Canada showing the location of the Boomerang Lake unconformity-type uranium prospect in the western Thelon Basin. The location of the map in Fig. 2 is also shown. Modified from Davidson and Gandhi (1989). AG = Amer Group; BLB = Baker Lake Basin; HB = Hornby Bay Basin; HG = Hurwitz Group; STZ = Snowbird tectonic zone; TMZ = Taltson magmatic zone; TTZ = Thelon tectonic zone; WD = Wollaston domain. B. Generalized lithostratigraphy of the Dubawnt Supergroup. Modified from Rainbird et al. (2003).

Thelon Basin, Canada (Fig. 1a), which was discovered in 1983 following ca. 15 years of geochemical and geophysical reconnaissance (Davidson and Gandhi, 1989). The current status of Boomerang Lake as a high-priority exploration target is based on a favorable geological setting, and the study of Davidson and Gandhi (1989) who described the prospect as possessing similar characteristics to unconformity-related U deposits in other basins, including the prolific U-producing Athabasca Basin, Canada (Fig. 1a).

Mineral deposits hosted in sedimentary basins often result from basin-scale processes that occur throughout basin evolution (Kyser et al., 2000; Kyser and Hiatt, 2003; Southgate et al., 2006; Kyser, 2007; Kyser and Cuney, 2008), which should be understood for the development of successful exploration models. Fluid flow pathways within the basin are required to allow the mass transport of metals to a site of mineralization. In unconformity-related U deposits, basinal fluids transport U and are potential reductants upon interaction with basement rocks (Kyser and Cuney, 2008). Diagenetic and hydrothermal alteration near these deposits are produced by a large volume of basinal fluids; for example, it is estimated that 236 million cubic meters (1% of the volume of Great Salt Lake, Utah) of basinal fluid flowed through the hydrothermally altered portion of the Zone K trend at Wheeler River in the Athabasca Basin (Cloutier, 2009).

Despite previous studies that focused on the eastern Thelon Basin (Fig. 1a; Renac et al., 2002; Hiatt et al., 2003, 2010; Holk et al., 2003; Palmer et al., 2004), little is known regarding the diagenesis and evolution of the western Thelon Basin, despite the presence of uranium mineralization at the Boomerang Lake prospect. In this study we integrate sedimentology, sequence stratigraphy, diagenesis, and mineral paragenesis to understand the paleohydrogeology of the western Thelon Basin in relation to the formation of unconformity-related U deposits. The tectonic and sedimentary evolution of the western Thelon Basin margin, which is currently understood from a regional perspective (Rainbird et al., 2003), is detailed based on the identification and correlation of lithofacies in a sequence stratigraphic framework, and synthesized in a depositional model. A paragenesis is presented that documents the diagenetic and hydrogeological evolution of the basin, allowing the distinction of diagenetic aquifers from diagenetic aquicludes. Potentially prospective zones for unconformity-related U mineralization are proposed based on intersections of fluid-conducting strata and favorable basement areas. Lastly, comparisons of key

sedimentological and diagenetic aspects in the western Thelon Basin are made with the contemporaneous eastern Thelon and Athabasca basins, both of which host unconformity-related U deposits.

2. Geological setting

The late Paleoproterozoic (Statherian) Thelon Formation is widespread over a ~500 km × 300 km area in the Thelon Basin, Northwest Territories and Nunavut, Canada (Fig. 1a). The Thelon Basin is one of several Paleoproterozoic, sandstone-dominated intracratonic basins in western Canada (Rainbird et al., 2003), and lies within the Archean Rae Domain. Early Paleoproterozoic supracrustal rocks of greenschist to amphibolite metamorphic grade overlie the Rae Domain. In the western Thelon area, supracrustal rocks consist of amphibolite-grade graphitic metapelite of unknown age and origin, and greenschist-grade quartzite and schist that are speculatively correlated with the Amer Group (Fraser and Miller, 2007).

Sedimentary rocks of the Thelon Basin, and the Baker Lake Basin in the eastern Thelon area, belong to the Dubawnt Supergroup (Fig. 1a and b) that includes the unconformity-bounded Baker Lake, Wharton, and Barrenslund Groups and have a composite thickness of 15 km (Gall et al., 1992; Rainbird and Hadlari, 2000; Rainbird et al., 2003). The Baker Lake and Wharton Groups consist of alluvial and aeolian sedimentary rocks intercalated with volcanoclastic rocks and ultrapotassic to rhyolitic flows (Cousens et al., 2001; Rainbird et al., 2003), and were deposited in fault-bounded sub-basins in the eastern Thelon area (Rainbird et al., 2003). The Barrenslund Group is dominated by sandstones and conglomerates of the Thelon Formation, and is in turn overlain by the relatively thin (~50 m) Lookout Point Formation siliceous, stromatolitic dolostone and the Kuungmi Formation potassic basalt flows (Rainbird et al., 2003).

The present-day thickness of the Thelon Formation is unknown, but may be in excess of 1000 m based on seismically-determined thickness of the basin fill in the western Thelon Basin (Overton, 1979). Shallowly dipping to horizontal bedding and lack of intense induration in the Thelon Formation contributes to low relief throughout the Thelon Basin and its poor exposure in outcrop. Wright (1955, 1967) and Donaldson (1969) did early mapping and sedimentological and stratigraphic studies of the

Thelon Formation and more recently, Hiatt et al. (2003) identified three unconformity-bounded stratigraphic sequences in the eastern Thelon Basin based on the study of numerous drill cores that penetrate the basal unconformity. The Thelon Formation is almost devoid of mud-dominated facies, typical of Proterozoic intracratonic basins, which were dominated by braided fluvial environments. Braid plain soils were very poorly developed due to the absence of land plants, and surface sediments were easily eroded (e.g. Schumm, 1968).

2.1. Uranium mineralization

Two uranium occurrences have been explored in the Thelon Basin. The Kiggavik and related deposits consist of ~36,600 t U in resources (Jefferson et al., 2007) and are located just beyond the southern margin of the eastern Thelon Basin (Fig. 1a). The Boomerang Lake uranium prospect is located at the margin of the western Thelon Basin (Fig. 1a).

Exploration at Boomerang Lake focused on two electromagnetic conductor trends termed the F- and the G-trends (Fig. 2). These trends are oriented northeast–southwest and correspond to the regional strike of foliation in the underlying Rae Domain and early Paleoproterozoic supracrustal rocks. The Boomerang Lake discovery zone is located near the southwest end of F-trend (Fig. 2) and occurs in fractured, brecciated, and clay-altered Thelon Formation sandstones and graphitic, metapelitic basement rocks (Davidson and Gandhi, 1989; Gandhi, 1989). The best intersection in the discovery zone assayed 0.42% U and 25 ppm Au over 0.5 m in clay-altered sandstone (Davidson and Gandhi, 1989). Although originally misidentified as uraninite (Davidson and Gandhi, 1989), it is now known that U at the Boomerang Lake prospect is hosted in the uncommon Ca–U⁴⁺ phosphate mineral trisramite (Beyer et al., 2010). Mineralization is associated with Ni + Co ± Cu sulfides, selenides, and arsenides, and anomalous concentrations of Cr, V, and Zn (Davidson and Gandhi, 1989). Basement rocks on the G-trend consist of Archean gneissic granitoids of the Rae domain and greenschist-grade quartzite and schist.

3. Methods

Approximately 3500 m of stratigraphic sections within the Thelon Formation were measured in detail (cm- to dm-scale resolution) from 31 diamond drill cores that all intersect the unconformity and are spread nearly 20 km along strike of the F- and G-trends. Five outcrop exposures (Fig. 2) provided fragmentary stratigraphic information due to limited vertical exposure (<10 m), but provided information regarding sedimentary structures and bedding relationships. Mean grain size, maximum clast size, sorting, sedimentary structures, bedding thickness, and framework grain composition were all noted, in addition to diagenetic features such as evidence of compaction and the abundance and nature of cements.

Mineral identification and paragenetic relationships were determined in about 500 samples from which polished thin sections were made and studied using standard transmitted- and reflected-light microscopy, and electron microscopy. Scanning electron microscopy was performed using an Amray 1830 scanning electron microscope (SEM) in back-scattered electron (BSE) mode, Queen's University, Canada, and a JEOL JSM-6400 SEM in BSE mode and secondary electron (SE) mode, Carleton University, Canada. Qualitative chemical analyses were determined using an Oxford energy dispersive X-ray spectrometer (EDS) coupled to the SEM. Electron microprobe analysis (EPMA) was performed by wavelength dispersive X-ray spectrometry on a Cameca Camebax MBX electron microprobe at Carleton University. An electron beam with a diameter of 5–10 µm, 15 kV accelerating voltage, and 20 nA current was used. Elemental weight percentages were calculated using

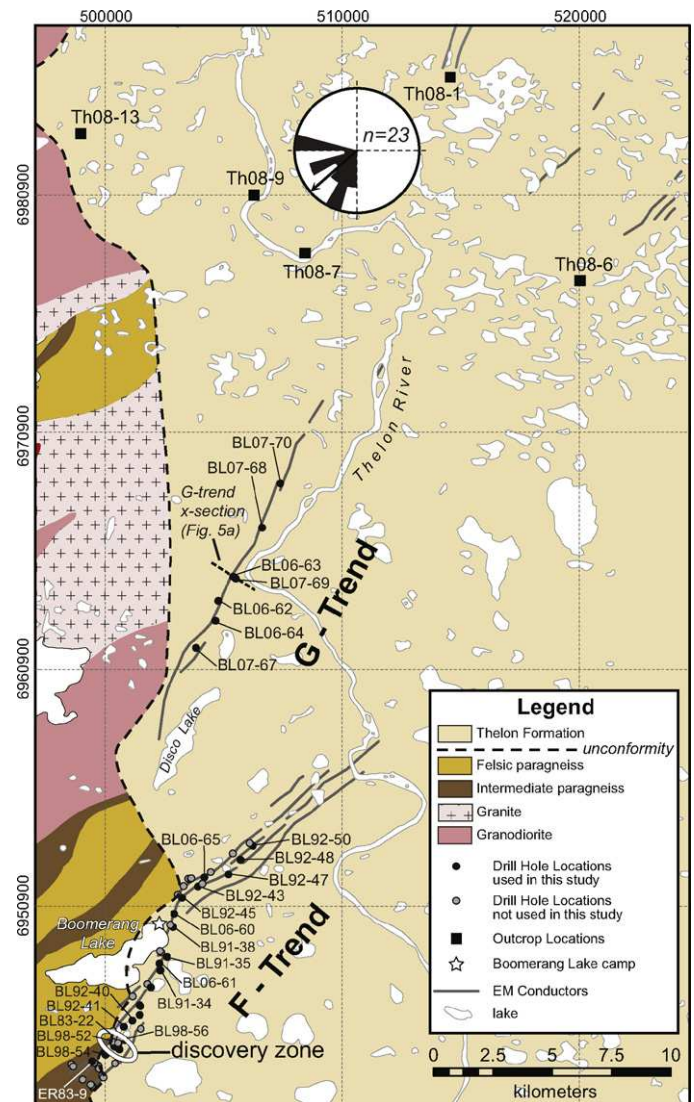


Fig. 2. Generalized geological map of the southwestern margin of the Thelon Basin. The F-trend and G-trend are the primary exploration corridors associated with the Boomerang Lake U prospect and are defined by the trends of geophysically-determined electromagnetic (EM) conductors. Stratigraphic sections were measured at drill hole locations shown as a black dot. The inset diagram near the top shows the distribution of paleocurrent measurements taken in the Thelon Formation exposed in outcrop. Grid coordinates are for UTM projection (Zone 13, NAD83).

a Cameca PAP matrix correction program. Analyses are accurate to 1–2% for major elements (>10 wt%) and 3–5% for minor elements (>0.5 to <5.0 wt%).

Field identification of phyllosilicates in drill core and hand sample was aided by the use of an ASD TerraSpec® short-wave infrared (SWIR) spectrometer and AusSpec TSG™ and Grasswood Geoscience Ltd. MinSpec4 software. SWIR analyses were taken at 1-m intervals for every stratigraphic section measured. Diagenetic phyllosilicates were separated from selected samples by crushing, ultrasound disintegration, and centrifugation for identification by X-ray diffraction (XRD) using a Philips X-Pert instrument at Queen's University, Canada.

