[PS]Upper Ordovician Incised Valley (Karst) Fill Deposits of Central Missouri: A Reinterpretation of Some "Pennsylvanian Filled Sinks"*

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Abstract

Small, isolated bodies of sandstone completely encased within carbonate strata are scattered in an east-west trending belt along the northern flank of the Ozark uplift in central Missouri. Physical sedimentary characteristics (erosional bases and margins, graded bedding, trough cross bedding, ripple bedding, and lateral accretion surfaces) indicate deposition by fluvial processes over a karst surface at the top of the Ordovician section. Historically, these sandstones have been interpreted as sink-hole collapse features of Pennsylvanian age based on a roughly circular geometry for many, chaotic bedding along some margins, presence of high-temperature clay minerals in associated mudstones, and stratigraphic position as the first sandstones above Ordovician carbonate formations. However, bedrock geologic mapping, outcrop architectural analyses, application of sequence stratigraphic concepts, comparison to ancient and modern analogs, and use of U-Pb detrital zircon geochronology indicate these deposits to actually be Upper Ordovician in age and to have been deposited by backfilling of narrow, steep-sided solution valleys following base-level fall and subsequent rise. This re-interpretation has important implications for timing of the tectonic and eustatic history of the Ozark region and subsequent sediment dispersal patterns. Additionally, it provides an ancient analog of lowstand "incised valley fills" in a mixed clastic/carbonate system, helping to better understand the geometry, extent, and lateral relationships of potential hydrocarbon reservoirs in such settings.

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Upper Ordovician Incised Valley (Karst) Fill Deposits of Central Missouri: A Reinterpretation of Some "Pennsylvanian Filled Sinks"

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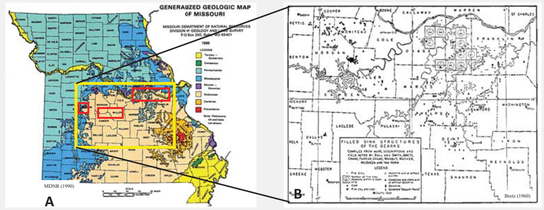
Abstract

Small, isolated bodies of sandstone surrounded by carbonate strata are scattered in an east-west trending belt along the northern flank of the Ozark uplift in central Missouri. Physical sedimentary characteristics (erosional bases and margins, graded bedding, trough cross-bedding, ripple bedding, and lateral accretion surfaces) indicate deposition by fluvial processes over a karst surface at the top of the Ordovician section for some of these features. Others contain planar to trough cross stratification and bioturbation that suggests deposition in a shoreface setting. Historically, these sandstones have been interpreted primarily as sink-hole collapse features of Pennsylvanian age based on a roughly circular geometry for many, chaotic bedding along some margins, presence of high-temperature clay minerals in associated mudstones, and stratigraphic position as the first sandstones above Ordovician carbonate formations. However, bedrock geologic mapping, outcrop architectural analyses, application of sequence stratigraphic concepts, comparison to ancient and modern analogs, and use of U-Pb detrital zircon geochronology indicate some of these deposits to actually be Upper Ordovician in age and to have been deposited by backfilling of narrow, steep-sided solution valleys following base-level fall and subsequent rise. This re-interpretation has important implications for timing of the tectonic and eustatic history of the Ozark region and subsequent sediment dispersal patterns. Additionally, it provides an ancient analog of lowstand "incised valley fills" in a mixed clastic/carbonate system, helping to better understand the geometry, extent, and lateral relationships of potential hydrocarbon reservoirs in such settings.

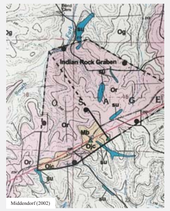
Distribution of "Filled Sinks" in Missouri



A: Red rectangles show areas mapped by the Missouri Geological Survey between 1998 and 2004 that include features interpreted as Pennsylvanian age "filled sinks." These areas, from west to east, include Truman Lake near the town of Warsaw, the Lake of the Ozarks region, and the area along the Missouri River between Fulton and St. Louis. The larger, black rectangle corresponds approximately to the area in which "filled sinks" have been identified, as shown in B. C shows a progressive northwest to southeast change in dominant clay composition for sink-fill material.

