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Journal of Geochemical Exploration 80 (2003) 221–240

JOURNAL OF GEOCHEMICAL EXPLORATION

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Relationships among sedimentology, stratigraphy, and diagenesis in the Proterozoic Thelon Basin, Nunavut, Canada: implications for paleoaquifers and sedimentary-hosted mineral deposits

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Received 3 April 2002; received in revised form 15 November 2002; accepted 30 November 2002

Abstract

The Thelon Basin, Nunavut, Canada, is host to unconformity-type uranium mineralisation and has the potential to host other economic deposits. The Thelon Formation (ca. 1750 Ma) is composed of thick (meters to tens of meters), poorly sorted, trough cross-bedded conglomerate and coarse-grained lithic arenite beds, and to a lesser extent, well-sorted, medium- to coarse-grained quartz arenite beds. Relatively rare, 1–12 cm thick, clay-rich siltstones to fine-grained sandstone layers punctuate the coarser lithofacies. Based on regional analysis of drill cores and outcrops, multiple unconformity-bounded sequences are defined in this fluvial-dominated sedimentary succession. Stratigraphic correlations are based on detailed lithofacies analysis, distinct changes in fining-upward cycle thickness, and intraformational surfaces (unconformities, transgressive surfaces, and paleosols).

Diagenetic and paragenetic relationships vary systematically with sedimentology and stratigraphy of the Thelon and provide a framework for understanding the evolution of fluid-flow systems in the context of basin hydrostratigraphy. Stratigraphic units with well-sorted textures, which lacked clay and unstable framework grains, originally were aquifers (depositional aquifers) during early basin evolution. However, pervasive, early quartz cementation radically reduced the porosity and permeability of these units, occluding pore throats and transforming them into aquitards. Proximal fluvial and alluvial fan lithofacies that contained detrital, mechanically infiltrated, and diagenetic clay minerals and/or unstable detrital grains originally had low permeabilities and only experienced minor quartz cementation. In the deep burial setting (2–7 km), these units retained sufficient permeability to allow diagenetic fluid flow (diagenetic aquifers) as suggested by feldspar dissolution, quartz dissolution, and formation and recrystallization of illite and other diagenetic reactions. Tracing potential diagenetic aquifer and aquitard units across the study area allowed development of a hydrostratigraphic model. In this model, diagenetic aquifers onlap onto, and focused basinal fluids into basement rocks to the east in the Thelon Basin (in the vicinity of the Kiggavik uranium deposit).

Keywords: Diagenesis; Sedimentology; Thelon; Sequence stratigraphy; Hydrostratigraphy

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doi:10.1016/S0375-6742(03)00192-4

1. Introduction

Proterozoic sedimentary basins cover extensive portions of the world's cratons. As hosts to extensive U, Pb, Zn, Cu, Ag, and Au deposits, they have been best studied and described on the North American and Australian continents (e.g., Lambert, 1989; Kyser et al., 2000). Sedimentary basin-hosted mineralisation processes are often related to large-scale movement of chemically active fluids; therefore, understanding fluid movement through the basin is of primary importance for mineral exploration (e.g., Garven and Freeze, 1984; Bethke, 1986; Kotzer and Kyser, 1995; Fayek and Kyser, 1997; Lee, 1997; Hiatt and Kyser, 2000). Petroleum geologists have studied sedimentary basin hydrodymanics intensively in an attempt to understand the evolution of pore systems at the critical times in basin evolution when petroleum migration occurs (e.g., Tyler and Finley, 1991; Harrison and Tempel, 1993; Galloway, 1984; Galloway and Hobday, 1996; Selley, 1998), but findings and concepts from this work have not been widely applied to sediment-hosted mineral systems. In this paper, we show that concepts developed in petroleum exploration that integrate sedimentology, diagenesis, and stratigraphy can be applied to the Proterozoic Thelon Basin of northern Canada (Fig. 1). Like many cratonic sandstone successions of Proterozoic age, the depositional history and geodynamic setting of the Thelon Basin are poorly understood despite the marked similarity in age and character of this basin to the relatively well-studied, uranium-rich Athabasca Basin to the southwest and the Pb-Zn-Ag-rich McArthur Basin in Australia (Kyser et al., 2000). The potential for the Thelon Basin to host economic uranium deposits is substantial (Gandhi, 1989; Miller, 1995), but lack of a detailed understanding of its internal stratigraphic framework makes it virtually impossible to make the stratigraphic correlations needed to guide mineral exploration.

The purpose of this paper is to apply the concepts developed by the petroleum industry to the Thelon

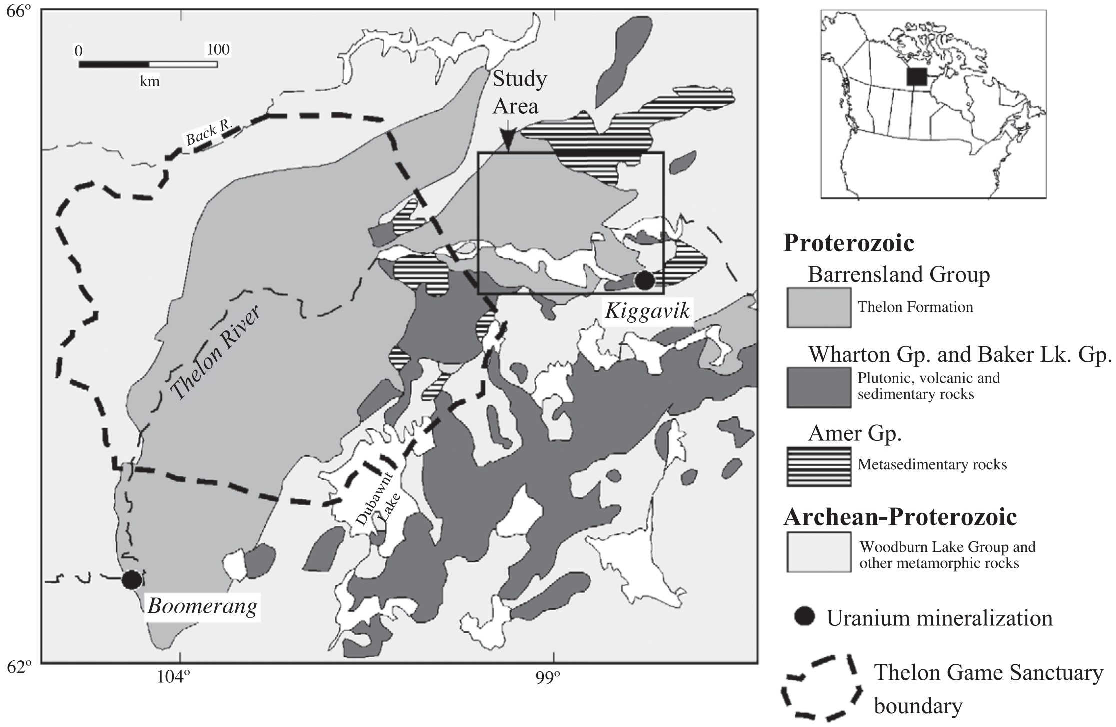

Fig. 1. Regional map that shows locations of the Thelon Basin in Canada (inset), study area, general geology of the surrounding area, and locations of the Kiggavik and Boomerang uranium deposits. Modified from Gall et al. (1992).

Basin (Fig. 1) as an example of the methodology that must be taken if the pathways for mineralising fluids are to be understood. Our objective is to combine sedimentological and sequence stratigraphic concepts with an understanding of the paragenetic sequence of diagenetic minerals in order to evaluate the hydrostratigraphy of the basin during the critical mineralisation stage of the basin's evolution. Linkage of diagenetic relationships in a sequence stratigraphic framework provides a basis for new exploration strategies that can be applied to unconformity-related uranium mineralisation, both in the Thelon Basin and in other Proterozoic sedimentary successions.

2. Background

In general, siliciclastic sedimentary successions experience progressive porosity and permeability loss during burial due primarily to (1) mechanical and chemical compaction, and (2) addition of authigenic minerals as cements (e.g., Nagtegaal, 1978; Pittman, 1979; Bjørlykke and Egeberg, 1993). Exceptions to this general relationship result when chemically active fluids lead to either near-surface precipitation of authigenic phases, or dissolution of detrital and authigenic phases (e.g., Schmidt and McDonald, 1979). Addition of authigenic phases can destroy porosity and permeability systems, while dissolution can create secondary porosity and permeability (e.g., Schmidt and McDonald, 1979; Pittman, 1979; Hiatt and Kyser, 2000). Evolution of hydrologic properties is, to a large degree, predictable based on lithology. For example, mud-rich sediments have very high initial porosity and relatively low permeability, but they quickly lose porosity with mechanical compaction and subsequently become barriers to fluid movement. Sand and sandstone can have vastly different initial hydrologic characteristics depending on their sorting, grain size, and the presence or absence of detrital clay matrix, unstable detrital grains, or cement phases (e.g., Pittman, 1979; Allen and Allen, 1990). How their porosity and permeability change with burial depend on the composition of detrital material and the burial rate (e.g., Nagtegaal, 1978).

Clay minerals play an added role in the evolution of porosity and permeability systems. This is not only because of their direct occlusion of pore space (reduced porosity) and restriction of pore throats (reduced permeability) but also by their ability to inhibit quartz cementation (e.g., Bjørlykke and Egeberg, 1993). Clay minerals in sandstone and conglomerate can have multiple origins. These include: (1) deposition as detrital material, (2) formation and accumulation in soils, (3) mechanical infiltration from above when detrital clay is carried down into sand and gravel by movement of groundwater, (4) diagenetic products resulting from alteration of unstable framework grains such as feldspar, or, more rarely, (5) hydrothermal processes (e.g., Pittman, 1979). The latter process is important near zones of mineralisation and fault-associated circulation systems but is generally not important for understanding the overall hydrology of a sedimentary basin.

2.1. Aquifer terminology

The term "aquifer" is defined by Bates and Jackson (1987) as "a body of rock that is sufficiently permeable to conduct groundwater and to yield economically significant quantities of water to wells and springs." In this study we use the term *depositional aquifer* to represent rock units that meet the criteria of this traditional definition. In depositional aquifers, preferential flow occurs in well-sorted, clay-free rock units. Because of the enhanced fluid flow through these units, they have a tendency to become cemented during early diagenesis, gradually loosing porosity and permeability. If cementation is sufficiently extensive, these once highly porous and permeable units can become aquitards during diagenesis (*diagenetic aquitards*).