4. Sedimentology and sequence stratigraphy of the Thelon Formation at Boomerang Lake

Four major lithofacies and several sub-facies are recognized in Thelon Formation sandstones at Boomerang Lake (Table 1; Figs. 3 and 4) and form four facies associations. All lithofacies were

Table 1
Description and interpretation of lithofacies.

Lithofacies	%*	Description	Interpretation
1. Breccia	<1	Clast supported cobble breccia; clasts are angular and are dominated by G-trend metasedimentary basement rocks; matrix is very poorly-sorted angular lithic wacke with minor (<5%) medium to coarse, moderately sorted quartz arenite; structureless; restricted to G-trend, where it exclusively overlies gneissic granitoid basement rocks that are in faulted juxtaposition with metasedimentary rocks	Breccia was deposited in talus slopes along faulted bedrock scarps by rock fall (e.g. Flint et al., 1986; Blair and McPherson, 1994); minor quartz arenite percolated into near-surface interstices upon winnowing by overland flow (Blair and McPherson, 1994)
2. Conglomerate	<5	Matrix-supported cobble conglomerate; clasts are subangular to rounded, granule- to cobble-sized, and are dominated by quartzite with minor schist on G-trend; matrix is very poorly- to moderately sorted sublitharenite to quartz arenite; stratification, grading, imbrication or other sedimentary structures were not observed	Conglomerate formed thin cobble to gravel beds at the bases of fluvial channels (e.g. Hein and Walker, 1977)
3. Sandstone	3a	30 Coarse pebble-bearing sandstone; thickly-bedded (2–8 m), structureless to trough cross-bedded, very coarse to medium-grained, moderately- to poorly-sorted quartz arenite; pebbles range in abundance from 10 to 30% of the rock, are subangular to subrounded, and are dominated by quartzite; sandstone originally contained up to 5% feldspar based on the distribution of rectangular, grain-sized patches of clay that replaced the feldspar; rare, cm-thick intervals of medium to fine, moderately sorted quartz arenite that cap poorly developed, meter-scale fining-upward successions	Pebble sandstone was deposited as channel-fill and laterally- or downstream-accreting compound bars in a high-velocity braided stream with relatively deep channels (e.g. Rust and Jones, 1987; Miall and Jones, 2003)
	3b ₁	35 Granule-bearing sandstone; typically thinly bedded (0.2–0.5 m), stacked, sheet-like bodies of pervasively trough cross-bedded granule to fine-grained, very poorly-sorted quartz arenite; meter-scale intervals of common, large (3–8 cm in diameter), light tan to white, angular to rounded, lithified mudstone rip-ups	
	3b ₂	5 Coarse- to fine-grained sandstone; planar laminated to low-angle cross-stratified, moderately sorted quartz arenite with intervals of lithified mudstone rip-ups; bedsets are 0.2–1.0 m thick and have tops displaying ripple cross-lamination where preserved; composite bedsets of subfacies 3b ₁ commonly grade upward into single bedsets of subfacies 3b ₂	
	3c	15 Medium-grained sandstone; structureless to trough cross-bedded coarse- to fine-grained, moderately- to well-sorted quartz arenite; minor ripple cross-stratification; thin (<0.5 m) intervals containing siltstone to mudstone rip-ups and mm-scale mudstone “stringers”; bedsets are 0.5–1.0 m thick; common meter-scale fining-upward successions that are capped by thin (<0.1 m) fine- to very fine-grained, well-sorted quartz arenite	
	3d ₁	5 Coarse interbedded sandstone; planar laminated to trough cross-bedded very coarse- to medium-grained, poorly-sorted quartz arenite interbedded on a centimeter-scale with medium- to fine-grained, moderately- to well-sorted quartz arenite with some mudstone rip-ups and “stringers”; mudstone rip-ups and stringers become more prevalent in a basinward direction; restricted to F-trend	
	3d ₂	5 Fine interbedded sandstone; planar laminated, trough cross-bedded, and ripple cross-stratified coarse- to fine-grained, poorly-sorted quartz arenite interbedded on a centimeter scale with medium- to very fine-grained, moderately sorted quartz arenite with common mudstone rip-ups and “stringers”; thin (<2 cm) intervals of mudstone with desiccation polygons and curled-up mud chips; restricted to F-trend	
4. Fine-grained sandstone and mudstone	<5	Low-angle to trough cross-stratified medium- to fine-grained, moderately sorted quartz arenite interbedded with very fine-grained quartz arenite to mudstone; cm-scale flame structures and sand injections into mudstone are present; successions are sporadically punctuated by thin (<1 m) intervals of matrix-supported cobble to pebble breccia and conglomerate; bedsets are 0.5–1.5 m thick and display some poorly developed fining-upward successions; restricted to G-trend overlying Lithofacies 1	Fine-grained sandstone to mudstone was deposited at or near a local base level such as a playa lake (e.g. Flint et al., 1986) or a “rift” lake (Scholz et al., 1990); sporadic breccia and conglomerate beds may be sheetflood deposits produced by brief, intense events such as flash floods

* Indicates approximate percentage of the total thickness of all lithofacies.

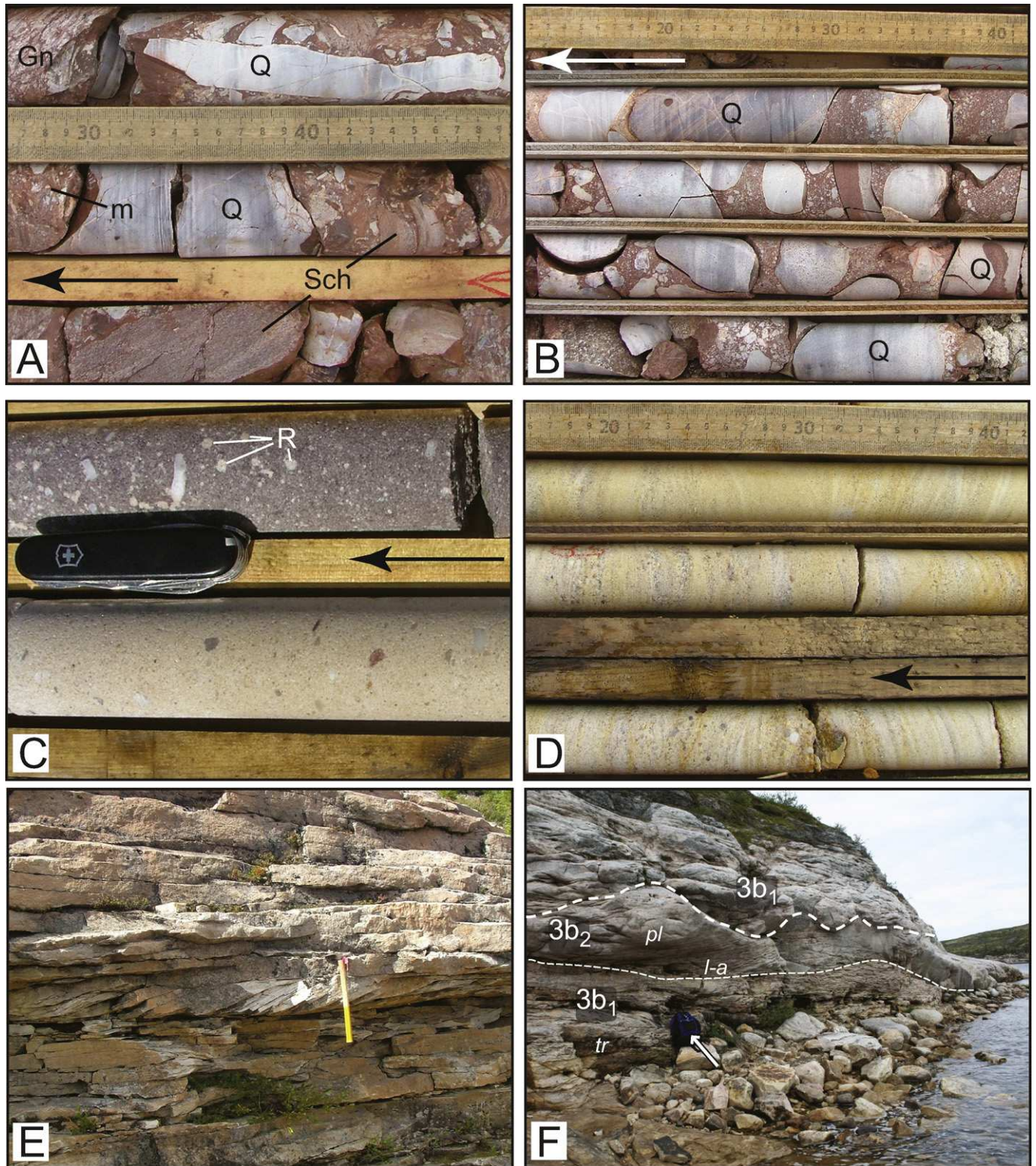


Fig. 3. A. Lithofacies 1 breccia. Clasts are angular and dominated by locally basement-derived metasediments (Q=quartzite; Sch=schist) with minor gneissic granitoids (Gn). Matrix (M) is very-poorly sorted. Black arrow indicates stratigraphic younging direction (drill hole BL07-67). B. Lithofacies 2 conglomerate. Clasts are rounded and dominated by quartzite (Q). White arrow indicates stratigraphic younging direction (drill hole BL92-50). C. Lithofacies 3a pebbly sandstone, displaying pebbles of quartzite. R = diagenetic reduction spots. Black arrow indicates stratigraphic younging direction (drill hole BL07-70). D. Lithofacies 3b₁ granule sandstone, showing very poor sorting and trough cross-beds. Black arrow indicates stratigraphic younging direction (drill hole BL92-50). E. Outcrop of Lithofacies 3b₁, displaying typical thin, broadly lenticular bedding with concave-up, erosive bases. Hammer is approximately 50 cm long (outcrop Th08-7). F. Outcrop showing a vertical transition (light dashed line) from trough cross-bedded (*tr*) sandstones of Lithofacies 3b₁ to low-angle cross-stratified (*l-a*) and planar laminated (*pl*) sandstones of Lithofacies 3b₂. The top of Lithofacies 3b₂ is erosively truncated (heavy dashed line) by the overlying bed of Lithofacies 3b₁. Arrow points to backpack for scale (outcrop Th08-9).

