PALEOKARST IN THE MIDALE BEDS,
CARNDUFF FIELD, SOUTHEAST SASKATCHEWAN

W.H. (Bill) Gatenby*
Husky Energy Inc., Calgary, Alberta

and

Scott Carter
Husky Energy Inc., Calgary, Alberta

ABSTRACT

Carnduff field produces light oil from the Midale and Frobisher Beds of Osagean (Mississippian) age. Core work has revealed significant occurrences of paleokarst in the Midale Beds, which are documented in this paper.

Carnduff field is situated at the updip erosional limit of the Midale Beds. A pre-Watrous paleo-geology map reveals the presence of NE-SW trending truncated anticlines and synclines. The synclines preserve relatively thick Midale Beds below the unconformity. Each of the five (5) main sub-units is exposed and porous beds are cemented with anhydrite on the flanks or crests of the anticlines.

From oldest to youngest, the five mapped sub-units of the Midale Beds are: (1) Frobisher-Evaporite: nodular anhydrite and tight dolomite; (2) Lower Vuggy: interbedded skeletal lime grainstones and packstones and stylolitic, fractured lime mudstones; (3) Upper Vuggy: mainly fractured lime mudstones; (4) MD1 (Lower Marly): massive porous skeletal lime packstone-grainstone; and (5) MD2 (Upper Marly): regionally dolomitized original skeletal wackestone. Sub-units 2-5 are informal members of the Midale Carbonate, designated strictly for this study.

Paleokarst in the Midale Beds in SE Saskatchewan is not currently well documented. In Carnduff, well logs and core offer ample evidence of Midale Beds paleokarst apparently concentrated along the paleo-highs where fractured Upper and Lower Vuggy were exposed. In core there is a continuum of expression ranging from solution enhancement of fractures to minor bedding plane controlled caves infilled with anhydrite, to major caves with complex fill and dolomitized country rock. Paleokarst features are highlighted on the pre-Watrous paleogeology map and core descriptions along with photographs are presented for three examples.

At unconformity time, karstification had increased porosity in the Midale Beds substantially. Unfortunately, the high permeability network also facilitated the influx of gypsum precipitating fluids in Upper Watrous (Jurassic) time and most original void space (and adjacent country rock) is solidly cemented.
Understanding the paleokarst complex in the field is critical to understanding the current porosity distribution in what is a complex, compartmentalized reservoir.

INTRODUCTION
Carneduff field (Figure 1) produces light oil from the Midale Beds and Frobiher Beds, both of Osagean (Mississippian) age (Figure 2). Renaissance Energy (now Husky Energy Inc.) purchased this field in early 2000 with plans to optimize the existing Midale Beds waterflood. As part of the ongoing technical assessment of this large property, the authors have measured some 48 Midale Beds cores (out of a total of 160 cut), many of which contain striking evidence of pre-Watrous aged paleo-karst. The purpose of this paper is to document these occurrences and discuss the economic significance of karstification in this oil reservoir.

BRIEF GEOLOGY OF MIDALE BEDS IN CARNDUFF FIELD AREA
As indicated on Figure 1, Carneduff field is situated at the extreme updip erosional edge of the Midale Beds. Figure 3 presents logs and core description for a typical "full" Midale section. As shown, the Midale Beds are divisible into five (5) main sub-units, which are described in detail in a later section. The important oil producing sub-units are Lower Vuggy and MD1. These and even finer subdivisions are easily correlated on logs and in core throughout the field where unaffected by erosion, solutioning or alteration associated with the pre-Watrous unconformity. Figure 4 is a pre-Watrous paleogeology map displaying the subcrop of important sub-units. The subcrop pattern reflects the existence of moderate relief NE-SW trending sub-unconformity anticlines and synclines which are truncated at the unconformity which was topographically subdued (Figure 5 - Upper Red Beds to Unconformity "mould map"). Figure 6, structure on the top of Lower Vuggy, illustrates the structural configuration below the unconformity.

As per Figure 4, the paleo-low areas contain relatively thick preserved Midale Beds section which thins regionally updip and, along strike, onto the paleo-highs. Depending on position, the paleohighs expose all or part of the Marly and Vuggy with each unit typically solidly cemented with anhydrite and dolomitized where it subcrops. The fluids responsible are generally assumed to have moved down into the Mississippian sub-crop through the Lower Watrous silts during deposition of the widespread Upper Watrous Evaporite (Kendall, 1975). The usual limitation of cementation to the sub-cropping sub-unit indicates stratification in the Midale beds significantly impeded vertical groundwater flow.

