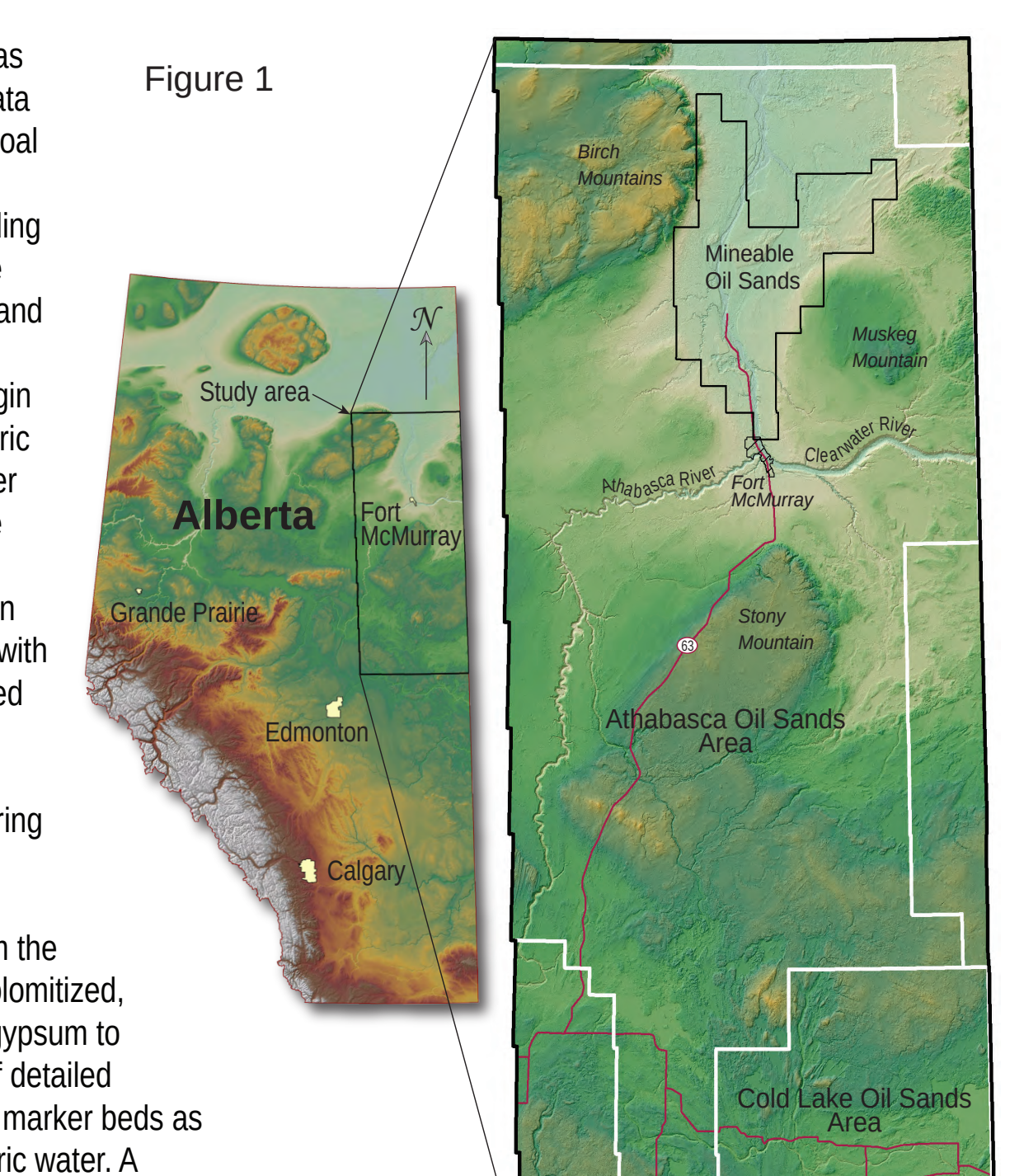
# Intrastratal Dedolomite and Secondary Gypsum in the Prairie Evaporite Formation of Northeastern Alberta: Diagenesis in a Carbonate-Sulphate System

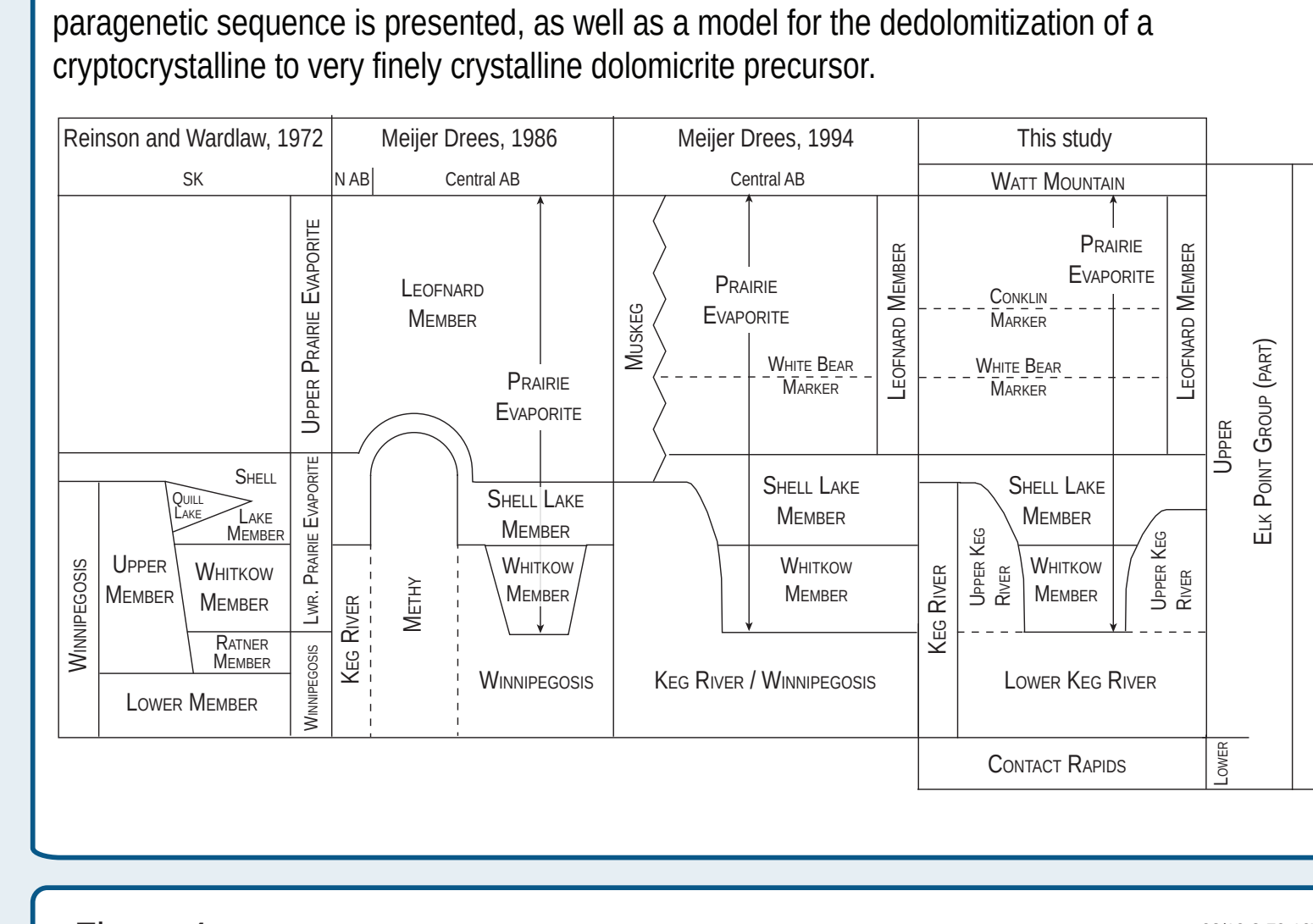
## Introduction

Mapping of the Middle Devonian Prairie Evaporite Formation was undertaken as a part of a regional assessment of Paleozoic strata in the oil sands areas of northeastern Alberta (Fig. 1). A major goal of the mapping program included a reassessment of the Prairie Evaporite halite dissolution scarp, a major NW–SE-trending intrastratal karst feature that has had a significant impact on the sedimentary succession in the region. During orogenic loading and the westward tilting of the Devonian succession, the Prairie Evaporite Formation was exposed along the eastern basin margin prior to and during Early Cretaceous deposition. Influx of meteoric water resulted in intrastratal karst within the succession.To better determine the location and architecture of the scarp, cumulative evaporite mineral (halite, anhydrite, and gypsum) mapping was undertaken to assess the nature and degree of dissolution within and east of the scarp. Evaporite mineral mapping was coupled with detailed correlation of Prairie Evaporite member- and marker-bed stratigraphy (Fig. 2). Marker beds are regionally extensive and consist of dolomudstone and anhydrite beds with lesser shale. They record pauses in evaporitic drawdown within the basin during the Middle Devonian. East of the dissolution scarp, the marker beds have survived dissolution, and show distinct diagenetic characteristics that point to the infiltration of meteoric water from the basin margin. The dolomudstone beds are partially to fully dedolomitized, and the anhydrite that encases them have been rehydrated to gypsum to varying extents. These observations, coupled with the results of detailed petrography and stable isotope analysis, point to the carbonate marker beds as being conduits for the infiltration of basin-margin derived meteoric water. A paragenetic sequence is presented, as well as a model for the dedolomitization of a cryptocrystalline to very finely crystalline dolomicrite precursor.

