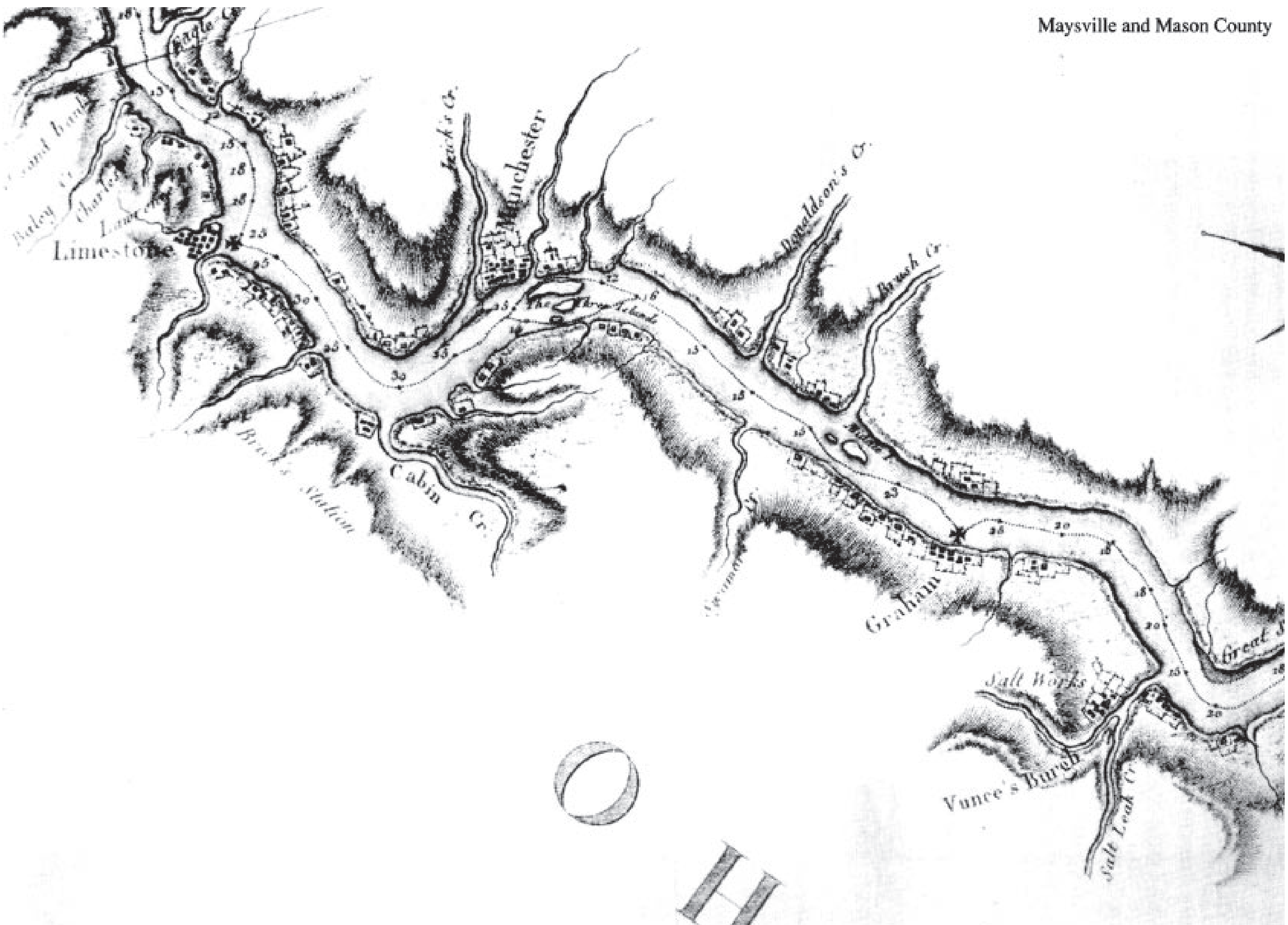
Lower Paleozoic Stratigraphy of the Maysville Area

Field Trip Leaders: Carlton Brett, James Zambito, and Frank Ettensohn



from Callot, 1826, Plate 9

With a Limestone Mine Tour of the Carmeuse Maysville Operation, courtesy of Carmeuse Lime, Maysville, Ky.

The town of Maysville, Ky., most likely got its start in 1773, when pioneer and explorer Captain John Hedges, traveling down the Ohio River, came upon a natural harbor and creek in what would be known later as the community of Limestone. This landing at Limestone Creek also had a buffalo trace that formed a roadway 40 feet wide up through the center of Kentucky. In 1775, frontiersman Simon Kenton (1755–1836), a key figure in opening up the frontier in northern and central Kentucky, paddled down the Ohio River and came upon rich cane fields at the very same location that Captain John Hedges found 2 years earlier. Kenton helped erect the first permanent structure there in what would become Maysville.

Limestone was one of the first important ports on the Ohio River and already in use by 1784. The Virginia legislature assigned a naval officer to collect tolls and supervise river traffic. By the next year, the port of Limestone was incorporated into the newly formed Bourbon County. This county included all of what we know of as Kentucky to the north, east, and southeast of Lexington, with Limestone being the preeminent port for the whole region. In 1789, Limestone and the rest of northeastern Bourbon County became Mason County, Va. In 1792, when Kentucky became a state, 34 new counties were formed from the original Bourbon County.

John May (1744–1790), a prominent Virginia attorney, surveyor, and a delegate of the Kentucky District of the Virginia legislature, would hear and decide on land disputes in Kentucky. In 1785, he was granted 800 surveyed acres by the Virginia legislature at Limestone. On December 11, 1787, the town of Maysville was formally created and named after John May. Yet the local post office was established on October 1, 1794, as Limestone with George Mitchell as postmaster, and not officially renamed Maysville until around 1799. The Limestone name persisted for many years, and as late as 1824 the town was still called by both names. On January 13, 1833, Maysville was incorporated as a city and became the county seat of Mason County in 1848 (Rennick, 1984).

Maysville became an important port, dealing in bourbon, hemp, and tobacco. Ferries crossed to Ohio, and a road was opened to Lexington by around 1800; this is also known as U.S. 68, and Limestone Street here in Lexington. By 1830, more than 150 steamboats stopped in Maysville in a month. The town continued to grow throughout the 19th century. The first three decades of the 20th century brought slower growth, highways bypassed the area, and the river lost some of its importance. Fortunately, because the highways bypassed Maysville, there was not huge developmental growth and the town retained much of its beautiful architecture.

Within the last three decades, the AA Highway (Ky. 546) has encouraged growth, and the Ohio River has been rediscovered for trade and recreational benefits.

