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Critical review

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Abstract: We review over 100 years of literature on Prairie buried valleys and till to provide a platform for future research and policy development. Buried-valley aquifers in the Prairies commonly yield abundant groundwater. They have distinct geologies and distinct stratigraphic settings, which impart them with distinct hydrogeological properties and give clues as to how they formed and filled. Prairie buried-valley aquifers are commonly encased in low-permeability strata: Cretaceous shale tends to underlie them and thick (10–300 m) low-permeability Quaternary till tends to overlie them. This reduces recharge, in rare cases nearly completely, while protecting groundwater resources from contamination and drought. It also tends to lead to highly mineralized groundwater chemistries. The stratigraphic positions of Prairie buried valleys also speak to their origin: those that subtend ('hang') from the bedrock unconformity were likely eroded by preglacial fluvial systems during late Tertiary uplift of the Rocky Mountains, whereas those that subtend from surfaces within the till package are likely glaciofluvial valleys eroded in proglacial spillway or tunnel-valley settings. Another key trait of Prairie buried valleys is that their fills tend to be heterogeneous and architecturally complex. Sand, gravel, mud, and diamicton are common; any one can dominate the fill at a given location. This heterogeneity, in conjunction with irregularity common to buried-valley bedrock floors, commonly causes aquifer compartmentalization and makes prediction of aquifer potential difficult prior to drilling. It also suggests that most Prairie buried valleys filled over time, and possibly over multiple glaciations, in multiple deposition environments.

Résumé : Nous avons effectué une analyse de la documentation parue depuis plus de 100 ans sur les vallées enfouies et le till des Prairies afin de fournir une plate-forme pour l'élaboration de politiques et la recherche future. Les aquifères de ces vallées enfouies fournissent habituellement d'abondantes quantités d'eau souterraine. Ils se démarquent par leur géologie et leur cadre stratigraphique, qui leur procurent des propriétés hydrogéologiques à part et fournissent des indications quant à la formation et au remblaiement des vallées hôtes. Ils sont habituellement encaissés dans des strates peu perméables : en général, ils reposent sur des shales du Crétacé et sont recouverts d'une épaisse couche de till (de 10 à 300 m) du Quaternaire, peu perméable. Cette situation a donc pour effet de réduire la recharge, qui dans de rares cas est pratiquement nulle, mais met toutefois les ressources en eau souterraine à l'abri de la contamination et de la sécheresse. Elle procure également à l'eau souterraine une composition chimique fortement minéralisée. La position stratigraphique des vallées enfouies des Prairies donne en outre des indices quant à leur origine : celles qui sont encaissées dans le substratum rocheux ont probablement été entaillées par des réseaux fluviaux préglaciaires pendant le soulèvement des montagnes Rocheuses au Tertiaire tardif. Par ailleurs, celles qui sont associées à des surfaces incluses dans les dépôts morainiques sont probablement des vallées fluvioglaciaires entaillées sous forme de chenal marginal proglaciaire ou de vallée-tunnel. Une autre caractéristique importante des vallées enfouies des Prairies a trait à leurs matériaux de remblaiement, qui sont hétérogènes et dont l'organisation présente une géométrie complexe. Ils sont le plus souvent constitués de sable, de gravier, de boue, de diamicton, et l'un ou l'autre de ces sédiments peut prédominer à un endroit donné. Cette hétérogénéité, conjuguée à l'irrégularité fréquemment observée du fond rocheux des vallées enfouies, entraîne souvent la compartimentalisation des aquifères, de sorte qu'il est difficile de prévoir leur potentiel avant d'entreprendre des forages. Il s'agit également d'une indication que la plupart des vallées enfouies des Prairies ont été remblayées avec le temps, et probablement au cours de glaciations successives, dans différents milieux de dépôt.

INTRODUCTION

Buried valleys eroded into bedrock and covered by till were first identified in the Prairies over 100 years ago along river cuts in Alberta and Montana (Fig. 1; Dawson, 1884; Bell, 1884; McConnell, 1885; Tyrrell, 1887; Calhoun, 1906; Alden and Stebinger, 1913). In the mid to late 1900s, these and other buried valleys were mapped systematically using water wells eastward into Saskatchewan, North Dakota, and Manitoba (e.g. Meneley, 1972; Paulson, 1982; Betcher et al., 2005), areas where the till cover is thicker, the water table closer to ground surface, and buried-valley outcrops consequently scarce (Lennox et al., 1988). These subsurface studies demonstrated that Prairie buried valleys were commonly much larger than the valleys on the modern land surface and that they were filled, in part, by porous, permeable sediment containing abundant, easily extracted groundwater. In a setting characterized by episodic drought and meagre groundwater yields, these were key findings. Today, buried valleys are important high-yield aquifers in many parts of the Prairies (e.g. Paulson, 1982). Their water is exploited for drinking, agriculture, and industrial applications, helping support the Prairie economy in times of abundance and sustain it in times of need.

There has been an extensive amount of work performed on Prairie buried valleys (Fig. 2) and, consequently, an extensive body of literature exists. As a gross generalization, the early outcrop-based work was regional in perspective, perhaps because it was federally funded, and it tended to focus on fundamental geological problems — how did the buried valleys form, how was the till deposited, etc. By contrast, the later, water-well–based work was more local in perspective, largely because it was funded by provincial and state governments, and it tended to focus more on applied hydrogeological problems particular to a given state or province — how big are the buried-valley aquifers, how are they recharged, what is the permeability of the overlying till, etc. The objective of this report is to cull data and ideas from both bodies of literature — the 'hydrogeological' and the 'geological' — in order to provide a broad, up-to-date review of Prairie buried-valley aquifers and the till aquitards that overlie them. The review is largely specific to the Canadian Prairies, but also incorporates literature from data-rich North Dakota.

TERMINOLOGY AND CONCEPTUAL MODELS

In common practice, the term *buried valley* is applied to any channel-form depression that initially formed on the Earth's surface but is now buried by sediment or rock (Russell et al., 2004). The term is non-genetic — a buried valley may have formed by tectonic, glacial, glaciofluvial, fluvial, or other processes — and it carries no connotation of stratigraphic position, other than the fact that the valley must be buried. In the Prairies, however, the term has tended to be reserved for valleys with a particular stratigraphic position, namely those that are eroded into bedrock and buried by diamicton (till) (e.g. all valleys in Fig. 1). The incision of these valleys is typically ascribed to preglacial rivers (Fig. 3a), proglacial streams (Fig. 3b), or, less commonly, subglacial streams (Fig. 3c). Buried valleys that do not incise down into bedrock are also present in the overlying till package, but they have proven too small to map regionally (Schreiner, 1990), and are commonly lumped together under the heading *inter-till aquifers* (Fig. 3) (e.g. Whitaker and Christiansen, 1972). These smaller buried valleys are not covered in this paper. For clarity, when referring to *Prairie buried valleys*, we are referring to valleys such as those in Figure 1 that are incised into bedrock and are buried by till.

BEDROCK

Buried valleys in the Canadian Prairies are incised into sedimentary bedrock of the Western Canadian Sedimentary Basin (WCSB) (Fig. 1). The term *bedrock* is used loosely here; much of the strata are poorly consolidated. The WCSB strata dip gently southwestward toward the mountains, and they are truncated by the angular unconformity that defines the top of bedrock, which dips gently in the opposite direction (Fig. 4). Older strata therefore form the bedrock substrate moving away from the mountains. Poorly consolidated, carbonate-poor, Cretaceous shale is the main bedrock substrate intersected in wells drilled through Prairie buried valleys (Fig. 5; Maathuis and Thorleifson, 2000). Cretaceous

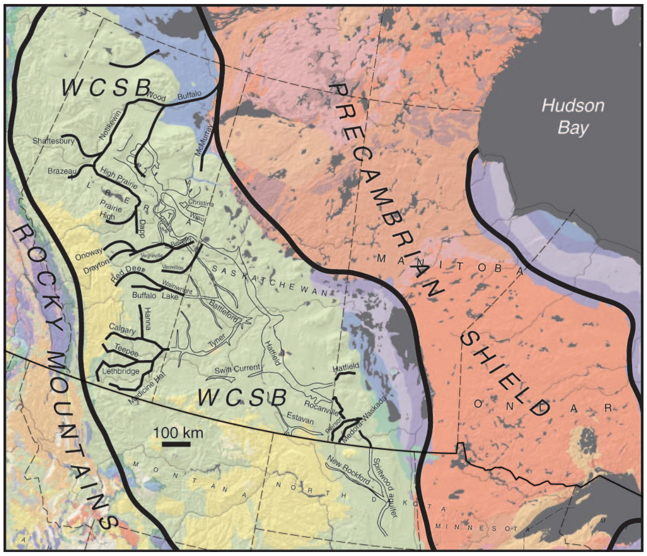


Figure 1. Buried valleys in the Canadian Prairies and North Dakota. Double black lines roughly define buried valley extents, whereas solid black lines correspond to buried valley thalwegs. WCSB stands for Western Canadian Sedimentary Basin. Red/orange colours are Precambrian Shield rocks; blue and purple are Paleozoic carbonate rocks; green is Mesozoic sedimentary rock (primarily shale); and yellow is Tertiary sedimentary rock. Compiled from Stalker (1961), Whitaker and Christiansen (1972), Kehew and Boettger (1986), Maathuis and Thorleifson (2000), Andriashek et al. (2001), Hinton et al. (2007), and Oldenborger et al. (2010).

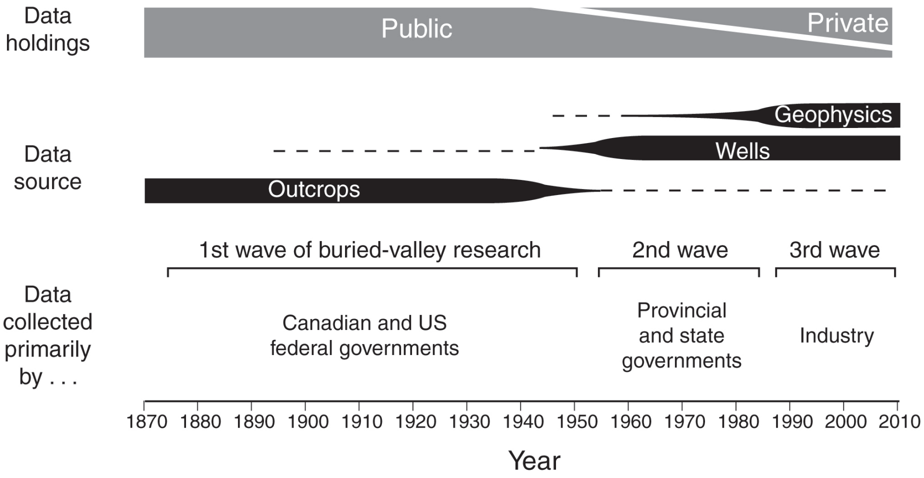


Figure 2. History of buried-valley research in the Canadian Prairies. Note that three 'waves' of research have occurred, each characterized by new insights afforded by a new data type — first outcrops, then wells, and, today, geophysics (primarily electromagnetic data). In reality, only private industry has entered into the third wave of research because few public electromagnetic surveys (e.g. Oldenborger et al., 2010) have been collected.