Figure 1



Study area
N
Alberta
Grande Prairie
Fort McMurray
Edmonton
Calgary
Birch Mountains
Mineable Oil Sands
Muskeg Mountain
Clearwater River
Athabasca River
Fort McMurray
Stony Mountain
Athabasca Oil Sands Area
Cold Lake Oil Sands Area
50 km

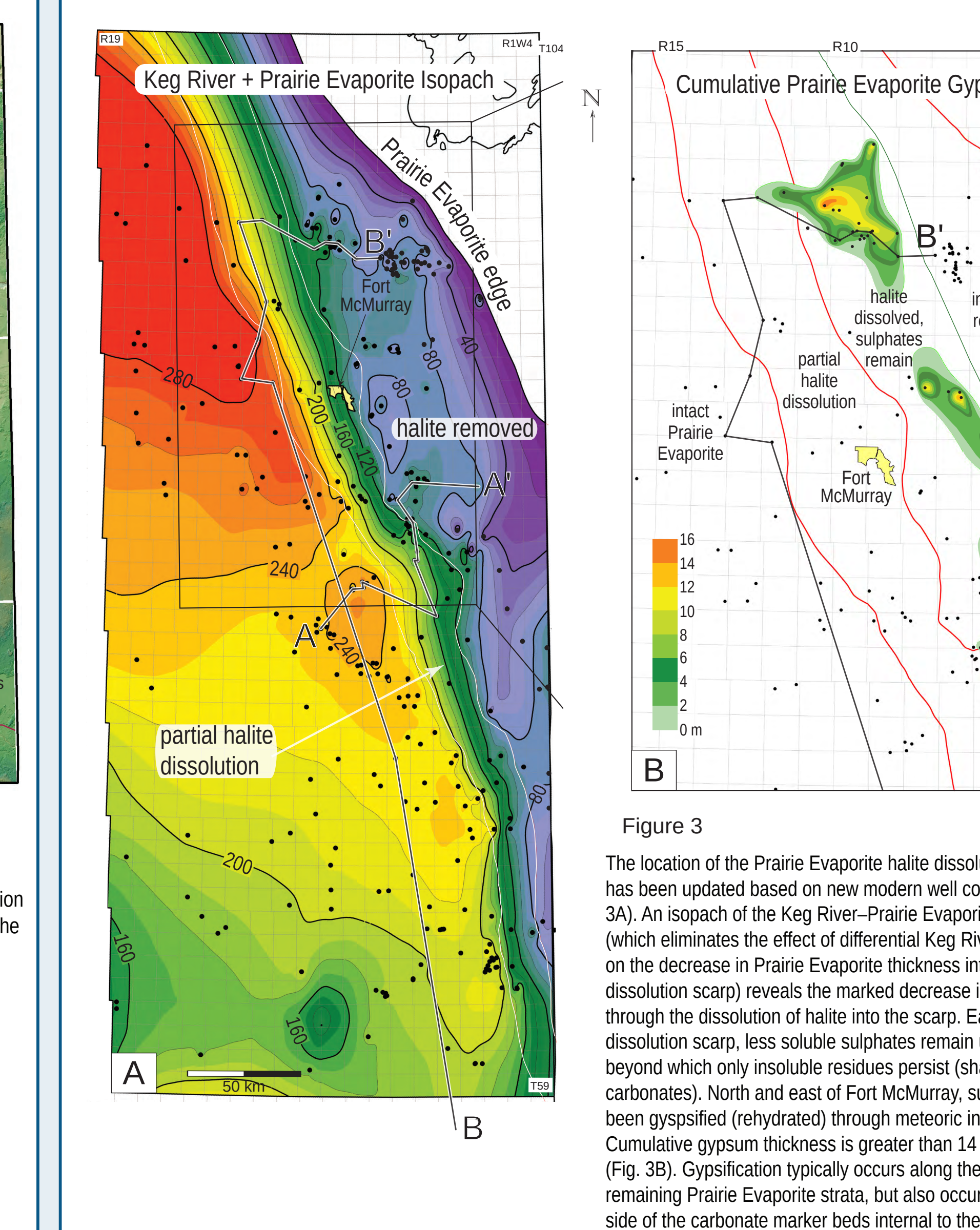


Reinson and Wardlaw, 1972
SK
Meijer Drees, 1986
N AB
Central AB
Meijer Drees, 1994
Central AB
This study
Watt Mountain
Upper Prairie Evaporite
Leofnard Member
Prairie Evaporite
Muskeg
Prairie Evaporite
White Bear Marker
Leofnard Member
Prairie Evaporite
Conklin Marker
White Bear Marker
Leofnard Member
Upper Elk Point Group (part)
Devonian
Shell
Quill Lake
Lake Member
Shell Lake Member
Shell Lake Member
Shell Lake Member
Upper Member
Whitkow Member
Ratner Member
Lower Member
Winnipegosis
Lwr. Prairie Evaporite
Winnipegosis
Keg River
Methy
Whitkow Member
Winnipegosis
Whitkow Member
Keg River / Winnipegosis
Keg River
Upper Keg River
Whitkow Member
Upper Keg River
Lower Keg River
Contact Rapids
Lower

Figure 2

Strata of the Prairie Evaporite Formation overly the dolomitized carbonates of the Keg River Formation. Initial evaporite deposition was constrained by the location of upper Keg River buildups, with the Whitkow Member halite restricted to interbuildup basins. Anhydrite of the Shell Lake overlies these deposits. Halite of the Leofnard Member, with a number of regionally mappable marker beds, record extensive evaporite deposition in the basin.

## Basin-Margin, Intrastratal Karst in the Prairie Evaporite Formation



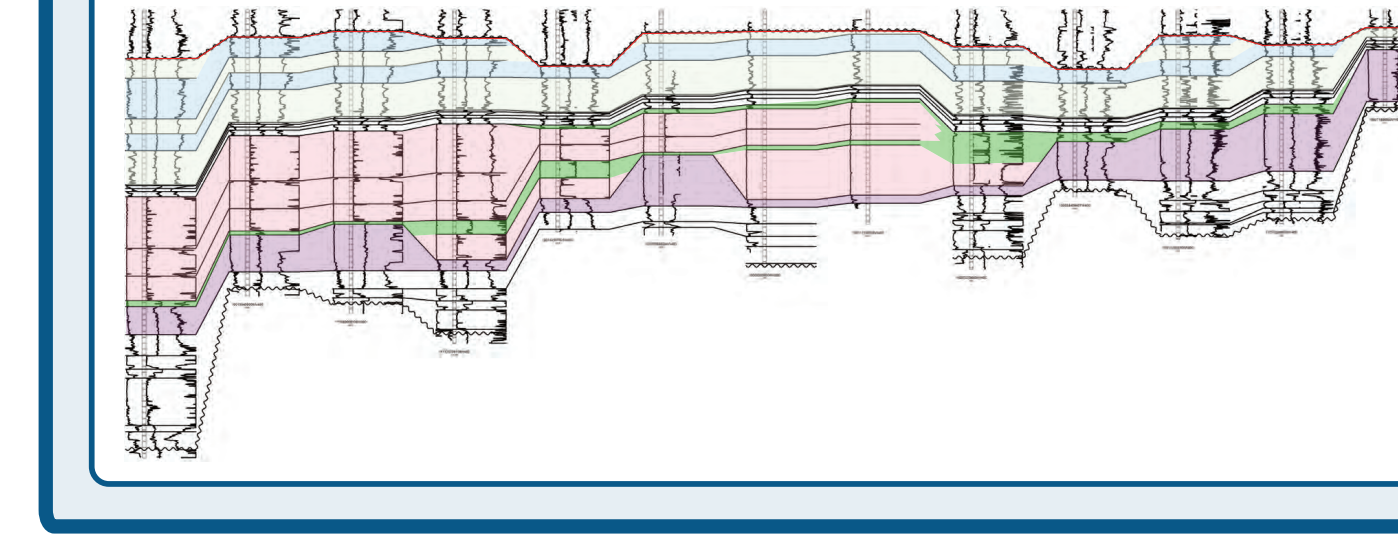
R19
R1W4
T104
Keg River + Prairie Evaporite Isopach
Prairie Evaporite edge
B'
Fort McMurray
halite removed
A'
A
partial halite dissolution
280
240
200
160
120
80
40
50 km
T59
A
B
N
R15
R10
R4
Cumulative Prairie Evaporite Gypsum
T100
T95
T90
T85
T80
B'
halite dissolved, sulphates remain
insoluble residues
partial halite dissolution
intact Prairie Evaporite
Fort McMurray
16
14
12
10
8
6
4
2
0 m
B