Lower Paleozoic Stratigraphy of the Maysville Area

Field Trip Leaders: Carlton Brett, James Zambito, and Frank Ettensohn

With a Limestone Mine Tour of the Carmeuse Maysville Operation, courtesy of Carmeuse Lime, Maysville, Ky.

2007 Spring Field Trip of the Kentucky Section of the American Institute of Professional Geologists

The Kentucky Section of the American Institute of Professional Geologists

Would like to thank the following sponsors for their generous contribution toward the 2007 Spring Field Trip and Awards Banquet

SPADE CORPORATION GEORGETOWN, KY
Spade Corporation

Environmental Science Corp.
LABORATORY SERVICES

REGENESIS
Advanced Technologies for Groundwater Resources

THE ALLEN CO. INC
WINCHESTER, KY.

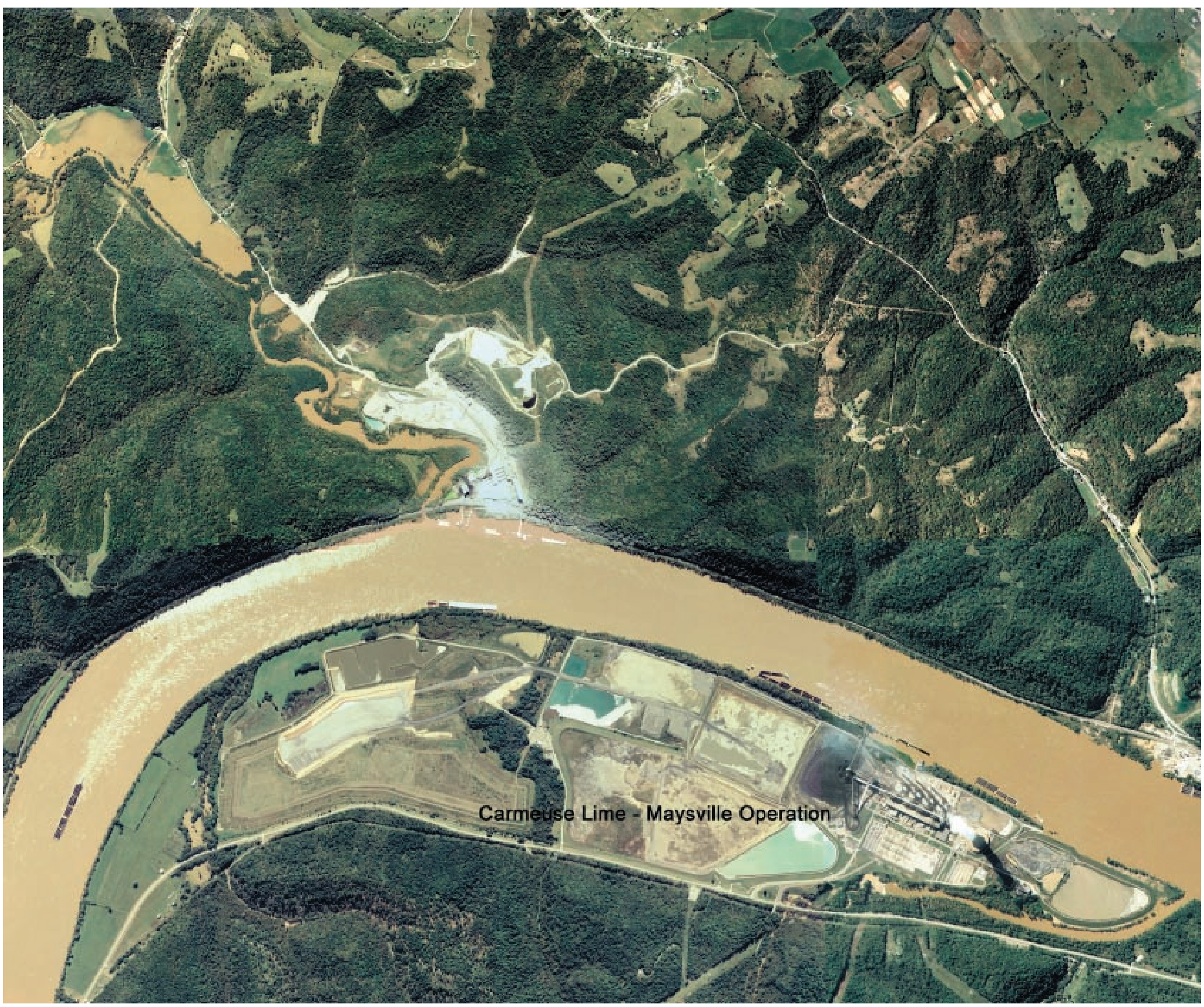
REPUBLIC Waste Services
Kentucky Landfills

Thomas P. Osborn, AAMS, CIC
Financial Consultant
affiliated with
AG EDWARDS
FULLY INVESTED IN OUR CLIENTS
859•276•6166

The Kentucky Section of the American Institute of Professional Geologists

would like to thank the following facilitators from Carmeuse North America for giving their time and allowing us to tour their facilities and mine.

Mark Davis, Facility Manager
Frank Hardy, Production Supervisor
Chris Imbrogno, Regional Environmental Manager
Joe Weber, Loss Prevention Manager
Tom Freese, Geologist – CAN Research Center
Gary Lewis, Mine Manager
Jeff Perkins, Process Engineer
John Kilgore, GU Supervisor



Brief Overview of the Development of the Dravo Lime Co. Cabin Creek Mine to the Carmeuse Lime, Maysville Operation

In the early 1970's, the Dravo Lime Co., a subsidiary of the Dravo Corp., purchased a 1,306-acre tract along Cabin Creek by the Ohio River, 4 miles east of Maysville. In 1974, it began developing a limestone mine and calcining plant there. The location on the Ohio River was ideal to facilitate barge shipments of processed lime to generating plants, as well as to handle incoming coal shipments to fuel the kilns. Engineering, design, and construction were largely done by the parent company's divisions and subsidiaries. Full operation of the new $50 million mine and lime plant was expected by the fall of 1976.

The target stone (high-calcium) was located in the Camp Nelson Limestone about 900 feet below the surface, which provided the final crushed stone needed for the calcination plant. The overall mine plan and design was to safely excavate the limestone using a highly mechanized operation with a production capacity of 10,000 tons per day on a two-shift, 5-day-a-week basis.