The more clay-rich units that originally have lower permeability also lose porosity and permeability during diagenesis but mainly through compaction rather than cementation. As a result, they can retain higher levels of permeability than the originally more permeable strata and may then allow burial pore fluid flow during the later phases of diagenesis. We use the term *diagenetic aquifer* to refer to such rock units, the permeability of which may be comparable to many petroleum reservoir units. These diagenetic aquifers are likely to be the main conduits for mineralising pore fluids during burial and peak diagenesis associated with mineralisation.

2.2. Proterozoic-basin stratigraphy and fluid flow

Based on reconnaissance-level work, many Proterozoic sedimentary basins, such as the Thelon and Athabasca basins of northern Canada, have the potential for development of extensive hydrologic circulation systems. They are filled with thick successions of coarse-grained sedimentary rocks and are almost completely lacking impermeable muddy facies. Determination of the nature of these hydrologic systems is of great importance with regard to the distribution of mineral deposits. The fundamental questions that need to be addressed when assessing the hydrology of these basins are: (1) Did stratigraphic/diagenetic barriers exist that would have constrained fluid flow or was flow uniform throughout the entire stratigraphic succession (i.e. could vertical thermal convection-driven flow occur)? (2) What was the geometry of the paleoaquifer units that existed when mineralising fluids were present? (3) And, if stratigraphic barriers did exist, did paleoaquifers intersect faults in basement lithologies that were favorable for mineralisation?

Because the depositional units can have very different hydrologic properties because of their lithologic properties (e.g., Galloway and Hobday, 1996; Miall, 1996), development of a basin-wide hydrologic model requires an understanding the internal three-dimensional architecture of the basin; the specific stratigraphic model employed becomes very important in this endeavor (e.g., Hiatt and Kyser, 2000). Early models applied to the Thelon and other basins of Proterozoic age involved a simple fining-upward stratigraphic succession with conglomerate and coarse-grained sandstone at the base, grading upward to fine-grained sandstone. Each stratigraphic unit was thought to be regionally extensive and spatially uniform (‘layer cake’’ model; e.g., Cecile, 1973). Close examination of numerous drill cores and outcrop exposures over a large region has shown that a simple “layer cake” fining-upward model is not representative of the Thelon Basin (Hiatt et al., 1999) and a more sophisticated stratigraphic model is required. Such nonuniformities in the stratigraphy have the potential to influence the hydrostratigraphy of the basin and thus must be fully documented in order to understand the evolution of fluid flow through the basin. Petroleum geologists have long recognized that Phanerozoic sedimentary facies have a complex spatial distribution of lithofacies that can produce substantial compartmentalization of depositional and diagenetic aquifer (reservoir) units. Development of a sequence stratigraphic framework allows these facies distributions to be understood and predicted.

The recognition that the Thelon Basin may have distinct diagenetic aquifers that are compartmentalized in a systematic way has profound implications for understanding basin hydrology and mineral exploration. Therefore, the purposes of this study are to show (1) that the sequence stratigraphic framework of the Thelon Formation exerted a fundamental control over the diagenetic history of the succession; (2) that these diagenetic processes in turn cause an “inversion” of the permeability structure, transforming the “depositional aquifers” into aquitards, and rock units with poor to moderately poor original hydrologic properties into “diagenetic aquifers”; and (3) that it is the hydrostratigraphy at critical time intervals during basin evolution that is of utmost importance to mineralisation and could have directed and focused fluid flow that led to mineralisation.

3. Geologic setting

The Thelon Basin (Fig. 1) is located in the Churchill geological province (Gandhi, 1989). The Thelon, Athabasca, Baker, and Hornby Bay basins are spatially and temporally related, Paleo- to Mesoproterozoic intracratonic basins floored by Archean and Paleoproterozoic basement rocks (Donaldson, 1973). These basins were formed in response to the Trans-Hudson Orogeny that is associated with the assembly of the megacontinents of Arctica (Canada, Siberia and parts of Greenland) and Atlantica (Africa and South America) during the Paleoproterozoic (2500–1600 Ma BP). All of these basins consist of thick sequences of mature quartz sandstone, conglomerate, and minor amounts of siltstone that lie unconformably over paleoregoliths developed on the underlying basement lithologies. The diagenetic and paragenetic relationships of the eastern portion of the Thelon Basin have been studied in detail by Renac et al. (2002), but an accurate stratigraphic and hydrostratigraphic model has been lacking.

Basement rocks beneath the Thelon Basin in the study area include a series of Archean metapelites and gneisses of the Woodburn Lake Group, Aphebian metapsammites to metapelites of the Amer Group (Fig. 1), and Late Aphebian sediments and volcanics (including the Pitz Formation volcanics) of the Wharton Group (Fig. 2). The overlying Helikian Thelon Formation, which is the focus of this study, belongs to the Barrensland Group and is composed of up to 2 km of conglomerate and coarse-grained sandstones that were deposited in braided fluvial to near-shore marine environments (Donaldson, 1973; Gall et al., 1992). In the western portion of the basin, the Thelon Formation is capped by thin, basalt flows of the Kuungmi (or Sanctuary) Formation (Fig. 2), which are stratigraphically overlain by stromatolite-bearing marine dolomites and evaporites of the Helikian Lookout Point Formation (Gall et al., 1992). The basalt attests to late tectonic activity during basin evolution; the dolomite of the Lookout Point suggest a marine transgression occurred, and point to the likely formation of saline brines that could have charged paleoaquifers and diagenetically altered the Thelon Formation sediments.

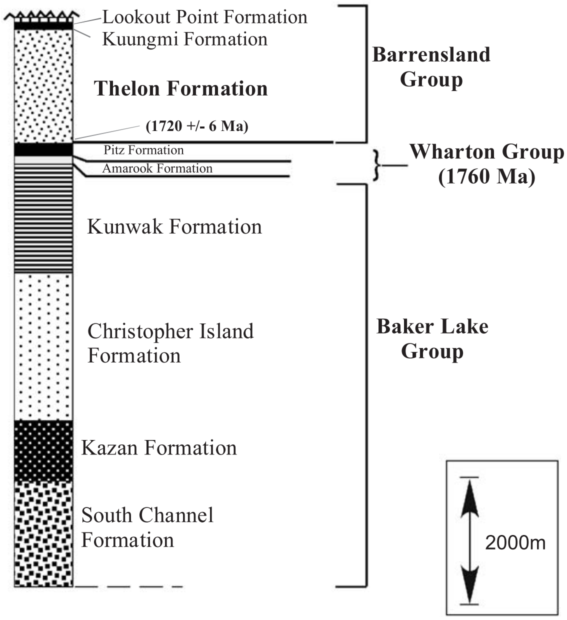

Fig. 2. Stratigraphic subdivision of the Dubawnt Super Group, Thelon Basin (based on Gall et al., 1992 and Rainbird and Hadlari, 2000).

As with other Paleoproterozoic basins, a paleoregolith, consisting of a paleosol horizon is locally preserved on the sub-Thelon Formation unconformity (Gall, 1994). The regolith and basal units of the Thelon Formation contain fluorapatite minerals of diagenetic origin with U–Pb ages of 1720 to 1760 Ma; these provide an approximate age for the onset of Thelon Formation sedimentation (Miller et al., 1989). The maximum age of the basin is constrained by the age of emplacement of fluorite-bearing granites into the underlying Amer Group at ca. 1753 Ma (Miller, 1995). Later events preserved in the eastern portion of the basin include Mackenzie diabase dikes at ca. 1270 Ma (LeCheminant and Heaman, 1989), and the accumulation of Ordovician limestones and Quaternary glacial deposits.

3.1. Uranium mineralisation in the Thelon Basin

The Thelon Basin is spatially and temporally related to the Athabasca Basin (Kyser et al., 2000) and is host to two interesting areas of uranium mineralisation, the Kiggavik deposit and Boomerang Lake Prospect (Fig. 1). Both of these are on the periphery of the basin; exploration in most of the western portion of the basin is prohibited because it is within a large game sanctuary (Fig. 1). The Boomerang Lake prospect has a complex metal inventory (Gandhi, 1989), with some similarities to the complex unconformity-type uranium deposits in the Athabasca Basin. This potential ore body is limited in extent and hosted in the Thelon sandstone; it is associated with graphitic basement rocks, and has an apparent age of ca. 1300 Ma (Gandhi, 1989). In contrast, the Kiggavik (Lone Gull) uranium deposit, which is located near Baker Lake on the eastern limit of the basin (Fuchs and Hilger, 1989), contains 40 million pounds U_3O_8 and is hosted in Archean–Proterozoic basement rocks that lack graphite. The Thelon sandstones have been eroded from the area around Kiggavik but are exposed about 2 km north of the deposit. The alteration assemblage and the ca. 1320 Ma age of samples from the deposit are similar to what is observed in the simple-type uranium deposits of the Athabasca basin (e.g., Kotzer and Kyser, 1995; Fayek and Kyser, 1997). If both these accumulations are unconformity-type uranium deposits as some of the preliminary studies would suggest, the Thelon could potentially contain substantial economic deposits of uranium.

4. Results

Ten drill cores and four outcrop exposures were described and logged in detail across the study area (Fig. 3). Outcrop exposures are generally poor in the Thelon Basin and provide only fragmentary stratigraphic information due to their limited thickness. Exploration drill cores provide extensive continuous stratigraphic records (up to 640 m for core DPR-6; Fig. 3). Detailed logs were completed for both outcrop exposures and drill core. The logs included grain size, sorting, composition, sedimentary structures, and diagenetic features. Approximately 100 thin sections were examined to constrain diagenetic relationships in their stratigraphic context.

4.1. Sedimentology

The Thelon Formation reaches a thickness of 1 km in the study area and can be divided into five broad lithofacies (Table 1). Lithofacies 1 consists of a coarse-grained trough cross-bedded, sublithic arenite to conglomerate (Fig. 4A). These pebbly to cobbly coarse-grained sandstones and conglomerates are poorly to moderately sorted, white to medium gray in color, and contain abundant well-rounded quartzite pebbles and cobbles that sometimes make up >50% of the rock. The gravel fraction of this lithofacies also contains minor volcanics from the underlying Pitz Formation, sandstones from the Pitz and other older sandstones, and metapelite clasts from the underlying Amer Group. Trough cross bedding, scour surfaces and asymmetrical ripple marks are present. This coarse-grained lithofacies suggests deposition in high-energy proximal braided river systems, and overlies both the basal and intraformational unconformities within the Thelon. Fluvial paleocurrent directions are dominantly west to northwest directed. Locally, Lithofacies 1a contains lithic pebble–cobble conglomerate with angular clasts of Amer Group metapelite and a muddy to sandy matrix suggestive of alluvial fan deposition (Table 1).