Figure 3

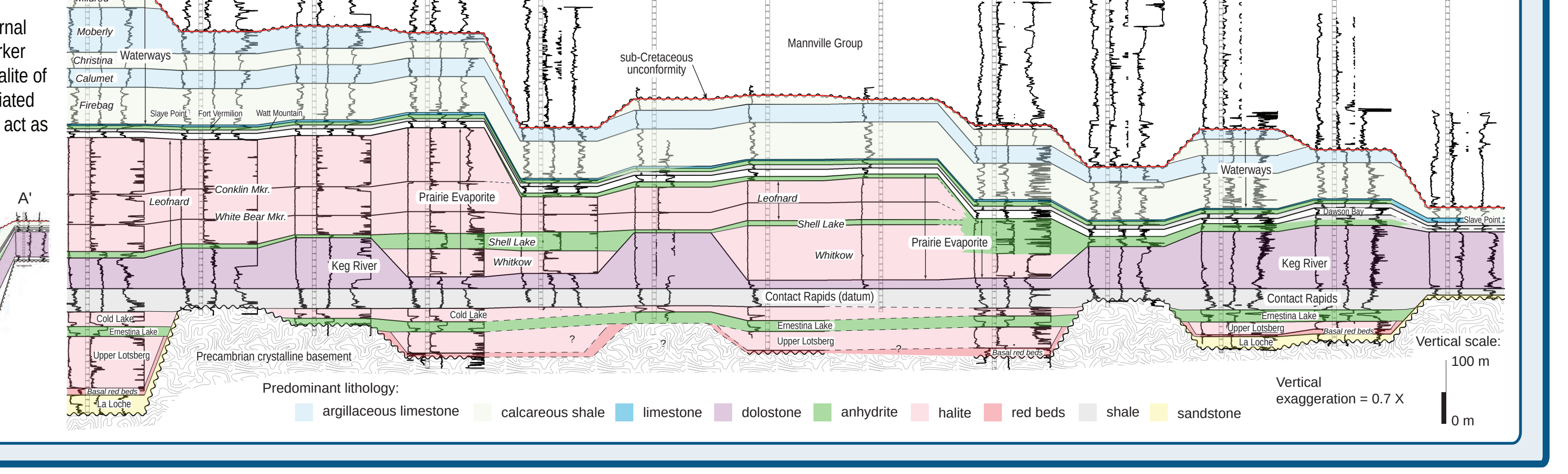
The location of the Prairie Evaporite halite dissolution scarp has been updated based on new modern well control (Fig. 3A). An isopach of the Keg River–Prairie Evaporite succession (which eliminates the effect of differential Keg River buildups on the decrease in Prairie Evaporite thickness into the dissolution scarp) reveals the marked decrease in thickness through the dissolution of halite into the scarp. East of the dissolution scarp, less soluble sulphates remain up to a point, beyond which only insoluble residues persist (shales and carbonates). North and east of Fort McMurray, sulphates have been gyspsified (rehydrated) through meteoric infiltration. Cumulative gypsum thickness is greater than 14 m in places (Fig. 3B). Gypsification typically occurs along the top of the remaining Prairie Evaporite strata, but also occurs on either side of the carbonate marker beds internal to the Prairie Evaporite Formation.

Figure 4

Regional cross-sections show the distribution of Prairie Evaporite Formation members related to underlying Keg River buildups. Whitkow Member halite is restricted to interbuildup basins, whereas the halite of the Leofnard Member—along with internal marker beds—is laterally extensive across the study area. Correlation of the marker beds into the dissolution scarp reveals that dissolution occured top-down, with halite of the Leofnard Member dissolving first. Eastward, the marker beds are undifferentiated due to difficulty in correlation. They are encased in the remaining sulphates, and act as conduits for fluid flow, likely playing a role in the dissolution history of the Prairie Evaporite Formation.



A
Structural cross-section
A'



02/10-8-79-10W4
15-34-80-9W4
F1/3-6-81-8W4
F1/12-7-81-8W4
14-29-79-5W4
7-8-82-6W4
3-9-82-6W4
11-21-82-6W4
7-32-83-6W4
3-34-84-7W4
11-20-85-6W4
02/10-26-85-6W4
7-18-85-3W4
A
A'
GR BD RES
Mildred
Moberly
Christina
Calumet
Firebag
Waterways
Slave Point
Fort Vermilion
Watt Mountain
sub-Cretaceous unconformity
Mannville Group
Leofnard
Conklin Mkr.
White Bear Mkr.
Prairie Evaporite
Shell Lake
Whitkow
Keg River
Contact Rapids (datum)
Cold Lake
Ernestina Lake
Upper Lotsberg
Basal red beds
La Loche
Precambrian crystalline basement
Waterways
Dawson Bay
Slave Pt.
Vertical scale:
100 m
0 m
Vertical exaggeration = 0.7 X
Predominant lithology:
argillaceous limestone
calcareous shale
limestone
dolostone
anhydrite
halite
red beds
shale
sandstone

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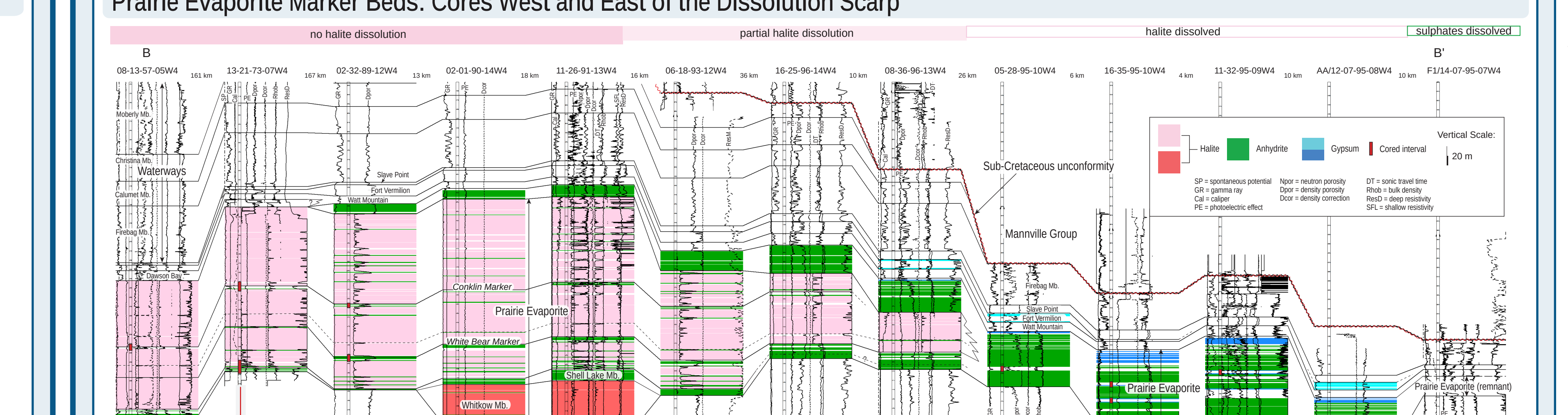
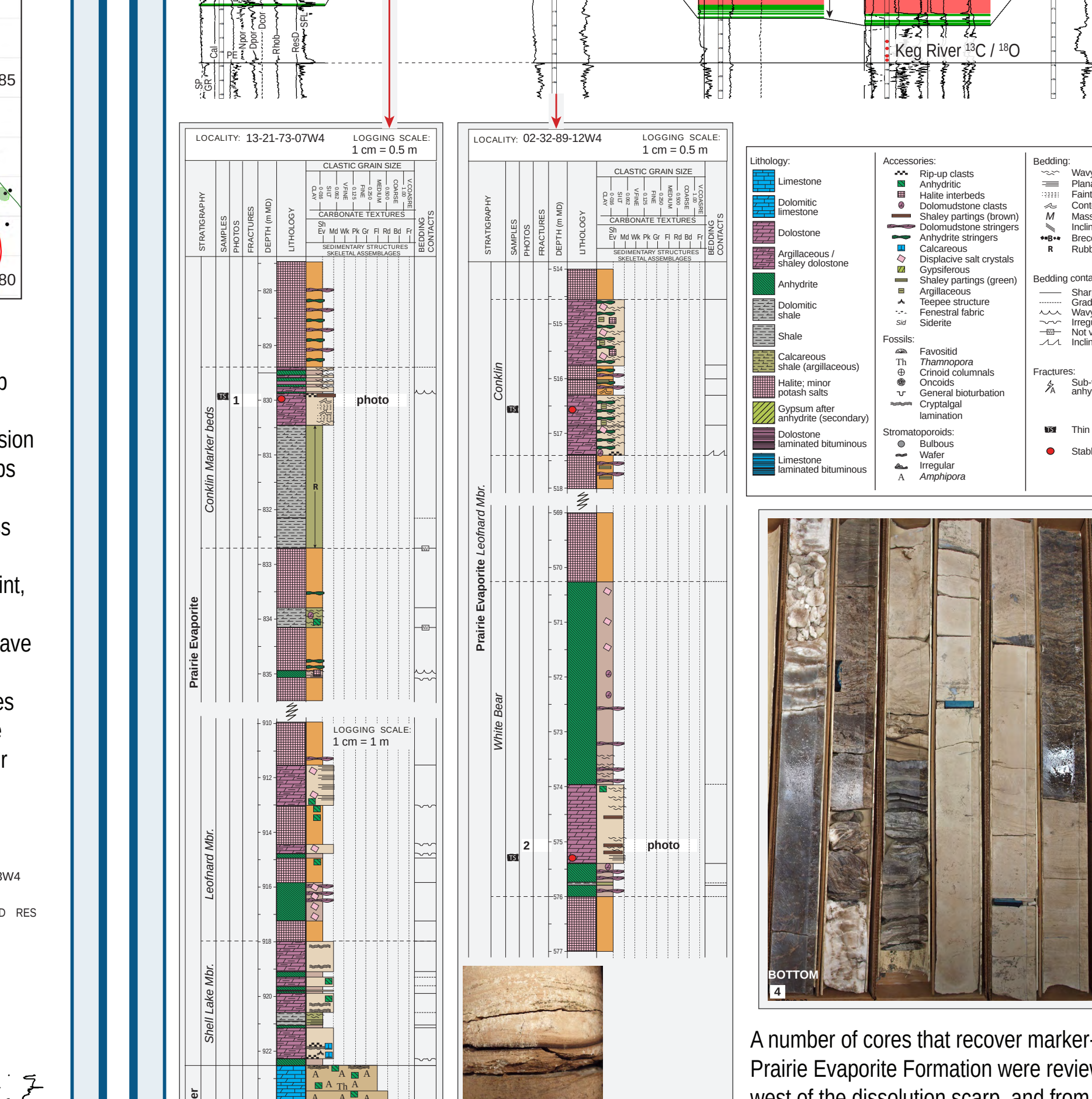
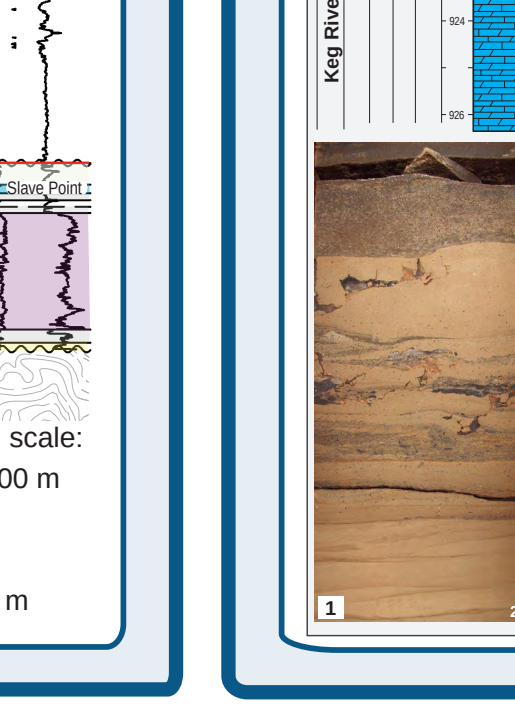
## Prairie Evaporite Marker Beds: Cores West and East of the Dissolution Scarp