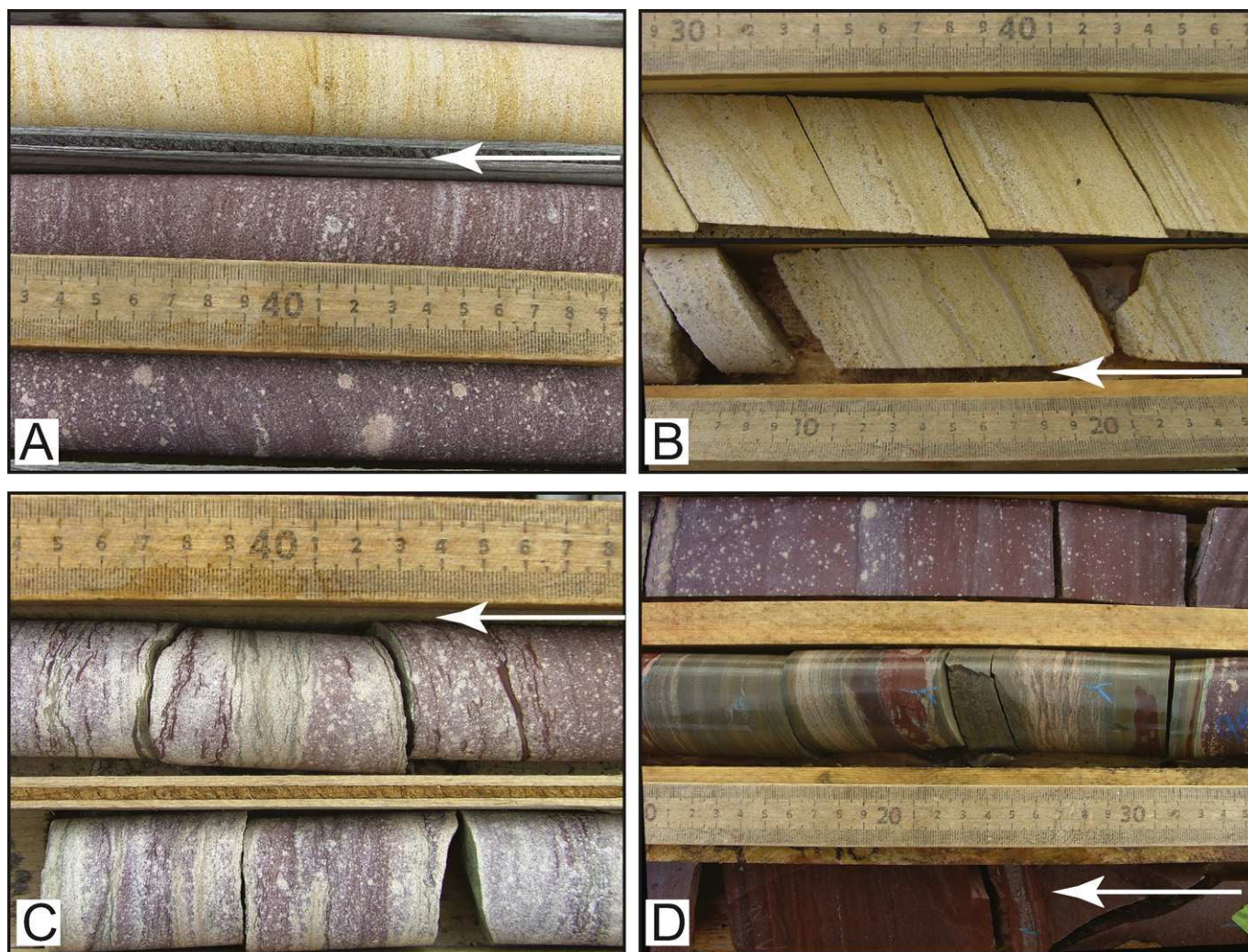


Fig. 4. A. Lithofacies 3c sandstone, showing coarse to medium grain size, well to moderate sorting, and trough cross-beds. White arrow indicates stratigraphic younging direction (drill hole BL92-50). B. Lithofacies 3d₁, showing cm-scale interbedding of fine-grained, well-sorted sandstone and very coarse-grained, poorly-sorted sandstone (top – drill hole BL06-61; bottom – drill hole BL06-60; white arrow indicates stratigraphic younging direction for both photos). C. Lithofacies 3d₂, fine-grained sandstone with mudstone rip-ups and stringers (drill hole BL92-48). D. Lithofacies 4 fine-grained sandstone (top row) interbedded with mudstone and ripple cross-laminated siltstone (bottom row). White arrow indicates stratigraphic younging direction (drill hole BL06-64).

described from diamond drill core, with the exception of Lithofacies 3b sandstone that was observed in both core and outcrop.

4.1. Lithofacies associations

There are four facies associations (FA) in Thelon Formation sandstones at Boomerang Lake. They are titled FA-1–FA-4.

The FA-1 comprises breccia (Lithofacies 1) that is overlain by sandstones and mudstones (Lithofacies 4). The distribution of FA-1 is restricted to the G-trend, and within G-trend is only present above the unconformity over gneissic granitoids that occur in the hanging wall of a basement fault zone. The fault zone currently displays a reverse sense of motion (Fig. 5a). This displacement occurred post-Thelon Formation deposition and suggests that the hanging wall was at least 20 m lower during deposition and likely normally displaced, creating depressions in which FA-1 was deposited. The abundance of footwall-sourced metasedimentary pebbles to cobbles in these units is further support for this depositional configuration.

The FA-2 comprises conglomerate (Lithofacies 2) and pebbly sandstone (Lithofacies 3a). This facies association displays rare, poorly developed channel storeys, and represents the generally coarse-grained, amalgamated remnants of bedforms deposited

near the bases of relatively deep, high-energy braided streams. On the G-trend, FA-2 overlies both the basal unconformity and the alluvial fan facies association, and becomes up to 195 m thick in a basinward direction (Fig. 5a–c). On the F-trend, FA-2 overlies the basal unconformity and also occurs at stratigraphically higher positions (Fig. 5d). It attains a thickness of at least 35 m towards the basin margin, and generally thins in a basinward direction where intersections are 3–25 m thick.

The FA-3 is composed of Lithofacies 3b. This facies association displays better-preserved channel storeys, represented by the lithofacies assemblage 3b₁ and 3b₂, which aggradationally stack to form deposits that are hundreds of meters thick (Figs. 5b, c). The predominantly coarse-grained sandstones in this facies association were deposited in high-energy braided streams that were probably shallower when compared to those in FA-2, based on decreased bedset thicknesses in Lithofacies 3b (Table 1). The FA-3 is dominant on the G-trend, where it is at least 200 m thick and overlies chiefly FA-2. It is less widespread on the F-trend, where it overlies FA-2 with thicknesses of at least 90 m.

The FA-4 comprises sandstone (Lithofacies 3c) and interbedded sandstone (Lithofacies 3d). The former lithofacies displays common, relatively well-preserved channel stories that were deposited in lower-energy, shallow braided streams, based on the gener-

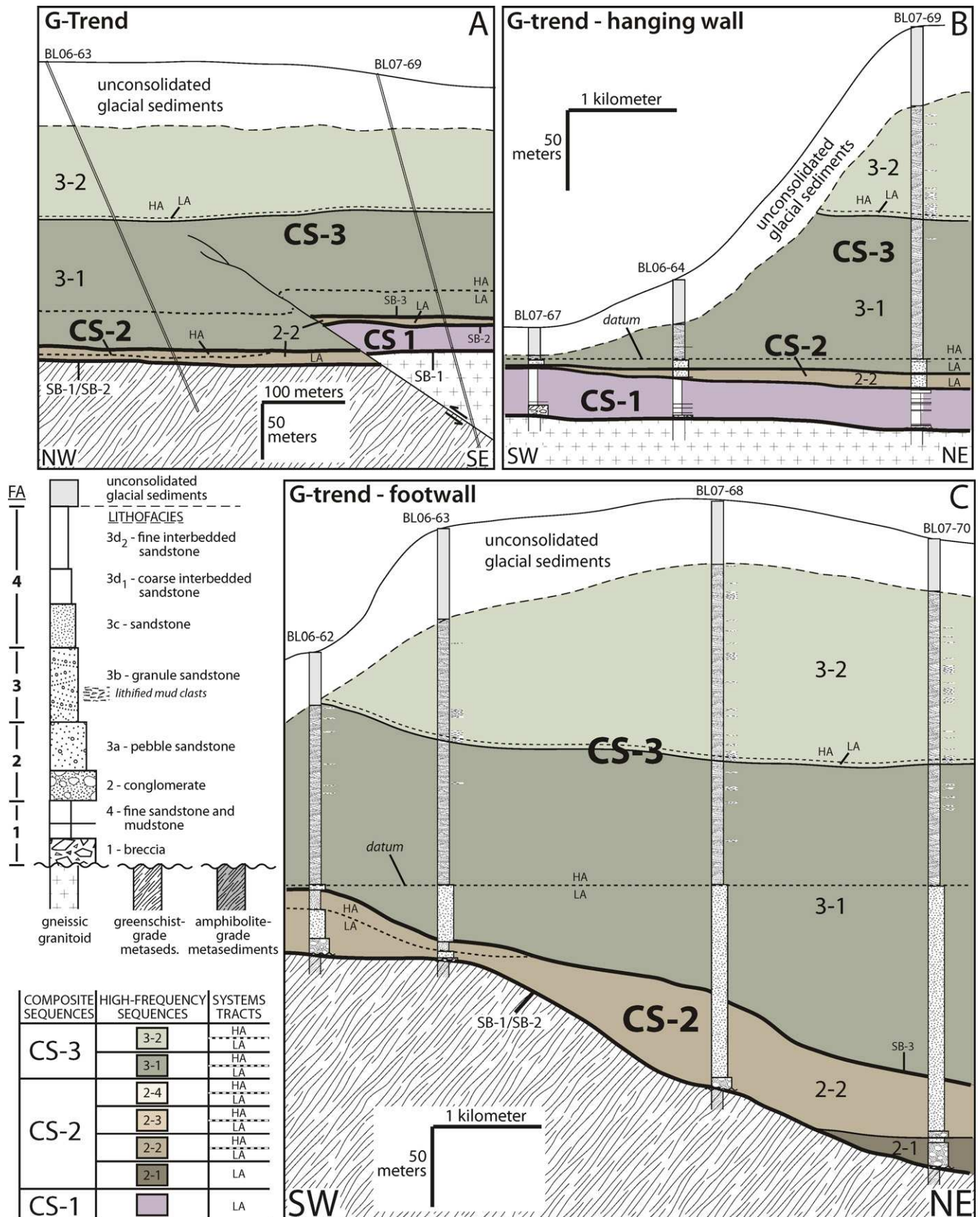


Fig. 5. Sequence stratigraphy of the Thelon Formation at Boomerang Lake. Longitudinal section lines on both the F- and G-trends are traced by the EM conductors shown in Fig. 2. A. Cross-section of G-trend. See Fig. 2 for location of section line. B. Longitudinal section of G-trend hanging wall. C. Longitudinal section of G-trend footwall. D. Longitudinal section of F-trend. The prefix "BL" is omitted from all drill hole labels for clarity. Fault symbol schematically shows where faulting at the basal unconformity was observed in drill core. SB = composite sequence boundary; HA = high-accommodation systems tract. LA = low-accommodation systems tract. FA = facies association.

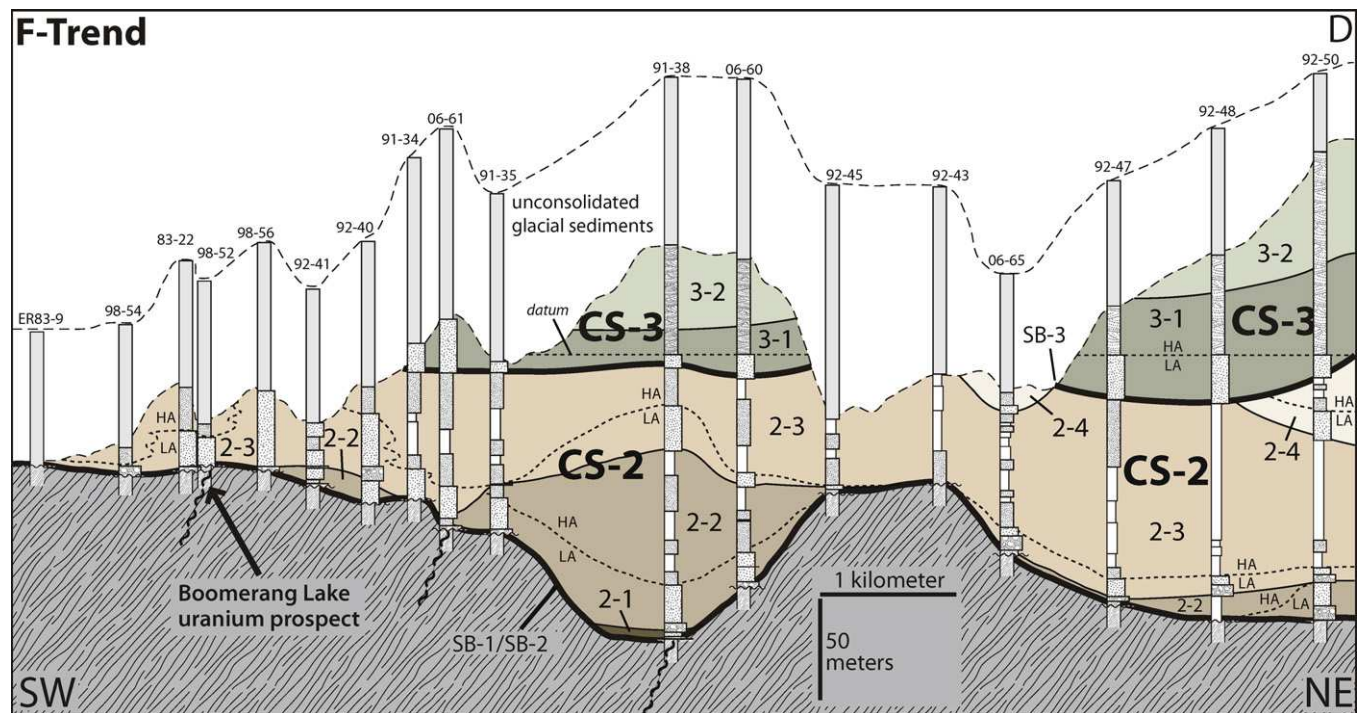


Fig. 5. (Continued).

ally finer-grain size, better-sorting, and thin nature of the bedsets (Table 1). Channels were possibly isolated from one another by the sediments of Lithofacies 3d, which were deposited in shallow channels to unconfined sheetfloods under conditions of variable discharge, based on the variable grain size and sedimentary structures, and thinly bedded nature of this lithofacies. The FA-4 is up to 80 m thick in a basinward direction on the F-trend, and has limited distribution on the G-trend with a maximum thickness of 12 m. On both trends this facies association principally overlies FA-2, and rarely overlies the unconformity on paleotopographic basement highs.

