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Abstract

Dolomitization of carbonate rocks is a subject of considerable interest due to association with oil and gas reservoirs and Mississippi Valley Type ore deposits. Conceptual two-dimensional models of dolomitization are common in the literature, however numeric models supported by high quality data are rare to nonexistent.

This paper presents three-dimensional (3-D) dolomitization patterns in the Salina Group A-1 Carbonate Unit and A-2 Carbonate Unit located in Sombra Township, Lambton County. The source data consists of percent dolomite measurements collected from 9727 drill cutting samples, stained with alizarin red, from 409 petroleum wells. Numerical interpolants of the percentage of dolomite versus limestone in the two formations are developed within the boundaries of lithostratigraphic formation layers derived from a 3-D geologic model of southern Ontario, published as GSC Open File 8795 (Carter et al. 2021b). The model was developed using Leapfrog© Works software with a 400 m grid resolution.

Results show that increased proportions of dolomite vs limestone in both formations are spatially associated with the flanks and crests of pinnacles in the underlying Lockport Group carbonates, over which the B Salt has been dissolved, and the downthrown side of the Dawn Fault and Becher faults. In the A-1 Carbonate there is an increase in dolomite content over a minority of incipient reefs in the Lockport, and in the A-2 Carbonate Unit there is a gradational increase in dolomite content upwards from a basal limestone to 100% dolomite.

The cross-cutting relationships of dolomite occurrence in the A-1 Carbonate on the flanks and crests of some pinnacles support a post-depositional burial diagenesis mechanism, consistent with previous interpretations. The pathway for the dolomitizing fluid was laterally through porous and permeable regional paleokarst in the underlying Lockport Group, uppermost Goat Island and Guelph formations, and upwards through the porous reefal carbonates of the pinnacles. Association of dolomitization haloes with dissolution features in halite of the overlying B Salt Unit further suggest that the dolomitizing fluids were also responsible for salt dissolution. The preferential association of dolomite with the Dawn and Becher faults suggest that movement of the dolomitizing fluid was also fault controlled.

This project demonstrates the feasibility and merit of assignment and interpolation of attribute values constrained by lithostratigraphic layers in the regional 3-D geologic model of southern Ontario. Spatial associations of dolomite with other geological features are more clearly resolved than in a 2-D study.

Introduction and Objectives

In North America, 80% of oil and gas reservoirs in carbonate rocks are hosted by dolomite (Zenger 1980) as are most Mississippi Valley Type Pb-Zn orebodies (Warren 1999, 2000). This also holds true for oil and gas reservoirs in southern Ontario (Carter et al. 2016a, b; Dorland et al. 2016) where dolomitized carbonates are geographically and stratigraphically extensive (e.g., Al-Aasm et al. 2021).

Post-burial diagenetic dolomitization models, for the Guelph Formation in southern Ontario, require pathways for movement of the dolomitizing fluids (Coniglio et al. 2003). The interpreted location of these pathways may be mapped or modelled if sufficient data on the spatial distribution of dolomite is available. To track these pathways, a detailed study of the geographic and stratigraphic occurrence of dolomite in the A-1 and A-2 Carbonate units was completed by Carter (1991) in the Township of Sombra in southern Ontario. In that study the spatial relationships of dolomite to associated geological features in the lower Salina Group carbonates and evaporites and the underlying Lockport Group carbonates were illustrated using two-dimensional cross-sections and structure, as well as isopach and isolith maps. These observations and interpretations were incorporated into a much broader study by Coniglio et al. (2003) covering the entire Michigan Basin portion of southern Ontario. At that time there was no technological capability of producing 3-D models. Subsequent to these studies, a 3-D geological model of the bedrock formations of southern Ontario was completed by Carter et al. (2021b).

The primary objectives of this project are:

1. To investigate the efficacy of assigning and interpolating dolomite data values within 3-D model formation volumes of Carter et al. (2021b).
2. Demonstrate the value of 3-D modelling to visualize and enhance the understanding of spatial relationships of dolomitization relative to other geological features and implications for processes of dolomitization in southern Ontario.
3. Create a 3-D visualization to test and illustrate the observations and interpretations of Carter (1991) and Conglio et al. (2003) regarding dolomite distribution in the lower Salina Group and underlying Lockport Group in relation to lithofacies, reefs (pinnacles and incipients), faults, and salt dissolution features, and the interpretation of related dolomitization processes and pathways.
4. Revise the interpreted locations of faults, pinnacle reefs and incipient reefs in the study area.

Project Scope

The project area is approximately 400 km^2 and covers the portion of the geographic township of Sombra located within the municipality of Lambton County in southern Ontario (Figure 1). Stratigraphically, the project encompasses, in ascending stratigraphic order, the Gasport, Goat Island and Guelph formations of the Lockport Group, and the overlying A-1 Evaporite, A-1 Carbonate, A-2 Anhydrite, A-2 Salt, A-2 Carbonate, B Anhydrite, B Salt, B Equivalent, and B units of the Salina Group (Figure 2). Note that percent dolomite 3-D numerical interpolants were developed only within the A-1 and A-2 Carbonate units.

Geology

Southern Ontario is underlain by crystalline metamorphic, igneous and metasedimentary rocks of the Precambrian basement and overlain by up to 1500 metres of Paleozoic marine sedimentary rocks of the Michigan and Appalachian Basin (Armstrong and Carter 2010). The study area lies within a structural depression known as the Chatham Sag, west of the Algonquin Arch and its southwestern extension, the Findlay Arch and wholly within the Michigan Basin (Figure 1).

Within southern Ontario, the Lockport Group comprises a gently dipping stacked sequence of dolostones and subordinate limestones of the Gasport, Goat Island, Eramosa, Guelph, and A-0 Carbonate formations, in ascending stratigraphic order, and thickening from west to east. A distinctive series of lithofacies belts are preserved in the Guelph Formation consisting of a regional paleokarst in the west, a carbonate platform in the east with carbonate banks/reefs, and an intervening belt of pinnacle structures/reefs separated by inter-pinnacle karst (Carter et al. 2021a) (see Fig. 3). West of the carbonate platform the uppermost few metres of the Goat Island Formation and Guelph Formation is porous and permeable and forms a regionally extensive and connected aquifer of brine and saline to sulphurous water in the intermediate to deep subsurface (Carter et al. 2021a).

Across most of southern Ontario, rocks of the A-1 and A-2 Carbonate units unconformably overlie dolomites and limestones of the Lockport Group (Figure 2). Together with the A-0 Carbonate Unit they are the lowermost carbonate formations in the Salina Group, occurring at depths of 460 m to 715 m within the study area. The Salina Group is comprised of a cyclical sequence of restricted marine to evaporitic carbonates, anhydrite, halite, and shaly carbonates (Mesolella et al. 1974; Nurmi and Friedman 1977). In Ontario, the Salina Group has a maximum thickness of 420 m. in the Sarnia area (Armstrong and Carter 2010). Within the study area, the A-1 Carbonate is predominantly limestone while the A-2 Carbonate is dolostone with subordinate limestone.

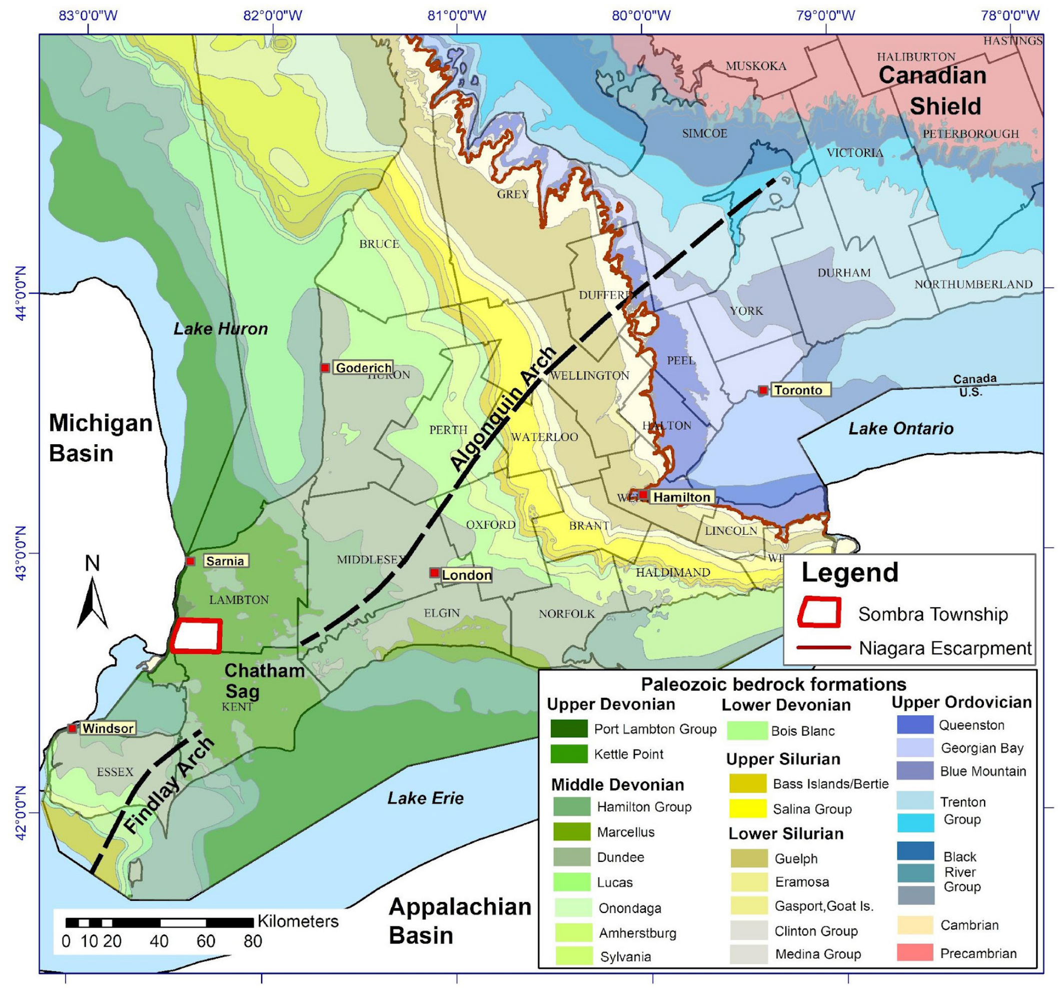

Figure 1. Bedrock geology of southern Ontario, adapted from Carter et al. (2019, 2021b) showing bedrock formations, structural arches and basins, and location of Sombra Township study area. Also shown are boundaries and names of counties/municipalities.

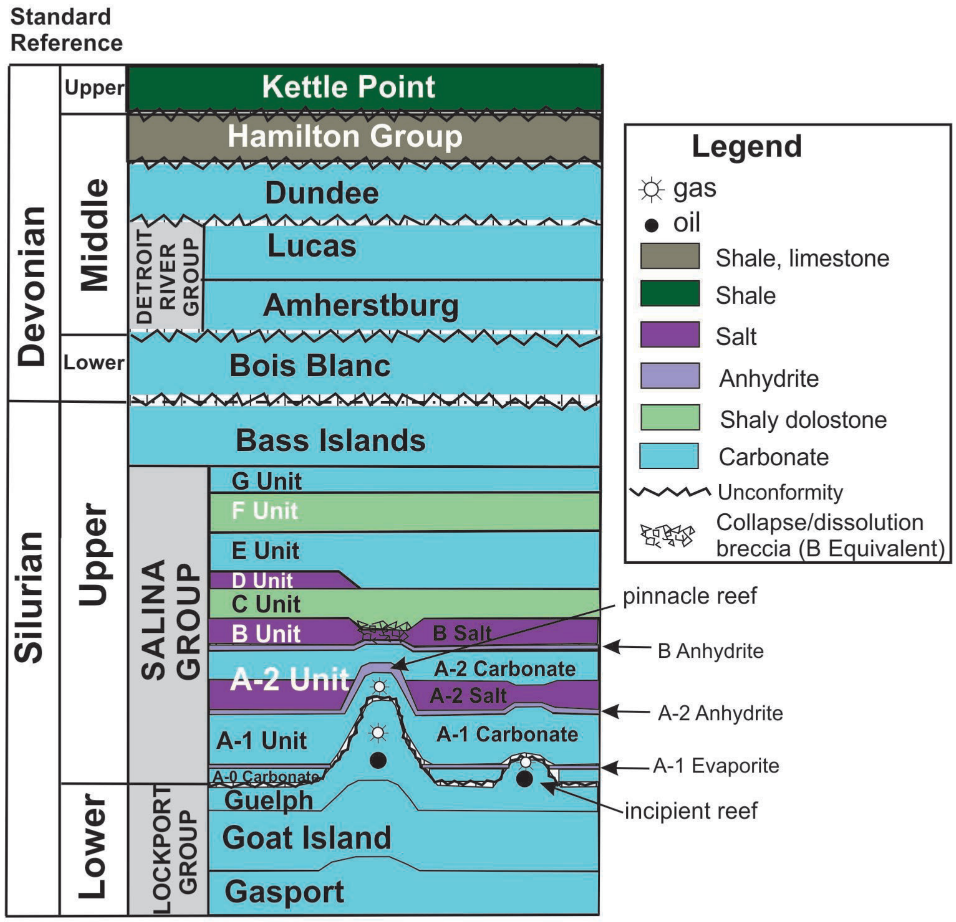

Figure 2. Lithostratigraphic chart of the Lower Silurian Lockport Group and overlying bedrock formations of Sombra Township, modified from Carter et al. (2019). The formations of interest to this study are the Lockport Group formations, and the lower 8 Salina Group units: A-0 Carbonate, A-1 Evaporite, A-1 Carbonate, A-2 Anhydrite, A-2 Salt, A-2 Carbonate, B Anhydrite, and B Salt.