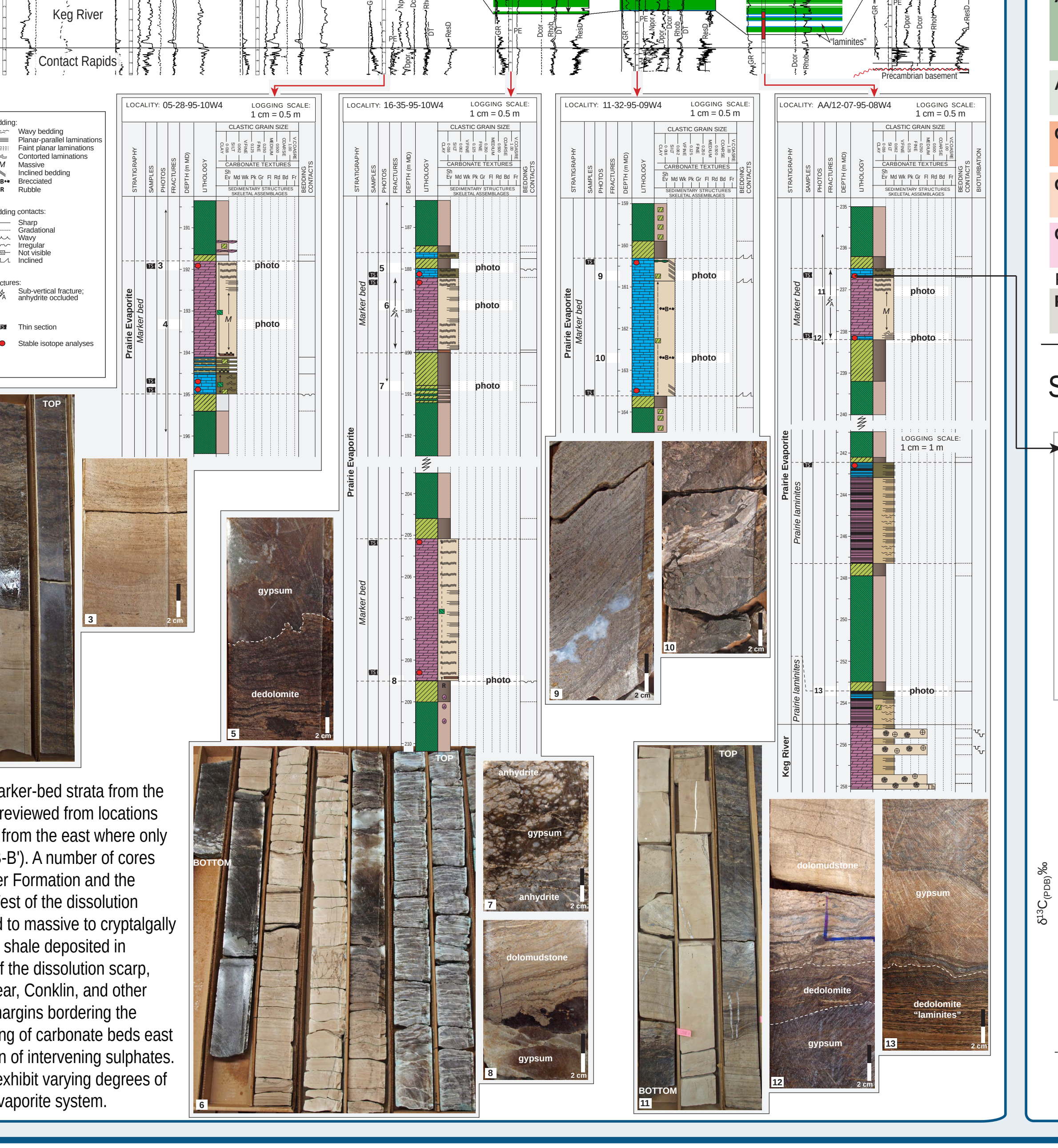


no halite dissolution
partial halite dissolution
halite dissolved
sulphates dissolved
B
B'
08-13-57-05W4
161 km
13-21-73-07W4
167 km
02-32-89-12W4
13 km
02-01-90-14W4
18 km
11-26-91-13W4
16 km
06-18-93-12W4
36 km
16-25-96-14W4
10 km
08-36-96-13W4
26 km
05-28-95-10W4
6 km
16-35-95-10W4
4 km
11-32-95-09W4
10 km
AA/12-07-95-08W4
10 km
F1/14-07-95-07W4
Moberly Mb.
Christina Mb.
Calumet Mb.
Firebag Mb.
Dawson Bay
Waterways
Slave Point
Fort Vermilion
Watt Mountain
Conklin Marker
Prairie Evaporite
White Bear Marker
Shell Lake Mb.
Whitkow Mb.
Keg River 13C / 18O
Keg River
Contact Rapids
Sub-Cretaceous unconformity
Mannville Group
Firebag Mb.
Slave Point
Fort Vermilion
Watt Mountain
Prairie Evaporite
Prairie Evaporite (remnant)
"laminites"
Precambrian basement
Halite
Anhydrite
Gypsum
Cored interval
Vertical Scale:
20 m
SP = spontaneous potential
GR = gamma ray
Cal = caliper
PE = photoelectric effect
Npor = neutron porosity
Dpor = density porosity
Dcor = density correction
DT = sonic travel time
Rhob = bulk density
ResD = deep resistivity
SFL = shallow resistivity