4.2. Paleocurrents

Paleocurrents were measured on trough cross-strata, ripples, and imbrication of mud clasts in outcrop exposures of Lithofacies 3b. Paleocurrent azimuths range from 180–275°, with a mean paleoflow direction around 230° (Fig. 2). Rainbird et al. (2003) reported a similar azimuthal range for the Thelon Formation in the southwestern Thelon Basin, and infer a westerly- to southwesterly-inclined regional paleoslope.

4.3. Sequence stratigraphy of the Thelon Formation at Boomerang Lake

The concepts of sequence stratigraphy, originally defined in strata deposited in marine to coastal environments (Mitchum et al., 1977; Van Wagoner et al., 1988), are applicable to terrestrial fluvial environments in which floodplains develop and are preserved, where the proportion of channel sandstones to overbank fines can help delineate systems tracts (Posamentier and Vail, 1988; Shanley and McCabe, 1991, 1994; Wright and Marriott, 1993). Application of sequence stratigraphic models to fluvial-dominated successions has also been facilitated where indicators of relative sea level are present such as intercalated marginal-marine to marine sediments and coal beds (Shanley and McCabe, 1991; Olsen et al., 1995; Van Wagoner, 1995; Strand, 2005; Ambrose et al., 2009), and by

the recognition of paleosols (Wright and Marriott, 1993; Aitken and Flint, 1995; McCarthy and Flint, 1998; Atchley et al., 2004; Cleveland et al., 2007; Fanti and Catuneanu, 2010). Correlation in fluvial-dominated successions has also been aided where laterally extensive outcrop is available so that surfaces can be traced and fluvial architectural elements can be discerned (McLaurin and Steel, 2007; Leleu et al., 2009). As such, sequence stratigraphic models are adapted with difficulty to Proterozoic fluvial successions such as the Thelon Formation in which deposition occurred predominantly in low-sinuosity, bedload-dominated streams (Schumm, 1968; Cotter, 1978) not typically associated with the development of mud-rich floodplains. Additionally, coeval marine deposits are not known in the Thelon Formation, it does not display discernable paleosols, and is not well-exposed in outcrop. The Thelon Formation at Boomerang Lake is, however, well-exposed in numerous, relatively closely spaced drill cores on both F- and G-trends, allowing for the recognition of a hierarchy of lateral surfaces (cf. Catuneanu et al., 2005).

4.3.1. Major bounding surfaces and packages

Major bounding surfaces display similar characteristics to sequence boundaries, as they represent periods of significant erosion and incision, mark changes in depositional environments, and are laterally extensive and recognized throughout the study area. Therefore the strata bounded by these surfaces are regarded as depositional sequences (Mitchum et al., 1977). However, the Thelon Formation sequences defined in this study contain nested internal discontinuities, and are better described as composite sequences (Mitchum and Van Wagoner, 1991).

Composite Sequence 1 (CS-1) is present only in the G-trend hanging wall section and comprises strata of the alluvial fan facies association. The base of CS-1 is Sequence Boundary 1 (SB-1) that marks the unconformity between older metamorphic basement rocks and younger Thelon Formation sandstones (Figs. 5a–d). SB-1 overlies a well-developed, regional regolith that penetrates up to 100 m into basement rocks (Gall, 1994) and was developed during subaerial exposure and chemical weathering by low-temperature,

low-latitude meteoric waters (Beyer et al., 2010). Up to 80 m of relief was developed on the unconformity on the F-trend during exposure (Fig. 5d).

Composite Sequence 2 (CS-2) is predominant on the F-trend but much thinner on the G-trend, and is composed of strata of FA-2 and FA-4. The base of CS-2 is SB-2, which is discerned from SB-1 in the G-trend hanging wall (Figs. 5a, b). In these exposures, SB-2 is a sharp, erosional surface that separates fine sandstone and rippled to laminated siltstone (Lithofacies 4) of FA-1 below from quartzite cobble conglomerates and pebbly sandstones (Lithofacies 2 and 3a) of FA-2 above. This marks a profound change in depositional environments, with filling of inter-fan paleotopographic lows before high-energy braided channels migrated over the fan deposits.

Composite Sequence 3 (CS-3) is discontinuously distributed on the F-trend (due to later erosion), predominant on the G-trend, and comprises strata of FA-2 and FA-3. The base of CS-3 is SB-3, which is recognized on both the F- and G-trends, and is a widespread surface of fluvial incision. SB-3 is placed where finer-grained and more thinly bedded sandstones of FA-4 are conspicuously truncated by thickly bedded pebbly sandstone (Lithofacies 3a) of FA-2 on both the F- and G-trends (Figs. 5a–d). Deep incision on G-trend resulted in the juxtaposition of Lithofacies 3a on either side of SB-3, making recognition of the surface difficult (Figs. 5a–c). In three intersections, SB-3 is marked by a quartzite cobble lag that is only a few clasts thick, and in two other intersections it is marked by sharp surfaces across which increases in bedding thickness occurs.

4.3.2. Minor bounding surfaces and packages

Minor bounding surfaces are placed where significant changes in fluvial style occur, indicated by widespread lithofacies dislocations within composite sequences. Previous sequence stratigraphic interpretations of fluvial-dominated strata have used the term 'fluvial aggradation cycles' (FACs) and FACSETs to describe nested successions within sequences, but rely heavily on paleopedological characteristics in fine-grained overbank sediments to help determine bounding surfaces (Atchley et al., 2004; Cleveland et al., 2007) and are not readily applicable to the Thelon Formation. Thelon Formation strata that are bounded by minor surfaces are instead referred to as high-frequency sequences (Mitchum and Van Wagoner, 1991).

CS-2 is composed of four high-frequency sequences (HFS), designated as HFS 2–1 through HFS 2–4 (Figs. 5a, c, d). HFS 2–1 and 2–2 are present on both F- and G-trends, with HFS 2–1 restricted to the deepest positions in the basin on both trends. HFS 2–3 and 2–4 are present only on the F-trend, with the former showing widespread distribution across the entire transect, and the latter showing limited distribution towards the northeast. The bases of HFS 2–1 to 2–3 are sporadically marked by relatively thin intervals of Lithofacies 2 conglomerates, and the basal bed of HFS 2–4 contains cm-scale, angular, fine-grained sandstone intraclasts.

CS-3 comprises two high-frequency sequences, designated as HFS 3–1 and HFS 3–2 (Figs. 5a–d). The base of HFS 3–1 is coincident with SB-3, and HFS 3–2 begins at the base of a ca. 6 m thick interval of granule to pebble sandstone with abundant, large (cm-thick), lithified muddy rip-ups. Above this surface, beds that contain lithified muddy rip-ups become more abundant than in HFS 3–1. HFS 3–1 and 3–2 are recognized on both F- and G-trends, but appear much thinner to the south on the F-trend.

4.3.3. Systems tracts

Systematic vertical lithofacies variability is observed within HFS in the Thelon Formation. Specifically, intervals that are tens of meters thick have basal units of FA-2 overlain by units of FA-3 or FA-4 (Figs. 5a, c, d), representing an overall upward decrease in the thickness of beds and bedsets, grain size, and the degree of channel belt amalgamation. All of these characteristics are likely

sedimentary responses to changes in the creation and filling of accommodation based on similarities to fluvial sequence stratigraphic models (cf. Miall, 1996, figures 13.5 and 13.6). Traditional systems tracts (Posamentier et al., 1988; Van Wagoner et al., 1990) that link such responses to changes in relative sea level are not applicable, and are substituted by low-accommodation versus high-accommodation systems tracts (Martinsen et al., 1999; Plint et al., 2001; Arnott et al., 2002; Catuneanu et al., 2009).

The low-accommodation (LA) systems tract comprises FA-1 and FA-2. Based on the localized distribution of FA-1, which is present only within the occurrence of CS-1 adjacent to a basement-rooted fault, it can be inferred that this facies association owes its preservation to space created by fault displacement, while the remainder of the study area was presumably under a regime of zero to low-accommodation. Low-accommodation characteristics of FA-2 include consistently coarse grain size, massive to cross-bedded sandstone lithologies with basal conglomeratic lags, poorly preserved channel storeys, and negligible preservation of fine-grained sediments. On the F-trend, LA systems tracts are prevalent towards the basin margin and taper to the east in a basinward direction (Fig. 5d). On the G-trend, however, LA systems tracts are well-preserved downdip and thin towards the basin margin to the west (Fig. 5a–c).

The high-accommodation (HA) systems tract is represented by FA-3 and FA-4. The latter strata display better preservation of channel storeys and fine-grained sediments, and a greater degree of channel belt isolation, whereas the former contains sheet-like strata that display aggradational stacking geometries. HA systems tracts thicken to the east in a basinward direction on both the F- and G-trends (Fig. 5b–d).

Martinsen et al. (1999) coined the term 'expansion surface' to describe surfaces or narrow zones that separate LA from HA systems tracts and that mark rapid changes in accommodation. Expansion surfaces are stratigraphically significant in the Thelon Formation and are readily correlated across both the F- and G-trends. For example, a prominent, widespread expansion surface is present in HFS 2–3 and is marked in several drill holes by an abrupt transition from Lithofacies 3a pebbly sandstone to Lithofacies 3d interbedded sandstone (Fig. 5d).

4.4. Interpretive depositional model for the western Thelon Basin margin

4.4.1. Composite Sequence 1: localized, fault-bounded alluvial fans and lakes

SB-1 represents the uplift and subaerial exposure of basement rocks prior to Thelon Formation deposition, which resulted in the development of a regionally extensive paleosol (Gall, 1994) and the incision of valleys (Fig. 5d). The initial stage of the Thelon Formation is recorded by normal-sense movement along basement-rooted faults that provided local accommodation for CS-1. Fault displacement probably did not exceed a few tens of meters based on the thickness of CS-1, and may have resulted from far-field stresses not directly associated with basin formation. Rockfalls off uplifted basement scarps were likely the source of Lithofacies 1 breccia, which accumulated in talus cones that partially filled fault-related depressions (cf. Flint et al., 1986). The depressions later hosted shallow lakes where the fine-grained sandstones and mudstones of Lithofacies 4 were deposited (Fig. 6a, b). It is unclear whether continued fault-related subsidence resulted in the formation of these lakes, or whether they represent a transition from an arid to a humid climate regime. A climatic origin is preferred, as the absence of CS-1 from the majority of the study area suggests that little to no accommodation was created regionally and the influence of regional tectonism in creating accommodation was probably minimal at this time.

