Tectonic, eustatic and climatic controls on marginal-marine sedimentation across a flexural depocentre: Paddy Member of Peace River Formation (Late Albian), Western Canada Foreland Basin

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ABSTRACT

In north-central Alberta and adjacent British Columbia, clastic strata of the middle to late Albian Peace River and Shaftesbury formations were deposited in alluvial to shallow-marine environments across the foredeep of the Western Canada Foreland Basin. A high-resolution, log and core-based allostratigraphic framework for the Paddy Member of the Peace River Formation established nine allomembers, PA to PI, bounded by flooding surfaces and apparently equivalent non-marine surfaces. Within the estimated 2 Myr. duration of the Paddy, allomembers allow the evolving palaeogeography and changing relationship between accommodation and sedimentation rates to be analysed on time-steps on the order of $10^5$ years. Paddy strata fill an arcuate depocentre ca 300 km wide, across which the rocks thin eastward from 125 m to ca 5 to 10 m. The northern part of the basin is occupied by muddy, offshore marine deposits that pass abruptly southward into a linear, WSW-ENE-trending body of sandstone deposited in a wave-dominated barrier-strandplain, at least 350 km long. Extending >200 km to the south of the strandplain was a region of shallow brackish to freshwater lagoons and lakes that graded to the SW into alluvial facies. Within the lagoon region, few-m thick, elongate and patchy sandstones represent river-dominated deltas. In allomembers PA to PG, these sandstones are concentrated in the west and south, implying supply from the western Cordillera. In allomembers PH and PI, sandstones are mainly in the east and have a distinctive, quartz-rich composition. They can be correlated eastward into the coeval Pelican Formation, and were sourced probably from the Canadian Shield on the opposite side of the basin. In the western foredeep, alluvial rocks comprise aggradational, unconfined floodplain deposits with ribbon sandstones, dissected, on at least nine separate levels, by palaeovalleys that are confined to the proximal foredeep. Valleys are 10 to 30 m deep, few km wide, and filled with multi-storey channel-bars of pebbly coarse sandstone or conglomerate. Valleys cut down from well-developed interfluve palaeosols that record a falling and then rising water table. Alternating aggradation and degradation, and advance and retreat of the alluvial gravel front is attributed to cycles of varying rainfall intensity, rather than tectonism or eustasy. Apparently, coeval transgressive-regressive successions in the lagoon and marine regions are attributed to few-m scale eustatic changes. On the NE margin of the basin, tidal sandstone fills a northward-opening estuary cut on the basal Paddy unconformity. This sandstone contains the first well-documented specimens of...
Gnesioceramus comancheanus (Cragin), proving contemporaneity with at least part of the marine Joli Fou Formation to the east. Paddy allomembers change shape upward from short blunt wedges, through more acutely tapered wedges, to sheets. This change reflects initially rapid flexural subsidence, attributed to active thickening of the adjacent orogenic wedge. A waning rate of deformation permitted wider dispersal of sediment across the basin, driving broad isostatic subsidence beneath increasingly sheet-like rock bodies. A major hiatal surface, VE3, records non-deposition or subtle erosion attributed to erosional unloading and uplift of the adjacent orogen. A subsequent marine transgression is attributed to renewed thickening of the tectonic wedge that triggered deposition of marine mudstone that thickens westward from 0 to >110 m over 300 km. A postulated Milankovitch-band climatic control on both local gravel supply (via fluctuating rainfall), and shoreline movement (via ?Antarctic glacio-eustasy or groundwater storage), might account for cycles of alternating incision and aggradation in the alluvial realm. The same mechanism may also explain why shallow-marine units such as the Cretaceous Viking and Cardium formations contain abundant conglomerate in lowstand shoreface deposits (higher river discharge), yet have highstand shorelines dominated by sandstone (lower river discharge).

INTRODUCTION

Because of abundant outcrop and subsurface data, Cretaceous strata of the Western Canada retro-arc foreland basin provide a superb opportunity to investigate cyclic sedimentation in clastic paralic deposits. Sedimentary facies can be integrated into a high-resolution allostratigraphic framework on a basin scale, enabling construction of palaeogeographic and isopach maps that reveal the interplay between sedimentation, tectonism and eustasy on time-steps of ≪1 Myr. Sedimentary facies can be examined in extensive exposures in the Rocky Mountain Foothills and the Peace River Plains, as well as in numerous cores. Stratigraphal bounding surfaces and principal facies types can also be traced in numerous wireline logs, locally calibrated by core, and mapped over the entire basin. This type of integrated approach is used here to reconstruct the palaeogeography and depositional history of the Paddy Member of the Lower Cretaceous (Albian) Peace River Formation across the foredeep of north-central Alberta and adjacent British Columbia (BC) (Figs 1 and 2). This investigation of the Paddy Member complements a study of the Harmon and Cadotte members that form the lower part of the Peace River Formation (Buckley et al., 2016).

The Paddy Member, and equivalent strata, span an array of depositional environments, from offshore marine in the north, through shoreface and lagoon, to alluvial in the south. Our new allostratigraphic correlations show that the marine and lagoonal portions of the Paddy depositional system are characterized by nine, widely mappable transgressive-regressive sequences bounded by flooding surfaces, suggestive of control by sea-level change. These sequences become progressively less recognizable when traced south-westward into coeval alluvial sediments of the coastal plain. Alluvial strata comprise successions of generally fine-grained, aggradational floodplain deposits that are punctuated, on at least nine distinct horizons, by coarser-grained sandstones that form single- or multi-storey valley-fills. In this inland setting, alternating phases of alluvial aggradation and degradation may most plausibly be attributed to changes in river discharge, linked to climate and rainfall cycles; control of these high-frequency (≪1 Myr) alluvial sequences by either sea-level change or tectonic movement seems unlikely. The Paddy strata therefore provide an example of a depositional system that accumulated in a high-accommodation foredeep setting in which different parts of the system were modulated by either high-frequency eustatic or climatic cycles that may share a common origin through Milankovitch forcing. This is one of the first examples where climate has been postulated to have influenced cyclicity in Cretaceous alluvial rocks in the Western Canada Foreland Basin; indeed, as observed by Gibling et al. (2011), ‘climatic effects appear to be under-represented in interpretations of alluvial sequences in general’.

Purpose of study

The purpose of this paper is to use a new regional allostratigraphic framework for the late Albian Paddy Member and associated units, as a basis on which to reconstruct the stratigraphic and palaeogeographic evolution of an actively subsiding foredeep that was occupied by a spectrum of alluvial, marginal- and shallow-marine
Specifically, the aims of the study were to: (i) use the regional allostratigraphic scheme developed by Rylaarsdam (2006), Buckley (2011) and Vannelli (2016), in order to establish temporal relationships across a range of depositional environments, both in the Paddy Member, and between the Paddy Member and adjacent units; (ii) interpret and map sedimentary facies in order to reconstruct depositional environments and palaeogeography; (iii) utilize palaeocurrent information to determine sediment dispersal directions; (iv) investigate patterns of tectonic subsidence through isopach maps; (v) investigate the possible influence of the underlying Precambrian Peace River Arch on sedimentation; (vi) use newly documented molluscan fossils to constrain the age of the Paddy strata; (vii) consider possible climatic controls on aggradational and degradational cycles, and on gravel supply in alluvial strata. As emphasized by Jordan (1995), and Paola (2000), both the interpretation and modelling of allogenic controls on foreland basins is strongly dependent on the availability of a detailed, three-dimensional physical stratigraphy, linked to a temporal framework and facies maps. Our detailed stratigraphic and sedimentological investigation of an evolving Cretaceous foredeep is intended to provide a case study that goes some way towards fulfilling the need for data from the geological record.

Fig. 1. Palaeogeographic reconstruction of North America showing the maximum transgressive extent of the Joli Fou-Skull Creek Sea at about 104 to 103 Ma, when the Polar Ocean and the Gulf of Mexico had merged through Texas and Kansas, allowing northward migration of the *Gnesioceramus* (‘Inoceramus’), *comancheanus* fauna. Detailed stratigraphic mapping in Alberta revealed the NE-trending ‘Smoky River Ridge’ (Vannelli et al. 2017), that separated the open marine Joli Fou depocentre in the east from the semi-enclosed Paddy depocentre to the west. Adapted from map by Dr. Ron Blakey (http://cpgeosystems.com).
Fig. 2. (A) Litho- and allostratigraphic terminology applied to mid-Albian to early Cenomanian rocks in different parts of Alberta and NE British Columbia (based on Wickenden, 1949; Alberta Study Group, 1954; Rudkin, 1964; Stott, 1982; Bloch et al., 1993; Roca et al., 2008; Hathway et al., 2013; Vannelli et al., 2017). Geochronology from: (1) Hathway et al., 2013; (2) Zonneveld et al., 2004; (3) Leckie et al., 1997; (4) Ogg & Hinnov, 2012. (B) Summary of master bounding surfaces, allostratigraphic units and geometric relationships between the Joli Fou, Paddy, Pelican and Viking alloformations across the study area (based on Roca et al. (2008), with revisions and additions by Buckley & Plint (2013); Henderson et al. (2014) and Vannelli et al. (2017). Paddy allomembers PA to PF thin and lap out eastward against a subaerial ridge (the 'Smoky River Ridge' of Vannelli et al., 2017), whereas marine Joli Fou mudstone laps out westward against the opposite side of the ridge. The datum for the diagram is the basin-wide VE3 disconformity. For simplicity, the geometry of the upper Viking allomember VD, between surfaces VE3 and VE4, is not represented.
Geological and tectonic setting

A genetic link between the Rocky Mountain Cordillera and the Western Canada retro-arc foreland basin has long been recognized (Bally et al., 1966; Price, 1973). This foreland basin accumulated over 5 km of clastic strata that provide a relatively expanded record of terrestrial and shallow-marine sedimentation through much of the Late Jurassic, Cretaceous and Palaeocene (Wright et al., 1994). Subsidence of the Western Canada Foreland Basin was initiated in the Early to Middle Jurassic as a result of the obduction of the exotic Intermontane Superterranne onto the western margin of North America during westward-directed subduction of oceanic lithosphere. A subsequent (? Jurassic, early Cretaceous) change in subduction polarity saw eastward-directed subduction of the oceanic Farallon Plate beneath both the obducted Intermontane Superterranne and cratonic North America, coincident with the opening of the central Atlantic Ocean (e.g. Engebretson et al., 1985; Gabrielse & Yorath, 1991; Monger, 1993, 1997; Price, 1994; Monger & Price, 2002; Evenchick et al., 2007; Plint et al., 2012). Imbrication and thickening of the crust adjacent to obducted terranes constructed an accretionary wedge that, by the Kimmeridgian, had risen above sea-level and was delivering sediment to the adjacent foreland basin to the east (Stott, 1984; Wright et al., 1994; Evenchick et al., 2007).

Early analyses of the foreland basin attributed flexural subsidence primarily to the static load of the Rocky Mountain Cordillera and basin-filling sediments (e.g. Beaumont, 1981; Jordan, 1981). It was later appreciated that both the thickness and width of the foreland basin succession appeared to be too great to be explained simply in terms of static loading, and an additional component of subsidence was attributed to a ‘dynamic load’ imposed by downward flow of asthenosphere entrained by the subducting plate (e.g. Mitrovica et al., 1989; Liu & Nummedal, 2004). Models show that the wavelength over which the upper plate is dynamically flexed increases as the dip angle of the subducted plate decreases. Thus, Cretaceous shallow-marine sediments onlapping onto the Canadian Shield in Saskatchewan and Manitoba, about 500 km east of the forebulge, are interpreted as evidence for wholesale westward tilting of North America due to low-angle subduction of the Farallon Plate.

The evolving palaeogeography of the foreland basin, characterized by regional transgressions and regressions, reflects the interplay between tectonic subsidence, eustatic change, and sediment delivery from both the western Cordillera and the Canadian Shield to the east. On the basis of petrographic and geochronological studies, it has been recognized that, during Aptian and Albian time, sediment was delivered to the Canadian portion of the basin by one or more, continent-scale, north- and west-flowing river systems with headwaters in the Canadian Shield, the Appalachians, and the Rocky Mountain Cordillera (Benyon et al., 2014; Blum & Pecha, 2014). In Aptian time, the detritus supplied by these rivers was confined to palaeovalleys cut in sub-Cretaceous rocks. However, during early Albian time, the topography was progressively buried beneath several hundred metres of clastic sediment that was deposited in a succession of northward-prograding alluvial and deltaic systems represented in Alberta by the Mannville Group and equivalent strata. The last vestige of this long-lived, north-flowing river system is preserved in the Peace River Formation, of which the middle Albian Harmon and Cadotte members record, respectively, an aggrading muddy shelf overlain by a northward-prograding sandy strandplain (Buckley et al., 2016; Fig. 2B).