Lithofacies 2 is composed of poorly sorted, subarkosic arenite that is coarse- to fine-grained and contains 6–10% white grain-sized clay patches. The clay patches represent diagenetic replacement of original feldspar grains and minor lithic fragments (primarily volcanic and quartzite). This lithofacies is composed of beds that, based mostly on drill core

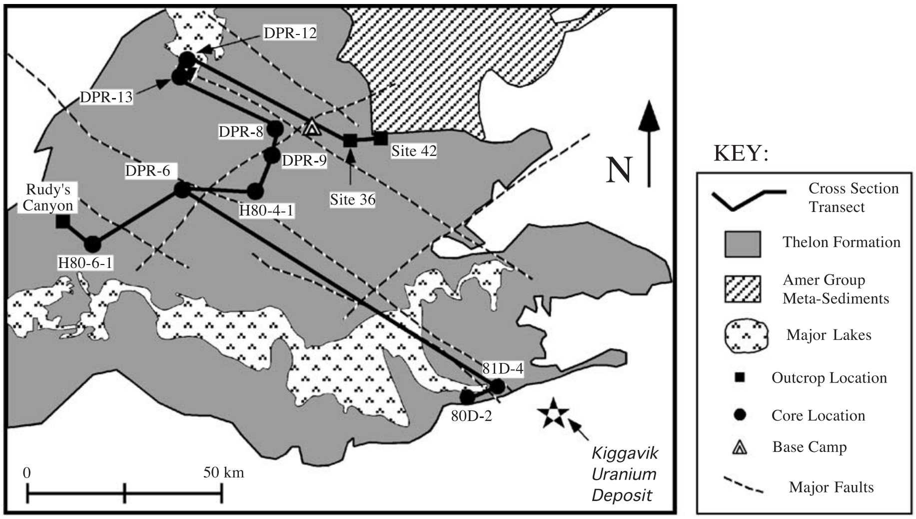

Fig. 3. Map of the study area (northeastern Thelon subbasin) with locations of drill cores and outcrops included in this study. The heavy lines between sample localities correspond to the transects shown in (Figs. 6, 7, 10, and 11).

Table 1
Description and inferred depositional environment of lithofacies recognized in this study

Lithofacies	Paleoenvironment
Lithofacies 1: Coarse-grained trough cross-bedded sublithic arenite and conglomerate; pebbly and cobbly coarse-grained sandstone and conglomerate; poorly to moderately sorted; white to medium gray; 6–10% white clay grains that represent replacement of original feldspar grains; abundant well-rounded quartzite pebbles and cobbles that sometimes make up >50% of the rock; the gravel fraction also contains minor volcanics, sandstone, and metapelite clasts; abundant trough cross bedding, scour surfaces, and asymmetrical ripple marks; unimodal paleocurrents.	high-energy, proximal braided-river channel deposits
Lithofacies 1a: Coarse-grained, structureless to trough cross-bedded lithic cobble breccia and conglomerate; maximum observed clast size = 15 cm; coarse-grained sand matrix-supported textures dominate; very poorly sorted; reddish brown to light gray color; coarse-grained fraction dominated by metamorphic rock fragments (metapelite, schist, and quartzite) with minor sandstone.	alluvial fan deposits
Lithofacies 2: poorly sorted subarkosic arenite; coarse- to fine-grained; 6–10% white clay grains that are assumed to represent replacement of original feldspar grains, and minor lithics (primarily volcanics and quartzite); generally structureless and thickly bedded; pebbles especially in the lower portion of units are less than 10%; grades into fine-grained sand near tops of units which are capped by clay-rich sandstone or siltstone and is often marked by red hematite stain; unimodal paleocurrents.	moderate to low-energy, medial braided-stream channel and overbank deposits
Lithofacies 3: thinly bedded quartz arenite; medium- to coarse-grained; moderately to very well-sorted; white to light gray; thin, platy (average 2 cm thick) bedding generally horizontal but contains abundant large-scale, low-angle (dips 3–5°) inclined bedding; abundant symmetrical wave and current ripple marks.	low-energy distal fluvial to upper shoreface
Lithofacies 4: cross-bedded well-sorted quartz arenite; medium- to coarse-grained; white to light gray; thin beds (< 1 cm thick); large-scale wedge-shaped cross bedding with foresets 2–3 m long that dip 20–30°.	aeolian dunes

observations, are generally structureless and thickly bedded. Beds fine-upward stratigraphically and are often pebbly at their base but grade into fine-grained sand near the top. These thick (2–19 m, average 9 m), upward-fining units are often capped by clay-rich, red iron oxide-stained fine-grained sandstone to siltstone horizons. Lithofacies 2 is interpreted to represent rapid in-channel deposition of braided stream bar to sheet channel and braid plain deposition. The clay-rich, hematite-stained siltstones represent paleosols that may have formed after abandonment in areas where channel filling, avulsion and/or incision occurred.

Lithofacies 3 is composed of thinly bedded, medium- to coarse-grained, well-sorted quartz arenite with large-scale, low-angle (dip < 10°) inclined bedding alternating with thin planar horizontal beds, and abundant wave and current ripple marks (Fig. 4B). This lithofacies is most common in the western and northern parts of the eastern subbasin and is interpreted to represent deposition in beach and upper shoreface settings. These environments may be associated with either marine or lacustrine settings. This lithofacies probably also contains beds deposited in paleoestuaries and deltaic settings, but as McCormick and Grotzinger (1993) pointed out, it can be very difficult

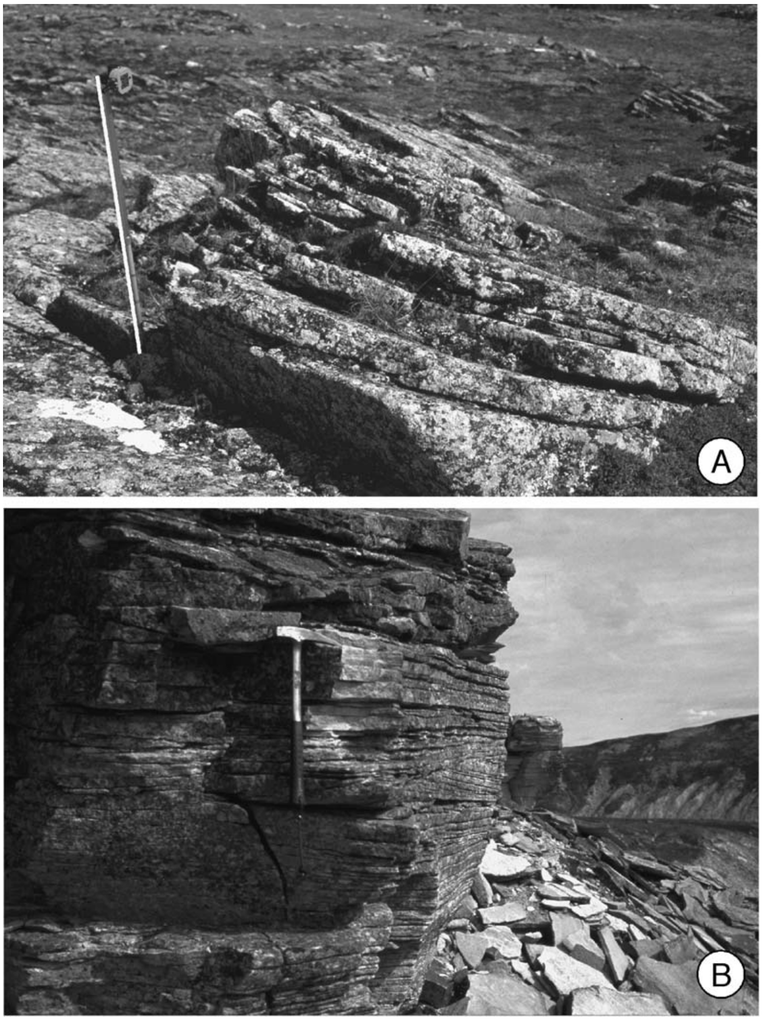

Fig. 4. (A) Photograph showing typical outcrop of coarse-grained fluvial Lithofacies 1 that characterizes diagenetic aquifers in the Thelon Formation; 1 m of Jacob's staff is visible. Site 36 (Fig. 3) location. (B) Outcrop exposure showing well-sorted, clay-free beach facies of Lithofacies 3 that forms a diagenetic aquitard; rock hammer is 40 cm long. Rudy's Canyon location (Fig. 3).

to distinguish between alluvial, lacustrine, and marine environments before macrofossils appeared in the fossil record.

The most distinctive lithofacies, Lithofacies 4, consists of thinly bedded, medium-grained, well-sorted quartz arenite with large-scale, high-angle wedge-shaped cross-bedding (foresets 2–3 m long that dip up to 25°), and reverse-graded individual laminae and beds. This lithofacies is stratigraphically limited and interpreted to represent aeolian deposition.

4.2. Sequence stratigraphy

Sequence stratigraphy is a genetic approach to the subdivision of sedimentary successions based on how depositional systems respond to changes in accommodation (i.e., the space available for sediment accumulation; e.g., Vail et al., 1977; Posamentier et al., 1988; Van Wagoner et al., 1990). Such space is created by base-level (i.e., sea- or lake-level) rise, decreased sediment supply, and/or tectonic subsidence (e.g., Shanley and McCabe, 1994). Changes in climate can also affect accommodation. In continental settings, climate change can modify the shape and/or position of the "fluvial equilibrium profile" (e.g., Schumm, 1968; Shanley and McCabe, 1994). Lowering this profile can cause streams to down cut and deposit coarse-grained sediments, whereas a climate change that causes the equilibrium profile to rise rapidly can produce the same end result as a transgression (even though the shoreline may, or may not, move). It is the *change* in accommodation through time, however, that determines stratigraphic packaging; the mechanism responsible for generating the