DETAILS OF MIDALE BEDS STRATIGRAPHY IN CARNDUFF FIELD
Lithofacies details of the five (5) main sub-units (Figure 3) pertinent to this study are listed below, starting with the oldest. Note that sub-units 2-5 are informal members of the Midale Carbonate, designated strictly for this study. These descriptions apply to the regional or background stratigraphy (i.e. where unaffected by karsting or alteration).

1. Frobiher Evaporite: Typically nodular anhydrite with interbeds of a red, mottled cryptocrystalline dolomite in the lower half. Near the upper contact with the Lower Vuggy, there is significant clay-rich matrix between anhydrite nodules.

2. Lower Vuggy: This 10 ft. (3.0 m) thick sub-unit consists of interbedded lime mudstones and skeletal (codiacean algae) packstones and grainstones. The mudstones are stylolitic with associated tension gashes which were open at unconformity time as evidenced by common clear anhydrite cement infill and red stain "halos". The grain-supported lithologies often have high primary or restored intergranular porosity and 0.5 to 300 md permeability. Grainy beds at all scales host dark metasomatic anhydrite (Kendall, e.a., 1978) which in Carneduff seems to predate the clear post-unconformity void filling anhydrite.

3. Upper Vuggy: This sub-unit consists of four (4) widely developed thin beds. At the base is a 4 ft. (1.2 m) thick massive cryptocrystalline, argillaceous dolomite (Marker Bed) which
is assumed to be primary and representative of a basin-wide salinity event. This interval has high porosity but very low permeability and is never oil stained or fractured. Overlying the dolomite with sharp contact is a thin, spiculitic packstone. It is very fine grained and appears to contain only minor codiacean algae. This unit, which has poor permeability and is rarely a significant producer, is overlain by a 15 ft. (4.6 m) thick "lithographic" lime mudstone which can be further divided into a lower tan, stylolitic, intensely fractured bed and an upper 4 ft. (1.2 m) grey argillaceous lime mudstone herein referred to as the "Dead Zone" (due to S.P. response), which is essentially unfractured and effectively isolates the Marly from the Vuggy as far as fluid flow is concerned.

4. MD1 (Lower Marly): This sub-unit consists of a single porous codiacean algae packstone bed about 10 ft. (3 m) thick. It has high intergranular primary or restored porosity and permeability typically in the 0.5 - 30 md. range. Engineering data suggests this beds is relatively unswept in the waterflood, which tends to "short circuit" through the fractured Vuggy.

5. MD2 (Upper Marly): This bed is regionally dolomitized far from the subcrop edge, presumably by reflux of Mg. rich brines during deposition of the Midale Evaporite. It appears to have originally been a burrowed spicular wackestone. It is only locally of reservoir quality in Carnduff.

The preceding describes the layercake original stratigraphy that was exposed at the pre-Watrous unconformity. Cross formational groundwater flow can be assumed to have been limited due to the stratification (frequent tight or shaly beds). Input of meteoric water into each bed at pre-Watrous unconformity time likely occurred primarily where that bed was exposed on the paleo-highs. Flow was probably focused in the naturally fractured beds.

KARST OVERPRINT
Paleokarst in the Midale Beds in SE Saskatchewan is not currently well documented. Smith (1980, pg. 27) interprets a dolomite breccia in a single well in Benson field to be a "sink hole" and comments that "the anhydritized zone is thicker on pre-Watrous topographic highs and in karstic features". Magas (1960, pg. 20) identifies thickness anomalies in the Midale Beds in Glen Ewen field (adjacent to Carnduff) where "conformably overlain by Midale evaporite". He offers no explanation, however similar features in Carnduff are clearly karst related. Kent e.a. (1998) include no examples of Midale Beds paleokarst in their overview of SE Saskatchewan (Williston Basin) paleokarst.

In Carnduff, well logs and core offer ample evidence of Midale Beds paleokarst, apparently concentrated along the paleo-highs where the fractured Upper and Lower Vuggy were exposed. Where limited to logs, evidence is in the form of missing marker beds or significant thinning of marker defined intervals. In core, there is a continuum of expression of the paleokarst ranging from solution enhancement of fractures (anywhere in the field) to minor bedding plane-controlled caves infilled with anhydrite (flanks of paleo-highs) to major caves with complex fill (on paleo-highs). In many cases, cores reveal striking paleokarst attributes where logs show no anomaly.