The north-flowing fluvio-deltaic system was drowned by eustatic rise in the early late Albian, with the formation of the Joli Fou-Skull Creek Sea, represented by marine mudstone of the Joli Fou and coeval Skull Creek and Thermopolis formations that extend throughout the Interior Seaway (Williams & Stelck, 1975; Vuke, 1984; Fig. 1). In the proximal foredeep of British Columbia and Alberta however, the rate of sediment supply was sufficiently high that terrestrial, lagoonal and marginal-marine conditions were maintained, despite eustatic rise and rapid tectonic subsidence; this part of the basin is now represented by rocks of the Paddy Member. In the marine portion of the basin, transgressive, offshore mudstone of the Joli Fou Formation is overlain by regressive sandstone assigned to the Viking Formation (in the SW), to part of the Paddy Member (in the NW), and to the Pelican Formation (in the NE; Fig. 2B). Viking, and most Paddy sandstones are chert-rich lithic arenites of Cordilleran provenance, whereas the most north-eastern part of the Paddy, and correlative deltaic sandstones of the Pelican Formation further to the east are dominated by quartz arenites, sourced from the Canadian Shield (Vannelli, 2016; Vannelli et al., 2017). The broad palaeogeographic setting of early Paddy time is summarized in Fig. 3A, in which the low-relief Smoky River Ridge separated the early Paddy depositional system from coeval marine Joli Fou and early Viking systems. By late Paddy time (Fig. 3B), the prograding Pelican delta system had closed the Seaway and was delivering quartz arenite to the eastern part of the Paddy depocentre (Vannelli et al., 2017).

Study area and database

The present study focuses on the western and central part of the foredeep between 54° and 56°50’N and west of
116°30' W, i.e. Townships 58 to 90 and west of Range 15 W5 (Fig. 4). Results are based on studies by Rylaarsdam (2006) and Buckley (2011), and include the eastern part of the study area of Henderson et al. (2014) and the western part of the study area of Vannelli (2016). Collectively, 1720 wireline logs were used to create the regional correlation grid, supplemented by measurement of 95 cores (total thickness 2052 m), and 28 outcrop sections (total thickness 2249 m), distributed over an area of about 91,000 km². Collections of molluscs from the Paddy alloformation exposed on the Heart River were made by Walaszczyk.

STRATIGRAPHY

Lithostratigraphy

The Peace River Formation is a clastic unit that was defined originally from exposures in the Peace River valley of north-central Alberta (McConnell, 1893; Wickenden, 1951; Badgley, 1952; Alberta Study Group, 1954). The formation extends beneath the subsurface of NW Alberta and adjacent British Columbia, and is exposed in the Rocky Mountain Foothills and in part of the Peace River valley. In the Plains and subsurface, the Peace River
Formation is divided, on lithostratigraphic grounds, into a lower, marine mudstone that forms the Harmon Member, a middle marine sandstone and conglomerate of the Cadotte Member and an upper, heterolithic, Paddy Member representative of marginal marine to terrestrial environments (Alberta Study Group, 1954). The Harmon Member is equivalent to the Hulcross Formation in the BC Foothills to the West, whereas the Cadotte and Paddy members are equivalent to the Boulder Creek Formation in the Foothills (Stott, 1982; Gibson, 1992; Fig. 2). Recent studies of the Harmon, Cadotte and equivalent rocks are given by Buckley & Plint (2013), Hathway et al. (2013), Henderson et al. (2014), Ausich et al. (2015) and Buckley et al. (2016) (Fig. 2).

The Paddy Member of the Peace River Formation rests sharply on the underlying Cadotte, and was first recognized as a distinct unit by Wickenden (1951). Biostratigraphic studies (Stelck et al., 1956), showed that a substantial hiatus existed between the Cadotte and Paddy members. This interpretation was supported by stratigraphic and sedimentological studies in the vicinity of Peace River town (Fig. 4), that showed that the top of the Cadotte Member was incised by palaeovalleys, up to ca 15 m deep, filled with Paddy strata.

Fig. 4. Map of study area showing the extent of individual study areas and the distribution of well log, core and outcrop data.
Although various lithostratigraphic, biostratigraphic and palaeoenvironmental studies have been conducted on disparate parts of the Paddy Member (e.g. Wickenden, 1951; Stelck et al., 1956; Singh, 1971; Smith et al., 1984; Leckie et al., 1989; Stelck & Leckie, 1990a,b; Leckie & Singh, 1991; Gibson, 1992; Leckie & Reinson, 1993; Ufnar et al., 2001, 2005), none of these investigations were conducted in the context of a regional physical stratigraphic framework. In consequence, it was not possible to interpret temporal or palaeogeographic relationships between the various study areas.

**Allostratigraphy**

Although lithostratigraphy provides a good basis for regional mapping of Cretaceous clastic rocks in the Western Canada foredeep, a more detailed depositional history can be reconstructed on the basis of allostratigraphic correlation (North American Commission on Stratigraphic Nomenclature, 2005). Allostratigraphy divides rock successions into approximately chronostratigraphic packages on the basis of bounding discontinuities. Unlike classical ‘Exxon’ sequence stratigraphy, allostratigraphy does not necessarily emphasize subaerial unconformities as master bounding surfaces. Because the Western Canada Foreland Basin was characterized generally by rapid subsidence, marine transgressive or flooding surfaces have proved to be the most practical surfaces by which to define allostratigraphic units (e.g. Plint et al., 2012).

To avoid the limitations of the extant lithostratigraphic schemes used for Albian-Cenomanian strata in Alberta and B.C. (e.g. Stott, 1982; Bloch et al., 1993), an informal allostratigraphic scheme was developed by Roca et al. (2008), based on an earlier model by Boreen & Walker (1991). Roca et al. (2008) proposed a lower Colorado allogroup composed of the Paddy, Joli Fou, lower and upper Viking, Westgate and Fish Scales alloformations (Fig. 2). The Paddy alloformation was separated from the underlying Cadotte alloformation (defined by Buckley & Plint, 2013), by a major unconformity surface termed PE0, and from the overlying upper Viking alloformation by unconformity surface VE3 (Fig. 2). The allostratigraphic relationships between the Paddy, Joli Fou, Pelican and Viking alloformations were subsequently elucidated by Vannelli et al. (2017). In the following discussion, all stratigraphic units will be considered to be allostratigraphically defined, following Roca et al. (2008), Buckley et al. (2016) and Vannelli et al. (2017).

Rylaardsdam (2006) and Roca et al. (2008) showed that the Paddy alloformation was composed, in ascending order, of nine regionally mappable allomembers termed PA to PI. These allomembers were subsequently traced northward as far as Township 90 (Buckley, 2011; Buckley & Plint, 2013; Fig. 4). The most important finding of Rylaardsdam (2006) and Buckley (2011) was that Paddy allmembers PA to PF were markedly wedge-shaped and onlapped eastward onto the top of the Cadotte alloformation, whereas allmembers PG to PI were almost tabular and extended across the entire study area (Fig. 2B).

In addressing the regional stratigraphic relationships of the Paddy alloformation, Roca et al. (2008) were unable to determine whether the transgressive surface (JE0) beneath the Joli Fou alloformation truncated all the Paddy alloformation, or merged laterally with the upper part of the Paddy. More recently (Vannelli, 2016; Vannelli et al., 2017), revised the interpretation of Roca et al. (2008), showing that marine mudstone of the entire Joli Fou alloformation lapped out westward against the ‘Smoky River Ridge’ (Fig. 3), and had no physical connection with eastward-onlapping lower Paddy allmembers PA to PF on the opposite side of the ridge. This geometrical relationship suggested that Joli Fou and lower Paddy rocks, which were deposited close to sea-level, were coeval, but occupied discrete depocentres. Estuarine, lagoonal and shallow-marine strata forming upper Paddy allmembers PG, PH and PI were traced eastward where they merged laterally with deltaic sandstones that formed allmembers PeA and PeB of the Pelican alloformation (Fig. 2B). Pelican allmembers PeA and PeB were in turn traced southward where they proved to be equivalent to Viking allmember VA of Roca et al. (2008), bounded below and above by erosion surfaces VE0 and VE1, respectively. Pelican allmembers PeC and PeD are bounded by surfaces VE1 and VE3 and are equivalent to Viking allmember VB. Pelican allmembers PeC and PeD toplap against surface VE3 and do not extend into the Paddy depocentre on the west side of the Smoky River Ridge (Fig. 2B; Vannelli et al., 2017).

Surface VE3 represents both a major lowstand unconformity and a subsequent marine transgression that deposited a blanket of mudstone across most of Alberta. In SW Alberta, the mudstone grades up into regressive nearshore sandstone and conglomerate, the top of which is marked by another lowstand unconformity surface, VE4. The rocks between surfaces VE3 and VE4 are assigned to Viking allomember VD (Roca et al., 2008). In NW Alberta, allomember VD lacks significant sandstone, being dominated by offshore marine mudstone, lithostratigraphically assigned to the lower part of the Shaftesbury Formation (Fig. 2A). Allomember VD thickens markedly across the study area, from a zero edge in the east to >110 m in the west.
Allostratigraphy of the Paddy alloformation

Figure 5 shows the location of seven summary cross-sections (Figs 6 to 12) that illustrate the new allostratigraphic interpretation of the Paddy alloformation. More detailed representations of the lateral variation in sedimentary facies are shown in three core cross-sections (Figs 13 to 15). Because detailed correlations for the region north of Township 73 were presented in Buckley & Plint (2013), the bulk of the stratigraphic data presented here is focussed on the region between Townships 59 and 73 (Figs 4 and 5).

Correlation method

In the Paddy alloformation, the most easily recognized and widely mappable bounding surfaces are marine transgressive or flooding surfaces (which are commonly composite, embodying subaerial emergence, followed by submergence). These flooding surfaces were correlated in loops throughout the grid of log cross-sections to ensure a consistent stratigraphy. However, traced landward to the south and west, marine and lagoonal rocks grade laterally into coeval coastal plain deposits in which marine flooding surfaces become progressively more difficult to
Fig. 6. Oblique dip cross-section extending east from Mt. Chamberlain. Note the progressive eastward thinning of the Paddy due to onlap of allomembers PA through PF onto surface PE0 which marks the unconformable contact with the underlying Cadotte alloformation. In contrast, allomembers PG to PI are traceable across the entire section. Multi-storey pebbly sandstones fill palaeovalleys that hang from many allomember boundaries. At Mt. Chamberlain, the top surfaces of allomembers PF and PG can be traced laterally from well-developed palaeosols to the surfaces that bound lenticular palaeovalley fills. At Mt. Spieker, the base of allomember PI is marked by a thin wave-rippled conglomerate (a transgressive lag), overlain by <1 m of wave-rippled sandstone and siltstone, erosively capped by a 12 m fluvial conglomerate with large-scale accretion surfaces (Fig. S2). A similar conglomerate caps Mt. Chamberlain Fig. S3). Legend is applicable to Figs 6 to 15. All wireline logs are paired gamma-ray (left) and resistivity (right). Intersections with other sections are indicated as e.g. (Fig. 7).
Fig. 7. Oblique dip section extending 170 km SW-NE, showing a transect from coastal plain to marine shoreface. At Quintette and Shikano mine cuts, an aggradational coastal plain succession is punctuated by either large, single-storey sandbodies, interpreted as channel-fills, or multi-storey sandbodies interpreted as valley-fills hanging from allmember boundaries. The 'non-marine' log facies can be traced NE to c-40-F93 P2, beyond which the log signature becomes more strongly dominated by sandier-upward successions representative of shallow lagoons and lagoonal deltas, as indicated by core in d-35-E93 P8. From well 6-21-76-12W6 to 10-11-81-12W6, the Paddy allomembers become increasingly dominated by clean sandstone deposited in a wave-influenced shoreface environment. Clean sandstone passes laterally over <5 km into heterolithic offshore facies in 3-27-81-12W6; this facies transition can be mapped as a linear belt across the entire study area (Fig. 5).
Fig. 8. Oblique dip section extending 95 km NE from the cored MD80-08 well. Note onlap of allomembers A and B onto the unconformable basal surface PE0. The MD80-08 core is dominated by a fluvo-lacustrine facies succession with numerous palaeosols, some of which are correlated with allomember boundaries. Cores in a-3-B 93 P/1 and 11-10-73-13W6 are of fluvo-lagoonal aspect. Stelck & Leckie (1990a) noted single specimens of foraminifera in the uppermost 2 m of mudstone in allomember I, together with pollen indicative of a late Albian age. Immediately above surface VE3, marine mudstone equivalent to Viking allomember VD contains an abundant foraminiferal fauna of the *Trochammina depressa* subzone that lies within the upper part of the *Haplophragmoides gigas* Zone. This fauna implies approximate age equivalence to the upper Joli Fou Formation to lower Viking Formation (e.g. Stelck & Koke, 1987; Tu et al., 2007).
Fig. 9. Oblique dip section extending 365 km from fluvio-lacustrine facies at Whatley Creek and Mt. Belcourt in the SW, across the Paddy depocentre to distal offshore facies in the far NE on the Peace River. Allomembers PA to PF onlap progressively onto the basal unconformity PE0 whereas allomembers PG-PI have a sheet-like geometry across the entire basin. Alluvial facies dominate in 16-31-64-12W6 but by 1-24-66-11W6 and 7-26-68-9W6, lacustrine, lagoonal and lagoonal-deltaic facies dominate. In the NE at Heart River site 7, the lower part of an estuarine channel-fill contains well-preserved specimens of Gnesioceramus comancheanus (see Fig. 16), 20 to 80 cm above the Cadotte-Paddy unconformity. This fauna provides definitive evidence of an early late Albian age for at least Paddy allomember F, and equivalence to part of the Joli Fou alloformation. Peace River site 2J is dominated by estuarine facies and site 5 is capped by 5 m of swaley-stratified shoreface sandstone. Sites 6 and 7 lie seaward of the shoreface sandstone belt and comprise bioturbated, heterolithic facies with hummocky cross-stratification and wave ripples.
recognize. Nevertheless, the alluvial succession provides evidence for alternating episodes of aggradation and degradation that suggest cyclical changes in the character of the alluvial system. Changes in alluvial accommodation rate were inferred from three lines of evidence: (i) more sandstone-rich and/or pedogenically modified deposits sharply overlain by dark, well-stratified, organic-rich mudstone, were interpreted as recording a rise in water table and lacustrine flooding of the underlying surface; (ii) one or more, closely superposed, well-developed palaeosols characterized by strong rubbly pedogenic fabric, bleaching and common spherulitic siderite were interpreted as representing subaerial unconformities, or at least times of low accommodation rate (Leckie et al., 1989; Ufnar et al., 2001, 2005); (iii) erosive-based, lenticular, multi-storey bodies of cross-stratified sandstone and conglomerate, typically 15 to >30 m thick, were interpreted as palaeovalley-fills that represent alluvial incision followed by aggradation. Importantly, nine major flooding surfaces could be traced across the marine part of the basin, and nine horizons of valley incision were identified in the alluvial region. This combination of stratigraphic features provided the basis for the correlation of Paddy strata from marine to non-marine environments (Figs 6 to 15).

