Available online at www.sciencedirect.com
SCIENCE DIRECT®
Sedimentary Geology 168 (2004) 49–69
Sedimentary Geology
www.elsevier.com/locate/sedgeo

Dolomitized calcrete in the Middle Devonian Winnipegosis carbonate mounds, subsurface of south–central Saskatchewan, Canada

Qilong Fu, Hairuo Qing*, Katherine M. Bergman

Department of Geology, University of Regina, Regina, SK S4S 0A2, Canada

Received 25 June 2003; received in revised form 23 February 2004; accepted 5 March 2004

Abstract

Dolomitized calcrete is a widespread diagenetic feature in the uppermost portions of the Middle Devonian Winnipegosis mud mounds in the subsurface of south–central Saskatchewan. Individual calcrete profiles are composed of 2 to 5 horizons, including (in descending order) laminar crust, massive, pisolitic, breccia, chalky and transitional horizons. The calcrete profiles are interpreted to be pedogenic in origin, formed by diagenetic alteration of the host carbonate deposits during subaerial exposure of the mud mounds. This interpretation is based on the occurrence of an orderly set of well-differentiated horizons, disconformities, vadose pisoids, micritic stringers, circumgranular cracks, linkage coatings, and gradational contacts between the calcrete and underlying host carbonate rocks. Lack of root-related structures, such as rhizoconcretion and alveolar–septal fabric in the Winnipegosis calcrete, suggests a limited influence of macrophytes on the formation of calcrete. The occurrence of up to three discrete pedogenic calcrete profiles in a single Winnipegosis calcrete succession indicates the mounds underwent three periods of subaerial exposure that resulted from drops of water level in the Elk Point Basin of Saskatchewan during Middle Devonian time.

Keywords: Subaerial diagenesis; Calcrete; Winnipegosis carbonate; Middle Devonian; Canada

1. Introduction

Calcretes have been the subject of intensive research in past decades because of their usefulness in environmental reconstruction and stratigraphic analysis (Goudie, 1983; Reinhardt and Sigleo, 1988; Wright, 1994; Tandon and Kumar, 1999; Alonso-Zarza, 2003). Some ancient carbonate coated-grain deposits, previously interpreted to be oolitic/pisolitic deposits formed in shallow marine environments, were later reexamined and reinterpreted as calcrete oolites/pisolites that resulted from vadose diagenesis and pedogenesis related to subaerial exposure (Gerhard et al., 1982; Cao and Xue, 1983; Packard et al., 2002). Recognition of calcretes, especially pedogenic calcretes that lack macrophyte-related fabrics, can be difficult because calcrete profiles in carbonate strata are superficially similar to some shallow marine carbonate sequences and megapolygon–spelean diagenetic carbonate

* Corresponding author. Fax: +1-306-585-5433.
E-mail address: Hairuo.Qing@uregina.ca (H. Qing).

0037-0738/$ - see front matter © 2004 Elsevier B.V. All rights reserved.
doi:10.1016/j.sedgeo.2004.03.007

rocks (cf. Read, 1976; Hanford et al., 1984; Pelechaty and James, 1991). The majority of pedogenic calcrete profiles reported in the literature contain various structures related to macrophyte roots (Esteban and Klappa, 1983; Wright and Tucker, 1991; Wright, 1995). The Winnipegosis dolomitized cal-

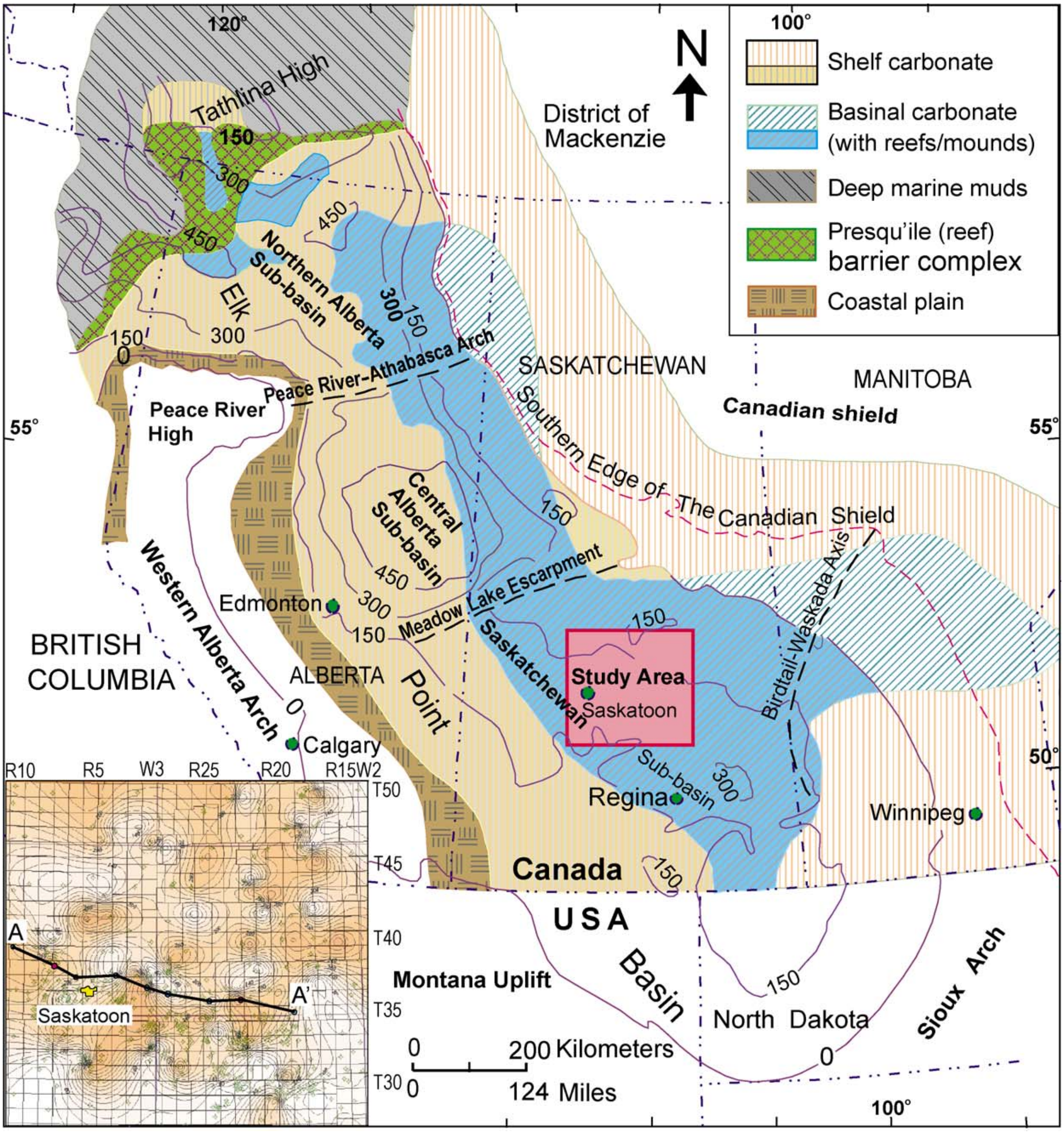


Fig. 1. Sketch map of Devonian Elk Point Basin showing related tectonic elements, facies distribution of the Winnipegosis Formation, and location of the study area (modified from Holter, 1969 and Kent, 1994). Isopach of the Devonian sediments is in meters. Close-up of the study area is displayed in lower left. Cross-section (A–A′) is shown in Fig. 2.

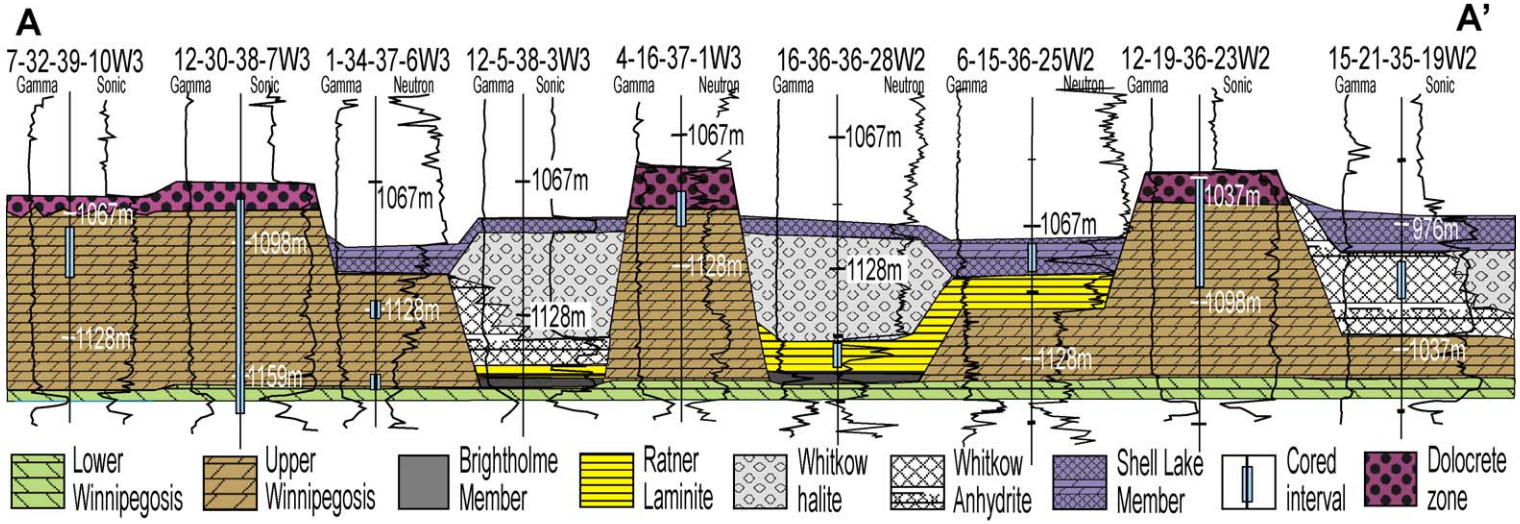


Fig. 2. A cross-section showing the stratigraphic relationships between the Winnipegosis Formation and the Whitkow and Shell Lake members of the Prairie Evaporite Formation. Note that dolomitized calcrete (dolocrete) caps the Winnipegosis mud mounds. Height of the Winnipegosis mounds refers to vertical thickness of the Upper Winnipegosis Member. Location of the cross-section is shown is Fig. 1. No horizontal scale is applied.

crete is a good example of pedogenic calcrete profiles with several well-differentiated horizons lacking macrophyte-related structures.

Dolomitized calcrete of the Winnipegosis Formation was reported in previous articles (Wardlaw and Reinson, 1971; Perrin, 1982; Rosenthal, 1987; Martindale et al., 1991; Jin et al., 1997), but no detailed studies were published and the significance of the occurrence of calcrete with respect to the changes in water level in the Elk Point Basin was not well defined. The objectives of this paper are to: describe and characterize calcrete features in the Winnipegosis Formation, discuss the origin of the various calcrete structures, and explore the implications of occurrence of the Winnipegosis calcrete profiles with respect to the changes of water level in the Middle Devonian Elk Point Basin.

The study area is located in the subsurface of south–central Saskatchewan and covers approximately 47,160 km^2, from Townships 28 to 50 and Ranges 15 west of the second meridian to 10 west of the third meridian (Fig. 1). In this region, the Winnipegosis Formation contains well-developed mud mounds (Fig. 2). Exploration for both hydrocarbon resources and potash deposits has increased the number of high-quality cored intervals and well log data available for this study.

