

Sedimentology and Facies Description of Mississippian Alida Beds, Williston Basin, Southeastern Saskatchewan

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Rott, C.M. and Qing, H. (2005): Sedimentology and facies description of Mississippian Alida Beds, Williston Basin, southeastern Saskatchewan; in *Summary of Investigations 2005*, Volume 1, Saskatchewan Geological Survey, Sask. Industry Resources, Misc. Rep. 2005-4.1, CD-ROM, Paper A-12, 10p.

Abstract

The Mississippian Alida Beds of southeastern Saskatchewan contain a number of prolific oil and gas pools and have produced significant amounts of hydrocarbons over several decades. The unit represents a variety of shallow-water carbonate lithologies interlayered with thin sandy beds. Core examination, well-log analysis, and thin-section petrography of the Alida Beds have been carried out to characterize the sedimentology, delineate facies, and describe the spatial distribution of the unit. Six main lithofacies identified in this study include: crinoidal mudstone/wackestone (and its dolomitized equivalent); echinoderm packstone/grainstone; oolitic packstone/grainstone; peloidal packstone/grainstone; a dolomitic sandstone locally interlayered with the carbonate facies; and a dense anhydrite-dolomite 'caprock' that cross-cuts all other facies. Depositional environments range from subtidal inner shelf to shelf edge and foreslope. Angular caprock clasts within the overlying 'red beds' indicate that the caprock formed before deposition of the Jura-Triassic Lower Watrous Formation.

Keywords: Alida, Mission Canyon, Mississippian, Williston Basin, sedimentology, facies, carbonate, caprock.

1. Introduction

The Mississippian Alida Beds are a suite of carbonate rocks present in the subsurface of southern Saskatchewan and much of the Williston Basin. They are host to significant hydrocarbon reserves and, together with the Mississippian Midale and Frobisher Beds, represent the most prolific oil-bearing strata in the northern Williston Basin. The reservoir quality of the Alida carbonate units is largely the result of a prolonged and complex series of diagenetic events (see Rott and Qing, this volume).

The sedimentology of the Alida Beds has not previously been documented in detail. Early work by Fuzesy (1960, 1966) includes facies descriptions of the combined Frobisher-Alida Beds. Based on lithological differences between the Frobisher and Alida Beds, and the presence of an erosion surface at the base of the interlayered Kisbey Sandstone (Perras, 1990; Kent, 2004), the Alida Beds are now commonly treated as a separate unit. Despite the significance of the Alida Beds as an oil-producing interval, studies of Alida oil pools are scarce in the published literature. Lake (1989, 1991) described the nature of transgressive-regressive cycles in the Alida Beds and divided them into five stratigraphic intervals. The importance of oolitic and skeletal facies as reservoir rocks was highlighted by Vigrass and Vigrass (1996). The first comprehensive examination of the diagenetic history of the Alida Beds in the Pheasant Rump Oil Pool by Mundy and Roulston (1998) showed that the development of secondary porosity considerably affected reservoir quality. It is the objective of the present paper to summarize some of the findings in regard to the sedimentology and facies descriptions of the Alida Beds on a more regional scale. The study area is located in southeastern Saskatchewan (Figure 1), encompassing Tp 10, Rge 10W2 to Tp 4, Rge 31W1.

2. Geologic Setting and Stratigraphic Framework

In the study area, the Alida Beds dip southwest toward the centre of the Williston Basin and are truncated by a regionally extensive unconformity. Uplift and tilting of the Mississippian strata in response to the Antler Orogeny, which was initiated in the Late Devonian and continued into Mississippian time (Richards *et al.*, 1994), led to erosion and subsequent exposure of the Alida Beds. The Mississippian (sub-Mesozoic) unconformity separates the Alida Beds from the overlying Lower Watrous "Red Beds" (Figure 2), a unit composed of interlayered sandstone and siltstone that is likely Late Triassic to Early Jurassic in age (Grant Gerla, pers. comm., 2004). Further basinward to the southwest, the Alida Beds are overlain by the Kisbey Sandstone, a mixed carbonate-siliciclastic unit. Mixed

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Figure 1 - Location map of the study area in the northern Williston Basin.

skeletal and oolitic carbonates of the Tilston Beds are found below the Alida Beds. Deposition of Alida sediments likely occurred in a carbonate shelf-type setting in shallow-marine waters (Kent, 1984a). There is a general consensus that the deposits are part of an overall shallowing-upward trend in the Mississippian (*e.g.*, Kent, 1984a, 1984b; Waters and Sando, 1987) and cyclicity has been identified on several scales (Elliot, 1982; Hoff, 1987; Lake, 1991). During Mississippian time, the Williston Basin was a broad embayment of shallow-marine waters connected to the open ocean through the Montana Trough (Figure 1). At this time during the Middle Osagean (Late Tournaisian) the study area was located around 5°N of the paleo-equator in a warm, semi-arid to arid climate (Gutschick and Sandberg, 1983; Smith and Dorobek, 1993; Kent *et al.*, 1998).

