Buried-valley aquifers in the Canadian Prairies: geology, hydrogeology, and origin

Don I. Cummings, Hazen A.J. Russell, and David R. Sharpe

Abstract: We review over 100 years of literature on Prairie buried valleys to provide a platform for future research and policy development. Prairie buried-valley fills commonly function as aquifers that yield abundant groundwater. They have distinct geologies and a distinct stratigraphic setting, which imparts them with distinct hydrogeological properties and gives clues as to how they formed and filled. Prairie buried-valley aquifers are commonly encased in low-permeability strata: Cretaceous shale commonly underlies 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 position of Prairie buried valleys also speaks to their origin: those that subvert (“hang”) from the bedrock unconformity were likely eroded by preglacial fluvial systems during late Tertiary uplift of the Rocky Mountains, whereas those that subvert 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 likely over multiple glaciations, in multiple depositional environments.
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; Bell 1884; Dawson 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. 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. The objective of this report is to cull data and ideas from both bodies of literature — the “hydrogeological” and the “geological” — to provide a broad, up-to-date review of Prairie buried-valley aquifers. 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 nongenetic — a buried valley may have formed by tectonic, glacial, glaciofluvial, fluvial, or other processes — and it carries no connotation of stratigraphic position, other than 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 intertill aquifers (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 Fig. 1 that are incised into bedrock and buried by till.

Prairie buried-valleys and their fills

The hydrogeological behaviour of Prairie buried-valley fills, which is described farther below in the section “Hydrogeology”, is a direct consequence of the processes that sculpted the Prairie bedrock surface and covered it in sediment, as described here.

Prairie buried valleys: stratigraphic position

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 is 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 in Saskatchewan and Manitoba (Fig. 5; Maathuis and Thorleifson 2000). Cretaceous sandstone forms bedrock locally and is more common in Alberta. Paleozoic carbonate
rock forms the bedrock substrate along the northeastern feather edge of the WCSB.  

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 today (Heller et al. 2003; Leckie 2006). The age of the gravels decreases with elevation: mammal fossils suggest that the Cypress Hills gravels are Eocene to Middle Miocene (47–22 Ma) in age, the Wood Mountain gravels are Middle Miocene (16–11.5 Ma), and 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 9.3–8.3 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 down-cutting 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 pre-glacial fluvial systems that performed the down-cutting 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 1.5–2 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 McLean 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 longstanding notion that pre-Quaternary 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; Upham 1894; Wilson 1903; Ambrose 1964; Shilts et al. 1987).

The surficial sediment package that covers the Canadian Prairies, of which buried-valley fills form a small part, is relatively thick (10–350 m) and is dominated by mud-rich diamicton. The diamicton-dominated sediment package forms a regional drape over bedrock, its variations in thickness accenting or subduing the otherwise bedrock-controlled landscape locally (Fig. 4). Diamicton covers almost all buried valleys and fills many of them, either in whole or in part.

In outcrop, Prairie diamicton is commonly stratified or massive (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 thrust 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). Diamictons of colluvial or glaciolacustrine origin may also be present (Proudfoot 1985).

Clastic particles (mud, sand, and gravel) in Prairie till come from three main bedrock sources: the WCSB, the Rocky Mountains, and the Precambrian Shield (Fig. 1). Till
Fig. 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. (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; Blumle 1972; Christiansen 1977; Kehe and Boettger 1986; Andriashek 2003). (C) Glaciofluvial incision of a tunnel valley driven by subglacial water flow (e.g., Andriashek 2003).

matrices tend to contain abundant clay particles, 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 derived from bedrock to the east are abundant in the gravel fraction (Dawson 1890; Flint 1955; Howard 1960), and their abundance decreases toward the mountains (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 US border near the Rocky Mountains, and their abundance decreases eastward (downslope) across the Prairies (Dawson 1890; Shetsen 1984; see also Shaw and Kellerhals 1982). Paleozoic carbonate rock clasts from the northeast edge of the WCSB commonly dominate the gravel fraction in sands in Manitoba and Saskatchewan (Dawson 1890) and in the US 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. Down-slope (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.

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 (e.g., Moran 1986), some of which contain fossils (Skwara Wolf 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). 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 reports difficulty in differentiating tills near Medicine Hat, Alberta, using traditional criteria (grain size, clay mineralogy, sand-grain lithology). He was only able to differentiate two till units because of the presence of an intervening lag-lined erosion surface.

