Lower McMurray Formation Sinkholes and Their Fill Fabrics: Effects of Salt Dissolution Collapse-subsidence Across the Northern Athabasca Oil Sands Deposit*

Paul L. Broughton[1]

Search and Discovery Article #51027 (2014)
Posted October 6, 2014

*Adapted from extended abstract prepared in conjunction with presentation at CSPG/CSEG/CWLS GeoConvention 2013, (Integration: Geoscience engineering Partnership) Calgary TELUS Convention Centre & ERCB Core Research Centre, Calgary, AB, Canada, 6-12 May 2013, AAPG/CSPG©2014

[1]Chevron Canada Resources, Calgary, Alberta T2P 0L7 (pbroughton@chevron.com)

Abstract

Numerous sinkhole collapse and sag structures are scattered across the sub-Cretaceous paleotopography of both the western and eastern segments of the giant Bitumont trough and beyond, which underlie the northern Athabasca oil sands deposit. Many of these pre-Cretaceous sinkholes remained inactive during the Aptian and were filled by lower McMurray sediments, but others were enlarged with reactivated Devonian salt dissolution at depth during lower McMurray deposition. Some of these sinkholes were initiated during the lower McMurray interval without precursor pre-Cretaceous sags. Other sinkholes sagged towards the close of the lower McMurray interval and were truncated by middle McMurray deposition. The morphogenesis of sinkholes during the lower McMurray deposition demonstrates continued dissolution of Middle Devonian salt beds into the Lower Cretaceous.

Introduction

The sub-Cretaceous paleotopography underlying the giant Lower Cretaceous Athabasca oil sands deposit, northern Alberta, has an orthogonal lattice pattern of cross-cutting troughs developed between lineament pairs. These troughs are up to 50 km long and 100 m deep. This structural lattice is interpreted to have been inherited from a similar pattern of dissolution collapse-subsidence troughs in the underlying Middle Devonian salt beds. Removal of more than 100 m of Middle Devonian halite salt beds fragmented and sagged the overlying Upper Devonian strata. Unusually low 1:2 to 1:3 thickness ratios of halite salt beds to the overlying strata resulted in the Upper Devonian strata collapses into underlying salt dissolution troughs being more cataclysmic during this earlier phase of salt removal. The slower but complete salt dissolution phase that followed removed remaining salt beds between the earlier troughs. This resulted in more gradual subsidence of the overlying strata, but also obliterated the earlier Middle Devonian pattern of giant cross-cutting salt dissolution troughs. Smaller, more focused, areas of this widespread dissolution-subsidence resulted in numerous sinkholes on the sub-Cretaceous surface. Many of these remained active throughout the lower McMurray period.

Observations and Interpretations

The morphogenesis of lower McMurray sinkholes and their fills include combinations of steeply dipping bed sags and chaotic collapse breccias that developed as underlying Upper Devonian fault blocks subsided throughout the lower McMurray period. Sinkholes are typically 20-50 m across. They may be single (Figure 1) or double structures (Figure 2) or amalgamated into linear sinkhole valleys (Figure 3) depending upon the scale and orientation of the underlying fault block subsidence. Many lower McMurray sag structures have fills with complex combinations of sagged beds, larger tilted blocs, and chaotic collapse breccias (Figure 4). Mine cuts (Figure 1) within the central Bitumont trough often exposed lower McMurray sags that extended upwards to the overlying contact with the middle McMurray interval, but not higher. All of these late stage lower McMurray sags were truncated by the advance of the fluvio-estuarine middle McMurray sand deposits.