Dip cross-sections

Four regional cross-sections (Figs 5 to 9) are oriented approximately parallel to the principal tectonic dip, which is towards the SW. These sections incorporate the most complete outcrop sections available in the Rocky Mountain Foothills and in the Peace River Plains, and show how bounding surfaces can be traced through intervening gamma-ray and resistivity well logs, locally supplemented by cores. Note that these are sections condensed from the original working lines (in which well spacing was typically 3 to 6 km), from which the majority of wells have been omitted. Each cross-section is described in the caption and only principal features are summarized here.

All dip sections show marked eastward thinning of the entire Paddy alloformation. This is primarily because allomembers PA to PF thin and onlap onto the basal unconformity PE0. In contrast, allomembers PG to PI do not onlap, show little change in thickness, and can be traced across the entire depocentre. This is well-illustrated in Fig. 9 which extends 365 km from the Foothills in the SW to the far NE corner of the study area. Thick, localized sandstone bodies, interpreted as valley-fills, consistently hang from allomember boundaries, with valley-fills being particularly numerous below the top of allomember E. Within allomember PI, a distinctive body of well-sorted conglomerate, in places >30 m thick, forms a lenticular
Fig. 11. Regional N-S strike line, 315 km long, showing gradual southward thinning of the Paddy as all members PC to PF onlap onto the basal unconformity. Non-marine facies appear to dominate in the 726-68-9W6 well, but further north in 10-3-72-12W6, abundant brackish-water molluscs indicate lagoonal conditions. Sandstone dominates the Paddy in b-28-G 93P/10 and 11-17-78-18W6 as the section crosses the northern, wave-influenced nearshore region (Fig. 5). North of 11-17-78-18W6, the Paddy becomes thinner and more muddy, passing into offshore heterolithic facies, such as are exposed at Lynx Creek (Fig. 12).
Fig. 12. Strike section linking fluvial-dominated succession at Mt. Spieker with mixed alluvial and lagoonal successions at Suncor access road and Dokie Ridge (poorly exposed), and offshore heterolithic facies at Maurice Creek and Lynx Creek. This transect crosses the wave-influenced sandy shoreface region of the Paddy between Dokie Ridge and Maurice Creek (Fig. 5), but the shoreface facies are not exposed. The sections at Suncor road and Lynx Creek, with correlations to nearby well logs, were illustrated in more detail by Buckley & Plint (2013). Note that the section at Suncor Road is located 1-8 km SSE of an equivalent section, formerly well-exposed on Commotion Creek, from which Bell (1956, 1965) described a Late Albian angiosperm flora.
body between Mt. Chamberlain and the MD 80-08 core. This conglomerate is interpreted to be a valley-fill that thins to zero in <20 km to the east of the outcrop belt.

**Strike cross-sections**

Three regional strike cross-sections (Figs 10 to 12), illustrate stratal architecture and facies in a broadly NW-SE direction, and are supplemented by three, shorter, approximately strike-oriented core cross-sections (Figs 13 to 15). The Paddy alloformation thins towards the SE as a result of the onlap of allomembers PA to PF onto the underlying Cadotte alloformation. The Paddy also shows more subtle thinning to the north where allomembers PA to PC lap out. This stratal geometry indicates that the Paddy depocentre was broadly dish-shaped, thinning radially away from a depocentre in the vicinity of Mt. Chamberlain (isopach patterns are discussed below).

Lateral environmental changes are dramatic, ranging from a wave-influenced shelf with heterolithic rocks including large hummocky cross-stratification (HCS) and gutter casts, such as seen at Lynx and Maurice creeks in the north (Fig. 12), grading southward through a linear nearshore sandstone belt, about 10 to 20 km wide (e.g. Fig. 13, wells 6-21-80-12W6 to 10-31-77-11W6), that in turn grades southward into a broad region dominated by heterolithic lagoonal deposits (Figs 14 and 15). Further southward, however, the succession becomes progressively dominated by alluvial floodplain and channel sediments, as seen in the southern portions of Figs 11, 14 and 15. In the far NW (Fig. 12), the succession at Suncor Road and Dokie Ridge also appears to be dominated by alluvial deposits, with thinner intercalations of brackish-water sediments.

**Biostratigraphy and age in an allostratigraphic context**

Because the Paddy alloformation consists largely of non-marine to marginal-marine deposits, it has proved difficult to date in terms of standard ammonite, bivalve or foraminiferal biozones. In the BC Foothills, Stelck & Leckie (1990a) sampled microfauna from the Hulcross and Boulder Creek formations in the MD80-08 core (Figs 5 and 8). At the base of the core, mudstone of the upper Hulcross Formation (equivalent to the Harmon Member of the Peace River Formation) yielded foraminifera typical of the middle Albian ammonite Zone of...
Pseudopulchellia pattoni, whereas sandstone of the overly-
ing Cadotte Member was barren. However, fossils from the
Cadotte in outcrop indicate a late middle Albian age (Stel-
ck, 1995). In the MD80-08 core, the non-marine portion of
the Boulder Creek Formation (i.e. the Paddy alloformation
of the present study; Fig. 2), is 114 m thick, of which only
the uppermost two metres of mudstone yielded single spec-
imens of non-diagnostic foraminifera together with angios-
perm pollen, the latter considered to be indicative of a late
Albian age (Sweet in Stelck & Leckie, 1990a; Fig. 8). In con-
trast, marine mudstone immediately above the VE3 surface
yielded an abundant foraminiferal fauna indicative of the
Trochammina depressa subzone typical of the upper part of
the Haplophragmoides gigas Zone.

Paddy strata, formerly well-exposed on Commotion
Creek (located 1.8 km WNW of the Suncor Road section,
Fig. 12), yielded an angiosperm flora considered to be of
late Albian age (Bell, 1956, 1965). Additional palaeo-
botanical and palynological investigations of Paddy strata
exposed in the Foothills, summarized by Gibson (1992),
failed to yield age information more definitive than ‘mid-
dle to late Albian’.

In the Goodfare area of NW Alberta, two cores (10-13-
72-13W6 and 6-25-72-12W6; Fig. 15), sampled the upper
part of the Paddy alloformation and the immediately
overlying marine mudstone that is here assigned
allostratigraphically to the upper Viking alloformation,
allomember VD (or the lithostratigraphic Shaftesbury or
Hasler formations; Fig. 2). Both cores yielded a diverse
assemblage of benthic foraminifera (Stelck & Leckie,
1990b) which appeared to include elements of the
H. gi-
gas and overlying M. manitobensis zones. However, Stelck
& Leckie (1990b) noted that the species were ‘long-ran-
ing and facies-controlled’, and it did not seem possible
to draw definitive conclusions as to the age of the upper
part of the Paddy Member. It was concluded, however,
that the fauna from the Paddy indicated stressed condi-
tions with wide variations in salinity. The fauna from the
marine mudstone above surface VE3 contained many taxa
typical of the upper part of the H. gigas Zone (Fig. 15).
Stritch & Schröder-Adams (1999) sought Paddy micro-
fauna in the 12-20-78-6W6 well but found a very impov-
erished assemblage from which no age could be determined.
Leckie & Reinson (1988, 1993), and Leckie & Singh (1991), investigated the stratigraphy of the Peace River Formation in the vicinity of Peace River town (Fig. 4), where they documented (but did not illustrate) macrofossils. Leckie & Reinson (1988, 1993) reported *Inoceramus cadottensis* McLearn (identified by C.R. Stelck, personal communication, 1987), from the upper middle Albian Cadotte Member, and also reported *I. cadottensis* in the Paddy Member (from an unspecified locality), immediately above the unconformity with the Cadotte. Leckie & Singh (1991), referring to their section 7 on the Heart River, reported decalcified, disarticulated specimens of *Gnesioceramus* ('*Inoceramus*') *comancheanus* Cragin (identified by C.R. Stelck, personal communication, 1989), immediately above the unconformity with the Cadotte Member; in that paper they make, however, no reference to *I. cadottensis*. Leckie & Singh (1991, p. 826) interpreted the *G. comancheanus* shells to have been reworked from the Joli Fou Formation. However (*ibid.* p. 836), the inoceramids were also interpreted as evidence of brackish-water sedimentation on the floor of an estuarine channel (implying that the inoceramids were contemporaneous with Paddy deposition). The reports of Leckie & Reinson (1988, 1993) and Leckie & Singh (1991) appear to give contradictory information concerning both the identity and implied age [(*I. cadottensis*, middle Albian) vs. *G. comancheanus*, late Albian], as well as the stratigraphic relationship of the shells (reworked vs. *in situ*).

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In an attempt to clarify the identity of the inoceramids, sites 6 and 7 on the Heart River were re-examined. At site 7, two main horizons containing *G. comancheanus* (Fig. 16B; see Walaszczyk & Cobban, 2016 for genus-level reinterpretation of the species), *Gnesioceramus* sp. and fragments of large *Inoceramus* sp. were located, all <1 m above the basal unconformity PE0. Regional correlation to the nearest well logs suggests that the bivalves occur in sandstone attributable to allomember PF, or less probably, to allomember PG (Fig. 9). The bivalves form imbricated stacks of disarticulated, convex-up, but totally decalcified shells, some of which exceed 20 cm in length. Shells are associated with large pieces of *Teredo*-bored wood and finer phytodetritus and form a lag at the base of an estuarine channel, as interpreted by Leckie & Singh (1991). The shells are generally well-preserved and show no evidence of having an enclosing matrix, or having been reworked from an older rock unit. At Heart River site 6, 400 m to the NNW of site 7, the uppermost part of the Cadotte allomformation (extending about 2 m below the PE0 unconformity) yielded abundant specimens of typical *Gnesioceramus anglicus* (Woods, 1911) (Fig. 16D) and *Gnesioceramus* cf.
Gnesioceramus anglicus also occurs in the basal part of the Paddy alloformation (Fig. 16C), where it co-occurs with other Gnesioceramus sp.