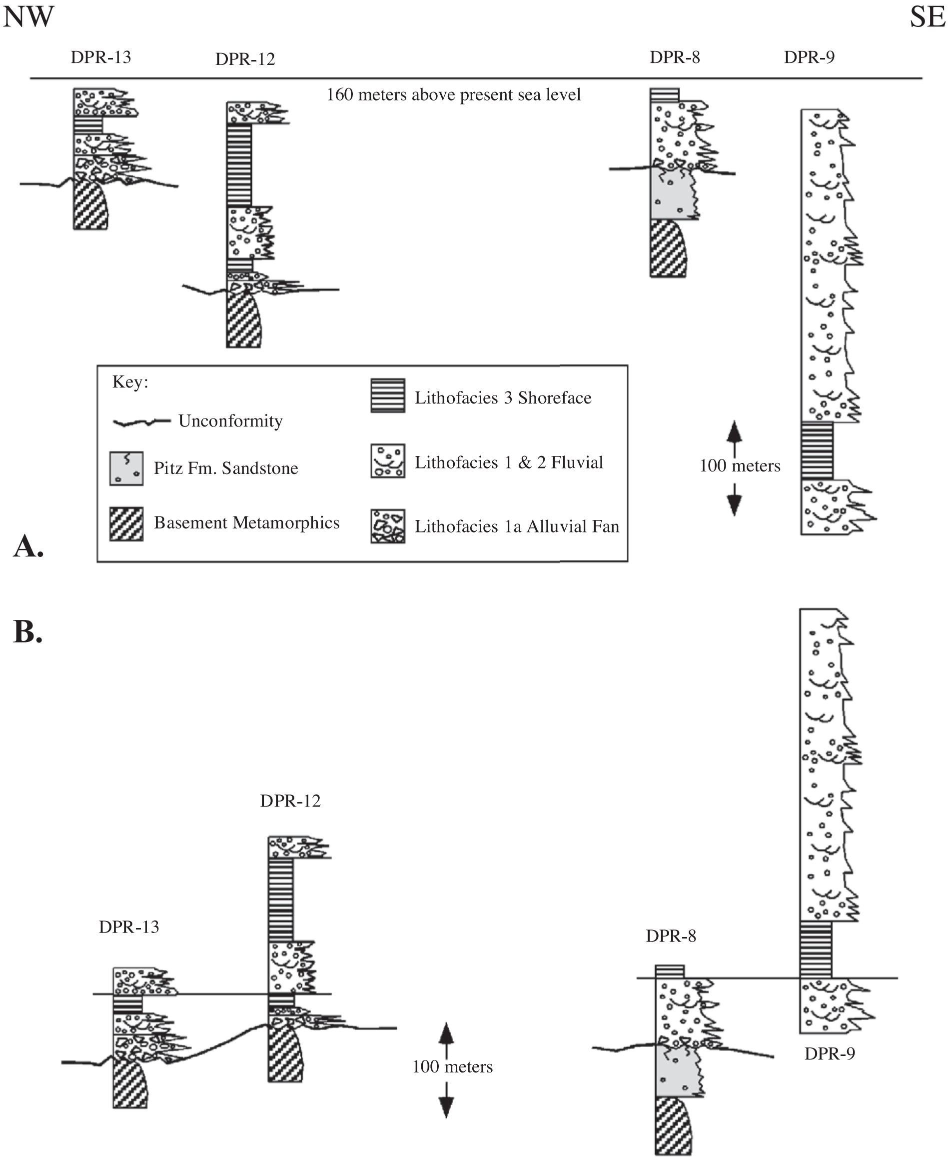

Fig. 5. Stratigraphic sections showing the vertical succession of lithofacies in four drill cores shown in Fig. 3. Each pair of cores spans a major fault. (A) Cores shown in their present-day vertical positions hung on the horizontal line representing the present-day 160-m topographic contour line. (B) The same drill cores restored to their original vertical relationships based on correlation of lithofacies. The inferred displacement on the faults is 140 m for DPR-12 and -13, and 350 m for DPR-8 and -9.

change need not be known to apply the concepts (Emery and Myers, 1996). Although sequence stratigraphy was first developed for use in marine deposits and many of the terms reflect this, its application to fluvial deposits has been the subject of much recent work (Shanley and McCabe, 1991, 1994; Wright and Marriott, 1993; Zaitlin et al., 1994; Aitken and Flint, 1995; Miall, 1997; McCarthy and Plint, 1998) and is well accepted. If there is no accommodation, fluvial erosion occurs, producing a regionally extensive unconformity that is termed a sequence boundary. Subsequently, as accommodation begins to be created, slowly at first, deposits begin to accumulate, but most of the sediment continues to be transported to more distal areas. The resulting deposits tend to be coarse grained, and the upward-fining channel-fill successions are thin, because of frequent cannibalization and amalgamation of slightly older deposits. Such deposits are termed the "lowstand" systems tract (e.g., Shanley and McCabe, 1994.) and are dominated by the coarse-grained facies of Lithofacies 1 in the Thelon Basin. As accommodation is created more rapidly during deposition of the "transgressive" systems tract, bypassing of sediment decreases and the deposits become finer grained. The degree of cannibalization decreases also, leading to the preservation of thicker upward-fining channel successions with a greater proportion of overbank deposits. Lithofacies 2 is interpreted to primarily represent such conditions. At the time when accommodation is at its maximum, the downstream shoreline may transgress into the study area, leading to the deposition of marine (or lacustrine) deposits (e.g., Lithofacies 3). Then, as the creation of accommodation slows during deposition of the "highstand" systems tract, bypassing and channel amalgamation increase again, until conditions mimicking the lowstand systems tract prevail again.

These concepts provide three means of correlating sections within the Thelon Formation (Figs. 5–7): the coarsest-grained deposits with thin, amalgamated channel deposits (i.e., Lithofacies 1; most often lowstand deposits that overlie sequence boundaries but

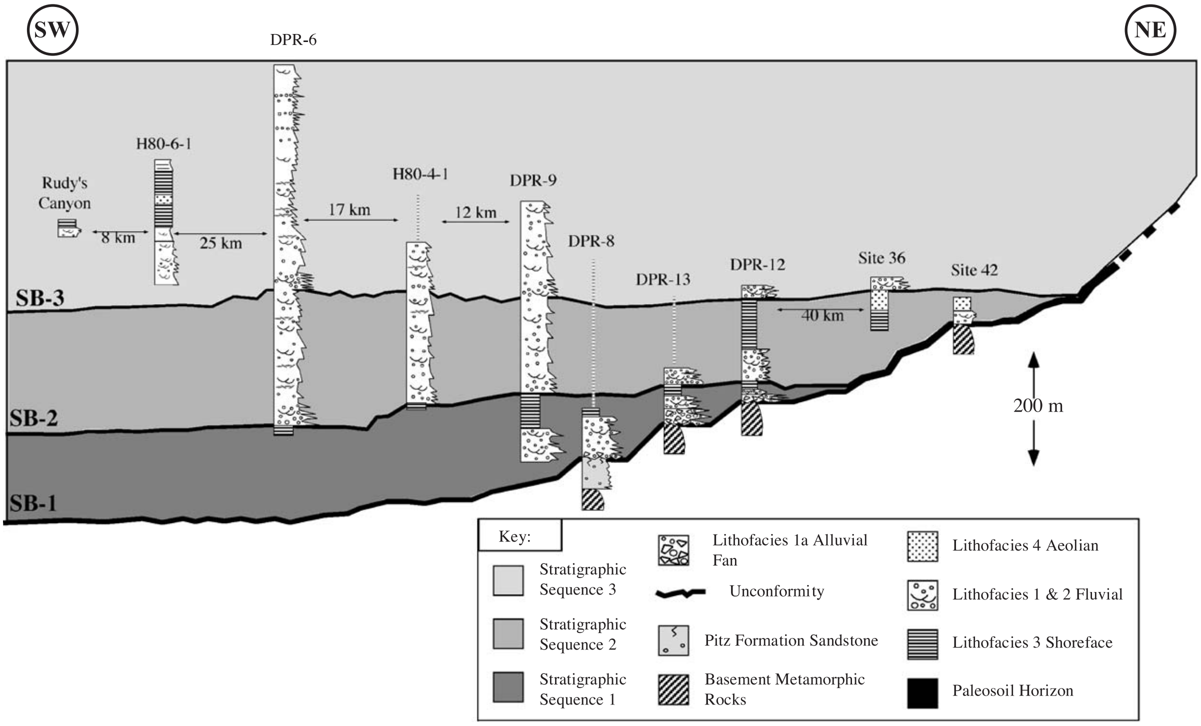

Fig. 6. Correlation diagram that shows the sequence stratigraphic model developed for the Thelon Formation using the concepts discussed in the text. Core and outcrop locations are shown in Fig. 3.

can occur at other points in the sequence); abrupt upward fining of fluvial deposits that accompany an upward increase in the thickness of fluvial-channel sediments (i.e., the transition from Lithofacies 1 to Lithofacies 2; the contact between the lowstand and transgressive systems tracts); and marine deposits (Lithofacies 3; the point of maximum accommodation or maximum flooding surface). Detailed examples of such correlations are shown in Fig. 5 where they are used to remove the effects of postdepositional fault movements.

Based on these stratigraphic data, a sequence stratigraphic model was developed for the Thelon Formation in which three depositional sequences are identified (Figs. 6 and 7). Within each sequence, there is a predictable succession of facies. The lower part of each, which overlies the sub-Thelon unconformity or the two intra-Thelon sequence boundaries, consists of the coarsest sediment. These deposits commonly contain an interstitial clay component that is interpreted to have formed either by the infiltration of fines because water tables were commonly low during lowstands and/or because of the soil-forming processes that occurred. The clay, in addition to that produced by alteration of detrital feldspar was likely a major factor in the later inhibition of quartz cementation that characterizes this stratigraphic interval in the Thelon Formation. These deposits are overlain by finer-grained deposits in which fine-grained, weakly developed paleosoils are present, and then by the quartz-rich facies. These rock units are composed of much more compositionally and texturally mature sediments due to their greater distance of transport and nature of the transport mechanisms (distal portions of braided streams, beach, and aeolian dune settings). The absence of clay and excellent initial hydrologic properties set the stage for preferential development of quartz cementation in these more quartz-rich facies.