3. Facies Description and Interpretation of Depositional Environments

The sedimentological and stratigraphic characteristics of the Alida Beds are based on examination of nearly 50 cores, more than 200 well logs, and 140 standard petrographic thin sections. Most wells are located in the Arcola, Buffalo Head, and Rosebank Fields, as well as in other smaller fields. In the study area, six main lithofacies have been identified: crinoidal mudstone/wackestone or dolo-mudstone/wackestone (facies C), echinoderm packstone/grainstone (facies E), oolitic packstone/grainstone (facies O), peloidal packstone/grainstone (facies P), dolomitic sandstone (facies SS), and an anhydrite-dolomite caprock (facies CR). Lithofacies C, E, O, P, and SS are characterized by typical sedimentary features, whereas facies CR is a diagenetic facies that cross-cuts other facies and is not depositional in origin. The main characteristics of each facies and their inferred depositional environments are described below.

a) Facies C: Crinoidal Mudstone/Wackestone (or dolo-mudstone/wackestone)

Facies C contains abundant crinoid ossicles up to 6 mm in diameter and brachiopod shells, varies in matrix dolomite content, and ranges from pale grey to yellowish or brownish grey (Figure 3). In some areas, echinoderm plates make up the bulk of this lithofacies. Other allochems are much less common and include bryozoans, solitary rugose corals, branching corals (*Syringopora*), ostracods, and kamaenid algae. Peloids and ooids are rare. Scattered quartz grains may occur locally (average size 70 to 100 µm). Facies C commonly has good interparticle and intercrystalline porosity (10 to 15%) and is typically oil stained. Bitumen is common and may occupy up to 30% of pore space. Stylolites up to 5 cm in amplitude occur within sediment packages and at package boundaries and are parallel to bedding. Blue-grey to white anhydrite nodules are common (average size <1 cm, up to 3 cm), and dark brown metasomatic anhydrite occurs as nodules, patches, and veins. More than 90% of crinoids and echinoid plates are replaced by anhydrite, most of which is of the equant and bladed type. Some ossicles are replaced by metasomatic anhydrite. The matrix of the crinoidal mudstone/wackestone facies is typically composed of anhedral, very finely crystalline dolomite rhombs.

The crinoidal facies generally consists of fining-upward packages of wacke- to mudstone, or packstone to wackestone in places. It is interlayered with thin crinoidal packstone or grainstone beds that range in thickness from several tens of centimetres to 1.30 m. The crinoidal grainstone is typically brittle, sometimes chalky, and exhibits

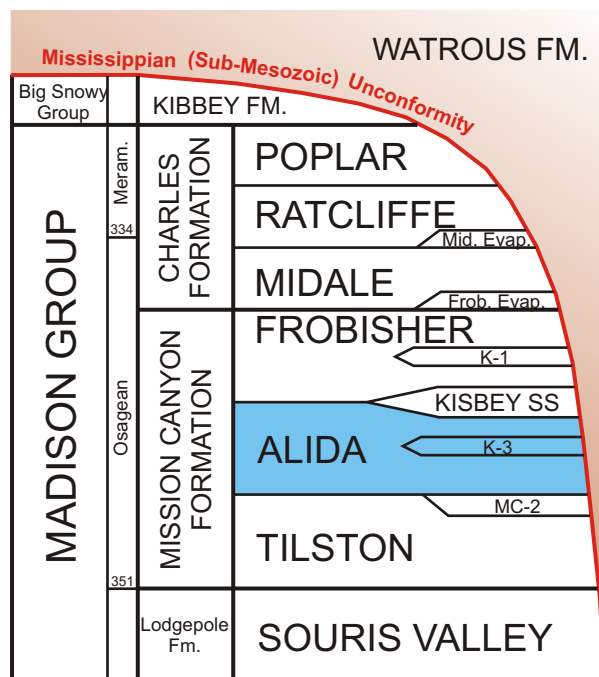


Figure 2 - Stratigraphic column showing Mississippian units along subcrop in southeastern Saskatchewan. Units within each formation are referred to as 'Beds'. The regional Mississippian (sub-Mesozoic) unconformity separates the units from the overlying Jura-Triassic Lower Watrous Member of the Watrous Formation. Also shown are selected stages and their approximate age boundaries (in Ma). "Meram." = Meramecian. Modified from Harris et al. (1966), Fuzesy (1966), and Kent (1984a).