The sub-Cretaceous paleotopography across the northern area of the Athabasca oil sand deposit includes a complex of cross-cutting sinkhole valley trends at a smaller (5 km) reticulate pattern scale compared to the giant (50 km) scale of cross-cutting collapse-subsidence troughs. This 100 km^2 terrain extends across Townships 98-99, Ranges 4-5, West 4th Meridian. Multiple deep sinkholes were aligned along linear, NW-SE and NE-SW oriented, multi-km long cross-cutting valleys that dissected the sub-Cretaceous paleotopography (Figure 3). These 3-5 km long linear sinkhole valleys connect 50-100 m deep sinkholes distributed along the valley floors. The cross-cutting sinkhole valleys formed an orthogonal lattice pattern contiguous with the underlying salt structured lattice of dissolution lineaments. Many of these deeper pre-Cretaceous sinkholes were subsequently enlarged during the lower McMurray interval. This resulted in the lower reaches of the deeper sinkholes being filled with collapse breccias of mixed lower McMurray clastics and Upper Devonian limestone blocks (Figure 5 and Figure 6). These lower sinkhole collapse breccias were covered by upper sinkhole fills of steeply dipping (20-40º) gravelly sand beds capped by multi-meter thick coal beds and under clays (Figure 5). These gravelly sands also accumulated along the valley floors between the sinkholes but usually with more moderate bed dips.

These coarse to gravelly sand upper sinkhole fills include beds with new clastic fill fabrics not previously observed in McMurray Formation strata, or elsewhere. These steeply dipping (20-40º dips) gravelly sand beds include sand grain and pebble fall-flow fabrics at the 10-30 cm scale of vertically oriented pebble trains that cascaded over and down sides of slump blocks. The near vertical pebble train falls-flows were frozen in place between adjacent slump blocks by almost immediate welding back together during the sinkhole fill collapse.

Almost all of the lower McMurray strata accumulated on the sub-Cretaceous unconformity between these sinkhole valleys were removed by glacial movements that scraped the Upper Devonian subcrop but preserved the sinkhole valley fills. The geometric configurations of these valleys indicate that the fills accumulated when fluvial stream channels discharged their loads into closed canyon structures entirely below the surrounding paleotopographic relief on all sides (Figure 3). These amalgamated sinkhole valleys were canyon-like structures that filled from above by braided rivers that cascaded over the precipitous rims. These cascading braided rivers resulted in canyon-filling smaller scale braid deltas with tens of meters thick, moderate to steeply dipping, gravelly sand deposits. Such lower McMurray braided delta deposits have better sorting, size grading, and clast orientations than fan-delta deposits. This lack of a muddy matrix resulted in high reservoir quality porosity and permeability properties, including very high bitumen saturations, compared to fan deltas. These sinkhole fills of steeply dipping gravelly sands passed upward into tens of meters thick top set coal beds, which are the thickest known in the McMurray Formation. Some of the thicker coal beds have under clays with dewatering and soft sedimentary deformations (Figure 5). Unusually thick mud slumps between the steeply dipping sands below and overlying coal beds are interpreted as collapse-slumps that resulted from additional underlying salt dissolution pulses.

Conclusions

It is commonly accepted that sub-Cretaceous paleotopography flooring the northern Athabasca oil sands deposit was configured by pre-Cretaceous dissolution of the Middle Devonian salt beds. This dissolution of the salt substrate has been reinterpreted to have been active throughout the lower McMurray period, and resulted in widespread sinkhole formation and deepening tied to differential subsidence of underlying Devonian fault blocks.

Acknowledgements

The author appreciates the support of Chevron Canada, Calgary, for this study of semi-regional bitumen distribution patterns across the northern Athabasca oil sands mining areas.

Figure 1. Two examples of lower McMurray sinkhole sags exposed by bench cuts in the Aurora mine in the south-central Bitumont trough. Each mine bench has a 12-15 m high cut face. These double sag structures have kaolin paleosol beds. Upper photograph courtesy of Syncrude; lower photograph courtesy of the Alberta Geological Survey.

Figure 2. Muskeg River mine cut face exposure of a sinkhole collapse (left) with faulted sides. This vertical fissure was subsequently filled with vertically oriented contorted muddy beds and debris as a result of the drag effects by the sinkhole sag (right). Photograph courtesy of Shell Canada.