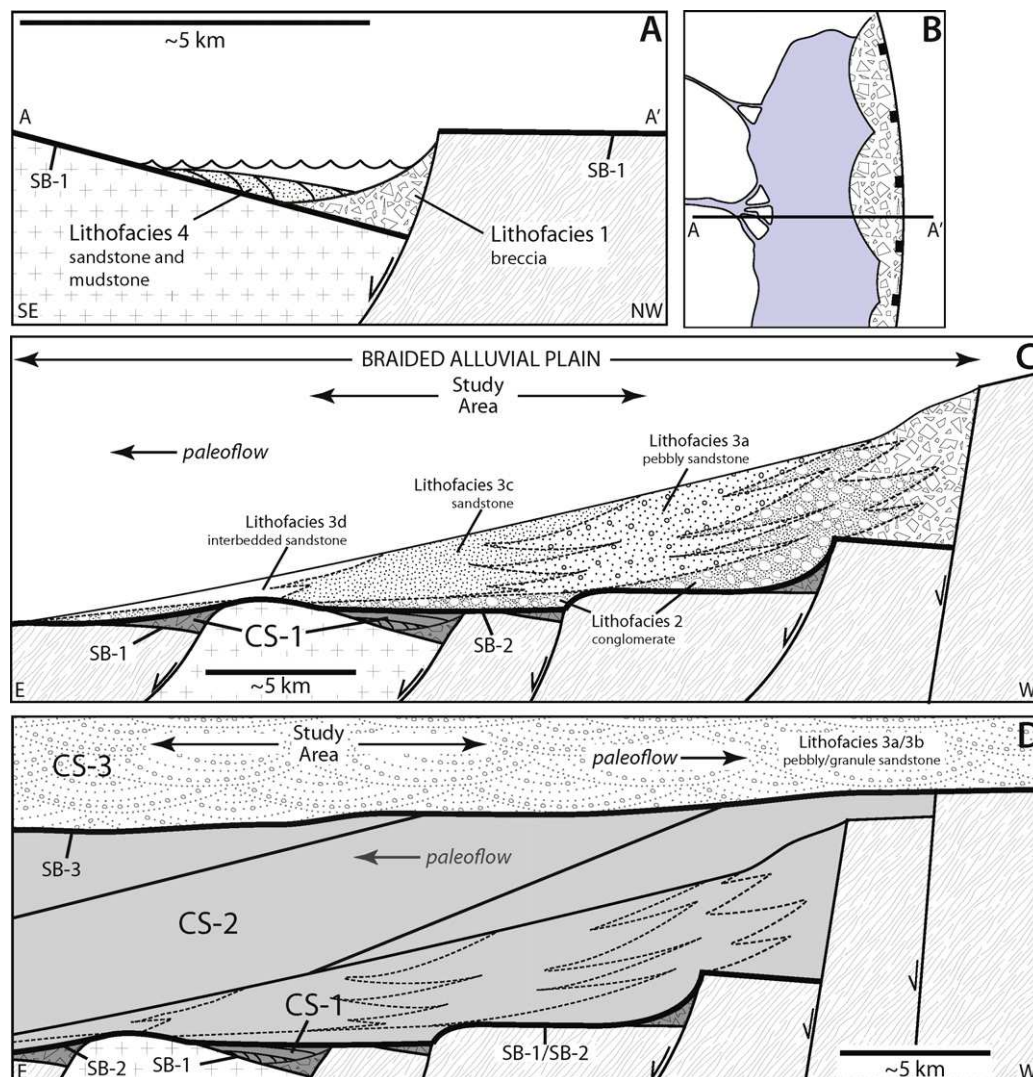


Fig. 6. A. Schematic cross-section displaying fault-related depositional environment for CS-1. See Fig. 6B for plan view. B. Plan view of Fig. 6A. Modified from Scholz et al. (1990). C. Schematic cross-section depicting development of braided alluvial plains during the deposition of CS-2. D. Schematic cross-section showing deposition of CS-3 in regional braid plains, which formed in response to post-Trans-Hudson crustal cooling and subsidence. Vertical exaggeration in all cross-sections is approximately 50 times.

4.4.2. Composite Sequence 2: basin-margin braided alluvial plains

SB-2 marks the transition from sedimentation in local, fault-related zones to a depositional system where significant accommodation was created and filled by strata of CS-2. Where well-preserved on F-trend, CS-2 is constructed of at least four high-frequency sequences that document fluctuating rates of creation of accommodation during this period. Accommodation was initially slow, as HFS 2–1 is represented solely by LA systems tracts that are restricted to paleotopographic lows, and increased through time based on the successively higher proportions of HA systems tracts in HFS 2–2 to 4 (Fig. 5d). Accommodation may have been provided by the extension of basin-bounding faults that occurred as the western Thelon Basin began to subside. HFS may be the sedimentary response to pulses of displacement along the faults that would have exposed basement source areas and steepened the basin margin. Based on the thickness of HFS, total displacement along bounding faults was probably at least several tens of meters. These bounding faults may have been located many kilometers from the study area, as thick successions of source-proximal facies such as breccias or conglomerates were not observed (Fig. 6c).

Upward fining and thinning of bedsets within HFS of CS-2 was probably a reflection of downstream fining and flow dispersion by channel bifurcation along a braided alluvial plain (*sensu* Rust, 1978) that sloped basinward from basement highlands (Fig. 6c). An eastwardly-dipping paleoslope is indicated by the downstream fining trend in HFS 2–3 (Fig. 5a), which is widespread and represents a time-equivalent transect along the alluvial plain. Fluctuating discharge and the influence of both streamflood and sheetflood processes in distal portions of the fan, indicated by Lithofacies 3d, would have been favored in pre-vegetation Paleoproterozoic times due to decreased bank cohesion and increased rates of run-off (Friend, 1978; Eriksson et al., 2006).

On the G-trend, FA-4 is poorly preserved relative to F-trend, suggesting that G-trend may have occupied more proximal portions of the braided alluvial plain in an area of higher paleotopography. This facies association is prevalent on F-trend, which probably occupied more distal portions of the braided alluvial plain in areas of lower paleotopography that were repositories for fine-grained sands and muds. The predominance of paleotopography on depositional environments such as alluvial fans and braided alluvial plains in CS-1 and CS-2 is consistent with the influence of extensional tectonics during the early stages of western Thelon Basin

formation. Basin-margin extensional faulting would have also facilitated the substantial downstream fining observed along braided alluvial plains, which occurred over a relatively short distance of 10–15 km in HFS 2–3 (Fig. 5d), by the creation of substantial accommodation over a relatively short distance (cf. Dalrymple, 2010). An extensional tectonic regime in the western Thelon Basin may be related to a post-1750 Ma, post-Whart Sequence, pre-Barrens Sequence period of extensional tectonics in the eastern Thelon Basin (Rainbird et al., 2003).

4.4.3. Composite Sequence 3: region-wide braid plains

SB-3 resulted from significant fluvial incision across the study area and represents a major change in depositional environment from basin-rimming, eastward-sloping braided alluvial plains to a region-wide braided fluvial depositional system with generally southwesterly-directed paleoflow (Fig. 2; Rainbird et al., 2003). Low-accommodation conditions during the initial stages of CS-3 are documented by occurrence of FA-2 in HFS 3–1 that overlie SB 3 and thin from north on G-trend to south on F-trend. The expansion surface in HFS 3–1 marks the creation of significant accommodation that persisted during deposition of the remainder of CS-3 based on the negligible proportion of low-accommodation systems tracts above this surface. At least hundreds of meters of accommodation were filled with HA systems tract strata of FA-3 that is present on both F- and G-trends, and in outcrop at least 40 km to the north. These thick, widely distributed, consistently coarse-grained and poorly-sorted strata are aggradationally-stacked, perennial braided stream deposits that formed in areally-extensive braid plains (e.g. Rust, 1984; Rainbird, 1992; Fig. 6d). The occurrence of such braid-plains in continental interiors was favored in the Proterozoic due to the assembly of large cratons as a sediment source, and the lack of stabilizing vegetation over such vast areas (Eriksson et al., 1998, 2006; Long, 2004). The establishment of this extensive drainage system in the western Thelon Basin probably accompanied the regional thermal subsidence of attenuated continental crust envisioned by Rainbird et al. (2003) as the root cause for the formation of the Barrens sequence, and is likely linked to the craton-wide deposition of sandstones that accumulated in several other contemporaneous basins in the western Churchill Province (Rainbird et al., 2003) and possibly beyond (Medaris et al., 2003; Hanly et al., 2006).

5. Diagenesis of the Thelon Formation

A paragenetic succession of diagenetic minerals and events based on petrographic observations is shown in Fig. 7, and the distribution of key diagenetic phases and features is shown in Fig. 8.

5.1. Early diagenesis

Early diagenesis refers to shallow sediment burial conditions (ca. 0–3 km), and corresponds to diagenetic stages 1 and 2 in the eastern Thelon Basin (Hiatt et al., 2010). Mechanical and chemical compaction, and the occlusion of primary and secondary intergranular porosity by cementation are the two principal early diagenetic events that affected the Thelon Formation.

Mechanical compaction is the earliest physical process observed. Prior to compaction, however, detrital grains had acquired thin (micron-scale) coatings of Fe-oxide (Fig. 9a). Compaction resulted in common long grain contacts and concavo-convex grain contacts (Fig. 9a). The Thelon Formation also displays evidence of chemical compaction in the form of stylolites. Occurrences range from individual sutures tens of microns thick with relief of less than 100 μm to stylolitic zones that are a few hundreds of microns thick. These features are best observed in thin section, but stylolitic zones are also visible in drill core,

especially older drill core in which the zones appear darker than surrounding sandstone (Fig. 9b). The loci for stylolite development are seams of muscovite that are tens to hundreds of microns thick. Mica-catalyzed stylolitization has been observed by many previous workers and is a probable source of the silica present in quartz overgrowth cements (Heald, 1955; Sibley and Blatt, 1976; Houseknecht, 1988; Björkum, 1996; Oelkers et al., 1996). In the Thelon Formation, Lithofacies 3c and 3d sandstones are preferentially susceptible to stylolitization and can contain dm-scale intervals of closely spaced (cm-scale) stylolites (Figs. 8 and 9b). They are present in finer-grained and better-sorted portions of the remaining two sandstone lithofacies, but are less common and poorly developed. Stylolites are rare to absent in Lithofacies 1, 2 and 4.

Primary intergranular porosity was occluded during early diagenesis by two temporally distinct phases. The first was quartz cement (Q1) as overgrowths, followed by Fe-phosphate (vivianite; P1a) cement. Q1 consists of syntaxial, isopachous to euhedral overgrowths upon detrital quartz grains (Fig. 9a). The original distribution of Q1 is difficult to determine, as most samples display partial to complete resorption of Q1 during subsequent deeper burial. Well-developed and well-preserved Q1 overgrowths that reduce primary porosity to less than 5% are rare, and preferentially affect coarse- to medium-grained, well-sorted sandstones. The timing of Q1 is at least partially contemporaneous with compaction, as some zones with well-developed quartz overgrowths show little compaction, indicating that the quartz cement maintained the pre-compaction grain framework. However, most samples show evidence of weak to moderate compaction that occurred prior to Q1 cementation (Fig. 9a). Vivianite followed Q1, is sparsely distributed in F-trend sandstones, and is best preserved in sandstone with well-formed Q1 overgrowths.

Local development of secondary intergranular porosity is associated with fluorapatite (P1b) cement and later quartz cement (Q2) associated with fractures (Fig. 7). P1b fluorapatite is common in sandstones on both F-trend and G-trend, most often within 10 m of the unconformity. Zoned prisms up to 150 μm long formed subsequent to Q1 based on cross-cutting relationships in thin section, and partially to entirely filled local secondary porosity (Fig. 9c). Q2 cement is associated with fractures displaying anastomosing or “horsetail” morphology that cross-cut Thelon Formation sandstones. Offsets on the order of centimeters to decimeters are observed across individual fractures that are centimeters wide, and across meter-scale zones of composite, multi-generational fractures. The fractures strike generally northwesterly and are steeply dipping. Q2 quartz cross-cuts Q1 quartz overgrowths and can display extensive resorption during later diagenesis.

5.2. Peak diagenesis

Peak diagenesis refers to deep sediment burial conditions (ca. 3–5 km), and corresponds to diagenetic stage 3 in the eastern Thelon Basin (Hiatt et al., 2010). The two major peak diagenetic processes affecting the Thelon Formation were the development of extensive secondary intergranular porosity and the occlusion of that porosity by phyllosilicates.

All Thelon Formation samples studied display at least some development of secondary porosity: rare, tightly Q1 cemented sandstones can show between 5 and 10% secondary porosity, and a few sandstone samples near the Boomerang Lake uranium prospect display up to 60% secondary porosity, with complete resorption of Q1 cement, and partial resorption of detrital quartz. The majority of samples display between 20 and 35% secondary porosity developed at the expense of Q1 and P1 cements.