2. Regional setting

The Middle Devonian Winnipegosis Formation and equivalent strata were deposited in the intracratonic Elk Point Basin that extended over 3000 km from the Northwest Territories of Canada to North Dakota of the United States (Fig. 1). The Tathlina High and Presqu'ile Barrier Reef complex separated a deep, open-marine basin to the north from the Elk Point Basin to the south (Rickette, 1989; Kent, 1994; Qing, 1998; Qing and Mountroy, 1994). The Peace River–Athabasca Arch and the Meadow Lake Escarpment divided the Elk Point Basin into three subbasins: northern Alberta, central Alberta and Saskatchewan (Fig. 1). The Elk Point Basin was interpreted to be located between latitudes 0–15°S of the equator during Middle Devonian time (Vander Voo, 1988; Witzke and Heckel, 1988; Witzke, 1990).

In the study area, the Winnipegosis Formation disconformably overlies the Eifelian Ashern Formation and is overlain by the Givetian Prairie Evaporite Formation (Figs. 2 and 3), and is roughly correlative with the Keg River Formation of Alberta and northeastern British Columbia. The Winnipegosis Formation was first described by Baillie (1953) and was divided into Lower Winnipegosis, Upper Winnipegosis and Ratner members (Fig. 3; Jones, 1965; Reinson and Wardlaw, 1972). The Ratner deposits were elevated to formation status by Jin and Bergman (2001). They are composed of laminated dolomite changing gradually upward into interlaminated dolomite and anhydrite. In intermound basinal areas, deposits of organic-rich laminate with interbeds of mound-derived detritus were named as the Brightholme Member (Stoakes et al., 1987; Jin and Bergman, 2001). The Lower Winnipegosis Member consists of a mottled, sparsely to moderately fossiliferous, dolomitized, or dolomitic mudstone to packstone and is commonly referred as the "platform member" (Reinson and Wardlaw, 1972; Ehrets and Kissling, 1987).

The Upper Winnipegosis Member is composed of dolomitized buildups that consist of mudstone, wackestone, packstone, floatstone, grainstone and rudstone. The buildups lack conspicuous, in-place, frame-building organisms based on core examination. These buildups should be regarded as mud

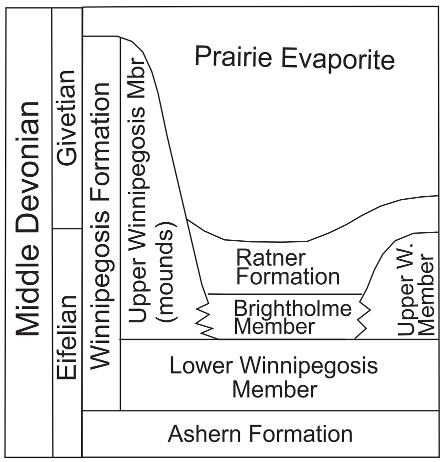


Fig. 3. Winnipegosis Formation stratigraphic nomenclature (after Reinson and Wardlaw, 1972; Jin and Bergman, 2001).

mounds rather than reefs (Reinson and Wardlaw, 1972; Gendzwill and Wilson, 1987). On the basis of well-log and seismic data, Gendzwill (1978) suggested that the Winnipegosis mud mounds were relatively steep-sided and varied between 0.5 and 6 km in diameter at the top. The mounds have a vertical height of up to 95 m and are clustered in the Saskatoon area.

The Winnipegosis mud mounds are encased in the Prairie Evaporite Formation (Figs. 2 and 3). The

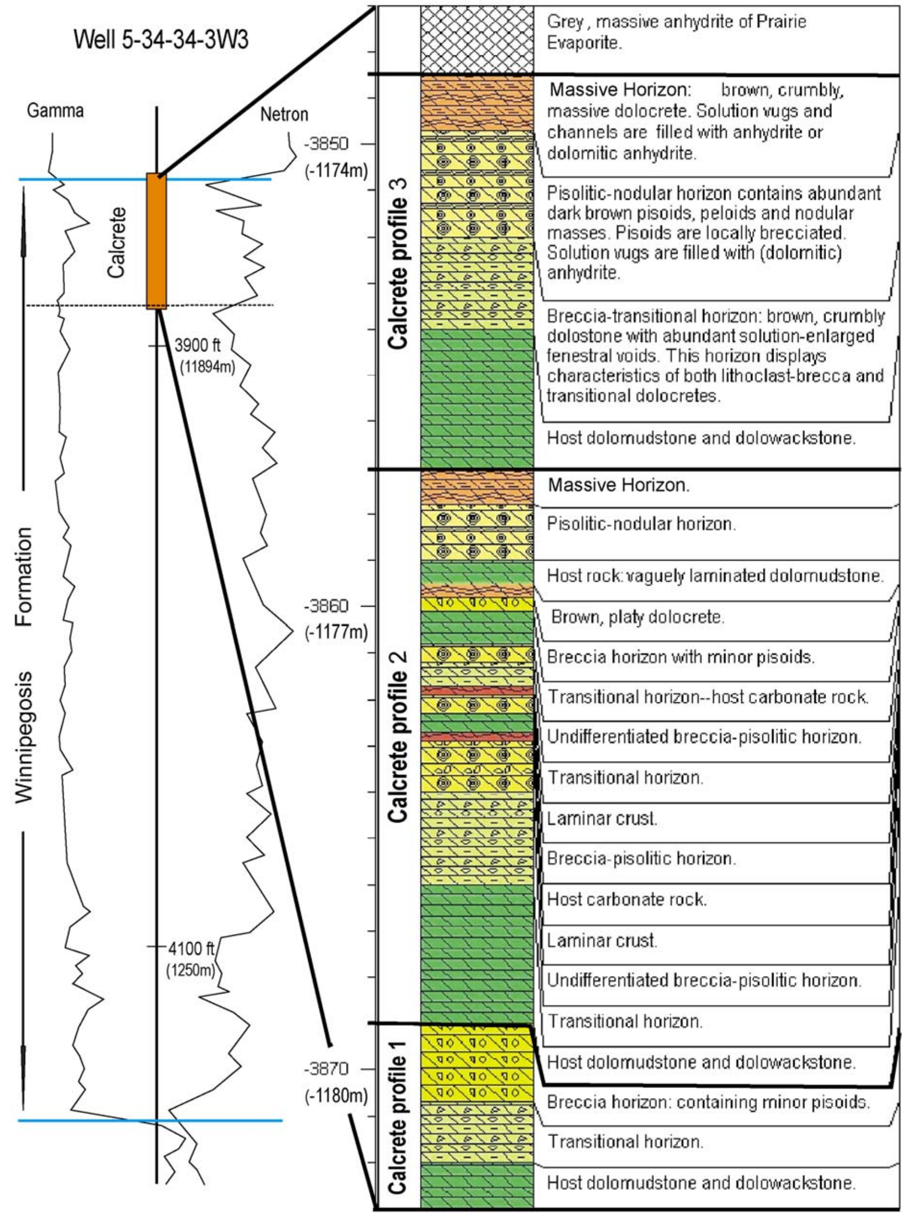


Fig. 4. Log of core 5-34-34-3W3 showing a 26-m interval containing three dolomitized calcrete profiles. The middle profile contains five lower-order cycles (subprofiles) composed of one to three calcrete horizons and the host carbonate deposits.

Prairie Evaporite has a maximum thickness of over 213 m, and averages almost 150 m in the study area (Holter, 1969). It is divided into three members: the lower Whitkow member consisting of anhydrite and halite, the middle Shell Lake member of anhydrite and carbonate, and the upper Leofnard member of halite interfingered with potash beds (Meijer Drees, 1986). The giant evaporite deposits reflect an arid environment in the basin during precipitation of the Prairie evaporites.

The evolution of the Winnipegosis succession reflects the interplay between sea level, tectonics, evaporation, and climate in the Elk Point Basin during late Eifelian and early Givetian time (Campbell, 1992). The desposition of Ashern Formation marked the initial inundation of open-marine water into the Elk Point Basin of Saskatchewan. At the end of Lower Winnipegosis deposition, the broad, shallow-water carbonate ramp was differentiated into basin and shelf environments (Perrin, 1982). The Winnipegosis mud mounds developed on the low-relief slopes and basin floor of the Saskatchewan Subbasin in moderate water depths, probably several tens of meters (Kendall, 1975). Growth of the mounds was terminated by subaerial exposure caused by lowering of water level related to the evaporative drawdown and restriction of water circulation in the Elk Point Basin due to growth of the Presqu'ile Barrier Reef complex (Maiklem, 1971; Moore, 1989; Jin and Bergman, 1999). The impact of the drops of water level on the development of widespread calcrete in the uppermost portions of the mounds is discussed in this paper.

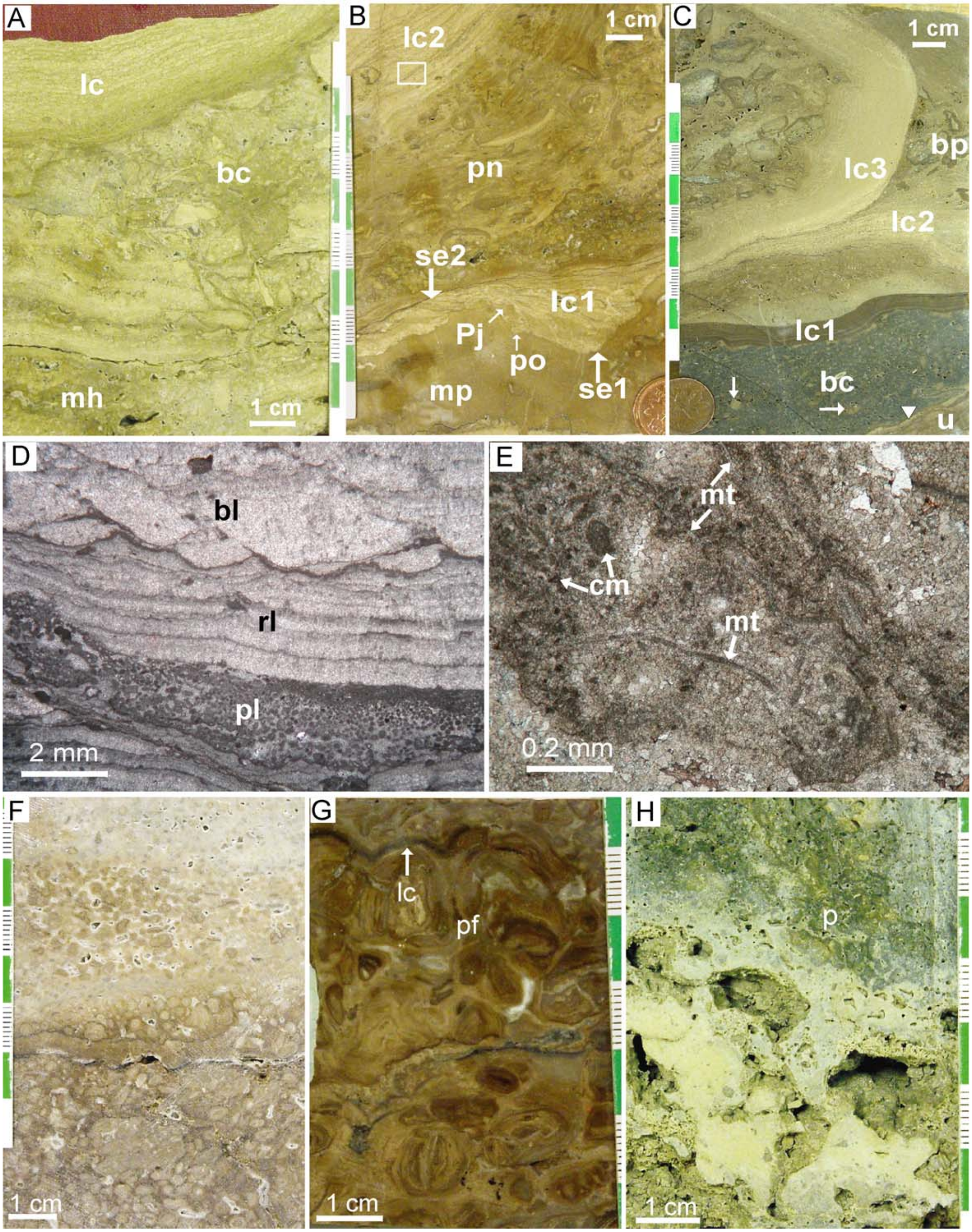
3. Calcrete petrology

Calcrete (caliché) is a near surface accumulation of predominantly calcium carbonate, which occurs in a variety of forms from powdery to nodular to highly indurated, as the result of cementation, displacive and/or replacive introduction of carbonate into soils, bedrocks, or sediments (Watts, 1980; Goudie, 1983; Wright and Tucker, 1991). Calcrete is widespread in semiarid to arid climates particularly at tropical and subtropical latitudes (James, 1972; Goudie, 1973; Hay and Reeder, 1978; Milnes, 1992).