Evidence Supporting "Sink Fills"

Since at least as early as 1855, isolated sandstones and mudstones, often containing coal, hematite ores, and ores of lead and zinc sulfides have been interpreted as sink and cave fills, primarily because of discontinuous, roughly circular to elongate outlines and bedding that is sometimes chaotic and which often dips toward the center of the outcrop.

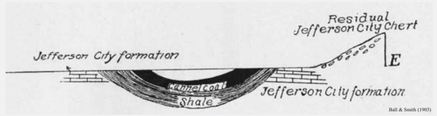


Outcrops of "filled sinks (Su)" as mapped by the Missouri Geological Survey on the Sunrise Beach Quadrangle. Su refers to "Sandstone unidentified," reflecting disagreement among mapping geologists at MDNR regarding their origin and age. Though not officially interpreted as Pennsylvanian, they were assigned the color scheme for Lower Pennsylvanian strata.

Dipping and contorted bedding in filled sinks. Photo A is from the north side of I-44 about 5 miles west of the city of St. Clair. Photo B is from Jefferson City. Photo C was taken in the city of Rolla.

Evidence Supporting a Pennsylvanian Age

Some "filled sinks" contain coal deposits. Others are interpreted as Pennsylvanian in age because of their stratigraphic position as the first significant sandstone above known Ordovician through Mississippian strata.



Stratigraphic column showing the interpreted relationship of the "Sandstone Unidentified" unit to older strata on the Sunrise Beach Quadrangle. The cross section shows a "filled sink" containing shale and coal near the northern boundary of the region where "filled sinks" are found.

Historical Models for "Filled Sink" Formation

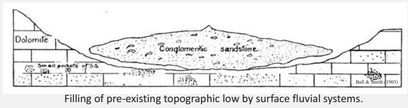
Despite over 150 years of recognition and study, the mode of formation for "filled sinks" remains elusive. This is due, in part, to an attempt to assign features with a significant range of characteristics to a single event, i.e. ascribing all "filled sinks" to deposition across a pre-Pennsylvanian erosional surface ("peneplain"); whereas, in reality, these differing deposits most likely reflect variable origins and timing. Though several models have been proposed, most rely on either collapse of isolated or stacked caverns, allowing Pennsylvanian deposits to fill subterranean voids or gradual settling into a void through concurrent dissolution and filling.

Variable "filled sink" Characteristics:

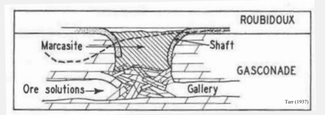
- Distribution (compositional gradation from north to south)
- Size (a few meters to more than half a kilometer)
- Subaerial shape and proportions (circular, thin and elongate, ridge capping, and irregular)
- Cross-sectional shape and proportions (lens, inverted funnel or cone, and irregular)
- Wall (rim)-rock structure (undisturbed, centripetal dip, or faulted)
- Wall-rock composition (dolostone, limestone, or sandstone)
- Fill Structure (stratified, simple "sag," highly folded, fractured, normal faulted, or thrust faulted)
- Fill composition (sandstone, clay, refractory clay, coal, chert, dolostone or limestone blocks, and ores of hematite, pyrite, and lead and zinc sulfides.
- Time of formation (before or during filling)

Proposed Formational Mechanisms:

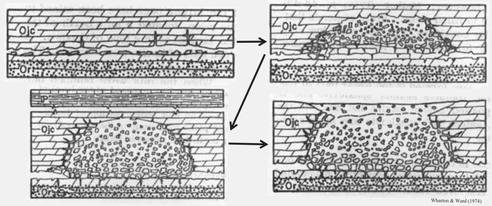
- Deposition in "unquiet seas"
- Localized thrusting
- Settling through steep, intersecting faults
- Filling of prior topographic lows
- Simple cave roof collapse
- Collapse of overlying (stacked) cave fills into lower caves
- Gradual floor solution and concurrent roof subsidence



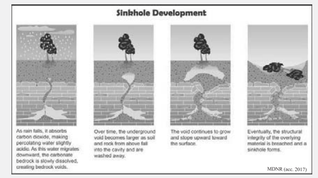
Filling of pre-existing topographic low by surface fluvial systems.