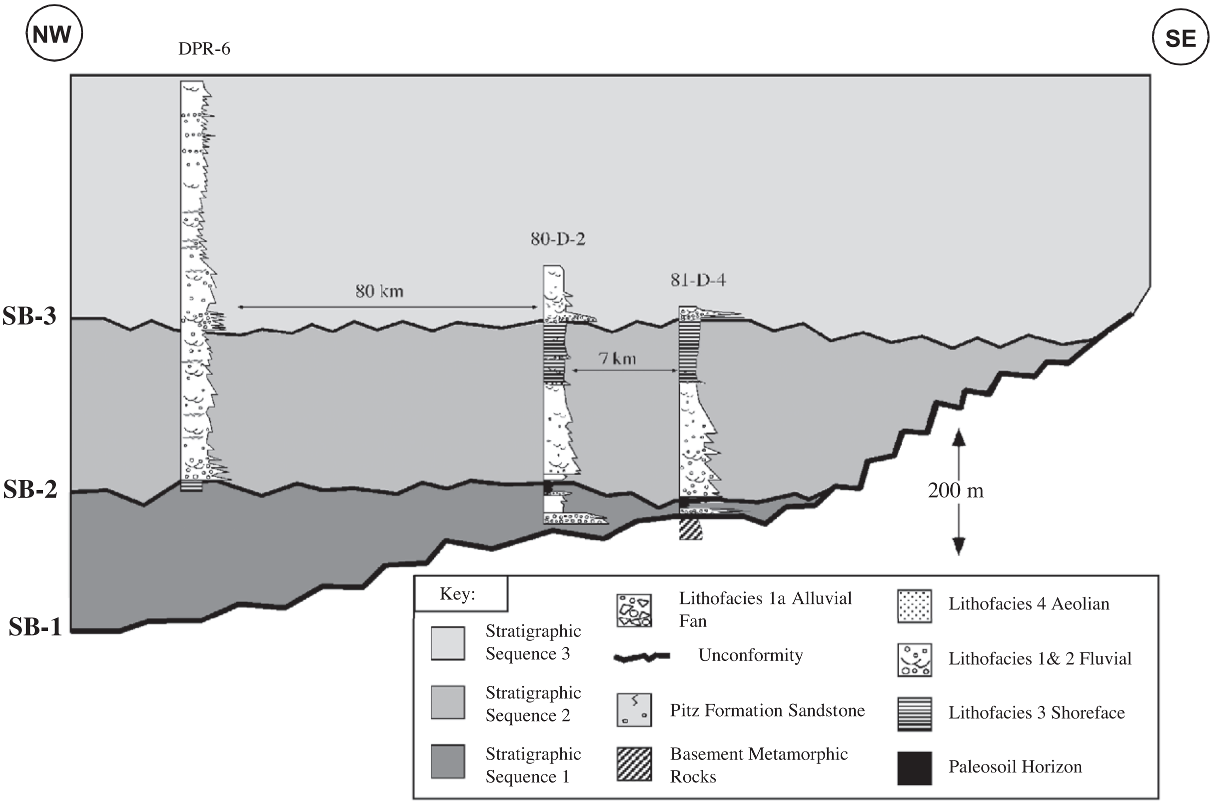

Fig. 7. Correlation of sequences along a northwest to southeast transect of the Thelon Formation. Core locations are shown in Fig. 3.

4.3. Diagenesis and fluid flow

Petrographic examination reveals a complex post-sedimentation, diagenetic history recorded in the Thelon Formation (Fig. 8; Kyser et al., 2000; Renac et al., 2002). Of the various diagenetic events, early (i.e., pre-1650 Ma) quartz cementation plays the most important role in reducing porosity and permeability (cf. Leder and Park, 1986; McBride, 1987). Therefore, in the absence of impermeable mud-rich facies, the degree to which sandstones experience early cementation, and the timing of that cementation, determines which rock units will conduct mineralising fluids during later basin evolution.

4.3.1. Early quartz cementation

Grain-to-grain spatial relationships give an indication of relative timing for quartz cementation with respect to burial depth (e.g., Pittman, 1979). In stratigraphic units that experienced early quartz cementation, grain-to-grain relationships show few signs of compaction (Fig. 9A and B). The earliest quartz cement in the Thelon Basin is an equant, isopachous cement phase (eq; Figs. 8 and 9C–F) that is found only in Lithofacies 3 and 4, rocks that would initially have been very permeable during early diagenesis because of the lack of clay matrix (Fig. 9A–F). Precipitation of this quartz cement phase would, however, have drastically reduced their permeability.

The next stage of cementation involved quartz precipitation during compaction through compaction-driven, grain-to-grain pressure solution (Fig. 9G and H). Quartz cement with this morphology is common in sandstones in general (e.g., McBride, 1987) and is well developed in clay-free facies of Lithofacies 3 and 4, and to a lesser extent Lithofacies 2. This burial-cement phase precipitates in open pores

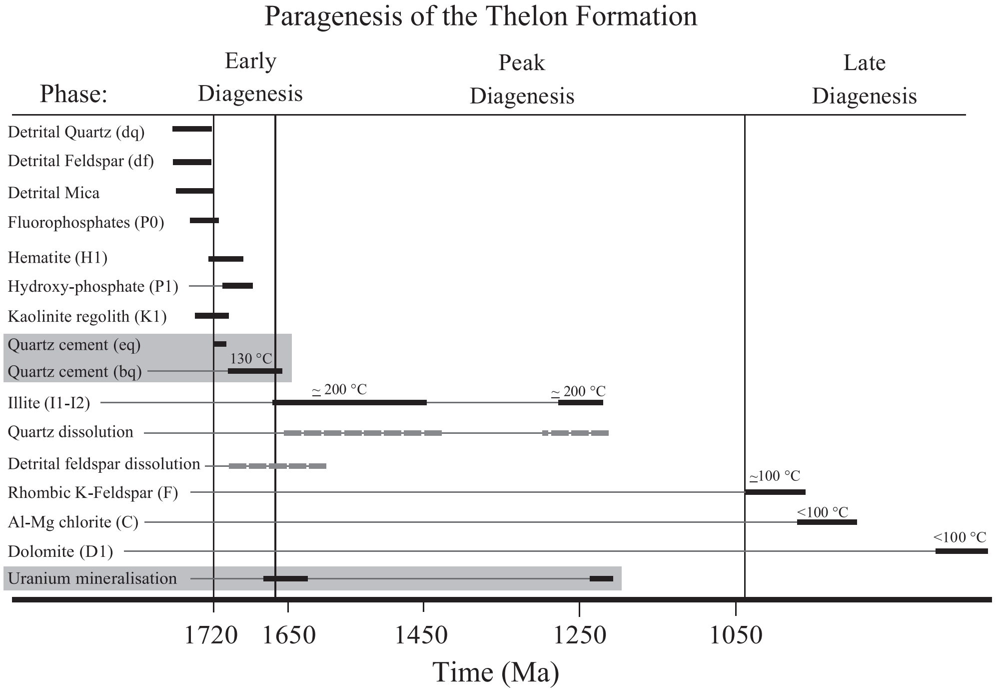

Fig. 8. Paragenetic sequence of Renac et al. (2002) for the Thelon Formation showing the early, peak, and late phases of diagenesis; deposition began at ca. 1720 Ma. Temperatures of events were calculated based on fluid inclusion or crystallinity measurements and the absolute ages were based on U–Pb, Ar–Ar, or interpolation. Note that uranium mineralisation occurred after the early quartz cement phase and postdates most of the later burial quartz cement phases; authigenic illite (I1 and I2) is associated with quartz dissolution and replacement. Detrital feldspar dissolution postdates at least some quartz cement and could have continued into peak diagenesis but is not well constrained paragenetically. Modified from Renac et al. (2002).

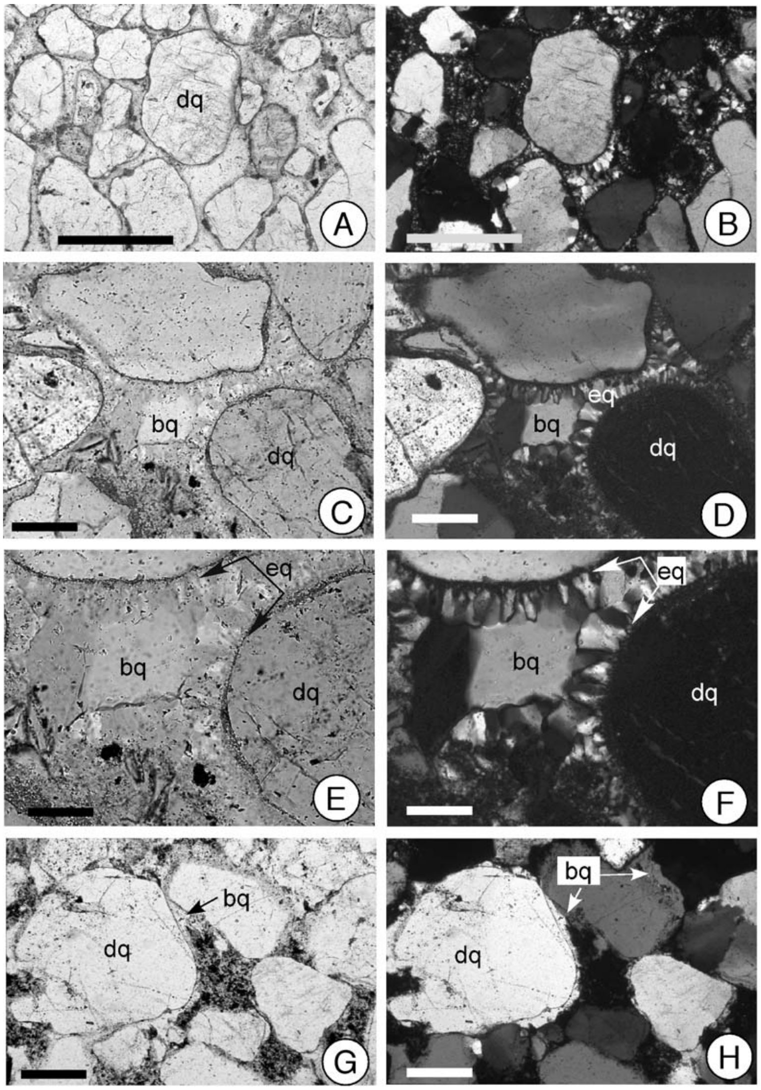

Fig. 9. (A and B) Photomicrographs in plane-polarized and cross-polarized light, respectively, that show a typical diagenetic aquitard texture (Lithofacies 4) that is pervasively cemented with quartz early in the burial history. The presence of "floating" grains and the absence of pressure-solution features indicate that the quartz cement was introduced before compaction. Note the absence of a clay matrix. Scale bar is 1 mm; outcrop sample 42c. (C and D) Photomicrographs in plane-polarized and cross-polarized light that show two distinct generations of quartz cement in a diagenetic aquitard. An early equant isopachous quartz cement phase (eq) directly overlies the detrital quartz grains (dq), and is overlain by a blocky, burial quartz cement phase (bq). Scale bar is 200 μm; Sample 42c. (E and F) Higher magnification views of same area as in C and D above that show the pore-throat-filling nature of the early quartz cement (eq). Scale bar is 100 μm; sample 42c. (G and H) Photomicrographs in plane and polarized light, respectively, that show a typical diagenetic aquifer texture developed in a fluvial, Lithofacies 1 sandstone. Burial quartz cement (bq) was originally present but was partially dissolved and replaced by illite, which itself was later leached and partially replaced by chlorite, creating well-developed microporosity (blue epoxy-filled areas). Scale bar is 500 μm; core sample DPR8—21.4 m.

adjacent to grain–grain pressure solution points and can overgrow earlier phases, such as the isopachous cement phase (Fig. 9C–F). Pressure solution can also occur with little cement precipitation and, in the absence of clay matrix, can result in "welded," interlocking grain fabrics.