The Cabin Creek Mine began excavating a slope to get mining equipment down the mining horizon and to provide truck access to the mine workings. This was through an 18-foot-wide by 10-foot-high, 3,000-foot-long –18˚ slope. This decline also contained the 42-inch-wide steel cable belt production conveyor, which was equipped with a hoist and track for the supply of equipment and materials underground. A 14-foot-diameter, concrete-lined vertical shaft was sunk to provide ventilation and human access to the mine below via a friction-hoist, double-deck, 40-person cage. The bottom of the shaft was located about 360 feet from the end of the slope. The mine horizon layout called for two similar panels, approximately 1,100 feet wide, to be mined simultaneously. The plan was for these panels to both be mined to their extremities, with the remainder of the area isolated by the panels being mined on a retreat pattern toward the mine center. Mining of the panels was by the room-and-pillar method using all-hydraulic drill equipment, which was the first of its type in the United States.

The rooms were created by using the top-heading-and-bench method of mining. First, the top 20 to 24 feet of the exposed stone from under the ceiling was removed by slicing into it, or top-heading. The benching phase concurrently removed 30 to 40 feet of the stone down to the floor. This process did not have to be cyclic, and resulted in an upper level, which eventually was blasted down to the lower level, creating room heights over 60 feet. This method enabled the drilling and blasting to be well ahead of the loading, always providing a stockpile of broken rock in the mine. The resulting room width was about 35 feet, leaving behind 25-foot by 50-foot pillars. This configuration produced an extraction ratio close to 72 percent. Depending on the size of the equipment for drilling and blasting, the primary crusher was moved every 550 feet along the centrally located conveyor so as to maintain an efficient weighted-average haul distance. Once above ground, the conveyors carried the limestone to a secondary crusher. Finally, the limestone went to a cone crusher and a recirculating conveyor system, resulting in the stockpile of 2-inch by 3/8-inch kiln feedstone.

The calcining system was designed and supplied by the Kennedy Van Saun Corp., a subsidiary of McNally Pittsburgh.

The KVS rotary lime kilns were specially designed to produce a highly reactive, soft-burned product. Crushed stone was preheated with exit gas, pushed through a single feed-spout duct above each kiln, where hot gases (approximately 1,900˚F) partially calcined the stone before it entered the kiln. The coal-fired rotary kilns were 203 feet in length and 17 feet in diameter. The pitch of the rotary kiln was 3/8 inch per foot and the drums rotated at a rate of 0.6 to 0.9 rpm by a 300-hp engine. Each kiln had a processing capacity of 907 tons per day. The lime was stored in three 186-foot-tall concrete silos with a combined capacity of 45,000 tons.

Carbonate Rocks and Their Uses

The principal carbonate rocks used by people and industry are limestone ($CaCO_3$) and dolomite ($CaCO_3 \cdot MgCO_3$). Compared to other rock or mineral commodities, carbonate rocks have long had more uses in satisfying the needs of people and industry. Carbonate rocks are found extensively on all of the continents. They form about 15 percent of the earth's sedimentary crust, and are available for exploration and mining from formations that range in age from Precambrian to Holocene (Carr and others, 1994). Carbonate rocks are so useful and abundant that they comprise about 75 percent of all stone quarried or mined. Kentucky ranks 25th in the nation in the quarrying or mining of carbonate rock (USGS Mineral Resources Web site).

For the paleontologist and rockhound, carbonate rocks preserve the greatest fossil record of ancient sea life. Because of their weight, bulk, durability, compressive strength, inert chemistry, and uniformity (crushed and broken), carbonate rock has been used as an aggregate to prevent further erosion of gullies, on trails and driveways, roads, and as one of the aggregate components in asphalt and concrete. It has been quarried as a dimensional building stone, and used on some of the world's most famous buildings and monuments. When crushed to a fine powder, it is used as an agricultural additive to the soil to lower the pH value. If the silica content of the carbonate rock is very low to negligible, the fine powder is applied to coal mine walls to keep methane from escaping out of the coal seam.

When limestone or dolomite is heated to a temperature to drive off the carbon dioxide, leaving behind calcium oxide, it is referred to as quicklime, or the loosely used term "lime." This process is called calcination. The alchemy of lime has been identified in an Arabic text printed in 1,000 A.D. (Freas, 1994). Lime is most used in the making of portland cement. The use of cement is documented as far back as the Roman Empire; the Romans used it far and wide in their great structures (Ames and others, 1994). Lime has many uses in many industries. The uses of lime are as follows:

- As a flux in the steel industry to remove impurities such as phosphorus, silica, aluminum oxide (alumina), and sulfur; with these impurities removed it extends the refractory life of furnaces (Freas, 1994).
- In the nonferrous metallurgy industry, such as copper, aluminum, and magnesium.
- In chemical manufacturing of various organic and inorganic chemicals.
- In the production of pulp and paper.
- Flue gas desulfurization.
- In the environmental field in treating water and wastewater.
- As paving material when mixed with fly ash, mortar, and asphalt.
- In the refining of sugar.
- As CO_2 absorbent in controlled atmospheric storages for fresh fruit and some vegetables.

Research and development on lime has increased the number of its uses in industrial applications as well as improving on known applications. One such area is in flue gas desulfurization. High-calcium limestone used in the calcination process to produce lime for scrubbing equipment lacks sufficient alkalinity to neutralize high-SO_2 concentrations. Scrubbing with the calcium-based lime also causes scale to build up in the scrubbing equipment. The scaling blocks flow of gas and slurry, and periodic shut-downs are needed to remove the scale.

In the early 1970's, extensive research into this problem by the Dravo Corp. produced a product called Thiosorbic® lime. Then–vice president of research for the Dravo Lime Co. Joseph G. Selmeczi and his staff developed the Thiosorbic® process. The researchers found that during the fluid-gas desulfurization process, magnesium oxide dominates the scrubbing solution (even though the ratio of calcium ions to magnesium ions is 20:1), promoting high alkalinity, thus increasing the scrubbing efficiency up to 94 percent removal of SO_2, compared to 74 percent using conventional lime, and eliminating scaling on the scrubbers.

In September 1998, Dravo Corp. merged with Carmeuse Lime Inc., a subsidiary of Carmeuse North America.

The Federal Clean Air Act Amendments of 1990 (Public Law 101-549), also known as the Acid Rain Bill, created a large demand for limestone and lime for reducing a greater percentage of SO_2 emissions from coal-burning power plants. Carmeuse NA Co., the technology division of Dravo Lime Inc., developed a new magnesium-enhanced lime-based wet flue-gas desulfurization process; it is an improvement on the older process, which has been in use for the past 25 years. In 2000, 27 percent of annual lime production was used in an improved version of the process, which can obtain an SO_2 removal efficiency of 99 percent while scrubbing flue gas from high-sulfur fuel. The old process produced the by-product calcium sulfite ($CaSO_3$), which had no use and had to be disposed of in landfills. The new process produces valuable by-products such as gypsum (calcium sulfate; $CaSO_4$) of 99 percent purity, and achieves a lime utilization of 99.9 percent (Benson and others 2003). If desired, the process can also produce the by-product magnesium hydroxide ($Mg(OH)_2$), which can be used for controlling sulfuric acid emissions, another pollutant (Benson and others 2003).