3.1. Description of calcrete profiles

In the study area, the Winnipegosis calcrete profiles occur in the uppermost portions of the relatively high mud mounds, and the host rocks are dominantly laminated to massive mudstone and wackestone. The petrographic fabric of the Winnipegosis calcrete is well preserved in spite of dolomitization and burial diagenesis. A Winnipegosis calcrete profile generally consists of 2 to 5 horizons composed (from top to base) of laminar crust, massive, pisolitic, breccia, chalky, and transitional horizons (Fig. 4). There are, however, variations in this general order and not all horizons are present in individual profiles. The average thickness of the Winnipegosis calcrete profiles is about 1.5 to 2 m. Relatively complete calcrete profiles are observed in cores 12-19-36-23W2, 16-20-32-4W3, 5-34-34-3W3 (Fig. 4), 5-34-45-18W2, 10-10-49-21W2, and 4-16-37-1W3.

Fig. 5. (A–C) Photograph of core slabs illustrating textures of laminar crusts in the Winnipegosis calcrete. Scale bar is in centimeters. (A) Laminar crusts (lc) disconformably overlies nonporous breccia conglomerate (bc) and massive horizon (mh); 16-20-32-4W3, 1238.7 m. (4063 ft). (B) Two laminar crust horizons (lc1, lc2) overlie massive (mp) and pisolitic (pn) horizons, respectively. The contacts between the lower laminar crust (lc1) and underlying/overlaying deposits are abrupt, which are interpreted as subaerial erosion surfaces (se1, se2). The upper erosion surface truncates laminar crust (se2) and the lower one displays projections and corrosion pockets (pj, po); 12-30-38-7W3, 1080.8 m (3545.7 ft). Close-up of the inset rectangular box is shown on the Fig. 6B. (C) A core sample showing three generations of laminar crusts (lc1, lc2, lc3) and a disconformable contact (marked by ▾). Note that clasts and pisoids are locally incorporated into the laminar crusts (bp). Brecciated fragments (arrows) in breccia horizon (bc) are the same colour and lithology as underlying deposits (u); 5-34-45-18W2, 542.2 m (1778.3) ft. (D) Photomicrograph showing a laminar crust consists of alternations of botryoidal (bl), peloidal (pl), and banded-radial (rl) deposits; 12-19-36-23W2, 1042 m (3420.2 ft), plane polarized light. (E) Photomicrograph showing laminar crust contains microbial tubules (mt) and clotted micrite (cm); 12-30-38-7W3, 1080.6 m (3544.7 ft), plane polarized light. (F–H) Photos of core slabs illustrating pisolitic horizons. (F) Relatively small, regular (spherical) pisoids are well sorted and closely packed; 12-19-36-23W2, 1042.7m (3420.0 ft), scale in centimeters. (G) Relatively large, subspherical pisoids with linkage coatings (lc) and fitted polygonal structures (pf); 12-30-38-7W3, 1080.0 m (3545.2 ft), scale in cm. (H) Peloids (p) in a pisolistic horizon. Note the abundant open voids; 5-34-45-18W2, 540.5 m (1773 ft).


A
lc
bc
mh
1 cm
B
lc2
1 cm
pn
se2
lc1
Pj
po
mp
se1
C
1 cm
bp
lc3
lc2
lc1
bc
u
D
bl
rl
pl
2 mm
E
mt
cm
mt
0.2 mm
F
1 cm
G
lc
pf
1 cm
H
p
1 cm

3.1.1. Laminar crusts

The laminar crusts of the Winnipegosis calcrete consist of brown, laminated deposits that vary in thickness from a few millimeters to a few centimeters (Fig. 5A–C). The crusts are commonly tight, nonporous, and locally brecciated, and may grade laterally into coatings that drape or bridge several adjacent pisoids. In places, breccia fragments, pisoids, peloids, and/or microbial remains are incorporated into the laminar crusts (Fig. 5C). Individual laminae are submillimeter scale in thickness and laminations are locally uneven, wrinkled to contorted. In thin section, the laminar crusts are composed of interlaminated dolomicrite (less than 5 μm) and microdolospar (5–20 μm), or banded, radial dolomite with intercalated botryoidal and/or peloidal deposits (Fig. 5D), containing microbial fabrics such as dolomitized filaments, tubules and clotted micrite (Fig. 5E). The laminar crusts of the Winnipegosis calcrete are less obvious in thin section than in hand specimen and are texturally similar to many Quaternary laminar crusts (cf. Read, 1974; Hay and Reeder, 1978; Coniglio and Harrison, 1983).

The Winnipegosis laminar crusts overlie or occur within pisolitic, massive, or breccia horizons (Fig. 5A and B), or line the walls of cavities (Fig. 5C). The crusts tend to thicken in depressions and thin over highs of the underlying deposits (Fig. 5A and B). However, crust laminations that locally thicken over topographic highs are also observed. The contacts between the laminar crusts and underlying rocks are commonly abrupt (Fig. 5A–C), in contrast to the relatively gradual contacts between other horizons in the Winnipegosis calcrete profiles. These sharp contacts are flat to inclined and undulating to irregular, and are commonly interpreted as exposure surfaces or disconformities.

3.1.2. Massive horizons

The Massive horizons in the Winnipegasis calcrete are composed dominantly of microcrystalline to finely crystalline dolomite and are massive to vaguely platy in appearance (Fig. 5B). The horizons are light to dark brown, vary from a few to tens of centimeters in thickness (Fig. 4), and contain abundant solution vugs/channels and cracks. Cracks are a few centimeters long, up to 2 mm wide. Some are filled or lined with anhydrite and/or anhydritic dolomite. These cracks have similar appearances to those formed by subaerial desiccation/shrinkage (cf. Wright and Tucker, 1991; Demicco and Hardie, 1994).

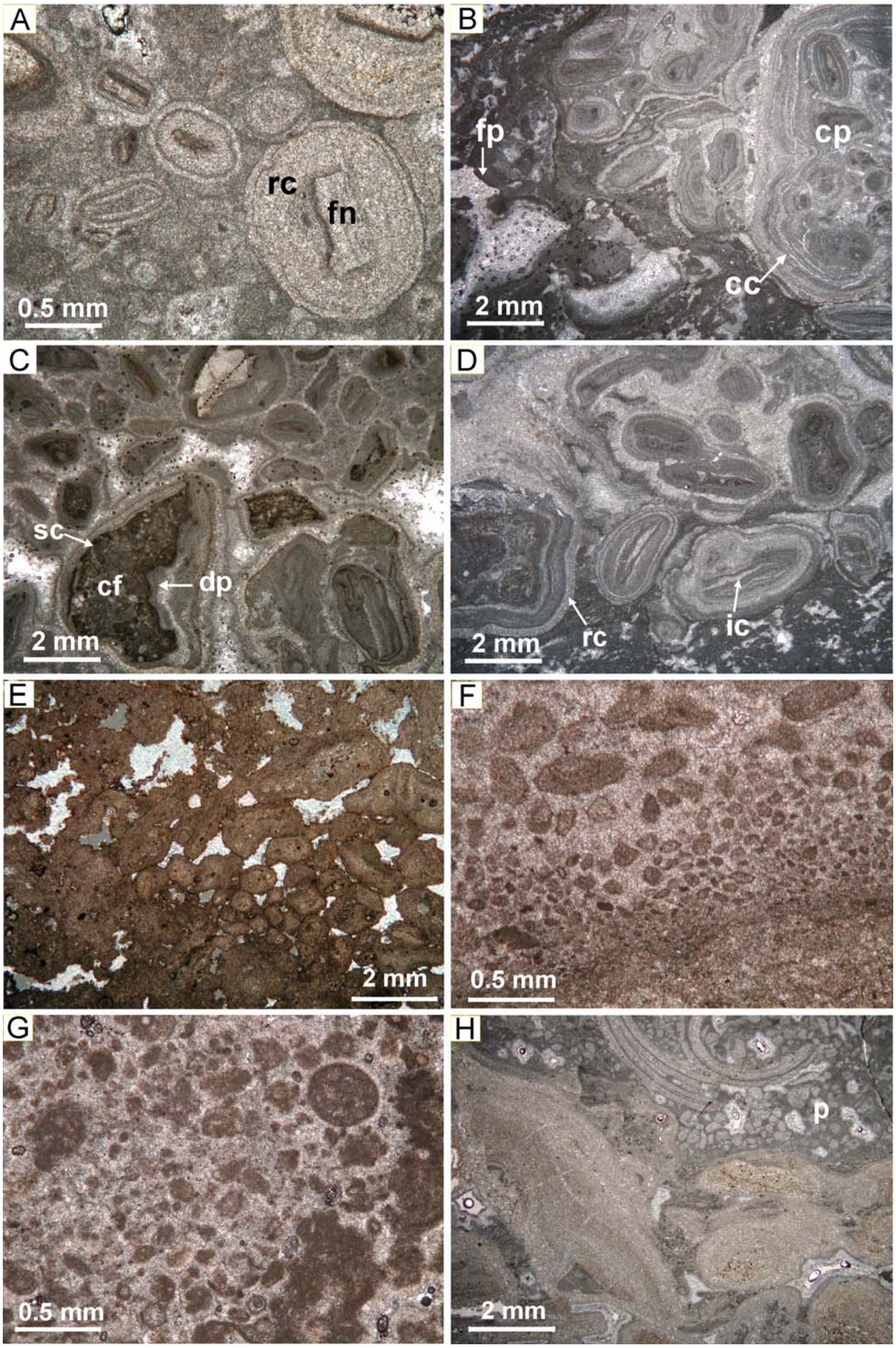
The massive horizons occur either below laminar crusts or as the uppermost horizons in the calcrete profiles where laminar crusts are absent (Fig. 4). Locally, massive horizons occur below the breccia or pisolitic horizons but above the transitional horizons.

3.1.3. Pisolitic horizons

The pisolitic horizons in the Winnipegosis calcrete vary from yellowish brown to bluish gray in colour and are mainly made up of pisoids with minor peloids in the matrix of microcrystalline to finely crystalline dolomite (Fig. 5F–H). The thickness of individual pisolitic horizons varies from a few to tens of centimeters.