grey brown to ochre brown. Numerous large crinoid and echinoid calcite plates (>0.5 mm, up to 3 mm in size) lend the rock a characteristic 'glassy' appearance. Other less abundant particles include brachiopod shell fragments, echinoid spines, bryozoans, kamaenid algae, ostracods, peloids, and ooids. Rugose corals, foraminifera, and gastropods are extremely rare. Quartz grains (average size 150 µm) may also occur, especially where overlain by sandstone (facies SS). The matrix is volumetrically insignificant and predominantly consists of anhedral, very finely crystalline dolomite rhombs. Interparticle porosity is good to very good (10 to 25%). Stylolites and chert nodules are rare. In contrast to the other facies, anhydrite nodules or anhydrite-plugged pores are very scarce in the crinoidal packstone/grainstone facies. Allochems also remain virtually unaffected by anhydritization. The facies tends to form fining-upward packages and is interlayered with beds of Lithofacies C (crinoidal mudstone/wackestone) as thin, sharp-based bands.

The high abundance of echinoderm debris and broken bioclasts in fining-upward sediment packages, and the lack of a muddy matrix, point to a high-energy, wave-agitated crinoidal bank environment. The banks likely developed around the shelf edge in shallow water at or above fair-weather wave base. During heightened wave

very good interparticle porosity (15 to 25%). It may contain numerous large rugose corals (1 to 4 cm). Shells and ossicles are commonly fragmented and abraded. Thin horizons of hard dolomitic wackestone/packstone and dolo-wackestone/packstone are also found within the crinoidal facies.

The crinoidal mudstone/wackestone facies is thought to be representative of low- to moderate-energy foreslope sediments deposited around the shelf edge of a rimmed carbonate shelf, and low-energy sediments deposited on the inner shelf, protected by crinoidal and oolitic banks. The interbedded layers of massive crinoidal packstone/grainstone are interpreted as storm beds (tempestites) derived from crinoidal banks (Facies E) in the vicinity.

b) Facies E: Echinoderm Packstone/Grainstone

Facies E differs from Facies C in that it consists primarily of massive packstone and grainstone in which crinoid ossicles and echinoid plates make up more than 80% of particles (Figure 4). It is present mainly in the central part of the study area (Arcola and Buffalo Head pools).

Echinoderm limestone beds remain largely undolomitized (except parts of the matrix) and are pale



Figure 3 - Core photograph of crinoidal wackestone. This facies is typified by scattered crinoid ossicles and brachiopod shell fragments. In this sample, most bioclasts have been replaced by white anhydrite. Crinoidal wackestone is widespread in the study area. Scale in centimetres. Well 8-1-6-33W1 (1121.70 m).



Figure 4 - Core photograph of fossiliferous echinoderm grainstone. Abundant crinoid ossicles and echinoid plates make up the bulk of the rock. Note cross-bedding evident in lower part of photograph. Scale in centimetres. Well 10-12-8-4W2 (1202.60 m).

horizontal cross-bedding have been identified in several cores. In two sediment packages, *Glossifungites* trace fossils were identified at the base of each package. In some instances, oolitic packages are extensively bioturbated. Intraclasts are common. Parts of this facies may be dolomitized, but this is rare. It has good interparticle and intercrystalline porosity averaging 10 to 15%. Anhydrite nodules are present in some wells, especially where vugs are absent. The nodules are sometimes large, up to 25 cm across, and are also present as small regular and metasomatic nodules.

In the central (Arcola Pool) and southern part (Rosebank Pool), fenestral porosity is dominant in much of the oolitic limestone (1 to 2 mm average pore diameter, up to 10 mm). Fenestrae are of the irregular type and may be filled with anhydrite (10 to 40%, average 20%), and less commonly with black bitumen (Figure 5b). Fenestral limestone beds sometimes have small vertical and horizontal cracks, as well as stylolites (up to 3 cm amplitude), and may exhibit signs of oxidation by a pinkish grey colour. Thin laminated crusts are common in fenestral rocks (1 to 2 cm thick, up to 10 cm; Figure 5a). Thin (1 m) units of bioturbated oolitic packstone without fenestrae are also observed. Sediments in the lower part of the oolitic facies can contain white tripolitic chert.