4.3.2. Peak and Late diagenesis

After compaction, the Thelon experienced a protracted diagenetic history (Renac et al., 2002). Peak diagenesis (i.e., events at temperatures >200 °C; Fig. 8) was characterized by the widespread development of pore-filling and replacive illite, quartz dissolution, and uranium mineralisation (Fig. 8; Renac et al., 2002). Stratigraphic intervals that were thoroughly cemented by early quartz and thus were impermeable largely escaped this illitization (Fig. 9A–F), whereas units that lacked extensive early quartz cement (Lithofacies 1, 1a, and 2) were strongly affected (e.g., Fig. 9G and H). Late diagenesis, consisting of the formation of authigenic K-feldspar, chlorite, and dolomite, had no influence on uranium mineralisation and are not considered further here.

5. Discussion

5.1. Diagenetic heterogeneities and basin compartmentalization

The results presented above show that there is a complex interrelationship between the nature of the sedimentary conditions, the stratigraphic organization of the Thelon Formation, and the subsequent diagenetic history that included uranium mineralisation.

5.1.1. Sedimentology, diagenesis, and hydrologic properties

Because braided streams dominated the Thelon Basin and fine-grained sediments are almost completely absent, diagenesis was very important in the development of aquitards and aquifers in the Thelon Formation. In most instances, the present-day porosity and permeability relationships are *opposite* to those that would be predicted based simply on lithofacies characteristics. It has long been noted that clay minerals inhibit quartz cementation (e.g., Leder and Park, 1986; McBride, 1987; Bjørlykke and Egeberg, 1993). Clay-free units in the Thelon Formation, such as Lithofacies 3 and 4 experienced extensive quartz cementation early in the burial history (Fig. 9A–F). These lithofacies represent deposition of compositionally and texturally mature sediments in aeolian and beach paleoenvironments. These early cements reduced drastically initial permeability of the sediments and as a result, stratigraphic units that were aquifers initially (depositional aquifers) became aquitards as their hydraulic conductivity became very small early in their diagenetic history. Quantitative evidence for this has been presented in the high $\delta^{18}O$ values (up to 25 ‰, SMOW) of these cements (Hiatt et al., 2001), and the older Ar–Ar ages of authigeneic illites (Kyser et al., 2000) relative to diagenetic aquifer facies (Lithofacies 1, 1a, and 2).

Stratigraphic units composed of compositionally and texturally less mature sediments, such as those of Lithofacies 1 and 1a, were deposited in fluvial settings, and would have had moderate to low porosities and permeabilities initially due to their lower degree of sorting. They were also much more likely to have had a significant detrital feldspar content due to their more proximal relationship to uplifted metamorphic and granitic highlands. As diagenesis proceeded, detrital feldspar grains were replaced by diagenetic illite (Fig. 8; Renac et al., 2002), which along with detrital and mechanically infiltrated matrix clay, would have inhibited quartz cementation. Compaction would have reduced, but not eliminated, their hydraulic conductivities (Fig. 9G and H). Consequently, these units remained conduits for subsequent fluid events, and are presently characterized by abundant diagenetic clay minerals, quartz dissolution (Fig. 9G and H), and water-filled irreducible mircoporosity. These units have much lower $\delta^{18}O$ values (ca. 14 ‰) of their quartz cements (Hiatt et al., 2001) and much younger Ar–Ar ages for their diagenetic illite (Kyser et al., 2000). This indicates that water–rock interaction occurred during peak diagenesis and beyond. Early-formed diagenetic aquitards, which focused fluid flow into diagenetic aquifers, are characterized by fewer diagenetic minerals such as illite and chlorite that are associated with deep burial (5–7 km) diagenesis (Fig. 8; Renac et al., 2002). Based on paragenetic relationships coupled with Ar/Ar isotope systematics, Renac et al. (2002; Fig. 8) showed that uranium mineralisation occurred after the initial stages of quartz cementation. Hiatt et al. (2001) estimated that the earliest quartz cements formed at the surface and in shallow burial settings (< 2 km). The timing of these early cements suggests that aquitards were developed in the Thelon Formation before the earliest uranium mineralisation event (Renac et al., 2002).

5.1.2. Hydrostratigraphy of the Thelon Basin

Based on integrating sedimentology, diagenetic relationships, and the sequence stratigraphic model presented above, the Thelon Formation can be partitioned into a series of aquitards and diagenetic aquifers (Figs. 10 and 11). This hydrostratigraphic subdivision shows that diagenetic aquifer units merge and onlap onto the basal unconformity in the eastern portion of the study area. This geometry would have resulted in focusing of diagenetic fluid flow toward the underlying basement in the eastern portion of the basin (Figs. 10 and 11) and could have established a flow system that delivered basinal fluids to sites of potential mineralisation (reducing lithologies in the underlying basement), such as in the vicinity of the Kiggavik deposit (Figs. 1 and 11). In general, these relationships suggest that the margins of the basin were generally favorable for mineralisation.

5.2. Thelon hydrostratigraphy and possible driving mechanisms for fluid flow

Potential driving mechanisms for fluid movement include compaction-driven expulsion of pore fluid, tectonic uplift/subsidence, and thermal convection (e.g., Einsele, 2000). Although it may be impossible to isolate one of these mechanisms as the definitive source of fluid flow in a specific ancient basin, the choice of one over the other can have profound consequences for basin evaluation and exploration strategy. For example, was mineralising fluid flow uniform throughout a basin or did the compartmentalization produced by the development of diagenetic aquitards direct or focus fluid flow? One possible driving mechanism that has been proposed to explain uranium mineralisation specifically in Proterozoic basins is thermal convection (Raffensperger, 1997). In this model, convection cells are established throughout the entire sedimentary succession filling the basin. Raffensperger (1997) developed this model

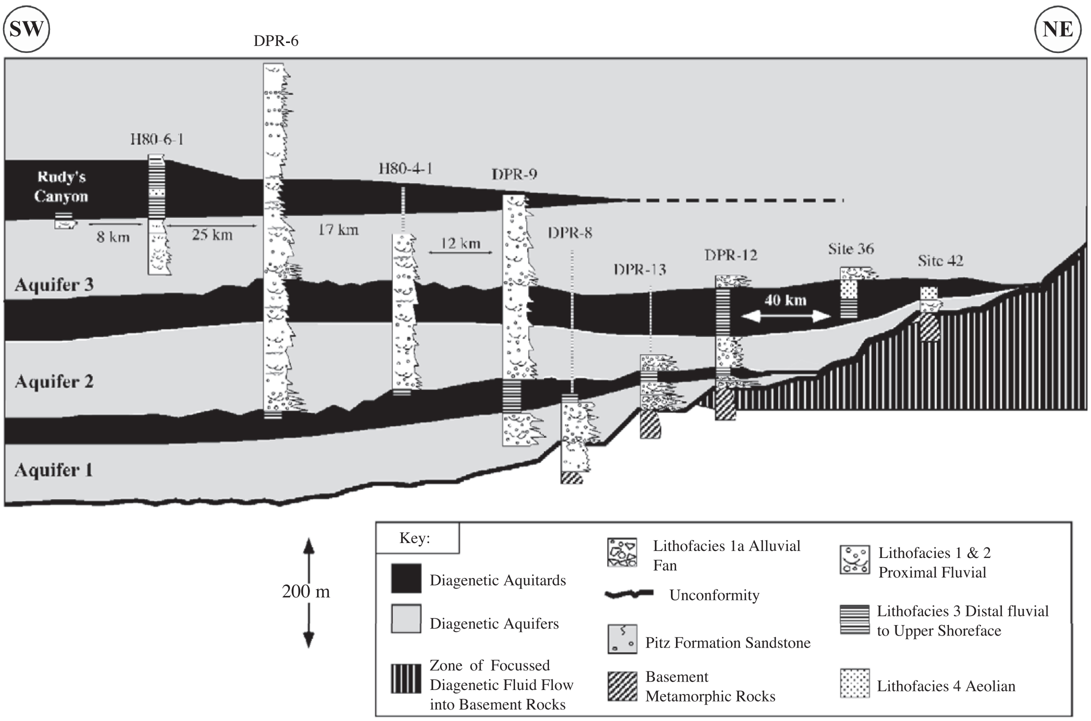

Fig. 10. Diagram showing hydrostratigraphic correlations in the Thelon Formation along a SW–NE transect. Compare with Fig. 6. Core and outcrop locations are shown in Fig. 3.

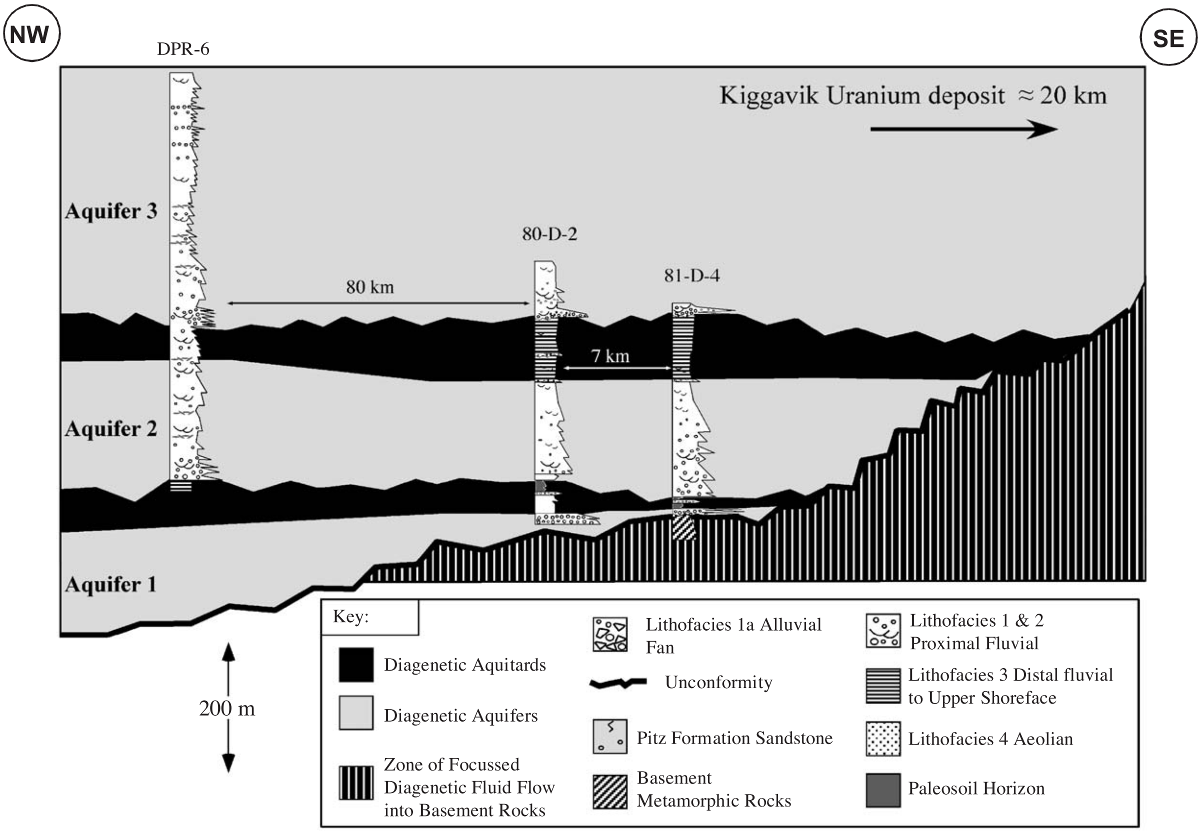

Fig. 11. Diagram showing hydrostratigraphic correlations in the Thelon Formation along a NW–SE transect. Compare with Fig. 7. Core locations are shown in Fig. 3.

