Synsedimentary Deformation in Laminated Dolostones and Evaporites of the Herald Formation (Red River): Signature of Late Ordovician Tectonic Activity in Southern Saskatchewan

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Abstract

Red River strata in the Williston Basin consist of a succession of large-scale carbonate-evaporite cycles whereby open-marine carbonates pass in turn into laminated dolomudstone and thence into subaqueous anhydrite. In southeastern Saskatchewan, the Yeoman Formation and the Lake Alma and Coronach members of the Herald Formation comprise two such cycles. Although possessing an overall 'layer-cake' stratigraphy, Lake Alma and Coronach strata in the study area (Townships 1 to17 and Ranges 1 to 24W2) exhibit marked variation in thickness, probably due to differential movement along lineaments spatially and genetically linked to the orthogonal northeast–southwest and northwest–southeast basement structural fabric. Consequently, if present, rock layers exhibiting synsedimentary deformation features caused by earthquakes – seismites – would be possible evidence for fault movement along these lineaments during sediment deposition, and/or shallow burial and early diagenesis.

Open-marine wackestones and packstones lack seismites probably because of reworking by wave action and the bioturbating infauna. By contrast, seismites are present in laminites and anhydrites which were deposited under low-energy conditions in which marine benthic animals were excluded because of elevated temperature and salinity. Brittle and quasi-brittle failures are indicated by microfaults, pseudo-intraclasts, and vein arrays. Soft-sediment deformation occurs in the form of convolute bedding, loop bedding, and dykelets. This variety of features is the result of the complex stresses that are generated during earthquake-induced ground motion, causing displacement, shearing, liquefaction, and fluid escape. These stresses are imposed on sediments of varying geotechnical properties while they are on the seafloor or shallowly buried.

Preliminary correlation of seismites observed in cores shows that the basal part of the Coronach Member records at least one widespread event, while most seismites in other intervals are geographically more limited. These observations indicate that the area was affected by earthquakes of a range of magnitudes and localized faulting of varying intensity.

Keywords: *Williston Basin, Upper Ordovician, Red River, dolostone, anhydrite, synsedimentary deformation, seismite, basement faulting, differential subsidence.*

1. Introduction

Small-scale deformation features in subaqueous carbonate, siliciclastic, and evaporitic facies are often attributed to gravitational slumping or dissolution-collapse. However, it is gaining acceptance amongst sedimentologists that many of these features were, instead, likely caused by syndepositional earthquakes and characterize deformed sediment layers known as 'seismites'. The range of such features reflects both the intensity of the ground motion and the rheology of the sediment. Water-saturated sediments exhibit a spectrum of properties from fluid to plastic to stiff, which is dependent on a variety of factors including: grain size, shape, and orientation; water content; organic-matter content; clay mineralogy; degree of cementation; and burial depth.

The most commonly recognized features of ancient seismites are convolute bedding and sandstone dykes, which have exact counterparts in unlithified sediments that have been subjected to earthquake-induced shaking and liquefaction (*e.g.*, Montenat *et al.*, 2007). However, muddy vein arrays (Brothers *et al.*, 1996) and shrinkage cracks containing injected sediment (Pratt, 1998a, 1998b) have also been ascribed to cyclic high pore pressures during shaking. Back-and-forth sliding along bedding planes can cause small-scale boudinage called 'loop bedding' (Calvo

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et al., 1998) as well as intrastratal disruption and pseudo-intraclast formation (Pratt, 1998a, 2001b). Seismic deformation of cemented carbonate sediment can lead to brittle failure, shown by microfaults and breccias (Pratt, 1994, 2002; Kahle, 2002). Because sediment rheology evolves during shallow burial and diagenesis, repeated earthquake-induced stresses may be recorded by a series of superimposed deformation features indicating progressive lithification (Pratt, 2001a).

The stratigraphic and geographic distribution of seismites also serves as evidence for the timing and magnitude of tectonic activity of nearby faults (*e.g.*, Sims, 1973; Onasch and Kahle, 2002; Migowski *et al.*, 2004; Weidlich and Bernecker, 2004; Paz and Rossetti, 2005). The likelihood that a seismic event gets recorded by a deformation feature is predicated not only on the magnitude of the earthquake and nature of the sediment, but also on taphonomy – the deformed sediment must escape being reworked. For this last reason, shoals and heavily bioturbated shallow-marine settings are not conducive to the preservation of seismites.

Subaqueous, low-energy, laminated dolostones and evaporites in Red River strata in the subsurface of southeastern Saskatchewan provide an opportunity to explore the range of possible seismic deformation features first observed in these rocks by Pratt and Haidl (2008). This area is underlain by a basement tectonic fabric composed in part of a series of lineaments that have an orthogonal alignment oriented northwest–southeast and northeast–southwest (Potter and St. Onge, 1991; Kreis and Kent, 2000). This structural configuration is a dominant part of the tectonic framework of the Williston Basin (Lefever *et al.*, 1987; Gerhard *et al.*, 1991). Differential thickness of units in the Red River indicates that some of these lineaments may have been tectonically active during sediment deposition. Moreover, later fault movements may have been the cause of fracture porosity and some of the faults possibly acted as fluid conduits. An understanding of seismite distribution, the purpose of this study, will help elucidate the behaviour of the basement during deposition of Red River sediments. Preliminary results are presented here.

2. Red River Strata

The Late Ordovician Red River succession forms part of the Tippecanoe sequence and displays a number of large-scale shallowing-upward, or 'brining-upward', cycles of limestone, dolostone, and anhydrite (Kendall, 1976; Longman and Haidl, 1996). The lowest unit is the Yeoman Formation, which is equivalent to the Selkirk, Doghead and Cathead formations in Manitoba (Figure 1). It comprises abundantly fossiliferous and bioturbated, variably dolomitized wackestone, packstone and, locally, grainstone. The overlying Herald Formation has a maximum thickness of approximately 38 m (Kendall, 1976) and is subdivided into the Lake Alma and Coronach members and the Redvers unit. The lower Lake Alma Member consists of laminated dolomudstone with variably dolomitized peloidal grainstone (Pratt and Haidl, 2008). The upper portion of the Lake Alma Member, informally called the Lake Alma anhydrite, is composed of two laminated and nodular anhydrite intervals separated by laminated dolomudstone. The Coronach member consists of four units. The lowest is a thin laminated dolomudstone which is overlain in turn by variably dolomitized wackestone to packstone, laminated dolomudstone, and laminated to nodular anhydrite (Urban and Qing, 2007). The Redvers unit, which is part of the last cycle in the Herald