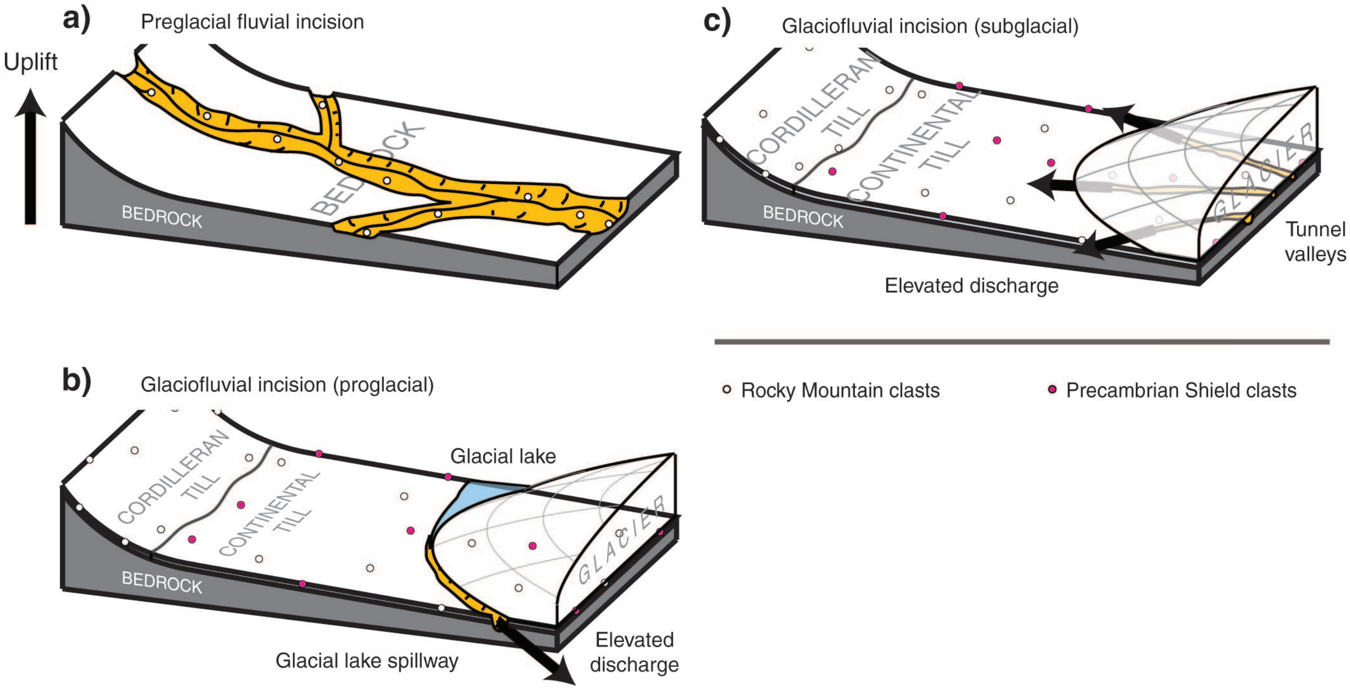


Figure 3. Conceptual models for Prairie buried-valley incision. The infilling of the buried valleys following incision is a separate matter that may have involved deposition in a number of different environments—fluvial, glaciofluvial, glaciolacustrine, subglacial, etc. **a)** Preglacial fluvial incision driven by tectonic uplift and landscape tilting (McConnell, 1885; Andriashek, 2003). **b)** Glaciofluvial incision of a spillway driven by proglacial lake drainage (e.g. Stalker, 1961; Bluemle, 1972; Christiansen, 1977; Kehew and Boettger, 1986; Andriashek, 2003). **c)** Glaciofluvial incision of a tunnel valley driven by subglacial water flow (e.g. Andriashek, 2003).

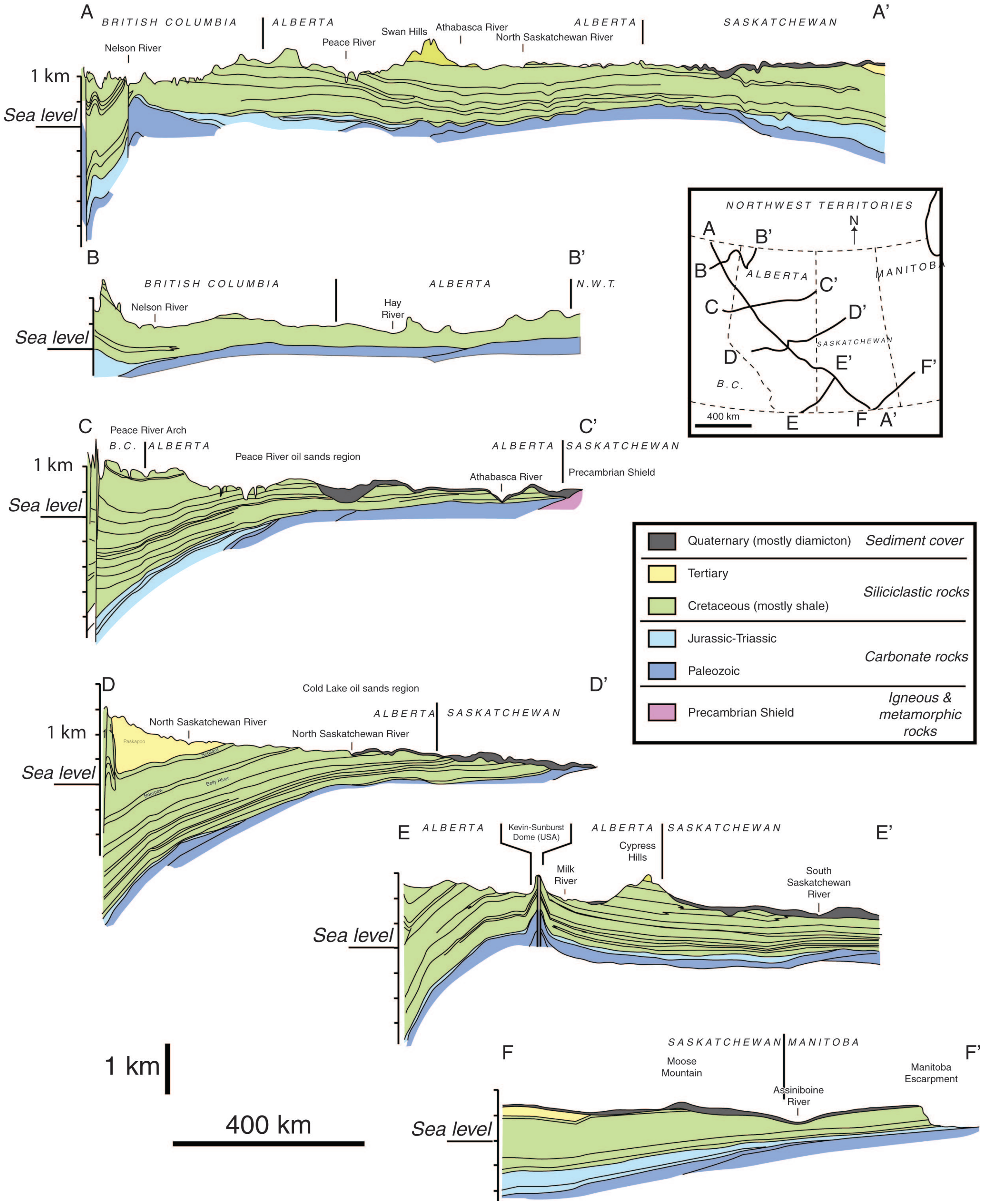


Figure 4. Bedrock and surficial sediment in the Canadian Prairies (*modified from* Leckie and Smith, 1992). In most places where Quaternary sediment appears absent, it is simply thin (<10 m; Fenton et al., 1994).

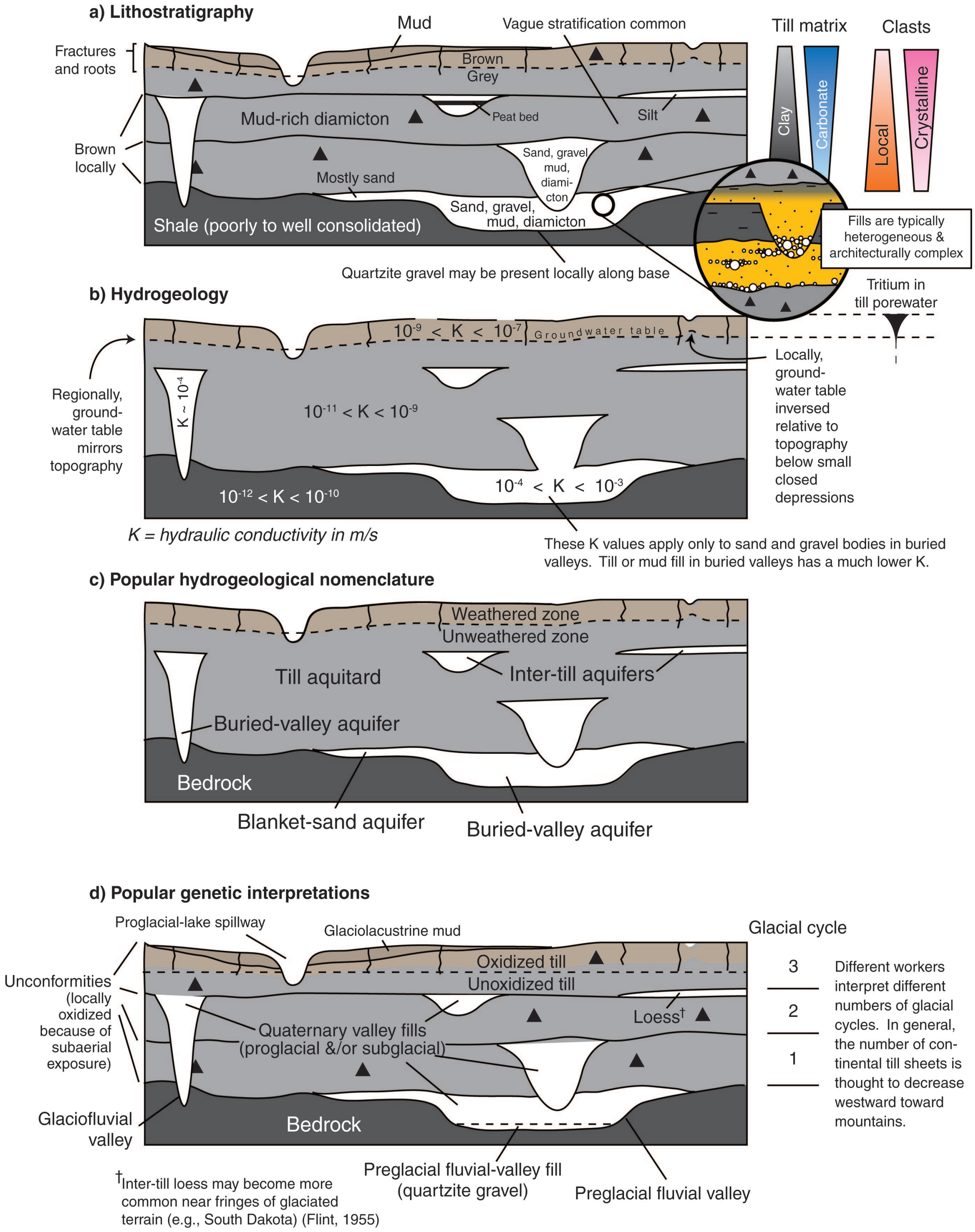


Figure 5. Geology and hydrogeology of the surficial sediment cover in the Canadian Prairies. Data and ideas from McConnell (1885), Dawson (1890), Alden and Stebinger (1913), Horberg (1952), Flint (1955), Stalker (1968), Christiansen (1968), Walton (1970), Meneley (1972), Grisak and Cherry (1975), Hendry (1982, 1988), Bredehoeft et al. (1983), van der Kamp et al. (1986), Keller et al. (1988), Cravens and Ruedisili (1987), Lennox et al. (1988), Andriashek and Fenton (1989), Schreiner (1990), Andriashek (2003), Roy et al. (2004), and Oldenborger et al. 2010). Vertical trends in till matrix properties from Meneley (1964) and Christiansen (1968), Schreiner (1990), and Andriashek (2003). Vertical trends in clast data from Dawson (1890), Horberg (1954), and Roy et al. (2004).

sandstone forms bedrock locally. Paleozoic carbonate rock forms the bedrock substrate along the northeastern feather edge of the WCSB.