Pinnacles and Incipients

The study area is located within the pinnacle and interpinnacle karst lithofacies belt of the Guelph Formation near its southeastern transition into a carbonate platform (Figure 3). A large number of carbonate buildups known as pinnacles and incipients occur within this lithofacies belt. Pinnacles are comprised of a stacked succession of dolomites and limestones of the Gasport, Goat Island, Guelph, and A-1 Carbonate formations, capped by the A-2 Anhydrite Unit of the Salina Group. Halite of the A-2 Salt Unit surrounds the pinnacles but does not extend over the crests due to non-deposition. The A-2 Carbonate completely envelopes the pinnacles, thinning over the crests and exhibiting a structural drape of approximately 30 metres that is believed to result from post-depositional compaction prior to lithification (Figure 4). For this study, incipients are presumed to be reefs, however no detailed studies of their origin have been published.

Pinnacles have been intensively studied in Ontario and Michigan because they form traps for oil and natural gas (Carter et al. 2016). In Ontario, some studies have proposed the pinnacles may be “karst towers” (Brintnell 2012; Brunton et al. 2012; Brunton and Brintnell 2020). However, this is not widely accepted and is contrary to recent studies in Michigan (Rine et al. 2017; Ritter and Grammer 2017; Trout et al. 2017; Wold and Grammer 2017) and earlier studies in Ontario and Michigan (Bailey 1986;

Friedman and Kopaska-Merkel 1991; Carter et al. 1994; Gardner and Bray 1984; Gill 1977; Sanford 1969; Smith 1988, 1990) that consider the pinnacle structures to be reefal in origin. There is, however, general agreement that the pinnacles have extensive karstic intervals as a result of subaerial exposure in the geologic past.

Pinnacles in Ontario generally have relief of approximately 100 m above the regional Guelph surface, ranging up to 128 metres (McMurray 1985) with basal areas ranging from 23 ha to a maximum of 368 ha. Incipients do not exceed 30 m in relief with basal areas of 16 to 20 ha (Koepke and Sanford 1966). Seven pinnacles have been identified in the study area: Dutton, Sombra, Terminus, Sombra 7-A-XI, Coveny, Bickford, and Wilkesport (Figure 5). Seventeen incipients have been identified in the study area based on structural relief above the regional Guelph surface. The first author has identified 93 pinnacles in southern Ontario: 69 host reservoirs of oil or natural gas or have been converted to natural gas storage, and 24 are salt-plugged or filled with brine.

Dolomitization

Silurian carbonates are regionally dolomitized throughout most of southern Ontario (Armstrong and Carter 2010). Exceptions occur in the Guelph Formation and the Salina A-1 Carbonate Unit and A-2 Carbonate Unit in westernmost portions of Lambton County (Coniglio et al. 2003; Carter 1991; Carter et al. 1994), which includes the study area. Coniglio et al. (2003) describe a westward transition in the Guelph Formation from pervasive dolomite in the regional carbonate platform and carbonate banks to pinnacles comprised partially or entirely of limestone in the western parts of the pinnacle belt. Within Sombra Township four of the pinnacles are dolomitized (Sombra, Sombra 7-A-VI, Dutton, Bickford) and three are limestone or partially dolomitized (Wilkesport, Coveny, Terminus).

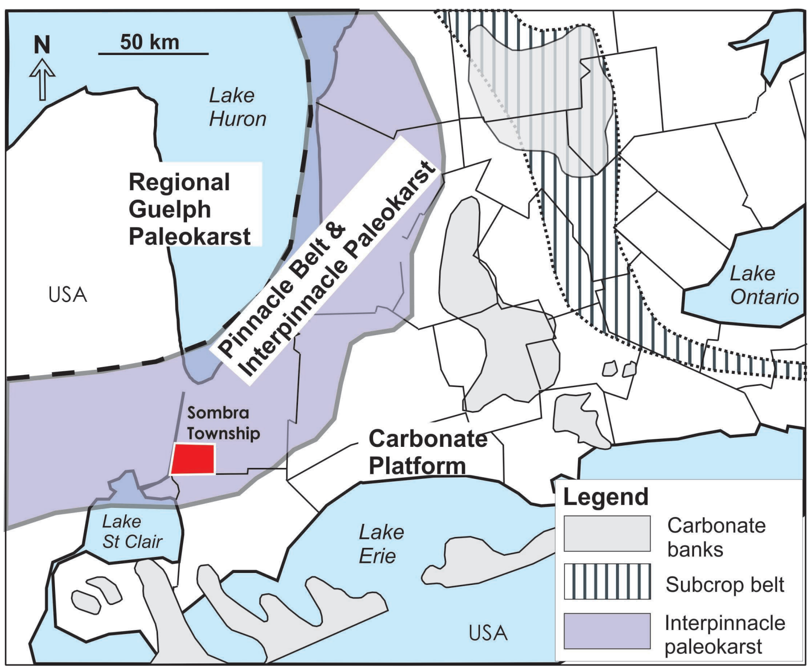

Figure 3. Lithofacies belts of the Guelph Formation in southern Ontario, showing carbonate banks/reefs on a southeast-dipping carbonate platform, regional paleokarst to the west, with an intervening pinnacle and interpinnacle karst belt. Revised from Sanford (1969), Bailey (1986), and Carter et al. (1994), using revised isopach data for the Guelph Formation and 3-D visualization (Carter et al. 2021b).

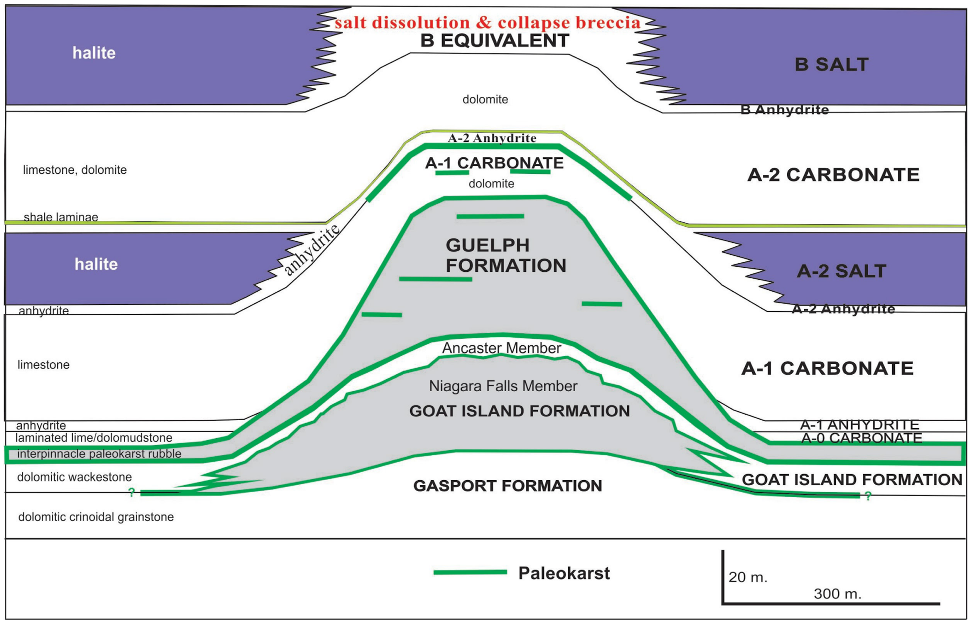

Figure 4. Conceptual model of a pinnacle, showing geologic relationships with regional strata of the Lockport Group and lower Salina Group. The example shown is for a pinnacle with a dissolution zone in the overlying B Salt Unit. Modified and adapted from Carter et al. (1994), Brintnell (2012), Brunton and Brintnell (2020) and Carter et al. (2021b).

B Salt Dissolution

Dissolution of halite in the overlying B Salt Unit has occurred on the downthrown side of the Dawn Fault at the transition to the carbonate platform, and over all three of the Becher faults (Figure 5). This is consistent with observations elsewhere in southern Ontario (Sanford 1969, 1977; Brigham 1971; Grieve 1955) and is interpreted to be the result of water movement along the faults in the geologic past. Our observations at salt mines in southern Ontario indicate that there is no present-day water movement along faults within the salt beds.

Circular salt dissolution zones in the B Salt over many of the pinnacles in Ontario (Sanford 1969, 1977; Brigham 1971) are interpreted to be the result of upward flow of formation water and/or seawater during burial compaction (Bailey 2000; Coniglio et al. 2003). Dissolution of halite in the B Salt Unit has occurred over the Dutton, Sombra, and Sombra 7-A-XI pinnacles. There is partial dissolution of halite in the B Salt Unit over the Terminus pinnacle, probably due to its proximity to the Dawn Fault.

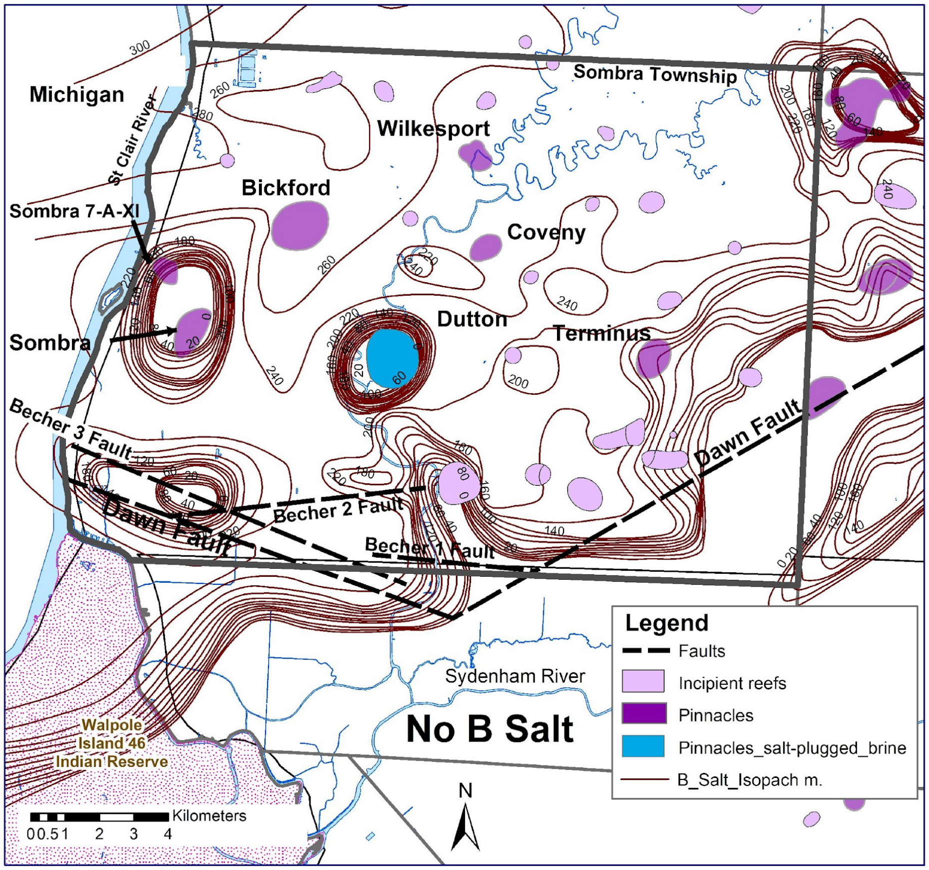

Figure 5. Pinnacles, incipient reefs, faults, and B Salt isopach 20 m contour interval) in the study area. Sense of movement is subvertical downthrown to the south on all faults. Dawn Fault has 40 m of displacement, 20 m on all others. Names of pinnacles within the study area are shown. Closely spaced isopach lines indicate salt dissolution, in particular on the south side of Dawn Fault, over the Dutton, Sombra and Sombra 7-A-XI pinnacles, and at the intersection of the Becher 3 Fault with the Dawn Fault and Becher 2 Fault.