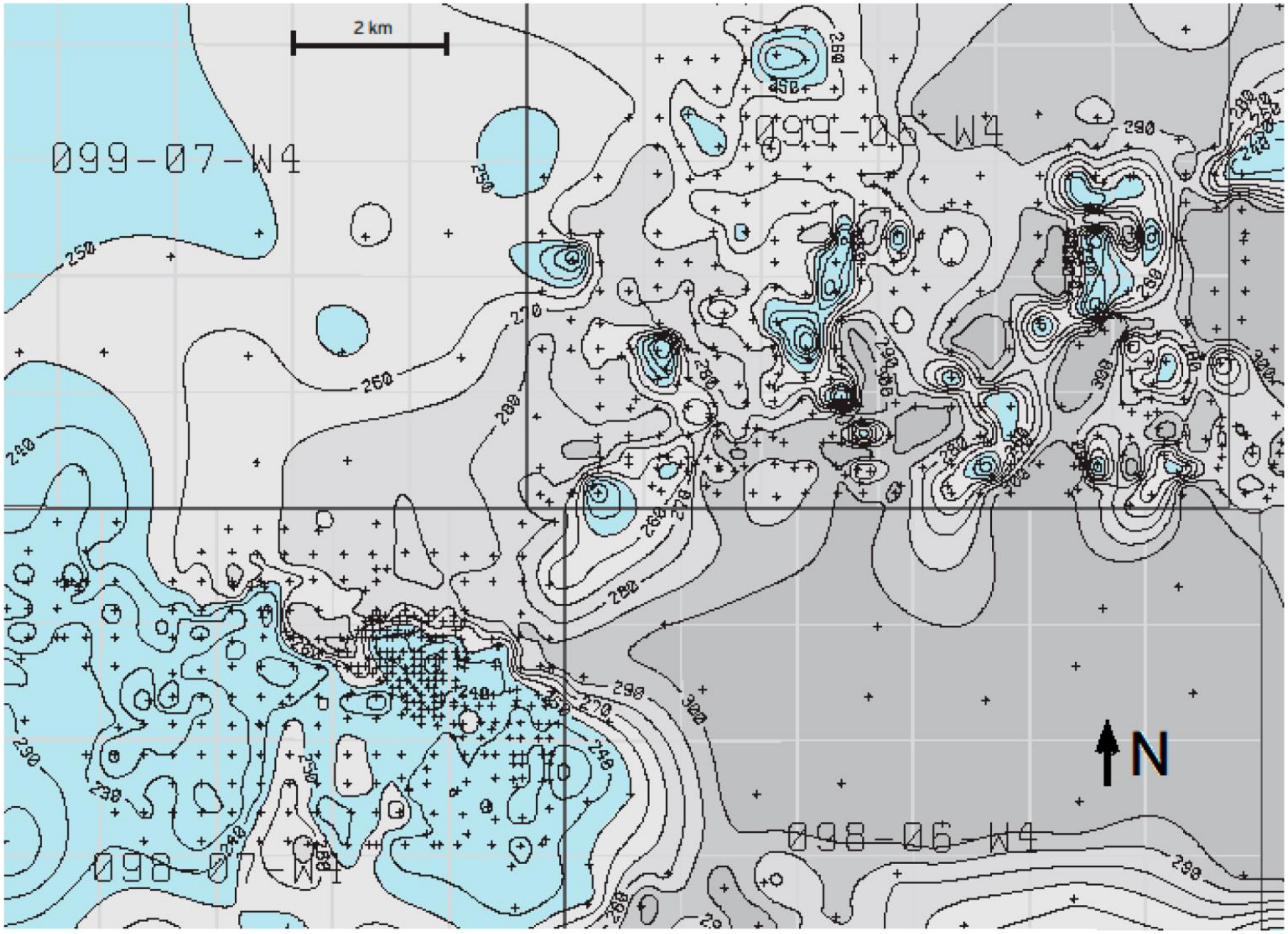

Figure 3. Sinkholes up to 100 m deep distributed along 3-5 km long cross-cutting linear sinkhole valleys that dissected the sub-Cretaceous paleotopography across a 100 km² area at the junction of the northeastern Bitumont trough with the eastern end of the lineament E valley. The reticulate pattern of these cross-cutting sinkhole valleys was inherited from the underlying NW-SE and NE-SW salt structured lineament lattice. This represents a small scale (5 km) version of the giant (50 km) lattice across the northern Athabasca oil sands deposit. Many of these 50-100 m deep pre-Cretaceous sinkholes were enlarged during the lower McMurray period with continued salt dissolution at depth. Sinkhole fill fabrics of these deep sinkholes are illustrated by Figure 5 and Figure 6 from the Syneco Firebag 1AA/09-11-99-06W4M well. 10 m contours are elevations above sea level.