References Cited (for two preceding papers)

Ames, J.A., Cutcliffe, W.E., and MacFadyen, J.D., 1994, Limestone and dolomite: Industrial Minerals and Rocks, 6th Edition, Published by the Society for Mining, Metallurgy, and Exploration Inc., p. 295–316.

Benson, L., Smith, K., and Roden, B., May 2003, New magnesium—An enhanced lime flue gas desulfurization process, Dravo Lime Inc.—Technology Center, A Carmeuse North America Company, Pittsburgh, Pa., www.carmeusena.com/Corporate/resources.asp?body=white_papers, 13 p.

Callot, G.H.V., 1826, A journey in North America, containing a survey of the countries watered by the Mississippi, Ohio, Missouri, and other affluing rivers: And on the towns, villages, hamlets, and farms of that part of the New World; followed by philosophical, political, military, and commercial remarks and by a projected line of frontiers and general limits: Paris; reprinted 1974, AMS Press, New York, Reprints of Rare Americana, no. 4, Plate 9.

Carr, D.D., Rooney, L.F., and Freas, R.C., 1994, Limestone and dolomite: Industrial Minerals and Rocks, 6th Edition, Published by the Society for Mining, Metallurgy, and Exploration Inc., p. 605–630.

Filson, J.,1793, Reproduction courtesy of the Kentucky Geological Survey to accompany “John Filson of Kentucke” by John Walton, Published by the University of Kentucky Press, Lexington, Ky., 1956.

Freas, R.C., 1994, Lime, industrial minerals and rocks: 6th Edition, Published by the Society for Mining, Metallurgy, and Exploration Inc., p. 589–604.

FSA-NAIP Digital Ortho Photo-imagery for Kentucky, 2004

Rennick, R., 1984, Kentucky place names: Lexington, University Press of Kentucky, 375 p.

USGS, minerals.usgs.gov

Other References

Benson, L., May 2002, New—Enhanced lime flue gas desulfurization process: Carmeuse North America, Pittsburgh, Pa., www.carmeusena.com/Corporate/resources.asp?body=white_papers, 12 p.

Carmeuse Natural Chemicals—Carmeuse Lime brochure, 28 p.

Freas, R.C., 1974, Dravo subsidiary starts construction on lime complex: Mining Engineering, Society of Mining Engineers, v. 26, no. 7, p. 28.

Freas, R.C., 1977, Dravo Corp. stakes a claim in SO_2 scrubber market: Mining Engineering, Society of Mining Engineers, v. 29, no. 4, p. 56–57.

Freas, R.C., Lane, W.H., and Krohn, D.J., 1977, How Dravo's "scrubber lime" mine is mechanized for high production: World Mining, p. 87–91.

Robertson, J.L., 1976, New Dravo lime plant is geared to growing scrubber needs: Rock Products, v. 74, no. 4, p. 64–66.

Selmeczi, J.G., 1976, Flue gas desulfurization by the Thiosorbic® process: Presented at the Third Annual International Conference on Coal Gasification and Liquification: What Needs to be Done Now!, University of Pittsburgh School of Engineering, August 3–5, 1976.

The Camp Nelson Formation near the Carmeuse Mine, Maysville, Kentucky

Frank R. Ettensohn and Richard A. Smath

Introduction

The Camp Nelson Formation is an Upper Ordovician (Mohawkian Stage; Turinian Series) carbonate sequence first described and named by Miller (1905); it is commonly referred to as the lower part of the "Blackriverian Stage," but because this stage name is easily confused with similar lithostratigraphic terms, use of the term has been formally discontinued (Leslie and Bergström, 1995). The Camp Nelson is largely composed of dense, micritic or microcrystalline limestones, and it is the massive, resistant nature of these rocks that has resulted in the steepest part of the Kentucky River gorge called The Palisades (Ettensohn and Hickman, 2002). The Camp Nelson Formation is the oldest exposed rock unit in Kentucky, and together with the overlying Oregon and Tyrone formations, forms the High Bridge Group. About 300 feet (91 m) are exposed in the type area along the gorge of the Kentucky River in central Kentucky, but subsurface analysis indicates that the unit is typically between 350 and 460 feet (107–140 m) thick.

The Camp Nelson Formation in Its Type Area

At Camp Nelson, the unit is composed largely of yellowish-brown, pelletal calcilutite with abundant, dolomite-filled, burrow mottles (Fig. 1). Preferential weathering of the burrow mottles gives rise to the characteristic "honeycomb" appearance (Fig. 2) in weathered sections (Fisher, 1970a, b), and it is the presence of this pronounced burrow mottling in both outcrop and cores (Plate 1, no. 1; Plate 2, nos. 5 and 6) that is the "signature" of the Camp Nelson Formation. Nonetheless, laminated dolostones, laminated calcilutites (Plate 1, no. 3), massive calcilutites (Plate 1, no. 2), ribbon-bedded calcilutite and dolostone, calcarenites (Plate 1, no. 4), breccias, and shales are also present locally throughout the unit (Figs. 3–4). In particular, however, two white calcilutite beds and a prominent open-marine shale bed near the middle of the formation and a shale or dolomitic mudstone unit near the top of the formation are prominent marker horizons (Fig. 3). The white calcilutite beds are commonly laminated and contain mudcracks and bird's-eyes, and the lower white bed (Figs. 5–6) is used as a common marker horizon called the M bed, white marker bed, or white micstone bed (Kuhnhenn and Haney, 1986; Gilreath and others, 1989; Ettensohn, 1992b; Ettensohn and others, 2002b). The calcarenites and breccias commonly have sharp, erosional bases and occur at the bases of shoaling-upward cycles; they are typically composed of poorly to well-sorted fossil fragments, pellets, and intraclasts. An argillaceous, dolomitic mudstone or calcareous shale, 5 to 12 feet (1.5–3.7 m) thick, commonly occurs near the top of the Camp Nelson, and it may be associated with stromatolites. Stylolites are also a common feature throughout the unit.

A sparse, molluscan-ostracod-tabulate coral ("*Tetradium*") fauna is present locally in the limestones, but especially in the breccias and calcarenites at the bases of the shoaling-upward cycles. The gastropod *Maclurites bigsbyi,* as well as coiled and orthocone cephalopods, are locally common. Open-marine faunas, including brachiopods, bryozoans, gastropods, crinoids, sponges, corals, ostracods, and trilobites, are more common in major shale partings.