The stratigraphically diagnostic foraminifera and molluscs reported from the Paddy alloformation and adjacent units all come from allomembers PF to PI and the immediately overlying marine mudstone, allostratigraphically assigned to allomember VD of the Upper Viking alloformation (Figs 2, 8, 9 and 15). Gnesioceramus comancheanus, which is of Temperate rather than Arctic affinity, provides evidence of an early late Albian age (Walaszczyk & Cobban, 2016), although the precise appearance level of this species is unknown. This bivalve is present in the Joli Fou Formation in Alberta, and also occurs in the Kiowa and Skull Creek formations in the United States (Stelck et al., 1956; Stelck, 1958; Koke & Stelck, 1985; Walaszczyk & Cobb, 2016). The presence of G. comancheanus, probably in Paddy allomember PF (or possibly in PG), at Heart River site 7 indicates temporal equivalence to either the uppermost Joli Fou alloformation or lowermost Pelican allomember PeA (equivalent to the lower Viking allomember VA; Vannelli et al., 2017; Fig. 2B).

Foraminifera from within the Paddy appear to be non-age-diagnostic. However, the marine mudstone between surfaces VE3 and VE4 is correlative with Viking allomember VD (or part of the lithostratigraphic Shaftesbury or Hasler formations; Fig. 2A), and contains a fauna indicative of the upper part of the H. gigas Zone that ranges from the upper part of the Joli Fou Formation to the Viking Formation, and is of early late Albian age (Stelck et al., 1956; Stritch & Schröder-Adams, 1999; Tu et al., 2007; Fig. 2).

Singh (1971) undertook a systematic palynological study of Albian strata across northern Alberta, including analysis of floras from our sites 1, 2 and 6 (Singh’s sites 4, 5, 7), on the Peace River (Figs 4 and 9). Singh recognized distinctive floras from the Cadotte and Paddy members where those units were classically developed in a nearshore facies at our site 2. To the north, at site 6,
where both Cadotte and Paddy strata have changed to a heterolithic offshore facies, Singh (1971) recognized only a ‘Cadotte’ Member. Burden (in Leckie & Burden, 2001), pointed out that the upper three samples from site 6, spanning ca 9 m, contained a palynoflora almost identical to the Paddy flora at site 2, implying that rocks of both middle Albian Cadotte and late Albian Paddy age were present at site 6, despite the lithostratigraphic assignment to only the ‘Cadotte’. Wireline log and core correlation established by Buckley & Plint (2013; see also Fig. 9) showed that the disconformable surface PE0, that separated Paddy from Cadotte strata, could be traced to outcrop at site 6 at a point that corresponds to the abrupt change in palynoflora noted by Singh (1971), thereby supporting the validity of the allostratigraphic correlation of surface PE0.

**Geochronology**

Available geochronological data are summarized in Fig. 2A. Zircons from a bentonite close to the base of the Harmon alloformation (generally accepted to approximate the base of the middle Albian in Western Canada (see review in Ausich et al., 2015), yielded a zircon U/Pb age of 108.038 ± 0.66 Ma (Hathway et al., 2013). In the Fort à la Corne kimberlite field of central Saskatchewan, perovskite crystals from two eruptive levels interstratified with marine mudstone of the Joli Fou Formation yielded an ‘early Joli Fou’ U/Pb age of 103.0 ± 1.0 Ma and a ‘late Joli Fou’ age of 102.8 ± 0.8 Ma (Zonneveld et al., 2004). Perovskite from another kimberlite in the same field was sampled 85 m below marine mudstone of the Westgate Formation, yielding an age of 101.1 ± 2.2 Ma (Leckie et al., 1997). The stratigraphic affinity of the latter sample is uncertain, possibly coeval with either the Viking or Westgate alloformations (McNeil & Gilboy, 2000; Kjarsgaard et al., 2007). The Albian-Cenomanian boundary, placed in Alberta at the ‘Base of Fish Scales Marker’ is currently dated at 100.5 ± 0.4 Ma (Ogg & Hinnov, 2012; Walaszczyk & Cobban, 2016). In the proximal foredeep, to the west of the Alberta-BC border, the base of the Fish Scales alloformation is placed at surface FE1; the latter surface merges eastward with an overlying erosion surface, the more commonly recognized Fish Scales Marker, to form a composite unconformity that extends across Alberta and Saskatchewan (Bloch et al., 1993; Roca et al., 2008; Angiel, 2013). If it is assumed that the base of the Paddy alloformation is of approximately the same age as the base of the Joli Fou alloformation, available radiometric dates suggest that the base of the Paddy alloformation is somewhat older than 103 Ma and that the top is probably older than 101.1 Ma, suggesting a span of ca 2 Myr.

**FACIES ASSOCIATIONS AND DEPOSITIONAL ENVIRONMENTS**

The Paddy alloformation represents a wide range of coeval depositional environments that range from offshore marine, through wave-influenced shoreface, brackish tidal lagoon, tidal estuary, alluvial plain and fluvial valley-fill. For brevity, these diverse environments are described, in tabular form, in terms of four facies associations (Table 1; Figs 17 to 26 and S1 to S3). Descriptions in Table 1 are supplemented by extended captions to Figs 17 to 26. Most of the facies described in Table 1 are readily interpreted in terms of well-established facies models.

**PALAEOGEOGRAPHY**

**Palaeogeographic maps**

Using the allostratigraphic framework (Figs 6 to 15), to place facies in both temporal and spatial context, it is possible to reconstruct the distribution of sedimentary environments within the Paddy depocentre. The palaeogeographic evolution of the Paddy is presented in three maps (Figs 27 to 29), that, collectively, summarize allmembers PA to PC, PD to PF and PG to PI. These maps illustrate the gradual eastward onlap of successive Paddy allmembers onto the eroded upper surface of the Cadotte alloformation. The Paddy system is differentiated into a northern, open marine environment that was separated from a southern, lagoonal and alluvial region by a narrow, WSW-ENE trending region of well-sorted sandstone indicative of a wave-dominated shoreface. To the south of the shoreface-strandplain, lagoonal sediments form metre-scale upward-shoaling successions characterized by a low-diversity molluscan fauna indicative of brackish to freshwater conditions, a generally low-diversity ichnofauna, and contain fine-scale heterolithic stratification suggestive of a local tidal influence (e.g. Fig. 24). This evidence suggests that the northern sandy strandplain was cut by inlets, allowing tidal exchange.

In early Paddy time (Fig. 27), marine sandstone and mudstone facies occupy the northern part of the depocentre, and appear to lap out northward against the underlying middle Albian Cadotte alloformation. Successive allmembers onlap progressively eastward onto the subtle topographic high termed the ‘Smoky River Ridge’ (Vannelli et al., 2017; Figs 3, 4 and 27). Palaeoflow indicators from fluvial channel-fill sandstones indicate flow mainly to the north and NE. By mid-Paddy time (Fig. 28), sediments had encroached further onto the western flank of the Smoky River Ridge. In the NE, the surface of the Cadotte alloformation was incised by at least one large valley system, mapped by Leckie et al. (1990). This valley...
### Table 1. Facies associations and interpreted depositional environments

| Facies Association | Description | Interpretation |
|--------------------|-------------|---------------|
| **A1** Alluvial | Mudstone to claystone, dark grey to black, laminated to flaky; typically forms units <1 m thick, exceptionally up to 10 m. May have cm beds of silt or very fine sand. Organic-rich with logs and root debris, may include dirty coal up to a few dm thick. May include roots, small siderite nodules & dinoturbation. | Shallow floodplain lake, swamp or marsh with perennially high groundwater table allowing organic matter to accumulate (cf. McCarthy & Plint, 1999; Lumsdon-West & Plint, 2005). |
| **A2** | Siltstone and mudstone, thinly bedded on mm scale; forms upward-coarsening successions on scale of 2 to 4 m; may be capped by cross-bedded sandstone of facies A5. Individual thin beds show reverse, or reverse-to-normal grading. Intense soft-sediment deformation & microfaulting is common. | Lake sediments, upward-coarsening suggests progradation of small lacustrine delta in a few m of water. Reverse- and normal-graded beds suggest deposition from accelerating and decelerating hyperpycnal flows (cf. Mulder et al., 2003). Cross-bedded sandstone may represent distributary-channel fill. Deformation may be due to spontaneous liquefaction or dinoturbation. (cf. McCarthy & Plint, 1999; Lumsdon-West & Plint, 2005). |
| **A3** | Siltstone to mudstone to very fine-grained sandstone; dark to mid-grey, weakly stratified to rubbly, organized in upward-coarsening packages typically 0.5 to 2 m thick. Sand structureless, or faint parallel or current ripple laminations. Typically heavily rooted, may have sp滴licite siderite, rare siderite nodules. | Poorly drained, heavily vegetated floodplain to ephemeral lake, weak pedogenic modification. Sandier-upward cycles record lake filling by floods, or levee progradation. (cf. McCarthy & Plint, 1999; Lumsdon-West & Plint, 2005). |
| **A4** | Siltstone to mudstone, cream to grey green, non-stratified, massive appearance with fine, weakly rippled texture; typically grades down into facies A3 but has sharp top. May have abundant roots, sp滴licite siderite, rare weathering. | Well-developed palaeosol with strong ped structure due to repeated wetting and drying. Pale colour indicates fluctuating water table with protected oxidation of organic matter. Siderite nodules indicate subsequent water-logging. (Ufnar et al., 2001). |
| **A5** | Very fine- to fine-grained sandstone, sharp base, sheet-shaped to lenticular, typically <1 m thick, composed of one or more discrete beds. Structureless or planar or current ripple laminated. Abundantly rooted, dinosaur track casts common on base. (McCrea et al., 2015). | Crevasse-splay and crevasse channel sands. Stacked sandstones may represent aggrading levee or crevasse-splay complexes (cf. McCarthy & Plint, 1999). |
| **A6** | Sandstone, coarse granular or pebbly to fine-grained; most commonly forms lenticular bodies with erosive base; sandbody typically upward-fining; 4 to 12 m thick, accretion surfaces may be visible. Lower part typically has dm-scale trough cross-stratification; upper part may have current ripples, abundant roots. | Channel-fill; lenticular geometry suggests most sandbodies represent non-migrating, ? anastomosed channels; other examples may represent meandering channels (cf. McCarthy et al., 1999; Makaske, 2001). |
| **A7** | Conglomerate, pebbles typically 15 to 20 mm, well-sorted, well-rounded, clast-supported, forming an erosive-based body up to 15 m thick; capping facies A6. Relatively undeformed, weakly planar, with local erosive bases. | Sharp, scoured base, large-scale accretion surfaces with orthogonal gravel dunes, multi-storey architecture, and rooted top surface. Conglomerate deposition on large gravelly point bars, probably within a valley. Anomalously coarse sediment may reflect isostatic uplift in late Paddy time, perhaps coupled with increased fluvial discharge leading to advance of alluvial sand: gravel boundary into the foredeep (e.g. Allen & Heller, 2012). Subsequent eustatic rise, coupled with flexural subsidence led to marine transgression at VE3 surface. |
Table 1. Continued.