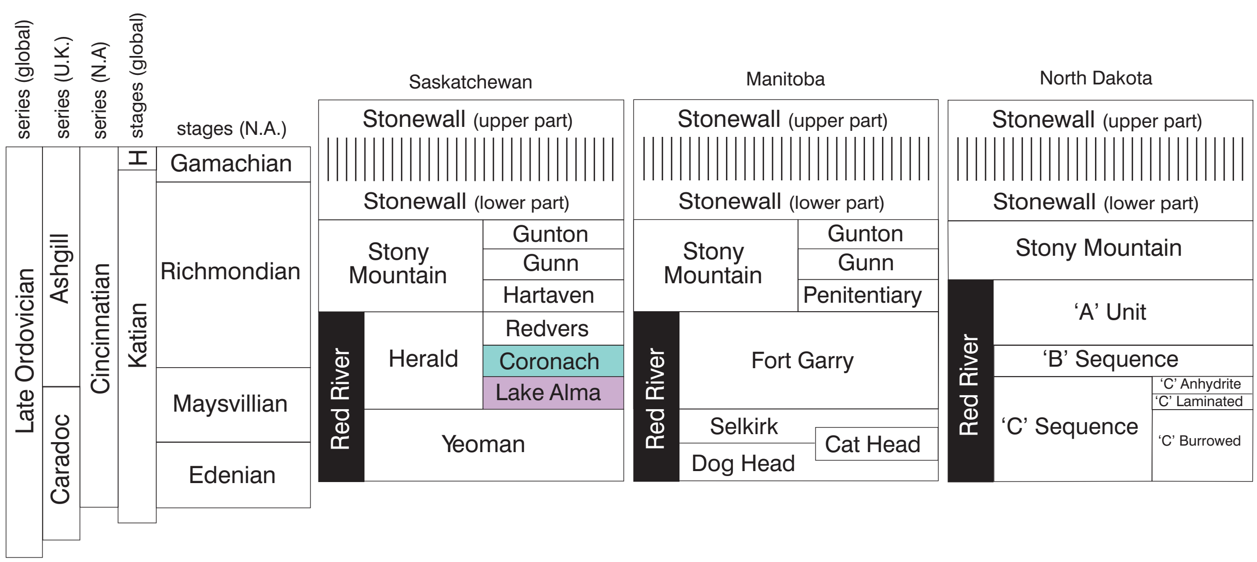

Figure 1 - Stratigraphic nomenclature and chronostratigraphy of Upper Ordovician Red River, Stony Mountain, and Stonewall strata in Saskatchewan and adjacent Manitoba and North Dakota. The Lake Alma and Coronach members of the Herald Formation are the focus of this study. In global stages, H = Hirnantian; see Bergström* et al.*, 2009. Vertically ruled pattern represents the hiatus between the Ordovician and Silurian portions of the Stonewall Formation (modified from Pratt and Haidl, 2008).

Formation, is dominated by variably dolomitized mudstone (Kendall, 1976); fossiliferous wackestone has been identified in at least one well (Kreis and Kent, 2000). In North Dakota, this last cycle is composed of a basal unit of burrowed wackestone and mudstone, a middle laminated dolostone unit, and a capping anhydrite (Longman and Haidl, 1996).

The contact between the Yeoman and the overlying Herald Formation is transitional and therefore difficult to define with consistency both on geophysical logs and in core (Kendall, 1976; Pratt *et al*., 1996; Pratt and Haidl, 2008). For the purpose of this paper, the Yeoman/Herald contact is placed at the boundary between darker coloured, partially dolomitized wackestones that are slightly to moderately burrowed and lighter coloured, non-burrowed laminated dolomudstones.

This study focuses on the Lake Alma and Coronach members in the study area which encompasses Townships 1 to 17 and Ranges 1 to 24W2 (Figure 2). Cores from 63 wells have been examined. Many of these wells lie on or in proximity to four basement features (Nesson Anticline, Brockton-Froid Lineament Zone, Cedoux-Midale Trend, and Montmartre-Weir Hill Trend), and several other wells are within or close to the area in which the Prairie Evaporite has been totally dissolved (Figure 2; Nimegeers and Haidl, 2004). Further study is under way to evaluate links between basement tectonics and salt dissolution, as well as to identify other basement structures in the study area.

These carbonate-evaporite cycles were deposited in an intracratonic basin in which, at certain times, anhydrite accumulated subaqueously in the central area (Kendall, 1976; Longman and Haidl, 1996). Fossiliferous bioturbated