The Camp Nelson Formation near the Carmeuse Mine

In the area of the Carmeuse Mine (former Dravo Mine), the Camp Nelson Formation is more than 600 feet in the subsurface and can only be viewed in the mine itself and via core. To provide some basic stratigraphic information before entering the mine, we examined the Cominco American Core CA-57 at the Kentucky Geological Survey Well Sample and Core Library. The core has been previously logged and analyzed chemically (Anderson and Barron, 1995) and was drilled about 13 miles (22 km) northeast of the Carmeuse Mine in northern Mason County (Fig. 7). Both the core and mine are present on the southeastern flank of the Carntown-Moscow Anticline, a small, northeast-trending anticlinal spur off the Cincinnati Arch, where the rocks are striking nearly NNW-SSE (Fig. 7) (Potter, 1993).

In order to better understand Camp Nelson stratigraphy and compare it with gamma-ray logs from the unit in the subsurface, an artificial gamma-ray log (Fig. 8) was prepared from the core using techniques outlined by Ettensohn and others (1979). Core lithologies were also described and compared with log signature from the core and with the gamma-ray signatures and lithologies from cores in south-western Ohio (Stith, 1986).

Stith (1986) divided the Camp Nelson into four informal units based on gamma-ray signatures, and these units are apparent in the log from the Cominco core as well. Stith defined the top of the Camp Nelson by his bentonite I, and although no discrete bentonite is present in the Cominco core, the top of the Camp Nelson there is defined by about 10 feet (639–649 feet) of bluish-gray, argillaceous calcilutite that registers as a prominent positive deflection on our curve (Fig. 8). The deflection is nearly as strong as two overlying bentonites (Fig. 8) and may reflect the inclusion of argillaceous, bentonitic components in the limestone. On the outcrop, a similar mudstone or shale unit is commonly present near the Camp Nelson–Oregon contact (Ettensohn, 1992b; Ettensohn and others, 2002b) (Figs. 3–4, 9). The contact can also be distinguished by the change from generally white, burrow-mottled calcilutites in the Camp Nelson to color-mottled, yellowish-gray dolosiltites (Fig. 10) that generally lack burrows, and the contact is very sharp in the core (Fig. 9).

Stith's "upper unit" is represented in the core by yellowish-gray calcilutites and fine-grained calcarenites with laminae and abundant burrow mottling in the 649–739 foot interval (Plate 1, nos. 1 and 2). The interval is represented on the log by an interval of less radioactive deflections that indicate a lesser contribution of argillaceous material. The base of this unit is defined by the prominent white marker or M bed (733–739 feet; Plate 1, no. 2), which is present on the outcrop (Figs. 3, 5), in the core (Fig. 6), and in the mine (Fig. 11). An argillaceous unit in the middle (700–709 feet) may be Stith's "Gant" or bentonite II, and may be equivalent to the prominent shale break noted by Ettensohn (1992b) above the white marker bed (Fig. 3). The presence of chert nodules in the core at 709 feet (Fig. 12) may reflect the bentonitic nature of the overlying argillaceous carbonates and the fact the silica was transported downward and deposited just below the unit as noted by Ettensohn (1992a) on exposures.

Underlying the white marker bed is Stith's "upper argillaceous unit," which is represented in the core by the more radioactive interval from 739 to 835 feet. In the core, this unit is composed largely of light to dark brownish-gray, fine-grained, argillaceous calcarenites (Plate 1, no. 4) and calcilutites (Plate 1, no. 3) with shaly laminae and flaser beds. The darker color of these limestones (Plate 1, nos. 3 and 4) no doubt reflects the presence of a greater argillaceous component.

The upper argillaceous unit is underlain by Stith's "Carntown unit," an interval of relatively pure, white calcilutites with light brownish-gray burrow mottles (Plate 2, nos. 5 and 6), which registers on gamma-ray profile as a series of negative deflections from 835 to 943 feet (Fig. 8). The white coloration of the unit and negative gamma-ray deflections both reflect the relatively pure nature of the carbonates and general absence of argillaceous and siliceous components. This unit also forms the top of the "Gull River limestone" of Ohio drillers (Wickstrom, 1996).

The basal unit of the Camp Nelson is the "lower argillaceous unit" of Stith, and in this core, it is represented by an interval (943–999 feet) of massive to laminated, light bluish-gray calcilutites (Plate 2, no. 7) with cyclic interbeds of light gray bird's-eye calcilutite and greenish-gray, silty dolosiltites; it is represented by the series positive (more radioactive) deflections at the base of the unit (Fig. 8). The contact with the underlying Wells Creek Formation at 999 feet is sharp but apparently overall gradational (Fig. 13).

The upper part of the Wells Creek Formation in the core is composed of dark greenish-gray, argillaceous, quartzose siltstones alternating with yellowish-gray, laminated dolosiltites. Like the overlying Camp Nelson, the Wells Creek is represented by a series of shallowing-upward cycles, with the muddy, dark greenish-gray siltstones representing basal transgres-

Figure 1. Camp Nelson bedding-plane surface showing grayish-orange, dolomitic burrow mottling in brownish-gray calcilutite or micritic limestone.

Figure 11. “White marker” or “M” bed near the base of a drift in the Carmeuse Mine. Note the sharp contact with overlying brownish-gray calcilutites and the bird’s-eyes in the marker bed.

Figure 6. Position of the “white marker” or “M” bed in the Cominco core.

Figure 9. Camp Nelson–Oregon contact and the overlying, dark argillaceous calcilutites in the Cominco core. The prominent bluish-gray color mottling defines the beginning of the Oregon Formation.

Figure 10. Typical grayish-orange dolosiltites with bluish-gray color mottling from the Oregon Formation in the Cominco core.

Figure 12. Chert nodules in the Cominco core below an argillaceous unit in the core that may represent Stith's (1986) bentonite II.