| Facies Association | Description | Interpretation |
|--------------------|-------------|----------------|
| **A8**             | Coarse to medium-grained sandstone and fine conglomerate forming complex, erosive-based, multi-storey body up to ca 27 m thick. Cross-stratification ubiquitous, sets commonly dm to >1 m thick. Master accretion surfaces bound packages typically 5 to 8 m thick & 100 to >400 m wide. Sandbodies may enclose localized units of rooted siltstone with organic matter. (Fig. 20, S2) | Coarse grain size, multi-storey and multi-lateral fill, and consistent dip of accretion surfaces for 100 to 400 m suggests deposition on coarse-grained point-bars in channels up to ca 10 m deep. Channels were confined to palaeovalleys. |
| **Lagoonal**       | Heterolthic, with very fine sandstone and siltstone interstratified on mm to cm-scale. Siltstone and sandstone beds commonly have wave- & combined-flow ripples. Sand beds may be normal, reverse-to-normal or reverse-graded. Wave ripples, synaeresis cracks and intense deformation common; BI variable from 0 to 6. Mudstone at base of c/u successions commonly contains abundant low-diversity bivalve fauna (*Brachydontes*, *Unionid*), gastropods (*Viviparus*) and foraminifera (*Steick & Leckie, 1990b*). Organized in siltier- and sandier-upward successions, typically 0.5 to 4 m, m thick (Figs 21, 22 and S1). | Molluscan and foraminiferal fauna indicate reduced salinity; ubiquitous upward-coarsening successions suggest progradation of small deltas into shallow water. Wave influence pervasive but insufficiently energetic to form HCS, suggests shallow water and short fetch. Abundant synaeresis cracks suggest inhibited dewatering, salinity changes, subaqueous clay shrinkage and water expulsion. Some deformation may be due to spontaneous liquefaction, other examples to dinoturbation. Sand beds may have been introduced by hyperpycnal flows but reworking by wave-generated currents produced the dominant normally graded beds. |
| **Estuarine**      | Sandstone, fine to medium-grained, typically well-sorted with abundant dm-scale trough and tabular cross-stratification. Cross-stratification may be multi-directional. Forms erosive-based units up to ca 10 m thick which may be partitioned by mud-draped accretion surfaces; mud-draped cross-sets, mud intraclasts, rare roots and concentrations of woody phytodetritus also present. BI low, 0 to 1. (Fig. 25A and B) | Large, tidally influenced channels within an estuary, filled by migrating dunes and bars. Detailed interpretations in *Leckie & Singh (1991).* |
| **E2**             | Heterolthic claystone to mudstone and fine sandstone interstratified on a cm to mm scale. Wavy, flaser and linsen bedding common, rooted horizons, BI highly variable from 0 to 4; locally highly deformed. Mudstone bodies may be lenticular on 10's of m scale. (Fig. 25C to F) | Facies indicate alternating current flow and slack water; may represent tidal flats flanking tidal channels; lenticular units fill abandoned channels. Local deformation probably dinoturbation. Detailed interpretations in *Leckie & Singh (1991).* |
appears to have started to fill in Paddy PF time with deposition of strongly tidally influenced sandstone, characteristically rich in comminuted plant debris. Teredo-bored logs are common, and *Gnesioceramus comancheanus* at Heart River site 7 (Figs 9 and 16), indicate a connection to the open sea to the north. By late Paddy time (Fig. 29), the Smoky River Ridge, separating the Paddy and Joli Fou depocentres had been buried and Paddy lagoonal and estuarine sediments merged eastward with easterly derived sediments of the Pelican delta (Vannelli et al., 2017; Fig. 3). A river from the Pelican system delivered coarse- to fine-grained quartz arenite to the Paddy depocentre, apparently crossing the Smoky River Ridge by following a pre-existing valley (Figs 28 and 29).

**Sandstone isolith maps**

Wireline logs were used to map the distribution and thickness of ‘clean’ sandstone (with a gamma-ray log
signature of <ca 85 API), in each of the nine Paddy allomembers (Figs 30 and S4 to S12); outcrop sections were not used for mapping because these data points were few, and widely spaced.

Allomembers PA and PB are dominated by alluvial sediments with minor lagoonal facies in the north (Figs 27 and 30). Sandstones are interpreted to represent fluvial channel-fills and lake and lagoonal deltas. In allomember PC (Fig. 30), most sandstone lies within the lagoonal region, where it forms the upper part of metre-scale, sandier-upward successions interpreted as shallow-water deltas.

In allomembers PD, PE and PF (Fig. 30), sandstone occupies two distinct regions. In the north, a WSW-ENE-trending, linear region of thicker (3 to 8 m) clean sandstone (Facies M1; Table 1, Fig. 26A), represents a more strongly wave-influenced marine shoreface environment, the northern limit of which is shown by a heavy broken line in Fig. 30. To the north of the shoreface extends a region of heterolithic facies (Facies M2, Table 1, Fig. 26B to D), in which the proportion of clean sandstone diminishes northward, in an offshore direction. To the south of the shoreface region, sandstones are thin (typically <3 m), commonly heterolithic, and form localized patches and ‘ribbons’, largely isolated in muddy lagoonal and lacustrine deposits. These thin, patchy sandstones cap sandier-upward successions (Figs 23A and 24A), and are interpreted as the mouthbar deposits of elongate, river-influenced deltas that prograded into a shallow, low wave-energy lagoon. The distribution of sandstone suggests that the rivers feeding these deltas entered the lagoonal region from both the SW and south (Fig. 31A). In some cases, sandstone ribbons can be traced northward where they merge with the ‘high-energy’ marine shoreface sandstone belt, suggesting that at times, the deltas prograded right across the lagoon and debouched directly into the sea, as shown schematically in Fig. 31A.

During deposition of allomembers PG, PH and PI (Fig. 30), the broad palaeogeographic organization remained similar to that of older allomembers, with thicker sandstone concentrated in a linear region representing a wave-dominated shoreface, to the south of which, thinner, patchy sandstones represent lagoonal deltas. In allomember PG, sandstone is concentrated in the western portion of the lagoon whereas the central and south-eastern part has very little sandstone. Sandstone distribution in allomember PH broadly resembles PG, but differs by including a lobate sandstone body in the SE suggesting that a new river system entered the lagoon from the east. In allomember PI, the distribution of sandstone, both in the marine shoreface and in the lagoon, suggests that the dominant source of sand was by then from the east, and that the SW side of the basin received little (Fig. 31B). In the far SW, allomember PI is erosively capped by a body of fluvial conglomerate (facies A7, Figs 19, 30, S2 and S3), that fills a valley and indicates
the advance of a gravelly river system into the foredeep, very late in Paddy time.

SUBSIDENCE

Isopach maps

Facies analysis shows that most of the Paddy rocks were deposited in low-lying coastal plain environments or in only a few metres of water, where rooted horizons indicate repeated aggradation to sea-level. Thus, throughout Paddy time, the long-term rates of accommodation and sediment supply were in near-equilibrium, and water depth probably never exceeded a few metres except in the offshore area in the north. In consequence, isopach maps (uncorrected for compaction), can be interpreted as providing a good approximation of long-term tectonic subsidence, with water depth treated as negligible.

The isopach map for the entire Paddy alloformation (Fig. 32A), shows an arcuate pattern of subsidence centred on the Mt. Chamberlain-Quintette Mine region. An elongate region of thickening extends away from this depocentre to the NE, where it overlies the crest of the Peace River Arch – a topographic feature of the Precambrian basement. The northern progradational limit of the Paddy shoreface sandstone corresponds closely to the northern margin of this elongate region of thickening, and also, in part, to the Hines Creek Fault that extends upward from underlying Palaeozoic rocks (e.g. Richards et al., 1994; Mei, 2006; Fig. 32A).

The subsidence history of the Paddy depocentre is illustrated in three isopach maps. Allomembers PA to PC are up to 40 m thick (Fig. 32B), and occupy a semi-circular, strongly wedge-shaped depocentre that records the initial subsidence of the Cadotte strandplain sandstone, the top of which originally approximated sea-level. The new

Fig. 19. (A) Aerial view of laterally accreted, channel-filling conglomerate (Facies A7) capping allomember PI on Mt. Chamberlain (Fig. 6); (B) Aerial view of conglomerate body in A, showing erosional channel base (yellow line), one accretion surface (orange line) and large, arcuate gravel trough cross-sets (pink lines) oriented at a high angle to the dip of the accretion surfaces. (C) Symmetrical ripples, average wavelength 90 cm, in fine conglomerate marking 20 cm thick reworked lag lying on marine transgressive surface VE3, Mt. Reesor south; Kathleen Vannelli (1.7 m) provides scale.
The Paddy depocentre was filled primarily with alluvial and lagoonal sediments (Fig. 27). Allomembers PD to PF record the continued subsidence and expansion of the Paddy depocentre, allowing accumulation of an arcuate wedge of strata that laps out eastward onto the underlying Cadotte alloformation (Fig. 32C). The wedge is distorted by a NE-elongate region of thickening, the northern margin of which coincides with the progradational limit of the Paddy strandplain shoreface. In contrast to underlying units, allomembers PG to PI (Fig. 32D), form a relatively sheet-like body, ca 10 to 15 m thick, that shows little thickening except very close to the deformed belt. Subtle thickening is also evident over the elongate trough seen in PD-PF. These uppermost Paddy strata blanket the Smoky River Ridge and merge eastward with the Pelican and lower Viking alloformations (Fig. 2B). Across the Paddy depocentre, surface VE3 is a hialtal surface at which rocks equivalent to Viking allomember VB are absent (Fig. 2B).

Marine mudstone of Viking allomember VD forms a wedge that thickens from a zero edge in the NE to >110 m in the proximal foredeep (Fig. 33). The strike of the flexed surface trends ~ north-south, in contrast to the NW-SE strike of the Paddy depocentre (Fig. 32A). A series of east-west profiles, drawn to scale across the study area at 55°15′N (Fig. 34), illustrate the evolving profile of the depocentre; an interpretation is discussed below.

**Interpretation of subsidence patterns**

Below the Paddy alloformation, middle Albian strata show an upward change from a wedge of marine mudstone (Harmon alloformation), to a sheet of shoreface sandstone that forms the Cadotte alloformation (Fig. 34). This geometric change was interpreted to record an initially rapid, but decelerating rate of flexural subsidence through a middle Albian tectonic 'loading cycle' (Buckley et al., 2016), and is directly comparable to model results.