Faults

A number of normal faults have been identified in southern Ontario by mapping of linear vertical displacements of formation top surfaces of the subsurface Paleozoic bedrock formations as recorded in petroleum well records (Brigham 1971a, b; Bailey and Cochrane 1984a, b, 1985, 1986, 1988a, b; Carter 1991). The fault locations and the youngest formation on which fault displacements occur have been compiled at a regional scale by Armstrong and Carter (2010). Fault locations within Sombra Township have been reviewed and revised by this study (Figure 5).

The regional Dawn Fault cuts across the southeast corner of the study area with a maximum observed displacement of 40 m, downthrown on the south side, and forms the northern edge of the Chatham Sag. There is vertical displacement of overlying formations as young as the Middle Devonian Hamilton Group (Carter et al. 2021b). Immediately north of the western extension of the Dawn Fault, three secondary faults have been identified, referred to here as the Becher faults, with vertical displacements of up to 20 m. These faults have formed structural traps for hydrocarbons in the Guelph Formation, A-1 Carbonate Unit and A-2 Carbonate Unit (Figure 6).

Silurian Oil and Gas Reservoirs

Six of the seven pinnacles identified in the study area form natural gas reservoirs and have been converted to use as natural gas storage reservoirs: Sombra, Terminus, Sombra 7-A-XI, Coveny, Bickford, and Wilkesport. Seventeen incipient reefs form reservoirs for natural gas and two, (i.e., Sombra 8-6-XV and Sombra 2-23-XII), are now utilized for storage of natural gas. (Figure 6). Structural traps related to the Dawn Fault and the Becher faults also form reservoirs for oil and natural gas in the dolomitized carbonates of the Guelph Formation and A-1 and A-2 Carbonate units in the southern and eastern portion of the study area.

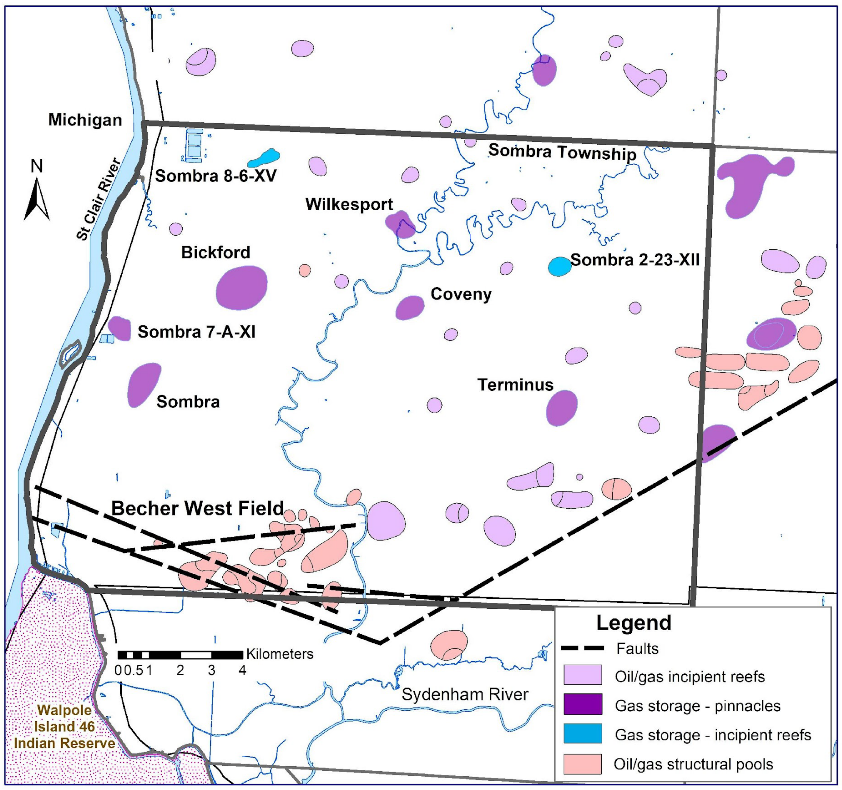

Figure 6. Fault locations, Silurian oil and natural gas reservoirs, and natural gas storage pools in the study area, coded by trap type as defined by Carter et al. (2016). The structural pools of the Becher West Field are closely related to faulting and dolomitization (Carter 1991, Carter et al. 2016) associated with the Becher faults and Dawn Fault. Natural gas storage pools are labelled and are hosted by pinnacles except for the Sombra 8-6-XV and Sombra 2-23-XII pools which are in incipient reefs.

Data Sources and Methods

The development of the 3-D dolomite model utilized a variety of data and digital geographic components including 2-D features (administrative boundaries, pinnacle/incipient boundaries, oil and gas pools, fault lines) and 3-D features (fault planes and model formation boundaries). Most of the data for dolomite/limestone percentages are from Carter (1991) supplemented by data acquired by geologists of the Oil, Gas and Salt Resources Library (OGSRL) and the Ontario Ministry of Natural Resources for well drilled between 1989 and 1997. The principal data sets that supported the model are listed in Table 1.

Table 1. Data sources.

Data Set	Description/Source	Application
Ontario Petroleum Data System (OPDS) database	Formation tops recorded in 409 petroleum well records in Sombra Township, for wells with TD dates preceding 1998. Ministry Natural Resource and Forestry – OGSRL	Primary data for model layer estimation
Oil, Gas and Salt Resources Library	Drill cuttings, well files, geophysical logs	QA/QC
Paleozoic bedrock stratigraphy	Carter et al. 2019	Stratigraphic assignment of model bedrock layers
3-D geological model	Carter et al. 2021b	Model layer boundaries for the Guelph, Goat Island, and Gasport formations, A-1 Evaporite, A-1 Carbonate, A-2 Anhydrite, A-2 Salt, A-2 Carbonate, B Anhydrite, and B Salt units
Regional faults	Armstrong and Carter 2010	Spatial correlation of faults, dolomitization
Local faults	Carter 1991, new interpretation by Carter in this study	Spatial correlation of faults with dolomitization
Petroleum reservoirs	OGSR Library	3-D oil and gas reservoir boundaries
B Salt isopach	Sanford 1977, updates by OGSRL	Spatial relationship of salt dissolution to dolomitization
Pinnacles, incipients digital boundaries	this study	Spatial relationship of pinnacles/incipients to dolomite distribution
Administrative boundaries	LIO	Geographic boundary of model
% dolomite vs limestone in drill cuttings	9727 dolomite/limestone determinations from Carter 1991, OGSRL 1989 to 1997	3-D interpolant of isopercent dolomite

Abbreviations: *OGSRL – Oil, Gas and Salt Resources Library.*

Well Records, Drill Cuttings and Dolomite Determinations

Petroleum well records of the Ontario Petroleum Data System (OPDS) are the primary data set used for model development. This study utilizes drill cuttings samples from 409 petroleum wells that intersect the A-1 and A-2 Carbonate units (Figure 7), of which there are 389 wells that have dolomite determinations for both formations, and 20 with data for only the A-2 Carbonate. Data/drill cuttings intervals are approximately 3 m in length. Details on the staining and visual estimation methods are summarized in Carter (1991). Data for dolomite vs limestone proportions were derived from alizarin red staining of drill cuttings samples for petroleum wells drilled to the end of 1997. A total of 9727 determinations of limestone/dolomite percentages are available, of which 8964 are from Carter (1991) and 763 from the OGSRL. All samples are archived at the OGSRL.

The dolomite data is tabulated as percent dolomite for the top depth of the sampled interval as determined from each sample vial examined. The bottom depth of each interval corresponds to the top depth of the next interval. For each well, the top depth of the contact with the next underlying formation is also recorded. For the A-1 Carbonate this is usually the A-1 Anhydrite and for the A-2 Carbonate it is usually the A-2 Shale. If the well reached total depth within either the A-1 Carbonate or the A-2 Carbonate this depth is recorded as "TD" (Total Depth). The top depth was used for modelling. A table of the data used for the dolomite interpolation is included with this open file. Table fields include: 'Licence' (Borehole licence ID); 'KB_Elev' (Kelly Bushing elevation in metres above sea level); 'Easting_N83_Z17' (X coordinate in metres); 'Northing_Z17_N83' (Y coordinate in metres); 'Top Depth (m)' (sampling top depth in metres from Kelly Bushing; 'Bottom Depth (m)' (sampling bottom depth in metres from Kelly Bushing; 'UOM' (original units of measure); 'Dolomite_Percent' (measured percent dolomite); 'Formation' (bedrock formation sampled). Coordinate projection is Universal Transverse Mercator, North American Datum 1983, Zone 17.

There is approximately one well per square kilometre with well density increasing over pinnacle structures where interwell distances are as little as 70 m. At interpinnacle locations the nearest well may be up to 1.3 km distant, resulting in considerable local clustering of data points. For each well there is a sample approximately every 3 metres in depth. This is the standard interval at which cuttings are collected during drilling using a cable tool rig. An average of 24 data intervals is recorded for each well location. This creates a data density that is highly skewed vertically/stratigraphically vs horizontally/geographically, which has implications for the 3-D interpolation process as discussed below.

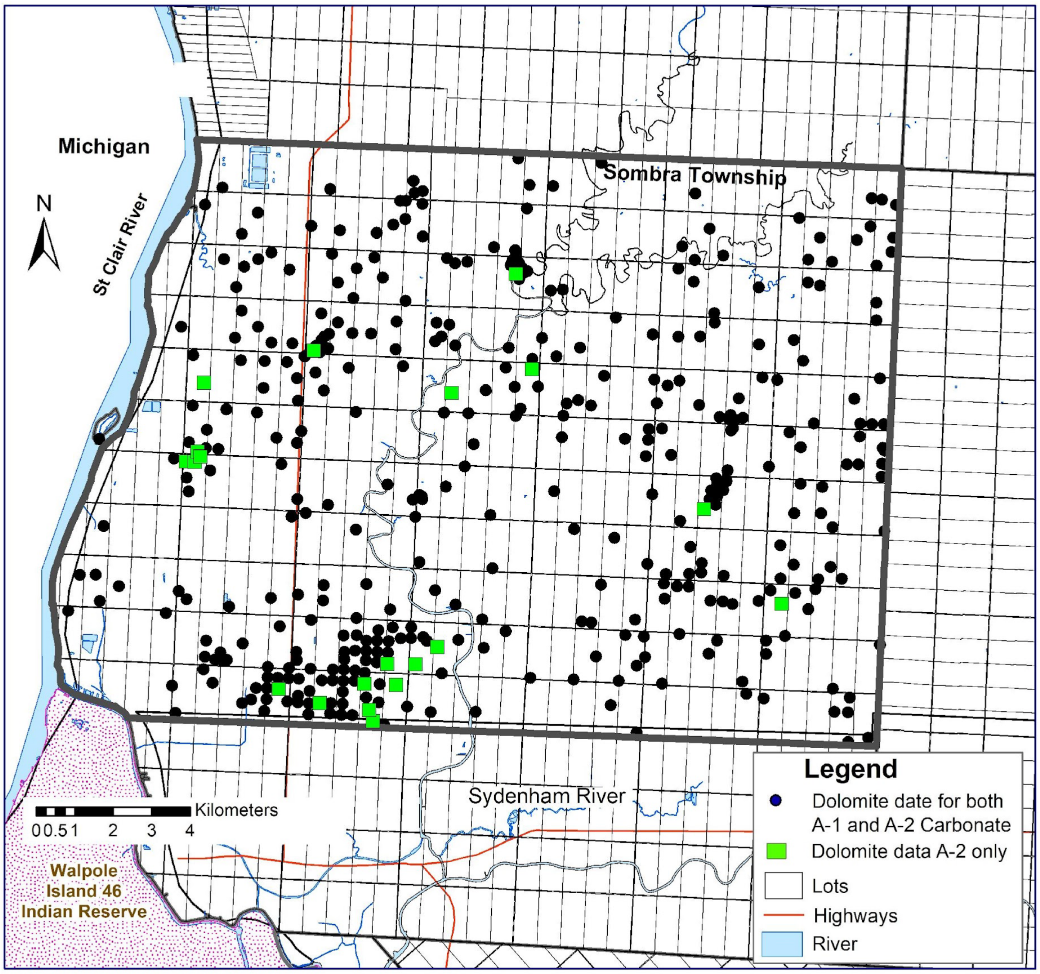

Figure 7. Location of petroleum wells within the study area where dolomite percentages for the Salina A-1 Carbonate Unit and A-2 Carbonate Unit are available. There are 389 wells with dolomite determinations for the A-1 Carbonate and A-2 Carbonate, and 20 with data for only the A-2 Carbonate.