Bedrock: Tertiary erosion

Adjacent to lowland areas, where most buried valleys are located, are rare flat-topped erosional bedrock uplands. Some of these, such as the Cypress Hills, Wood Mountains, and Flaxville Hills in Alberta, Saskatchewan, and Montana, are erosively capped by pebble–cobble quartzite gravel derived from the Rocky Mountains (Fig. 6; McConnell, 1885; Alden and Stebinger, 1913; Collier and Thom, 1918; Leckie, 2006). The quartzite gravels contain paleoflow indicators, rare large clasts (up to 40 cm), and sedimentary structures that suggest deposition by powerful northeastward-flowing braided rivers at a time when slope gradient was greater than that existing today (Heller et al., 2003; Leckie, 2006). The age of the gravels decreases with elevation: mammal fossils suggest the Cypress Hills gravels are Eocene to early Miocene (47–22 Ma) in age, that the Wood Mountain gravels are middle Miocene (16–11.5 Ma), and that the Flaxville gravels are late Miocene (10–5 Ma) (Leckie, 2006). Tephra layers in eolian silt overlying the Cypress Hills and the adjacent top-bedrock unconformity yield dates of 9.3 to 8.3 Ma (Barendregt et al., 1997). Buried valleys, though at lower elevations, overlie the upland-capping gravels stratigraphically (Fig. 6), which suggests they formed and filled in the last 5 Ma.

Even though largely unconsolidated, the upland-capping quartzite gravels are the youngest strata typically referred to as bedrock. They are interpreted to record aggradational events that punctuated widespread Tertiary fluvial downcutting caused by tectonic uplift of the Cordillera and tilting of the Prairie land surface (McConnell, 1885; Upham, 1894; Collier and Thom, 1918; Heller et al., 2003; Leckie, 2006). The preglacial fluvial systems that performed the downcutting are interpreted to have spanned the continent, flowing eastward from the Rocky Mountains to the Labrador Coast via Hudson Bay (Fig. 7). Elevated coal rank in shallowly buried WCSB strata suggests that upwards of 1.5 to 2 km of WCSB strata was eroded (Bustin, 1991) and transferred to the Labrador coast (Upham, 1894; MacMillan, 1973; Hiscott, 1984), transforming this part of the Atlantic passive margin into "… the principal Tertiary depocentre for eastward migrating fine grained clastic detritus from north-central North America" (Balkwill et al., 1990). Similar clastic pulses were delivered to continental margin basins by most major North America rivers during the Tertiary, including the St. Lawrence (Wade and MacLean, 1990) and the Mississippi (Galloway et al., 2000), indicating widespread erosion of the continent. The volume of sediment in these deposits is orders of magnitude greater than that deposited offshore during the Quaternary, which reinforces the long-standing notion that Tertiary rivers were in many places equally if not more important than Quaternary glaciers in generating the landscape we observe today in the Prairies and elsewhere (McConnell, 1885; Wilson, 1903; Ambrose, 1964; Shilts et al., 1987).

PRAIRIE TILL

The surficial sediment cover in the Prairies is thick (10–350 m) and dominated by mud-rich diamicton. The diamicton package forms a regional drape over buried-valley fills and the adjacent WCSB bedrock, its variations in thickness accenting or subduing the otherwise bedrock-controlled

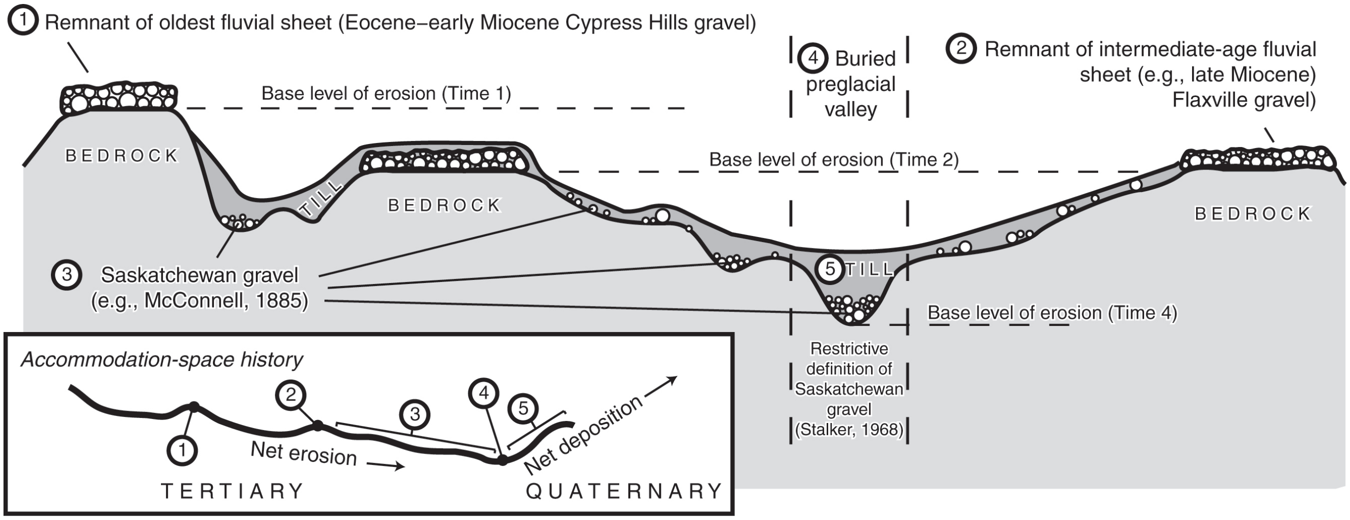


Figure 6. Cartoon depicting the stratigraphic position, elevation, and relative age of Rocky Mountain-derived, quartzite-rich gravel units deposited during Tertiary erosion of the Canadian Prairies. Based in part on ideas and data in McConnell (1885), Upham (1894), Collier and Thom (1918), Stalker (1968), and Leckie (2006), among others.

landscape locally (Fig. 4). Diamicton fills some buried valleys completely, and accounts for a large proportion of the fill of others (e.g. Howard, 1960).

Prairie till: sedimentology

In outcrop, Prairie diamicton is commonly stratified (Fig. 8), although massive diamicton is also reported (Dawson, 1890; Proudfoot, 1985). Where stratified, thin sand lenses are common (Shaw, 1982). In places, stratification is distorted and irregular (Proudfoot, 1985). Striated clasts are common; striated boulder pavements are present locally (Christiansen, 1968); rare low-angle drag folds and thrust faults are observed in underlying sediment (Proudfoot, 1985); and kilometre-scale thrusted masses of bedrock occur locally (Aber et al., 1989). These observations suggest that most diamicton in the Canadian Prairies is till (Christiansen, 1968, 1992; Shaw, 1982; Proudfoot, 1985; but see Dawson, 1890).

Prairie till: depositional models

A variety of depositional models has been proposed to explain the origin of Prairie till. Massive diamicton has been interpreted to be the product of subglacial lodgement and/or deformation (Proudfoot, 1985); stratified diamicton with sand lenses and local deformation has been interpreted to be supraglacial melt-out till (Shaw, 1982; Proudfoot, 1985); and layered, locally deformed diamicton with silt and sand interbeds and dropstone-like clasts has been interpreted to be the product of debris flows and sediment rain-out in ice-contact water bodies (Proudfoot, 1985). Of these models, supraglacial melt-out in particular is commonly invoked, especially when explaining odd, ubiquitous features on the till-covered Prairie landscape, such as omni-present closed depressions commonly referred to as Prairie potholes or sloughs.

Prairie till: clast provenance

Clastic particles (mud, sand, and gravel) in Prairie till come from three main bedrock sources: the Western Canadian Sedimentary Basin (WCSB), the Rocky Mountains, and the

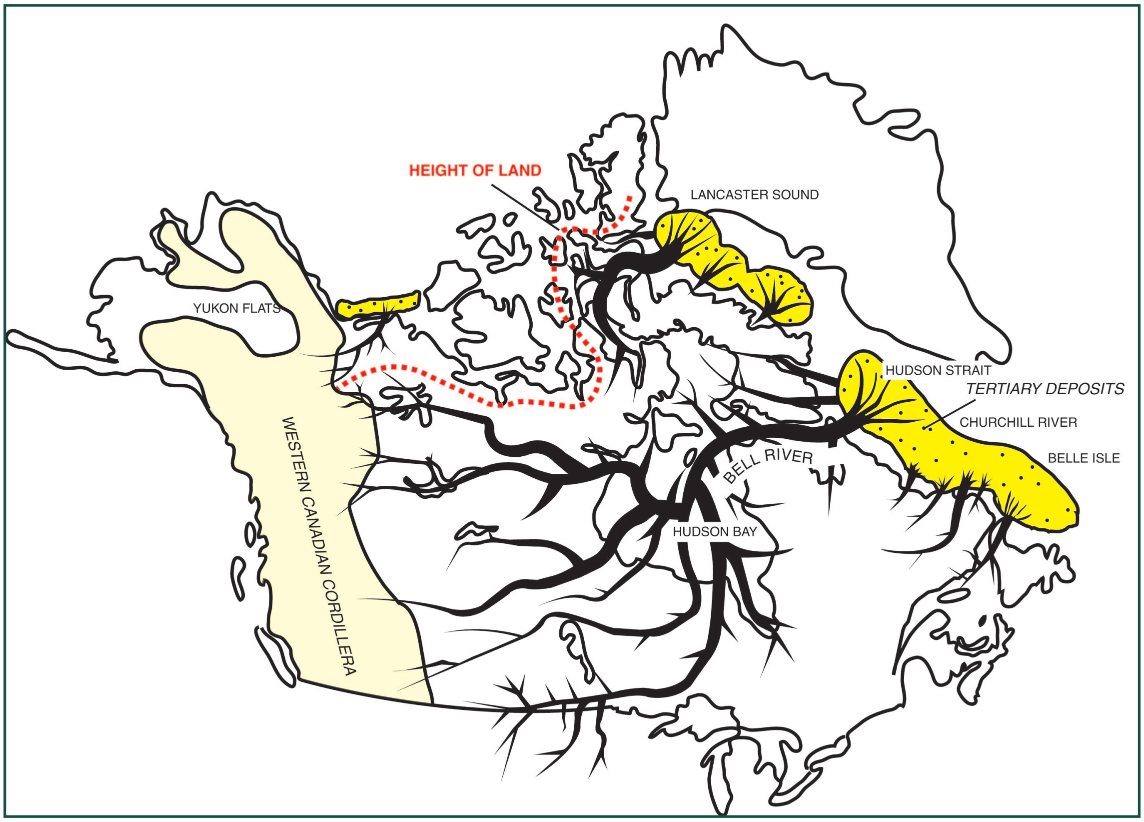


Figure 7. Conceptual depiction of Tertiary ('preglacial') fluvial systems in the Canadian Prairies. Modified from MacMillan (1973) and Duk-Rodkin and Hughes (1994), who drew from ideas of early geologists, including McConnell (1885), Dawson (1890), Upham (1894), Bell (1895), and Bauer (1915), among others.