LOCALITY: 13-21-73-07W4
LOGGING SCALE: 1 cm = 0.5 m
LOCALITY: 02-32-89-12W4
LOGGING SCALE: 1 cm = 0.5 m
CLASTIC GRAIN SIZE
CARBONATE TEXTURES
STRATIGRAPHY
SAMPLES
PHOTOS
FRACTURES
DEPTH (m MD)
LITHOLOGY
BEDDING CONTACTS
Conklin Marker beds
Prairie Evaporite
Leofnard Mbr.
Shell Lake Mbr.
Keg River
Conklin
White Bear
photo
LOGGING SCALE: 1 cm = 1 m
Lithology:
Limestone
Dolomitic limestone
Dolostone
Argillaceous / shaley dolostone
Anhydrite
Dolomitic shale
Shale
Calcareous shale (argillaceous)
Halite; minor potash salts
Gypsum after anhydrite (secondary)
Dolostone laminated bituminous
Limestone laminated bituminous
Accessories:
Rip-up clasts
Anhydritic
Halite interbeds
Dolomudstone clasts
Shaley partings (brown)
Dolomudstone stringers
Anhydrite stringers
Calcareous
Displacive salt crystals
Gypsiferous
Shaley partings (green)
Argillaceous
Teepee structure
Fenestral fabric
Siderite
Fossils:
Favositid
Thamnopora
Crinoid columnals
Oncoids
General bioturbation
Cryptalgal lamination
Stromatoporoids:
Bulbous
Wafer
Irregular
Amphipora
Bedding:
Wavy bedding
Planar-parallel laminations
Faint planar laminations
Contorted laminations
Massive
Inclined bedding
Brecciated
Rubble
Bedding contacts:
Sharp
Gradational
Wavy
Irregular
Not visible
Inclined
Fractures:
Sub-vertical fracture; anhydrite occluded
Thin section
Stable isotope analyses
TOP
BOTTOM
3
4
2 cm



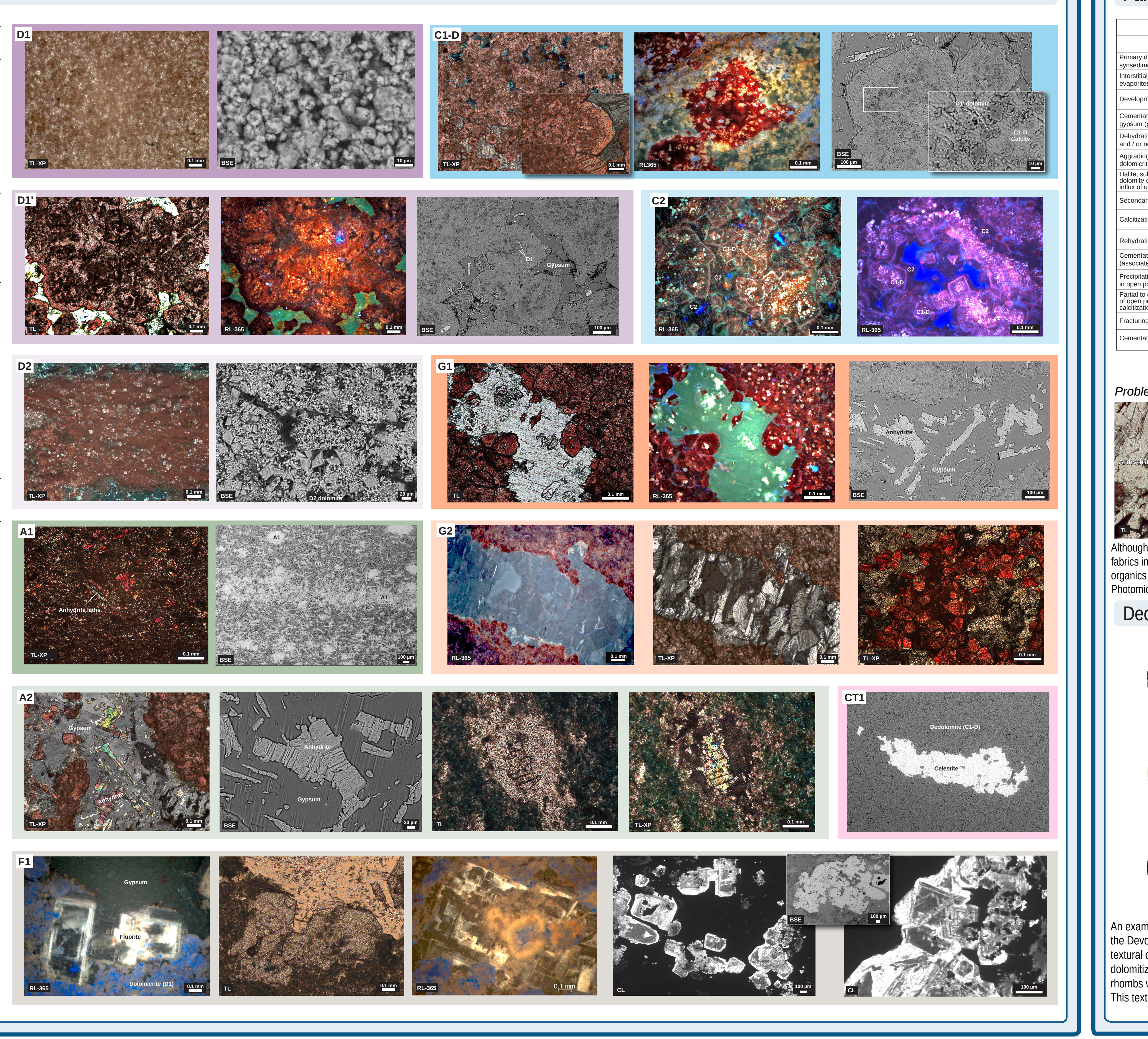


LOCALITY: 05-28-95-10W4
LOGGING SCALE: 1 cm = 0.5 m
LOCALITY: 16-35-95-10W4
LOGGING SCALE: 1 cm = 0.5 m
LOCALITY: 11-32-95-09W4
LOGGING SCALE: 1 cm = 0.5 m
LOCALITY: AA/12-07-95-08W4
LOGGING SCALE: 1 cm = 0.5 m
Prairie Evaporite
Marker bed
Prairie laminites
Keg River
photo
LOGGING SCALE: 1 cm = 1 m
gypsum
dedolomite
anhydrite
gypsum
anhydrite
dolomudstone
gypsum
dolomudstone
dedolomite
gypsum
dedolomite "laminites"
TOP
BOTTOM
5
6
7
8
9
10
11
12
13
2 cm

A number of cores that recover marker-bed strata from the Prairie Evaporite Formation were reviewed from locations west of the dissolution scarp, and from the east where only sulphates remain (cross-section B-B'). A number of cores taken from the top of the Keg River Formation and the Prairie Formation "laminites" were also reviewed for comparison. West of the dissolution scarp, the White Bear and Conklin marker beds comprise laminated to massive to cryptalgally laminated dolomudstone beds associated with anhydrite and lesser shale deposited in sabkha-like environments, all of which are encased in halite. East of the dissolution scarp, dolomudstone beds—interpreted to be correlative with the White Bear, Conklin, and other unmapped marker beds—are encased in anhydrite with gypsified margins bordering the dolostones. Increased thicknesses and inclined to brecciated bedding of carbonate beds east of the scarp suggest amalgamation of such beds through dissolution of intervening sulphates. Dolomudstones, including the Prairie "laminites", east of the scarp exhibit varying degrees of dedolomitization consistent with diagenesis in a mixed carbonate-evaporite system.

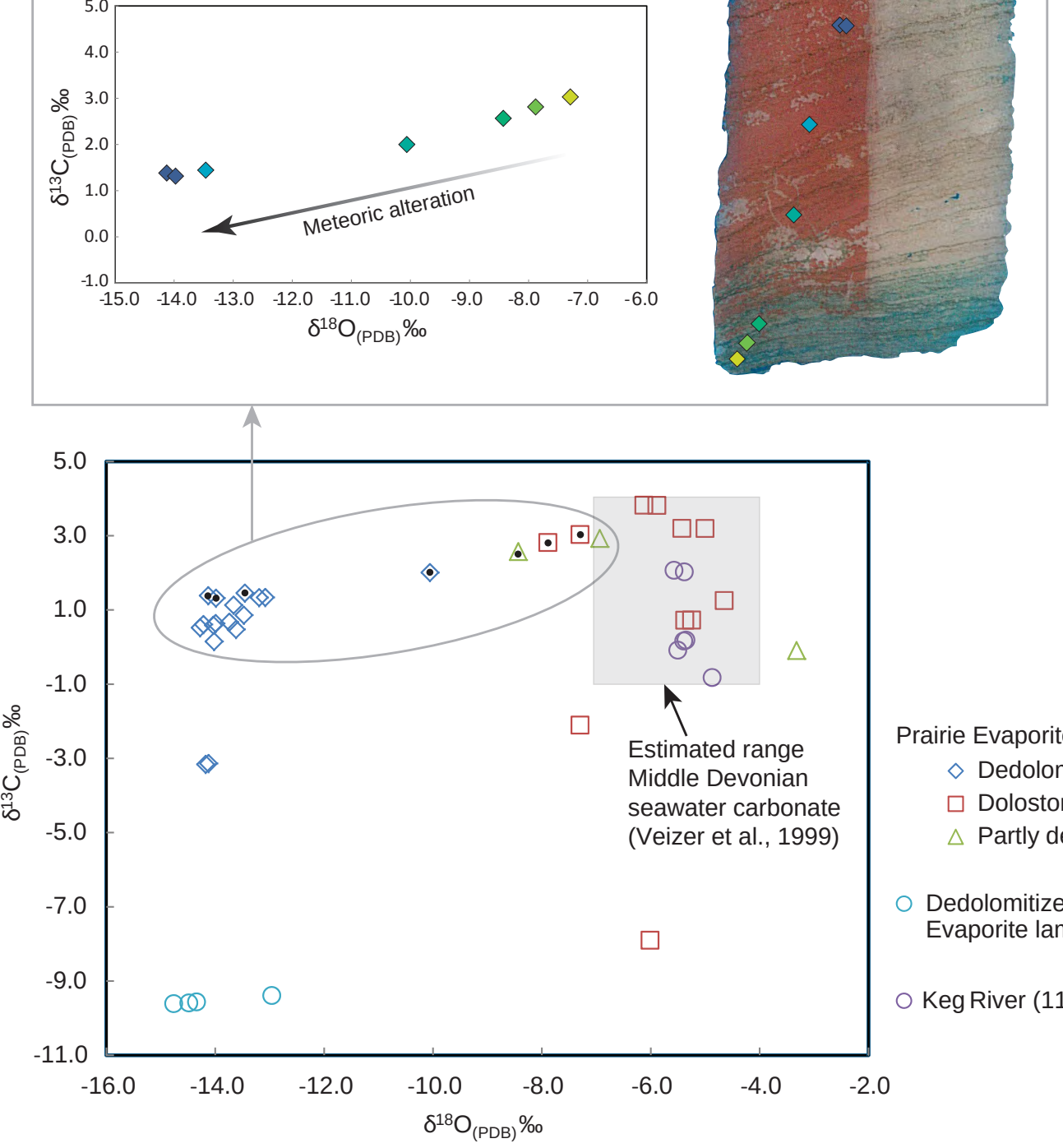
## Diagenesis in Prairie Evaporite Marker Beds