to explain the origin of unconformity-type uranium deposits of the Athabasca Basin of northern Canada and the McArthur Basin of northern Australia. This model predicts that uranium mineralisation would occur anywhere within the basin where the basin-filling succession is underlain by reducing lithologies (graphitic schists are the most common in the Athabasca Basin). The reducing lithologies are needed to cause precipitation of insoluble uraninite (reduced uranium) from oxidizing basinal brines in which uranium is soluble (e.g., Kotzer and Kyser, 1995; Fayek and Kyser, 1997). The requirements for this model are that the basin-filling succession be thick (>2 km) and have relatively homogeneous vertical and horizontal hydraulic conductivities (Raffensperger, 1997).

Because sedimentary successions must meet a relatively simple set of requirements, the appropriateness of this model is testable. At first approximation, many Proterozoic sedimentary basins, such as the Athabasca and Thelon basins, would appear to meet the criteria for the thermal convection model. They are filled with thick successions of sandstone and conglomerate and almost completely lack impermeable muddy facies. However, as shown above, the subtle depositional differences that exist between systems tracts, coupled with the stratigraphic control over later diagenesis, led to the development of distinct diagenetic pathways for the fluid flow in different systems tracts in the Thelon Formation. As a result, permeabilities were not homogeneous at the time when the uranium mineralising fluids were moving in the basin. Thus, it is unlikely that the thermal convection mechanism could operate given the complexity of the Thelon Basin's hydrostratigraphy.

Further support of a fundamental stratigraphic control over mineralising fluid flow comes from the distribution of radiogenic lead in the Athabasca, McArthur, and Thelon basins (Holk et al., this volume). Holk et al. show that fluids that carried uranium and its radioactive daughter elements moved laterally and were largely focused along the basal unconformities in all three of these basins. This lateral flow is a direct result of the hydrostratigraphy of these basins that should be taken into account to constrain exploration strategies. If, as the thermal convection model predicts, the paleoflow were vertically oriented, then one would expect to see a vertically oriented lead isotope signal. Such a signal would be predicted in drill cores from directly over and near the large uranium deposits in the Athabasca Basin, however, as Holk et al. (this volume) demonstrate, this is not the case. The results of Holk et al. (this volume) also lend support for hydrostratigraphic focusing of basinal fluids into zones where diagenetic aquifers onlap basement lithologies (Figs. 10 and 11). Their data for the Thelon Basin show that the most radiogenic lead isotopic signatures come from just such zones (e.g., drill core 80-D-2; Figs. 3 and 11).

5.3. Implications for exploration in other Proterozoic basins

Sedimentology plays a large role in basin hydrology especially when, as is the case for the Thelon Formation, the basin is dominated by continental depositional systems (e.g., Hiatt, 2000). For example, petroleum geologists have shown that aquifer (reservoir) compartmentalization can be extreme in Phanerozoic meandering fluvial systems but may be less developed in braided systems (e.g., Galloway and Hobday, 1996). This is a fundamental factor that must be taken into account in the study of Proterozoic basins because the absence of land plants would have meant that soils and terrestrial sedimentation would have been very different relative to the Phanerozoic. Soils would not have had the binding, fine-grained sediment trapping, or the enhanced chemical weathering effects that are facilitated by plants. Thus, the alluvial plain environment would have been without cohesive riverbanks inhibiting the development of meandering streams. Instead, braided streams would have dominated the terrestrial landscape forming extensive sand and gravel-covered braid plains (Schumm, 1968; Eriksson et al., 1998). The exposed unprotected alluvial plains would have been subject to the action of wind that would have resulted in the transport of fine-grained sediment probably producing large-scale dust storms (Dalrymple et al., 1985; Eriksson et al., 1998). As a result, very little mud is found in Proterozoic fluvial environments and few depositional aquitards would have existed in terrestrial basins, thus, diagenetic constraints on hydrologic characteristics would have been much more important relative to those of the Phanerozoic.

Understanding paleohydrologic systems in terms of basin evolution requires the integration of information derived from the sedimentology, stratigraphy, diagenesis, and geology of ancient basin-filling successions. Combination of these is required to understand how ancient mineralising systems operated, and to guide exploration. In particular, because most sedimentary rock-hosted economic deposits involved fluid flow at some point during the burial history, it is important to understand the hydrostratigraphy of a basin at specific intervals in its evolution. Timing of the development of diagenetic aquitard and diagenetic aquifer units is critical to understand the potential mineralising fluid movement in the Thelon Basin. It is not directly important to know where the aquifers were immediately after deposition (depositional aquifers), or even how porosity and permeability is distributed today because late diagenetic events have obscured the hydrologic characteristics that these rocks would have had at the time mineralising fluids were flowing in the basin. It is instead important to know the nature of diagenetic aquifers and aquitards when mineralising fluids were circulating through the basin-filling sedimentary rocks.

6. Summary

Development of a framework that integrates the sedimentology, stratigraphy, and diagenesis as a means to understand the paleohydrology of the Thelon Basin provides a methodology to track the evolution of Proterozoic basins from creation through mineralisation events, and beyond. The important findings that have come from this research include:

1. The stratigraphic relationships in the Thelon Basin are much more complex than previously realized. This research has shown that the Thelon Formation sandstones are composed of five distinct lithofacies representing a range of fluvial, aeolian, and shoreface (beach) depositional environments that exhibit a distinct stratigraphic hierarchy.
2. Regional-scale changes in accommodation (it is not necessary to know the cause) produced a stratigraphic packaging in the Thelon Basin that would later determine the diagenetic and paleohydrologic evolution of the basin. The resulting gross sequence stratigraphic framework consists of three depositional sequences. These sequences were correlated across the eastern subbasin, and within this framework a hydrostratigaphic model was developed.
3. Diagenesis has greatly complicated the relationship between sedimentary facies and the porosity and permeability of the succession. In most instances, the present-day porosity and permeability relationships are opposite to those that would be predicted based on lithofacies characteristics. Intense early quartz cementation is associated with absence of clay in sedimentary units and with high degrees of compositional and textural maturity. Thelon stratigraphic intervals that were deposited in aeolian, beach, and to a lesser extent, distal fluvial environments, were cemented by quartz early in their burial history because of their lack of clay minerals and their greater initial hydraulic conductivities. Thus, rocks with some of the highest initial permeabilities (depositional aquifers) become diagenetic aquitards, whereas those rocks that were originally less permeable were not cemented early and acted as aquifers as diagenesis progressed (diagenetic aquifers). It is clear that sedimentologic and stratigraphic relationships must be taken into account to understand the paleohydrology of ancient basins and thus the potential distribution of mineral deposits.

Acknowledgements

We would like to thank the staff at Cameco, most notably Ted O'Connor, Jim Marlatt, Dave Thomas, Charles Roy, Vlad Sopuck, and Garth Drever for providing logistical, technical, and geological assistance and advice. We thank Matthew Pranter, Andrew Miall, and Darrel Long, for thoughtful reviews that improved the final version of this manuscript. We also thank colleagues at Queen's University for valuable discussion and laboratory assistance, including Sarah Palmer, Paul Polito, and Kyle Durocher. This project was funded through a Natural Science and Engineering Research Council of Canada (NSERC) and Cameco through a Collaborative Research and Development, and NSERC operating grants to TKK.

References

Aitken, J.F., Flint, S.S., 1995. The application of high-resolution sequence stratigraphy to fluvial systems: a case study from the Upper Cretaceous Breathitt Group, eastern Kentucky, USA. Sedimentology 42, 3–30.

Allen, P.A., Allen, J.R., 1990. Basin Analysis: Principles and Applications. Blackwell, Oxford.

Bates, R.L., Jackson, J.A., 1987. Glossary of Geology. American Geological Institute, Alexandria, VA.

Bethke, C.M., 1986. Hydrologic constraints on the genesis of the Upper Mississippi Valley mineral district from Illinois Basin brines. Economic Geology 81, 233–248.

Bjørlykke, K., Egeberg, P.K., 1993. Quartz cementation in sedimentary basins. American Association of Petroleum Geologists Bulletin 77, 1538–1548.

Cecile, M.P., 1973. Lithofacies analysis of the Proterozoic Thelon Formation, Northwest Territories. MSc thesis, Carleton University, Ottawa, 119.

Dalrymple, R.W., Narbonne, G.M., Smith, L., 1985. Eolian action and the distribution of Cambrian shales in North America. Geology 13, 607–610.

Donaldson, J.A., 1973. Possible correlation between Proterozoic strata of the Canadian shield and North American cordillera. Belt Symposium 1, 61–75.

Einsele, G., 2000. Sedimentary Basins: Evolution, Facies, and Sediment Budget. Springer-Verlag, Berlin.

Emery, D., Myers, K.J., 1996. Sequence Stratigraphy. Blackwell, London.

Eriksson, P.G., Condie, K.C., et al., 1998. Precambrian clastic sedimentation systems. Sedimentary Geology 120, 5–53.

Fayek, M., Kyser, T.K., 1997. Characterization of multiple fluid-flow events and rare-earth-element mobility associated with formation of unconformity-type uranium deposits in the Athabasca Basin. Canadian Mineralogist 35, 627–658.