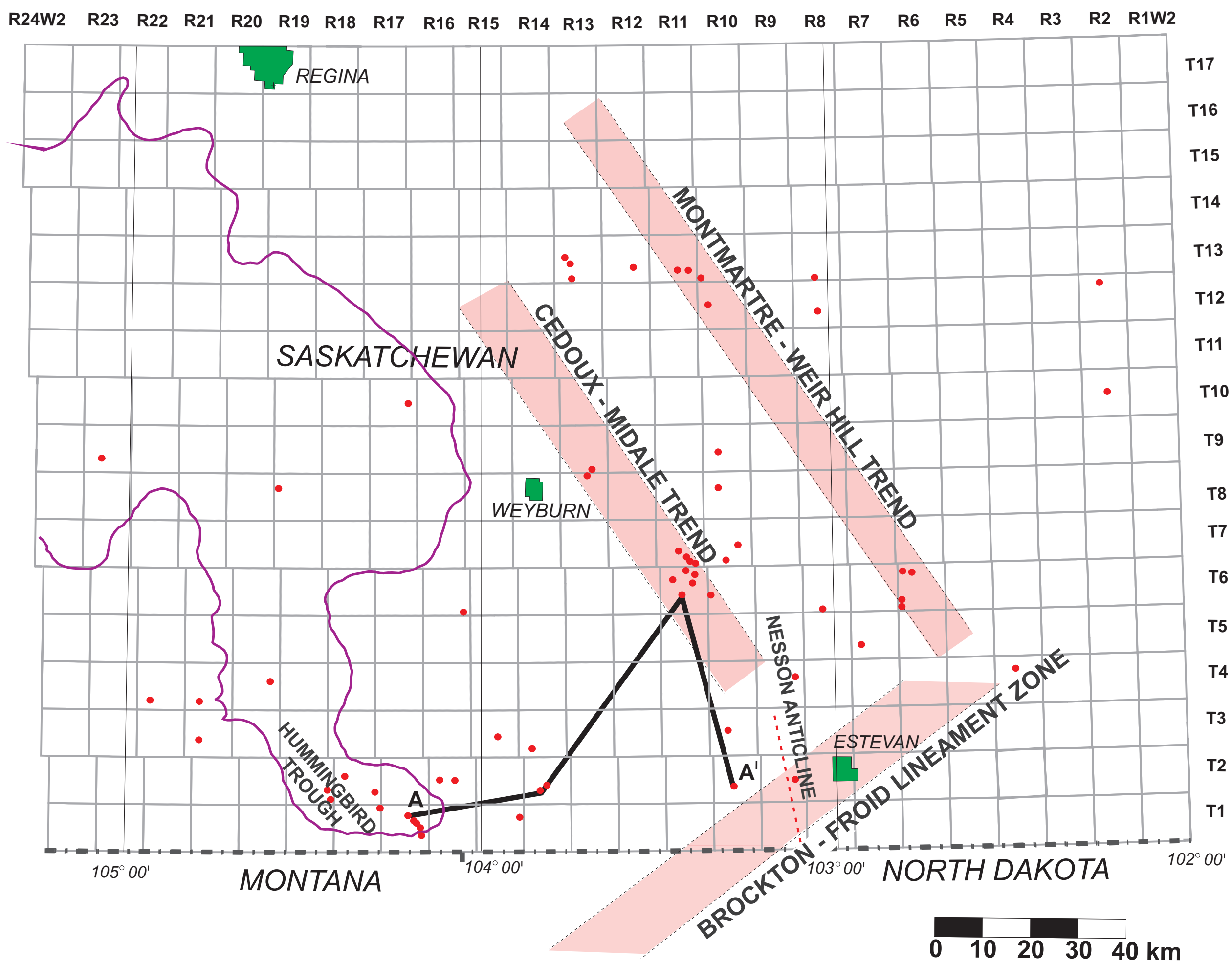

***Figure 2** - Map of the study area extending from Townships 1 to 17, Ranges 1 to 24W2 showing the locations of examined wells (red dots) and the cross-section A–A' (Figure 8). The three pink-coloured bands are trends of basement structural lineaments thought to have been active during deposition of the Herald Formation. Also shown is the location of the northern extension of the Nesson Anticline. The purple line delineates the area where total dissolution of the Middle Devonian Prairie Evaporite salts has occurred; the Hummingbird Trough occupies the southern part of this area (modified from Nimegeers and Haidl, 2004).*

carbonate units record deposition under shallow, open-marine conditions. The laminated carbonate mudstone intervals were deposited in a relatively low-energy subtidal setting (Pratt and Haidl, 2008). The rarity of fauna in this facies has been ascribed to elevated salinity, but increased seawater temperature may have been an important cause.

The Lake Alma anhydrite is present over the entire study area and ranges from <2.5 to 7.5 m in thickness with pronounced variation over short distances (Figure 3; Nimegeers and Haidl, 2004). The cores lack evidence of solution-collapse that would suggest partial removal of the anhydrite. The thickness variation could, therefore, be due to differential subsidence possibly associated with movements along underlying faults.

By contrast, the Coronach anhydrite unit is less geographically widespread and is preserved primarily in the southwestern portion of the study area where general thickening from 0 to 5 m occurs toward the Canada–U.S.A. border (Figure 4; Nimegeers and Haidl, 2004). This thickening can be ascribed to greater subsidence in the centre of the Williston Basin. Lateral thickness variations along the margin of the anhydrite are present but are less pronounced than those shown by the Lake Alma anhydrite. They may also be due to differential subsidence possibly associated with movements along underlying faults.

3. Preliminary Results

Deformation structures have not been identified in the bioturbated wackestones and packstones of the Yeoman Formation and Coronach Member of the Herald Formation. This may be because of taphonomic barriers to preservation of such features or because basement faults were not active during deposition of these strata. On the other hand, seismites have been identified in several intervals in dolomudstone laminites and anhydrites of the Lake Alma and Coronach members. Brittle failure in dolomudstone is seen as vertical microfaults and intraclast-like breccias (Pratt and Haidl, 2008, Figure 8G). Quasi-brittle deformation resulted in *en echelon* arrays of straight to zigzag-shaped, clay-filled veins (Figure 5A; Pratt and Haidl, 2008, Figure 8F) and low-angle, thrust-like microfaults and disruption into pseudo-intraclasts (Figure 5B). Soft-sediment deformation in dolomudstones ranges from