Figure 4 superimposes all currently identified paleokarst occurrences on the pre-Watrous paleogeology. On the map, the occurrences are qualitatively categorized as follows:
<table>
<thead>
<tr>
<th>Category</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>K1</td>
<td>Minor, shallow cave/void development limited to sub-cropping sub-unit. Both vertical fissures (joint control) and horizontal fissures up to 6 inches (15 cm) high (bedding plane control) as well as multiple irregular voids larger than 1/2 inch (1.3 cm) in diameter. Host beds generally dolomitized and cemented with anhydrite. Rarely a fine breccia or Spearfish silt within voids. Main infill by clear to white anhydrite (after gypsum). Limestone immediately beneath deepest horizontal cave may be virtually unaltered. This type of paleokarst is found on flanks of highs to well out in paleo-lows. Figures 7a and 7b show log/core data for an example of this category. Note the presence of porous, oil-saturated limestone immediately beneath the thin karstified zone.</td>
</tr>
<tr>
<td>K2</td>
<td>Deeper minor cave/void development in sub-units beneath the subcropping unit. Usually not continuous from surface down. Seems to be most common in the naturally fractured Upper and Lower Vuggy. Infill as in &quot;K1&quot;. Host rock usually cemented with anhydrite.</td>
</tr>
<tr>
<td>K2A</td>
<td>Dolomitization or red coloration in units below subcropping unit. Often accompanies significant void development (K2) but may occur without. The dolomites are extremely variable, reflecting different original limestone textures. Dolomitized skeletal packstones/grainstones are coarsely crystalline with often enhanced reservoir quality. Dolomitized Upper Vuggy mudstones (originally dense, lithographic limestone) are often highly porous but with extremely fine crystal size. Permeabilities as high as 20 md. have been noted. Red stain is mainly encountered in argillaceous beds like the &quot;Dead Zone&quot; or solution seams.</td>
</tr>
<tr>
<td>K3</td>
<td>Major, possibly multistorey, cave development usually at the Upper/Lower Vuggy level with roof rock inferred to be MD1 or MD2. Caves typically contain host rock derived breccia and the host rock and breccia are dolomitized. Individual chambers are up to 20 ft. (6.1 m) high. As per Loucks and Hanford, 1992 (pg. 30) we recognize cave roof crackle breccia, chaotic breakdown breccia, and transported breakdown breccia. In addition, frequent occurrences of well-sorted Spearfish silt or sand influvium suggest very competent streamflow through cave network. Significant void space still existed between breccia blocks and at the roof of caverns at U. Watrous time and was filled with clear anhydrite (after gypsum?) cement. Thin section work is incomplete but evidence of speleothems or cave cements is rare and equivocal. As per Figure 4, cored examples are well up on paleohighs.</td>
</tr>
<tr>
<td>L</td>
<td>Inferred paleo-karst occurrences based strictly on log data. Typically based on missing section or obvious replacement of specific beds by different lithology.</td>
</tr>
</tbody>
</table>
EXAMPLES OF MAJOR PALEOKARST FEATURES
Figures 8a to 8e present log/core data, core photos and thin section photos for 11-22-2-34 W1M which encountered strongly karstified (K3) Midale Beds with several apparent levels of cave fill bottoming in mid-Frobisher evaporite, some 47 feet (14.3 m) below the unconformity. As interpreted, the lower cave fill (4215-4225 ft.) consists of a mixed breccia made up of fragments of dolomite and anhydrite recognizable as original Upper and Lower Vuggy and Frobisher Evaporite (Figure 8b). The upper 2 ft. of original void was infilled with well sorted Spearfish sand 37 ft. (11.3 m) below the unconformity. This lower fill is overlain by a 5 ft. (1.5 m) interval which may be, in part, in-situ crackle brecciated Midale Vuggy which is overlain by approximately 8 ft. (2.4 m) of striking cave fill breccia which is tightly packed at the base and loosely packed higher up with clear, gray anhydrite cement infilling interfragment voids. The main cave roof (4186-4204 ft) appears to be in Upper Vuggy and MD1-MD2, which have been mainly dolomitized (note oil stain at base). Gravitational stresses in the roof are evidenced by silt and anhydrite filled horizontal and chaotic fissures (Figure 8c). Above this disrupted "roof" is another interval of breccia, in part sitting with sharp contact against what could be the vertical wall of a cave which has been exhumed as the unconformity lowered itself through the Mississippian. The breccia is overlain directly by typical Red Beds.

Figures 9a to 9c present log/core data, core photos and a thin section photo for 11-20-2-33 W1M, which encountered a very unusual apparent cave fill. The cave bottomed in Lower Vuggy (which is not dolomitized) and had its roof in MD2? of which only about 4 ft. (1.2 m) remains below the unconformity. The cave fill is 23 ft. (7 m) in thickness and consists primarily of inch/cm scale fragments of tan, partly vugular limestone (generally resembling Midale lithologies) in a matrix of sandy marl. There are rare beds of well-sorted Spearfish sand. This fill has retained high porosity and was perforated and produced reasonably well. As a breccia, this fill differs dramatically from all others identified in core. The fine clast size would seem to suggest a much greater degree of transportation and abrasion than the typical angular, coarse collapse breccias. The retention of porosity is probably due to relatively low permeability limiting influx of cementing brines during the Upper Watrous.