A variety of models has been proposed to explain how Prairie tills were deposited. 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 omnipresent closed depressions commonly referred to as Prairie potholes or sloughs.

Several macroscopic stratigraphic trends are commonly reported in the Prairie till package that also lend insight into how Prairie tills formed. For example, clay content is commonly observed to decrease irregularly upward, whereas matrix carbonate tends to exhibit the opposite trend (Fig. 5A). 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-centered 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. 8). This cut off bedrock from subsequent erosion, except where till was thin and patchy, where local dispersal trains could still form (e.g., Sioux quartzite dispersal train, South Dakota; Flint 1955). Some authors report increasing proportions of crystalline clasts in stratigraphically higher and younger tills (Fig. 5A; Dawson 1890; Horberg 1954; Andriashek and Fenton 1989). This would seem to support the Meneley model. It 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: 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, on a broad scale, similar to those
of modern rivers (Fig. 9). 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; Maathuis 1980; Maathuis and Schreiner 1982a, 1982b; 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. 9). 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. 10). Most have heights and widths that are greater than those of modern alluvial 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. 10). 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 the valley (Fig. 10) and have highly irregular bedrock floors (Shaver and Pusco 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. 11). Electromagnetic data, where available (e.g., Oldenborger et al. 2010), corroborate this view (Fig. 12). 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 sedimentary units (Fig. 11). 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, the sand and gravel units (aquifers) in Prairie buried-valley fills change in lithology and grain size moving across the Prairies (Fig. 13). Near the Rocky Mountains, Rocky Mountain-derived quartzite, chert, and in places, limestone clasts are abundant, WCSSB clasts are rare, and Precambrian Shield clasts are typically absent (Dawson 1890; Stalker 1968; 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 WCSSB starts to become more abundant and, in places, is observed to be dominant. For example, Kelly (1966) reports that >90% of the gravel in a portion of the Spiritwood buried valley, North Dakota, consists of WCSSB 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 aquifer material: it accounts for most subtilt 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-valley fills in Saskatchewan (Whitaker and Christiansen 1972; Maathuis and Schreiner 1982a, 1982b; 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 in Saskatchewan (Whitaker and Christiansen 1972) or the Empress Formation in Alberta (e.g., Andriashek 2003).

The quartzite gravel observed at the base of many Prairie buried-valley fills deserves additional discussion. 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 WCSSB sandstone and shale (McConnell 1885; Alden and Stebinger 1913; Horberg 1952; Stalker 1963). McConnell (1885) coined 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 parts of Saskatchewan (Christiansen and Parizek 1961; Whitaker and Christiansen 1972). Whitaker and Christiansen (1972) report abundant green epidote and black rock fragments in the associated sand fraction in southwest Saskatchewan, and similarly, Andriashek (2003) describes 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: (i) stratigraphic position, (ii) provenance of basal fill, (iii) valley orientation, and (iv) valley cross-sectional shape (Fig. 3; Dawson 1884; McConnell 1885; Upham 1894; Bell 1895; Calhoun 1906; Flint 1955; Stalker 1961; Stalker 1968; Farvolden 1963; Bluemle 1972; Whitaker and Christiansen 1972; Christiansen et al. 1975, 1977; Kezew and Beettger 1986; Andriashek 2003). Of these, stratigraphic position and the basal fill provenance are the most diagnostic. Preglacial buried valleys should invariably subside (“hang”) from the bedrock unconformity. Their basal fills should be western-derived (e.g., no Shield clasts), provided subsequent erosion has not removed them. The orientation of preglacial valleys should be roughly parallel to paleoslope, which was likely northwestward 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 pre-glacially 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. Reoccupation of preglacial valleys by glaciofluvial systems can juxtapose glaciofluvial fill next to preglacial fill along the valley floor, which can complicate interpretation of valley origin (Andriashek 2003). 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; Keew 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 Fig. 10 is interpreted based on these traits alone. However, a clear link between valley origin and valley size or 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 (ice marginal) 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 (Keew and Boettger 1986), and New Rockford (Keew 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 organics, 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 (e.g., Lethbridge — Proudfoot 1985; 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 center 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 subtil radiocarbon dates from Saskatchewan gravels in western Alberta (Jackson et al. 2011).