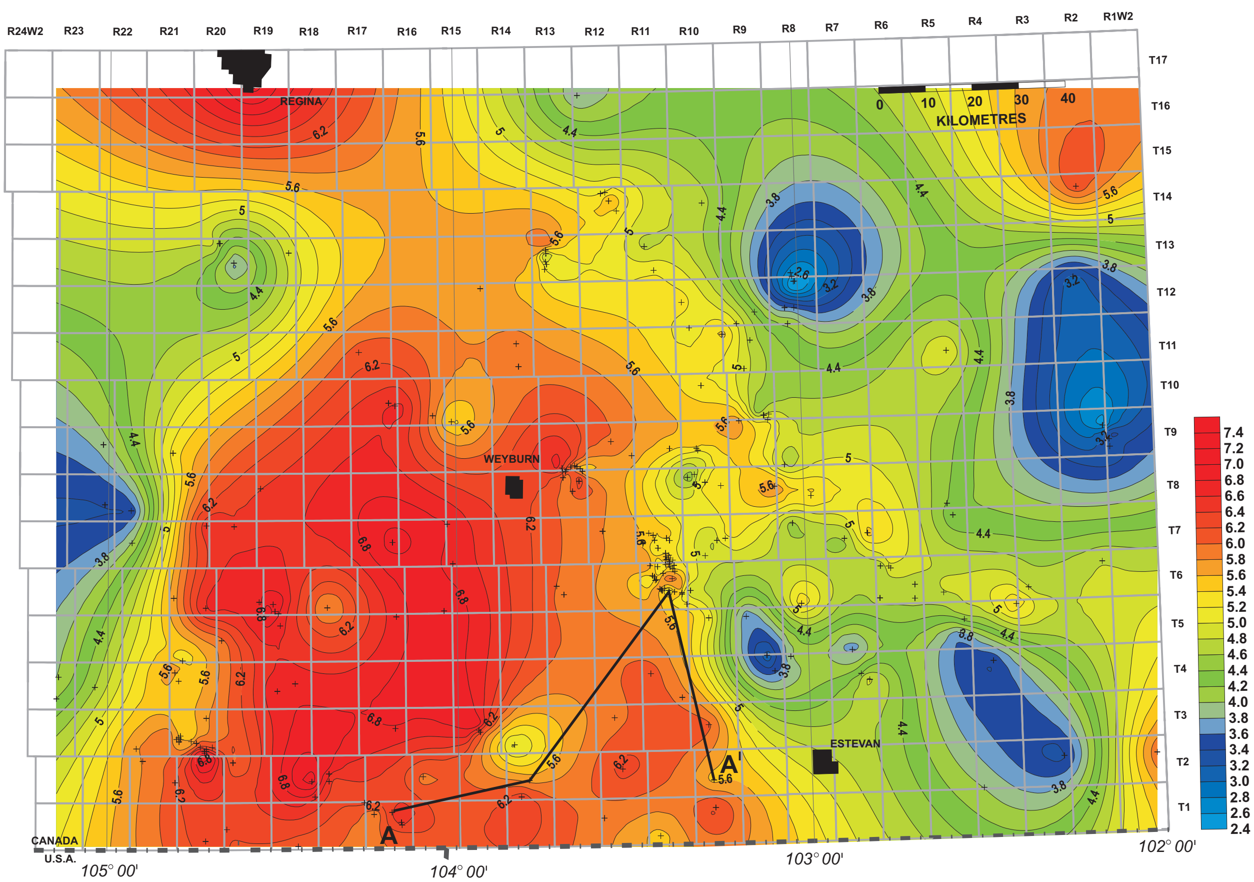

Figure 3 - Isopach map of the Lake Alma anhydrite in the Herald Formation; contour interval 0.2 m (modified from Nimegeers and Haidl, 2004). Also shown is the location of cross-section A–A' (Figure 8).

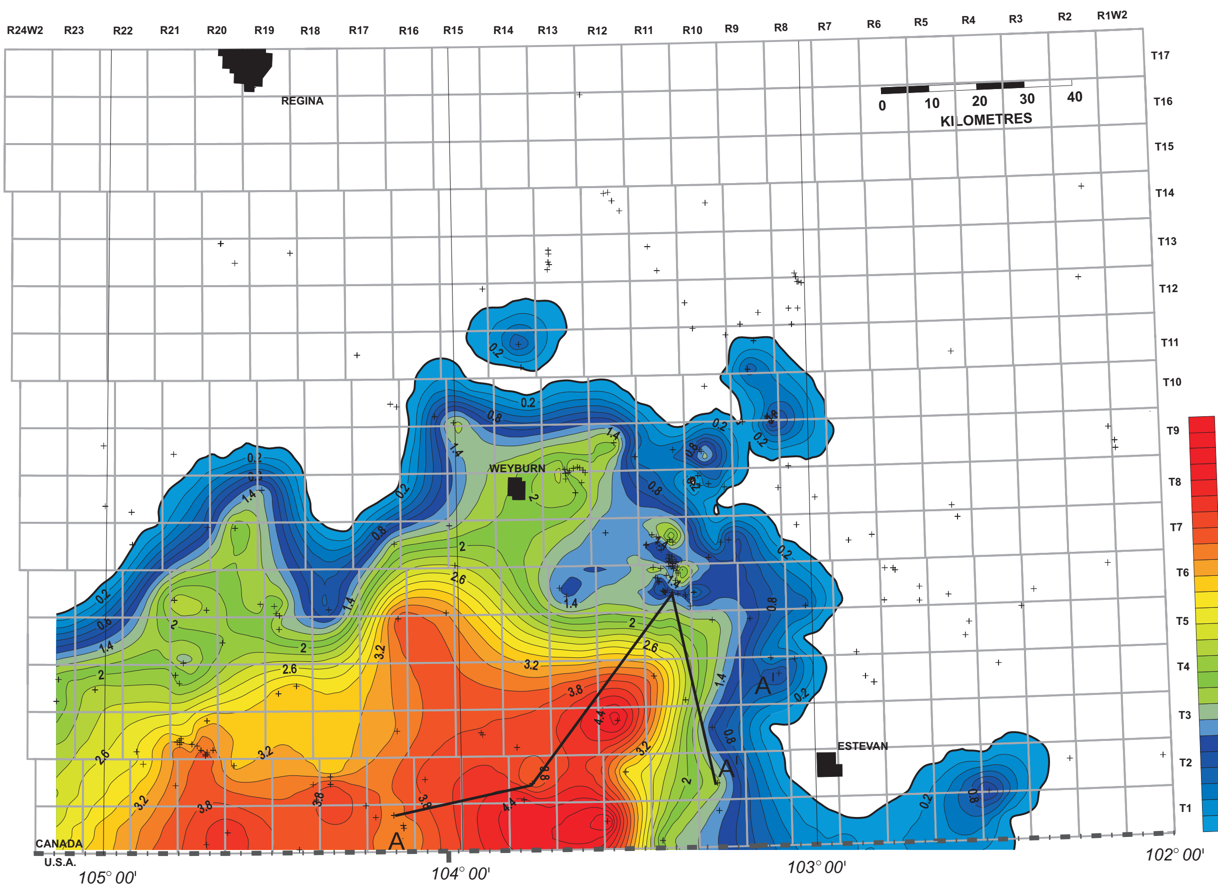

Figure 4 - Isopach map of the Coronach anhydrite in the Herald Formation; contour interval 0.2 m (modified from Nimegeers and Haidl, 2004). Also shown is the location of cross-section A–A' (Figure 8).

convolute bedding together with low-angle microfaults (Figure 6A; Pratt and Haidl, 2008, Figure 8D), to loop bedding (Figure 6B), mudstone-filled dykelets comparable to molar-tooth structure (Figure 6C), and 'microboudinage' (Figure 6D; Pratt and Haidl, 2008, Figure 8A). Convolute bedding and dykelets also occur in the anhydrites (Figure 7), although these features are difficult to detect because of the enterolithic aspect of much of the anhydrite.