Fuchs, H.D., Hilger, W., 1989. Kiggavik (Lone Gull): an unconformity related uranium deposit in the Thelon Basin, Northwestern Territories, Canada. In: Muller-Kahle, E. (Ed.), Uranium Resources and Geology of North America. International Atomic Energy Agency, Vienna, pp. 429–454. IAEA-TECDOC-500.

Gall, Q., 1994. The Proterozoic Thelon paleosol, NWT, Canada. Precambrian Research 68, 115–137.

Gall, Q., Peterson, T.D., Donaldson, J.A., 1992. A proposed revision of Early Proterozoic stratigraphy of the Thelon and Baker Lake basins, Northwest Territories. Current Research, Part C. Geological Survey of Canada, Paper 92-1 C, pp. 129–137.

Galloway, W.E., 1984. Hydrogeologic regimes of sandstone diagenesis. In: McDonald, D.A., Surdam, R.C. (Eds.), Clastic Diagenesis. American Association of Petroleum Geologists Memoir, vol. 37, pp. 3–13.

Galloway, W.E., Hobday, D.K., 1996. Terrigenous Clastic Depositional Systems: Applications to Fossil Fuel and Groundwater Resources. Springer-Verlag, Berlin.

Gandhi, S.S., 1989. Geology and uranium potential of the Thelon and adjacent basement in comparison to the Athabasca Basin region. In: Muller-Kahle, E. (Ed.), Uranium Resources and Geology of North America. International Atomic Energy Agency, Vienna, pp. 411–428. IAEA-TECDOC-500.

Garven, G., Freeze, R.A., 1984. Theoretical analysis of the role of groundwater flow in the genesis of stratabound ore deposits: I. Mathematical and numerical model. American Journal of Science 284, 1085–1124.

Harrison, W.J., Tempel, R.N., 1993. Diagenetic pathways in sedimentary basins. In: Horbury, A.D., Robinson, A.G. (Eds.), Diagenesis and Basin Development, vol. 36. American Association of Petroleum Geologists Studies in Geology, Tulsa, OK, pp. 69–86.

Hiatt, E.E., 2000. Sedimentology and sequence stratigraphy in basin analysis and paleohydrologic studies. In: Kyser, K. (Ed.), Fluids and Basin Evolution. Mineralogical Association of Canada, Ottawa, pp. 19–38.

Hiatt, E.E., Kyser, T.K., 2000. Links between depositional and diagenetic processes in basin analysis: porosity and permeability evolution in sedimentary rocks. In: Kyser, K. (Ed.), Fluids and Basin Evolution. Mineralogical Association of Canada, Ottawa, pp. 63–92.

Hiatt, E.E., Kyser, T.K., Dalrymple, R.W., 1999. Sequence stratigraphy of the Proterozoic Thelon Formation, Nunavut Territory, Canada: accommodation space and systems tracts in an ancient fluvial-dominated clastic system. Abstracts with Programs - Geological Society of America 31, 424.

Hiatt, E.E., Fayek, M., Kyser, T.K., Polito, P., 2001. The importance of early quartz cementation events in the evolution of aquifer properties of ancient sandstones: isotopic evidence from ion probe analysis of sandstones from the McArthur, Athabasca, and Thelon basins. Abstracts with Programs - Geological Society of America 33, A74.

Kotzer, T.G., Kyser, T.K., 1995. Petrogenesis of the Proterozoic Athabasca Basin, northern Saskatchewan, Canada, and its relation to diagenesis, hydrothermal uranium mineralisation and paleohydrology. Chemical Geology 120, 45–89.

Kyser, T.K., Hiatt, E.E., Renac, C., Durocher, K., Holk, G.J., Deckart, K., 2000. Diagenetic fluids in paleo- and meso-Proterozoic sedimentary basins and their implications for long protracted fluid histories. In: Kyser, K. (Ed.), Fluids and Basin Evolution. Mineralogical Association of Canada, Ottawa, pp. 225–262.

Lambert, I.B., 1989. Precambrian sedimentary sequences and their mineral and energy resources. In: Price, R.A. (Ed.), Origin and Evolution of Sedimentary Basins and their Energy and Mineral Resources. IUGG Geophysical Monograph, vol. 48. American Geophysical Union, Washington, D.C., pp. 169–173.

LeCheminant, A.N., Heaman, L.M., 1989. Mackenzie igneous events, Canada: Middle Proterozoic hot-spot magmatism associated with ocean opening. Earth and Planetary Science Letters 96, 38–49.

Leder, F., Park, W.C., 1986. Porosity reduction in sandstone by quartz overgrowth. American Association of Petroleum Geologists Bulletin 70, 1713–1728.

Lee, M.-K., 1997. Predicting diagenetic effects of groundwater flow in sedimentary basins: a modeling approach with examples. In: Montañez, I.P., Gregg, J.M., Shelton, K.L. (Eds.), Basin-Wide Diagenetic Patterns: Integrated Petrologic, Geochemical, and Hydrologic Considerations. Society for Sedimentary Geology, Special Publication, vol. 57, pp. 3–14.

McBride, E.F., 1987. Quartz cement in sandstones: a review. Earth-Science Reviews 26, 69–112.

McCarthy, P.J., Plint, A.G., 1998. Recognition of interfluve sequence boundaries: integrating paleopedology and sequence stratigraphy. Geology 26, 387–390.

McCormick, D.S., Grotzinger, J.P., 1993. Distinction of marine from alluvial facies in the Paleoproterozoic (1.9 Ga) Burnside Formation, Kilohigok Basin, N.W.T., Canada. Journal of Sedimentary Petrology 63, 398–419.

Miall, A.D., 1996. The Geology of Fluvial Deposits: Sedimentary Facies, Basin Analysis, and Petroleum Geology. Springer-Verlag, Berlin.

Miall, A.D., 1997. The Geology of Stratigraphic Sequences. Springer, Berlin.

Miller, A.R., 1995. Polymetallic unconformity-related uranium veins in lower Proterozoic Amer Group, Pelly Lake map area, northern Thelon Basin, Churchill Province, Northwest Territories. Geological Survey of Canada, Current Research 1995-C, 151–161.

Miller, A.R., Cumming, G.L., Kristic, D., 1989. U–Pb, Pb–Pb, and K–Ar isotopic study and petrography of uraniferous phosphate-bearing rocks in the Thelon Formation, Dubawnt Group, Northwest Territories, Canada. Canadian Journal of Earth Sciences 26, 867–880.

Nagtegaal, P.J.C., 1978. Sandstone-framework instability as a function of burial diagenesis. Journal of the Geological Society of London 135, 101–105.

Pittman, E.D., 1979. Recent advances in sandstone diagenesis. Annual Review of Earth and Planetary Sciences 7, 39–62.

Posamentier, H.W., Jervey, M.T., Vail, P.R., 1988. Eustatic controls on clastic deposition I—conceptual framework. In: Wilgus, C.K., Hastings, B.S., Kendall, C.G.St.C., Posamentier, H.W., Ross, C.A., Van Wagoner, J.C. (Eds.), Sea-Level Changes—An Integrated Approach, vol. 42. Special Publication of the Society of Economic Paleontologists and Mineralogists, Tulsa, OK, pp. 109–124.

Raffensperger, J.P., 1997. Evidence and modeling of large-scale groundwater convection in Precambrian sedimentary basins. In: Montañez, I.P., Gregg, J.M., Shelton, K.L. (Eds.), Basin-Wide Diagenetic Patterns: Integrated Petrologic, Geochemical, and Hydrologic Considerations, vol. 57. Society for Sedimentary Geology, Special Publication, Tulsa, OK, pp. 15–26.

Rainbird, R.H., Hadlari, T., 2000. Revised stratigraphy and sedimentology of the Paleoproterozoic Dubawnt Supergroup at the northern margin of Baker Lake Basin, Nunavut. Geological Survey of Canada, Current Research 2000-C8. 9 pp.

Renac, C., Kyser, T.K., Durocher, K., Dreaver, G., O'Connor, T., 2002. Comparison of diagenetic fluids in the Proterozoic Thelon and Athabasca basins, Canada: implications for long protracted fluid histories in stable intracratonic basins. Canadian Journal of Earth Sciences 39, 113–132.

Schmidt, V., McDonald, D.A., 1979. The role in secondary porosity in the course of sandstone diagenesis. In: Scholle, P.A., Schluger, P.R. (Eds.), Aspects of Diagenesis, vol. 26. Society of Economic Paleontologists and Mineralogists Special Publication, Tulsa, OK, pp. 171–207.

Schumm, S.A., 1968. Speculations concerning paleohydrologic controls of terrestrial sedimentation. Geological Society of America Bulletin 79, 1573–1588.

Selley, R.C., 1998. Elements of Petroleum Geology. Academic Press, London.

Shanley, K.W., McCabe, P.J., 1991. Predicting facies architecture through sequence stratigraphy—an example from the Kaiparowits Plateau, Utah. Geology 19, 742–745.

Shanley, K.W., McCabe, P.J., 1994. Perspectives on the sequence stratigraphy of continental strata. American Association of Petroleum Geologists Bulletin 78, 544–568.

Tyler, N., Finley, R.J., 1991. Architectural controls on the recovery of hydrocarbons from sandstone reservoirs. In: Miall, A.D., Tyler, N. (Eds.), The Three-Dimensional Facies Architecture of Terrigenous Clastic Sediments and its Implications for Hydrocarbon Discovery and Recovery, vol. 3. Society for Sedimentary Geology, Concepts in Sedimentology and Paleontology, Tulsa, OK, pp. 1–5.

Vail, P.R., Mitchum Jr., R.M., Thompson III, S., 1977. Seismic stratigraphy and global changes in sea level: Part 3. Relative changes of sea level from coastal onlap. In: Payton, C.E. (Ed.), Seismic Stratigraphy—Applications to Hydrocarbon Exploration, vol. 26. American Association of Petroleum Geologists, Memoir, Tulsa, OK, pp. 63–81.

Van Wagoner, J.C., Mitchum, R.M., Campion, K.M., Rahmanian, V.D., 1990. Siliciclastic sequence stratigraphy in well logs, cores, and outcrops. American Association of Petroleum Geologists Methods in Exploration Series, vol. 7. Tulsa, OK, 55 pp.

Wright, V.P., Marriott, S.B., 1993. The sequence stratigraphy of fluvial depositional systems: the role of floodplain sediment storage. Sedimentary Geology 86, 203–210.

Zaitlin, B.A., Dalrymple, R.W., Boyd, R., 1994. The stratigraphic organization of incised-valley systems associated with relative sea-level fall. Incised-Valley Systems: Origin and Sedimentary Sequences, vol. 51. SEPM Spec. Pub., Tulsa, OK, pp. 45–60.