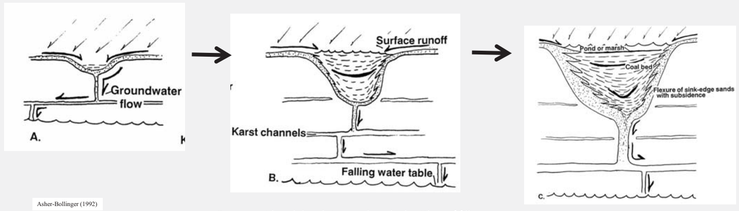
Roof collapse and subsequent filling.



Concurrent roof collapse and fill.



Collapse of stacked caverns (based on modern sink holes).

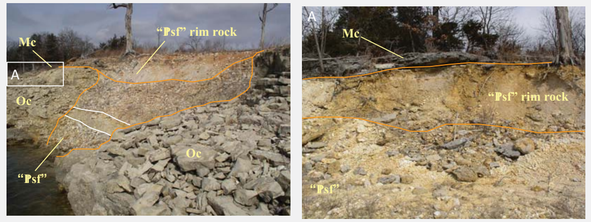


Concurrent basal dissolution and gradual settling of fill.

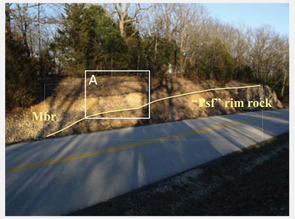
Evidence for a Pre-Pennsylvanian (Ordovician?) Age for some "Filled Sinks"

Though there is a progressive change in characteristics of both "sink fill" and surrounding "rim rock" from north to south throughout the outcrop area, all "filled sinks" have been interpreted as having formed on a single "peneplain" across earlier Paleozoic strata that dip away from the present Ozark Plateau. The primary reason being they contain the first significant sandstones above older Paleozoic strata, which are almost entirely carbonate. However, many of those along an east/west trending belt through in the central portion of the outcrop area are capped by either Mississippian strata of the Chouteau Group or Mississippian chert residuum derived from the Burlington Formation, demonstrating at least a Pre-Mississippian age. In one small region, the state geologic map shows discontinuous outcrops of Devonian strata overlying Pennsylvanian rocks, indicating an even earlier age. Additionally, the sandstone within these "fills" closely resembles that of the St. Peter Sandstone and occurs exclusively within wall rock of Ordovician stratigraphic units, suggesting it is also either St. Peter or reworked St. Peter. Finally, recent analyses of detrital zircons indicate an affinity much more closely related to Ordovician strata than to Pennsylvanian units.

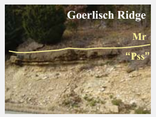
Capping by Mississippian Strata (Outcrop Data)



An Outcrop located along the north shore of Harry S. Truman Reservoir showing a thin bed of the Mississippian Chouteau Group (Mc) overlying both Pennsylvanian sink fill ("IPsf") deposits and the Ordovician Cotter Dolomite (Oc). The right-hand photo is an enlargement of the white rectangle in the left-hand photo.

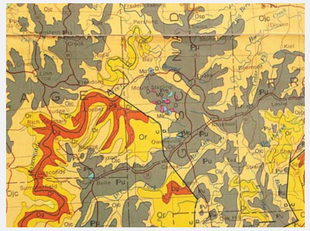


A road cut near the town of Pershing showing a thick bed of chert residuum derived from the Mississippian Burlington Limestone (Mbr) overlying a Pennsylvanian "filled sink ("IPsf") rim rock. The right-hand photo is an enlargement of the white rectangle in the left-hand photo.