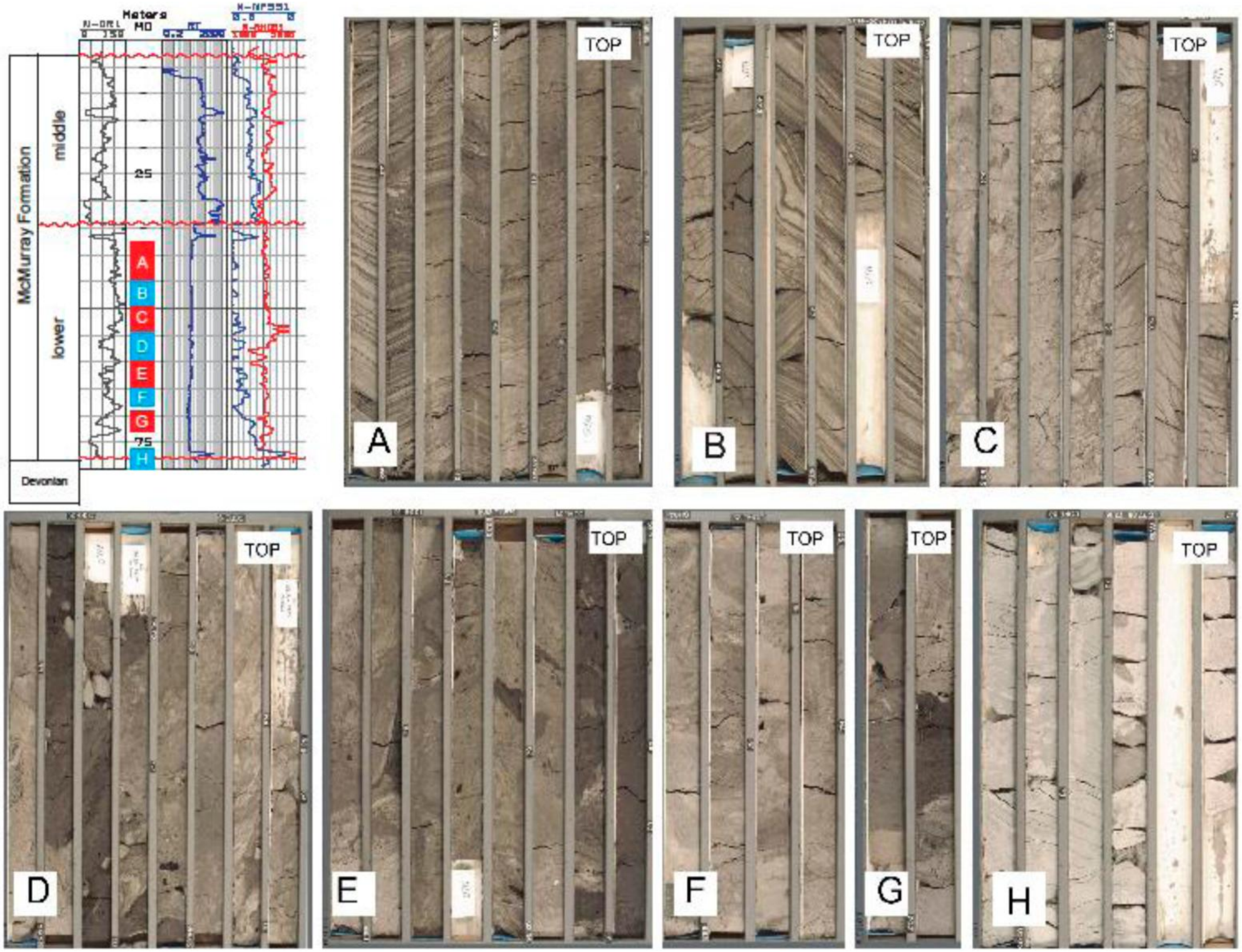

Figure 4. Sinkhole collapse sag of the entire lower McMurray interval penetrated by a well located in the south-central Bitumont trough: (A-B) upper levels of the sag with steeply dipping lower McMurray beds (36.65-44.50 m, 44.75-48.50 m depths); (C) chaotic lower sinkhole fills of tilted beds and collapse breccia (48.50-53.50 m depth); (D) collapse breccia with chaotic muddy and coaly lenses with calcite cemented sand nodules (53.90-59.50 m depth); (E) chaotic slumped coaly mud beds (59.50-65.10 m depth); (F-G) chaotic slumped mud beds (65.10-68.1 m, 69.2-70.70 m depths); (H) chaotic bed slumps on calcite cemented sand (76.60-80.05 m depth). Each core slat is 75 cm.