| Type | Description | Crystal size (diam.) | Morphology | CL/365 UV fluorescence |
|---|---|---|---|---|
| DOLOMITE | | | | |
| D1 | Dolomicrite: cloudy, dark organic material present in varying amounts | Cryptocrystalline ≤10 µm | Anhedral (nonplanar-A) | None, minor orange fluorescence between grains; likely organics |
| D1' | Dolomite: cloudy crystals floating in dedolomite (C1-D) matrix | Cryptocrystalline ≤10 µm | Anhedral (nonplanar-P) | None |
| D2 | Dolomite: crystals floating in dolomicrite, rare | 10–50 µm | Euhedral (planar-P) | None |
| CALCITE | | | | |
| C1-D | Dedolomite: surrounds remnant dolomite (D1'), twinning visible | ? (poikilotopic) | Poikilotopic | Light pink (365, Alizarin); strongest on rim |
| C2 | Calcite: void-filling cement, may replace G1/A1 | ≤3 mm | Subhedral (planar-C and -S) | None |
| SULPHATES | | | | |
| A1 | Anhydrite: laths floating in dolomicrite (D1), amalgamated laths form laminae and nodules | 20–300 µm | Euhedral | None |
| A2 | Anhydrite: corroded crystals, anhydrite cores | ≤500 µm | Subhedral (corroded) | None |
| G1 | Gypsum: infills fenestral or dissolution porosity | ? (poikilotopic) | Poikilotopic | None |
| G2 | Gypsum: undulose extinction, satin spar and alabaster | 50–200 µm | Anhedral | None |
| CT1 | Celestite: secondary, pore filling | Up to 1 mm (one measurement) | Anhedral | None |
| FLUORITE | | | | |
| F1 | Fluorite: cubic crystals, associated with gypsum (G1) | 20–400 µm | Euhedral | White (365) zoned (CL) |



D1
TL-XP
0.1 mm
BSE
10 µm
C1-D
TL-XP
0.1 mm
RL365
0.1 mm
BSE
100 µm
D1 dolomite
C1-D Calcite
10 µm
D1'
TL
0.1 mm
RL-365
0.1 mm
BSE
D1'
Gypsum
100 µm
RL-365
C2
C1-D
C2
RL-365
0.1 mm
D2
TL-XP
0.1 mm
BSE
D2 dolomite
20 µm
G1
TL
0.1 mm
RL-365
0.1 mm
BSE
Anhydrite
Gypsum
100 µm
A1
Anhydrite laths
TL-XP
0.1 mm
BSE
A1
D1
100 µm
G2
RL-365
0.1 mm
TL-XP
0.1 mm
A2
Gypsum
Anhydrite
TL-XP
0.1 mm
BSE
Anhydrite
Gypsum
20 µm
TL
0.1 mm
TL-XP
0.1 mm
CT1
Dedolomite (C1-D)
Celestite
F1
Gypsum
Fluorite
Dolomicrite (D1)
RL-365
0.1 mm
TL
0.1 mm
RL-365
0.1 mm
CL
BSE
100 µm
CL
100 µm

### Stable Isotopes



The pattern of decreasing $\delta^{13}C_{(PDB)}$ and $\delta^{18}O_{(PDB)}$ values in the marker bed and Prairie "laminites" is consistent with meteoric diagenesis. Samples taken from dedolomitized sections show a clear negative deviation from the estimated ranges for $\delta^{13}C_{(PDB)}$ and $\delta^{18}O_{(PDB)}$ for Middle Devonian seawater carbonate (Veizer et al., 1999). Negative shifts in isotopic values are evident in data from single thin sections that grade from precursor dolomite to dedolomite (see thin section to the left). Precursor dolomites from the marker beds west of the scarp, and from the underlying Keg River Formation, fall within the estimated range for the Middle Devonian.

The negative shift in $\delta^{13}C_{(PDB)}$ values in the marker bed dedolomites is interpreted as the influence of meteoric-derived $CO_2$ and / or $CO_2$ derived from the oxidation of organic matter during diagenesis. Evidence for the latter process is best documented in the dedolomitized, organic-rich beds of the Prairie Evaporite laminites, which yield highly negative $\delta^{13}C_{(PDB)}$ values (light blue open circles).

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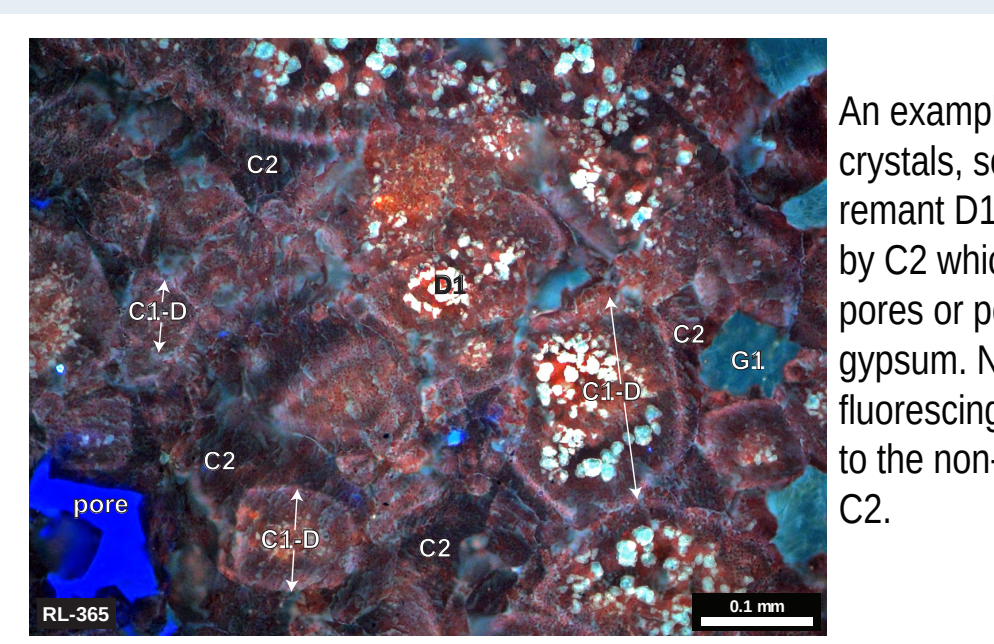
Intrastratal Dedolomite and Secondary Gypsum in the Prairie Evaporite Formation of Northeastern Alberta: Diagenesis in a Carbonate-Sulphate System