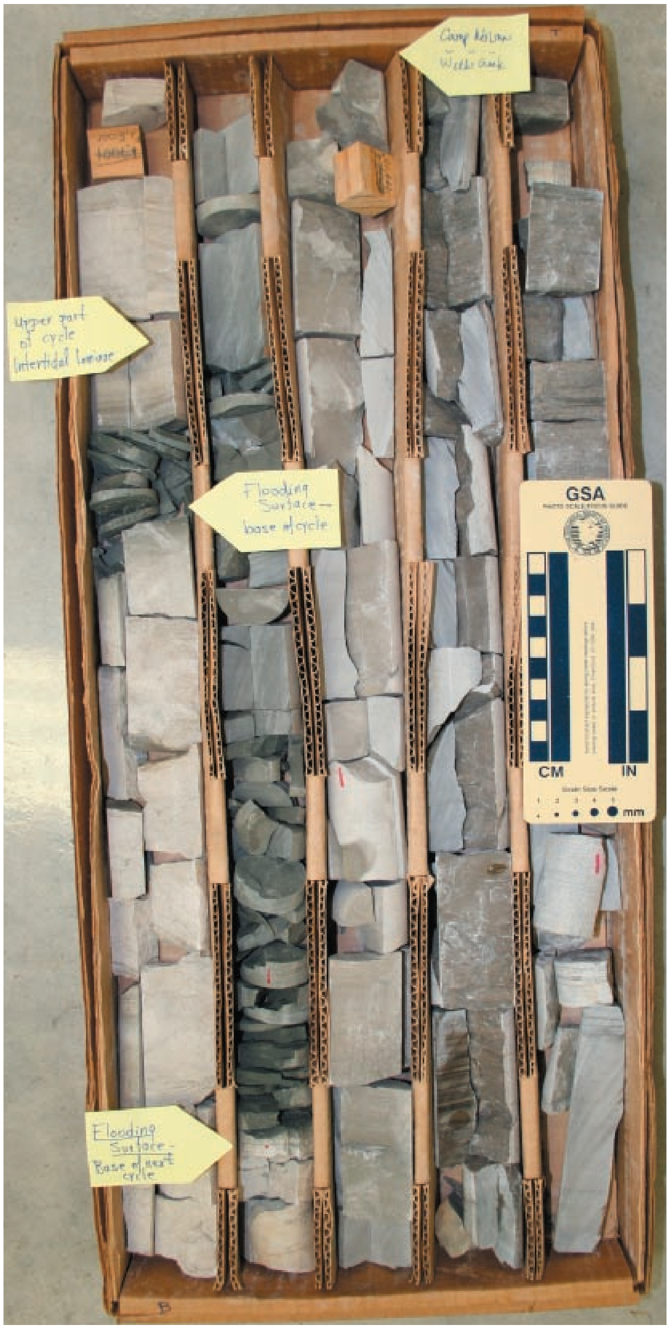


Figure 13. Sharp contact between the Wells Creek and Camp Nelson formations in the Cominco core.

Figure 14. Typical cyclic Wells Creek lithologies from the Cominco core. Dark greenish-gray units represent the basal, transgressive parts of each cycle.

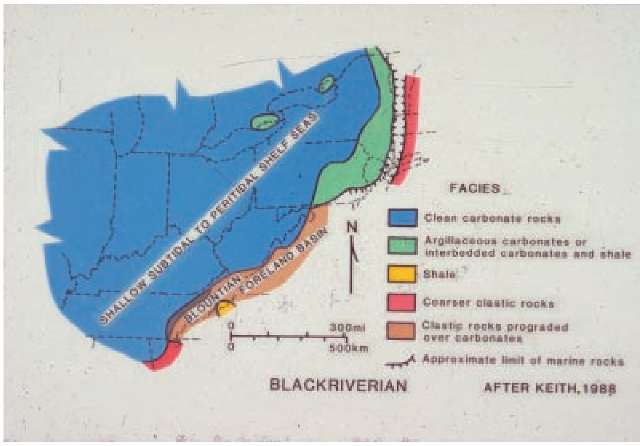


Figure 15. Schematic drawing of the extensive Black River platform across Kentucky parts of which the Camp Nelson limestones were deposited.

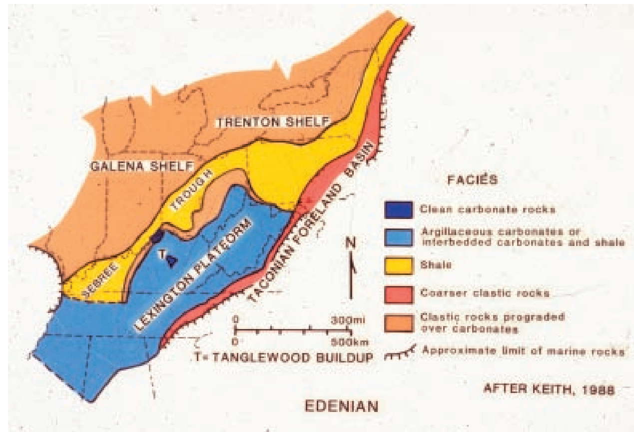


Figure 16. Schematic drawing of east-central United States after the collapse of the Black River Platform and differentiation of the cratonic area into platforms and troughs.

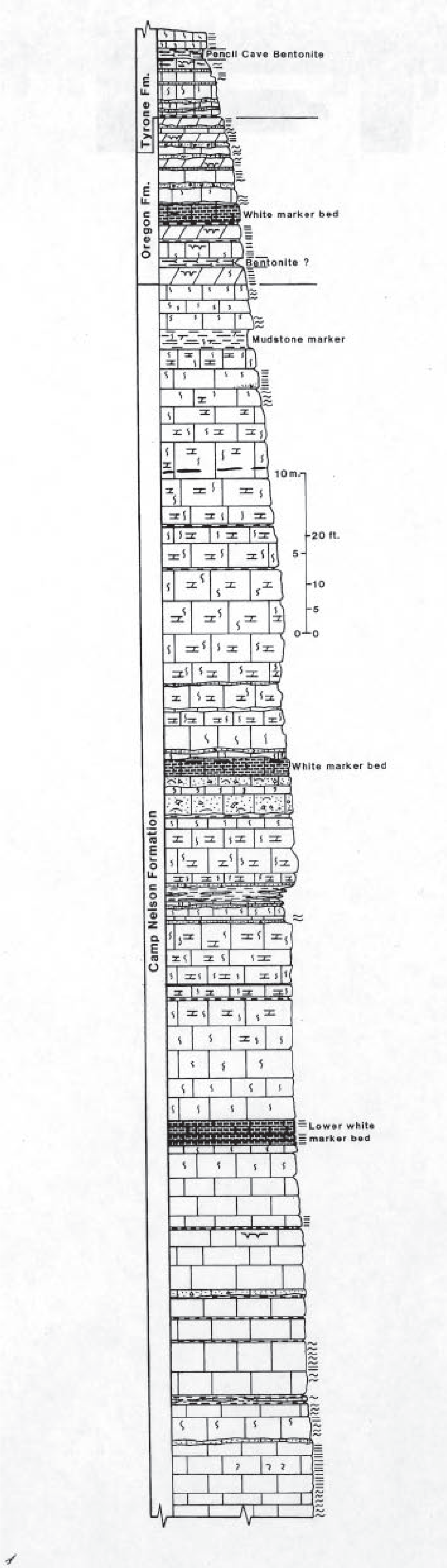


Figure 3. Stratigraphy of the Camp Nelson Limestone.