Formation Tops

Carter et al. (2019, 2021) completed an extensive QA/QC review of formation top data which was used to model upper and lower contacts of formation layers in the 3-D geological model of southern Ontario. Review of formation tops for the Lockport Group and A-1 Carbonate in wells that penetrated pinnacles resulted in reassignment of formation top picks for both the A-1 Carbonate and Guelph

Formation within the 7 pinnacles in Sombra Township. Prior to the QA/QC review the A-1 Carbonate had been misidentified as the Guelph Formation on the crests of pinnacles. Dolomite determinations previously assigned to the Guelph Formation in Carter (1991) were reassigned to the A-1 Carbonate in 50 wells for this study.

Faults

Location of faults in the study area were revised using 3-D visualization of linear displacements of the A-2 Carbonate Unit and Rochester Formation surfaces. Vertical 3-D planes of these faults, at their revised locations as mapped on the upper surface of the A-2 Carbonate Unit, have been added to the 3-D model (see Figure 5).

Cultural and Geographic Data

Boundaries for geographic townships (Townships Improved), highways (Transportation), and streams and shorelines (Shorelines 100K, Water Bodies 10-50 K) were obtained from geospatial databases maintained by Land Information Ontario (https://geohub.lio.gov.on.ca). The boundaries for counties were obtained from the PetroGIS application maintained by the Petroleum Operations section of MNRF. Cultural and geographic features that occur on the surface are not included due to the depth at which the subject formations occur.

Quality Assurance and Quality Control

Model iterations were reviewed by examination of vertical slices at different orientations through all significant geological features, including faults, pinnacles and incipient reefs. Features flagged for referral for further quality assurance / quality control (QA/QC) review included: anomalous highs or lows on formation surfaces not related to reefs or salt dissolution, irregular and rapid variations in thickness not related to salt dissolution, missing formation top picks for the Gasport Formation, Goat Island Formation, and A-1 Carbonate Unit, and, and gaps in the A-1 and A-2 model formation layers.

QA/QC Process

Well locations and drill collar/rig floor elevations were the subject of previous QA/QC by Carter and Castillo (2006) and Carter et al. (2019) and were not revised for this study. The principal focus of the QA/QC review was validation of dolomite vs limestone determinations made by Carter (1991) and subsequent workers at the Oil, Gas and Salt Resources Library. The editing procedures comprised the following:

- matching of scanned hard-copy data records with row entries in the data file
- determination of missing formation top picks for the Gasport, Goat Island, and Guelph formations and the A-1 Carbonate Unit for wells drilled within a pinnacle structure.
- gaps in model layers
- identification and correction of data entry errors

Interim model revisions were generated as necessary to monitor progress and identify data quality issues as a data quality control on 3-D data interpolation and modelling. Data quality issues were identified by visual review of model layer surfaces and cross-sections. Anomalies were investigated by examination of geophysical logs, drill cuttings, well file reports and the source records for dolomite determinations. The formation top picking procedure and standards were adopted from Armstrong and

Carter (2010). ArcMAP® was used in the QA/QC process to provide spatial context to the geology for the QA/QC analysis.

3-D Numeric Modelling

Leapfrog® Works (Seequent Limited) implicit 3-D modelling software was used to develop the models. In Leapfrog® Works, Radial Basis Function (RBF) interpolants describe physical quantities that vary continuously in 3-D space. Isosurfaces based on interpolants are used to visualize the 3-D distribution of the interpolated quantity by defining discreet volumes in a numeric model.

The model domain volume was confined geographically by the Sombra township boundary and the southern boundary of Lambton County. The A-1 and A-2 Carbonate model volumes from Carter et al. (2021b) were also used to complete the 3-D boundary for interpolated data values. Percent dolomite values from Carter (1991) and the OGSRL for both A-1 and A-2 Carbonate units were used to develop two 3-D numerical models.

The borehole coordinates and depth to measured percent dolomite values were converted into two separate 3-D vector point datasets with dolomite percent attributes for each of the A-1 and A-2 Carbonate models. To offset the effects of local clusters of data points within individual boreholes in the vertical direction as well as the tendency for borehole clustering around pinnacles and incipient reefs, a trend was applied to the interpolants. For both models, a trend surface was created based on sampling the upper contact surface of the formation outside of mapped pinnacles and incipients. This yielded sub-horizontal trend surfaces that conform to the general orientation of bedrock layers in the study area ignoring the local topographic relief of pinnacles and incipients. Trend surfaces were used to develop structural trends that were, in turn, used to influence the 3-D dolomite interpolants. Through several trials, it was found that a weight factor of 30 applied to the structural trends yielded the most geologically plausible result.

Several iterations of each numeric model were developed and evaluated against the input datasets to identify and correct depth errors in the datasets (Table 2). The digital models were viewed using free Leapfrog® Viewer software, v.2023.1.1, available on the developer's website (at time of publication): (https://www.seequent.com/products-solutions/leapfrog-viewer/).

Table 2. Summary of model development.

Iteration	Layers, Data Edits, Modelling Activities	Application and Model Review
1.1		
1.2		Incremental improvements
1.3		Incremental improvements; identify new QA/QC priorities
1.4	Trial application of horizontal/vertical weighting of the 3-D interpolation ranging from 1:1 to 50:1.	Incremental improvements; identify new QA/QC priorities
2.0	12 model geological layers, 3-D interpolants of dolomite percentage for each of the A-1 Carbonate and A-2 Carbonate units	Finalization of model development, prepare for release, prepare report

Model resolution is 400 m matching the resolution of the model formation layers in the 3-D geological model (Carter et al. 2021b). A vertical exaggeration of 20x used to provide a practical display for viewing relatively thin formations in the large geographic area. This accentuates the apparent vertical size of geologic features and the apparent dip on their flanks, especially for pinnacles and incipient reefs of the Guelph Formation.

Results

Leapfrog Viewer software has been used to visualize the dolomite distribution in the A-1 Carbonate and A-2 Carbonate units in relation to other geological features. Representative plan views and cross-sections of the distribution of dolomite vs limestone in the A-1 Carbonate Unit and A-2 Carbonate Unit are presented in Appendix 1.

The 3-D modelled volume for the A-1 Carbonate Unit is 10.53 km^3, and for the A-2 Carbonate Unit is 13.58 km^3. Average thickness of the A-1 Carbonate is 33.7 m. and for the A-2 Carbonate is 42.8 m.

The interpolated dolomite vs limestone percentages are rendered within the boundaries of model formation layers of the A-1 Carbonate and A-2 Carbonate units using an isopercent interval of 20%. The volumes of these intervals are summarised in Table 3. The A-1 Carbonate is predominantly limestone while the A-2 Carbonate is predominantly dolomite. Average dolomite content of the A-1 Carbonate is <35% whereas 75% of the A-2 Carbonate is comprised of dolomite or dolomitic limestone (>40% dolomite).

There is a very close association of dolomite with geological features in the overlying and underlying bedrock (see Figure 8, 9). Geological observations and insights from the model can be summarized as follows.

- In the absence of pinnacles and faults the A-1 Carbonate is a limestone.
- The basal few metres of the A-2 Carbonate is comprised of limestone, with an upward gradation to 100% dolomite in the uppermost few metres.
- The A-1 Carbonate is completely dolomitized on the downthrown side of the Dawn Fault and Becher faults.
- Dolomite content in both formations increases on the flanks and crests of pinnacles over which the B Salt has been dissolved.
- Over two incipient reefs there is an increase in dolomite content in the A-1 Carbonate Unit

Table 3. Calculated volumes for each 20-percentile dolomite interval for the A-1 Carbonate and A-2 Carbonate.

Isopercent dolomite	A-1 Carbonate (km³)	A-1 Carbonate (% total)	A-2 Carbonate (km³)	A-2 Carbonate (% total)
<20	5.32	50.52	1.37	10.09
20-40	1.57	14.91	2.01	14.80
40-60	0.96	9.12	2.40	17.67
60-80	0.96	9.12	2.92	21.50
80-100	1.72	16.33	4.88	35.94
total	10.53	100.0	13.58	100.0

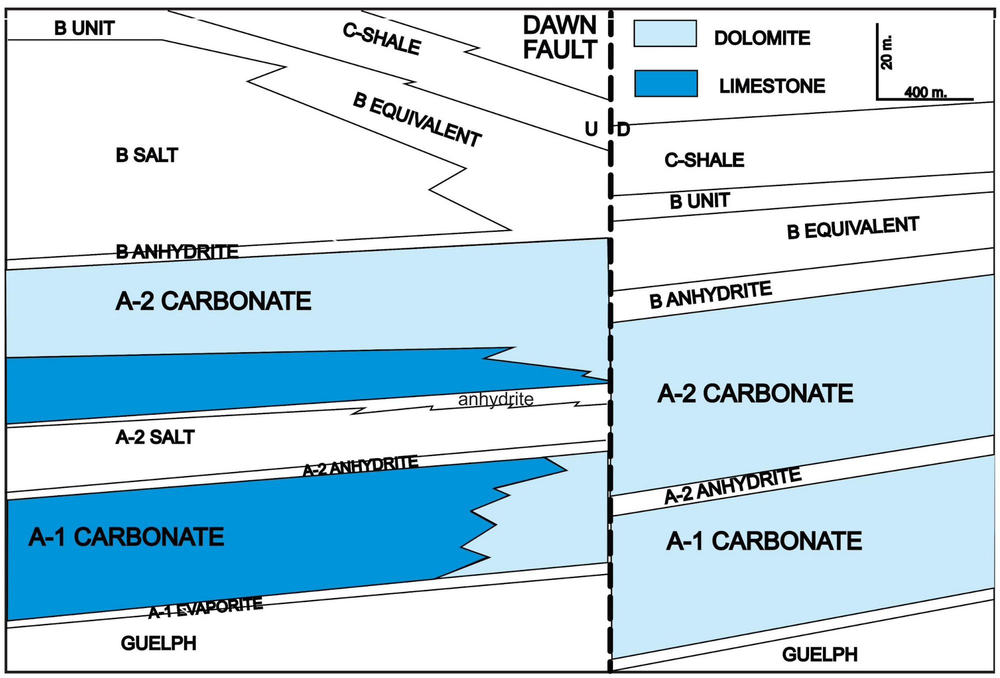

Figure 8. Schematic representation of dolomitization patterns in the vicinity of the Dawn Fault and Becher faults. Modified from Carter 1991.