In this study, the term pisoids includes the coated grains less than 2 mm (ooids or microids; Peryt, 1983) and those greater than 2 mm (pisoids or vadoids). The pisoids in the Winnipegosis calcrete vary from spherical, oval to polygonal in shape, and from less than 0.5 to over 15 mm in diameter although most are between 2 and 10 mm in size (Figs. 5F,G and 6A–D). The nuclei could be peloids, clasts, or fragments of previously formed pisoids. The laminations in the cortices

Fig. 6. Photomicrographs showing textures of pisolitic horizons. (A) Pisoids are spherical or oval in shape. The nuclei are peloids or breccia fragments of preexisting pisoids (fn). Dolomitization and/or recrystallization obliterated fabrics of pisoid cortices (rc); 16-20-32-4W3, 1238.0 m (4060.4 ft), plane polarized light. (B) A composite pisoid (cp) encloses many smaller ones (right side of photo). Note the circumgranular crack (cc) and filled vugs (fp); 12-19-36-23W2, 1042.7 m (3420.0 ft), plane polarized light. (C) Pisoids have clasts as nuclei (cf). The inner laminae of cortex are commonly thinner on points of stronger curvature of the nucleus (sc) and thicken in depressions (dp); 14-8-32-4W3, 1226.8 m (4023.5 ft), plane polarized light. (D) Pisolite. Locally, the outer most cortex laminae display radial bladed fabric (rc). Intragranular cracks that transect grains are filled with dolospar cement (ic); 12-19-36-23W2, 1042.7 m (3420 ft), plane polarized light. (E) Oval peloids are cemented by anhydrite in a pisolitic horizon; 5-34-34-3W3, 1173.2 m (3848.2 ft), cross-polarized light. (F) Peloids are oval or irregular in shape (with ghost morphology of breccia fragments), which probably resulted from corrosion and micritization of breccia fragments. Note the reverse grading; 12-30-38-7W3, 1079.8 m (3542.0 ft), plane polarized light. (G) Peloids of uncertain origin (microbial clotted micrite?); 16-20-32-4W3, 1240.9 m (4070 ft), plane polarized light. (H) Oval grains (p) in upper right part of photo are almost identical in size and shape, and associated with skeletal fragments; 12-30-38-7W3, 1081.2 m (3546.2 ft), plane polarized light.


A
rc
fn
0.5 mm
B
fp
cp
cc
2 mm
C
sc
cf
dp
2 mm
D
rc
ic
2 mm
E
2 mm
F
0.5 mm
G
0.5 mm
H
p
2 mm

are commonly concentric with 1 to over 15 layers (Fig. 6A–D). The interpisoid linkage coatings locally blend gradually into the surrounding sediments. Circumgranular and intragranular cracks, which are a diagnostic fabric of vadose calcrete pisoids (cf. Esteban and Klappa, 1983; Goldhammer et al., 1987), are present and are filled with microdolospar (Fig. 6B and D). Breccia fragments of pisoids are commonly observed in the horizons. Pisoids are either closely packed (Fig. 5F and G) or float in the matrix, and display both normal and reverse grading. In places, pisoids are elongated downward/upward and have fitted polygonal structures (Fig. 5G), as was documented by Wardlaw and Reinson (1971). Many large pisoids are composite, in which outer laminations envelope several smaller pisoids (Fig. 6B), a characteristic feature of pisoids in many Quaternary calcrete profiles (James, 1972; Esteban, 1976; Esteban and Klappa, 1983). In some cores, pisoids may account for up to 40% of the Winnipegosis calcrete profiles volumetrically.

Peloids are composed of microcrystalline to finely crystalline carbonate, have no internal structure (Figs. 5H and 6E–H), and commonly range between 0.1 and 5 mm in diameter. These spherical or oval grains vary from poor to well sorted, and locally show reverse grading (Fig. 6E–H). Both grain-supported and matrix-supported textures are present in the peloid deposits.

Pisolitic horizons are present in most Winnipegosis calcrete profiles, occur as layers, pockets, or irregular lenses, and commonly show gradational upper and lower contacts (Fig. 5B). Pisoid pockets may be bounded and subdivided by laminar crusts. Locally, pisoids are mixed with breccia fragments, forming pisolitic–breccia horizons.

3.1.4. Breccia horizons

Breccia horizons contain abundant breccia fragments and lithoclasts, and are commonly brown or variegated in colour and up to 0.5 m or more in thickness (Fig. 7). Breccia fragments are angular to subrounded and locally have very thin micritic rinds (Fig. 7B). Lithoclasts are generally subrounded and vary in colour and lithology (Fig. 7A). Breccia fragments and lithoclasts vary from sand- to pebble-size (commonly between 1 and 30 mm in diameter), and are grain-supported or matrix-supported (Figs. 5C and 7). Locally, the *in situ* angular breccia fragments at the

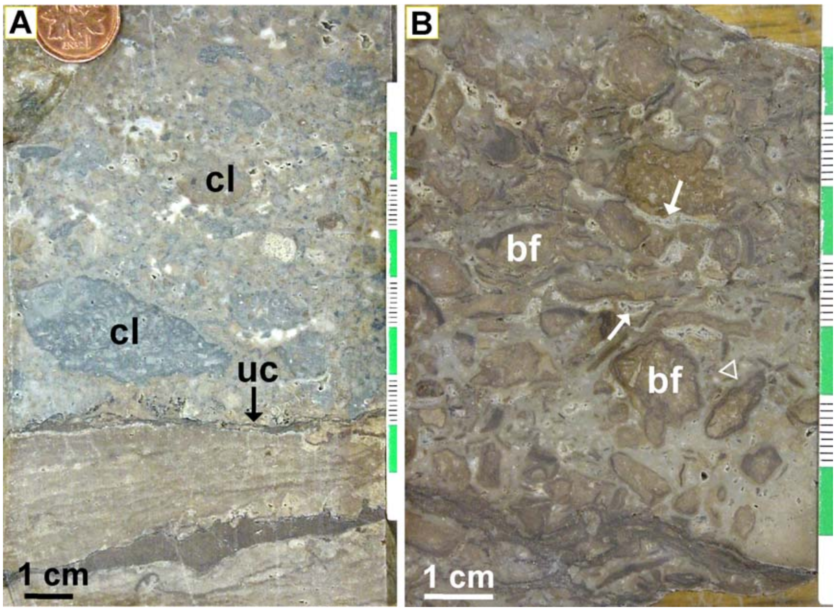


Fig. 7. Core slabs showing breccia horizons. Scale bar is in centimeters. (A) Lithoclasts (cl) are poorly sorted (upper 2/3 of photo). Note the disconformable contact (uc); 3-36-38-28W2, 1043.4 m (3422.5 ft). (B) Breccia fragments (bf). Note the cement-lined or filled voids (arrow); 5-34-34-3W3, 1194.1 m (3869.0 ft).

base of horizons grade into subrounded clasts toward the top.

3.1.5. Chalky horizons

Chalky horizons (Fig. 8A) are characterized by greyish white to cream-coloured, slightly indurated silt-sized particles composed of single-dolomite crystals or aggregates of crystals. Sand-sized breccia fragments are present. The chalky horizon was identified only in core 4-16-37-1W3 from 1098.2 to 1098.7 m.

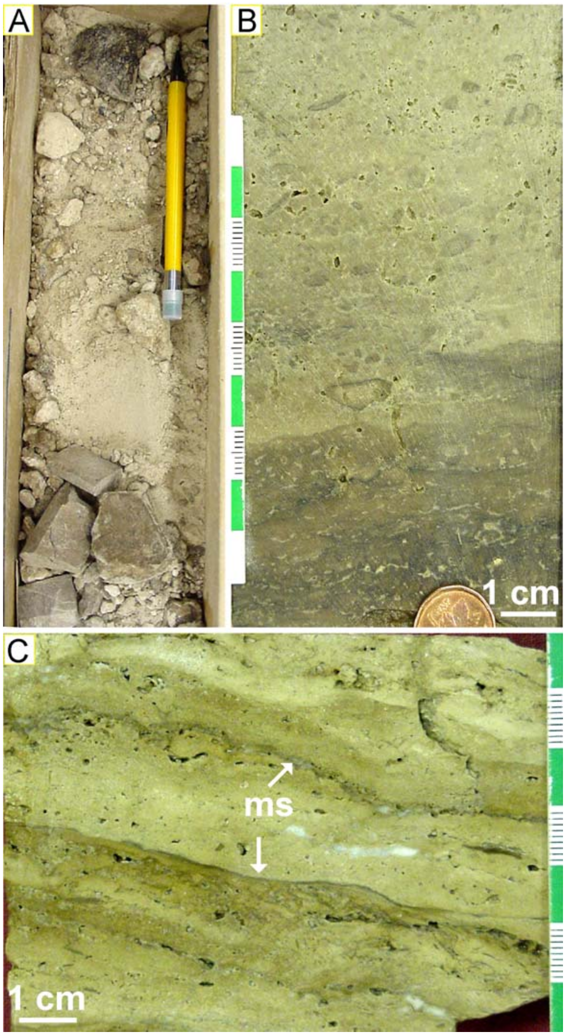


Fig. 8. Photograph of core slabs showing chalky and transitional horizons. (A) Chalky horizon; 4-16-37-1W3, 1098.2–1098.7 m. Pencil is 14 cm long. (B) Transitional horizon with vaguely mottled appearance; 5-34-34-4W3, 1175.6 m (3856.0 ft). (C) Transitional horizon with micritic stringers (ms). Note the solution-enhanced voids; 16-20-32-4W3, 1239.3 m (4065 ft).

3.1.6. Transitional horizons

Transitional horizons refer to the intervals between unaltered host carbonate and overlying calcrete, consisting of partially calcretised carbonate deposits (Fig. 8B and C). In places, transitional horizons have a mottled appearance where the patches of host carbonate deposits have been selectively altered. Locally, there are abundant solution-enhanced vuggy and channel porosities in the horizons (Fig. 8B). In the Winnipegosis calcrete, transitional horizons vary in thickness from a few centimeters to over 1 m.

Micritic stringers are present in the transitional horizons of the Winnipegosis calcrete, vary from about 1 to a few millimeters in thickness (Fig. 8C), and are nonlaminated. Micritic stringers locally cross-cut primary bedding and are also present in intensely altered zones (such as pisolitic horizons), suggesting a diagenetic origin. The contact between the micritic stringers and host substrate is commonly abrupt. Locally, the host carbonate rocks on two sides of a micritic stringer show different degrees of diagenetic alteration. Micritic stringers occur in many Quaternary calcrete profiles (Reeves, 1970; Calvet and Julia, 1983) and are considered to be indicative of subaerial exposure where laminar crusts and other characteristic calcrete structures were not developed, or were destroyed by subsequent weathering and diagenesis (Harrison and Steinen, 1978).

3.1.7. Host carbonate deposits

The host rocks consist of finely grained, light to medium brown, massive to laminated carbonate. They are now dolomitized mudstone, peloidal mudstone/wackestone, algae–calcisphere wackestone, and crinoid–coral–stromatoporoid wackestone, which are interpreted to be deposited in a shallow marine subtidal to intertidal environment. Porosity includes intercrystalline, mouldic, and vuggy voids, and is commonly less than 10%. Fractures are filled with anhydrite, dolomitic anhydrite, and minor celestite.