Proglacial spillway incision is the primary mechanism by which most glaciofluvial buried valleys in the Canadian Prairies are thought to have formed (e.g., Stalker 1961; Kehew and Boettger 1986). Only a small minority of the buried valleys have been interpreted to be tunnel valleys (Andriashek 2003). This is in stark contrast to glaciated parts of Europe, where most buried valleys are interpreted to be tunnel valleys (e.g., Huuse and Lykke-Andersen 2000). Are tunnel valleys simply not as prevalent in the Canadian Prairies? Does this suggest a fundamental difference in the behaviour of North American and European Quaternary ice sheets? To address this, let us compare the characteristics of buried valleys eroded into bedrock across northern Europe (Stackebrandt et al. 2001) with those in the Prairies. The buried valleys described by Stackebrandt et al. (2001) are equally spaced at
about 5–20 km apart, and each buried valley tends to be 5–10 km wide, 50–100 km long, and 100 m to several hundred metres in depth. They form an array of “overdeepened” closed depressions. These characteristics are most reasonably explained if they are tunnel valleys eroded by pressurized meltwater flowing from beneath an ice-sheet toward its margin. In the glaciated North American Prairies, similar but smaller buried valleys are present on the modern landscape, some of which form radiating arrays, have upslope profiles, and contain eskers (e.g., Wright 1973). These valleys are most reasonably interpreted as tunnel valleys eroded during the last deglaciation. However, buried valleys with similar characteristics have not been identified in the subsurface, despite over half a century of drilling. This does not mean that buried tunnel valleys do not exist in the Canadian Prairies; many of the small, unmapped “intertill” buried valleys that are fully contained in the till package (e.g., Whitaker and Christiansen 1972) could potentially be tunnel valleys, as could buried valleys that incise down into older, preglacial buried-valley fills (e.g., Andriashek 2003). Small tunnel valleys incised into bedrock may be ubiquitous, but simply too small to identify given the current data. However, arrays of wide (5–10 km), deep (hundred of metres), equally spaced (5–20 km) closed depressions similar to those of Northern Europe, if present, are not widespread.

Two of the largest buried valleys in the Prairies, the Hatfield and the Spiritwood, are enigmatic and deserve additional attention. Stratigraphically, both overlie till locally, in
addition to being buried by it; their fills are therefore Quaternary in age. Because of their orientations, both are hypothesized to have been eroded by proglacial ice-contact streams that flowed along former ice fronts (or ice front?; Christiansen 1977; Kehew and Boettger 1986). However, they are very wide and shallow (Fig. 10), a trait typically associated with preglacial buried valleys (Stalker 1968), and quite dissimilar to the comparatively small, narrow valleys on the modern land surface interpreted to be proglacial spillways (Kehew et al. 2009). Furthermore, if they formed as envisioned, a gravitational gradient would have been necessary to drive flow along the ice front. However, both the Hatfield and the Spiritwood exhibit little to no drop in elevation over their mapped extents — even the modern Red River, which has an extremely low gradient, seems steep in comparison (Fig. 9). Some form of hydraulic gradient must have existed when the valleys were eroded. The landscape must have been tilted as a result of differential glacio-isostatic loading or Cordilleran tectonics. Alternatively, pressurized subglacial meltwater drove flow, and the idea that these buried valleys record former ice margins needs to be reevaluated.

Hydrogeology

The till-dominated sediment package that covers the Prairies exerts a first-order control on the hydrogeological behaviour of buried-valley aquifers at depth. Although multiple till units are thought to exist throughout most of the Prairies, from a hydrogeological standpoint, only two units have tended to be recognized at any given location, a thin brown weathered zone below ground surface, typically 5–20 m thick, and a grey and commonly thicker unit of unweathered zone below this (Fig. 5B). Intervening mud layers tend to have similar permeabilities as the till in these zones (e.g., Kathol and McPherson 1975). Fractures tend to be confined to the weathered zone (Hendry 1982, 1988; Keller et al. 1988), but in places can extend through unweathered zone 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 from $10^{-11}$ to $10^{-9}$ m/s, respectively (Table 1). Solute transport is thought to be dominated by molecular diffusion in unweathered till and by fracture
Fig. 13. 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 highly simplified. Western Canadian Sedimentary Basin clasts are also not shown. Till thickness changes not shown. The piezometric surface, as depicted, is greatly simplified. While it indeed becomes closer to ground surface moving eastward, there will be considerable local variability; in most places, it will resemble a subdued replica of the ground surface. 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 road map 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). Data and ideas from McConnell (1885), Stalker (1963), Proudfoot (1985), Whitaker and Christiansen (1972), and Jackson et al. (2011).