SIGNIFICANCE OF KARSTIFICATION IN CARNDUFF OIL RESERVOIR
At unconformity time, evidence suggests that karstification had significantly increased Midale Beds porosity. Substantial cavernous porosity existed above the breccia or influvium and between blocks in the breccia within caves. In addition, the surrounding country rock was subject to intense fabric selective solutioning. Unfortunately, this high permeability network also facilitated the influx of gypsum precipitating brines during Upper Watrous time. This process was extremely effective to the point that all remaining cavernous porosity and most fissures and inch/cm scale voids appear to have been totally cemented. Worst of all, the intergranular porosity in close proximity was also severely reduced. Thus, the MD1 bed which had little fissure or cavern development, tends to be porous right up to its subcrop, while the Upper and Lower Vuggy, with significant fissure and cavern development, may be tight as far out as the cave network extended. Since the cave network might be expected to be complex, it follows that the edges of Lower Vuggy porosity may be difficult to define. Application of karst models may prove useful in predicting the limits of porous Lower Vuggy in this complex, compartmentalized reservoir.

The economic importance of accurately predicting the porosity distribution is illustrated by 14-22-2-34 W1M (see Figure 4). This failed Frobisher horizontal well was perforated in the Lower Vuggy in the build section as a "bail out". The surprisingly good results (initial rate of 120 bopd at 45% watercut) can only be explained as resulting from "banking" of oil between the nearest injector row and the "tight" paleokarst complex.

Of less certain significance is the locally developed secondary dolomite. Where dolomitization of the productive Lower Vuggy occurs, the process may increase porosity substantially, but if associated voids are large, the dolomite may be largely cemented by anhydrite. Probably more interesting is the alteration of original non-reservoir Upper Vuggy mudstones to high porosity very
finely crystalline, often oil-stained dolomites. This type of dolomite is perforated in a number of wells but its contribution to production or its potential value as a target is unknown.

Finally, as demonstrated in the 11-20-2-33 W1M well (Figure 11), cave fill sediment may occasionally be porous and permeable. As with the alteration dolomite, potential value as a target is unknown.

**SUMMARY AND CONCLUSIONS**

As suggested at the outset, the purpose of this paper is to document the existence of paleokarst in the Midale Beds at Carnduff. The examples presented clearly indicate the Midale Beds subcrop at Carnduff was a karst surface with significant sub-surface groundwater flow occurring in cave complexes preferentially developed in the naturally fractured Upper and Lower Vuggy along pre-unconformity anticlines. Even as the cave network formed, it was being infilled by wall and roof collapse as well as infiltration of significant volumes of Spearfish silt and sand. Nevertheless, significant secondary porosity in the country rock and large open voids in the cave fills still existed as shoreline and shallow marine sediments of the Lower Watrous Red Beds overstepped the surface. Downward flow of gypsum-precipitating brines during Upper Watrous time was focused in the cave complexes which are now generally tight.

Important unresolved issues include:

1. Presumably, dolomitization of country rock surrounding cave/void networks is closely related to gypsum precipitation which ultimately nearly totally filled macro-void space. Why is some of this “alteration” dolomite tight and some porous and potential reservoir?

2. Is the paleokarst complex confined to the Midale Beds or is it part of a bigger system, including overlying Ratcliffe and underlying Frobisher Beds?

3. Why is solutioning (cave formation) not focused in the anhydrite units above and below the Midale carbonates? Is solutioning in these units self-limited by the formation of tight residuum.

4. Karst implies substantial influx of fresh water into the Midale Beds along their subcrop. How far basinward is phreatic meteoric diagenesis important in the Midale?

The magnitude and common occurrence of paleokarst features in Carnduff and general lack of references to paleokarst in the basin would seem to be contradictory. Kent e.a. (1998), in the most detailed study of paleokarst in the basin, list 18 major and minor occurrences in all Mississippian units (none in Midale). In Carnduff, review of 48 cores has resulted in the identification of 31 occurrences of major or minor paleokarst features in the Midale Beds alone. The implication is that our understanding of this unconformity surface is far from complete.

**ACKNOWLEDGEMENTS**

The authors would like to thank Husky Energy Inc. for permission to publish this report, Carol Fisher of Husky Energy for preparing the illustrations and Leanne Gatenby for typing the text.