The oolitic limestone is interpreted to represent high-energy oolitic shoal deposits that developed at and around the paleo-shelf edge.

d) Facies P: Peloidal Packstone/Grainstone

Peloidal limestone (Figure 6) has been observed mainly in the Arcola and Buffalo Head pools in the central part of the study area. Peloids are well sorted, spherical to sub-spherical, and generally less than 0.5 mm in size (average 200 to 300 µm). They consist of dark grey to black, structureless micrite or dolomicrite. Peloids may be coated by one or several lamellae and can thus resemble ooids. Peloidal packstone and grainstone are commonly intermixed with shell fragments, crinoids, echinoid plates, ooids, kamaenid algae, and bryozoans. Quartz grains may locally occur. Peloid content varies and other grains such as crinoids and echinoids are often more abundant in parts of the facies. Packages with abnormally high algal content, reaching up to 50% of grains, have been recognized. The matrix is normally composed of dolomicrite, which can be very similar in appearance to peloids and make differentiation between matrix and particles difficult. Cementation and grain replacement by anhydrite are rare.

activity and storm events, crinoidal sand was transported to nearby foreslope (facies C) and inner shelf (facies P + C) environments as thin, sharp-based layers of packstone/grainstone.

c) Facies O: Oolitic Packstone/Grainstone

The oolitic packstone/grainstone facies is characterized by abundant ooids and ranges from pale grey to yellowish grey (Figures 5a and 5b). Peloids and pisoids may also be present (up to 60%), but are sometimes indistinguishable from micritized ooids. In thin section, oolitic packstone/grainstone typically consists of more than 80% or 90% ooids and in many cases are the only type of allochem present. Ooids commonly show a poorly developed internal structure due to extensive micritization and, as a result, may resemble “peloids” without lamellae and central nucleus. Thus, differentiation between ooids and peloids can be ambiguous. Ooids are typically composed of microcrystalline calcite. Rare light grey, euhedral, finely crystalline dolomite rhombs (20 to 50 µm) may line some lamellae within the coated grains. Oolitic grainstone is relatively matrix poor; the proportion of matrix reaches only up to around 5%, comprising light grey, very finely to finely crystalline dolomite rhombs that envelop the ooids. The finely crystalline dolomite rhombs (20 to 70 µm) are typically euhedral to subhedral. Facies O can also be fossil-rich containing crinoids, brachiopods, gastropods, bryozoans, and less commonly rugose corals. Bioclasts are typically fragmented and abraded.

Facies O generally forms massive sediment packages that fine upward in the top portions. Trough and