Figure 8. Diamicton (till) exposed in a pit along the Qu'Appelle River valley, Saskatchewan. Mud-rich till such as this tends to cover buried-valley aquifers throughout the Canadian Prairies. Note stratification, which is common in Prairie till. G. Matile (Manitoba Geological Survey) for scale. 2012-001

Precambrian Shield (Fig. 1). Till matrices tend to contain abundant clay particles (Fig. 9), abundant mud-sized carbonate particles (e.g. Christiansen, 1968), and, in places, coal fragments (McConnell, 1885; Sloan, 1972) and rare Cretaceous radiolarians and foraminifera (McConnell, 1885). Paleozoic carbonate rock fragments are abundant in the gravel fraction (Dawson, 1890; Flint, 1955; Howard, 1960), and their abundance decreases toward the mountains (Dawson, 1890). These observations suggest that Prairie till was derived, at least in part, from shale- and carbonate-rich strata of the WCSB (McConnell, 1885; Dawson, 1890; Meneley, 1964; Christiansen, 1968, 1992; Schreiner, 1990; Andriashek, 2003). However, clastic particles from non-WCSB sources are also common. This is particularly evident when examining the gravel fraction, which commonly contains abundant resistant clasts from bedrock sources outside the WCSB. For example, Rocky Mountain quartzite clasts make up about one tenth to half of the 'far-travelled' (non-WCSB) clasts in 'continental' (non-Cordilleran) till along the U.S. border near the Rocky Mountains, and their abundance decreases eastward (downslope) across the Prairies (Dawson, 1890; Shetsen, 1984; *see also* Shaw and Kellerhals, 1982). Precambrian Shield clasts make up about one quarter to one third of the 'far-travelled' (non-WCSB) clasts in till along the U.S. border between the Manitoba and Missouri escarpments (Dawson, 1890; Howard, 1960), and their abundance decreases in the opposite direction, toward the mountains (Dawson, 1890; Shetsen, 1984; *see also* Shaw and Kellerhals, 1982). Paleozoic carbonate rock clasts from the northeast edge of the WCSB commonly dominate the pebble fraction in tills in Manitoba and Saskatchewan (Dawson, 1890) and in the U.S. states south of this (Flint, 1955; Howard, 1960), their abundance decreasing westward (Dawson, 1890; Shetsen, 1984). Even rare Omar erratics, presumably from the east side of Hudson Bay, are present locally (Prest et al., 2000). To explain this body of observations, interplay between two dispersal processes is typically invoked. Downslope (eastward and northward) fluvial dispersal of Rocky Mountain clasts is thought to have occurred during preglacial (Dawson, 1884) and interglacial (Evans and Campbell, 1995) times, whereas upslope (westward or southward) dispersal of Precambrian Shield clasts by ice sheets flowing outward from the Shield is thought to have occurred during Quaternary glaciations (Schreiner, 1990). These processes are thought to have generated Prairie till that contains a melange of clasts from the two 'exotic' sources — the Precambrian Shield and the Rocky Mountains — in addition to abundant particles derived from WCSB bedrock.

Prairie till: stratigraphy

Stratigraphically, Prairie tills tend to be distinguished, mapped, and dated using some combination of the following (in approximate decreasing order of importance): matrix carbonate content, geophysical well-log signature, clay content, sand-grain and pebble lithology, presence of intervening weathering profiles, presence of intervening mud, sand, or gravel layers or boulder pavements, jointing and staining, preconsolidation pressure, radiocarbon dating, magnetostratigraphy, tephra-layer dating, and relative age dating using fossil assemblages (e.g. Christiansen, 1968, 1992; Proudfoot, 1985; Schreiner, 1990; Barendregt et al., 1997; Andriashek, 2003; Maathuis et al., 2011). Several observations are of note. Prairie tills are normally magnetized, which suggests they were all deposited in the latter part of the Quaternary, over the past 0.8 Ma (Barendregt and Irving, 1998). Some buried tills are capped by regionally extensive oxidized zones, which are thought to attest to periods of interglacial or interstadial subaerial weathering (Schreiner, 1990; Andriashek, 2003). Thicker intra-till units of mud, sand, and/or gravel are locally present, some of which contain fossils (Woolf, 1981; Barendregt and Irving, 1998) and woody organics (Dawson, 1884; Proudfoot, 1985). These are commonly interpreted to be interglacial or interstadial deposits (e.g. Christiansen, 1968, 1992; Proudfoot, 1985; Barendregt and Irving, 1998). Early workers interpreted two or three till units in Alberta (Dawson, 1884; Horberg, 1952), Montana (Alden and Stebinger, 1913), North Dakota (Howard, 1960), and Saskatchewan (Meneley et al., 1957). Today, the trend in many places is toward increasing subdivision — upwards of six till sheets now tend to be mapped in the subsurface of Saskatchewan (Schreiner, 1990; Christiansen, 1992), whereas four (Andriashek, 2003) or fewer tills tend to be mapped in Alberta (Horberg, 1952; Barendregt and Irving, 1998). (In western Alberta, many argue that continental and Cordilleran ice sheets only coalesced once during the Quaternary, during the last glacial maximum (Jackson et al., 2011)). By contrast, many workers now argue that a single continental till sheet, dating from the last glacial maximum, exists in western Alberta (e.g. Jackson et al., 2011). In some places, such as southeast Saskatchewan (Schreiner, 1990), any attempt at lithostratigraphic subdivision remains problematic. Proudfoot (1985) also reported difficulty in differentiating tills near Medicine Hat, Alberta, using traditional criteria (grain size, clay mineralogy, sand-grain lithology). He was only able to subdivide the till package into two units because of the presence of an intervening lag-lined erosion surface.

Several macroscopic stratigraphic trends are commonly reported in the Prairie till package. For example, clay content is commonly observed to decrease irregularly upward, whereas matrix carbonate tends to exhibit the opposite trend (Fig. 5 a). This mirrors the shale-over-carbonate stratigraphy of the WCSB fill (Schreiner, 1990), which prompted Meneley (1964) to postulate a till dispersal model in which successive Shield-centred Quaternary ice sheets flowed into the Prairies, stripped WCSB strata from the edge of the Shield, and plastered it downflow, forming an aggrading till package (Fig. 10). Some authors reported increasing proportions of crystalline clasts moving upward in the till package (Fig. 5a; Dawson, 1890; Horberg, 1954; Andriashek and Fenton, 1989), which would seem to support this model. The Meneley model remains the most common way of explaining how till was sourced and deposited in the Canadian Prairies (e.g. Schreiner, 1990; Andriashek, 2003).

PRAIRIE BURIED VALLEYS AND THEIR FILLS

The significance of Prairie buried valleys and their sometimes exotic fills has interested workers since they were first discovered and described. In this section, the physical traits of Prairie buried valleys and their fills are described and hypotheses regarding their origin are discussed.

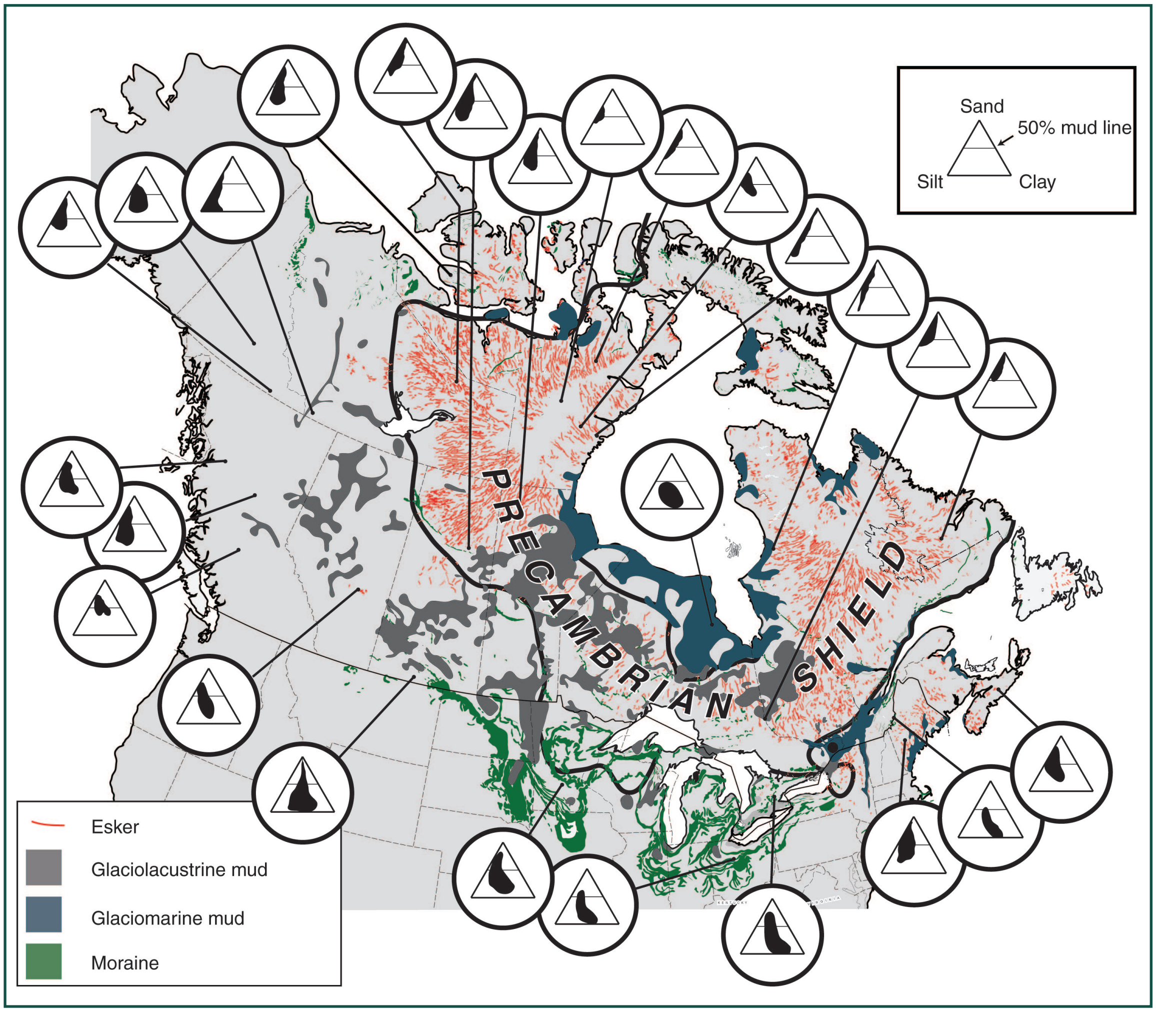


Figure 9. Till texture (<2 mm grain-size fraction) across North America. Compiled from references listed in Cummings (2011).