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Fig. 20. Valley-fill facies A8. (A) Oblique aerial view of part of the NE face of Mt. Chamberlain (strike approx NW-SE), showing the complete Paddy succession from PE0 to VE3. Orange lines mark the base of five, multi-storey bodies of sandstone and fine conglomerate (facies A8); some master accretion surfaces within the sandbodies are delineated in white. The height of the accretion surfaces suggests channel depths of the order of 5 to 8 m. The sandbodies are interpreted as valley-fill deposits that, in this section, hang from subaerial unconformities at the top surfaces of allomembers PC, PD, PE, PF and PG. The vertical cliff at top of section is fluvial valley-filling conglomerate of facies A7. The images in B & C were taken to the left of the portion of cliff shown here. (B) Approximately 6 m thick body of fine conglomerate and granular coarse sandstone in allomember PC, showing master accretion surfaces dipping approx NW, across which dunes migrated towards the north, each forming a sharp-based bed of unstratified conglomerate grading up into faintly cross-stratified granular sandstone. (C) Two stacked, ca 2 m thick trough cross-sets of coarse- to medium-grained sandstone, interpreted as representing large subaqueous dunes; allomember PE.
Fig. 21. Lagoonal facies L1. (A) Mud-rich heterolithic facies with well-developed combined-flow ripples (CFR) in very fine-grained sandstone. Sandstone beds typically have sharp, slightly erosive bases, and grade upward into mudstone. Other mudstone beds are internally structureless and have sharp base and top and may represent fluid mud deposits (FM, cf. Ichaso & Dalrymple, 2009). Bioturbation Index (BI) = 0. Allomember PE, Dome Goodfare 6-3-72-11W6, 1681 m. (B) Heterolithic facies in which very fine sandstone beds show reverse- and reverse-to-normal grading, interpreted as recording subtly accelerating and decelerating hyperpycnal flows issuing from distributaries in flood (cf. Mulder et al., 2003; Bhattacharya & MacEachern, 2009). Deformation structure may be due to water-escape; BI = 0. Allomember PF, CanHunter ESSO Elmworth 8-13-69-11W6, 1911 m. (C) Sand-rich heterolithic facies dominated by current ripple cross-lamination, with foresets picked out by fine phytodetritus. Low-diversity bioturbation includes small Helminthopsis, Planolites, Skolithos?. Image from 1 m below top of allomember PF, and probably represents proximal delta-front, with bedload transport by river effluent. Dome Goodfare 6-3-72-11W6, 1677 m. (D) Mud-rich heterolithic lagoonal facies dominated by normally graded beds of coarse silt and very fine sand, locally moulded into wave ripples (WR) and combined-flow ripples (CFR). BI is highly variable between beds and may reflect short-term changes in salinity. Fragments of bivalve and gastropod shells are concentrated at one level. Sediment emplacement may have been by hyperpycnal flows sufficiently energetic to erode sediment deposited during the rising stage of the flow (Mulder et al., 2003). Allomember PH, Dome Total Goodfare 6-25-72-12W6, 1599 m (see Fig. 15). (E) Plan view of synaeresis cracks, filled with very fine sand. Cracks lack the regular polygonal pattern typical of desiccation. Allomember PF, BP et al. Belloy 6-34-78-2W6 505 m. (F) Heterolithic facies, with BI = 0, showing normal, reverse and reverse-to-normally graded beds with subtly wave-reworked sandstone lenses. Mudstone beds are traversed by sand-filled synaeresis cracks, ptygmatically folded due to compaction. Some crack-fills traverse several beds. Gradual dewatering appears to have been inhibited by thick fluid mud layers, and by lack of bioturbation, resulting in rapid expulsion of water and sand along fractures after some burial had occurred. Allomember PE, Dome Total Goodfare 10-23-72-11W6, 1585 m (see Fig. 14). (G) Black mudstone from lowest part of an upward-coarsening lagoonal succession, containing a current-winnowed layer of convex-up, disarticulated bivalves (U = a Unionid, possibly Pleuroblema), and gastropod (V, probably Viviparus), both of which are typical of fresh to low-salinity conditions. Allomember PG, CanHunter ESSO Elmworth 8-13-69-11W6 1907 m. (H) Black lagoonal mudstone with a current-winnowed concentration of disarticulated, monospecific Unionid bivalves indicative of reduced salinity conditions. Allomember PG, Dome Steeprock 13-16-72-12W6 1647 m.
Fig. 22. Lagoonal facies L1 and L2. (A) Thinly bedded lagoonal facies L1 comprising mostly sharp-based, subtly normal-graded beds of very fine sandstone, many showing low-amplitude wave ripples (WR), interstratified with mudstone; one bed shows coarsening-fining grading (diamond shape). Sand- and mud-filled synaeresis cracks (Sy) are pervasive; BI = 0 to 2, including small Planolites and Helminthopsis. Facies suggests stressed environment with lowered salinity and rapid sedimentation. 50 cm below top of allomember PF, Dome Total Goodfare 6-17-72-11W6, 1648 m. (B) Heterolithic lagoonal facies L1 composed mainly of sharp-based, subtly normal-graded beds, some forming wave ripples. Bioturbation, including Cylindrichnus, Planolites and Teichichnus, is relatively pervasive (BI = 3 to 5), and may be indicative of higher salinity and/or lower sedimentation rate. 50 cm below top of allomember PD, Dome Goodfare, 6-3-72-11W6, 1683 m. (C) Overview of sandier-upward succession in allomember PH, with heterolithic facies L1 (offshore lagoon) grading up into ripple cross-laminated fine sandstone of facies L2 (delta-front). A sharp, granule-strewn transgressive surface (Tr) marks the base of allomember PI. The uppermost 20 cm of allomember PH is intensely deformed (Df), as shown in more detail in (D). Dome Goodfare, 6-3-72-11W6, 1665 to 1669.5 m. (D) Detail of (C) showing intense deformation at top of allomember PH; the stratigraphic position at top of a lagoonal delta suggests that deformation might be due to dinosaur trampling. Transgressive surface (TS) marks base of allomember PI. (E) One of a series of isolated, punch-down structures at the rooted top of a sandier-upward lagoonal succession (facies L2); the intense deformation and microfaulting suggest that these structures are dinosaur footprints made in unconsolidated sediment (cf. Lockley, 1991; McCrea et al., 2015). Allomember PH, Joachim Creek, scale = 20 cm (Fig. 10). (F) Loading of very fine-grained sandstone into mudstone, immediately beneath lagoonal delta-front sandstone; structure suggests rapid, possibly flood-related deposition of sand on thixotropic mud. Allomember PH, CanHunter Noel, d-10-F 939/8, 1802 m. (Gi to Giii) Three views of the same core piece. Heterolithic lagoonal facies L1, in which very fine sandstone beds show both reverse-to-normal, and normal grading. BI = 0 to 1. Stratification is pervasively disturbed by sand dykes, microfaults and soft-sediment deformation. Deformation probably attributable to sudden water expulsion, possibly due to seismic shock. Allomember PH, CanHunter et al. Red Rock, 6-31-63-6W6, 2580 m.
The evolution of stratal geometry from ‘wedge’ to ‘sheet’ during the middle Albian is repeated in the Paddy alloformation during the late Albian. At a first order, the wedge-shape of the entire Paddy alloformation reflects asymmetrical flexural subsidence adjacent to the fold and thrust belt as a response to both the advance, and thickening, of the orogenic wedge (e.g. Platt, 1988; Flemings & Jordan, 1989; Jordan &...
The point of onlap of Paddy allomembers against the subaerial surface formed by the underlying Cadotte alloformation, advanced eastward at least 250 km during Paddy time. Although long-term stratal onlap onto a forebulge can be attributed to advance of the leading edge of the deformed belt, the rate of such advance is likely to have approximated ca 10 to 20 km/Myr (e.g. Jordan et al., 1988; Einsele, 2000; DeCelles & DeCelles, 2001; Naylor & Sinclair, 2007). This rate is too low to explain the observed >250 km shift in the point of onlap over the ca 2 Myr duration of Paddy deposition. Instead, it seems likely that
a combination of internal thickening of the orogenic wedge on out of sequence thrusts, coupled with the distributed load of the sediment filling the foredeep, was primarily responsible for subsidence and the advance of the point of onlap (cf. Flemings & Jordan, 1989; Johnson & Beaumont, 1995; Varban & Plint, 2008). The arcuate shape of the Paddy depocentre (Fig. 32), suggests that flexure took place in front of a salient, of the order of 200 km in strike length, in the adjacent deformed belt. Such a salient may have formed in response to a locally thicker sedimentary section, a locally weaker detachment, or a localized indentor, amongst other reasons (cf. Macedo & Marshak, 1999).

Divided into three time-steps, it is evident that the lower and middle Paddy rocks (PA-PF) form prominent wedges whereas the upper Paddy (PG-PI) is almost sheet-like (Figs 32B to D and 34). In the absence of geochronological information, it is assumed, for simplicity, that each of the three rock units represent an approximately equal increment of time. On the basis of the observed stratal geometry, it can be inferred that the rate of loading by the orogenic wedge, and consequent asymmetrical flexural subsidence of the foredeep, diminished through Paddy time, as summarized and interpreted in Fig. 34. Prior to Paddy deposition, tectonic quiescence is inferred to have resulted in a very low rate of flexural subsidence during

Fig. 25. Estuarine Facies. (A) Oblique aerial view of part of Peace River site 2 (Fig. 4) showing the entire thickness of the Paddy alloformation between surfaces PE0 and VE3. Channel-filling sandstone bodies (facies E1), with large-scale accretion surfaces compose most of the Paddy, and are capped by a thin, sheet-like marine sandstone (above orange line). (B) Detail of channel-filling sandstone (red rectangle in A) with multi-directional, dm-scale trough and tabular cross-stratification separated by inclined master bounding surfaces that probably represent macroform topography. The yellow line (also shown in A), marks the base of a major channel-base erosion surface and is mantled with large sandstone intraclasts. (C) Overview of Heart River site 6, with PE0 and VE3 surfaces indicated. At this locality, a muddy estuarine channel plug (facies E2), is visible in the foreground, capped by a more sheet-like heterolithic body characterized by flaser, lenticular and wavy bedding, with rooted horizons; this facies probably represents a tidal flat. K. Vannelli for scale. (D) Detail, located by red rectangle in (C), illustrating rooted, heterolithic tidal flat facies (E2), capping a channel plug. Scale bar = 20 cm. (E) Detail of (D) showing lenticular bedding comprising isolated wave ripples in very fine sandstone, draped with silty claystone; this facies may be indicative of the upper part of a tidal flat. Scale bar marked in cm. (F) Intense, localized deformation in tidal flat facies (located in C); these structures are common along certain horizons and may have been produced by dinosaurs walking across the tidal flat. Scale bar marked in cm.
which three stacked sheets of Cadotte strandplain sandstone were deposited, probably in response to high-frequency eustatic cycles (Buckley et al., 2016; Fig. 34). Renewed subsidence of the most proximal foredeep in early Paddy time (PA to PC), may be interpreted as evidence of the onset of a new phase of deformation that led to thickening of a segment of the orogenic wedge to the SW. Over time, the rate of internal deformation and uplift of the wedge diminished, resulting in a decreasing rate of flexural isostatic subsidence. Sediment eroded from the orogenic wedge was dispersed across alluvial to shallow-marine environments in the adjacent foredeep. The increasingly acutely tapered sediment wedges of allomembers PD to PF may record a diminishing rate of tectonic subsidence and the increasing influence of a distributed sediment load (Flemings & Jordan, 1989). This trend is carried to an extreme in the very thin and sheet-like geometry of Paddy allomembers PG to PI. These units suggest that by late Paddy time, the rate of deformation in the orogenic wedge, and attendant flexure of
the basin margin, were minimal. Accommodation across the foredeep was generated primarily by isostatic subsidence driven by the accumulating sediment body that eventually buried what might be considered the local ‘forebulge’ (i.e. the Smoky River Ridge; Fig. 34).

Across the Paddy depocentre, rocks equivalent in age to Pelican allomembers PeC and PeD, and coeval Viking allomember VB, are absent (Vannelli et al., 2017; Figs 2B and 34). This hiatus is interpreted as having been a consequence of a phase of tectonic inactivity, accompanied by erosional degradation of the adjacent orogen that led to subtle isostatic uplift of both the orogen and the proximal foredeep. Major post-Paddy palaeovalleys were locally incised into the VE3 surface at this time (see Discussion below). Moreover, the unique conglomerate valley-fill capping allomember PI in the far west (Figs 19C, 32D, S2 and S3), may provide additional evidence of isostatic uplift of the proximal foredeep, that resulted in

Fig. 27. Palaeogeographic summary of Paddy allomembers PA to PC. The progressive onlap of Paddy allomembers onto the eroded upper surface of the Cadotte alloformation is indicated. All available core and outcrop control, supplemented by log interpretation, was used to map palaeoenvironments. The ‘intermittently saline’ region is characterized by interstratified lagoonal and alluvial facies. The lagoonal region was occupied by elongate river-dominated deltas (data not shown, for simplicity). Palaeoflow data from large fluvial channels and valleys indicate mean flow to the north and NE. A narrow, linear region of clean, well-stratified sandstone forms a strandplain separating the lagoon from open marine facies to the north.
steepened rivers that promoted the eastward advance of the alluvial gravel front very late in Paddy time (cf. Heller & Paola, 1992; Allen & Heller, 2012).

The alluvial and marginal-marine deposits of the Paddy are abruptly blanketed by offshore marine mudstone of Viking allomember VD. This unit forms a very prominent wedge that records transgression of the entire depocentre in response to renewed tectonic loading and flexure (Figs 19C, 33 and 34). Rapid subsidence trapped nearshore sandstone in the most westerly part of the basin, resulting in a foredeep dominated by mudstone (cf. Ballato et al., 2008; Varban & Plint, 2008). The rotation of the strike of the flexed surface, from NW-SE in Paddy time, to N-S in Viking VD time suggests that the locus of active loading had migrated to the north in VD time, possibly in response to a regional-scale change in the kinematics of accreted terranes on the continental margin (Plint et al., 2012).

The eastern margin of the Paddy depocentre is the Smoky River Ridge, the crest of which is defined by the mutually opposed onlap limits of Paddy allomember PF

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**Fig. 28.** Palaeogeographic summary of Paddy allomembers PD to PF, showing continued onlap onto the underlying Cadotte alloformation. Brackish-water lagoonal facies locally extended far to the SW reaching the Whatley Creek section. The wave-dominated northern shoreline is characterized by SCS. Large gutter casts at Lynx Creek are oriented shore-perpendicular and indicate storm wave approach from the north. Palaeocurrent data from fluvial channels and valleys indicate mean flow to the N and NE. In the NE, a palaeovalley incised into the Cadotte alloformation was mapped by Leckie et al. (1990), but appears to have accumulated sediment only from allomember PF time onward.
in the west, and the marine Joli Fou alloformation in the east (Vannelli et al., 2017; Figs 3 and 29). Although the Smoky River Ridge has some characteristics of a classical flexural forebulge, the linear, SW-NE trend of the ridge does not mimic the arcuate pattern of flexure seen in the proximal foredeep (Fig. 32). Moreover, the Ridge shares neither a common trend nor location with the Peace River Arch. The origin of this topographic feature remains enigmatic.

Non-flexural control on subsidence and palaeogeography

Superimposed on the arcuate moat that forms the Paddy depocentre is a NE-elongate region in which Paddy strata thicken subtly over the crest of the Peace River Arch (Fig. 32A and C). The crest of the Arch is dissected by various horst and graben structures that were active primarily in the Late Palaeozoic (O’Connell, 1994). During
the Mesozoic, the Arch underwent broad sagging, as mapped by Buckley et al. (2016). These authors recognized that the Hines Creek Fault had been active during latest Cadotte time (allomember CC, late middle Albian), but prior to this, the fault appears to have had little effect on the thickness of the Harmon and Cadotte alloformations. Nevertheless, the northern progradational limit of the Cadotte strandplain closely coincides with the northern margin of the thickened Cadotte ‘trough’, suggesting that differential subsidence exerted some influence on shoreface progradation (Buckley et al., 2016; Fig. 32A). Isopach mapping of overlying Paddy strata (Fig. 32A) shows that renewed displacement of ca 20 m took place on the Hines Creek Fault during Paddy time, although differential subsidence to the west of ca 119°W cannot be attributed to any fault mapped in public domain data (Fig. 32A). The Fort
St. John-Blueberry Graben (‘FJG’ in Fig. 23A), mapped and interpreted as having been active during the Cretaceous (Mei, 2006), does not appear to have influenced subsidence during Paddy time.