Additional examples between Lake of the Ozarks and St. Louis of Mississippian chert residuum overlying "Pennsylvanian filled sink" deposits.

Capping by Mississippian Strata (Map Data)



Official geologic map for the State of Missouri showing the presence of isolated outcrops of Devonian and Mississippian strata overlying a persistent outcrop belt of Pennsylvanian deposits.

Correlation Through Detrital Zircon Geochronology

Detrital zircon geochronology demonstrates a much closer correlation to undisputed Ordovician strata than to undisputed Pennsylvanian units in central Missouri.

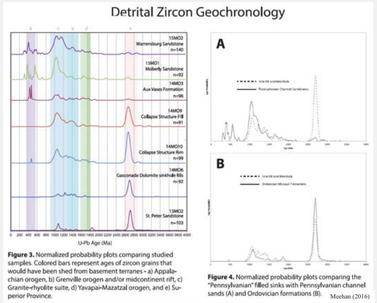


Figure 3. Normalized probability plots comparing studied samples. Colored bars represent ages of zircon grains that would have been shed from basement terranes - a) Appalachian orogen, b) Grenville orogen and/or midcontinent rift, c) Granite-rhyolite suite, d) Yavapai-Mazatzal orogen, and e) Superior Province.

Figure 4. Normalized probability plots comparing the "Pennsylvanian" filled sinks with Pennsylvanian channel sands (A) and Ordovician formations (B). Meehan (2016)

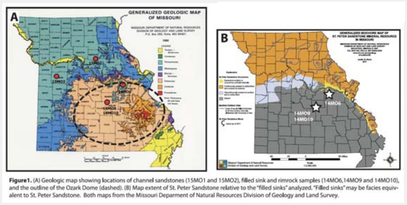
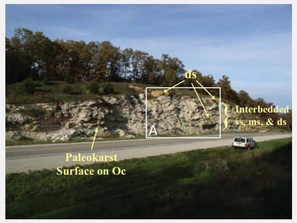
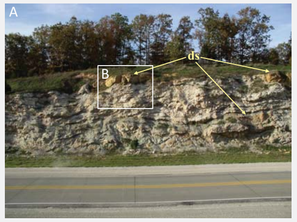


Figure1. (A) Geologic map showing locations of channel sandstones (15MO1 and 15MO2), filled sink and rimrock samples (14MO6,14MO9 and 14MO10), and the outline of the Ozark Dome (dashed). (B) Map extent of St. Peter Sandstone relative to the "filled sinks" analyzed. "Filled sinks" may be facies equivalent to St. Peter Sandstone. Both maps from the Missouri Deparment of Natural Resources Division of Geology and Land Survey.

Interfingering with Ordovician Strata



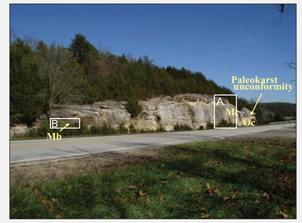


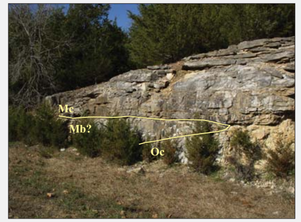
Interfingering of dolostone (ds), sandstone (ss), and mudstone (ms) above a karst surface capping the Cotter Dolomite (Oc) along Highway 50 at Cave Hill Road. The upper right-hand photo is an enlargement of the white rectangle in the upper left-hand photo. The lower photo is an elargement of the white rectancle in the upper right-hand photo.

Interfingering of channel-form sandstones (IPsf) with dolostones of the Cotter Dolomite (Oc) in the city of Washington.