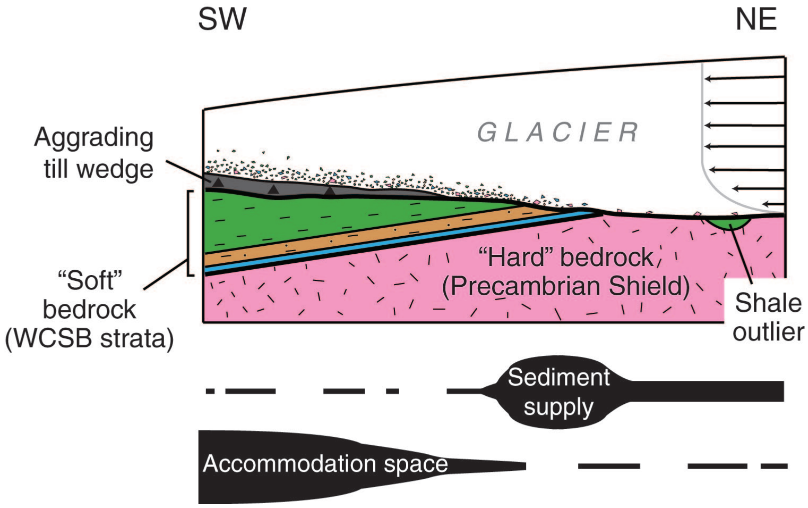


Figure 10. The Meneley model of till deposition in the Prairies. Cartoon formulated from Meneley (1964), Schreiner (1990) and Andriashek (2003).

Prairie buried valleys: orientation and slope

Buried valleys in the Canadian Prairies have two main orientations (Fig. 1). The first is parallel to bedrock slope: most trend roughly northeastward–southwestward and have slopes and orientations that are similar to those of modern rivers (Fig. 11). Some of these, such as the Tyner and Battleford, converge and join in a downslope direction (Fig. 1), giving the impression that they once functioned as tributaries. The second major orientation of Prairie buried valleys is roughly across slope (Fig. 1). The Hatfield buried valley is a prominent example (Christiansen et al., 1975, 1977; Christiansen, 1977; Maathuis, 1980; Maathuis and Schreiner, 1982a,b; Schreiner and Maathuis, 1982). It trends perpendicular to most nearby buried valleys, and its valley floor exhibits little to no net drop in elevation over hundreds of kilometres, a trait shared by the similarly prominent Spiritwood buried valley in North Dakota (Fig. 11). Another commonly cited buried valley that crosses bedrock slope is the New Rockford buried valley in North Dakota (Kehew and Boettger, 1986).

Prairie buried valleys: size and shape

As mentioned previously, Prairie buried valleys tend to be large (Fig. 12). Most have heights and widths that are greater than those of modern alluvial (self-formed) rivers (Baker, 2001; Gibling, 2006) and greater than those of incised valleys on the modern Prairie landscape (e.g. Wright, 1973; Kehew et al., 2009). In terms of cross-sectional shape, the height-to-width ratio of Prairie buried valleys varies considerably (Fig. 12). In general, larger buried valleys, such as the Hatfield and Spiritwood, tend to have broader, shallower cross-sectional shapes, whereas smaller buried valleys, such as the Gregoire and Holyoke, tend to have narrower, deeper shapes. Some well mapped buried valleys (e.g. Spiritwood, Hatfield) pinch and swell considerably in height and width along valley (Fig. 12) and have highly irregular bedrock floors (Shaver and Pusc, 1992). In some larger valleys, one or more smaller inset valleys are observed to be incised into the bedrock floors (Farvolden, 1963; Andriashek, 2003; Oldenborger et al., 2010).

Prairie buried valleys: sedimentary fill

Drilling and geophysical data suggest that Prairie buried valley fills are, as a general rule, heterogeneous and architecturally complex (Fig. 13). Electromagnetic data, where available (e.g. Oldenborger et al., 2010), corroborate this view (Fig. 14). Sand, gravel, mud, and diamicton (till) are common fill components. Buried-valley fills can consist almost entirely of diamicton (Howard, 1960; Hinton et al., 2007), almost entirely of mud (Huxel, 1961), or almost entirely of sand and gravel (Andriashek, 2003), although they more commonly consist of a mix of these materials (Fig. 13). In the rare cases where sand and gravel dominate a fill, thick intervening mud units tend to be present (e.g. the ~10 m thick mud layer in Gregoire buried valley; Andriashek, 2003). Huge blocks of glacially transported bedrock, some greater than 100 m thick and 10 km in length, are rarely observed (Andriashek and Fenton, 1989). In situ tree trunks are rarely present (Proudfoot, 1985). Despite this variability, several common themes emerge: numerous valleys contain permeable sand and/or gravel bodies along their bases, and their upper portions are commonly filled with mud-rich diamicton (till). However, confident prediction of the volume and location of permeable elements within Prairie buried valleys prior to drilling remains elusive, at least in the absence of electromagnetic data.

When viewed as a whole, Prairie buried-valley fills change in lithology and grain size moving across the Prairies (Fig. 15). Near the Rocky Mountains, Rocky Mountain–derived quartzite, chert and, in places, limestone, clasts are abundant, WCSB clasts are rare, and Precambrian Shield clasts are typically absent (Dawson, 1890; Stalker, 1968;

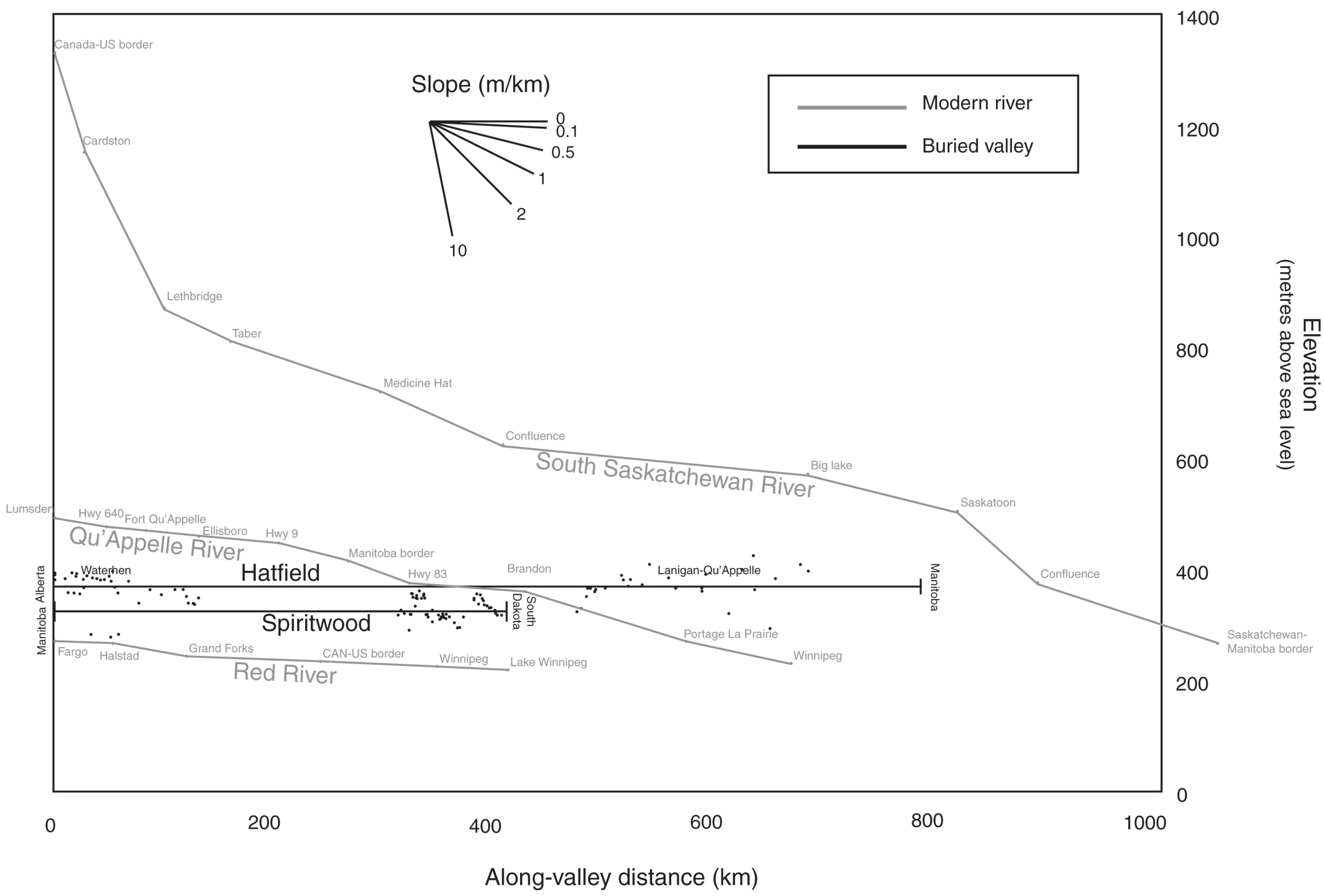


Figure 11. Slope of the Hatfield buried valley, Saskatchewan, a major cross-slope buried valley, plotted relative to the slope of modern rivers. Note that little to no downslope drop in elevation occurs in the Hatfield thalweg over its mapped extent. The Spiritwood buried valley in North Dakota is similar. Because the surficial sediment cover is thin and regionally drapes bedrock (Fig. 4), downslope-trending buried valleys (not depicted) tend to have similar slopes as the modern rivers in their vicinity. Hatfield data from Maathuis (1980) and Maathuis and Schreiner (1982a,b). Spiritwood data from various North Dakota county groundwater reports (Armstrong, 1982; Randich and Kuzniar, 1984; Shaver, 1984).