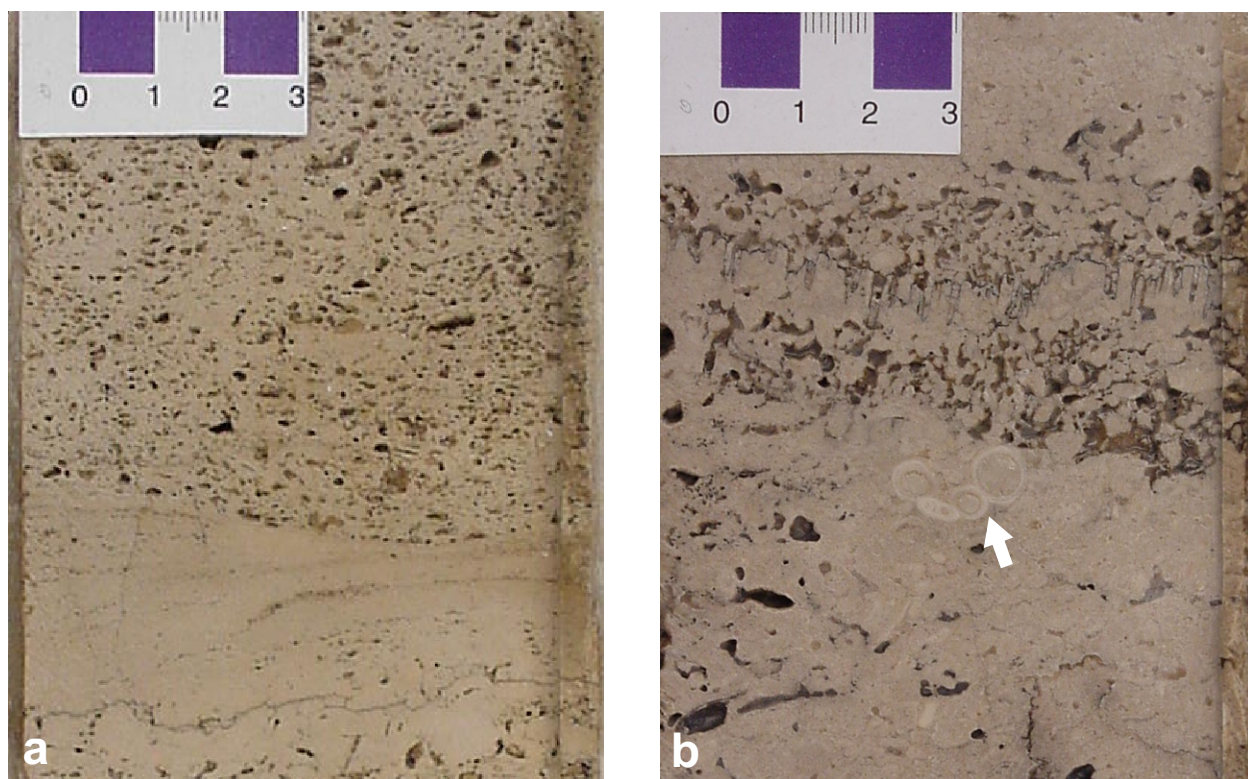


Figure 5 - Core photographs of oolitic limestone facies, both from well 6-33-4-32W1. Scale in centimetres. a) Oolitic grainstone with well developed fenestral porosity; only about 10% of pores are filled with anhydrite; lower part of photograph shows ca. 3 cm thick laminated crust; 1106.80 m. b) Partially compacted oolitic grainstone; rare, interpenetrating pisoids are also present (arrow); most of the pore space has been destroyed by compaction and infilling by anhydrite (light grey and grey-brown) and bitumen (black); 1117.00 m.

Sediment packages typically fine upward. A “chalky” appearance and good to very good interparticle (10 to 25%) and minor moldic porosities are also characteristic. Peloidal limestone beds are generally undolomitized, except for thin beds that contain higher proportions of mud that are slightly to moderately dolomitic. Anhydrite nodules are rare. The peloidal limestone may grade upward into crinoidal packstone/grainstone with mixed peloidal-crinoidal lithologies at the transition.

Peloids are indicative of low-energy, protected, shallow-water settings. The depositional environment of this facies is interpreted as subtidal inner shelf. Periodic influx of echinoderms, shell fragments, and other particles by wave and storm action resulted in mixed rock types.

e) Facies SS: Dolomitic Sandstone

Throughout the study area, sandstone packages with a dolomite-mud matrix are locally interbedded with crinoidal limestone (facies C) and oolitic packstone/grainstone (facies O). The sandstone facies closely resembles the Kisbey Sandstone overlying the Alida Beds. Facies SS locally corresponds to the quartz sand-rich K-3 interval of Legault (1999), but thin, discontinuous sandy horizons also occur above and below the K-3 within the Alida Beds.

The sandstone is yellowish grey, bluish grey, or greenish grey (Figure 7), and is characterized by a paucity of fossil material, except for sporadic shell fragments and ooids generally found in its lowermost portion. The rocks of this lithofacies are composed of fine sand (150 to 200 μm) and vary from sandstone (dolomite or calcite content less than 10%), to sandy limestone or dolostone (>50% carbonate content). Sand particles are well sorted and subrounded, although some grains may be subangular to angular in shape. The unit is relatively homogeneous with a lack of sedimentary structures, except for occasional faint horizontal bedding. Stylolites (<0.5 cm amplitude) have been observed. The unit contains rare dark glassy chert. Anhydritization has not affected the sandstone as much as in other facies. Small anhydrite nodules (<1.0 cm) and anhydrite-filled pores are rare, but may be locally present in the top portion of the unit. In general, anhydrite does not volumetrically exceed 12% of the rock. Most anhydrite is represented by small equant crystals (<100 μm) filling interparticle pores and replacing parts of the matrix.