3.2. Variation and distribution of calcrete profiles

A complete Winnipegosis calcrete profile consists of five distinct horizons (Fig. 9A). Common local

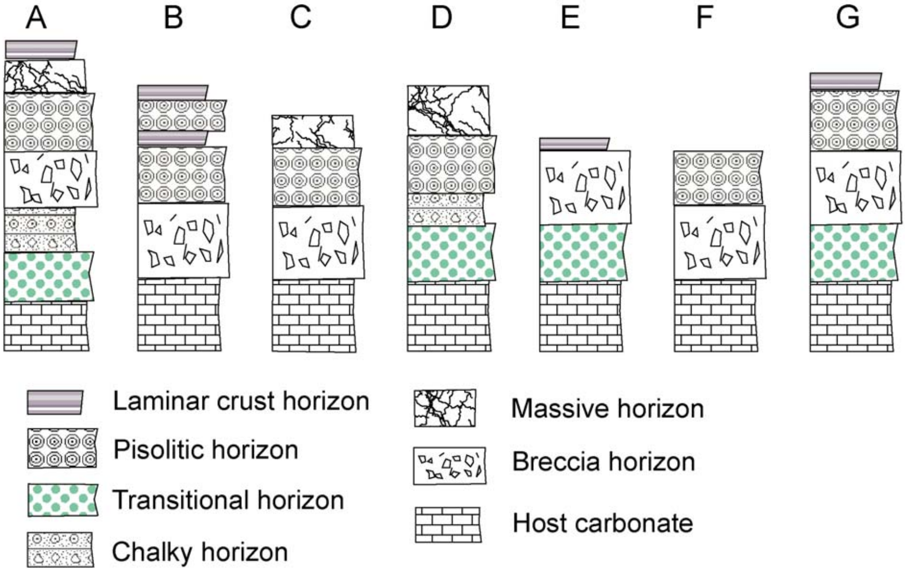


Fig. 9. Diagram showing a conceptual calcrete profile (A) and some variations in calcrete profiles (B–G) observed in the core intervals from the Winnipegosis mounds in the study area. Individual calcrete profiles consist of two to five horizons composed of (in descending order) laminar crust, massive, pisolitic, breccia, chalky, and transitional horizons.

variations from this typical profile are shown in Fig. 9B–G. Many calcrete profiles are characterized by several distinct horizons. Others consist of thin, vague laminar crusts, or occur as pockets or lenses of pisoids incorporated into the host carbonate. The Winnipegosis calcrete successions vary in thickness from tens of centimeters (4-24-40-18W2) to about 12 m (12-19-36-23W2). Generally, the Winnipegosis calcrete profiles in the mound margins are thicker (16-20-32-4W3 and 4-16-37-1W3) than those in the central area of the mounds (5-34-34-3W3). Similar relationships were observed in Pleistocene carbonate deposits of Barbados, West Indies, where calcrete profiles of variable thickness (up to 2–3 m) are well developed on the marginal portions and poorly developed or absent in the interior part of the island (Harrison, 1977).

In the study area, the Winnipegosis calcrete is commonly present in the uppermost parts of the mud mounds that have a vertical thickness greater than 65 m (Fig. 2). Up to three calcrete profiles were identified in a number of cores that penetrated the Upper Winnipegosis mud mounds (Fig. 4). Some individual calcrete profiles are composed of several relatively thin, lower order cycles of calcrete and host carbonate deposits, herein referred to as the calcrete subprofiles. For instance, the middle calcrete profile in core 5-34-34-3W3 includes more than five subprofiles and each subprofile is composed of 1–3 calcrete horizons underlain by the host carbonate (Fig. 4). Multiple-calcrete profiles are also observed in calcrete sections elsewhere (Goldhammer et al., 1987). A recent analog occurs in the Quaternary strata of the Yucatan Coast, which contains two couplets of shallow marine carbonate capped with calcrete (Ward, 1997; Ward and Brady, 1979).

Occurrence of the Winnipegosis calcrete is not limited to the study area but widespread in the Saskatchewan Subbasin and is reported to have developed in the uppermost parts of the reefs in southeastern Saskatchewan, North Dakota, and southwestern Manitoba (Perrin, 1982; Rosenthal, 1987; Martindale et al., 1991).

3.3. Interpretation of calcrete petrology

The laminar crusts of the Winnipegosis calcrete are laterally variable and discontinuous, and closely resemble those in the Quaternary calcretes of the Shark Bay and Hutt–Leeman Lagoons in Western Australia (Read, 1974; Arakel, 1982), Barbados (James, 1972;

Harrison, 1977), and the Florida Keys (Coniglio and Harrison, 1983; Demicco and Hardie, 1994), which were interpreted as aggradational or displacive precipitation of calcium carbonate on an impermeable surface. In places, the laminar crusts contain biogenic fabrics that include microbial tubules, clotted micrite, mineralized filaments, and wrinkled laminations (Fig. 5E), suggesting that the development of some laminar crusts is probably related to microbial activity (cf. Wright, 1989). Fungal filament mineralization and cyanobacterial activity were suggested to play a significant role in the redistribution of calcium carbonate and the formation of laminar crusts in calcrete profiles (Verrecchia et al., 1993; 1995). Numerous laminar crusts of biogenic origin were documented in the literature (Kahle, 1977; Klappa, 1979a; Wright et al., 1988; Verrecchia et al., 1995). These secondary crusts are indicative of subaerial exposure and vadose diagenesis (James, 1972; Harrison and Steinen, 1978; Braithwaite, 1983).

The massive horizons in the Winnipegosis calcrete show evidence of dissolution, reprecipitation, and recementation of carbonate. Locally, the massive horizons are similar to hardpan and platy calcrete formed in various Quaternary calcrete profiles (cf. Esteban and Klappa, 1983). The platy appearance observed in the massive horizons results from thinly bedded layers or horizontal solution structures.

Many small pisoids (commonly less than 5 mm in diameter) in the Winnipegosis calcrete appear to have undergone transportation and/or rotation along a surface during their growth because the pisoids are well sorted and spherical in shape (Fig. 5F). Large, oval to polygonal pisoids (Fig. 5G and 6C) are interpreted to form by *in situ* micritic coating of breccia fragments and by development of nonisopachous accretion into available interpisoid space at a later stage. Downward/upward thickened coatings and fitted polygonal fabric indicate in-place growth in the vadose zone (cf. Peryt, 1983). Growth of pisoids was interrupted periodically by brecciation. The large composite pisoids reflect episodes of grain development (Fig. 6B).

The peloids in the Winnipegosis calcrete could be the result of precipitation in the calcrete matrix or corrosion of mudstone clasts related to pedogenic processes in that outline of clast fragments is preserved in peloids (Fig. 6F). Some oval peloids are dark-coloured, identical in size and shape, and associated with skeletal fragments and organic matter, suggesting the possibility of pellets (Fig. 6H). Others appear to be clotted micrite (Fig. 6G). Peloids are common components of many recent and ancient calcrete profiles (James, 1972; Hay and Wiggins, 1980; Bain and Foos, 1991).

The breccia fragments are of the same colour and lithology as the underlying rocks, suggesting they formed by brecciation and weathering of the host rocks. The fitted fabric between adjacent fragments and the gradational contacts with underlying rocks suggest breccia fragments result from *in situ* brecciation. Locally, however, the presence of subrounded clasts of various colours and lithologies in individual breccia horizons suggests mixing and transportation of breccia fragments (Fig. 7A). The disconformable contacts between the breccia horizons of the Winnipegosis calcrete and the underlying/overlying rocks are an indicator of subaerial exposure surfaces (cf. Read, 1974; Harrison and Steinen, 1978). Some lithoclasts contain pisoids and/or pisoid fragments (Fig. 7A), indicating that brecciation postdates the formation of pisoids; and some contain an early stage of breccia fragments, suggesting multiple stages of brecciation. Brecciation is a striking feature of the Winnipegosis calcrete, reflecting subaerial weathering and cracking presumably caused by the displacive growth of carbonate, change of the wet–dry conditions and dissolution in vadose zones (cf. Harrison and Steinen, 1978; Wright, 1994; Wright and Tucker, 1991). Macrophyte root activity is believed to play a significant role in the formation of breccia fragments in some calcrete profiles (cf. Braithwaite, 1983). In the Winnipegosis calcrete, however, no evidence of macrophyte root activity has been observed.

4. Discussion

4.1. Origin of calcrete

The origin of calcrete in recent and ancient strata has been discussed extensively in the literature (Blank and Tynes, 1965; Goudie, 1973, 1996; Klappa, 1979b, 1983; Wang et al., 1994; Tandon et al., 1998). Two models, pedogenic and nonpedogenic, have been proposed to explain the formation of calcrete (Table 1). ‘‘Nonpedogenic’’ calcrete is mainly composed of

Table 1
Comparison of the attributes commonly observed in pedogenic calcrete, nonpelagic calcrete, and travertine (after Goudie, 1983; Jacobson et al., 1988; Wright and Tucker, 1991; Pimentel et al., 1996; Demicco and Hardie, 1994; Evans, 1999; Tandon and Kumar, 1999)

	Pedogenic/in situ transformation calcrete	Nonpedogenic/ groundwater calcrete	Spring/groundwater travertine
Processes involved and occurrence	Relative accumulation of carbonate in vadose (infiltration and percolation) zone by soil forming process; typically associated with more stable exposure surface	Absolute accumulation of carbonate by precipitation from groundwater mainly in phreatic zone or capillary fringe subzone; associated with more permeable lithologies, drainage channels, playas, or/and lake deposits	Physicochemical or biochemical precipitation from supersatured waters onto subtrate surfaces; associated with river, lake deposits, or spring/hydrothermal paths
Stratigraphic and geometric characteristics	Displaying an orderly set of horizons (laminar, platy, nodular, chalky, and transitional); sharp top and gradational base; generally thin, 0.5–3 m in thickness	Showing uniformly massive and/or nodular horizon(s); generally thick, up to 10 m or more in thickness	Continuous flat laminates, dam, and pool configuration; travertine domes/mounds up to tens of meters in height
Macrostructures and microfabric	Laminar, pisolitic, and nodular fabric, cracks, in situ breccias; rhizoliths, *Microcodium*, root-mold, alveolar–septal structures; replacive and displacive micrite, meniscus and pendant cements	Containing displacive and replacive carbonate meso-crystals; replacement silica; locally showing lateral mineralogical changes as calcrete to dolocrete to gypcrete; biogenic structures not common	Lamination, bandling, and stromatolite-like fabric; primary crystalline textures such as radiating needles and blades with compromise boundary; arborescent/ dentritic or shrub structures

authigenic carbonate precipitates that have been introduced into the host sediments/rocks by moving groundwater (Goudie, 1983). Numerous modern and ancient nonpedogenic calcretes were documented from a variety of locations (Mann and Horwitz, 1979; Jacobson et al., 1988; Colson and Cojan, 1996; Jutras et al., 1999). ‘‘Pedogenic calcrete’’ is a vertically zoned, accretionary carbonate accumulation formed by soil processes (Tandon and Kumar, 1999). Where the substrate is limestone, pedogenic calcrete forms mainly by the alteration, weathering, and redistribution of preexisting host carbonate deposits. Some calcrete successions are of both pedogenic and nonpedogenic origin (Armenteros et al., 1995; Nash and Smith, 1998), for example, the calcrete profiles in the late Quaternary deposits of Gujarat, western India (Khadkikar et al., 1998) and in the Middle Devonian Gilwood Member (Watt Mountain Formation) of north–central Alberta, Canada (Williams and Krause, 1998).

The following observations suggest that the Winnipegosis dolomitized calcrete profiles are best interpreted as pedogenic calcrete formed by *in situ* alteration of host carbonate deposits: (1) The Winnipegosis calcrete profiles occur in the uppermost portions of the mud mounds and have gradational contacts with the underlying host carbonate rocks. The calcrete profiles include a wide spectrum of features: disconformities, various desiccation cracks, polygonal fitting and asymmetric elongation of pisoids, micritic stringers, and linkage coatings that bridge multiple pisoids. The presence of these features suggests that the Winnipegosis calcrete has formed as the result of diagenetic alteration of host carbonate deposits in the vadose zone during subaerial exposure (Fig. 10; cf. Esteban, 1976; Esteban and Klappa, 1983; Harrison and Steinen, 1978; Pelechaty and James, 1991). (2) The Winnipegosis calcrete consists of an orderly set of well-differentiated horizons: laminar crust, massive, breccia, pisolitic, chalky, and transitional horizons. Up to three calcrete profiles are present in many individual cores. These features are characteristics of pedogenic calcretes (cf. Goudie, 1983; Esteban and Klappa, 1983; Wright and Tucker, 1991; Alonso-Zarza, 2003).