There are 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), which 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). Data and ideas from McConnell (1885), Stalker (1963), Proudfoot (1985), Whitaker and Christiansen (1972), and Jackson et al. (2011).

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 10 km along the 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).

Heterogeneity within buried-valley fills from till layers, glaciolacustrine mud units, 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 alone. 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).

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 mineralized water in the overlying deposits (Fig. 14A). 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. 14B). Only rarely do groundwater chemistries indicate complete isolation from surface water sources (e.g., West Fargo aquifer; Shaver 2010).

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

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Weathered, fractured till (bulk) (m/s)</td>
<td>5×10⁻⁹ to 2×10⁻⁷</td>
<td>—</td>
<td>1.8×10⁻⁷</td>
<td>7.41×10⁻⁸</td>
</tr>
<tr>
<td>Weathered, fractured till (intergranular) (m/s)</td>
<td>10⁻¹⁰</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>Inter till aquifer (m/s)</td>
<td>—</td>
<td>2×10⁻⁵ to 4×10⁻⁸</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>Unweathered till (m/s)</td>
<td>—</td>
<td>1×10⁻⁹ to 1×10⁻¹⁰</td>
<td>5×10⁻⁹*</td>
<td>5×10⁻¹⁰</td>
</tr>
<tr>
<td>Buried-valley sand and (or) gravel bodies (m/s)†</td>
<td>6×10⁻⁹*</td>
<td>—</td>
<td>1.8×10⁻⁹*</td>
<td>4.27×10⁻⁹</td>
</tr>
<tr>
<td>Shale (m/s)**</td>
<td>—</td>
<td>1×10⁻⁹ to 1.4×10⁻¹²</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>Sandstone (m/s)</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
</tbody>
</table>

* Un weathered but fractured till.
† Till and mud, which also occur in buried valleys, have lower permeability.
** Bredehoef et al. (1983) suggest Western Canadian Sedimentary Basin shale in vicinity of Great Plains aquifer, US, has hydraulic conductivity of 1.6 × 10⁻¹¹ m/s.

Fig. 14. Chemistry of water in Prairie buried-valley aquifers.
(A) Chemistry of water in a surficial sediment aquifer (Cheyenne delta) and bedrock aquifers (Dakota) in Sargent County, North Dakota (Armstrong 1982). Note that water in surficial sediment aquifers (Cheyenne delta) is less mineralized than that in the bedrock aquifer, which is in turn less mineralized than that in the karstic aquifer. Similar observations are common throughout the Prairies (e.g., Maathuis 2010). (B) 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).
The till aquitards that cover buried valleys limit recharge to buried-valley aquifers. 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).

Exactly how buried-valley aquifers are recharged remains an open question. Some postulate that interconnected 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).

Conclusions

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 both the till aquitards and the buried-valley fills: risk involved in the development of 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. 2009) and in the rare public data sets that have been collected (Oldenborger et al. 2010), a tool does exist that can successfully be used to do this, namely electromagnetic data (Fig. 12). These data have the potential to provide new insights into Prairie buried valleys and till that rival those afforded by outcrops in the late 1800s and by water wells in the mid to late 1900s. Continuous cores and seismic data, which have also 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.

Acknowledgements

This work was funded by the Groundwater Mapping Program and the Groundwater Geoscience Program at the Geological Survey of Canada (GSC), Earth Science Sector, Natural Resources Canada. Lionel Jackson (GSC) sent us inpress data, now published in Jackson et al. (2011), which helped clarify several issues. Greg Oldenborger (GSC) provided Fig. 14 and made useful comments on the manuscript. We benefitted from discussions with Andrew Karvonen (MDH Solutions), Gaywood Matile (Manitoba Geological Survey), Bryan Schreiner (Saskatchewan Research Council), Robert Shaver (North Dakota State Water Commission), and Garth van der Kamp (Environment Canada). Bob Betcher (Manitoba Water Stewardship), Gaywood Matile, and Bryan Schreiner graciously organized field trips during our visits to Manitoba and Saskatchewan. A review by Marc Hinton (GSC) helped improve text and figures prior to journal submission. Two anonymous reviewers and Associated Editor Tim Fisher are thanked for their constructive comments and suggestions.

References


Published by NRC Research Press


hydrogeology of buried-valley aquifers in Canada in *Proceedings of the 5th Joint CGS and IAH-CNC Groundwater Specialty Conference*, pp. 26–33.