Interpretation of the depositional origin of the sandstone units is problematic. Lack of cross-bedding or a basal lag deposit argues against the possibility of tidal channels to explain the provenance of these fine sands. Sorting, grain

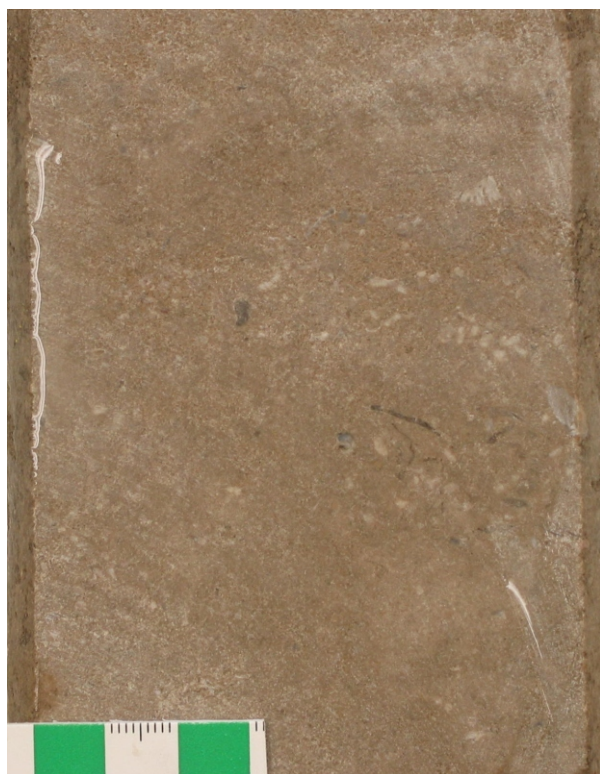


Figure 6 - Core photograph of peloidal limestone facies. This fossiliferous peloidal packstone contains abundant crinoid ossicles and echinoid plates as well as shell fragments and kamaenid algae. Scale in centimetres. Well 12-18-8-3W2 (1193.00 m).



Figure 7 - Core photograph of dolomitic sandstone facies. This sample of bluish grey sandstone is from a 4 m thick sandy interval that is stratigraphically equivalent to the K-3. The interval is sandwiched between oolitic limestone units of the Alida Beds. Scale in centimetres. Well 6-12-4-33W1 (1188.60 m).

size and rounding may point to an eolian origin of the quartz grains from a nearby continental source. It is suggested that Facies SS, and probably also the Kisbey Sandstone itself, represent submarine accumulations of wind-transported sand, possibly during major sand storms, from dunes in the vicinity. The wind-blown sand and dust particles settled on the shallow seafloor where they mixed with carbonate mud and grains. Similar, modern-day processes are known from the northwest-African continental shelf, which experiences a significant influx of sand and dust derived from the Sahara during periodic storm events (Carlson and Prospero, 1972; Windom, 1975).

f) Facies CR: Anhydrite-Dolomite Caprock

An anhydritic dolostone is present underneath the Lower Watrous Red Beds where the Alida Beds are truncated by the sub-Mesozoic unconformity. This “caprock” constitutes the dolomitized and anhydritized equivalent of one of the above facies with the majority of pores occluded by anhydrite. Caprock thickness ranges from around 1 to 3 m in the northern part of the study area, and from 0 to 10 m in the central and southern parts. The contact with the overlying Lower Watrous is usually sharp. Angular rip-up clasts of caprock can be seen in the bottom 10 to 50 cm of the Red Beds (Figure 8). These clasts are commonly intersected by blue-grey anhydrite veins; the latter are absent in the surrounding sandstone and siltstone. Large vugs and cavities filled with sandstone/siltstone and collapse breccia composed of angular caprock dolostone have been observed at various locations along the unconformity.

The pale blue-grey to brown-grey anhydrite-dolomite caprock is dense with no significant pore space. Fossil content and sedimentary structures vary depending on the host lithology that was diagenetically altered. Due to the low porosity and permeability of this rock, oil staining is virtually absent. However, light and medium oil staining has been observed in parts of the caprock near the subcrop edge, particularly in the Manor Pool (Tp 7, Rge 2W2). Most pores are filled with blue-grey to light blue anhydrite. Where fenestral porosity was originally present in the host rock, the vugs are now completely occluded by anhydrite. Anhydrite nodules are widespread and may exceed 7 cm in diameter. The caprock normally contains numerous horizontal and few vertical blue-grey anhydrite veins that are up to 5 cm thick. Bioclasts have been replaced by equant, bladed, and randomly oriented bladed anhydrite, the former type being dominant. Small equant, bladed, and, rarely, fibrous anhydrite replaces parts of the matrix. Horizontal and vertical microcracks filled with anhydrite are common. The matrix of the caprock is a dark brown, anhedral to



Figure 8 - Core photograph of basal Lower Watrous sandstone-siltstone showing angular rip-up clasts from the anhydrite-dolomite caprock. Some of the clasts, located about 60 cm above the Alida-Lower Watrous unconformable contact, contain grey anhydrite veins (arrow) and nodules. Greyish blue anhydrite nodules are present in the surrounding sandstone/siltstone and probably represent a different anhydrite generation. Scale in centimetres. Well 4-35-8-3W2 (1206.80 m).

subhedral dolomicrite, containing blurred outlines of rare euhedral to subhedral, slightly larger (30 to 50 μm) dolomite rhombs.