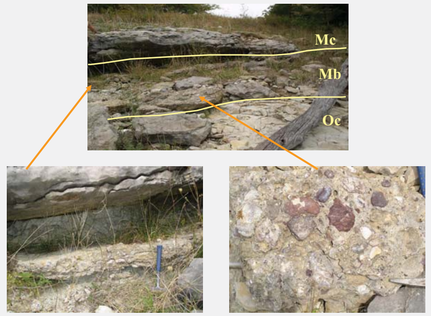
Complex Unconformity

The unconformable surface between Ordovician (Ibexian) and Mississippian (Kinderhookian) strata of the northern Ozark Plateau region represents at least 113 million years. Through this span, there is, undoubtedly, a complex history of base-level fluctuation, which is indicated by a spotty, but diverse, record of discontinuous stratigraphic units that range significantly both in time and expression and include at least some "filled sinks." Below is an example of non-"filled sink" features found at the same stratigraphic horizon as the "filled sinks" of this study.





Expression of the Ordovician/Mississippian unconformity near the southern shore of Harry S. Truman Reservoir, with Cotter Dolomite (Oc) below and the Chouteau Group (Mc) above. The lower left-hand photo is an enlargement of white rectangle A in the upper photo and shows a karst surface veneered with a thin green mudstone. The lower right photo is an enlargement of white rectangle B in the upper photo and includes a wedge-shaped deposit of the Mississippian Bachelor Formation (Mb).

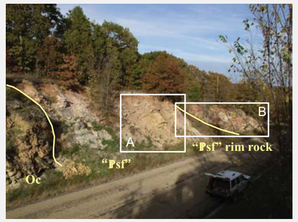


Details from an exposure of the Bachelor Sandstone as it appears along the Ordovician/Mississippian unconformaty along the western edge of the Harry S. Truman Reservoir. The lower left photo shows a green mudstone lying above a colorful cherty conglomerate shown in the lower right photo.

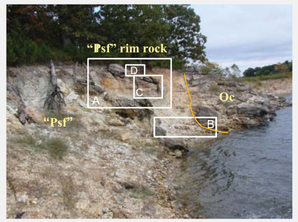
Evidence for an incised Valley Origin for some "Filled Sinks"

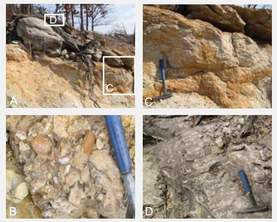
"Filled sinks" have a variety of expressions in terms of both fill and structure. Some are dominated by clay, others filled with sandstone. Some are highly deformed, others relatively undisturbed. The "sinks" under consideration consist primarily of a relatively undeformed, texturally and compositionally very mature quartz arenite sandstone with sharp lateral contacts. A thin layer of clay can be present at the base and along margins of the sand bodies but is not universal. Deformation, in most cases, is restricted to margins and appears to be the result of differential compaction above and within carbonate strata that are not completely lithified. Sedimentary facies and facies associations suggest deposition within both fluvial and shoreline systems. Some deposits have nearly vertical walls with chert fragments and silicified stromatolites attached to their margins. These conditions suggest incision of a karst surface during a base-level fall, followed by a subsequent base-level rise and back filling of the incised valley.

Deposition by Fluvial Processes



A "filled sink" and associated "rim rock" at Cave Hill. The "rim rock" (Photo B) is lens shaped, undeformed, has sharp lower and lateral contacts, and consists primarily of trough cross-stratified sandstone interpreted to be a fluvial active-channel fill. Adjacent to it is a succession of thinly-bedded sandstones and mudstones (Photo A) that are mostly structureless, though one bed appears to contain indistinct ripples. The thinly-bedded interval has variegated colors due to either paleosol development or diagenetic mineralization and is thought to represent overbank, possibly, splay deposition. The "sink" is bound to the southwest by a small "pinnacle" of Ordovician Cotter Dolomite (Oc).