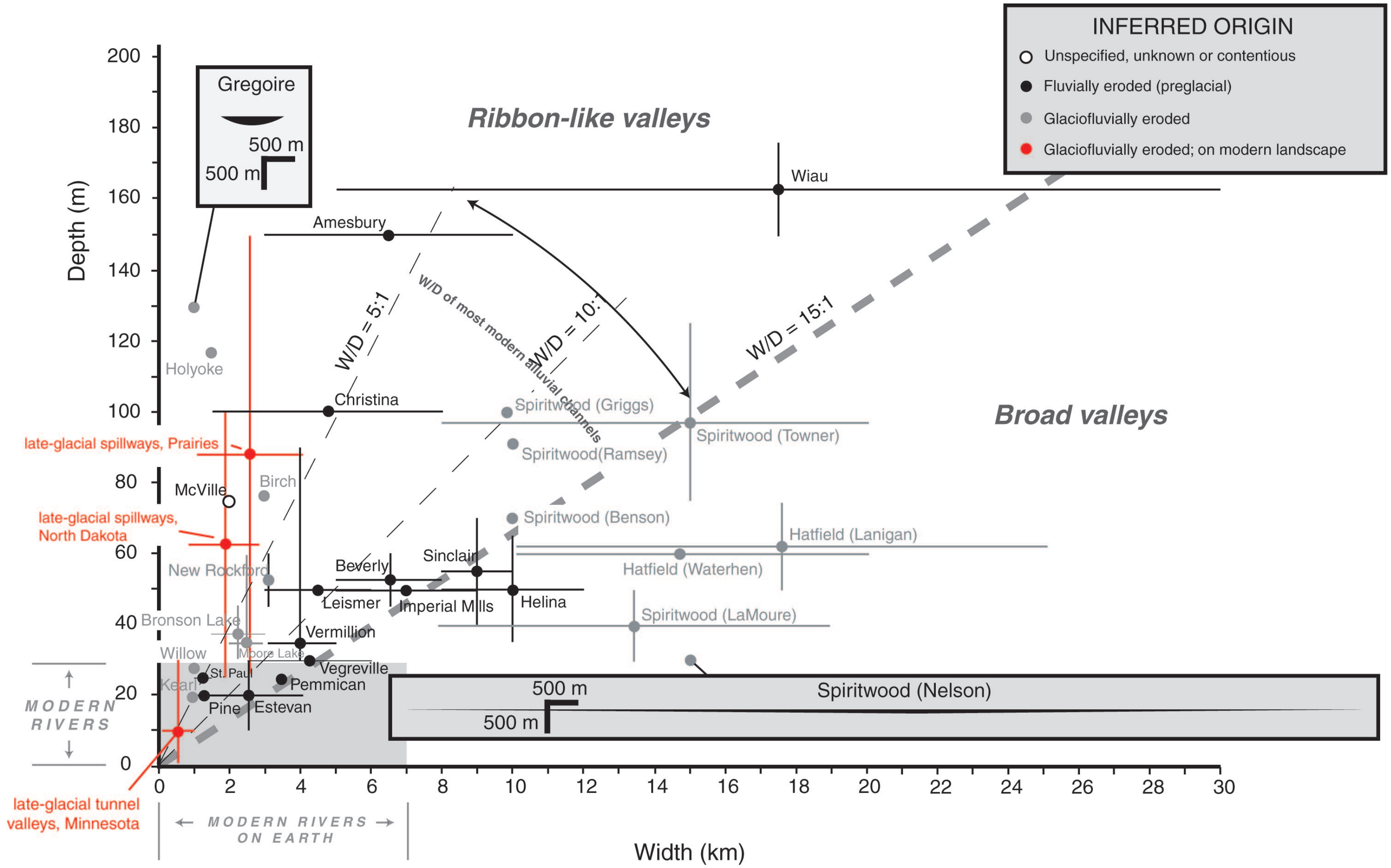


Figure 12. Heights and widths of Prairie buried valleys, along with inferred origin. Also shown are heights and widths of incised valleys on the modern Prairie landscape (in red) and heights and widths of modern alluvial rivers worldwide (grey box). Data from Trapp (1968) for the New Rockford (Foster County); Wright (1973) for tunnel valleys on land surface in Minnesota; Downey (1973) for the Spiritwood (Nelson County); Downey and Armstrong (1977) for the Spiritwood (Griggs County) and the McVille; Randich (1977) for the Spiritwood (Benson County); Armstrong (1980) for the Spiritwood (LaMoure County); Hutchinson and Klausing (1980) for the Spiritwood (Ramsey County); Maathuis (1980) for the Hatfield buried valley (Lanigan); Maathuis and Schreiner (1982a) for the Hatfield buried valley (Waterhen); Randich and Kuzniar (1984) for the Spiritwood (Towner County); Kehew and Boettger (1986) for dimensions of spillways on the landsurface in North Dakota and for inferred origin of Spiritwood and New Rockford; Andriashek and Fenton (1989) for the Helina, Sinclair, Vermillion, Beverly, Vegreville, St. Paul, Moore Lake, Bronson Lake, and Holyoke buried valleys; van der Kamp and Maathuis (2002) for the Estevan buried valley - dimensions may refer to height and width of aquifer body, possibly not bedrock buried valley; Andriashek (2003) for the Wiau, Leismer, Christina, Amesbury, Imperial Mills, and Gregoire buried valleys; Gibling (2006) for the W/D terminology and ratios for modern alluvial rivers; Andriashek and Atkinson (2007) for the Birch, Kearl, Willow, Pemmican, and Pine buried valleys; Kehew et al. (2009) for spillways on the landsurface in the Prairies.

Jackson et al., 2011). Fills are gravel-rich. Mud layers are scarce. Moving downslope away from the mountains, the abundance of Rocky Mountain–derived limestone clasts decreases rapidly (Dawson, 1890), leaving quartzite and chert as the predominant lithologies. Precambrian Shield clasts start to be observed, typically near the top of buried-valley fills (McConnell, 1885), but also at the base of some buried valleys (Whitaker and Christiansen, 1972; Andriashek and Fenton, 1989; Andriashek, 2003). In Saskatchewan, where Precambrian clasts are present in the fill, the associated sand tends to be carbonate rich (Whitaker and Christiansen, 1972). Gravel from the WCSB starts to become more abundant, and in places is observed to be dominant. For example, Kelly (1966) reports that more than 90% of the gravel in a portion of the Spiritwood buried valley, North Dakota, consists of WCSB shale. Thick mud units start to be more frequent, in places dominating the middle portion of the fill, as observed in valleys such as the Estevan (van der Kamp et al., 1986), Medicine Hat (Proudfoot, 1985), Tyner (Karvonen, 1997), and Wiau (Andriashek, 2003). Sand commonly replaces gravel as the predominant fill material: it accounts for most sub-till sediment exposed near Edmonton in central Alberta (Rutherford, 1937), becomes increasingly common in buried valleys east of Lethbridge in southern Alberta (Jackson et al., 2011), and dominates the permeable parts of buried valleys in Saskatchewan (Whitaker and Christiansen, 1972; Maathuis and Schreiner, 1982a,b; Schreiner and Maathuis, 1982). By lithostratigraphic convention, all gravel, sand, and mud between bedrock and till in the Prairies is referred to as the Empress Group (commonly referred to as the Empress Formation in Alberta (e.g. Andriashek, 2003)) (Whitaker and Christiansen, 1972).

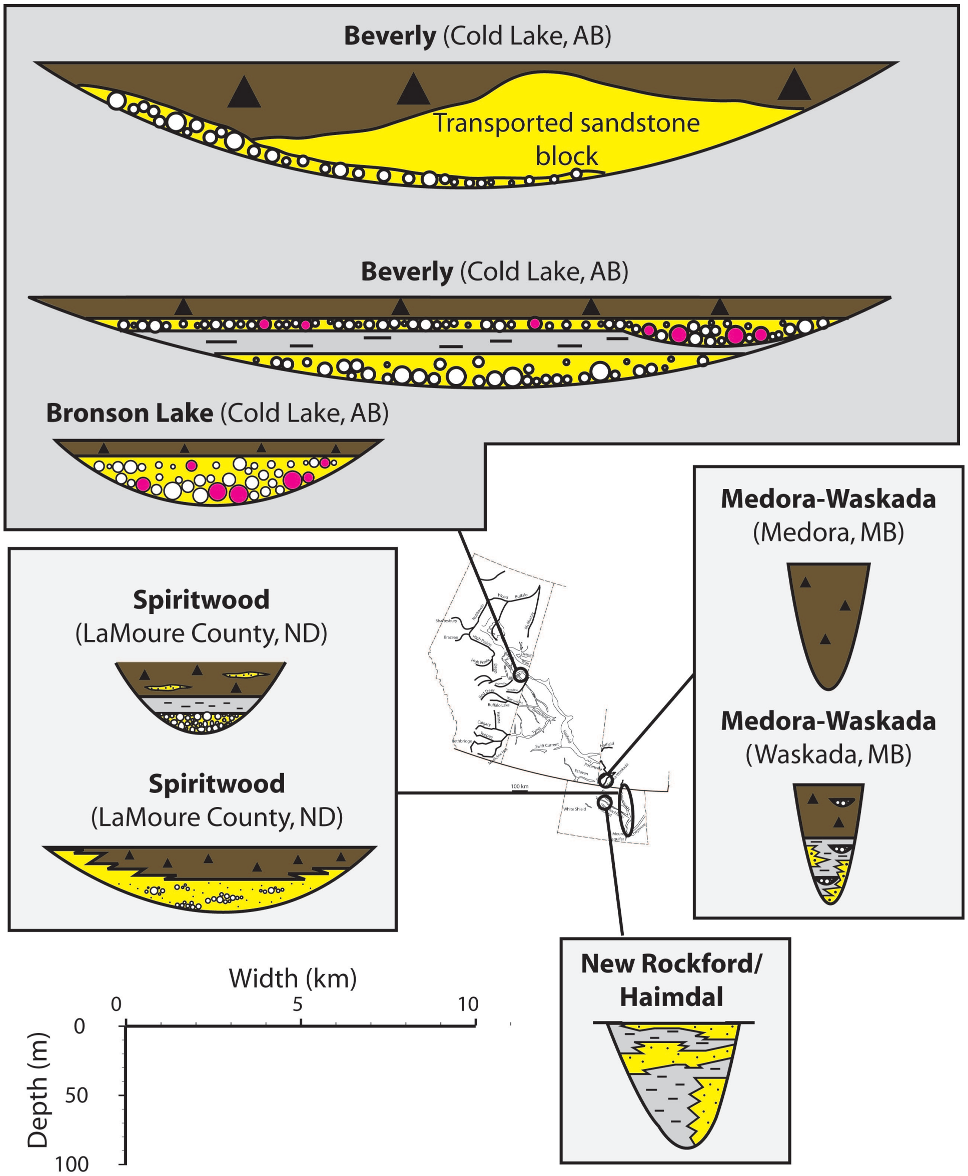


Figure 13. Cross-sections and fills of several buried valleys in the Canadian Prairies and North Dakota. All examples are constrained by multiple wells or wells and seismic data. Note common presence of sand and/or gravel at valley base, diamicton (till) in upper part of valley, and a thick till cover (not shown). Note that till was intersected beneath parts of the Spiritwood buried valley in LaMoure County, North Dakota (the lower of the two Spiritwood cross-sections shown), which indicates the valley fill subtends from a surface within the till. Pink clasts are Shield clasts. Data from Huxel (1961), Kehew and Boettger (1986), Andriashek and Fenton (1989), Shaver and Pusc (1992), and Hinton et al. (2007). Grey – mud, yellow – sand, white circles – gravel, pink circles – Shield gravel, brown with triangles – diamicton.

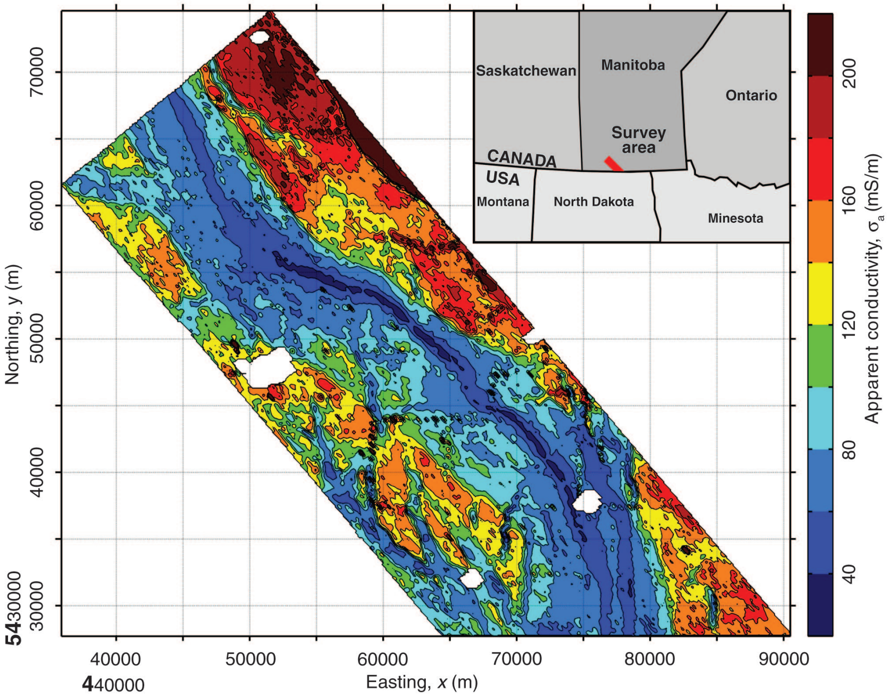


Figure 14. Electromagnetic (EM) image of the Spiritwood buried valley aquifer in Manitoba, just north of the border with North Dakota (figure courtesy of G. Oldenborger). The blue colours correspond roughly to the Spiritwood buried valley (~10 km wide) and the red and yellow colours to its interfluves. Note presence of multiple smaller channel-like features, including at least two narrow channels (dark blue) that are inset along the base of the Spiritwood. Drilling suggests that most of the Spiritwood at this location is filled with mud-rich till (Hinton, pers. comm., 2010). By contrast, the smaller inset channels are known to locally contain sand and gravel units that yield abundant groundwater (W.L. Gibbons and Associations, unpub. rept., 2009). These smaller inset channels had proven difficult to delineate using wells alone. The EM data, by contrast, clearly outline the inset channels, thus simplifying the groundwater exploration process in this area.