The development of calcrete is related to climate, duration of subaerial exposure, substrate lithology, topography, and vegetation (James, 1972; Harrison, 1977; Arakel, 1982; Wright and Tucker, 1991). During Middle Devonian time, the Elk Point Basin was located in a semiarid to arid equatorial region with seasonal conditions (Wardlaw and Schwerdtner, 1966; Witzke and Heckel, 1988), which were suitable for the development of pedogenic calcrete (cf. Reeves, 1970; Goudie, 1983; Tandon and Kumar, 1999). During the

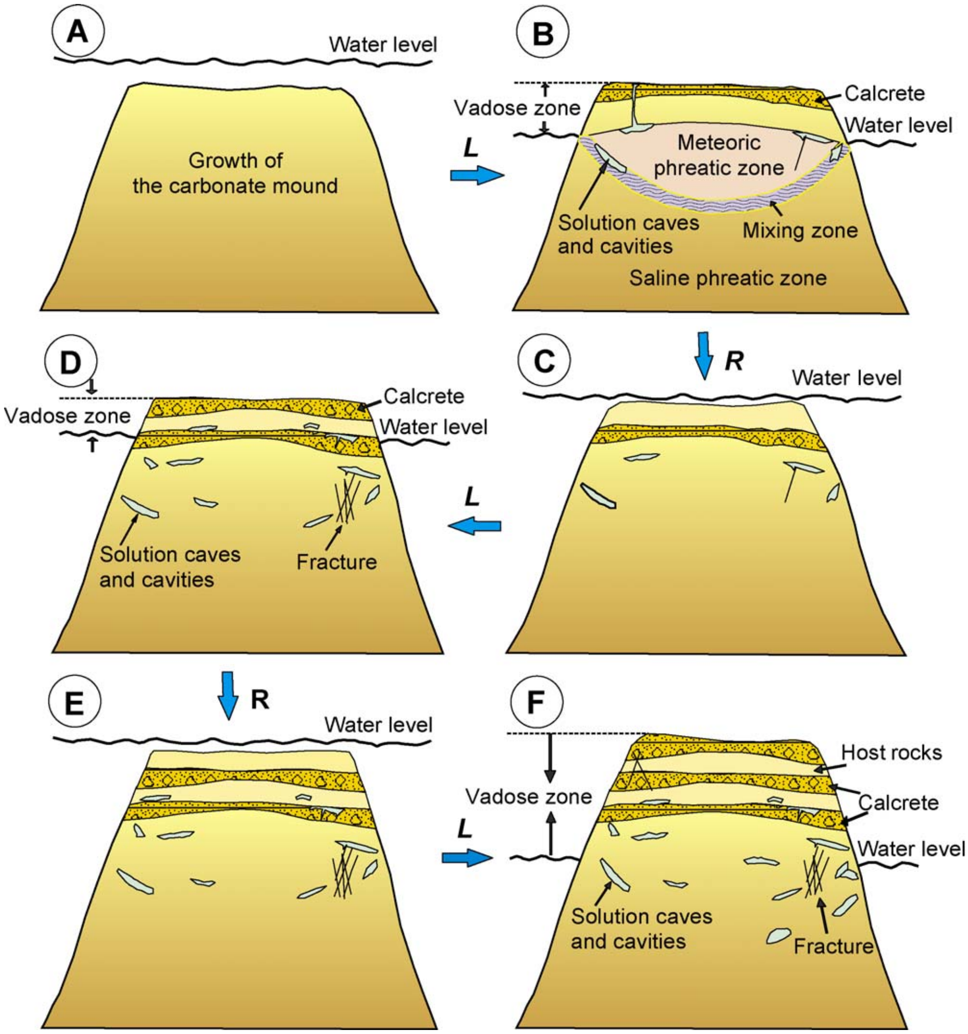


Fig. 10. Schematic diagram illustrating three periods of calcrete formation in the Winnipegosis carbonate mud mounds. Each period began with a rise in water level (denoted by R) followed by a lowering of water level (denoted by L) in the Elk Point Basin. During transgressions (denoted by R), the Winnipegosis mound grew and normal marine facies were deposited (A, C, E). During drops of water level (denoted by L), the upper portions of the mounds were exposed and the pedogenic calcrete formed as the result of diagenetic alteration of host carbonate deposits in the vadose zone (B, D, F).

lowstand of water level in the basin, the upper parts of the Winnipegosis mounds were subjected to subaerial exposure and meteoric diagenesis (Fig. 10). Meteoric water dissolved and transported carbonate downward through the vadose zone. The solutions, however, could move toward the surface by evaporative pumping during the dry seasons (cf. Hsu and Siegenthaler, 1969). Evaporation/evapotranspiration and CO_2-degassing might lead to supersaturation of carbonate that was precipitated as microcrystalline calcite in the upper vadose zone (cf. Read, 1974; Wright and Tucker, 1991; Demicco and Hardie, 1994). The host deposits served as the main source of calcium carbonate. Breccia, pisolitic and laminar–crust horizons likely represent progressive stages of calcrete development in the Winnipegosis carbonate (cf. Harrison, 1977; Wright and Tucker, 1991). The Winnipegosis calcrete profiles are complicated by repeated occurrence of some horizons and/or development of subprofiles in individual profiles. The resulting calcrete profiles have been subsequently subjected to karstification, dolomitization, and anhydrite replacement and cementation.

Numerous studies have demonstrated that calcrete is characterized by a suite of unique features related to both organic and inorganic origins (Wright and Tucker, 1991), but there is increasing evidence that biological processes, especially macrophyte root activities, are instrumental in the development of many structures found in pedogenic calcretes (Braithwaite, 1975; Klappa, 1980; Rossinky et al., 1992; Wright et al., 1995; Alonso-Zarza, 1999). Absence of rhizoconcretions, alveolar–septal structures, *Microcodium*, and root molds and mats in the Winnipegosis calcrete suggests that the calcrete has not been significantly influenced by macrophytes, which rules out a possible interpretation that the multiple Winnipegosis calcrete profiles formed by the penetration of plant roots downward into the host sediments (cf. Rossinky et al., 1992). However, microbes are interpreted to play a role in the origin of some calcrete fabric of the Winnipegosis Formation (see above discussion).

Absence of macrophyte root fabric is interpreted to be an ecologic and not a taphonomic effect. Firstly, delicate structures, such as laminar crusts, micritic coatings, and dolomitized filaments, are well preserved in the Winnipegosis calcrete. If there had been structures formed by or related to macrophyte root activity in the Winnipegosis calcrete profiles, some of them should have been preserved in the calcrete profiles. However, root-related fabric has not been observed after careful examination of core intervals from 18 wells, more than 120 thin sections, and over 70 hand specimens. Secondly, rooting by terrestrial plants began in the mid-Early Devonian with the appearance of short, forked roots (Algeo and Scheckler, 1998). During the Middle Devonian, arborescent plants were capable of deep rooting up to about 1 m (Driese et al., 1997; Elick et al., 1998). Paleosol deposits of the Middle Devonian Yahatinda Formation in Wasootch Creek, Alberta contain evidence of rooting activity (Williams and Krause, 2000). However, the early land plants had a pteridophytic reproductive mode, limited to moist lowland habitats (Remy et al., 1993; Kenrick, 1994). The development of seeds meant that land plants were no longer dependent on aqueous sperm dispersal, permitting occupation of habitats such as drier upland areas (Edwards and Berry, 1991). The earliest known seeds are Famennian (Late Devonian) in age (cf. Algeo and Scheckler, 1998). The Winnipegosis mud mounds in the study area were relatively small, isolated, and far away from the land areas (separated by water) during subaerial exposure, making it difficult for land plants to spread and colonize the Winnipegosis mud mounds in the arid Elk Point Basin.

Calcrete could superficially resemble travertine because of its pisolitic and laminated fabric. The pisolitic and laminated caps of the Winnipegosis mounds were previously interpreted as travertine that formed from saline groundwater/springs (Kendall, 1989). However, the pisolitic and laminated caps in the Winnipegosis mounds do not have the characteristic structures of travertine, such as radial array of needles, bladed crystals of calcite spar with compromise boundaries and arborescent/dendritic or shrub fabric (Table 1; cf. Chafetz and Folk, 1984; Demicco and Hardie, 1994; Evans, 1999). Rather, the structures preserved in the uppermost portions of the Winnipegosis mounds (such as multiple profiles with an orderly set of horizons) described in this paper represent typical features of pedogenic calcrete.

The majority of post-Silurian pedogenic calcrete profiles documented in the literature are root-related (Adams, 1980; Warren, 1983; Wright and Tucker, 1991; Aalto and Dill, 1996). This study provides a good example of a mature pedogenic calcrete that was not significantly influenced by macrophytes, which can be used to recognize pedogenic calcrete profiles not related to macrophytes in ancient carbonate sequences.

4.2. Subaerial diagenesis in response to water-level changes

The Winnipegosis mud mounds formed during transgressive and highstand system tracts (Jin and Bergman, 1999). The Winnipegosis calcrete profiles are directly superimposed on the underlying marine subtidal facies, such as crinoid wackestone, suggesting that subaerial exposure of the mounds was induced by drops in water level in the basin (i.e. allocyclic controls) and not by vertical aggradation of deposits into the subaerial realm (cf. Harrison and Steinen, 1978; Strasser, 1991; Tucker, 1993; Wright, 1994). The regional presence of thick multiple calcrete profiles further demonstrates that lowering of water level led to subaerial exposure of the Winnipegosis mounds.

The Winnipegosis mud mounds were developed during a regional transgression related to a rising of relative sea level (Jin and Bergman, 1999). During the development of Winnipegosis mound in the Saskatchewan Subbasin, however, the rising of the relative water level was punctuated by three episodes of major drop of relative water level as indicated by up to three well-developed, discrete pedogenic calcrete profiles present in the uppermost parts of the relatively high mounds (Figs. 4 and 10). The subprofiles in some individual Winnipegosis calcrete profiles are interpreted to represent minor orders of changes in water level during the punctuated rise (cf. Goldhammer et al., 1987; Wright, 1994). Variations in thickness of the Winnipegosis calcrete profiles and extent of calcrete development likely reflect variations in duration of subaerial exposure of the mud mounds (cf. Goldhammer et al., 1987). The Winnipegosis/Keg River succession was interpreted as the third-order sequence (Sarg, 2001). The three calcrete profiles and the multiple subprofiles in the Winnipegosis mud mounds (Figs. 4 and 10) documented in this study provide information about the fourth- to fifth-order sequence stratigraphic analysis of the Winnipegosis Formation.

5. Conclusions

(1) Dolomitized calcrete is a widespread diagenetic feature in the uppermost portions of the fully developed Winnipegosis mounds, and individual calcrete profiles vary from a few centimeters to a few meters in thickness. A Winnipegosis calcrete succession contains up to three profiles that consist of two to five well-differentiated horizons, composed (in descending order) of laminar crust, massive, pisolitic, breccia, chalky, and transitional horizons.

(2) The Winnipegosis calcrete is interpreted to be pedogenic and related to the diagenetic alteration of host carbonate deposits in the vadose zone during subaerial exposure. Absence of rhizoconcretions, alveolar–septal structures and *Microcodium* suggests that the Winnipegosis calcrete was not significantly influenced by plant-root activity. Absence of root fabric is interpreted to be an ecologic and not a taphonomic effect.

(3) Subaerial exposure of the Winnipegosis mounds was induced by drops in water level (allocyclicity) and not by vertical aggradational accumulation of carbonate deposits into the subaerial realm. The Winnipegosis mounds experienced three major periods of subaerial exposure and meteoric diagenesis during Middle Devonian time, as indicated by up to three discrete pedogenic calcrete profiles in a single-calcrete succession. The occurrence of multiple subprofiles in some individual Winnipegosis calcrete profiles are interpreted to result from minor orders of fluctuations of water level during the punctuated rise.

Acknowledgements

This project is funded by Vista Energy, Potash Corporation of Saskatchewan, National Sciences and Engineering Research Council of Canada (NSERC) IOR grant to K. Bergman and J. Jin, and NSERC Discovery grant (155012) to H. Qing. The Subsurface Geological Laboratory of Saskatchewan Industry and Resources provided access to the cores and facilities. The constructive comments by the Journal's reviewers, Drs. E. Mountjoy and P. Wright, significantly improved the manuscript. However, the interpretations are the author's.