Figure 2. Typical honeycomb weathering in the Camp Nelson; Camp Nelson, Ky.

sive parts of each cycle (Fig. 14). The dark basal parts of each cycle are also commonly intensely burrowed (Plate 2, no. 8).

Figure 5. The “white marker” or “M” bed that occurs at the base of Stith’s (1986) upper unit; Camp Nelson, Ky.

Figure 4. Mudstone/shale unit in the upper part of the Camp Nelson; probably equivalent to Stith’s (1986) bentonite I; Camp Nelson, Ky.

Economic Aspects

Most of the Camp Nelson mined in central and northern Kentucky is used for industrial, construction, and agricultural purposes (Dever and others, 1994; Anderson and Barron, 1995). Low-silica, carbonate rock dust is used for explosion abatement in underground coal mines. These carbonates are also used as construction stone, spoil-bank reclamation, and acid-mine-drainage neutralization. It is also used to reduce sulfur dioxide emissions from coal-burning power plants in fluidized-bed-combustion and flue-gas-desulfurization processes. In particular, chemically pure limestones are used for production of lime, portland cement, agricultural lime, flux for steel and other metallurgical industries, and fertilizer fillers. Many of these uses require low-silica compositions, and hence, limestones in the Carntown and upper units are preferentially selected, while argillaceous and bentonitic carbonates from the lower, middle, and upper parts of the unit are avoided (Dever and others, 1994; Anderson and Barron, 1995).

In southern and central Kentucky, the Camp Nelson and its equivalents locally contain fractured-carbonate reservoirs with oil and gas (Wickstrom, 1996). Much of the fracturing is thought to be related to reactivation of deep structures, and the fracturing

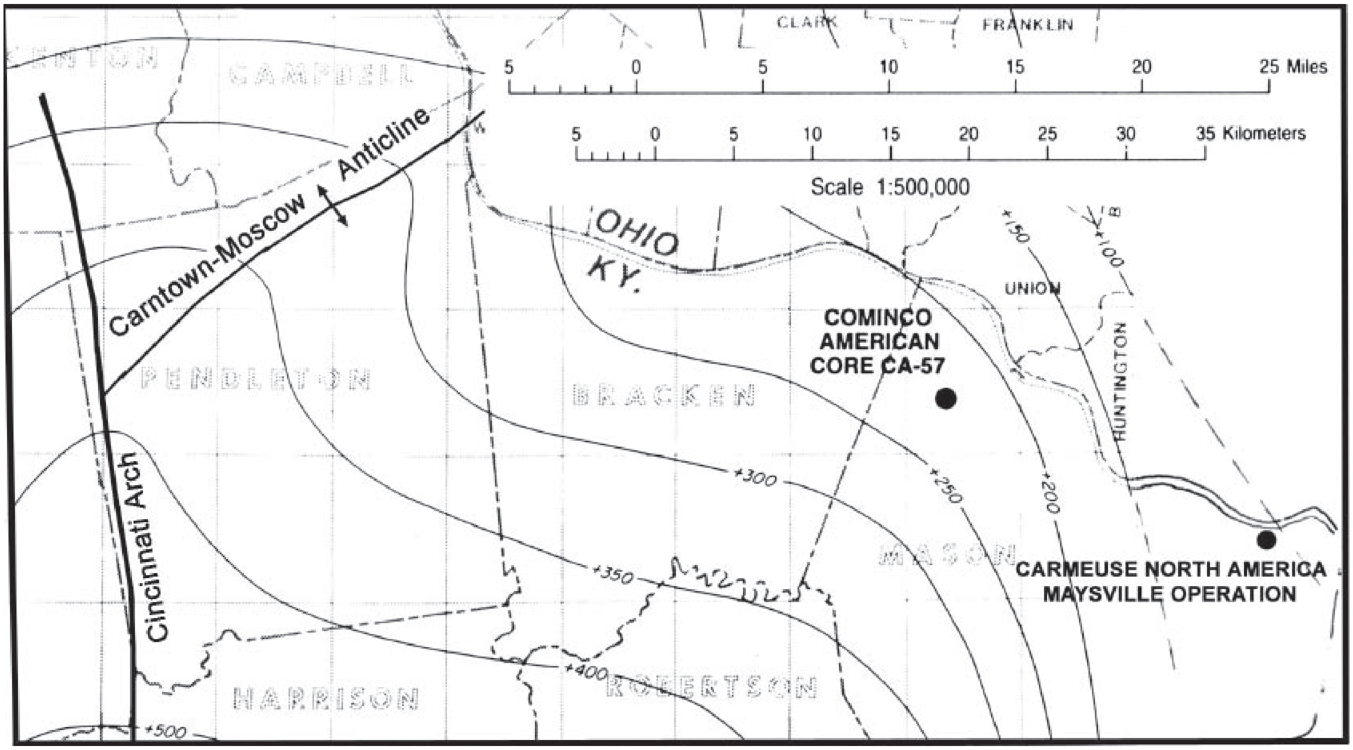


Figure 7. Structure-contour map on top of the Camp Nelson and map showing the location of the Carmeuse Mine and Cominco core in Mason County, relative to regional structures. Modified from Potter (1993).

is commonly associated with secondary dolomitization. According to Wickstrom (1996), production is especially prevalent in clean, fractured micrites from the Gull River interval, which are bounded above and below by argillaceous zones.

Depositional Environments

The rocks of the High Bridge Group, including the Camp Nelson Formation, were deposited on east-central parts of a continent, now called Laurentia, during waning phases of the Blountian tectophase, an early phase of the Taconian Orogeny (Ettensohn, 1991, 1994). As is typical during final phases of orogeny, the adjacent foreland basin filled with sediments, giving rise to an overall shallowing-upward, regressive regime that prevailed throughout the basin and adjacent parts of the craton (Ettensohn, 1991, 1994). The High Bridge Group and many other very similarly appearing Blackriverian rocks from New York to Tennessee were deposited during this time across an extensive, shallow, carbonate platform in east-central United States (Fig. 15) called the Black River Platform (Keith, 1989; Ettensohn and others, 2002a). Environments across the platform represented very shallow-subtidal to peritidal conditions, probably no deeper than 60 feet (18 m) deep, and because of its shallow nature and distance from the open ocean, much of the time the platform would have acted as a restricted platform or shelf lagoon like the Bahamian Platform today (e.g., Newell and others, 1959; Purdy, 1963a, b). Although mixed clastics and carbonates predominate in equivalent units near the tectonic highlands (Fig. 15), away from the highlands, subtropical carbonate, pelletal muds become dominant across the platform because of its former presence at about 25º south latitude (Scotese, 1997) in the evaporative trade-wind belt where such carbonates are formed in abundance (e.g., Lees, 1975). Although carbonate muds and pelletal muds are the preeminent sediments throughout the High Bridge Group, the environments in which they were deposited changed in a systematic way upward in section from shallow, open-marine to transitional and finally to intertidal.