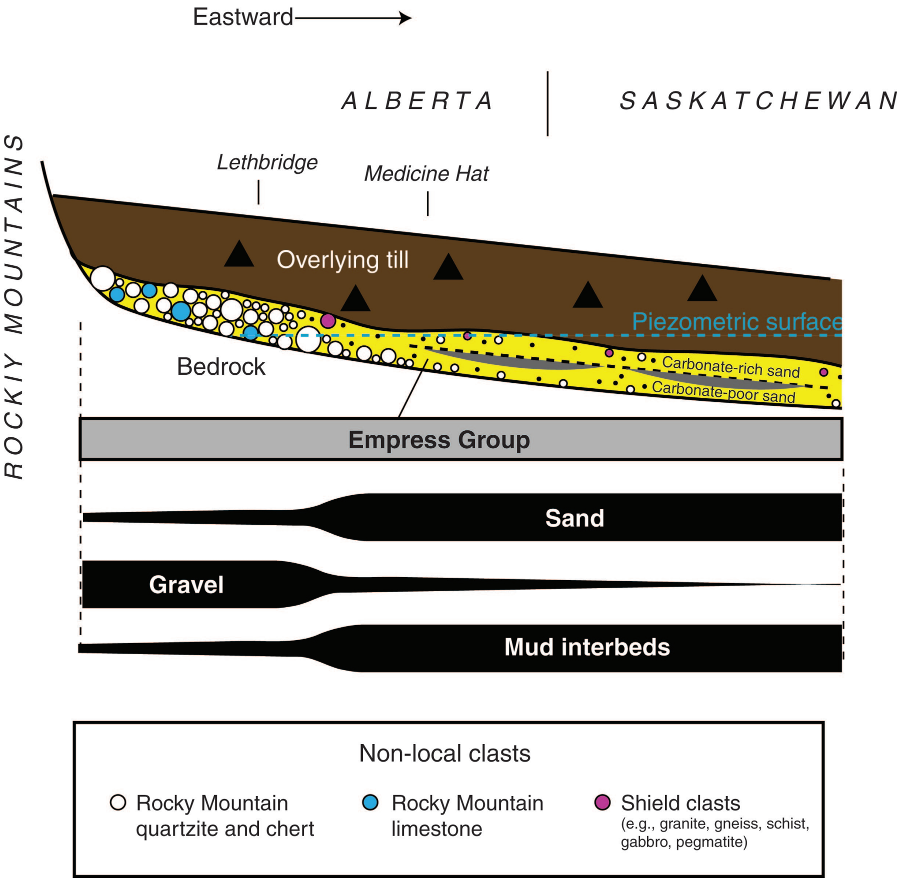


Figure 15. Gross changes in buried-valley aquifer geology across the Canadian Prairies. For simplicity, diamicton, a common fill component, is not depicted in the buried-valley fill, and the heterogeneity inherent to Prairie buried-valley fills is either not shown or is highly simplified. The cartoon is not specific to any given buried valley, but rather attempts to depict changes in aquifer material within buried valleys as a whole. Because of this, it should be seen as a conceptual tool, not a roadmap for predicting aquifer potential. Many slope-parallel buried valleys, such as the Lethbridge (McConnell, 1885; Proudfoot, 1985), Estevan (Christiansen and Parizek, 1961; van der Kamp et al., 1986), Tyner (Karvonen, 1997), and Wiau (Andriashek, 2003), share some if not most of these traits. Cross-slope buried valleys—and specifically the Hatfield—share few if any of these traits (Meneley, 1972). WCSB clasts also not shown. Data and ideas from McConnell (1885), Stalker (1963), Proudfoot (1985), Whitaker and Christiansen (1972), and Jackson et al. (2011).

The quartzite gravel observed at the base of many Prairie buried valley fills deserves additional scrutiny. Dawson (1884), McConnell (1885), and Tyrrell (1887) first observed quartzite gravel deposits over bedrock and beneath till along the South Saskatchewan River and its tributaries. Where originally described near Lethbridge, Alberta, the gravel consists of over 50% pinkish to white quartzite and dark-coloured chert, with minor amounts of maroon and greenish argillite, grey limestone, volcanic rocks, diorite, and locally derived WCSB sandstone and shale (McConnell, 1885; Alden and Stebinger, 1913; Horberg, 1952; Stalker, 1963). McConnell (1885) called the gravel unit the *South Saskatchewan gravel*, interpreted it to have a Rocky Mountain provenance, and argued that it was younger than, and possibly in part sourced from, the quartzite gravel capping the adjacent erosional Cypress Hills uplands (Fig. 6). Similar deposits were subsequently observed in the subsurface of Montana (Calhoun, 1906), North Dakota (Bluemle, 1972), northern Alberta (Bell, 1884; Andriashek, 2003), and in various part of Saskatchewan (Christiansen and Parizek, 1961; Whitaker and Christiansen, 1972). Whitaker and Christiansen (1972) reported abundant green epidote and black rock fragments in the associated sand fraction in southwest Saskatchewan, and, similarly, Andriashek (2003) described the associated sand in northeastern Alberta as having a ‘salt-and-pepper’ appearance. Authors have generally eschewed the original term *South Saskatchewan gravels* in favour of the term *Saskatchewan gravels* (Dawson and McConnell, 1895; Calhoun, 1906) or *Saskatchewan gravels and sands* (Rutherford, 1937; Stalker, 1963). In Alberta, the lower contact of the Saskatchewan gravels locally overlies oxidized bedrock (Dawson, 1884). Its upper contact is locally disturbed by ice-wedge casts (Westgate and Bayrock, 1964) and, elsewhere, is locally oxidized (Alden and Stebinger, 1913; Morgan et al., 2008). Radiocarbon dates on organics recovered from the unit in Alberta have yielded finite radiocarbon ages (Jackson et al., 2011).

Prairie buried valleys: origin

Four main criteria have been used to interpret how and when Prairie buried valleys became incised: 1) stratigraphic position, 2) provenance of basal fill, 3) valley orientation, and 4) valley cross-sectional shape (Fig. 3; Dawson, 1884; McConnell, 1885; Upham, 1894; Bell, 1895; Calhoun, 1906; Flint, 1955; Stalker, 1961, 1968; Farvolden, 1963; Bluemle, 1972; Kehew and Boettger, 1986; Whitaker and Christiansen, 1972; Christiansen et al., 1975; Christiansen et al., 1977; Andriashek, 2003). Of these, stratigraphic position and the basal fill provenance are the most diagnostic. Preglacial buried valleys should invariably subtend (‘hang’) from the bedrock unconformity. Their basal fills should be western-derived (e.g. no Shield clasts), provided subsequent erosion has not removed them. (Reoccupation of preglacial valleys by glaciofluvial systems can juxtapose glaciofluvial fill next to preglacial fill along the valley floor, which can complicate interpretation (Andriashek, 2003)). Their orientation should be roughly parallel to paleoslope, which was likely north-westward during the late Tertiary, similar to today (Leckie, 2006). Finally, because they are thought to have formed over a prolonged time period, they are generally envisioned to be relatively wide (e.g. Stalker, 1968), presumably because of multiple side-wall failures coupled with lateral combing of the channel across the valley floor. Buried valleys interpreted to be preglacially incised include the Estevan (Meneley et al., 1957), Lethbridge (McConnell, 1885) and Wiau (Andriashek, 2003).

Glaciofluvial buried valleys, by contrast, should subtend from a surface in the overlying till package, provided they did not form in front of the first advancing ice sheet. Till may therefore be intersected beneath them. Their basal fills may contain eastern-derived clasts (e.g. Shield granite or gneiss) transported upslope by previous continental ice sheets. The orientations of glaciofluvial buried valleys do not have to follow paleoslope: spillways or other forms of ice-front–parallel streams may cross slope (Stalker, 1961; Christiansen, 1977; Kehew and Boettger, 1986), whereas tunnel valleys may trend upslope in places (Andriashek, 2003). Glaciofluvially incised valleys (spillways and tunnel valleys) are generally envisioned to be small, narrow and deep: the glaciofluvial origin of many of the smaller buried valleys in Figure 12 is interpreted based on these traits alone. However, a clear link between valley origin and valley size/shape is difficult to prove: some of the largest, widest Prairie buried valleys — most notably the Hatfield and Spiritwood — are also interpreted to be glaciofluvial in origin, and this correlation is not obvious in the global data set of Gibling (2006). Buried valleys interpreted to have been glaciofluvially incised include the Hatfield (Christiansen, 1977), Spiritwood (Kehew and Boettger, 1986) and New Rockford (Kehew and Boettger, 1986).

The preceding deals with the *incision* of buried valleys in the Canadian Prairies. How these valleys became *filled* with sediment is a somewhat separate issue that may or may not relate to the processes of incision. The heterogeneity typical of Prairie buried valleys suggests that many were filled over the course of multiple events involving deposition and erosion in some combination of preglacial fluvial, glaciofluvial, glaciolacustrine, and subglacial environments. The common presence of till in valley fills (e.g. Huxel, 1961) coupled with the rare presence of organic materials, such as tree trunks (Proudfoot, 1985), in addition to sand, gravel, and mud units, suggests that many buried valleys filled over the course of multiple glaciations. A prominent mud unit that separates western-derived sediment below from eastern-derived sediment in several buried valleys, for example Lethbridge (Proudfoot, 1985) and Wiau (Andriashek, 2003), may record proglacial lake development in front of the first advancing continental ice sheet (Proudfoot, 1985). Deposition of the Saskatchewan gravels and sands was likely periglacial in part, given the locally observed ice-wedge casts (Westgate and Bayrock, 1964). It could also have been highly diachronous: deposition may have stopped earlier in Saskatchewan and Manitoba, which were closer to the centre of continental glaciation and thus presumably covered by earlier Quaternary continental ice sheets, whereas it may have continued until much later in western Alberta, where an ice-free corridor is hypothesized to have existed until the last glacial maximum (Jackson et al., 2011). This would help explain the young sub-till radiocarbon dates from Saskatchewan gravels in western Alberta (Jackson et al., 2011).