**REFERENCES**

Fuzesy, L.M., 1960, Correlation and subcrops of the Mississippian strata in South-Eastern and South-Central Saskatchewan: Saskatchewan Department of Mineral Resources Report Number 51, 63 p.


Figure 1: Distribution of Midale Beds Oilfields in SE Saskatchewan, highlighting Camduff Field. After Smith, 1980

Figure 2: Stratigraphic nomenclature for Mississippian and overlying units - SE Saskatchewan. Modified from Fuzesy, 1980
Figure 3: Well Logs/Core Log for 7-18-2-33W1
Regional or "full" Midale Carbonate Section
Figure 7b: Midale Beds Core: 5-25-2-34W1 (4107 -4148 ft.)

Well encountered minor paleo-karst features (K1 category). Normal or regional Lower Vuggy and MD1 are overlain by tight MD2 with several 3-4 inch probably horizontal "caves". Note high porosity MD1 immediately overlain (stylolitic contact) by anhydrite cave fill.

A = Anhydrite(Cave Fill) DM = Dolomite Marker (Base Upper Vuggy) LV = Lower Vuggy RB = Red Beds

Upper Vuggy

DM = Dolomite Marker
SM = Stylolitic Lime Mudstone
DZ = Dead Zone
Figure 8a: Well Logs/Core Log for 11-22-2-34W1
K3 Category - Major Cave Development

See Figure 10 for Lithology Index
Figure 8b: Midale Beds Core: 11-22-2-34W1 (4203.9 - 4226 ft.)

Well encountered a major cave fill (category K) in Midale Beds. A lower multi-story chamber (4203.9 - 4226 ft.), replacing Unit Froebisher evaporite and most of the Vuggy limestone, contains a mixed breccia including recognizable Vuggy limestone and L. Watrous (Red Beds) influent. The roof, visible at the top, is dolomitized and oil-stained Upper Vuggy Lime Mudstone. Note the loosely packed, anhydrite cemented breccia at the top of the fill.

S = Siltstone  SS = Sandstone  R = Roof or 'in-situ'  TS = Thin Section  A = Anhydrite
Figure 8c: Midale Beds Core: 11-22-2-34W1 (4177.6 - 4203.2 ft.)

The roof of the lower cave tops at 4185.7 feet. Numerous silt or anhydrite filled horizontal 'cracks' and chaotic fractures are visible (crackle breccia). Another breccia above the roof may be the fill of an exhumed cave. A vertical contact between breccia and apparent in-situ dolomite visible through the upper 5 feet may be a cave wall.

A = Anhydrite  S = Siltstone  TS = Thin Section  B = Breccia  R = Roof or 'in-situ'
Figure 8d: Thin Section Photo: 11-22-2-34W1 (4208.5 ft.)

Cave fill. Shows contact between large dolomite fragment and infiltered Spearfish Sand.

A = Anhydrite  D = Dolomite  SS = Sandstone

Figure 8e: Thin Section Photo: 11-22-2-34W1 (4189 ft.)

Fine laminated sand/silt fill at base of minor horizontal cave. Space above sand totally cemented with anhydrite.

A = Anhydrite  S = Siltstone  SS = Sandstone
Figure 9a: Well Logs/Core Log for K3 Catagory - Major Cave Development
Figure 9b: Midale Beds Core: 11-20-2-33W1 (4081 -4134 ft.)

Well encountered 24 feet of cave fill (category K3), consisting of small, angular clasts of Limestone in a sandy marl matrix. The well was perforated and has produced from the cave fill.

F = Cave Floor  R = Cave Roof  A = Anhydrite  S = Siltstone  TS = Thin Section
B = Breccia  FE = Frobisher Evaporite
Figure 9c: Thin Section Photo: 11-20-2-34W1 (4093.4 ft.)

Matrix of unusual permeable cave fill breccia. Appears to be largely fine carbonate, but common quartz sand grains. (arrows)
Figure 10: Lithology Index for Core Logs

- Core Log Lithology Index
- Breccia (Mosaic to mixed)
- Dolomite
- Lime Packstone/Grainstone
- Lime Mudstone/Mackstone
- Argillaceous Lime Mudstone (Marlstone)
- Dolomitic Argillaceous Mudstone
- Siltstone
- Sandstone
- Anhydrite (Primary or Secondary)
- ACCESSORIES/MODIFIERS
- Lime Mudstone ibeds
- Anhydritic
- Argillaceous
- Dolomitic
- Styloclitic/Fractured
- Codiacan Algae
- Brachiopods/Crinoids
- Sponge Spicules
- Grain Supported ibeds