Secondary porosity was occluded by a suite of phyllosilicate minerals during peak diagenesis. Kaolinite cement (K1) was the earliest of these phases and is nearly ubiquitous in the Thelon

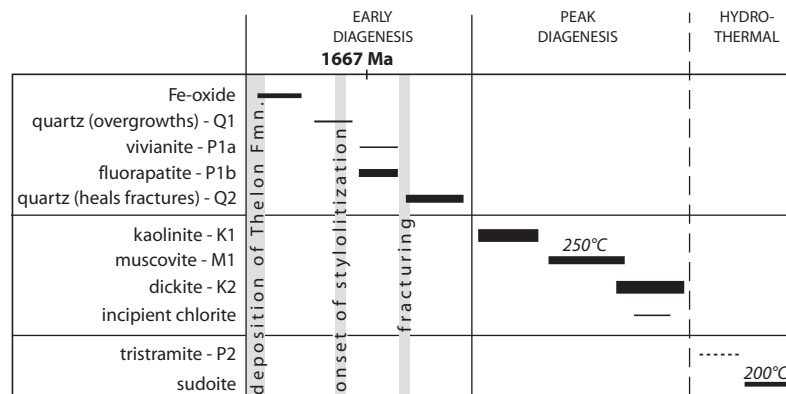


Fig. 7. Paragenesis of diagenetic events and minerals. 1667 Ma age of early diagenesis is inferred from Davis et al. (2008). Temperatures are from Beyer et al. (2010).

Formation. A small proportion of K1 is present replacing detrital feldspar and mica, recognizable in thin section as grain-sized (100 s of microns), striated blocky books with sweeping extinction. The majority of K1 is present filling intergranular secondary porosity as vermiform to book-like aggregates tens to hundreds of microns in size (Fig. 9d), and rarely displays discernable grain-replacive textures. With increasing depth, this variety of K1 kaolinite becomes finer-grained, with books less than 10 μm in size, forming dense cement that completely fills secondary porosity.

Muscovite (M1) variably replaces K1 kaolinite (Fig. 9d). The distribution of M1 is roughly depth-dependant, as more deeply buried samples show an increasing percentage of M1 replacing domains within K1 books. However, fine-grained, dense K1 cement is less susceptible to replacement by M1 (Fig. 9e). M1 after K1 is also concentrated in zones of intense stratabound alteration ranging from a few decimeters to several meters in thickness (Fig. 8), and was observed in several intersections. Sandstones in these intervals are friable due to the abundance of clay minerals, and most often belong to the relatively fine-grained FA-4. Friable, intensely clay-altered sandstones near the Boomerang Lake prospect, and centimeters of clay-altered sandstone gouge present on both trends are associated with faults and fractures that are younger than the stratabound alteration.

Dickite (K2) formed subsequent to M1 muscovite. Samples with high percentages of dickite have masses of equant, blocky K2 filling secondary porosity that are not overprinted by M1 (Fig. 9e). The distribution of K2 is stratigraphically influenced, as it is nearly absent in CS-1, restricted to certain zones within CS-2, but widespread in CS-3 (Fig. 8).

A chlorite-like phyllosilicate was observed altering K1- and M1-altered detrital feldspar and muscovite grains. It follows M1 muscovite paragenetically based on this observation, but relationships with K2 dickite were not observed because this phase is restricted to decimeter- to meter-scale successions of Lithofacies 3c and 3d on F-trend (Fig. 8), where it gives a fine-grained, dark green-speckled appearance to light-colored sandstone in core (Fig. 9f). Based on EMPA, the mineral is not true chlorite, as it is deficient in Mg and Fe, has differing Si/Al ratios relative to typical chlorite, and contains significant K, an element that is not incorporated into true chlorite (Deer et al., 1992; Table 2). Hence this phase is herein referred to as incipient chlorite, as it represents partial chloritization of the host grains.

6. Discussion

6.1. Paleohydrogeology of the Thelon Formation

The paleohydrogeology of the Thelon Formation, that is the hydrogeology of the Thelon Formation during peak diagenesis and

into the hydrothermal alteration phase, was determined using an interpretive process in which the pore space evolution was reconstructed based on the distribution and paragenesis of diagenetic minerals and compaction features determined petrographically and from SWIR and XRD. The paleohydrogeology of the Thelon Formation must be determined in such a way because present-day petrophysical properties of Thelon Formation sandstones are not a proxy for the paleohydrogeology of these sandstones during peak diagenesis, as they have been affected by subsequent late diagenetic, hydrothermal and tectonic events that resulted in the addition of new mineral phases, and dissolution of previously existing phases. Three paleohydrogeological units in the Thelon Formation are recognized. These are diagenetic aquifers, diagenetic aquicludes, and diagenetic aquitards.

Diagenetic aquifers are strata that had sufficient porosity and permeability during peak diagenesis to conduct basinal fluids throughout peak diagenesis and into the hydrothermal alteration phase (Hiatt et al., 2003). K2 dickite characterizes diagenetic aquifers in the Thelon Formation at Boomerang Lake, as it is the paragenetically latest mineral to form during the peak diagenetic stage (Figs. 7 and 9e), and indicates sandstones were conducting fluids throughout peak diagenesis. This interpretation is corroborated by studies in petroleum reservoir sandstones in which the transformation from kaolinite to dickite is favored in rocks with high water/rock ratios (W/R), which are effectively high porosity and permeability (e.g. Lanson et al., 2002; De Bona et al., 2008). It is also supported by the calculated stable isotopic composition of fluids in equilibrium with K2, which tend towards lower (more fluid-buffered) $\delta^{18}\text{O}$ values ($\delta^{18}\text{O}_{\text{fluid}} = 4.3\text{--}9.2\text{‰}$) when compared to the generally higher $\delta^{18}\text{O}$ values ($\delta^{18}\text{O}_{\text{fluid}} = 7.6\text{--}9.4\text{‰}$) of fluids in equilibrium with the earlier assemblage K1 kaolinite + M1 muscovite, which are more rock-buffered (Beyer et al., 2010). The distribution of K2 in Thelon Formation sandstones does not support a depth/temperature influence on the formation of dickite (Ehrenberg, 1990; Lanson et al., 1996; Beaufort et al., 1998), as the more deeply buried CS-2 on F-trend contains significantly less dickite than the overlying CS-3 (Fig. 8).

K2 dickite in the Thelon Formation preferentially occurs in the generally coarser-grained and more poorly-sorted FA-2 and FA-3 (Figs. 5 and 8). Grain-to-grain compaction first affected these sediments based on the presence of common long and concavo-convex grain boundaries, which contributed to early quartz (Q1) cementation as a result of pressure solution. Pervasive cementation by Q1 is not observed, however, and was probably prevented by small percentages of primary detrital clays that were deposited with the sands. It is also possible that pressure solution was inhibited once Q1 began to stabilize the sandstone framework (Ehrenberg, 1990), thus eliminating a source of Si and preventing further Q1 cementation. This allowed the development of extensive secondary

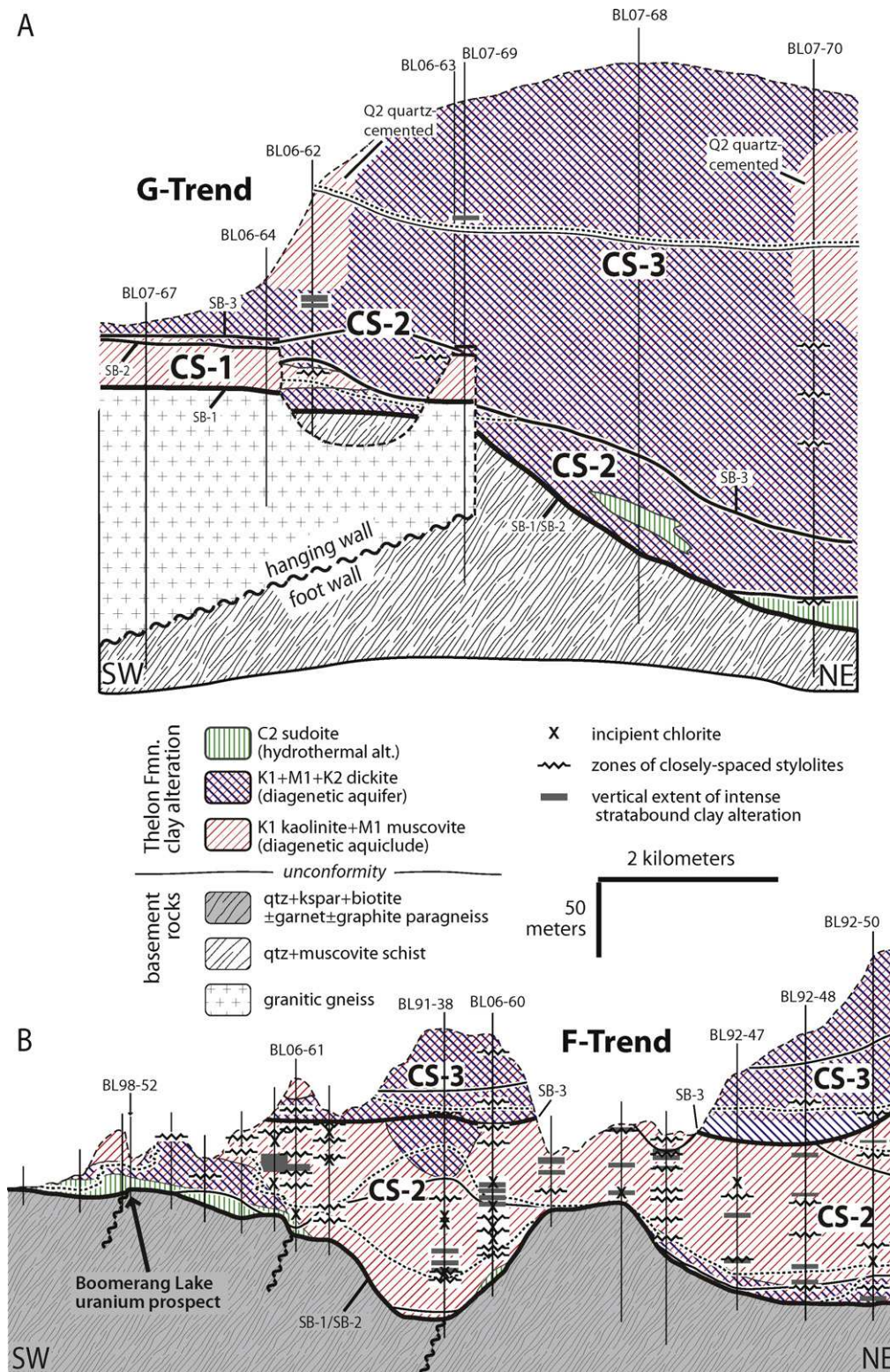


Fig. 8. Distribution of key diagenetic minerals and features in a sequence stratigraphic context. A. Composite longitudinal section of the G-trend hanging wall and footwall. B. Longitudinal section of the F-trend.

intergranular macroporosity during subsequent peak diagenesis as the temperature and reactivity of basinal fluids increased upon deep burial. The reaction between basinal fluids and detrital clays and feldspar produced the assemblage K1 kaolinite followed by M1 muscovite, occluding secondary intergranular macroporosity (Ehrenberg, 1990). A high proportion of macroporosity remained into later peak diagenesis, however, as basinal fluids were still

present to react with K1 kaolinite and remaining detrital feldspar to produce K2 dickite.