HYDROGEOLOGY

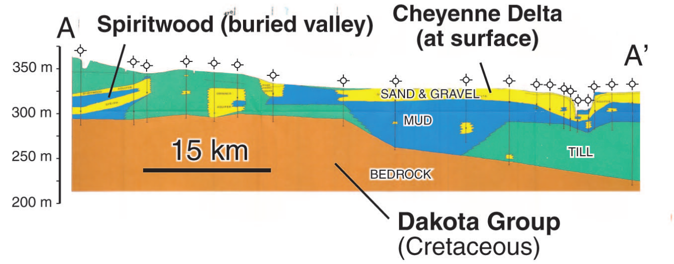
The hydrogeology of Prairie buried-valley aquifers is a function of their distinct geologies and their distinct stratigraphic setting. In particular, the thick till that overlies Prairie buried valleys appears to commonly limit recharge. In areas where several tens of metres of till overlie buried valleys, hydraulic-head responses to precipitation events tend to be muted or absent, and recovery of head following intense pumping can take years (van der Kamp et al., 1986). Where till cover is thick, small annual fluctuations in head occur, but they have been postulated to primarily record seasonal changes in surface-moisture loading, not seasonal recharge (van der Kamp and Maathuis, 1991). Theoretically, direct connection is more likely where the till cover is thinner, for example in parts of Alberta, or possibly where heterogeneity exists in the overlying till package (Andriashek, 2003). The chemistry of groundwater in buried-valley aquifers tends to be intermediate between the chemistry of more highly mineralized water in bedrock and the less highly mineralized water in the overlying deposits (Fig. 16). In some flow systems, groundwater chemistry in buried valley aquifers has been observed to evolve and become more highly mineralized between recharge and discharge zones (Fig. 17). Only rarely do groundwater chemistries indicate complete isolation from surface-water sources (e.g. West Fargo aquifer; Shaver, 2010). Viewed macroscopically, buried-valley fills tend to be more permeable than the surrounding strata (Table 1; Fig. 5). Pump tests have generated drawdown cones that extend over ten kilometres along valley (e.g. Estevan – van der Kamp et al., 1986). Some buried valleys may operate as regional groundwater drains, with modern rivers commonly functioning as discharge zones (Shaver, 1984; van der Kamp et al., 1986). How buried-valley aquifers are recharged remains an open question; some postulate that interconnected inter-till aquifers, such as those that appear present above the Spiritwood in southern Manitoba (Oldenborger et al., 2010), may function as recharge pathways (Andriashek, 2003; Shaver, 2010). Ubiquitous Prairie potholes (e.g. Fig. 5b) may also help focus recharge locally (Meyboom, 1966; Sloan, 1972; Berthold et al., 2004). Viewed at higher resolution, heterogeneity within buried-valley fills from till layers, mud-filled channels, and irregularities on shale bedrock floors is common, and it may commonly function to compartmentalize the aquifers and create localized flow systems (Shaver and Pusc, 1992). These barriers to flow are difficult to map using water-well data. As such, buried-valley fills tend to be modelled as homogeneous entities, even though they are anything but. Bulk hydraulic conductivities of 10^{-1} to 10^{-3} cm/s have been used (Table 1).

Hydrogeologically, Prairie till is typically subdivided into two units, a thin layer of brown *weathered till* below ground surface, typically 5 to 20 m thick, and a grey and commonly thicker unit of *unweathered till* below this (Fig. 5b). Fractures tend to be confined to the weathered till (Hendry, 1982, 1988; Keller et al., 1988), but in places can extend through unweathered till also (Grisak and Cherry, 1975). Weathered till tends to be one or more orders of magnitude more permeable than unweathered till: bulk hydraulic conductivities for the former and latter range from 10^{-9} to 10^{-7} m/s and 10^{-11} to 10^{-9} m/s, respectively (Table 1). Solute transport is thought to be dominated by molecular diffusion in unweathered till and by fracture flow in weathered till (e.g. Hendry and Wassennar, 2009). Downward groundwater velocities in unfractured till are low: Shaw and Hendry (1998) estimate values of 0.5 to 0.8 m per 10 000 years near Saskatoon, Saskatchewan. Porewater in weathered till is commonly enriched in tritium, oxygen-18, and deuterium, suggesting that the zone is hydrogeologically active (Hendry, 1988). The chemistry of porewater in inter-till aquifers (Maathuis, 2010) and in thin sand layers in the till (Keller et al., 1988) tends to be similar to that of the porewater in the till.

SUMMARY AND A LOOK FORWARD

The current state of knowledge of Prairie buried-valley aquifers and the till aquitards that overlie them is based on over 100 years of outcrop work and more than 50 years of subsurface water-well mapping. Major buried valleys have been delineated and the first-order nature of some of their fills is understood. The next step forward will involve mapping the heterogeneity of till aquitards and buried-valley fills: risk involved in the development of buried-valley aquifers would be considerably reduced if recharge pathways and valley-fill heterogeneities could be estimated with confidence ‘before the drill bit.’ As demonstrated by industry over the past several decades (e.g. Golder Associates Ltd., unpub. rept., 2009) and in the rare public data that have been collected (Oldenborger et al., 2010), a tool does exist that can successfully be used to do this, namely electromagnetic data (Fig. 14). Electromagnetic data has the potential to provide new insights into Prairie buried valleys and till that rival those afforded by studying outcrops in the late 1800s and water wells in the mid to late 1900s. Continuous cores and seismic data, which have rarely been collected in the Prairies, would considerably augment new insight. Collection of new data sets that integrate these types of data currently offers the most accurate, most cost-effective way of rapidly advancing the understanding of buried-valley aquifers in the Canadian Prairies.

	Spiritwood	Cheyenne Delta	Dakota Group (sandstone and shale)
Dissolved solids (mg/l)	1200	386	2680
Sodium (mg/l)	208	23	880
Sodium as % of total cations	48	~30	53-98
Sulfate (mg/l)	>250	37	1090
Chloride (mg/l)	88	low	high
Hardness (mg/l)	220–1000	170–410	140
Response to precip/evap	smooth and < 1 m	spiky and > 1 m	?



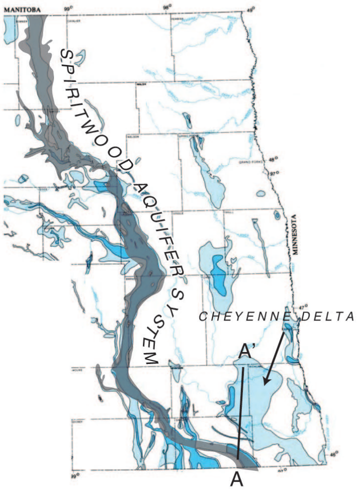
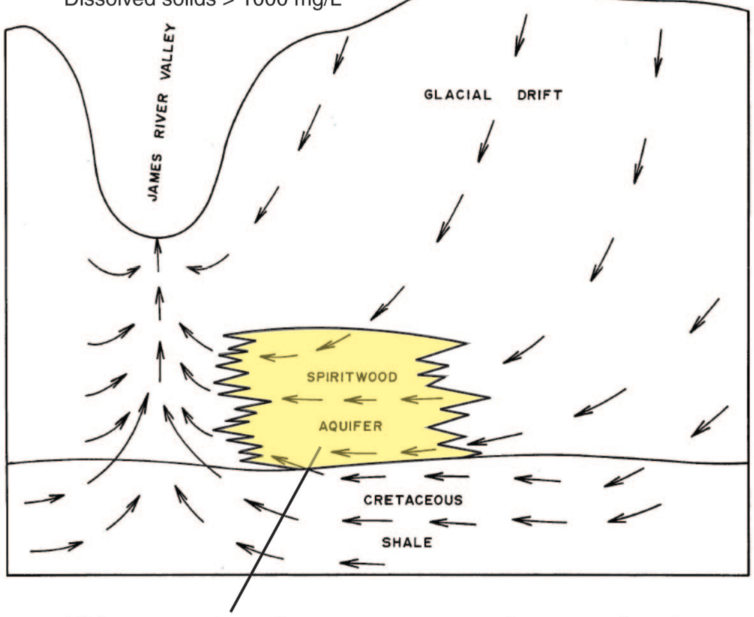


Figure 16. Chemistry of porewater in a surficial sediment aquifer (Cheyenne delta), a buried valley aquifer (Spiritwood), and a sandstone bedrock aquifer (Dakota) in Sargent County, North Dakota (Armstrong, 1982). Note that water in surficial aquifer contains less dissolved solids than that in the buried valley aquifer, which in turn contains less than the water in the sandstone aquifer. Although exceptions occur (Shaver, 2010), similar observations are common throughout the Prairies (e.g. Maathuis, 2010).



Dicharge areas

High Na, SO_4 and Cl
Low Ca, Mg and CO_3
Dissolved solids > 1000 mg/L

Recharge areas

High Ca, Mg and CO_3
Low Na, SO_4 and Cl
Dissolved solids < 750 mg/L

Mixing process in aquifer is dominated by hydrochemical facies of overlying glacial drift...

...except where upward gradients occur (e.g., discharge zones). Here the mixing process is impacted more by the hydrochemical facies of the underlying shale.

Figure 17. Hypothetical model depicting the chemical evolution of groundwater as it passes from recharge to discharge zone in a portion of the Spiritwood buried valley aquifer, North Dakota (Shaver, 1984).

Table 1. Published hydraulic conductivity values for surficial sediment and bedrock in the Prairies

Stratigraphic unit	ALBERTA		SASKATCHEWAN						MANITOBA	SOUTH DAKOTA
	Hendry (1982)	**Lennox et al. (1988)**	**Walton (1970)**	**Meneley (1972)**	**van der Kamp et al. (1986)**	**Lennox et al. (1988)**	**Keller et al. (1988) Dalmeny site**	**Keller et al. (1988) Warman site**	**Grisak and Cherry (1975)**	**Cravens and Ruedisili (1987)**
Weathered, fractured till (bulk)	5 x 10^{-9} to 2 x 10^{-7} m/s		--	--	--	--	5 x 10^{-9} m/s	--	1.8 x 10^{-9} m/s	7.41 x 10^{-8} m/s
Weathered, fractured till (intergranular)	10^{-10} m/s		--	--	--	--	--	--	6 x 10^{-11} to 2.7 x 10^{-11} m/s	--
Inter-till aquifer	--		--	2–4 x 10^{-4} m/s	--	--	--	--	--	--
Unweathered till	--		6 x 1.0^{-9} m/s	1.0^{-9} m/s	1 x 10^{-10} to 1 x 10^{-9} m/s	--	5 x 10^{-9} m/s*	5 x 10^{-11} m/s	1.8 x 10^{-9} m/s*	4.27 x 10^{-9} m/s
Buried valley sand and/or gravel bodies**	--	1.6 x 10^{-3} m/s (Police Point)	--	2–4 x 10^{-4} m/s	--	1.2 x 10^{-5} to 1.5 x 10^{-4} m/s (Hatfield; Estevan)	--	--	--	--
Shale***	--		--	--	1.4 x 10^{-12} m/s	--	--	--	--	--
Sandstone				1–5 x 10^{-4} m/s						

* Unweathered but fractured till.
** Till and mud, which also occur in buried valleys, have lower permeability.
*** Bredehoeft et al. (1983) suggest Westen Canadian Sedimentary Basin shale in vicinity of Great Plains aquifer, USA, has hydraulic conductivity of 1.6 x 10^{-11} m/s.

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