The caprock is not a depositional feature, but rather a diagenetic facies that was emplaced after the sedimentation of all other lithofacies had been completed. Angular caprock rip-up clasts above the unconformity are proof that the alteration zone formed *before* deposition of the Lower Watrous clastics was initiated. This contradicts earlier theories by Kendall (1975) who suggested that the caprock was created after or during Watrous deposition. Calcium sulphate-charged fluids may have originated from a late or post-Mississippian, but pre-Watrous, coastal sabkha environment.

4. Facies Distribution

The distribution of the facies described in the previous section is shown in a local structural cross section (Figure 9). A number of problems are associated with correlation of individual facies in the Alida Beds. These include: 1) lack of core, especially in the lower portion of the Alida at the contact with the Tilston Beds, as well as a virtual absence of Alida core in the deeper parts of the basin away from the subcrop zone; 2) lack of geophysical well log data in the lower portions of the unit; 3) difficulties in establishing and characterizing type log signatures of most facies due to diversity of controlling factors such as the presence or absence of anhydrite filled vugs, chert nodules, etc.; and 3) rapid lateral facies changes that cannot always be resolved even if well spacing is tight. The cross section presented here is based mainly on information from core.

A local development of the oolitic facies close to the subcrop edge can be seen in the cross section. Coarse-grained crinoidal/echinoderm deposits also occur locally, interfingering with the crinoidal mudstone/wackestone facies. The position of the echinoderm mound in the southwestern part of the cross section (lighter green shading) has been inferred based on the presence of the oolitic and crinoidal facies farther to the northeast, but its local extent is unknown due to lack of core and well log information. The dolomitic sandstone facies occurs as a thin, discontinuous bed that seems to be absent at the site of a local crinoidal bank deposit at well 9-3-8-4W2. Peloidal limestone has been found below the Kisbey Sandstone, separated by a thin layer of crinoidal mudstone/wackestone. The caprock is present across all facies and beds underneath the sub-Mesozoic unconformity, but varies in thickness from northeast to southwest. Generally, the caprock thickens towards the northeast. This is in part due to the various sandy horizons that immediately underlie the Lower Watrous. Intervals that are composed of siliciclastic material are less susceptible to the alteration process that has formed the caprock in carbonates elsewhere. The caprock is thus poorly developed in both the dolomitic sandstone facies and the Kisbey Sandstone, as well as in rocks of the lowermost Frobisher Beds, which appear to be composed of reworked Kisbey sands.

5. Conclusions

In southeastern Saskatchewan, rocks of the Mississippian Alida Beds can be grouped into six major lithofacies. These include oolitic packstone/grainstone, echinoderm packstone/grainstone, crinoidal mudstone/wackestone, peloidal packstone/grainstone, dolomitic sandstone, and the anhydrite-dolomite caprock. The latter immediately underlies the sub-Mesozoic unconformity as a thin diagenetic layer of variable thickness cross-cutting all other facies. Angular caprock rip-up clasts found in the basal sandstone/siltstones above the unconformity indicate that the caprock formed before Lower Watrous deposition. The caprock is abnormally thin or poorly developed where dominantly sandy lithologies subcrop at the unconformity. The sediments making up the facies of the Alida Beds have been deposited on a broad, shallow carbonate shelf. Oolitic and echinoderm facies represent carbonate build-ups along the shelf edge, whereas much of the crinoidal and thickened skeletal mudstone/wackestone was laid down in