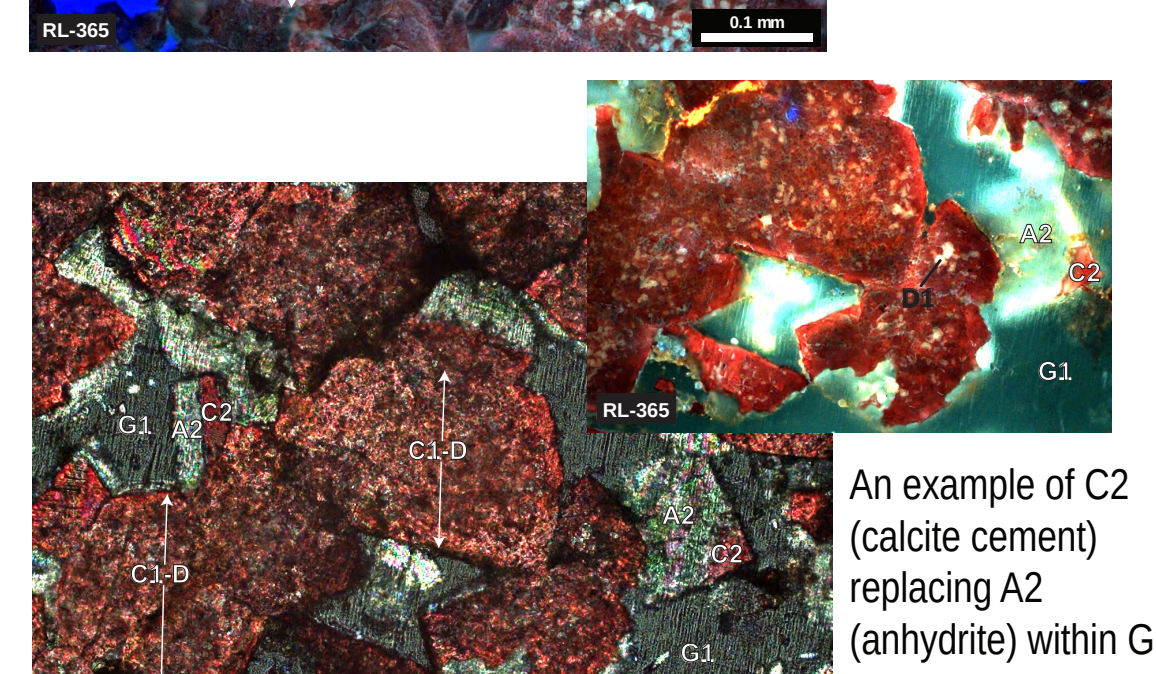
## Paragenesis

| Diagenetic Event | | Diagenetic Environment | | | |
|---|---|---|---|---|---|
| Process | Observed mineral type | near surface | shallow burial | intermediate to deep burial | late near surface (telogenesis) |
| Primary dolomite or synsedimentary dolomitization | D1 | ▬ | ··· | | |
| Interstitial precipitation of evaporites (precursor to A1) | A1 | ▬ | ▬ | | |
| Development of fenestral pores | | ▬ | | | |
| Cementation of fenestral pores with gypsum (precursor to A2) | A2 | ▬ | ▬ | | |
| Dehydration of primary gypsum and / or new lath growth | A1 | | | ▬ | |
| Aggrading neomorphism of dolomicrite (D1) | D2 | | | ···▬··· | |
| Halite, sulphate and some dolomite dissolution through influx of undersaturated water | | | | | ▬ |
| Secondary porosity creation | | | | | ▬ |
| Calcitization of dolomicrite (D1) | C1-D | | | | ▬·· |
| Rehydration of anhydrite (A1) | G1 | | | | ▬····· |
| Cementation of pores (associated with G1) | F1 | | | | ·········· ? ·········· |
| Precipitation of Sr-rich sulphate in open pores | CT1 | | | | ▬·· |
| Partial to complete cementation of open pores; G1 and A1/A2 calcitization | C2 | | | | ··▬ |
| Fracturing (subglacial recharge) | | | | | ▬ |
| Cementation of fractures | G2 | | | | ▬ |



C2
D1
C1-D
C2
G1
C1-D
C2
pore
C2
C1-D
C2
RL-365
0.1 mm

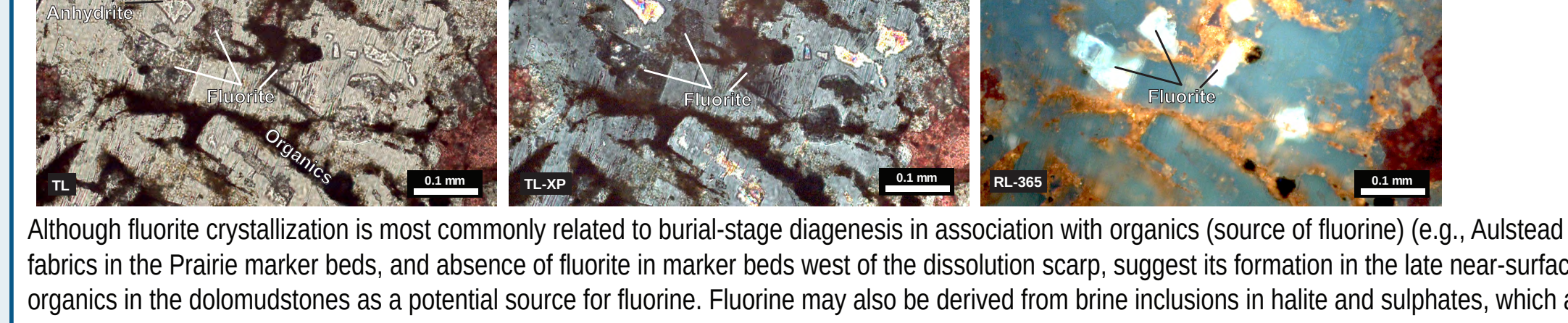
An example of C1-D crystals, some with remant D1', surrounded by C2 which lines open pores or pores filled with gypsum. Note the fluorescing C1-D relative to the non-fluorescing C2.



A2
C2
G1
RL-365
G1
A2
C2
C1-D
C1-D
C2
G1
TL-XP
0.1 mm

An example of C2 (calcite cement) replacing A2 (anhydrite) within G2 (poikilitopic gypsum). C1-D (dedolomite) is characterized by the presence of remnant unstained dolomicrite inclusions (D1'), best observed in reflected light microscopy.

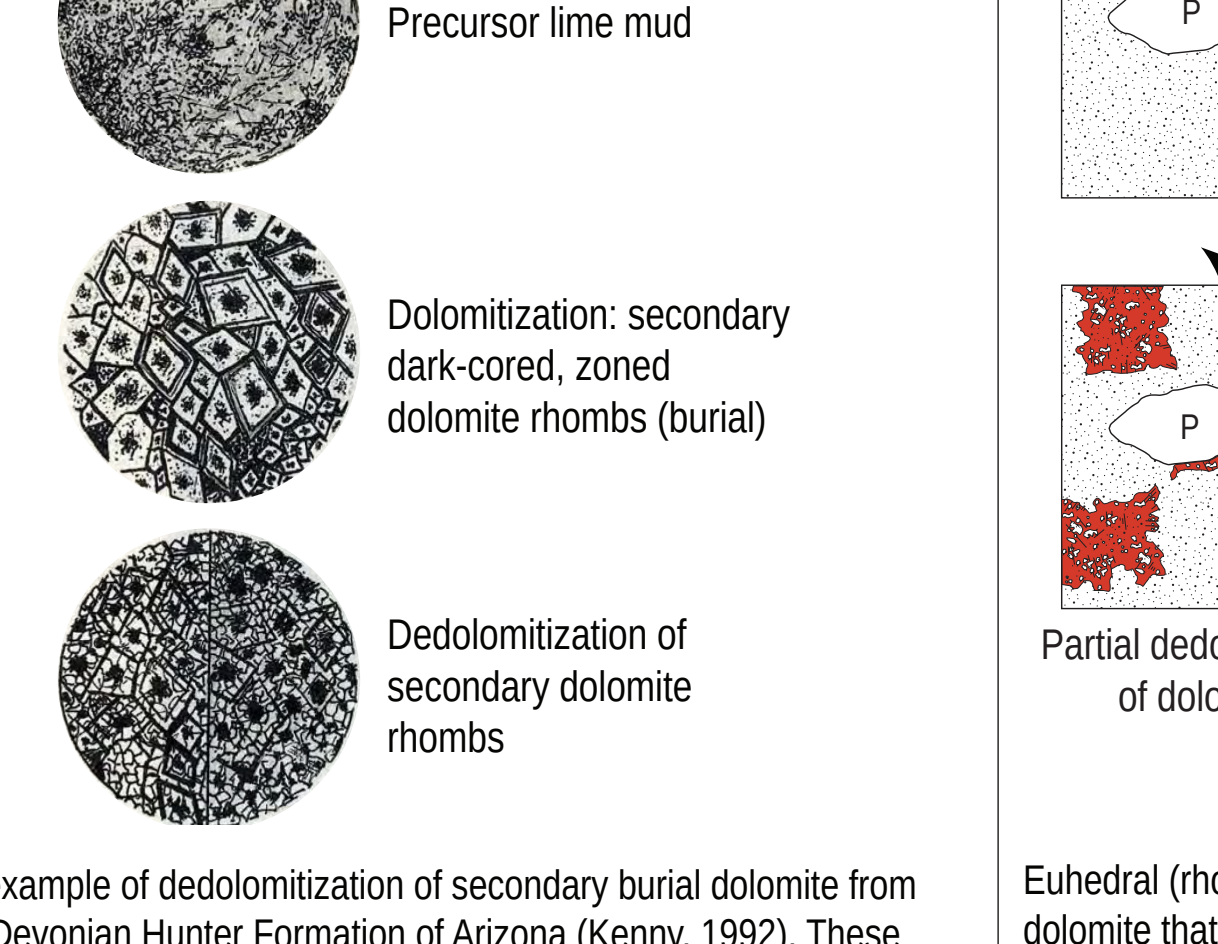
### Problematic Fluorite



Gypsum
Anhydrite
Fluorite
Organics
TL
0.1 mm
Fluorite
TL-XP
0.1 mm
Fluorite
RL-365
0.1 mm