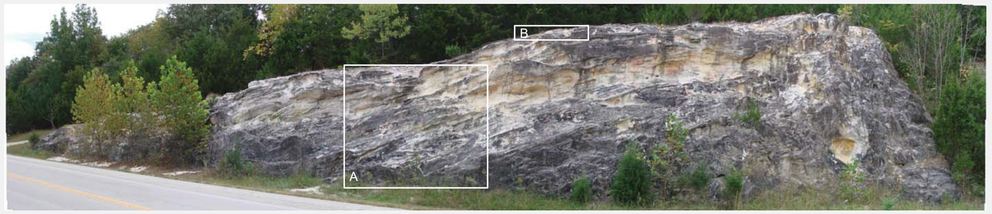




A "filled sink" deposit along the north shore of Harry S. Truman Reservoir, demonstrating a facies association reminiscent of active fluvial channel fill. White rectangular boxes on the left photo are enlarged in the photos on the right. Photo B is a colorful chert (similar to that found in the Bachelor Formation described in Panel 2) found along the contact between the "sink fill" and underlying Cotter Dolomite (Oc). Photo C is a trough cross-bedded sandstone, making up the main body of the rim rock. The succession is capped by a ripple-bedded sandstone (Photo D.)

Trough Cross-bedded quartz arenite covering a paleokarst surface east of the Harry S. Truman Reservoir dam. The photo on the right is an enlargement of the white box in the photo on the left.

Deposition by Shoreface Processes



A "filled sink" west of Jefferson City dominated by beds 1- to 2-m thick of poorly-cemented, trough cross-bedded (Photo A) and horizontally-laminated (Photo C) quartz arenite, with some ripple bedding (Photo B) near the top of the outcrop. Photos A and B are enlargements of white rectangles in the upper photo. Photo C is of the same sand body but from the outcrop on the opposite side of the highway. These are interpreted as upper shoreface (trough cross bedding) and foreshore (horizontal laminations) deposits and strongly resemble outcrops near St. Louis of the St. Peter Sandstone.

A "filled sink" south of the town of Ottersville. This outcrop consists mostly of trough cross-bedded (Photo A) and horizontally-laminated (Photo B) beds of sandstone up to about 0.5 m thick, representing upper shoreface and foreshore deposits, respectively. The top of the outcrop is highly burrowed (Photos C and D) and may represent a flooding surface. Photos A through D are enlargements of white rectangles in the upper photo.

Conclusions

Based on stratigraphic position beneath Mississippian strata and residuum, interfingering with Ordovician-age units, and detrital zircon data, some features referred to as "Pennsylvanian filled sinks" appear to actually be Ordovician in age.

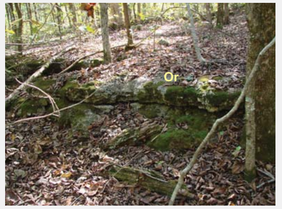
Sedimentary facies and facies associations suggest these features were deposited by fluvial and coastal processes, rather than rapid collapse or gradual settling into solution caverns.

Extremely narrow, linear outcrops with nearly vertical, parallel walls but horizontal to slightly-dipping internal bedding and attachment to walls of materials mostly unconsolidated at the time of sedimentation suggest deposition as incised valley fill following a base-level lowstand.

Incised Valley Margins

Three examples of "blossom rocks," referring to "filled sink" deposits consisting of sandstones which form resistant, usually circular hills surrounded by carbonates. Each of these is from the Lake of the Ozarks region. Photo A, from the Lake Ozark Quadrangle, is found enclosed by the Ordovician Roubidoux Formation (Or). Photo B is located on the Green Bay Terrace Quadrangle and is found within the Ordovician Gasconade Dolomite. This outcrop is locally known as Standing Rock because of it's narrow, vertical sheet-like occurrence. Photo C is within the Roubidoux Formation but on the Toronto Quadrangle.

Margins of "blossom rocks" are often nearly vertical and commonly contain angular chert fragments (Photo A – Standing Rock) or silicified stromatolites (Photo B – Lake Ozark Quadrangle), suggesting incorporation of relatively unconsolidated material from incised valley walls.



Bedding in both "blossom rock (Photo A) and surrounding wall rock (Photo B) ranges from horizontal to slightly dipping. Both photos are from the Toronto Quadrangle.