Diagenetic aquicludes are strata that experienced a reduction in porosity and permeability during peak diagenesis, and probably did not conduct peak diagenetic basinal fluids upon the onset of hydrothermal alteration. Diagenetic aquicludes are dominated by a K1 kaolinite + M1 muscovite mineral assemblage and only minor K2

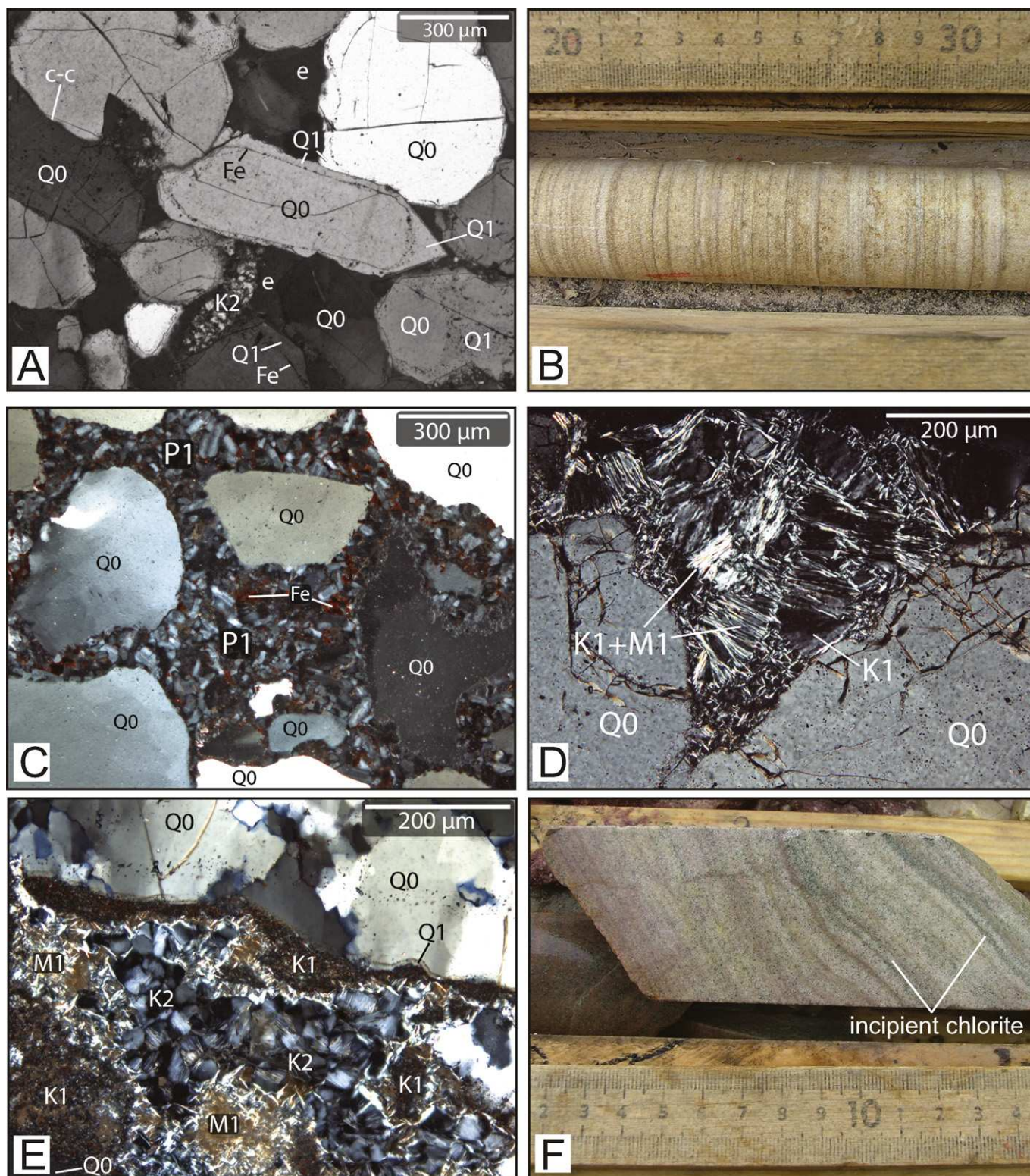


Fig. 9. A. Detrital quartz grains (Q0) show early rims of Fe-oxide (Fe), and concavo-convex contacts (c-c) as a result of mechanical compaction. Euhedral quartz cement (Q1) overgrows Q0 grains. Peak diagenetic dickite (K2) fills weakly-developed secondary porosity. e = epoxy (outcrop Th08-7; cross-polarized light). B. Closely spaced stylolites appear as dark lines in drill core and here are developed in medium- to fine-grained, moderately sorted Lithofacies 3c sandstone (drill core BL98-58). C. Fluorapatite (P1) cement fills secondary porosity. Q1 overgrowths either did not form or were completely resorbed (sample BL07-70-370.4; cross-polarized light). D. Relatively coarse books of kaolinite (K1) fill secondary porosity and are variably replaced by muscovite (M1) (sample BL83-22-80.2; cross-polarized light). E. Concentric occlusion of secondary porosity by peak diagenetic phyllosilicates in Lithofacies 2 conglomerate. Q1 overgrowths are almost completely resorbed in contact with fine-grained K1 kaolinite, which is partially altered by M1 muscovite. The last phase is a coarse kaolin mineral that occludes the pores, and is interpreted as dickite (K2) based on SWIR-guided petrography of Thelon Formation sandstones (sample BL92-50-240.0; cross-polarized light). F. Incipient chloritization of Lithofacies 3d₂ sandstone in drill core, appearing as fine dark "specks" (drill core BL06-60).

Table 2

Average electron microprobe analysis of incipient “chlorite” compared with typical chlorite and muscovite.

Sample	1			2			3		
	Weight %	±		Weight %	±		Weight %	±	
SiO ₂	42.41	1.29		29.80	2.5		48.50	1.42	
Al ₂ O ₃	24.96	3.13		19.20	2.9		34.44	0.91	
FeO	10.18	2.23		7.40	1.1		1.11	0.39	
MnO	0.10	0.03		<D.L.	n/a		0.02	0.02	
MgO	4.40	1.17		21.80	2.7		1.17	0.30	
TiO ₂	1.71	0.43		<D.L.	n/a		0.13	0.20	
Cr ₂ O ₃	<D.L.	n/a		<D.L.	n/a		0.01	0.01	
CaO	0.06	0.02		0.10	0.1		0.09	0.06	
Na ₂ O	0.07	0.02		0.10	0.1		0.12	0.12	
K ₂ O	4.81	0.87		0.10	0.1		9.31	0.75	
Cl	0.06	0.03		n/a	n/a		0.01	0.01	
F	0.26	0.06		n/a	n/a		0.32	0.28	
O≡Cl	0.01	0.01		n/a	n/a		0.00	0.00	
O≡F	0.11	0.03		n/a	n/a		0.18	0.10	
Total	89.03	0.41		82.80	3.40		95.12	1.23	
Atomic proportions									
Number of oxygens	28			28			22		
Tetrahedral sites									
Si	7.90	0.08		6.30	n/a		6.34	0.08	
Al ^{IV}	0.10	0.08		1.70	n/a		1.66	0.08	
Sum	8.00			8.00			8.00		
Octahedral sites									
Al ^{VI}	5.37	0.6		3.07	n/a		3.69	0.05	
Fe	1.59	0.4		1.31	n/a		0.12	0.04	
Mn	0.02	0.01		0.00	n/a		0.00	0.00	
Mg	1.23	0.35		6.89	n/a		0.23	0.06	
Ti	0.24	0.06		0.00	n/a		0.01	0.02	
Sum	8.45			11.27			4.01		
Interlayer site									
Ca	0.01	0.01		n/a	n/a		0.01	0.01	
Na	0.03	0.01		n/a	n/a		0.03	0.03	
K	1.15	0.23		n/a	n/a		1.55	0.13	
Sum	1.19			n/a			1.58		
Anions									
Cl	0.02	0.01		n/a	n/a		0.00	0.00	
F	0.15	0.03		n/a	n/a		0.18	0.10	
OH	15.83	0.03		n/a	n/a		3.82	0.12	
Sum	16.00			n/a			4.00		

Notes: 1 = incipient “chlorite” (Boomerang Lake, Thelon Basin); 2 = clinocllore in sandstone (Wheeler River, Athabasca Basin; Cloutier et al., 2010); 3 = M1 muscovite (Boomerang Lake, Thelon Basin); atomic proportions calculated on an anhydrous basis; <D.L. = below detection limit; n/a = not analyzed or not applicable; OH calculated by subtraction.

dickite, suggesting these units had lower *W/R* relative to diagenetic aquifers that inhibited the formation of dickite. Lower *W/R* in these sandstones is reflected by higher (more rock-buffered) $\delta^{18}\text{O}$ values of fluids in equilibrium with the K1 + M1 assemblage relative to those associated with K2 dickite (Beyer et al., 2010).

The K1 + M1 assemblage dominates the matrix-rich FA-1 and the generally finer-grained, better-sorted FA-4 (Figs. 5 and 8). These facies associations were repositories for silt and clay captured in paleotopographic lows, the latter being deposited in lower-energy depositional environments during high-accommodation intervals of HFS. The increased clay content in these sediments had two major effects on their hydrogeological development, specifically promotion of stylolitization during early diagenesis, and the occlusion of secondary intergranular macroporosity during peak diagenesis.

Diagenetic aquicludes shared similar shallow burial conditions to diagenetic aquifers, based on commonly observed weak to moderate grain-to-grain compaction and variable occurrences of remnant Q1 overgrowths. With further compaction, however, stylolitization occurred in strata with higher percentages of detrital clays. Stylolitization provided an additional source of Si during early

diagenesis and probably promoted a higher degree of Q1 cementation, observed in well-sorted units that are more common in these strata, and likely contributed to the lower *W/R* suggested for diagenetic aquicludes. This is supported by studies of reservoir sandstones in which increased stylolite frequency is correlated with decreased porosity through the physical closure of pores and the redistribution of quartz cement (Bloch et al., 2002; Oelkers et al., 1996; Walderhaug, 1996; Bjørkum et al., 1998). Q2 quartz cement also locally contributed to lower *W/R* in Thelon Formation sandstones, demonstrated by the lack of K2 dickite in two Q2-silicified intervals of drill holes BL06-62 and BL07-70 (Fig. 8).

Diagenetic aquicludes continued to conduct basal fluids during the onset of peak diagenesis based on the widespread secondary intergranular macroporosity. As peak diagenesis progressed, secondary intergranular macroporosity was occluded by K1 kaolinite followed by M1 muscovite. Frequent zones of intense stratabound K1 + M1 alteration (Fig. 8) reflect the greater amount of detrital clays deposited in these sandstones relative to diagenetic aquifers; this contributed to the occlusion of pore networks to the extent that these units could no longer effectively conduct later basal fluids associated with K2 dickite. Strata that do not contain K2

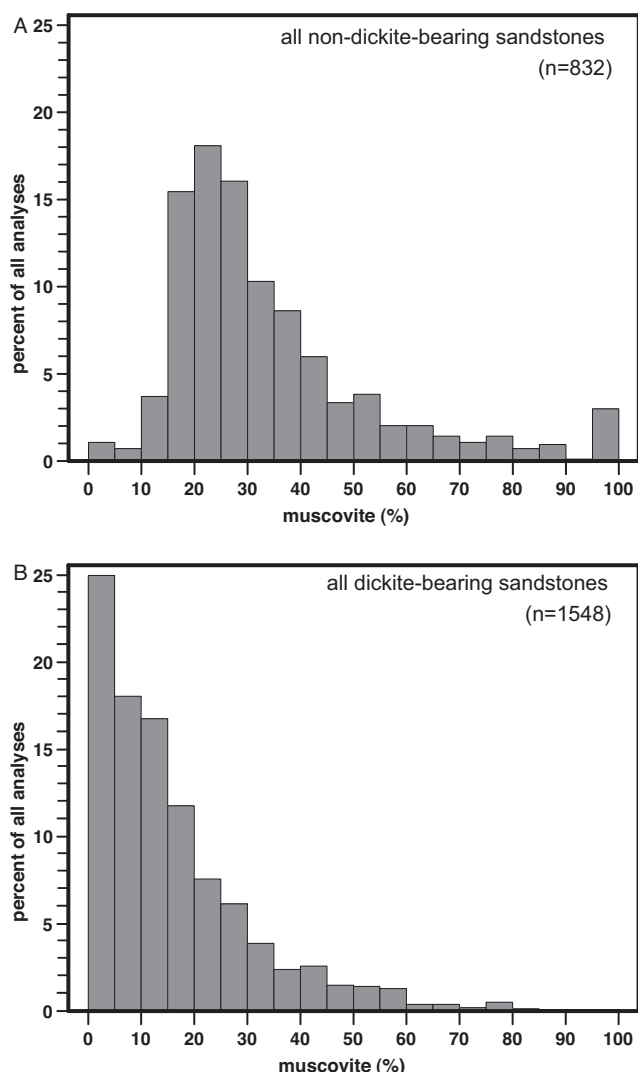


Fig. 10. a. Histogram of muscovite abundance in all non-dickite bearing Thelon Formation sandstone (diagenetic aquicludes), with the highest percentage of samples containing 20–25% muscovite. b. Histogram of muscovite abundance in all dickite bearing Thelon Formation sandstone (diagenetic aquifers), with the highest percentage of samples containing 0–5% muscovite.

show a higher proportion of M1 muscovite based on SWIR analysis (Fig. 10), which may have also been a significant factor in the closure of secondary pore networks, as studies of reservoir sandstones have shown that the intense “illitization” of sandstones can accompany significant reduction of permeability due to the mineral’s efficiency in bridging pore throats (Ehrenberg and Nadeau, 1989; Ehrenberg, 1990).