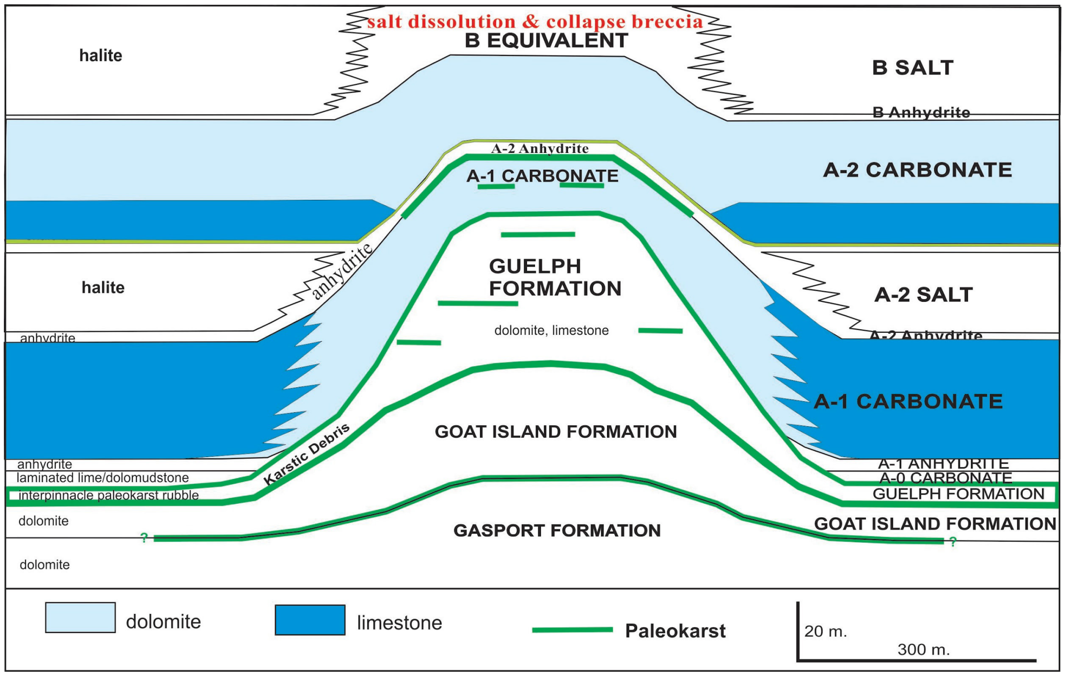

Figure 9. Schematic representation of dolomitization patterns in the vicinity of a pinnacle over which there has been dissolution of the halite of the B Salt Unit.

Discussion

The Oil, Gas and Salt Resources Library in London, Ontario is a public repository of data on the subsurface Paleozoic geology and hydrogeology and petroleum and bedrock resources of southern Ontario. The OGSRL actively maintains a modern digital database (OPDS) of geological formation tops and related information on occurrences of water, oil, and natural gas in the subsurface bedrock formations. This data has been used by the Geological Survey of Canada to construct 3-D models of the bedrock geology (Carter et al. 2019, 2021b) and hydrostratigraphy of southern Ontario (Carter et al. 2022). Other OGSRL datasets are less well-known and not actively maintained. The legacy OGSRL dataset is ideally suited for a case study of 3-D data interpolation of dolomite vs limestone of the A-1 and A-2 Carbonate Unis within the model formation layers of Carter et al. (2021b). The structure of the existing data tables, with modifications, was amenable to constructing the 3-D interpolants, and the availability of a full set of scanned hard copy records of the source data greatly facilitated QA/QC of the data. Use of this dataset provided considerable time and cost savings and added value to the work previously completed by Carter (1991).

The model bedrock formation layers of the 3-D bedrock geologic model of Carter et al. (2021b) provided viable containers for 3-D interpolants of the dolomite vs limestone proportions within the two formations. The surfaces of the modelled layers were also useful in creating a more accurate interpretation of the position of previously mapped faults, as well as identification of previously undocumented faults. The model formation surfaces were also used to define the lateral extent of Guelph pinnacles and incipients more accurately. These two refinements were directly relevant to the modelling objectives as dolomite was preferentially associated with pinnacles and faults.

The patterns of dolomitization in relation to other geological features are further defined due to data improvements based on evaluations of model iterations in 3-D context. 3-D numeric models and visualizations more thoroughly determine and more clearly display dolomitization patterns than the 2-D interpretations and illustrations of Carter (1991).

The cross-cutting relationships of dolomite occurrences in the A-1 Carbonate observed in the model on the flanks and crests of some pinnacles are strongly supportive of a post-depositional dolomitization mechanism. Coniglio et al. (2003) proposed that regional dolomitization of the Guelph Formation, and probably the underlying carbonates of the Goat Island and Gasport formations, occurred as a result of downward and lateral seawater flux through the carbonate platform during early burial diagenesis, with local upwards flow within pinnacles and preferential dolomitization of the A-1 Carbonate and A-2 Carbonate around and above dolomitized pinnacles. They also note that dissolution of halite of the B Salt Unit above selected pinnacles can also be explained by this upward seawater flux. The most likely pathway for lateral movement of dolomitizing fluids is through a complex interconnected network of pore spaces (see Carter et al. 2023) in the porous and permeable paleokarst of the regional and interpinnacle Guelph Formation and uppermost Goat Island Formation.

Data issues that contribute to uncertainty regarding the accuracy/reliability of the 3-D interpolants include:

- sparse data and missing or incomplete data,
- unrecognized faults and reefs,
- no data for wells drilled since 1997
- well/data clustering

Summary and Conclusions

A 3-D geological model of dolomitization patterns in the regional limestones of the Salina A-1 and A-2 Carbonate units has been completed at a spatial resolution is 400 m. The model is built within the 3-D geological model of the bedrock of southern Ontario (Carter et al. 2021b) and utilizes the boundaries of model formation layers of the A-1 Carbonate Unit and A-2 Carbonate Unit for containment of interpolated data values. Geologic relationships are illustrated using model layers of 12 bedrock formations representing, in ascending stratigraphic order, the Gasport, Goat Island and Guelph formations of the Lockport Group, and the A-1 Evaporite, A-1 Carbonate, A-2 Anhydrite, A-2 Salt, A-2 Carbonate, B Anhydrite, B Salt, B Equivalent, and B units of the overlying Salina Group (Figure 2).

Greater than 65% of the A-1 Carbonate is comprised of limestone (< 40 percent dolomite) whereas 75% of the A-2 Carbonate is comprised of dolomite or dolomitic limestone (> 40 percent dolomite).

Increased proportions of dolomite vs limestone are spatially associated with the following:

- the flanks and crests of pinnacles over which the B Salt has been dissolved
- the crests of some but not most incipient reefs
- the downthrown side of the Dawn Fault and Becher faults for both the A-1 Carbonate and A-2 Carbonate
- the upper half of the A-2 Carbonate Unit

This project demonstrates the feasibility of adding 3-D point attribute data to the regional model formation layers of Carter et al. (2021b) for visualization and analysis. The regional geological model supports more detailed and local scale analysis initiatives. It also demonstrates the value of applying modern digital data interpretation and visualization tools to extract new geological insights from legacy datasets. Previous data analysis by Carter (1991) and Coniglio et al. (2003) was limited to 2-D structural and isopach/isolith realizations, however the development of a full 3-D volume model greatly facilitates the visualization of dolomite distribution. A unique function of the 3-D model realisation is the accurate measurement of volumes and relative percentages of dolomite vs limestone.

The cross-cutting relationships of dolomite occurrence in the A-1 Carbonate Unit on the flanks and crests of some pinnacles are strongly supportive of a post-burial dolomitization mechanism as proposed by Coniglio et al. (2003). The most likely pathway for the dolomitizing fluid was through the porous and permeable paleokarst of the underlying regional Guelph Formation and upwards through the porous reef carbonates of the pinnacles. The association of the dolomitization haloes with halite dissolution features in the overlying B Salt Unit suggest that the dolomitizing fluids may also have been responsible for salt dissolution. Preferential association of dolomite with the Dawn and Becher faults suggest movement of dolomitizing fluids also occurred along these faults.

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This project could not have been completed without the extensive archive of physical and digital petroleum well data collected, managed, and maintained by the Petroleum Operations Section of the Ministry of Natural Resources and Forestry (MNRF) and the OGSRL. Operation of the OGSRL is funded by mandatory fees on petroleum well licences, drill core and drill cutting sample processing fees, Library user fees, and data sales, paid to the Oil, Gas and Salt Resources Trust. The Ontario Oil, Gas and Salt Resources Corporation, through the Ontario Petroleum Institute, is thanked for providing administrative and management support to the OGSRL, in its role as Trustee of the Oil, Gas and Salt Resources Trust. A table of the data used for the dolomite interpolation is included with this open file, courtesy of the OGSRL.

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References

Al-Aasm, Ihsan S., Crowe, R., and Tortola, M. 2021. Dolomitization of Paleozoic Successions, Huron Domain of Southern Ontario, Canada: Fluid Flow and Dolomite Evolution." Water 13 (17). https://doi.org/10.3390/w13172449

Armstrong, D.K. and Carter, T.R. 2010. The subsurface Paleozoic stratigraphy of southern Ontario; Ontario Geological Survey, Special Volume 7, 301p.

Bailey, S.M.B. 1986. A new look at the development, configuration and trapping mechanisms of the Silurian Guelph reefs of southwestern Ontario. In Proceedings, Ontario Petroleum Institute, 25th Annual Meeting, London, Ontario, v.25, Technical Paper 16, 28p.

——— 2000. The extremely complicated, 'simple' pinnacle reef reservoirs of Ontario. Ontario Petroleum Institute, vol.39, technical paper 3, 33p.

Bailey Geological Services Ltd. and Cochrane, R.O. 1984a. Evaluation of the conventional and potential oil and gas reserves of the Cambrian of Ontario; Ontario Geological Survey, Open File Report 5499, 72p.

——— 1984b. Evaluation of the conventional and potential oil and gas reserves of the Ordovician of Ontario; Ontario Geological Survey, Open File Report 5498, 77p.

——— 1985. Evaluation of the conventional and potential oil and gas reserves of the Devonian of Ontario (Volume 1); Ontario Geological Survey, Open File Report 5555, 178p.

——— 1986. Evaluation of the conventional and potential oil and gas reserves of the Silurian sandstone reservoirs of Ontario; Ontario Geological Survey, Open File Report 5578, 275p.

——— 1988a. Isopach top Guelph to top Rochester, southern Ontario. Ontario Geological Survey, Preliminary maps 2992 to 3019

———1988b. Structure top Salina A-2 Carbonate, southern Ontario. Ontario Geological Survey, Preliminary maps 3020 to 3041

Brigham, R.J. 1971. Structural geology of southwestern Ontario and southeastern Michigan. Ontario Department of Mines and Northern Affairs, Paper 71-2, 110 p.

Brintnell, C. 2012. Architecture and stratigraphy of the Lower Silurian Guelph Formation, Lockport Group, southern Ontario and Michigan; University of Western Ontario, unpublished MSc thesis, 242 pp.

Brunton, F.R. and Brintnell, C. 2011. Final update of Early Silurian stratigraphy of the Niagara Escarpment and correlation with subsurface units across southwestern Ontario and the Great Lakes Basin; in Summary of Field Work and Other Activities 2011, Ontario Geological Survey, Open File Report 6270, p.30-1 to 30-11.

——— 2020. Early Silurian sequence stratigraphy and geological controls on karstic bedrock groundwater flow zones, Niagara Escarpment region and the subsurface of southwestern Ontario; Ontario Geological Survey, Groundwater Resources Study 13.

Brunton, F.R., Brintnell, C., Jin, J., and Bancroft, A.M. 2012. Stratigraphic architecture of the Lockport Group in Ontario and Michigan – A new interpretation of Early Silurian "basin geometries" and "Guelph Pinnacle Reefs"; in 51st Annual Conference – Ontario – New York, Oil & Gas Conference, October 23–25, 2012, Niagara Falls, Ontario, p.1-37.

Carter, T.R. 1991. Dolomitization patterns in the Salina A-1 and A-2 Carbonate units, Sombra Township, Ontario. Ontario Petroleum Institute, proceedings 30th annual conference, 27 p.

Carter, T.R., Brunton, F.R., Clark, J., Fortner, L., Freckelton, C.N., Logan, C.E., Russell, H.A.J., Somers, M., Sutherland L., and Yeung, K.H. 2019. A three-dimensional geological model of the Paleozoic bedrock of southern Ontario. Ontario Geological Survey, Groundwater Resources Study 19 / Geological Survey of Canada, Open File 8618. https://doi.org/10.4095/315045

Carter, T.R., Clark, J., Colquhoun, I, Dorland, M., and Phillips, A. 2016a. Ontario oil and gas plays 1 – exploration, production and geology. Canadian Society of Petroleum Geologists, Reservoir 43, (08), 19-25.