Throughout Paddy deposition, a linear, wave-dominated strandplain separated the open sea to the north from an extensive region of very shallow lagoons that extended for several hundred km to the south and west,
Stratigraphic and geographic distribution of Paddy palaeovalleys

Although log signatures do not permit unequivocal correlation to outcrop, the valley-filling units exposed in the Foothills (e.g. Figs 20A, S2 and S3), appear to be correlative with comparable ‘blocky’ units represented in wireline logs (e.g. a-86-K 93 P/3 in Fig. 6; c-76-D 93 P/2 in Fig. 7). Each coarse-grained valley-fill (facies A7, A8) observed in wireline logs appears to hang from a surface that can be correlated down-dip with a flooding surface that bounds one of the Paddy allomembers. This stratigraphic relationship suggests that there is some temporal, but not necessarily genetic, relationship between episodes of up-dip alluvial aggradation and degradation, and down-dip episodes of shoreline transgression and regression. Valley-filling sandbodies are particularly numerous at the top of allomember PE, although the reason for this is unknown. Sandstone and pebbly sandstone valley-fills in Paddy allomembers PA to PH are confined to the proximal part of the foredeep, whereas the valley-filling conglomerate in allomember PI has an even more limited distribution in the Foothills outcrop belt and immediately adjacent subsurface (Fig. 35). Palaeocurrent data compiled from valley-filling sandstones exposed between Mt. Chamberlain and Mt. Belcourt show that rivers had a mean flow towards the NNE (Fig. 35).

A second population of sandstone-filled valleys, up to 38 m thick, cut down from the VE3 surface, and are shown in blue in Fig. 35. These valley-fills all post-date the Paddy and are spatially disjunct from the intra-Paddy palaeovalleys. The apparent pattern of tributary valleys suggests that the post-Paddy valleys drained to the south, although data are too sparse to make a definite interpretation. These post-Paddy valleys are interpreted as having formed during a phase of tectonic quiescence (discussed above), when erosion and isostatic uplift of the proximal basin margin led to fluvial erosion and/or bypass, expressed as the VE3 unconformity. To the east and south of the studied area, rocks at least partially contemporaneous with the hiatus represented by VE3 include Pelican allomembers PeC and PeD, and Viking allomember VB. Each of these shallow-marine rock units is typically <20 m thick, and they attest to continued limited subsidence in the more easterly and southerly part of the basin, towards which rivers are inferred to have drained (Fig. 2B; Plint et al., 2016; Vannelli et al., 2017).

Alluvial aggradation and degradation

Although valley incision across coastal plains can be attributed to the rejuvenating effect of eustatic sea-level fall on rivers (e.g. Blum & Törnqvist, 2000), it is...
Fig. 32. Isopach maps, contours in metres. (A) Total thickness of Paddy alloformation between surfaces PE0 and VE3. Also shown are the northern and southern margins of the Peace River Arch (a structural element of the Precambrian basement), the Hines Creek Graben (HCG), bounded to the north by the Hines Creek Fault, and the Fort St. John-Blueberry Graben (FJG). The isopach pattern shows both progressive thickening into the western foredeep, indicative of flexural subsidence, and also a trough-like region of thickening extending to the NE. The northern boundary of this trough is relatively abrupt and coincides, in part, with the Hines Creek Fault. The northern progradational limit of the Paddy shoreface sandstone also corresponds closely to both the HCG as well as the northern margin of the thickened trough. Graben structures after Mei (2006); boundary of Peace River Arch after O’Connell et al. (1990) and McMechan (1990). (B) Allomembers PA-PC, where the 0 m contour marks the onlap limit onto the eroded surface of the underlying Cadotte alloformation. (C) Allomembers PD-PF showing continued flexural subsidence in the west, and development of an elongate NE-trending trough over the crest of the Peace River Arch, partially coincident with the Hines Creek Graben (shown in A). (D) Allomembers PG-PI showing much more tabular geometry relative to underlying allomembers, with only minor thickening adjacent to the deformed belt. Over the crest of the Smoky River Ridge, Paddy facies merge laterally with deltaic sediments of the Pelican alloformation.
difficult to apply this explanation to the Paddy valleys. Paddy valleys cannot be traced across the lagoonal area, or to the marine shoreline, being confined to the proximal foredeep (Fig. 35). There, a relatively high rate of subsidence would have tended to negate the effect of eustatic fall, making river incision unlikely (Clevis et al.,...
2004). It is therefore necessary to consider non-eustatic effects.

River incision can result from tectonic uplift, and subsequent subsidence can trigger alluviation. It is, however, questionable whether alluvial systems of the scale represented by the Paddy rocks, were capable of recording cyclical changes in accommodation on a timescale of $<10^6$ years (cf. Paola et al., 1992; Blum & Törnqvist, 2000; Blum et al., 2013). Notwithstanding the modelling results of Naylor & Sinclair (2007), it seems unlikely that a tectonic mechanism was available that could alternately raise and lower the entire Paddy depocentre nine times on a timescale of the order of $10^5$ years per cycle, in order to produce the nine transgressive-regressive successions, and the nine alluvial aggradational-degradational packages that are observed. The argument against a tectonic control is strengthened by the progressive change in the geometry of Paddy allomembers, from wedges to sheets. This change suggests that the rate of tectonically driven subsidence, and, presumably, the rate of thickening of the orogenic wedge, diminished through Paddy time (Fig. 32).

It is increasingly widely recognized, both in models, and from observation of the rock record, that change in the intensity of precipitation can have a profound effect on the stability of alluvial systems by altering the balance between discharge and sediment load. Note however that not all river systems respond to such change in the same way (Paola et al., 1992, 2009; Holbrook, 2001; Pratt et al., 2002; Goodbred, 2003; Gibling et al., 2005, 2011; Jain et al., 2005; Milana & Tietze, 2007; Blum et al., 2013; Scherler et al., 2015; Dey et al., 2016). There is evidence from the Himalayan Foreland Basin that widespread aggradation of the Ganga alluvial plain took place when the Indian Monsoon weakened and river discharge diminished. In contrast, periods of stronger monsoon rains increased stream capacity, which lead to deep (tens of m), incision of alluvial plains, and corresponding sediment starvation and pedogenesis across interfluves (e.g. Goodbred, 2003; Gibling et al., 2005, 2011). The strength of the Indian Monsoon appears to have fluctuated on a $10^4$ years timescale, in response to Milankovitch climate cycles.

The Paddy valley-fills are invariably much coarser-grained, including granules and small pebbles, relative to
the enclosing sediments. The appearance of gravel at specific horizons in a fluvial succession could be interpreted as evidence for uplift of the source-area, a decrease in subsidence rate or an increase in the discharge of rivers (Heller & Paola, 1992). The fact that in the Paddy rocks, gravelly sediment is invariably confined to valley-fills strongly suggests a linkage between valley incision, here interpreted as reflecting increased stream power relative to sediment load, and the delivery of coarser-grained sediment. As emphasized by Blum & Törnqvist (2000) and Holbrook (2001), aggradation-degradation cycles on the ca $10^5$ years frequency, such as are seen in the Paddy alloformation, are most likely to record cyclical changes in discharge related to climate change on a Milankovitch timescale (Fig. 36). Given the relatively limited availability of detailed stratigraphic data, and the poor age control available, it is not

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Fig. 34. A series of scale cross-sections drawn east-west at 55°15′N to show the evolution of successive sedimentary units and interpreted activity in the adjacent orogenic wedge. Middle Albian Cadotte sandstone sheets are abruptly replaced by strongly tapered Paddy wedges (PA-PC) that record loading by an actively thickening orogenic wedge. Overlying allomembers PD-PF show continued flexural subsidence and onlap, but gradually transition to more acutely tapered wedges, culminating in sheet-like allomembers PG-PI, the latter suggesting diminishing tectonic load with subsidence increasingly driven by the distributed sediment load. The hiatus at VE3 is interpreted to record tectonic quiescence and subtle isostatic uplift of the degrading orogen, whereas the pronounced marine mudstone wedge formed by allomember VD records the onset of a new phase of thickening in the orogen.
possible to draw any more definite conclusions regarding specific linkages between climate, possible vegetation change, and the 'fossilized' sedimentary response. It does however seem reasonable to infer that the appearance of a unique, conglomerate-filled valley at the top of allomember PI might be an indication of the wholesale advance of the 'gravel front' in the river system in response to a very low rate of flexural subsidence, or even subtle isostatic uplift, that can be inferred from the sheet-like geometry of the enclosing strata and the extensive VE3 unconformity (Figs 32D, 34 and 35).

**DISCUSSION**

Flooding surfaces, recognizable in both lagoonal and shallow-marine rocks, provide a practical means to divide the more basinward part of the Paddy depositional system into allomembers (Figs 6 to 15). Flooding surfaces typically juxtapose shallower- and deeper water facies that are suggestive of only modest changes in water depth, perhaps no more that ca 5 m. The limited dip extent of shoreface sandstones fronting the lagoon system indicates that the marine shoreface underwent limited lateral migration (order of km) during each relative sea-level cycle, also suggestive of minor sea-level change. There is no evidence that detached lowstand shoreface sandstones were deposited. Thus, the marine-influenced part of the system suggests a long-term relative rise in sea-level that corresponds to tectonic subsidence of the depocentre, punctuated by episodic transgressions and regressions that might reflect episodic changes in the rate of subsidence, minor eustatic variation or, possibly, changes in the rate of sediment supply. The fact that allomembers PG-PI can be traced, with only minor thickening, for ca 300 km from the foredeep to the Smoky River Ridge (‘?forebulge’), suggests that they formed in response to a uniform accommodation change that spanned the foredeep; on an allomember timescale, such a change is most likely to have been eustatic.

It was argued above that high-frequency cycles of alluvial aggradation and degradation in the up-dip part of the basin were more likely to record some form of climatic control on river systems, superimposed on a long-term deceleration in the rate of tectonic subsidence. Interpreted valley-filling sandbodies represented in wireline logs are sharply overlain by mudstone, the basal surface of which appears to correlate with a marine or lagoonal transgressive surface down-dip. Where accessible at outcrop, coarse-grained valley-fills are commonly immediately overlain by lacustrine or muddy floodplain facies. Although by no means conclusive, these stratigraphic relationships suggest a possible genetic linkage
Fig. 36. Cartoons to summarize interpreted relationship between cycles of increasing and decreasing rainfall, and the behaviour of rivers. (A) Minimum rainfall promotes river avulsion and widespread aggradation of the alluvial plain; diminished discharge may have coincided with eustatic rise that tended to drown lagoonal deltas. (B) Increasing to maximum rainfall increased river transport capacity, promoting channel incision to form valleys, possibly linked to greater sediment delivery and progradation of lagoonal deltas, possibly coincident with eustatic fall. (C) Diminishing rainfall reduces transport capacity and rivers back-fill with coarser-grained sand and gravel; limited palaeocurrent data suggest large-scale accretion surfaces represent point-bars.
between minor eustatic changes in sea-level, manifest as transgressive-regressive successions, and changes in precipitation and river discharge, manifest as aggradation-degradation cycles on the adjacent alluvial plain, and possibly as changes in the rate and volume of sediment delivered to lagoon deltas and the marine shoreline.

The effects of changes in both discharge and sea-level were modelled by Milana & Tietze (2007). These model studies showed that unconformities could develop in the alluvial part of the basin in response to increased discharge, and that a second population of unconformities developed in the nearshore part of the basin in response to sea-level changes. However, there was little or no physical connection between the up-dip and down-dip unconformities, and the two types of unconformity only formed simultaneously when sea-level fell in synchrony with an increase in river discharge. Under all other regimes, the surfaces could not be correlated or treated as time-planes in a sequence-stratigraphic sense.