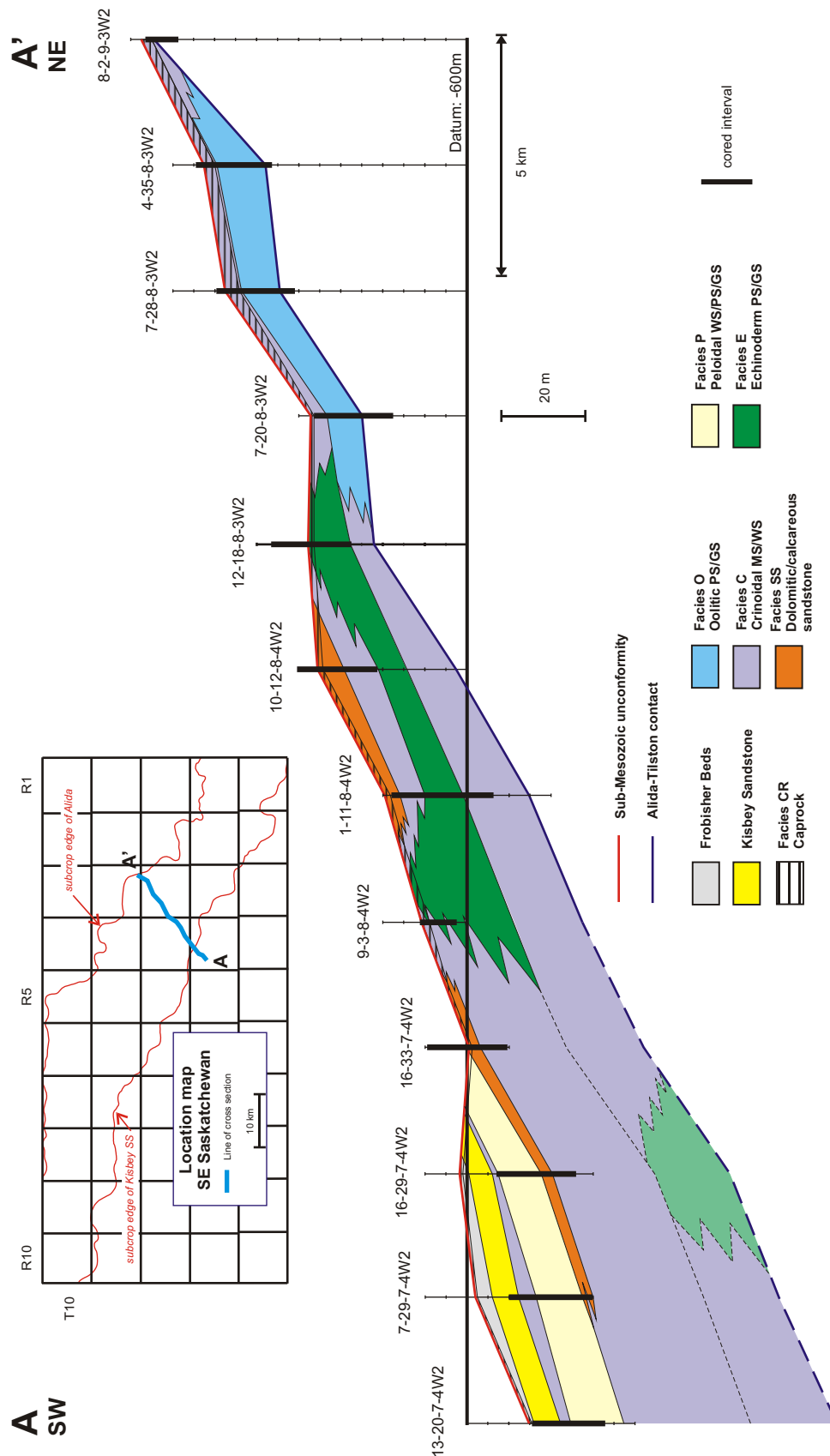


Figure 9 - Southwest-northeast structural cross section of the Alida Beds across the Arcola and Buffalo Head pools. Line of section is located in the central part of the study area (see inset map). In the cross section, the Alida Beds are overlain by the Jura-Triassic Lower Watrous Formation and underlain by the Mississippian Tilston Beds. Total horizontal distance between wells is about 20 km. The lighter shaded occurrence of Facies E in the southwest portion of the cross-section is an inferred location of an echinoderm mound as discussed in the text.

lower energy, restricted subtidal settings. The sandy layers that are sandwiched between the carbonate beds are interpreted to consist of a significant proportion of eolian-derived quartz.

Detailed knowledge of the distribution of the facies is important for a thorough understanding of reservoir heterogeneity in the Alida Beds. Further research needs to be conducted on facies distribution, with particular focus on caprock thickness variations and their underlying controls.

6. Acknowledgments

We thank the Saskatchewan Industry and Resources Subsurface Geological Laboratory for providing free access to their examination facilities and the friendly support of their staff. Special thanks are extended to Dr. D.M. Kent and John Lake for their stimulating and thought-provoking discussions. Our thanks are also due to Dr. Guoxiang Chi for taking time off his schedule to review the paper. The project is funded by PTRC Weyburn Phase-1 Consortium and by a NSRC Discovery Grant (155012) to HQ.

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