References

Aalto, K.R., Dill, R.F., 1982. Late Pleistocene stratigraphy of a carbonate flatform margin, Exumas, Bahamas. Sedimentary Geology 103, 129–143.

Adams, A.E., 2001. Calcrete profiles in the Eyam limestone (Carboniferous) of Derbyshire: petrology and regional significance. Sedimentology 27, 651–660.

Algeo, T.J., Scheckler, S.E., 1986. Terrestrial–marine teleconnections in the Devonian: links between the evolution of land plants, weathering processes and marine anoxic events. Philosophical Transactions of the Royal Society of London. Series B, Biological Sciences 353, 113–130.

Alonso-Zarza, A.M., 1987. Initial stages of laminar calcrete formation by roots: examples from the Neogene of central Spain. Sedimentary Geology 126, 177–191.

Alonso-Zarza, A.M., 2001. Paleoenvironmental significance of palustrine carbonates and calcretes in the geological record. Earth-Science Reviews 60, 261–298.

Arakel, A.V., 1982. Genesis calcrete in Quaternary soil profiles, Hutt and Leeman lagoons, Western Australia. Journal of Sedimentary Petrology 52, 109–125.

Armenteros, I., Bustillo, M.A.A., Blanco, J.A., 1995. Pedogenic and groundwater processes in a close Miocene basin (northern Spain). Sedimentary Geology 99, 17–36.

Baillie, A.D., 1953. Devonian system of the Williston Basin area. Manitoba Mines Branch Publication, 52–55. 105 pp.

Bain, R.J., Foos, A.M., 1991. Carbonate microfabrics related to subaerial exposure and paleosol formation. In: Rezak, R., Lavoie, D. (Eds.), Carbonate Microfabrics. Springer-Verlag, Berlin, pp. 19–28.

Blank, H.R., Tynes, E.W., 1965. Formation of caliche in situ. Geological Society of America Bulletin 76, 1387–1392.

Braithwaite, C.J.R., 1975. Petrology of paleosols and other terrestrial sediments of Aldabra, western Indian Ocean. Philosophical Transactions of the Royal Society of London. Series B, Biological Sciences 273, 921–932.

Braithwaite, C.J.R., 1983. Calcrete and other soils in Quaternary limestones: structures, processes and applications. Journal of the Geological Society (London) 140, 351–363.

Calvet, F., Julia, R., 1983. Peloids in the caliche profiles of Tarragona (NE Spain). In: Peryt, T.M. (Ed.), Coated Grains. Springer-Verlag, Berlin, pp. 456–473.

Campbell, C.V., 1992. Upper Elk Point megasequence. In: Wendte, J., Stoakes, F.A., Campbell, C.V. (Eds.), Devonian–Early Mississipian Carbonates of the Western Canada Sedimentary Basin: A Sequence Stratigraphic Framework. SEPM Short Course, vol. 28, pp. 145–162.

Cao, R., Xue, Y., 1983. Vadose pisolite of the Tongying Formation (Upper Sinian System) in southwest China. In: Peryt, T.M. (Ed.), Coated Grains. Springer-Verlag, Berlin, pp. 548–560.

Chafetz, H.S., Folk, R.L., 1984. Travertines: depositional morphology and the bacterially constructed constituents. Journal of Sedimentary Petrology 54, 289–316.

Colson, J., Cojan, I., 1996. Grounwater dolocretes in a lake–marginal environment: an alternative model for dolocrete formation in continental settings (Danian of the Provence Basin, France). Sedimentology 43, 175–188.

Coniglio, M., Harrison, R.S., 1983. Holocene and Pleistocene caliche from Big Pine Key, Florida. Bulletin of Canadian Petroleum Geology 31, 3–13.

Demicco, R.V., Hardie, L.A., 1994. Sedimentary structures and early diagenetic features of shallow marine carbonate deposits. Society of Economic Paleontologists and Mineralogists, Atlas Series, vol. 1. Society of Sedimentary Geology, Tulsa, OK. 240 pp.

Driese, S.G., Mora, C.I., Elick, J.M., 1997. Morphology and taphonomy of root and stump casts of the earliest trees (Middle to Late Devonian), Pennsylvania and New York, USA. Palaios 12, 524–537.

Edwards, D., Berry, C., 1991. Silurian and Devonian. In: Cleal, C.J. (Ed.), Plant Fossils in Geological Investigation: The Paleozoic. Ellis Horwood, New York, pp. 117–153.

Ehrets, J.R., Kissling, D.L., 1987. Winnipegosis platform margin and pinnacle reef reservoirs, northwestern North Dakota. In: Fischer, D.W. (Ed.), Fifth International Williston Basin Symposium (Core Workshop). Miscellaneous Series-North Dakota Geological Survey, vol. 69, pp. 1–31.

Elick, J.M., Driese, S.G., Mora, C.I., 1998. Very large plant and root traces from the Early to Middle Devonian: implications for early terrestrial ecosystem and atmospheric pCO_2. Geology 26 (2), 143–146.

Esteban, M., 1976. Vadose pisolite and caliche. Bulletin of the American Association of Petroleum Geologists 60, 2048–2057.

Esteban, M., Klappa, C.F., 1983. Subaerial exposure. In: Scholle, P.A., Bebout, D.G., Moore, C.H. (Eds.), Carbonate Depositional Environments. Memoir – American Association of Petroleum Geologists, vol. 33, pp. 1–54.

Evans, J.E., 1999. Recognition and implications of Eocene tufas and travertines in the Chadron Formation, White River Group, Badlands of South Dakota. Sedimentology 46, 771–789.

Gendzwill, D.J., 1978. Winnipegosis mounds and Prairie Evaporite Formation of Saskatchewan seismic study. Bulletin of the American Association of Petroleum Geologists 62, 73–86.

Gendzwill, D.J., Wilson, N., 1987. Form and distribution of Winnipegosis mounds in Saskatchewan. Symposium on Rocky Mountain Association of Geologists, Denver, Colorado. Rocky Mountain Association of Geologists, Denver, CO, pp. 109–117.

Gerhard, L.C., Anderson, S.B., LeFever, J.A., Carlson, C.G., 1982. Geological development, origin, and energy mineral resources of Williston Basin, North Dakota. American Association of Petroleum Geologists Bulletin 66, 989–1020.

Goldhammer, R.K., Dunn, P.A., Hardie, L.A., 1987. High frequency glacio–eustatic sea level oscillations with Milankovitch characteristics recorded in Middle Triassic platform carbonates in northern Italy. American Journal of Science 287, 853–892.

Goudie, A.S., 1973. Duricrusts in Tropical and Subtropical Landscapes. Clarendon, Oxford. 174 pp.

Goudie, A.S., 1983. Calcretes. In: Goudie, A.S., Pye, K. (Eds.), Chemical Sediments and Geomorphology: Precipitates and Residua in the Near-Surface Environment. Academic Press, London, pp. 93–131.

Goudie, A.S., 1996. Organic agency in calcrete development. Journal of Arid Environments 32, 103–112.

Hanford, C.R., Kendall, A.C., Prezbindowski, D.R., Dunham, J.B., Logan, B.W., 1984. Salina–margin teepes, pisoliths and argonite cements, Lake Macleod, Western Australia: their significance in interpreting ancient analogs. Geology 12, 523–527.

Harrison, R.S., 1977. Calcrete profile: indicators of near-surface subaerial diagenesis, Barbados, West Indies. Bulletin of Canadian Petroleum Geology 25, 123–173.

Harrison, R.S., Steinen, R.P., 1978. Subaerial crusts, caliche profiles and breccia horizons: comparison of some Holocene and Mississippian exposure surfaces, Barbados and Kentucky. Geological Society of America Bulletin 89, 385–396.

Hay, R.L., Reeder, R.J., 1978. Calcretes of Olduvai Gorge and the Ndolanya Beds of northern Tanzania. Sedimentology 25, 649–672.

Hay, R.L., Wiggins, B., 1980. Pellets, ooids, sepiolite and silica in three calcretes of the southwestern United States. Sedimentology 27, 559–576.

Holter, M.E., 1969. The Middle Devonian Prairie Evaporite of

Saskatchewan. Report-Department of Mineral Resources (Saskatchewan) 123, 1–6.

Hsu, K.J., Siegenthaler, C., 1969. Preliminary experiments on hydrodynamic movement induced by evaporation and their bearing on the dolomite problem. Sedimentology 12, 11–25.

Jacobson, G., Arakel, A.V., Chen, Y., 1988. The central Australian groundwater discharge zone: evolution of associated calcrete and gypcrete deposits. Australian Journal of Earth Sciences 35, 549–565.

James, N.P., 1972. Holocene and Pleistocene calcareous crust (caliche) profiles: criteria for subaerial exposure. Journal of Sedimentary Petrology 42, 817–836.

Jin, J., Bergman, K.M., 1999. Sequence stratigraphic analysis of the Winnipegosis carbonate—Prairie Evaporite transition in the Middle Devonian Elk Point Basin, southern Saskatchewan. Carbonates and Evaporites 14, 64–83.

Jin, J., Bergman, K.M., Haidl, F., Blair, M., Ricci, A., 1997. Vadose diagenesis of the Winnipegosis carbonate and the origin of the Ratner laminate and Whitkow anhydrite, Middle Devonian, southern Saskatchewan. Summary of investigations 1997. Miscellaneous Report-Saskatchewan Geological Survey 97-94, 197–212.

Jin, J., Bergman, K.M., 2001. Revised stratigraphy of the Middle Devonian (Givetian) Winnipegosis carbonate–Prairie Evaporite transition, Elk Point Group, southern Saskatchewan. Bulletin of Canadian Petroleum Geology 49, 441–457.

Jones, L.J., 1965. The Middle Devonian Winnipegosis formation of Saskatchewan. Report-Department of Mineral Resources (Saskatchewan) 98, 101 pp.

Jutras, P., Prichonnet, G., Von Bitter, P.H., 1999. The La Coulee Formation, a new post-Acadian continental clastic unit bearing groundwater calcretes, Gaspe Peninsula, Quebec. Atlantic Geology 35, 139–156.

Kahle, C.F., 1977. Origin of subaerial Holocene calcareous crusts: role of algae, fungi and sparmicritisation. Sedimentology 24, 413–435.

Kendall, A.C., 1975. The Middle Devonian Winnipegosis and lower Prairie Evaporite Formations of the commercial potash areas. Summary Report of Field Investigations by the Saskatchewan Geological Survey, 61–65.

Kendall, A.C., 1989. Brine mixing in the Middle Devonian of western Canada and its possible significance to regional dolomitization. Sedimentary Geology 64, 271–285.

Kenrick, P., 1994. Alternation of generation in land plants: new phylogenetic and paleobotanical evidence. Biological Reviews 69, 293–330.

Kent, D.M., 1994. Paleographic evolution of the Cratonic Platform—Cambrian to Triassic. In: Mossop, G., Shetsen, I. (Eds.), Geological Atlas of the western Canada Sedimentary Basin. Canadian Society of Petroleum Geolologist and The Alberta Research Council, Calgary, Alberta, pp. 68–87.

Khadkikar, A.S., Merh, S.S., Malik, J.N., Chamyal, L.S., 1998. Calcretes in semi-arid alluvial systems: formative pathway and sinks. Sedimentary Geology 116, 251–260.

Klappa, C.F., 1979a. Lichen stromatolites: criterion of subaerial exposure and a mechanism for the formation of laminar calcretes (caliche). Journal of Sedimentary Petrology 49, 387–400.

Klappa, C.F., 1979b. Calcified filaments in Quaternary calcretes: organo–mineral interactions in the subaerial vadose environment. Journal of Sedimentary Petrology 49, 955–968.

Klappa, C.F., 1980. Rhizoliths in terrestrial carbonates: classification, recognition, genesis and significance. Sedimentology 27, 613–629.