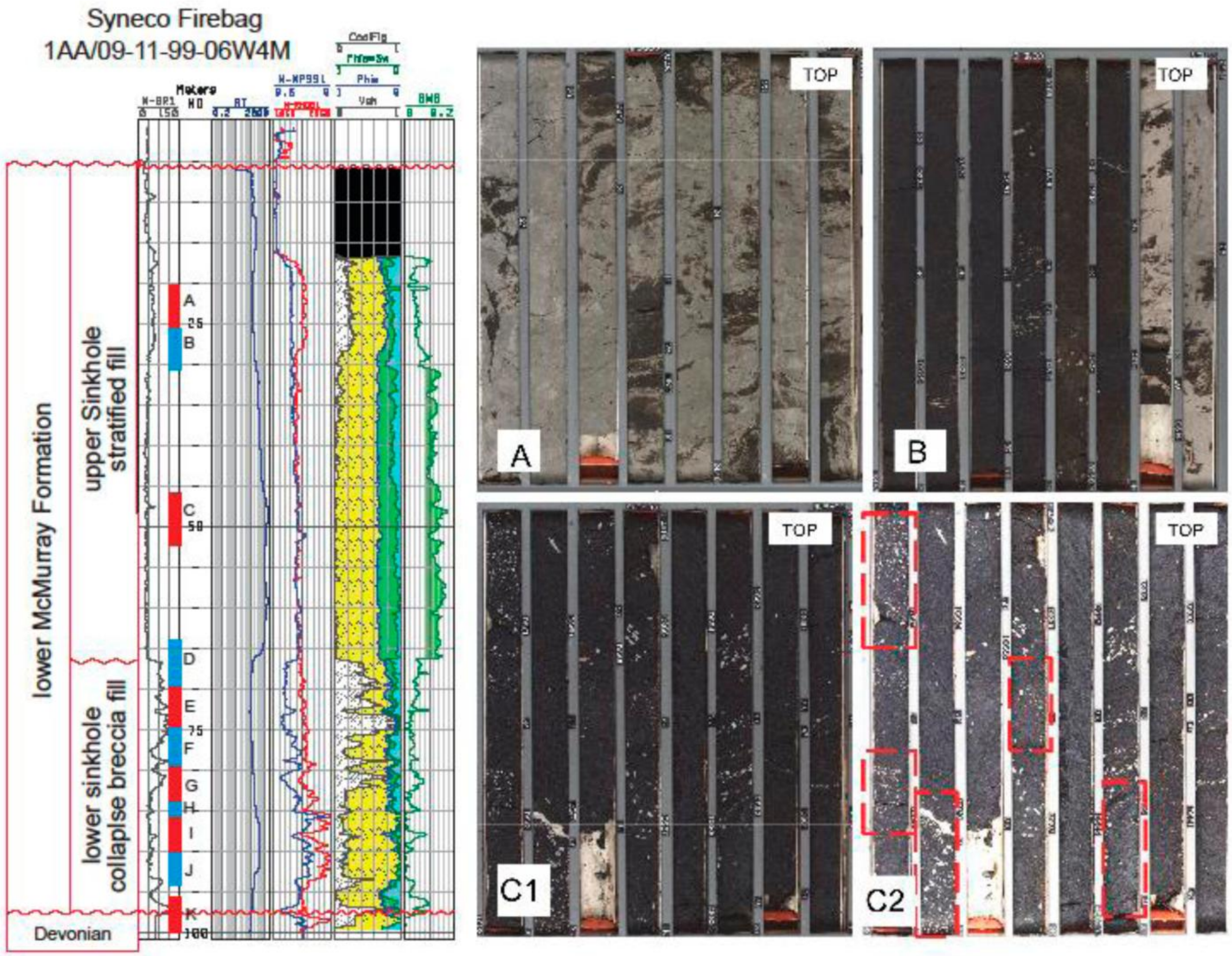

Figure 5. Cored intervals penetrating the deep sinkhole fill of the Syneco Firebag 1AA/09-11-99- 06W4M well located within the 100 km² area with deep sinkholes across Townships 98-99, Ranges 4-5 W4M. This upper sinkhole interval (0-66 m depth) accumulated stratified, steeply dipping (30-40º), gravelly sand beds that accumulated as a result of a braided river discharge into the sinkhole void (B-C). Beds slumps resulted in pebble grain fall-flows that cascaded over and down sides of slump blocks (C1, 45.83-51.93 m depth; heavy bitumen stain; C2, color altered: red frames). The vertical orientations of these pebble train fall-flows were frozen in place by almost immediate opening and closure between adjacent slump blocks. Overlying under clay mud beds also slumped (A, 21.43-27.46 m depth) resulting in massive soft sedimentary deformations triggered by continued underlying salt dissolution collapse. A 12 m thick top set coal bed accumulated within the sinkhole confines. These upper sinkhole fills overlie lower sinkhole chaotic fills (Figure 6). Each core slat is 75 cm.