Brittle and quasi-brittle features formed as a consequence of tensional and compressional stresses, the former causing type I fracturing (extensional), and the latter causing shearing and sliding which led to intrastratal disruption and vein arrays. By contrast, convolute bedding involved folding because the shallow-buried sediment was plastic. Where it is associated with low-angle microfaults, interbedding of sediments of varying rheology, *e.g.*, from soft to stiff such that some layers were more cohesive and resisted deformation while other layers and bedding planes were zones of weakness, is suggested. On the other hand, primary lamination in anhydrite did not exert a control on the style of folding, suggesting that there were no rheological differences over the deformed interval. Loop bedding was caused by shearing along bedding planes which 'balled up' softer mud laminae. Microboudinage was probably caused in a similar way, but was accompanied by the squeezing of sediment between the nodular domains. Dykelets were generated when seismic shaking liquefied the sediment and, as it lost shear strength, equant mud-sized particles were injected into dewatering-induced shrinkage cracks. During the latter stages of shaking, the dykelets were themselves plastically deformed, because the host sediment's rheology had evolved with fluid expulsion. This is a relatively rare feature but occurs in both dolomudstone and anhydrite.

The stratigraphic distribution and frequency of seismites varies across the study area (Figure 8). Some wells show only one or two deformed intervals, while others may contain up to a dozen. Seismites appear to be absent in only two wells. Most or all of these seismites are presumed to record individual earthquake events, because no layers showed clear evidence of having been deformed twice or that a single event deformed more than about 20 cm of sediment thickness. Multiple seismites in a single well suggest frequent activity of the source fault (or faults). Some seismites appear to be laterally correlatable, indicating that the epicentre was near enough to these wells or the earthquakes were of sufficient magnitude to have had a widespread effect. The dykelets at the base of the Coronach

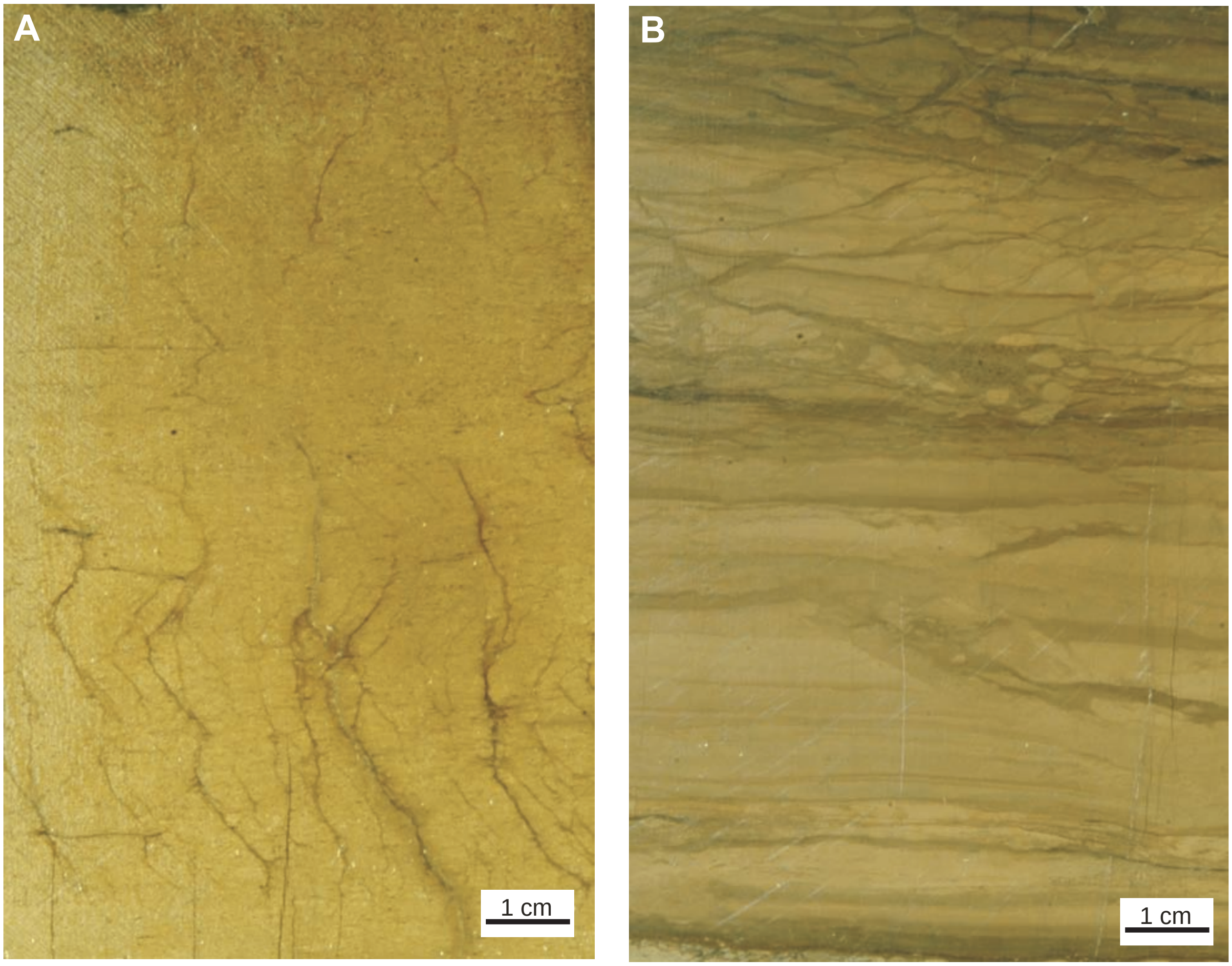

Figure 5 - Quasi-brittle deformation in laminated dolomudstone. Vertically oriented slabbed cores. A) Zigzagging,* en échelon *shear veins. Lower Lake Alma Member, 16-20-08-10W2, 2432 m. B) Obliquely oriented shear veins, thrust-like microfaults, loop bedding, and pseudo-intraclasts. Lower Coronach Member, 11-14-07-10W2, 2495 m.

Member (Figure 6C) are an example of a deformation feature that can be traced across the whole study area. Seismites in parts of the Herald Formation are clearly valid evidence for faulting events, and thereby have the potential to provide a window onto synsedimentary basement tectonism.

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5. References

Bergström, S.M., Chen, X., Gutiérrez-Marco, J.C., and Dronov, A. (2009): The new chronostratigraphic classification of the Ordovician system and its relations to major regional series and stages and to $\delta^{13}C$ chemostratigraphy; Lethaia, v42, p97-107.