Increasing hydrogeological isolation within diagenetic aquicludes promoted the accumulation of Mg and Fe ions, likely the product of reactions between remnant basinal fluids occupying secondary intergranular microporosity and detrital components, which were responsible for the incipient chloritization of M1 muscovite. Chloritization does not occur in diagenetic aquifers due to increased W/R that would have prevented the concentration of such reaction products (Fig. 8). Similar relationships between chloritization and permeability have been observed in other siliciclastic basins (Anjos et al., 2003; De Bona et al., 2008).

Diagenetic aquitards are strata that experienced a significant reduction in porosity and permeability during early diagenesis and conducted little peak diagenetic basinal fluids (Hiatt et al., 2003). Typical diagenetic aquitards are clay-dominated rocks such

as shale, and also well-sorted, clay-free sandstones that become pervasively cemented by early diagenetic quartz overgrowths. Mudstone intervals in Lithofacies 4 constitute diagenetic aquitards and contribute to the low permeability of FA-1, but are no more than 2 m thick and are laterally restricted. Additionally, lithofacies composed exclusively of well-sorted, quartz-cemented sandstones are not present. As such, these diagenetic aquitards comprise a minimal component of the Thelon Formation at Boomerang Lake.

6.2. Implications for unconformity-related U exploration

Models for the formation of unconformity-related U deposits require high basinal fluid flux near structurally offset portions of basal unconformities (Kyser and Cuney, 2008), focused by basement paleotopography or confining diagenetic aquitards. At Boomerang Lake, we can predict where potentially high basinal fluids flux zones intersect favorable positions at the unconformity by correlating diagenetic aquifers and aquicludes within the established sequence stratigraphic framework (Fig. 8).

Strata of CS-2 exclusively overlie the unconformity on the F-trend (Fig. 5d). In eastern and central portions of the trend, CS-2 contains relatively thin diagenetic aquifers that overlie the unconformity in paleotopographic lows, but is dominated by relatively thick diagenetic aquicludes composed of FA-4. Towards the basin margin to the west, CS-2 is dominated by relatively thin diagenetic aquifers composed of FA-2, which overlie the Boomerang Lake U prospect. The location of the prospect at the intersection of a re-activated basement fault and the diagenetic aquifers is not surprising from a hydrogeological standpoint. However, the known extent of U mineralization is limited and consists of U-phosphate, a phase not typically associated with unconformity-type U deposits, and was associated with high- $\delta^{18}\text{O}$ fluids reflecting low W/R (Beyer et al., 2010). Additionally, two other locations where faults offset the unconformity and occupy favorable paleotopographic positions along the F-trend (Fig. 7; BL06–61 and BL91–38) do not show intense alteration that would be expected if the faults had conducted basinal fluids. Based on these characteristics of the Boomerang Lake U prospect and the F-trend extension, it is apparent that basinal fluid flow in CS-2 was reduced by relatively thick diagenetic aquicludes, which may have prevented the transport of U in sufficient quantities to form an economic U deposit. Diagenetic aquicludes in CS-2 also likely prevented potentially U-bearing basinal fluids, which were being conducted in diagenetic aquifers of the overlying CS-3, from reaching the unconformity. The high proportion of diagenetic aquicludes in CS-2 and its widespread distribution considerably reduce the prospectivity of the present-day extent of F-trend for unconformity-related U mineralization from a hydrogeological standpoint.

Strata of CS-2 overlie the unconformity on the footwall of G-trend (Fig. 5c). CS-2 is generally thinner here when compared to the F-trend and contains a significantly lower proportion of diagenetic aquicludes. CS-2 is in turn overlain by thick diagenetic aquifers contained in CS-3. Thus, the total thickness of diagenetic aquifers that were potential suppliers of basinal fluids to the unconformity for much of the G-trend is an order of magnitude greater than that on the F-trend. A less ideal hydrogeological configuration is present on the hanging wall of G-trend, where diagenetic aquicludes in CS-1 insulate the diagenetic aquifers of CS-2 and CS-3 from the unconformity (Fig. 5b). While this may have locally influenced basinal fluid flow, the diagenetic aquicludes in CS-1 may have had little influence on regional hydrogeology based on their thin nature and limited areal distribution predicted from the depositional model. Thick successions of strata dominated by diagenetic aquifers in CS-2 and CS-3, and the limited distribution of diagenetic aquicludes make the current extent of G-trend prospective for unconformity-related U mineralization from a hydrogeological standpoint.

6.3. Comparison with the eastern Thelon and Athabasca basins

Evaluation of U-deposit prospectivity and the adaptation of exploration models in the western Thelon Basin can be guided by comparing and contrasting the sedimentologic and paleohydrogeologic evolution at Boomerang Lake with the evolution of the eastern Thelon and Athabasca basins that both host known unconformity-related U mineralization. The Thelon Formation in the western Thelon Basin displays distinct sedimentological differences when compared to its counterpart in the eastern Thelon Basin. In the eastern basin, the Thelon Formation contains distal fluvial/upper shoreface and aeolian facies (Lithofacies 3 and 4, respectively, of Hiatt et al., 2003) that are several tens of meters thick. The Thelon Formation at Boomerang Lake in the western basin does not contain such facies, and suggests a more proximal setting removed from the influences of a shoreline, and dynamic sand-covered fluvial braid plain environments in which aeolian dune fields were not preserved. In this sense the Thelon Formation in the western basin is similar sedimentologically to the lower portions of the Manitou Falls Formation in the Athabasca Basin, (MFb and MFc of Ramaekers, 1990) that were deposited in proximal to distal braided streams (Ramaekers, 1990; Ramaekers and Catuneanu, 2004; Long, 2006; Hiatt and Kyser, 2007).

The sedimentological differences between the Thelon Formation in the western and eastern Thelon Basin resulted in contrasting paleohydrogeological evolution during diagenesis. The generally medium-grained, well-sorted, and clay-free Lithofacies 3 and 4 in the eastern basin became extensively cemented by early diagenetic quartz overgrowths and formed stratigraphically significant diagenetic aquitards that compartmentalized intervening diagenetic aquifers (Hiatt et al., 2003). The lack of these facies in the western basin led to the development of thicker, less compartmentalized, regionally extensive diagenetic aquifers such as those on the G-trend, which are similar to the widespread diagenetic aquifers in the Manitou Falls Formation (Hiatt and Kyser, 2007) of the Athabasca Basin.

The diagenetic mineral assemblages in the eastern and western Thelon Basins are also distinct. Kaolin minerals (kaolinite and dickite) are the predominant peak diagenetic phyllosilicates in the western basin, but are minor in the eastern basin where illite/muscovite is dominant, with the exception of the SE portion of the eastern basin near the Kiggavik U deposit (Renac et al., 2002). This important mineralogical distinction may be a result of differing sediment source areas or processes affecting sediment weathering. As basinal sediments are considered to be the source of U in some models of unconformity-related U deposits (e.g. Kyser and Cuney, 2008), the possibility of differing sediment sources for the eastern and western basin implies that each sub-basin may have distinctly different U metallogenic potentials. Additionally, Renac et al. (2002) described late diagenetic, authigenic K-feldspar and Al–Mg chlorite in the eastern basin that formed from late fluids isotopically resembling evaporated seawater. These conspicuous late phases were not observed at Boomerang Lake, which may reflect the more proximal depositional environments envisioned for the southwestern basin. With respect to diagenetic mineral assemblages, the western Thelon Basin more closely resembles the kaolin-rich Manitou Falls Formation, where the predominant diagenetic mineral is dickite (Zhang et al., 2001).

The sedimentological and diagenetic differences between the eastern and western Thelon Basin noted above indicate that each area was essentially a separate sub-basin, possibly with distinct source areas and differing depositional environments. Additionally, each sub-basin probably had different structural influences and depths of burial, and different levels of water/rock interaction that led to distinct diagenetic paths. The western Thelon Basin evolved more similarly to the eastern Athabasca Basin, and success-

ful exploration models developed there may be directly applicable to the western Thelon Basin based on their similarities.

7. Conclusions

The Paleoproterozoic Thelon Formation in the western Thelon Basin at Boomerang Lake contains four lithofacies and several sub-facies that were grouped into four facies associations, representing deposition in alluvial fan and braided fluvial environments. A sequence stratigraphic interpretation for the Thelon Formation is proposed, based on a relative hierarchy of widespread surfaces exposed in numerous drill holes. The surfaces mark significant sub-aerial exposure or change in depositional environment, and bound three composite sequences and a nested series of high-frequency sequences. Low-accommodation and high-accommodation systems tracts are recognized in most high-frequency sequences, and substitute for traditional systems tracts that are linked to changes in eustatic sea level, proxies for which were not observed in the Thelon Formation.

A depositional model based on the sequence stratigraphic interpretation was derived to explain the evolution of the western Thelon Basin. The oldest composite sequence was deposited as talus and lacustrine sediments in local fault-related depressions that may have been initiated by far-field stresses during the nascent stages of Thelon Basin formation. The next composite sequence represents the first widespread deposition in the area, and comprises strata deposited in braided alluvial plains that drained uplifted basement at the western basin margin. Nested high-frequency sequences are presumed to be individual plains that formed in response to basin-bounding fault displacement and changes in the rate of creation of accommodation. The youngest composite sequence was deposited in regionally widespread braid plains during a period of post-orogenic lithospheric cooling, represented by aggradationally-stacked, consistently coarse-grained strata.

The composite sequence that overlies the Boomerang Lake U prospect on the F-trend is dominated by diagenetic aquicludes that did not conduct U-bearing basinal fluids during the hydrothermal alteration phase. Finer, muddier diagenetic aquicludes accumulated in distal portions of braided alluvial plains, and became isolated from basinal fluid flow during diagenesis due to stylolite-catalyzed quartz cementation and pervasive occlusion of secondary porosity by K1 kaolinite + M1 muscovite, and partial chloritization. Low basinal fluid flux at the Boomerang Lake prospect resulted in restricted, uneconomic U-phosphate mineralization despite previous reports of “fine-grained pitchblende” mineralization (Davidson and Gandhi, 1989). Diagenetic aquifers dominate the G-trend to the north, and likely conducted U-bearing basinal fluids throughout diagenesis, including the hydrothermal alteration phase. These coarse-grained, poorly-sorted strata contained minor primary detrital clay, which inhibited early diagenetic stylolitization and associated quartz cementation, prevented secondary porosity from being highly occluded by peak diagenetic phyllosilicates. Prolonged interaction with basinal fluids resulted in the K1 kaolinite + M1 muscovite + K2 dickite assemblage in diagenetic aquifers. Intersections of re-activated basement faults with the thick diagenetic aquifers of G-trend are the preferred exploration target at Boomerang Lake.

The western Thelon Basin evolved distinctly from the eastern Thelon Basin, and each is considered as a separate sub-basin. The eastern Thelon Basin contains stratigraphically significant, aquitard-prone shoreface and aeolian facies, and displays an illite/muscovite-dominated diagenetic mineral assemblage. In contrast, the western Thelon Basin evolved in a similar fashion to the eastern Athabasca Basin represented by the Manitou Falls Formation based on the predominance of braided fluvial deposi-

tional environments and a kaolin-dominated diagenetic mineral assemblage. Successful exploration methods in the Athabasca Basin may be applicable to the western Thelon Basin based on their similarities, specifically in geological environments as in the case of the G-trend where thick diagenetic aquifers overlie the unconformity.

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