Carter, T.R., Fortner, L.D., Russell, H.A.J., Skuce, M.E., Longstaffe, F.J., and Sun, S. 2021a. A hydrostratigraphic framework for the Paleozoic bedrock of southern Ontario. Geoscience Canada, v. 48, p. 23-58. https://doi.org/10.12789/geocanj.2021.48.172

Carter, T.R., Hamilton, D., Phillips, A., Dorland, M., Colquhoun, I., Fortner, L., and Clark, J. 2016b. Ontario oil and gas 3. Silurian and Devonian conventional plays; Canadian Society of Petroleum Geologists, Reservoir v.43, issue 10, p.18-26.

Carter, T.R., Larmagnat, S., Sun, S., Letellier, P., and Russell, H.A.J. 2023. Porosity characterization using medical computed tomography scans of two deeply buried paleokarst aquifers in Silurian carbonates, southern Ontario, Canada. Hydrogeology Journal, https://doi.org/10.1007/s10040-023-02668-9

Carter, T.R., Logan, C.E., Clark, J.K., Russell, H.A.J., Brunton, F.R., Cachunjua, A., D'Arienzo, M., Freckelton, C., Rzyszczak, H., Sun, S., and Yeung, K.H. 2021b. A three-dimensional geological model of the Paleozoic bedrock of southern Ontario—version 2. Geological Survey of Canada, Open File 8795, 1 .zip file. https://doi.org/10.4095/328297

Carter, T.R., Logan, C.E., Clark, J.K., Russell, Priebe, E.H., and Sun, S. 2022. A three-dimensional hydrostratigraphic model of the Paleozoic bedrock of southern Ontario. Geological Survey of Canada, Open File 8927, 2022, 58 pages, https://doi.org/10.4095/331098

Carter, T.R., Trevail, R.A., and Smith, L. 1994. Core workshop: Niagaran reef and inter-reef relationships in the subsurface of southwestern Ontario; Geological Association of Canada–Mineralogical Association of Canada, Annual Meeting, Waterloo 1994, Field Trip A5 Guidebook, 38p.

Coniglio, M., Zheng, Q., and Carter, T.R. 2003. Dolomitization and recrystallization of middle Silurian reefs and platformal carbonates of the Guelph Formation, Michigan Basin, southwestern Ontario; Bulletin of Canadian Petroleum Geology, v.51, no.2, p.177-199.

Dorland, M., Colquhoun, I., Carter, T.R., Phillips, A., Fortner, L., Clark, J., and Hamilton, D. 2016. Ontario Oil and Gas. Cambrian and Ordovician conventional plays. Canadian Society of Petroleum Geologists, Reservoir, 43, issue 9, 18-25.

Friedman, G.M. and Kopaska-Merkel, D.C. 1991. Late Silurian pinnacle reefs of the Michigan Basin; in P.A. Catacosinos and P.A. Daniels, Jr. (eds.). Early sedimentary evolution of the Michigan Basin. Geological Society of America, Special Paper 256, p. 89-100.

Gardner, W.C. and Bray, E.E. 1984. Oils and source rocks of Niagaran reefs (Silurian) in the Michigan Basin; in J.G. Palacas, (ed.), Petroleum Geochemistry and Source Rock Potential of Carbonate Rocks, American Association of Petroleum Geologists, Studies in Geology, no.18, p.33-44.

Gill, D. 1977. The Belle River Mills Gas Field: productive Niagaran reefs encased by sabkha deposits, Michigan Basin; Michigan Basin Geological Society Special Paper 2, 188 p.

Grieve, R.O. 1955. Leaching (?) of Silurian salt beds in southwestern Ontario as evidenced in wells drilled for oil and gas; Canadian Institute of Mining and Metallurgy, Transactions v.58, p.12-18.

Koepke, W.E. and Sanford, B.V. 1966. The Silurian oil and gas fields of southern Ontario; Geological Survey of Canada, Paper 65-30, 137p.

McMurray, M. 1985. Geology and organic geochemistry of Salina A-1 Carbonate oil source-rock lithofacies (Upper Silurian), southwestern Ontario. unpublished MSc thesis, University of Waterloo, Waterloo, Ontario, Canada.

Mesolella, K.J., Robinson, J.D., McCormick, L.M. and Ormiston, A.R. 1974. Cyclic deposition of Silurian carbonates and evaporites in Michigan Basin; American Association of Petroleum Geologists Bulletin, v.58, no.1, p.34-62.

Nurmi, R.D. and Friedman, G.M. 1977. Sedimentology and depositional environments of basin-center evaporites, Lower Salina Group (Upper Silurian), Michigan Basin; American Association of Petroleum Geologists, Studies in Geology No.5, p.23-52.

Rine, M.J., Garrett, J.D., and Kaczmarek, S.E. 2017. A new facies architecture model for the Silurian Niagaran pinnacle reef complexes of the Michigan Basin, in Advances in Characterization and Modeling of Complex Carbonate Reservoirs—In Memory of Eric Mountjoy. SEPM Special Publication No. 109, p. 1-17. doi: http://dx.doi.org/10.2110/sepmsp.109.02

Ritter, A. and Grammar, G.M. 2017. Utilizing sequence stratigraphy to develop a depositional model for Silurian (Niagaran) reefs in the Michigan Basin; in .G.M. Grammer, W.B. Harrison III, and D.A. Barnes (eds.), Paleozoic Stratigraphy and Resources of the Michigan Basin. Geological Society of America Special Paper 531, p.81-103. doi:10.1130?2017.2531(05)

Sanford, B.V. 1969. Silurian of southwestern Ontario; Ontario Petroleum Institute, paper 5, 44 p.

Sanford, B.V. 1977. Distribution, thickness and three-dimensional geometry of salt deposits in southwestern Ontario; Geological Survey of Canada, Open File 401, 11 maps and section, scales 1:250 000 and 1:125 000. Geological Survey of Canada, Open File 401.

Smith, L. 1990. Karst episodes during cyclic development of Silurian reef reservoirs, southwestern Ontario; in T.R. Carter, ed., Subsurface geology of southwestern Ontario - a core workshop. Ontario Petroleum Institute, 555 Southdale Road E, London, Ontario, p. 69-88.

Smith, L., Grimes, D.J., and Charbonneau, S.L. 1988. Karst episodes and permeability development, Silurian reef reservoirs, Ontario; in Geoscience Research Grant Program, Summary of Research 1987–1988, Ontario Geological Survey, Miscellaneous Paper 140, p.124-132.

Somers, M.R. 2017. Paleozoic bedrock geology of southern Ontario; Oil, Gas and Salt Resources Library, Open File Data Release 2017-2, pdf file, accessed at https://s3.amazonaws.com/downloads.ogsrlibrary.com/open/OFDR-2017-2-OGSR-Petroleum-Well-Subcrop-Revision.pdf, 2020_01_30.

Trout, J.L., Grammer, G.M., and Harrison, W.B. 2017. Windward vs. leeward variability of faunal distribution in a Silurian (Wenlockian) pinnacle reef complex—Ray Reef, Macomb County, Michigan; in .G.M. Grammer, W.B. Harrison III, and D.A. Barnes (eds.), Paleozoic Stratigraphy and Resources of the Michigan Basin. Geological Society of America Special Paper 531, p.131–155. doi:10.1130/2017.2531(07)

Warren, J.K., 1999. Evaporites: Their Evolution and Economics. Blackwell Scientific Publications, Oxford, 438 pp

Warren, J. 2000. Dolomite: occurrence, evolution and economically important associations. Earth-Science Reviews 52, p. 1-81.

Wold, J.L. and Grammer, G.M. 2017. Rock-based 3-D reservoir characterization of a Silurian (Niagaran) reef—Ray gas storage field, Macomb County, Michigan; in .G.M. Grammer, W.B. Harrison III, and D.A. Barnes (eds.), Paleozoic Stratigraphy and Resources of the Michigan Basin. Geological Society of America Special Paper 531, p. 105–129. doi:10.1130/2017.2531(06)

Zenger, D.H., Dunham, J.B., and Ethington, R.L., 1980. Concepts and models of dolomitization. SEPM Special Publication 28, 320 pp.

Appendix 1: Three-dimensional plan views and cross-sections of the 3-D model

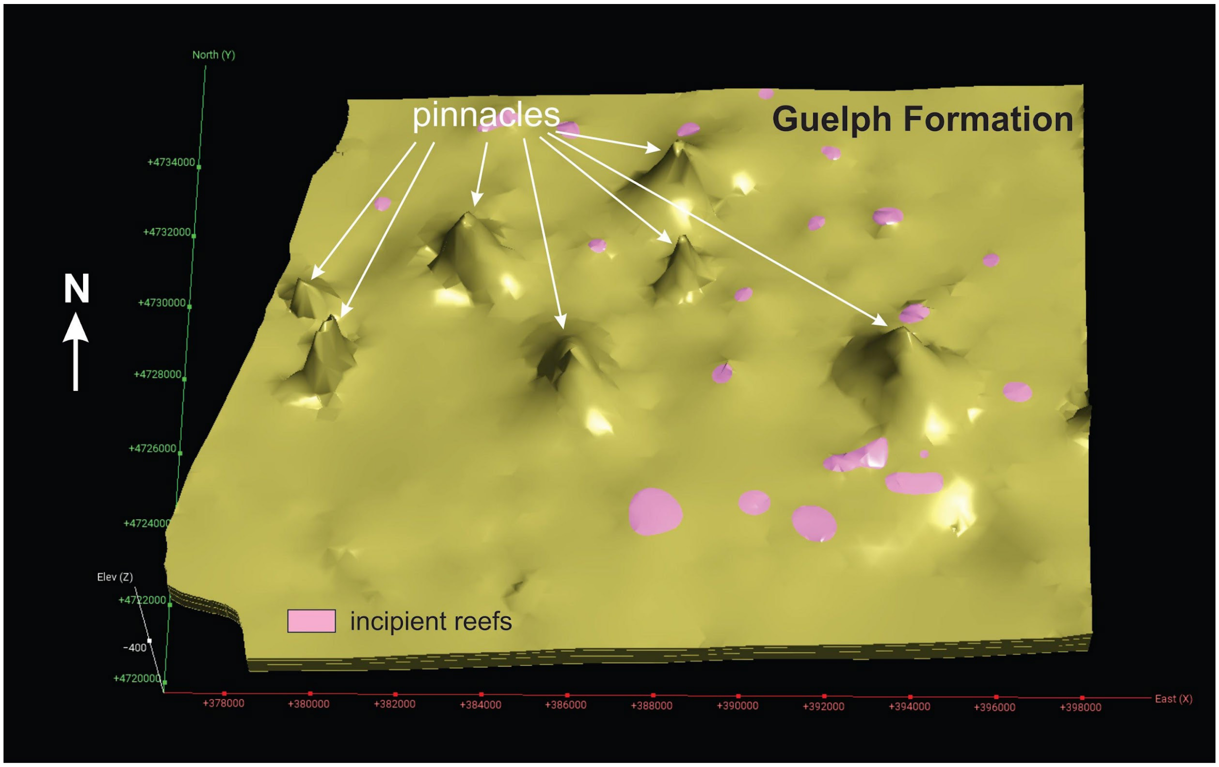

Figure 1-1. 3-D view of Guelph Formation showing pinnacles and incipient reefs within the study area.