**Broader implications of climate-controlled sediment supply**

The Paddy alloformation provides a relatively unusual opportunity to track facies changes and depositional cyclicity from a relatively up-dip location that included gravelly rivers, to coastal and offshore areas dominated by fine-grained sandstone and mudstone. The potential recognition of discharge-related cycles of alluvial aggradation and degradation, linked to the advance and retreat of the alluvial gravel front, may help resolve a long-standing enigma in other Cretaceous units in the Western Canada Foreland Basin. It has long been recognized that shallow-marine units such as the late Albian Viking Formation and late Turonian Cardium Formation include distinct highstand and lowstand systems tracts (e.g. Downing & Walker, 1988; Plint, 1988; Pattison & Walker, 1992; Davies & Walker, 1993). Lowstand shoreface deposits are commonly erosively based, coarse sandstone or conglomerate that form bodies which are sometimes basinally isolated in offshore mudstone. Conversely, highstand to falling-stage shoreface deposits are generally composed of fine to very fine-grained sandstone, largely devoid of pebbles except in the vicinity of major river mouths. Although the geometry of bounding surfaces, facies offsets and stacking pattern show that these marine conglomeratic facies were deposited in lowstand shoreface settings, no satisfactory explanation has been advanced to explain why coarser-grained sediments were deposited mainly at sea-level lowstand. Conglomerate and coarser-grained sandstone is also present in palaeovalleys in the Viking Formation at oilfields such as Crystal, Sundance and Edson; and also in the coeval Bow Island Formation at, for example, the Blood-Magrath pool. These valley-fills are enclosed in highstand deposits lacking pebbles (Cox, 1991; Pattison & Walker, 1994, 1998).

On the basis of comparison with the Paddy alluvial system, it is here postulated that the episodic delivery of gravel to the Viking and Cardium shorelines was driven by increased precipitation in the hinterland. We speculate that \(10^5\) years Milankovitch-band climatic cycles controlled eustatic change (via waxing and waning Antarctic ice caps, steric change, groundwater storage), and simultaneously modulated rainfall over the Rocky Mountain Cordillera, resulting in a combined ‘upstream + downstream’ control on sedimentation, spanning alluvial to marine environments.

The fact that gravel reached the shore in Viking and Cardium time may have been a fortuitous consequence of the prevailing tectonic regime. The most well-developed lowstand conglomerates in the Viking Formation are in allmembers VA and VB, and also in the middle part of the Cardium alloformation between surfaces E3 and E6. Both of these intervals of rock are regional-scale, sheet-like bodies that either thin and pinch out up-dip, or show minimal thickening, indicating deposition under conditions of no, or very low flexural subsidence (Shank & Plint, 2013; Plint et al., 2016). Viking and Cardium shoreface sandstones have little or no equivalent up-dip alluvial deposits suggesting that rivers flowed over a seaward-inclined surface that bypassed sediment, including gravel, to the shore. In contrast, deposition of all but the uppermost part of the Paddy took place during a phase of relatively rapid flexural subsidence that promoted alluvial aggradation and limited the downstream advance of the gravel front.

Additional evidence of a climatic control on Cretaceous sedimentation is provided by several other formations. For example, in the Cenomanian Dunvegan Formation in west-central Alberta, four separate horizons of sandstone-filled palaeovalleys, that maintain an average depth of ca. 21 m throughout their length, were mapped for up to 320 km across successive the delta plains (Plint & Wadsworth, 2003). The great length but modest depth of these valleys was difficult to reconcile with a purely ‘downstream’ sea-level control on incision, prompting Plint & Wadsworth (2003) to infer that incision of the more up-dip reaches may have been a response to a change in the discharge regime of the rivers, in response to Milankovitch-band climate cycles.

An abrupt change in fluvial style between two superposed palaeovalley systems in the Turonian Notom delta (Utah) was attributed, at least in part, to an increase in discharge, linked to high-frequency climate change (Li et al., 2010). The late Albian Mill Creek Formation in SW Alberta (in part coeval with the Paddy), consists primarily
of fine-grained alluvial sandstone and mudstone but also contains isolated ‘channel-fills’ up to 60 m thick and 22 km wide, composed of coarse, braided river conglomerate (Leckie & Krystinik, 1995). Leckie & Krystinik (1995) inferred that episodic delivery of coarse gravel to a basin otherwise dominated by sand and mud may have been a consequence of erosional degradation of the orogen that resulted in exposure of plutons in the Omineca Belt, and also to regional isostatic uplift that steepened stream gradients, causing more effective gravel transport. Given the similarity of the ‘bimodal’ Mill Creek alluvial system to that of the Paddy, it is here suggested that the alternate delivery of coarse and fine-grained sediment may have been primarily a response to climatically controlled changes in river discharge, rather than to tectonic affects.

**CONCLUSIONS**

1. The Paddy alloformation is a clastic succession of late Albian age (ca ? 103.5 to 101.5 Ma), that forms a wedge up to ca 125 m thick, confined to an arcuate flexural depocentre, ca 300 km wide, adjacent to the Rocky Mountain fold and thrust belt in NW Alberta and adjacent British Columbia. Muddy heterolithic offshore marine facies occupy the northern part of the depocentre, and grade southward into a linear wave-dominated strandplain that fronted a broad region of shallow brackish lagoons that in turn passed south- and westward into an alluvial plain.

2. Marine and lagoonal deposits can be divided into nine allomembers, PA to PI, on the basis of flooding surfaces mappable in wireline logs, core and outcrop. Traced into the alluvial realm, flooding surfaces appear to lie at the base of alluvial or lacustrine mudstones that cap well-developed palaeosols, or bodies of pebbly sandstone or conglomerate that fill palaeovalleys. Paddy allomembers PA to PF form wedges that onlap progressively eastward onto the eroded upper surface of the middle Albian Cadotte alloformation, the latter forming a broad subaerial ridge (the ‘Smoky River Ridge’, that has some characteristics of a forebulge). Marine mudstone of the late Albian Joli Fou alloformation laps out westward against the opposite side of the Ridge. Allomembers PG to PI form thin sheets that blanket the Ridge, and merge eastward with deltaic rocks that form allomembers PeA and PeB of the marine Pelican alloformation (and are equivalent to Viking allomember VA to the south).

3. On the NE margin of the depocentre, allomember PF includes estuarine sandstone that fills a northward-opening palaeovalley. Disarticulated valves of *G. conmancheanus* form a channel-base lag and confirm a late Albian age. This fauna, coupled with physical stratigraphic relationships suggest that allomember PF is contemporaneous with the upper part of the marine Joli Fou alloformation. Paddy allomembers PA-PF are inferred to be broadly contemporaneous with the Joli Fou as a whole.

4. Isolith maps of clean sandstone reveal a WSW-ENE trending strandplain, about 20 km wide, consisting of stacked shoreface sandbodies, 5 to 8 m thick, separated by ravinement surfaces. Within the lagoonal region to the south, sandstones are thin (<3 m) with a patchy, ribbon-like distribution interpreted to represent river-dominated deltas that prograded into a few m of water. In allomembers PA to PG, lagoonal deltas are confined largely to the south and west, implying supply from the adjacent Cordillera. In allomembers PH and PI, sandstone bodies appear in the east. Where exposed on the Peace River, these eastern sandstones have an extremely quartzose composition comparable to deltaic sandstones of the Pelican alloformation. The Pelican deltas were sourced from the Canadian Shield and closed the entire Seaway in late Paddy time.

5. From bottom to top, Paddy allomembers change shape from short, blunt wedges, through more acutely tapered wedges, to sheets. This geometric change may record initially rapid subsidence adjacent to an actively thickening sector of the orogenic wedge. The upward change to more sheet-shaped rock bodies may reflect diminishing rates of deformation and flexural subsidence, during which rivers degraded the orogen. Fluvial and marine processes distributed sediment across the basin, driving broad isostatic subsidence, creating sheet-shaped rock bodies.

6. The top of the Paddy alloformation is the basin-wide unconformity surface VE3, which represents an hiatus equivalent, in part, to Viking allomember VB and Pelican allomembers PeC and PeD. The VE3 surface records subtle erosion or bypass across the Paddy depocentre that may reflect tectonic quiescence in the adjacent orogen, during which erosional degradation led to isostatic uplift in the west. Post-Paddy valleys, up to ca 40 m deep, cut down from VE3 in the more eastern part of the basin and suggest drainage to the south.

7. In the west, alluvial Paddy strata comprise packages of aggradational, fine-grained, unconfined floodplain and ribbon channel deposits, punctuated by erosive-based, multi-storey bodies of pebbly sandstone or conglomerate, interpreted as valley-fills. Valley-fill deposits are confined to the inner ca 100 km of the foredeep. Valleys cannot be traced far into the lagoon, nor to the marine shoreline. Valley incision and periodic advance of the gravel front is tentatively attributed to cyclical
increases in precipitation and river discharge, whereas valley-filling and then deposition across unconfined floodplains was a consequence of diminishing discharge and transport capacity. Neither tectonic nor eustatic mechanisms adequately explain the location, scale, or frequency of alluvial aggradation-degradation cycles.

8 Across the entire depocentre, shallow water and alluvial Paddy strata are abruptly overlain, at surface VE3, by offshore marine mudstone of Viking allomember VD. This unit forms a pronounced wedge that thickens from 0 m in the east to >110 m in the west and indicates the onset of a new phase of tectonic loading driven by renewed thickening in the adjacent orogenic wedge.

9 Regional stratigraphic relationships between lagoonal and alluvial strata suggest that fluvial incision and the advance of the gravel front coincided with coastal progradation whereas transgression was accompanied by valley-filling and then aggradation of fine-grained alluvium. Orbitally paced cycles of precipitation may have modulated alluvial dynamics on a basin scale whereas distant forcing (e.g., Antarctic glaciation, groundwater storage, etc.) may have exerted a synchronous control on minor eustatic change. This postulated linkage between discharge and eustasy could explain why other Cretaceous shallow-marine units in Western Canada (e.g., Viking, Cardium formations), were preferentially supplied with gravel at times of sea-level lowstand, but were dominated by sandstone at highstand.

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Supporting Information

Additional Supporting Information may be found online in the supporting information tab for this article:

**Figure S1.** Lagoonal facies. Core transect through Paddy allmembers PF through PI, showing sandier-upward successions composed of muddy, heterolithic lagoonal deposits of facies L1, gradationally overlain by fine-grained, wave-rippled and planar-laminated delta-front sandstone of facies L2. Transgressive surfaces bounding allmembers are shown by arrows; minor flooding surface within allmember PH is indicated by FS. Intense deformation (Dtb)
near the top of allomember PI may be dinoturbation. Upper boundary of the Paddy alloformation is the regional transgressive surface VE3. Each core sleeve is 75 cm long; Dome et al. Sinclair 14-12-73-13W6, 1586-1602 m.

**Figure S2.** A. Composite aerial panorama of the NE face of Mt. Spieker showing the complete Paddy succession from the basal PE0 surface to the marine transgressive surface VE3, with interpreted allomembers indicated. A measured stratigraphic section is given in Figure 6. Medium to coarse-grained pebbly sandstone forms a series of complex, multi-storey valley-fills in allomembers PE and PG; allomember PF is interpreted to have been erosionaly removed at this locality. Allomember PI is dominated by a multi-storey conglomerate-filled valley. B. Detail image of lower part of allomember PI showing palaeosol at top of PH, a 15 cm, wave-rippled conglomerate lag, overlain by wave-rippled fine sandstone and siltstone, erosionaly truncated by fluvial conglomerate. C. Detail of conglomerate transgressive lag, interpreted to mark the base of allomember PI, overlain by thinly-bedded, wave-rippled sandstone and siltstone. D. Fallen block of transgressive lag in (C) showing conglomerate-filled desiccation polygons penetrating the top of the underlying palaeosol that caps allomember PH.

**Figure S3.** Composite aerial panorama, facing SW, of a cirque on the north face of Mt. Chamberlain, showing the complete Paddy succession from the basal surface PE0 to the marine transgressive surface VE3 (see Fig. 6 for measured section). Coarse grained to pebbly sandstone fills multi-storey valleys in allomembers C, D, E, G and H whereas the valley-fill in allomember I is composed of fine conglomerate. Some of the major bounding surfaces, and internal accretion surfaces, are highlighted. Mountain goat (encircled) gives an impression of scale.

**Figure S4.** Isolith map of clean sandstone in Paddy allomember PA.

**Figure S5.** Isolith map of clean sandstone in Paddy allomember PB.

**Figure S6.** Isolith map of clean sandstone in Paddy allomember PC.

**Figure S7.** Isolith map of clean sandstone in Paddy allomember PD.

**Figure S8.** Isolith map of clean sandstone in Paddy allomember PE.

**Figure S9.** Isolith map of clean sandstone in Paddy allomember PF.

**Figure S10.** Isolith map of clean sandstone in Paddy allomember PG.

**Figure S11.** Isolith map of clean sandstone in Paddy allomember PH.

**Figure S12.** Isolith map of clean sandstone in Paddy allomember PI.