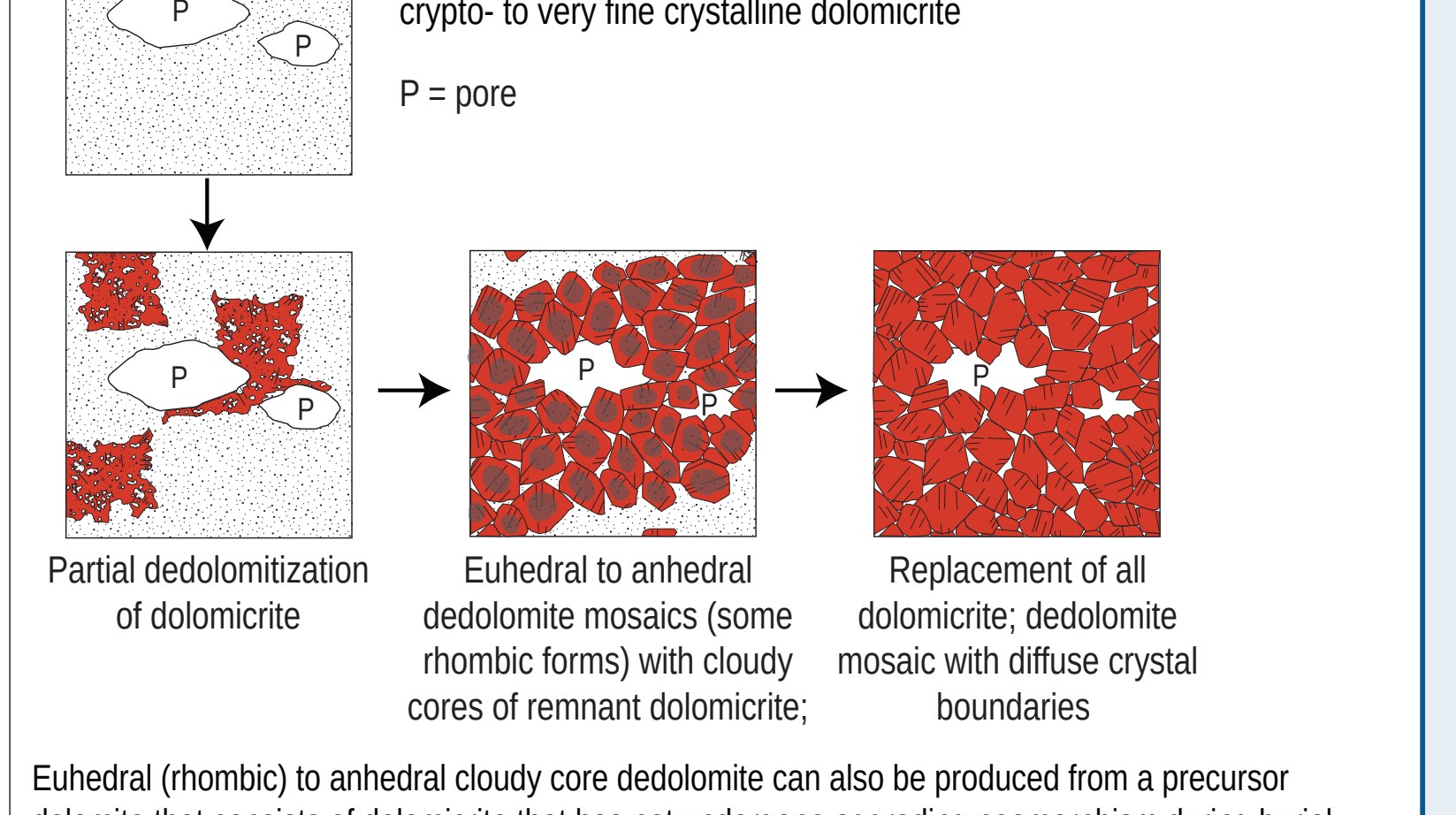
Although fluorite crystallization is most commonly related to burial-stage diagenesis in association with organics (source of fluorine) (e.g., Aulstead and Spencer, 1985), textural fabrics in the Prairie marker beds, and absence of fluorite in marker beds west of the dissolution scarp, suggest its formation in the late near-surface diagenetic environment, with organics in the dolomudstones as a potential source for fluorine. Fluorine may also be derived from brine inclusions in halite and sulphates, which are released during dissolution. Photomicrographs above show fluorite associated with organics and gypsum crystal terminations after anhydrite laths.

## Dedolomitization Fabrics and Model



Devonian Hunter Formation
Precursor lime mud
Dolomitization: secondary dark-cored, zoned dolomite rhombs (burial)
Dedolomitization of secondary dolomite rhombs

An example of dedolomitization of secondary burial dolomite from the Devonian Hunter Formation of Arizona (Kenny, 1992). These textural characteristics are commonly reported in the literature; burial dolomitization creates masses of aggrading neomorphic dolomite rhombs with "cloudy" cores and inclusion-free, limpid zoned rims. This texture can be preserved during dedolomitization.



Prairie Evaporite Marker Beds
P
P
Precursor dolomite:
crypto- to very fine crystalline dolomicrite
P = pore
P
P
P
P
P
Partial dedolomitization of dolomicrite
Euhedral to anhedral dedolomite mosaics (some rhombic forms) with cloudy cores of remnant dolomicrite;
Replacement of all dolomicrite; dedolomite mosaic with diffuse crystal boundaries

Euhedral (rhombic) to anhedral cloudy core dedolomite can also be produced from a precursor dolomite that consists of dolomicrite that has not undergone aggrading neomorphism during burial diagenesis to produce secondary dolomite rhombs. In this case, the cloudy cores in the dedolomite mosaics are remnant dolomicrite that have yet to be fully replaced by calcite. Distinct rhombic to sub-rhombic crystals of twinned calcite are observed. The relatively clear rims and cloudy cores may be confused with a precursor carbonate rock that consisted of burial dolomite rhombs as in the Hunter Formation in the previous example.

## Summary

Mapping of the Paleozoic succession in northeastern Alberta has been undertaken to better understand the distribution of Devonian strata underlying the economically important oil sands areas. The Prairie Evaporite Formation represents an important unit as it has undergone extensive intrastratal karstification through the influx of basin-margin-derived meteoric water. Top-down dissolution of halite and sulphates within the Prairie Evaporite has led to structural compensation and subsidence of the overlying Devonian succession. Within the Prairie Evaporite, a number of marker beds comprising dolomicrite and anhydrite record decreases in the intensity of evaporitic drawdown across the restricted basin in Alberta. These marker beds are laterally continuous, and are shown to have survived the dissolution events in the zone of halite dissolution and further eastward. These marker beds display complex diagenetic fabrics that are consistent with diagenesis under the influence of meteoric water, and in the presence of sulphates. A number of important findings are presented below.

- East of the Prairie Evaporite halite dissolution scarp, less soluble sulphates remain in the Prairie Evaporite succession, and display extensive gypsification (rehydration).
- Gypsification of anhydrite also occurs immediately adjacent to undifferentiated dolomudstone marker beds that are considered correlative with mapped marker beds west of the dissolution scarp.
- The observed distribution of gypsum within the anhydrite of the Prairie Evaporite succession is consistent with top-down dissolution, and points to the dolomudstone marker beds as conduits for fluid flow in northeastern Alberta.
- **With the amalgamation of marker beds through the dissolution of intervening sulphates, Prairie Evaporite marker beds may form significant conduits for flow in areas east of the dissolution scarp.** Dedolomitized Prairie "laminites", resting on or near the Keg River Formation, have been previously interpreted as potential aquifers within the region (Stoakes et al., 2013), however, these units are much less laterally extensive, and potentially discontinuous, given that they are restricted to the interbuildup basins of the Keg River Formation.
- Varying degrees of dedolomitization within the dolomudstone marker beds, which occurs exclusively in close proximity to rehydrated anhydrite (i.e., gypsum). This suggests that the dissolution of the sulphates was a primary source for the $Ca^{2+}$ needed for the dedolomitization of the precursor dolomudstones—a finding consistent with a number of diagenetic studies assessing the nature of dedolomitization within carbonate-sulphate systems.
- Stable C and O isotope data corroborate the interpretation that dedolomitization resulted from fluids derived from a meteoric source.
- Dedolomite fabrics within the marker beds are similar to those observed in rocks in which the precursor dolomite comprised secondary burial rhombs with cloudy cores and more limpid rims. **Here we show that aggrading neomorphism of fine-grained carbonates during burial diagenesis, resulting in rhombic crystal fabrics, is not necessary to produce cloudy cored euhedral (rhombic to sub-rhombic) textures during dedolomitization—these dedolomite textures can be derived from a dolomicrite precursor.**
- The use of reflected light microscopy greatly aides in distinguishing remnant dolomicrite (D1') from inclusion-rich burial-dolomite cores in dedolomite fabrics.
- Based on textural characteristics and location considerations within the marker beds, fluorite is interpreted as authigenic and to be part of the telogenetic sequence, rather than having formed during burial stages.

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