Brothers, R.J., Kemp, A.E.S., and Maltman, A.J. (1996): Mechanical development of vein structures due to the passage of earthquake waves through poorly consolidated sediments; Tectonophys., v260, p227-244.

Calvo, J.P., Rodríguez-Pascua, M., Martín-Velázquez, S., Jiménez, S., and De Vicente, G. (1998): Microdeformation of lacustrine laminite sequences from Late Miocene formations of SE Spain: an interpretation of loop bedding; Sediment., v45, p279-292.

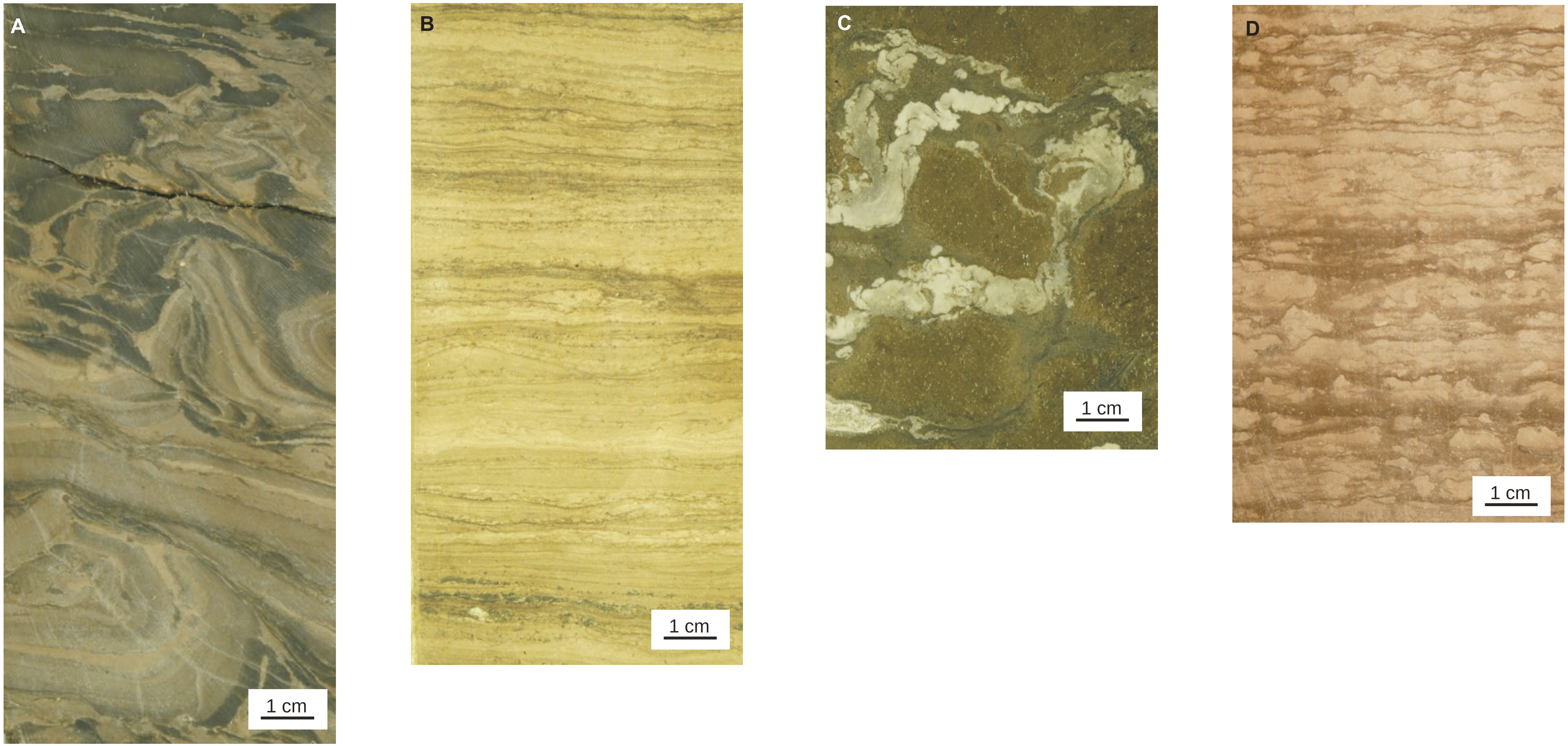

Figure 6 - Soft-sediment deformation in laminated dolomudstone. Vertically oriented slabbed cores. A) Convolute bedding consisting of laterally folded laminae (recumbent at bottom), thrust-like microfaults, mudstone-filled dykelets (at top) and buckled and broken laminae (in the centre). Lower Lake Alma Member, 06-04-06-8W2, 2625 m. B) Undeformed plane and wavy laminae with intercalated loop bedding (increasingly common towards the top). Lower Lake Alma Member, 06-18-06-10W2, 2635 m. C) Vertically folded and tilted, mudstone-filled dykelets (molar-tooth structure). Basal Coronach Member, 03-06-06-6W2, 2560 m. D) Disrupted and detached thick laminae, with boudin-like nodules separated by injected sediment; thin laminae show loop bedding. Basal Lake Alma Member, 15-28-12-2W2, 1935 m.