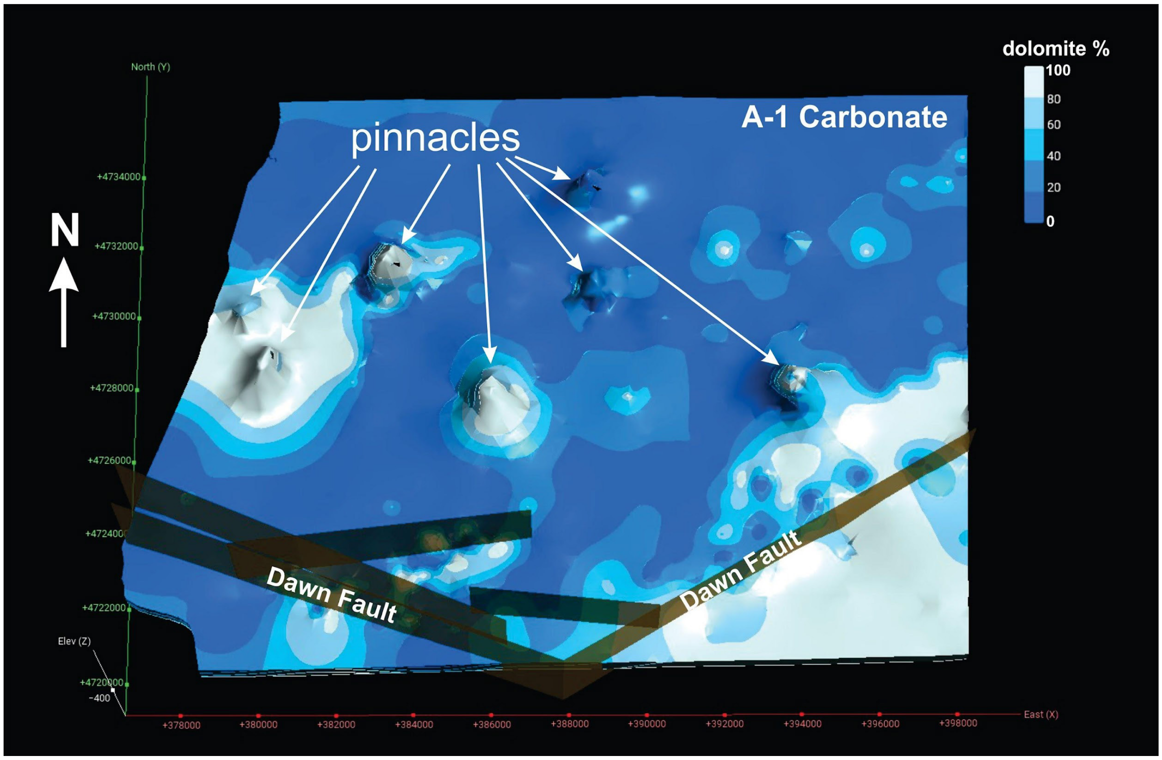

Figure 1-2. 3-D view of A-1 Carbonate Unit showing isopercent dolomite distribution and spatial relationship to pinnacles and faults. The cross-cutting haloes of dolomite above the Sombra, Sombra 7-A-VII, and Dutton pinnacles correspond to the location of salt dissolution features in the overlying B Salt.

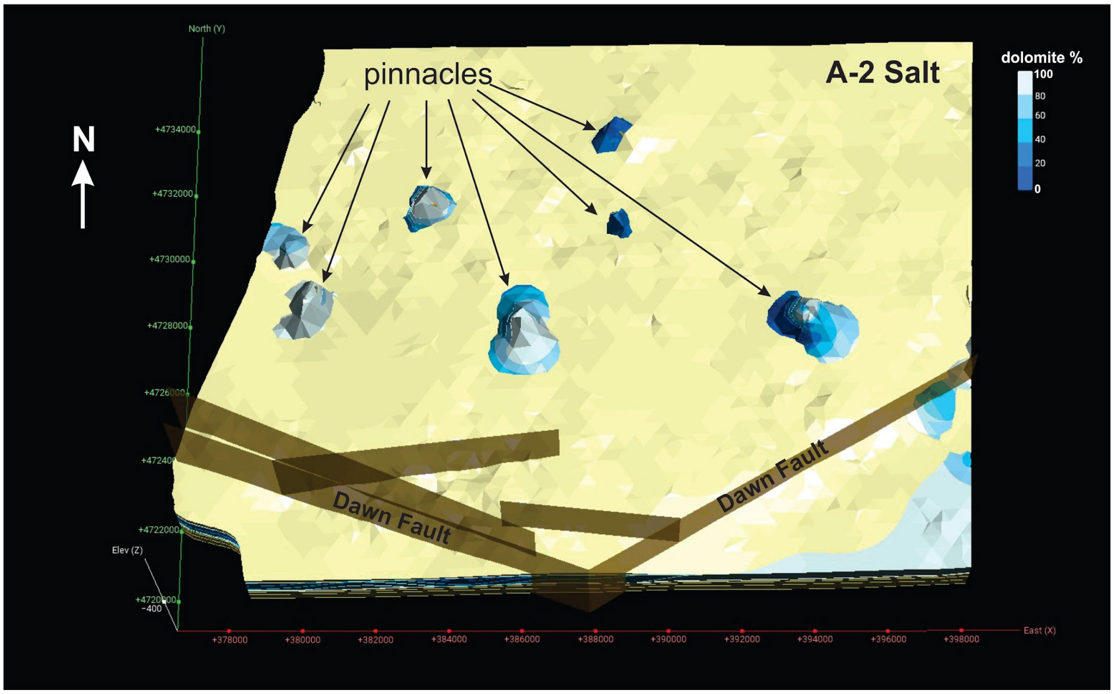

Figure 1-3. 3-D view of A-2 Salt showing areas of depositional pinch-out of the salt over underlying Guelph Formation pinnacles capped by A-1 Carbonate Formation limestones and dolomites. Pinnacle crests extend up to 40 metres above the top of the A-2 Salt.

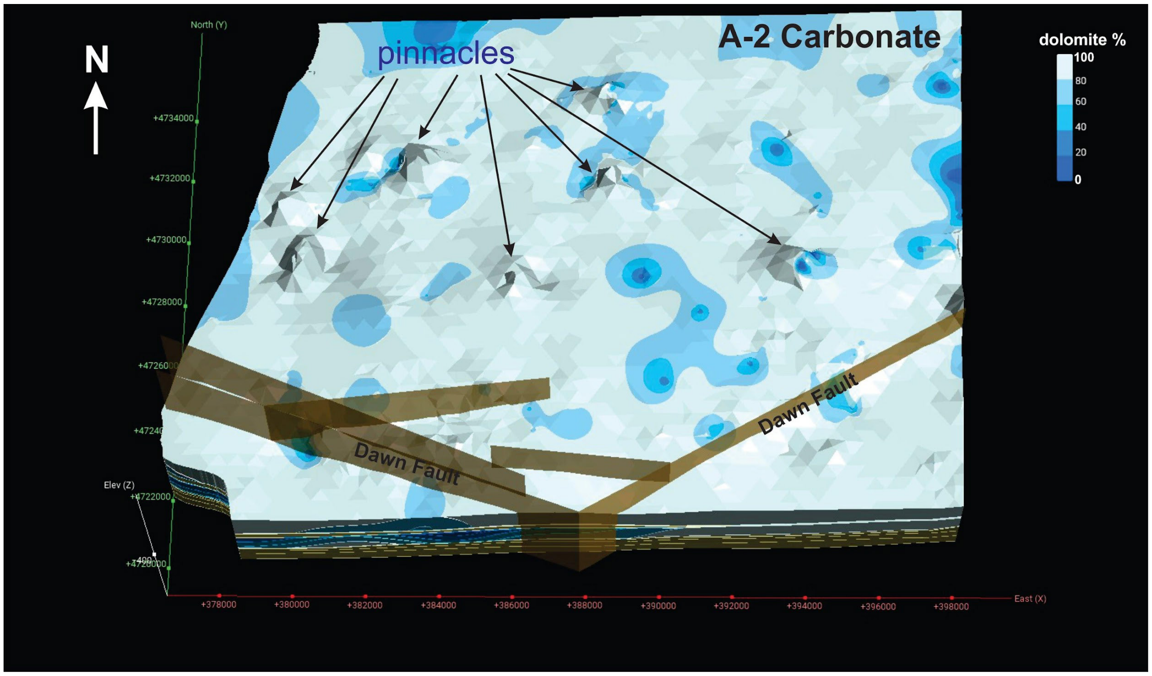

Figure 1-4. 3-D view of A-2 Carbonate showing isopercent dolomite distribution and spatial relationship to pinnacles and faults. The structural highs on this surface are compactional drapes over the underlying Guelph pinnacles.

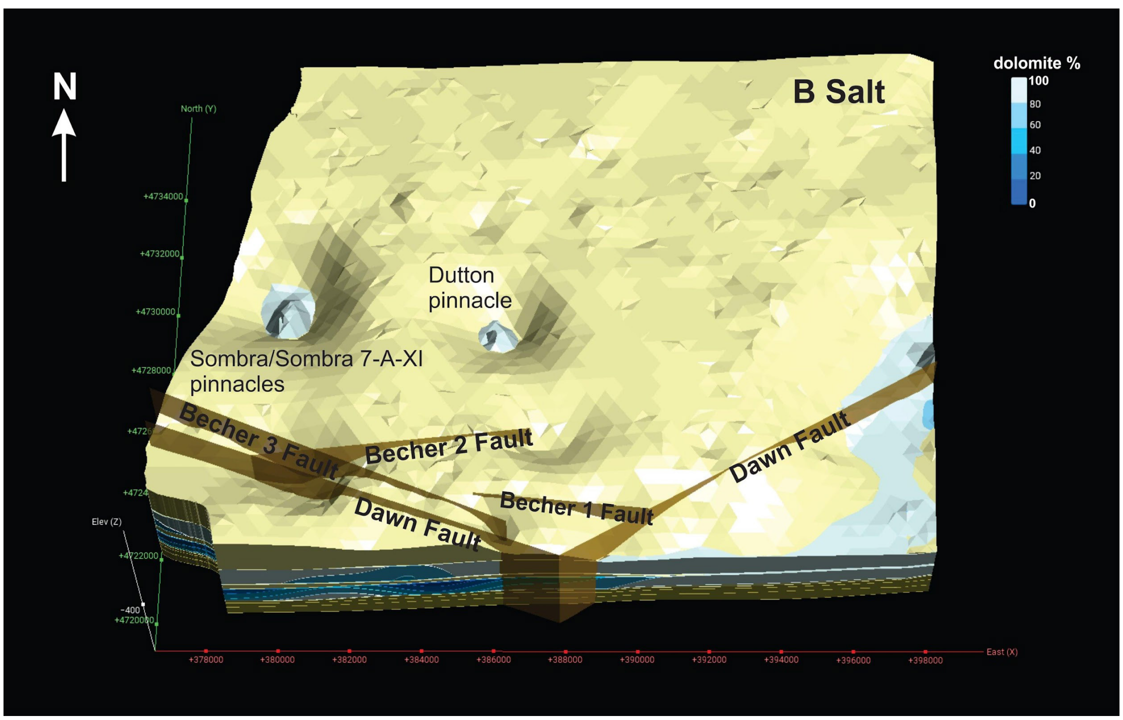

Figure 1-5. 3-D view of the B Salt Unit showing salt dissolution southeast of the Dawn Fault, at the intersection of the Dawn Fault with the Becher 1 and Becher 2 faults, and over the crests of the underlying Sombra and Dutton pinnacles.

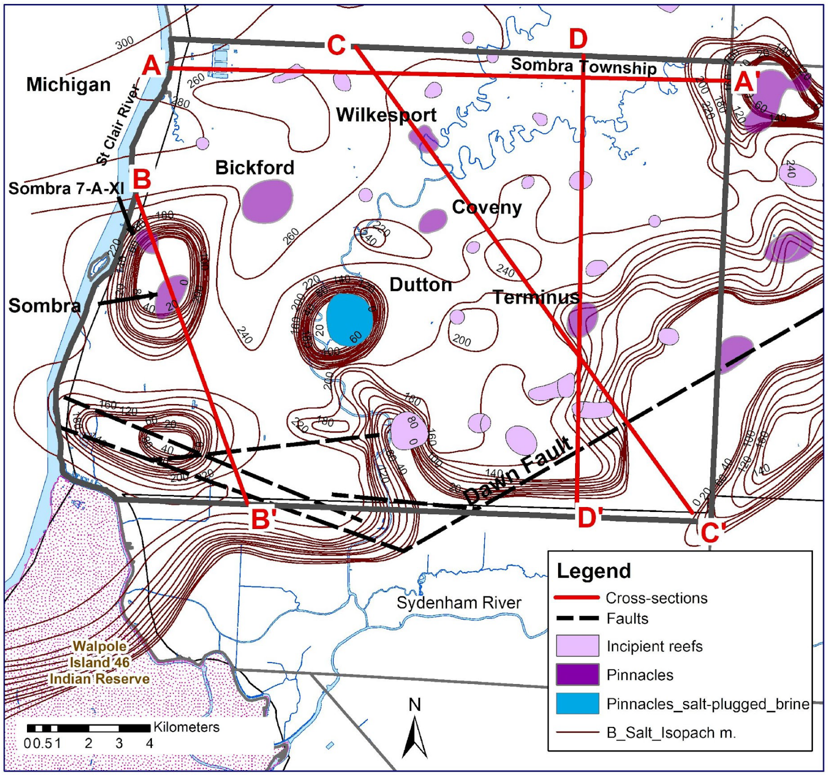

Figure 1-6. Location of cross-sections A-A', B-B', C-C', and D-D' in figures 1-7 to 1-10 below.