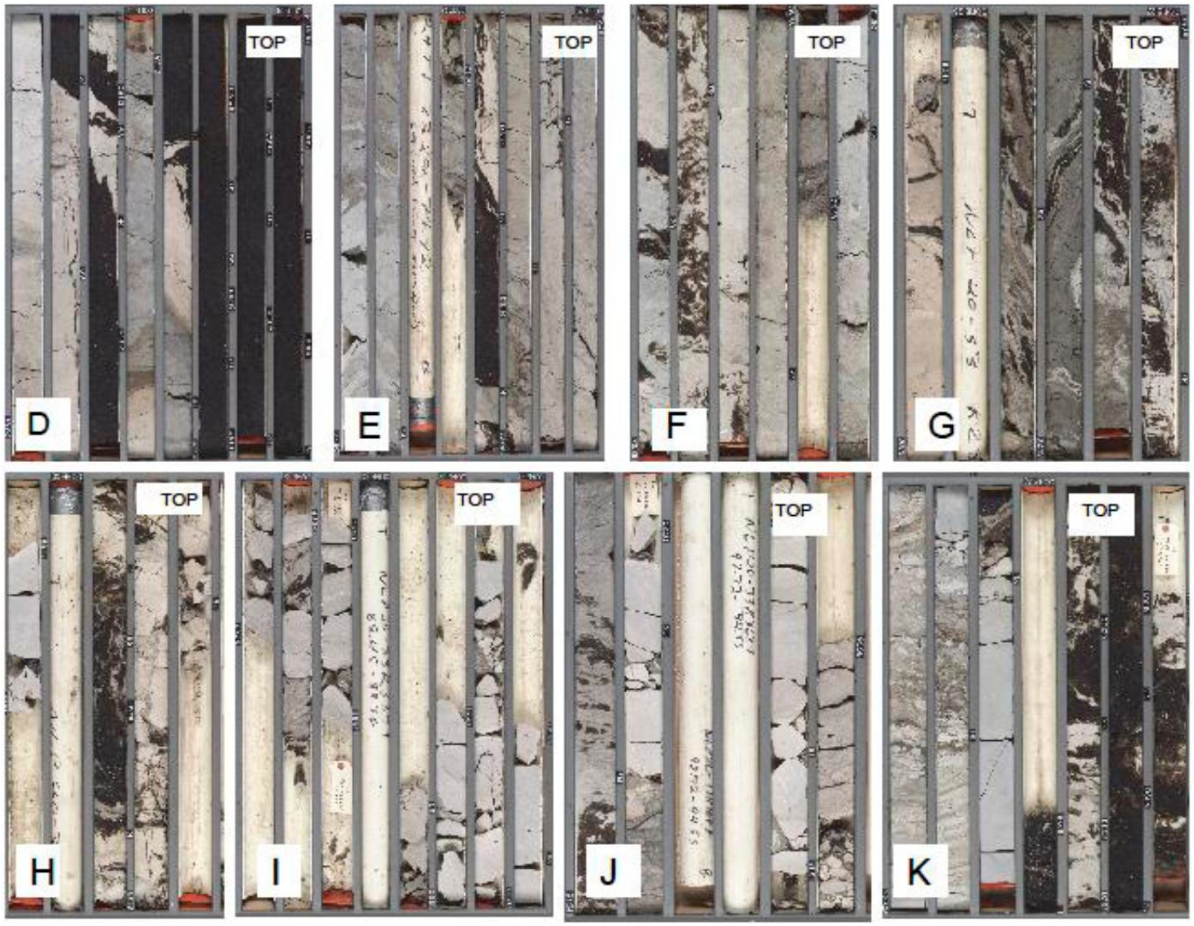

Figure 6. The lower reaches (66-100 m depth) of this deep sinkhole penetrated by the well Syneco Firebag 1AA/09-11-99-06W4M filled with chaotic breccias of caved Devonian limestone blocks and mud mixed with lower McMurray gravelly sand and kaolin lenses: (D) contact between upper sinkhole fill of stratified sands with lower sinkhole fill of slumped and contorted mud beds mixed with discontinuous bitumen saturated sand lenses (64.08-70.05 m depth); (E) slumped mud blocks and contorted near vertical beds (70.05-74.80 m depth); (F) chaotic mixtures of slumped mud blocks and heterolithic sandy beds (74.80-79.38 m depth); (G) contorted, near vertical, grey mud and white kaolin beds mixed with bitumen saturated gravelly sand lenses; slump fracture offsets (79.38-83.04 m depth); (H) collapse breccia of Devonian limestone blocks and contorted lower McMurray bitumen saturated sand lenses and contorted thin mud beds (83.73-85.78 m depth); (I) breccia pipe mosaic of disconnected limestone blocks with void fills of bitumen saturated sands (85.78-90.05 m depth); (J) breccia pipe mosaic of disconnected limestone blocks (90.05-94.24 m depth); (K) bitumen saturated sand wedge on mosaic of disconnected limestone blocks overlying Devonian conglomeratic breccia (95.63-100.09 m depth. The overlying upper reaches of this sinkhole are illustrated by Figure 5. Each core slat is 75 cm.