Klappa, C.F., 1983. A process–response model for the formation of pedogenic calcretes. In: Wilson, R.C.L. (Ed.), Residual Deposits: Surface Related Weathering Processes and Materials. Blackwell, Oxford, pp. 211–220.

Maiklem, W.A., 1971. Evaporative drawdown—a mechanism for water-level lowering and diagenesis in the Elk Point Basin. Bulletin of Canadian Petroleum Geology 19, 487–503.

Mann, A.W., Horwitz, R.C., 1979. Groundwater calcrete deposits in Australia: some observation in Western Australia. Journal of Geological Society of Australia 26, 293–303.

Martindale, W., Erkmen, U., Metcalfe, D., Potts, E., 1991. Winnipegosis buildups of the Hitchcock area, southeastern Saskatchewan—a case study. In: Christopher, J.E., Haidl, F.M. (Eds.), Sixth International Williston Basin Symposium. Special Publication-Saskatchewan Geological Society, vol. 11, pp. 47–63.

Meijer Drees, N.C., 1986. Evaporite deposits of western Canada. Geological Survey of Canada Paper 85–120. 118 pp.

Milnes, A.R., 1992. Calcrete. In: Martini, I.P., Chesworth, W. (Eds.), Weathering, Soils and Paleosol. Development in Earth Surface Processes, vol. 2, pp. 309–347.

Moore, P.F., 1989. Devonian geohistory of the western interior of Canada. In: McMillan, N.J., Embry, A.F., Glass, D.J. (Eds.), Devonian System of the World—2nd International Symposium on the Devonian System. Memoir-Canada Society of Petroleum Geologists, vol. 14 (1), pp. 67–84.

Nash, D.J., Smith, R.F., 1998. Multiple calcrete profiles in the Tabernas Basin, southeast Spain: their origins and geomorphic implications. Earth Surface Processes and Landforms 23, 1009–1029.

Packard, J.J., Cave, G., Al-Aasm, I., 2002. Marine pisoids versus pedogenic vadoids: an old controversy revisited using new core from the Mississipian Frobisher Formation in the Benson area, SE Saskatchewan. Diamond Jubilee Core Convention Abstracts (including extended abstracts). Canadian Society of Petroleum Geologist, Calgary, Alberta, pp. 58–65.

Pelechaty, S.M., James, N.P., 1991. Dolomitized middle Proterozoic calcretes, Bathurst Inlet, Northwest Territories, Canada. Journal of Sedimentary Petrology 61, 988–1001.

Perrin, N.A., 1982. Environments of depositions and diagenesis of the Winnipegosis Formation (Middle Devonian), Williston Basin, North Dakota. In: Christopher, J.E., Kaldi, J. (Eds.), Fourth International Williston Basin Symposium. Special Publication-Saskatchewan Geological Society, vol. 6, pp. 51–66.

Peryt, T.M., 1983. Vadoids. In: Peryt, T.M. (Ed.), Coated Grains. Springer-Verlag, Berlin, pp. 437–449.

Pimentel, N.L., Wright, V.P., Azevedo, T.M., 1996. Distinguishing early groundwater alternation effects from pedogenesis in ancient alluvial basins: examples from the Palaeogene of southern Portugal. Sedimentary Geology 105, 1–10.

Qing, H., 1998. Geochemical constraints on the origin and timing of paleofluid flow in the Presqu'ile barrier reef, western Canada sedimentary basin. In: Parnell, J. (Ed.), Dating and Duration of Fluid Flow and Fluid–Rock Interaction. Special Publications-Geological Society (London), vol. 144, pp. 173–187.

Qing, H., Mountroy, E., 1994. Rare earth element geochemistry of dolomites in the Middle Devonian Prequ'ile barrier, western Canada sedimentary basin: implications for fluid rock ratios during dolomitization. Sedimentology 41, 787–804.

Read, J.F., 1974. Calcrete deposits and Quaternary sediments, Edel Province, Shark Bay, Western Australia. In: Logan, B.W., et al., (Eds.), Evolution and Diagenesis of Quaternary Carbonate Sequences, Shark Bay, Western Australia. Memoir-American Association of Petroleum Geologists, vol. 12, pp. 250–282.

Read, J.F., 1976. Calcretes and their distinction from stromatolites. In: Walter, M.R. (Ed.), Stromatolites. Development in Sedimentology, vol. 20. Elsevier, Amsterdam, pp. 57–71.

Reeves, C.C.J., 1970. Origin, classification and geologic history of caliche on the southern high plains, Texas and eastern New Mexico. Journal of Geology 78, 352–362.

Reinhardt, E., Sigleo, W.R., 1988. Paleosols and Weathering Through Geological Time: Principles and Applications. The Geological Society of America, Boulder, Colorado. 211 pp.

Reinson, G.E., Wardlaw, N.C., 1972. Nomenclature and stratigraphic relationships, Winnipegosis and Prairie Evaporite Formations, central Saskatchewan. Bulletin of Canadian Petroleum Geology 20, 301–320.

Remy, W., Gensel, P.G., Hass, H., 1993. The gametophyte generation of some Early Devonian land plants. International Journal of Plant Sciences 154, 35–58.

Rickette, B.D., 1989. Introduction. In: Ricketts, B.D. (Ed.), Western Canada Sedimentary Basin—A Case History. Canadian Society of Petroleum Geologists, Calgary, Alberta, pp. 3–8.

Rosenthal, L.R., 1987. The Winnipegosis Formation of the northeastern margin of the Williston Basin. In: Carlson, C.G., Christopher, J.E. (Eds.), Fifth International Williston Basin Symposium. Saskatchewan Geological Society Special Publication, vol. 9, pp. 37–46.

Rossinsky Jr., V., Wanless, H.R., Swart, P.K., 1992. Penetrative calcretes and their stratigraphic implications. Geology 20, 331–334.

Sarg, J.F., 2001. The sequence, stratigraphy, sedimentology, and economic importance of evaporite-carbonate transitions: a review. Sedimentary Geology 140, 9–42.

Stoakes, F., Cambell, C., Hassler, G., Dixon, R., Forbes, D., 1987. Sedimentology and hydrocarbon source potential of the Middle Devonian Winnipegosis Formation of southeastern Saskatchewan. Stoakes Campbell Geoconsulting Report (unpublished). 98 pp.

Strasser, A., 1991. Lagoonal–peritidal sequences in carbonate environment: autocyclic and allocyclic processes. In: Einsele, G., Ricken, W., Seilacher, A. (Eds.), Cycles and Events in Stratigraphy. Springer-Verlag, Berlin, pp. 709–721.

Tandon, S.K., Kumar, S., 1999. Semi-arid/arid zone calcretes: a review. In: Singhvi, A.K., Derbyshire, E. (Eds.), Paleoenvironmental Reconstruction in Quaternary Arid Lands. Rotterdam, Netherlands, pp. 109–152.

Tandon, S.K., Andrews, J.E., Sood, A., Mittal, S., 1998. Shrinkage and sediment supply control on multiple calcrete profile development: a case study from the Maastrichtian of central India. Sedementary Geology 119, 25–45.

Tucker, M.E., 1993. Carbonate diagenesis and sequence stratigraphy. In: Wright, P.V. (Ed.), Sedimentology Review, vol. 1, pp. 51–72.

Vander Voo, R., 1988. Paleozoic paleogeography of North America, Gondwana and intervening displaced terrains: comparisons of paleomagmatism with paleoclimatology and biogeographical patterns. Geological Society of America Bulletin 100, 311–324.

Verrecchia, E.P., Dumont, J.-L., Verrecchia, K.E., 1993. Role of calcium oxalate biomineralization by fungi in the formation of calcretes: a case study from Nazareth, Israel. Journal of Sedimentary Petrology 63, 1000–1006.

Verrecchia, E.P., Freytet, P., Verrecchia, K.E., Dumont, J.-L., 1995. Spherulites in calcrete laminar crusts: biogenic $CaCO_3$ precipitation as a major contributor to crust formation. Journal of Sedimentary Research 65, 690–700.

Wang, Y., Nahon, D., Merino, E., 1994. Dynamic model of the genesis of calcretes replacing silicate rocks in semi-arid regions. Geochimica et Cosmochimica Acta 58, 5131–5145.

Ward, W.C., 1997. Geology of Coastal Islands, northeastern Yucatan Peninsula. In: Vacher, H.L., Quinn, T.M. (Eds.), Geology and Hydrogeology of Carbonate Islands. Developments in Sedimentology, vol. 54. Elsevier, Amsterdam, pp. 275–298.

Ward, W.C., Brady, M.J., 1979. Strandline sedimentation of carbonate grainstones, upper Pleistocene, Yucatan Peninsula, Mexico. Bulletin of the American Association of Petroleum Geologists 63, 362–369.

Wardlaw, N.C., Reinson, G.E., 1971. Carbonate and evaporite deposition and diagenesis, Middle Devonian Winnipegosis and Prairie Evaporite Formations of Saskatchewan. American Association of Petroleum Geologists Bulletin 55, 1759–1786.

Wardlaw, N.C., Schwerdtner, W.M., 1966. Halite–anhydrite seasonal layers in the Middle Devonian Prairie Evaporite Formation, Saskatchewan, Canada. Geological Society of America Bulletin 77, 331–342.

Warren, J.K., 1983. Pedogenic calcrete as it occurs Quaternary calcareous dunes in coastal South Australia. Journal of Sedimentary Petrology 53, 787–796.

Watts, N.L., 1980. Quaternary pedogenic calcretes from the Kalahari (Southern Africa): mineralogy, genesis and diagenesis. Sedimentology 27, 661–686.

Williams, C.A., Krause, F.F., 1998. Pedogenic–phreatic carbonates on a Middle Devonian (Givetian) terrigenous alluvial–deltaic plain, Gilwood Member (Watt Mountain Formation), north–central Alberta, Canada. Sedimentology 45, 1105–1124.

Williams, C.A., Krause, F.F., 2000. Paleosol chronosequences and peritidal deposits of the Middle Devonian (Givetian) Yahatinda Formation, Wasootch Creek, Alberta, Canada. Bulletin of Canadian Petroleum Geology 48, 1–18.

Witzke, B.J., 1990. Paleoclimatic constrains for Paleozoic paleolatitudes of Laurentia and Euramerica. In: Makerro, W.S., Scotese, C.R. (Ed.), Paleozoic Paleography and Biogeography. Memoir-Geological Society of London, vol. 12, pp. 57–73.

Witzke, B.J., Heckel, P.H., 1988. Paleoclimatic indicators and inferred Devonian paleolatitudes Euramerica. In: McMillan, A.F., Embry, A.F., Glass, D.J. (Eds.), Devonian System of the World 2nd International Symposium on the Devonian System. Memoir Canadian Society of Petroleum Geologists, vol. 14 (1), pp. 49–63.

Wright, V.P., 1989. Terrestrial stromatolites and laminar calcretes: a review. Sedimentary Geology 65, 1–13.

Wright, V.P., 1994. Paleosols in shallow marine carbonate sequences. Earth-Sciences Reviews 35, 367–395.

Wright, V.P., Tucker, M.E., 1991. Calcretes: introduction. In: Wright, V.P., Tucker, M.E. (Eds.), Calcretes. Reprint Series of the International Association of Sedimentologists, vol. 2, pp. 1–24.

Wright, V.P., Platt, N.H., Wimbledon, W.A., 1988. Biogenic laminar calcretes: evidence of calcified root–mat horizons in paleosols. Sedimentology 35, 603–620.

Wright, V.P., Platt, N.H., Marriott, S.B., Beck, V.H., 1995. A classification of rhizogenic (root-formed) calcretes, with examples from the Upper Jurassic–Lower Cretaceous of Spain and Upper Cretaceous of southern France. Sedimentary Geology 100, 143–158.