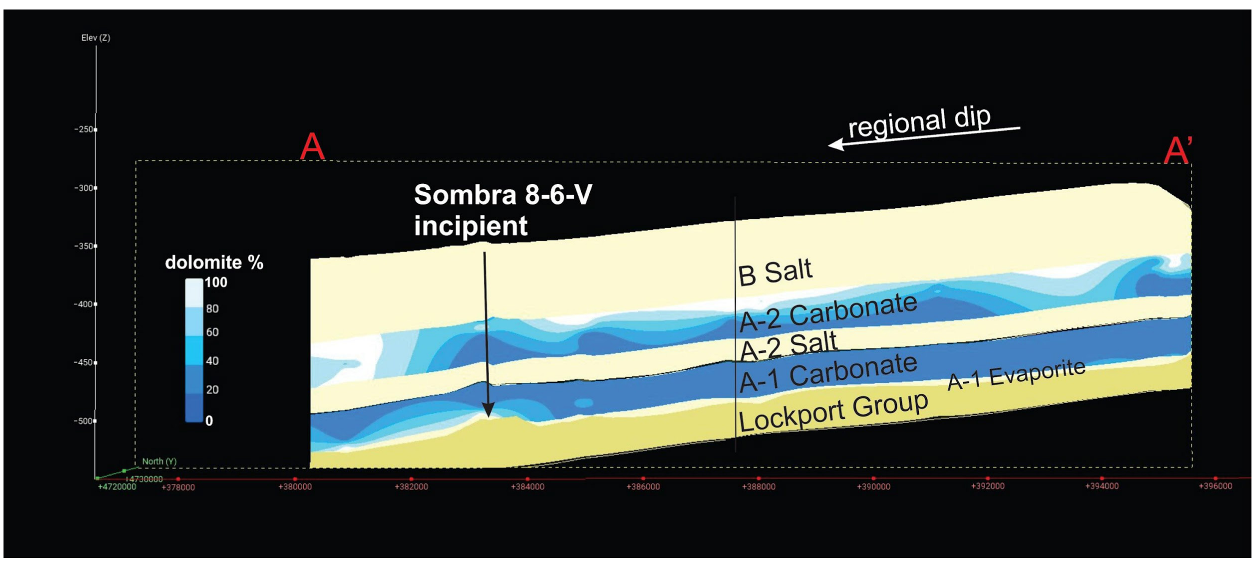

Figure 1-7. West (A) to east (A') cross-section showing stratigraphic distribution of dolomite vs limestone. The A-1 Carbonate is dominantly limestone with the exception of a halo of dolomite and dolomitic limestone near the Sombra 8-6-V incipient reef. The lower half of the A-2 Carbonate is dominantly limestone with a gradational upward transition to dolomite.

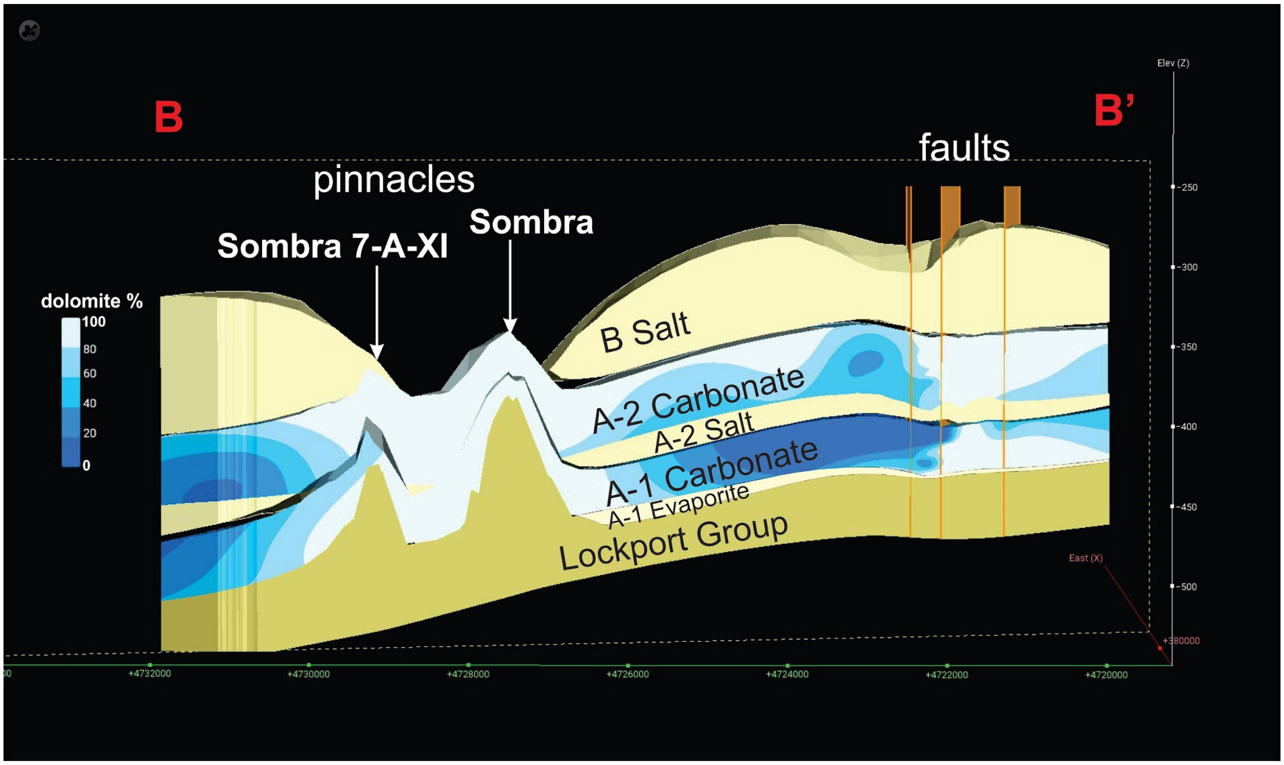

Figure 1-8. Northwest (B) to southeast (B’) cross-section through the Sombra and Sombra 7-A-XI pinnacles and the Becher and Dawn faults. Regional dip is to the northwest, interrupted by vertical displacements downwards on the south sides of the faults. The pinnacles are encased in a halo of 100% dolomite which cuts vertically across regional limestone of the A-1 Carbonate and merges laterally with the upper dolomite of the A-2 Carbonate. The dolomite haloes coincide with a circular dissolution feature in the overlying B Salt. Both formations are dominantly comprised of dolomite on the downthrown side the faults.

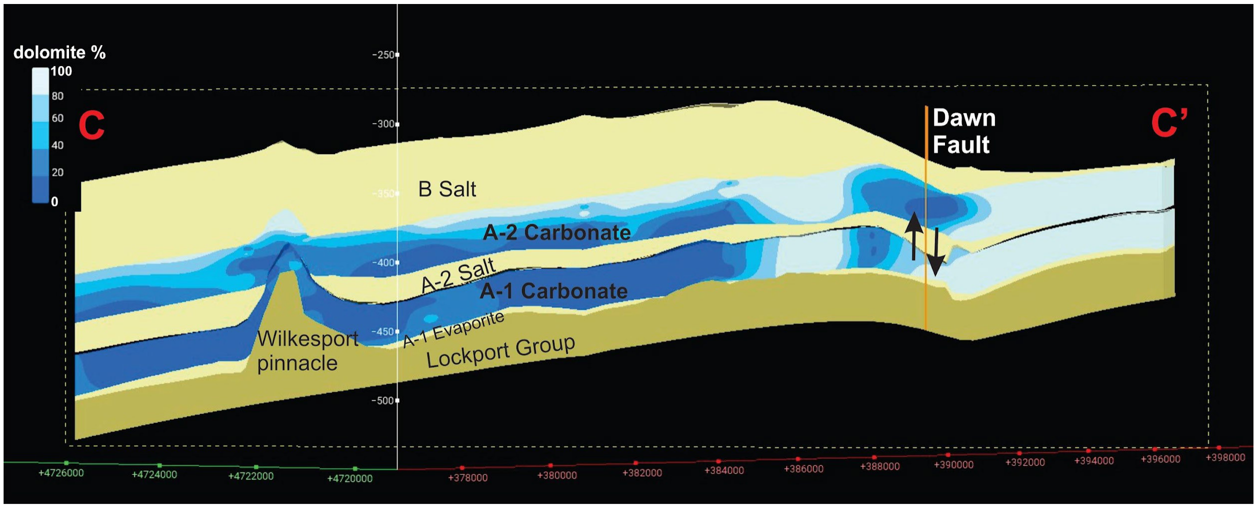

Figure 1-9. Northwest (C) to southeast (C') cross-section through the Wilkesport pinnacle and the Dawn Fault showing regional limestones of the A-1 Carbonate and an upward gradation from limestone to dolomite in the A-2 Carbonate. Regional dip to the northwest is interrupted by the Dawn Fault. There is no dissolution of the B Salt over the Wilkesport pinnacle and no dolomite halo in the A-1 Carbonate or A-2 Carbonate. Both formations are 100% dolomite south of the Dawn Fault corresponding to a dissolution front in the B Salt. The area of 100% dolomite north of the fault is on the southwest flanks of the Terminus pinnacle coinciding with a rapid decrease in thickness of the B Salt not shown in this cross-section.

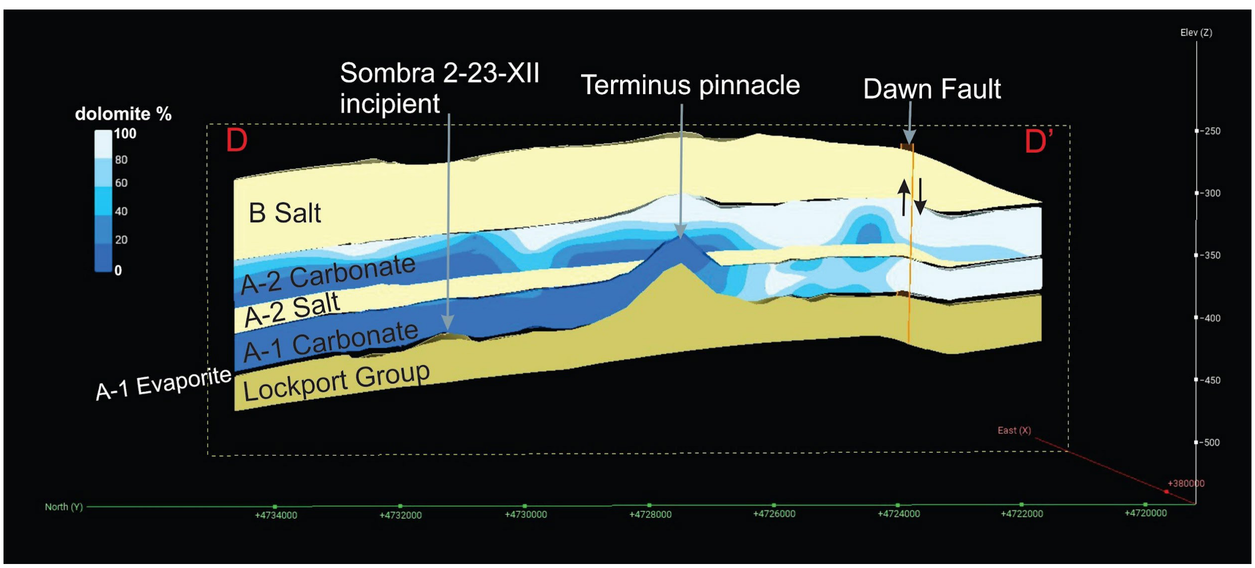

Figure 1-10. North (D) to south (D') cross-section through the Terminus pinnacle and the Dawn Fault showing regional limestones of the A-1 Carbonate and an upward gradation from limestone to dolomite in the A-2 Carbonate. There is no increase in dolomite associated with the Sombra 2-23-XII incipient reef or the Terminus pinnacle. Both formations are 100% dolomite on the south (downthrown) side of the Dawn Fault coinciding with a rapid thinning of the B Salt approaching a salt dissolution front.