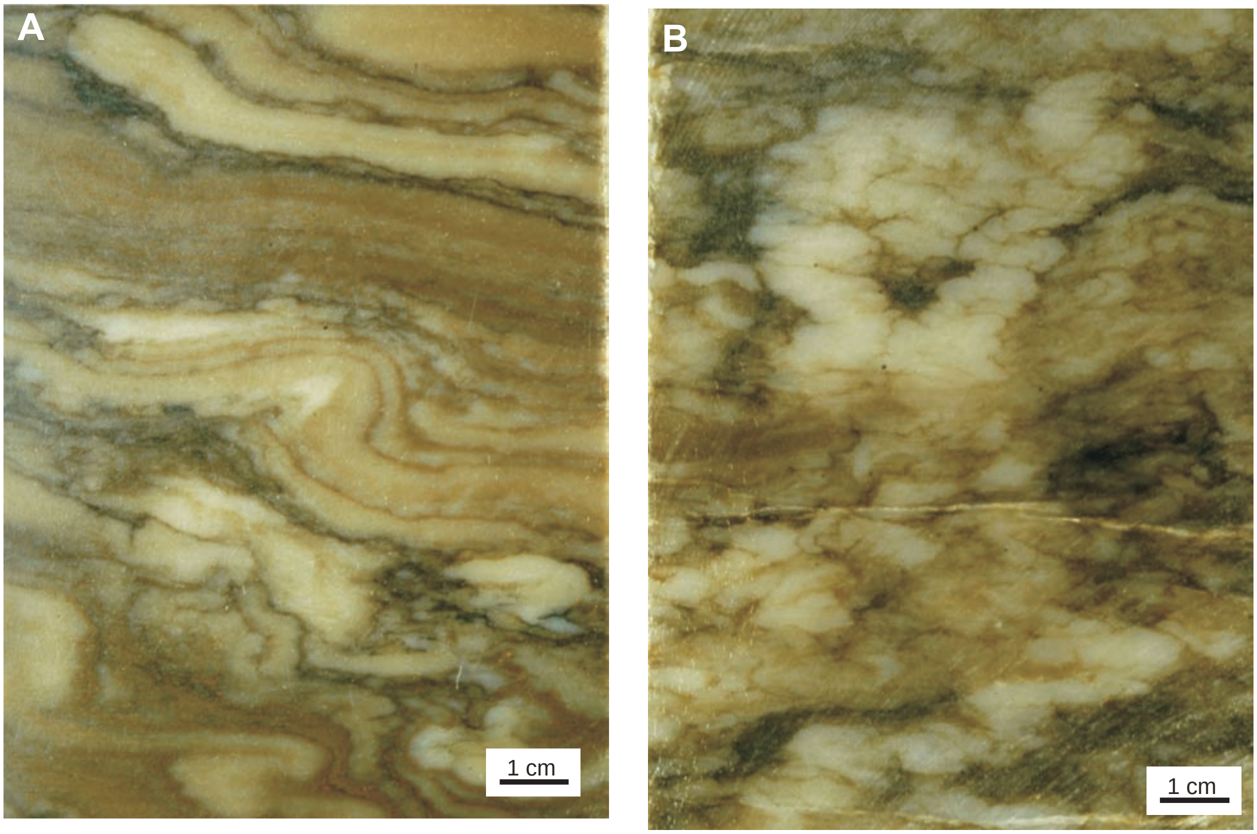

Figure 7 - Soft-sediment deformation in anhydrite. Upper Lake Alma Member. Vertically oriented slabbed cores. A) Laterally folded laminae, in places disrupted into irregular nodules and lenses. 15-09-02-14W2, 3036.4 m. B) Vertically folded dykelets. 15-04-07-10W2, 2541 m.

Gerhard, L.C., Anderson, S.B., and Fischer, D.W. (1991): Petroleum geology of the Williston Basin; *in* Leighton, M.W., Kolata, D.R., Oltz, D.F., and Eidel, J.J. (eds.), Interior Cratonic Basins, AAPG Memoir 51, p507-559.

Kahle, C.F. (2002): Seismogenic deformation structures in microbialites and mudstones, Silurian Lockport Dolomite, northwestern Ohio, U.S.A; J. Sediment. Resear., v72, no 1, p201-216.

Kendall, A.C. (1976): The Ordovician Carbonate Succession (Bighorn Group) of Southeastern Saskatchewan; Sask. Dept. Miner. Resour., Rep. 180, 186p.

Kreis, L.K. and Kent, D.M. (2000): Basement controls on Red River sedimentation and hydrocarbon production in southeast Saskatchewan; *in* Summary of Investigations 2000, Volume 1, Saskatchewan Geological Survey, Sask. Energy and Mines, Misc. Rep. 2000-4.1, p21-42.

Lefever, J.A., Lefever, R.D., and Anderson, S.D. (1987): Structural evolution of the central and southern portions of the Nesson anticline, North Dakota; *in* Carlson C.G. and Christopher, J.E. (eds.), Fifth Williston Basin Symposium, Saskatchewan Geological Society, Spec. Publ. No. 9, p147-156.

Longman, M.W. and Haidl, F.M. (1996): Cyclic deposition and development of porous dolomites in the Upper Ordovician Red River Formation, Williston Basin; *in* Longman, M.W. and Sonnenfeld, M.D. (eds.), Paleozoic Systems of the Rocky Mountain Region, Rocky Mountain Section, Soc. Sediment. Geol., p29-46.

Migowski, C., Agnon, A., Bookman, R., Negendank, J.F.W., and Stein, M. (2004): Recurrence pattern of Holocene earthquakes along the Dead Sea transform revealed by varve-counting and radiocarbon dating of lacustrine sediments; Earth Planet. Sci. Lett., p301-314.

Montenat, C., Barrier, P., d'Estevou, P.O., and Hibsch, C. (2007): Seismites: an attempt at critical analysis and classification; Sediment. Geol., v196, p5-30.

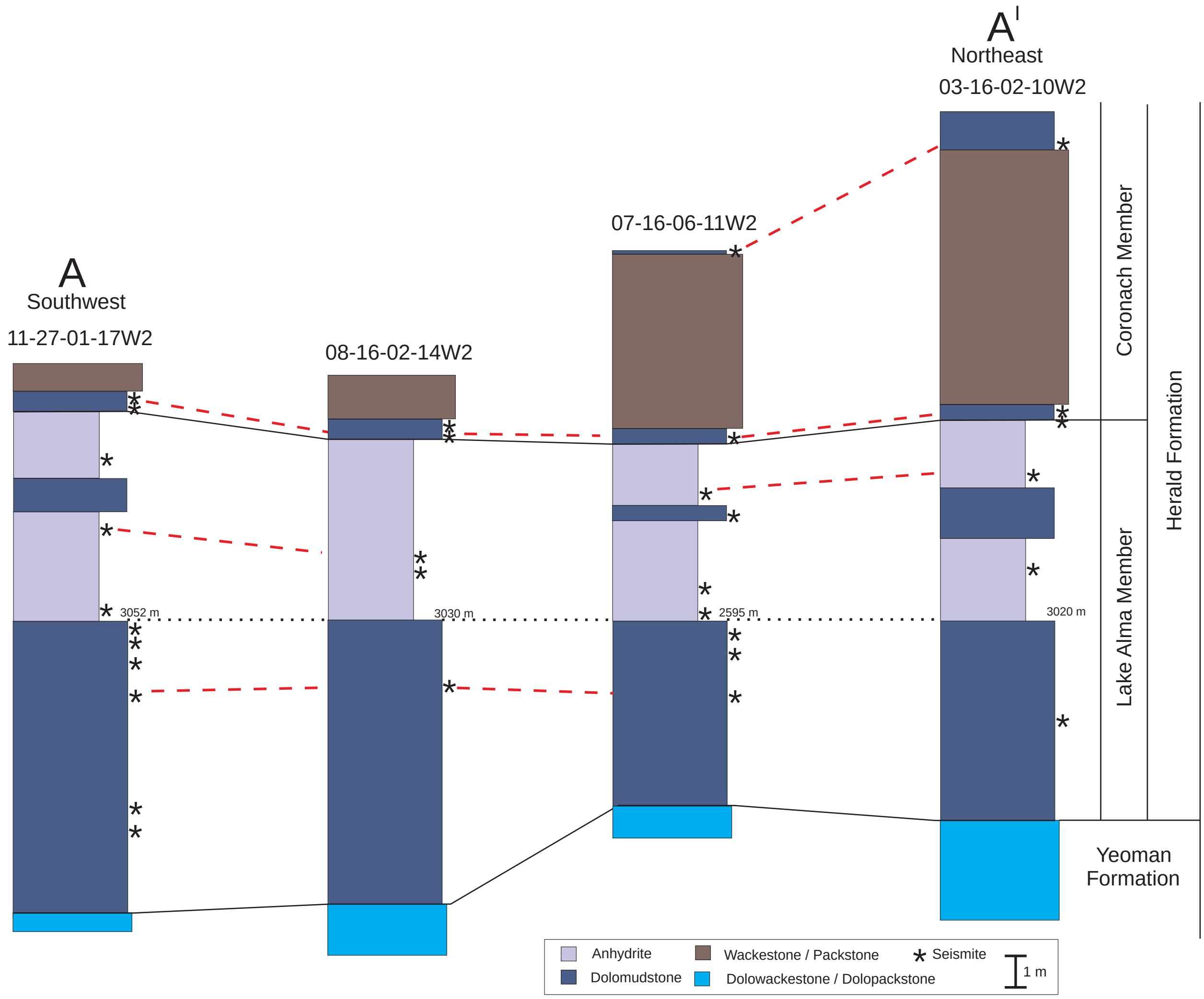

Figure 8 - Correlation of selected wells from southeastern Saskatchewan showing the stratigraphic occurrence of seismites in the Lake Alma and Coronach members of the Herald Formation. Datum, defined by black dotted line, is the base of the Lake Alma anhydrite. Upper solid black line shows correlation of the contact between the Lake Alma and Coronach members; lower solid black line defines contact between the Yeoman Formation and Lake Alma Member. Dashed red lines show possible correlation of individual seismites.

Nimegeers, A.R. and Haidl, F.M. (2004): Lower Paleozoic anhydrites in southeastern Saskatchewan (Townships 1 to 17, Ranges 1W2 to 24W2); *in* Summary of Investigations 2004, Volume 1, Saskatchewan Geological Survey, Sask. Industry and Resources, Misc. Rep. 2004-4.1, CD-ROM, Paper A-4, 18p.

Onasch, C.M. and Kahle, C.F. (2002): Seismically induced soft-sediment deformation in some Silurian carbonates, eastern U.S. Midcontinent; *in* Ettensohn, F.R., Rast, N., and Brett, C.E. (eds.), Ancient Seismites, Geol. Soc. Amer., Spec. Pap. 359, p165-176.

Paz, J.D.S. and Rossetti, D.F. (2005): Linking lacustrine cycles with syn-sedimentary tectonic episodes: an example from the Codo Formation (Late Aptian), northern Brazil; Geological Mag., v142, p269-285.

Potter, D. and St. Onge, A. (1991): Minton Pool, south-central Saskatchewan: a model for the basement induced structural and stratigraphic relationships; *in* Christopher, J.E. and Haidl, F.M. (eds.), Sixth Williston Basin Symposium, Saskatchewan Geological Society, Spec. Publ. No. 11, p21-33.

Pratt, B.R. (1994): Seismites in Mesoproterozoic Altyn Formation (Belt Supergroup), Montana: a test for tectonic control of peritidal carbonate cyclicity; Geol., v22, p1091-1094.

__________ (1998a): Syneresis cracks: subaqueous shrinkage in argillaceous sediments caused by earthquake-induced dewatering; Sediment. Geol., v117, p1-10.

__________ (1998b): Molar-tooth structure in Proterozoic carbonate rocks: origin from synsedimentary earthquakes, and implications for the nature and evolution of basins and marine sediments; Geol. Soc. Amer. Bull., v110, p1028-1045.

__________ (2001a): Septarian concretions: internal cracking caused by synsedimentary earthquakes; Sedimentol., v48, p189-213.

__________ (2001b): Oceanography, bathymetry and syndepositional tectonics of a Precambrian intracratonic basin: integrating sediments, storms, earthquakes and tsunamis in the Belt Supergroup (Helena Formation, c. 1.45 Ga), western North America; Sediment. Geol., v141/142, p371-394.

__________ (2002): Tepees in peritidal carbonates: origin via earthquake-induced deformation, with example from the Middle Cambrian of western Canada; Sediment. Geol., v153, p57-64.

Pratt, B.R., Bernstein, L.M., Kendall, A.C., and Haidl, F.M. (1996): Occurrence of reefal facies in Red River strata (Upper Ordovician), subsurface Saskatchewan; *in* Summary of Investigations 1996, Volume 1, Saskatchewan Geological Survey, Sask. Energy and Mines, Misc. Rep. 96-4, p147-152.

Pratt, B.R. and Haidl, F.M. (2008): Microbial patch reefs in Upper Ordovician Red River strata, Williston Basin, Saskatchewan: signal of heating in a deteriorating epeiric sea; *in* Pratt, B.R. and Holmden, C. (eds.), Dynamics of Epeiric Seas, Geol. Assoc. Can., Spec. Pap. 48, p315-352.

Sims, J.D. (1973): Earthquake induced structures in sediments of Van Norman Lake, San Fernando, California; Sci., v182, p161-163.

Urban, M. and Qing, H. (2007): Preliminary core description and lithofacies analysis of the Ordovician Coronach Member, Herald Formation, southeastern Saskatchewan; *in* Summary of Investigations 2007, Volume 1, Saskatchewan Geological Survey, Sask. Energy and Resources, Misc. Rep. 2007-4.1, CD-ROM, Paper A-3, 13p.

Weidlich, O. and Bernecker, M. (2004): Quantification of depositional changes and paleo-seismic activities from laminated sediments using outcrop data; Sediment. Geol., v166, p11-20.