The Camp Nelson Formation reflects the early, shallow open-marine part of the High Bridge Group and is specifically interpreted to represent a shallow-ramp, somewhat restricted, platform-lagoonal environment like most of the Bahamian Platform lagoon today (Newell and others, 1959; Purdy, 1963a, b). Such an environment typically exhibits heavily

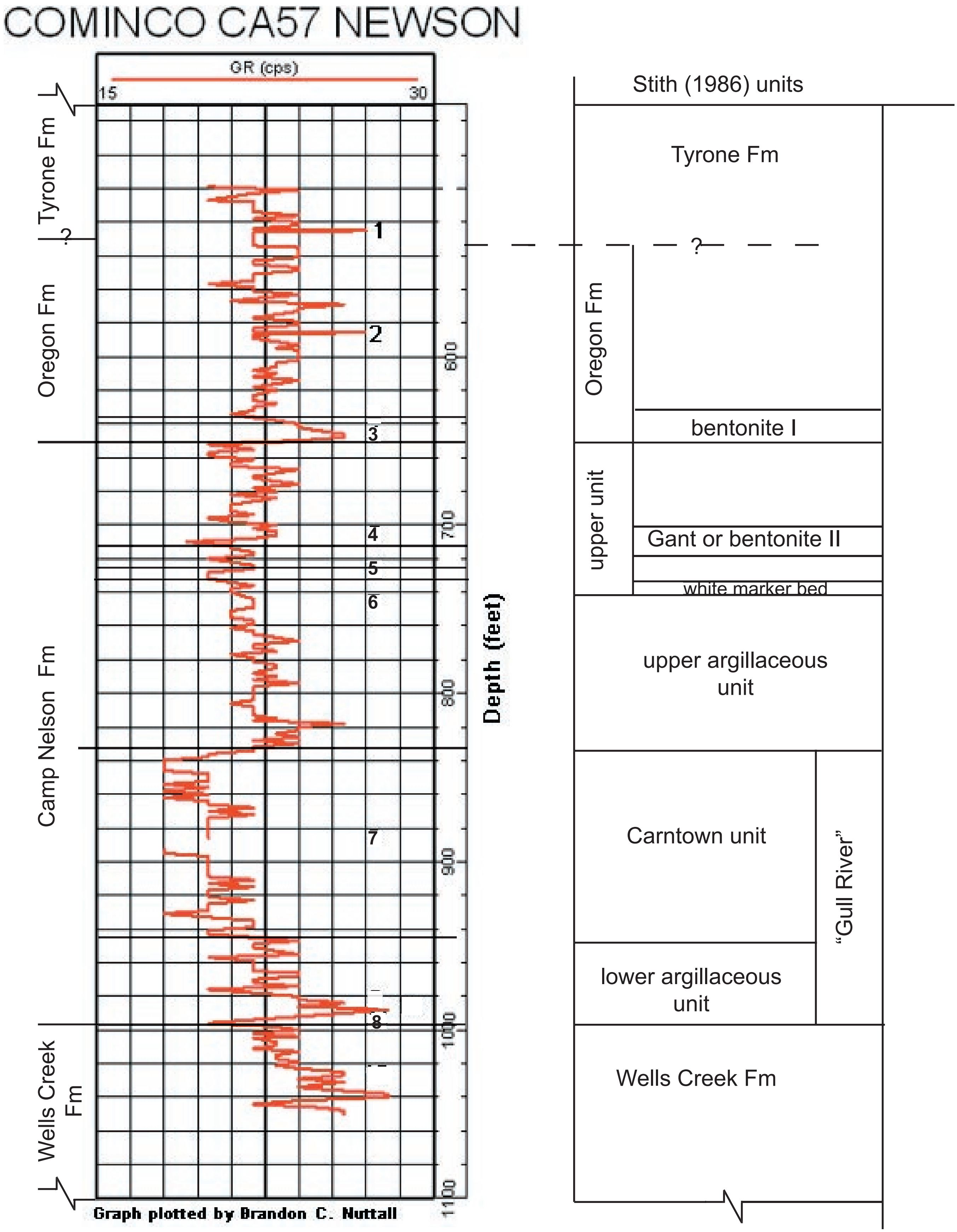


Figure 8. Artificial gamma-ray log made from the Cominco core showing lithostratigraphic units and Stith's (1986) informal units in the Camp Nelson. Numbers on log: 1. Pencil Cave bentonite at 525 ft; 2. unnamed bentonite; 3. argillaceous unit at top of Camp Nelson; equivalent to Stith's (1986) bentonite I; 4. Stith's Gant on bentonite II; 5. top of white marker bed; 6. base of white marker bed; 7. 4 ft of core missing; 8. Camp Nelson–Wells Creek contact.

burrowed, pelletal muds. The muds are commonly produced by the disaggregation of calcareous green algae, pelletized as they pass through the guts of burrowers, and redistributed across the lagoon and onto adjacent tidal flats by storms and tides (Shinn and others, 1969). So the Camp Nelson platform lagoon may have similarly provided pelletal muds for the Oregon and Tyrone tidal flats, and it is possible that colonies of the coral *Tetradium* acted as baffles to trap the sediment in the shallow waters on and near the tidal flats (Walker, 1973; Kuhnhenn and others, 1981). The dolomitic mottling that is so common reflects the abundant bioturbation that was present in the Camp Nelson carbonate muds, and this bioturbation apparently provided zones of permeability for dolomitizing solutions during later diagenesis (Fisher, 1970b). The extensive, shallow waters of the platform lagoon probably limited exchange with waters from more open-marine settings, meaning that the lagoon may have become hypo- or hypersaline at times, and this may account for the restricted nature of the fauna (mollusks, ostracods, corals, and burrowing worms) throughout most of the unit. However, open-marine fauna may be found in the calcarenites and breccias at the base of the cycles, which probably represent major storms or local transgressive incursions that brought with them open-marine waters and fauna. In contrast, some of the thicker shale beds and argillaceous zones, commonly with more diverse marine faunas, probably represent regional transgressions with tectonic or eustatic origins.

High Bridge (Turinian) deposition was abruptly ended by a period of regional uplift and erosion represented by an unconformity at the Tyrone-Lexington contact; the Mud Cave bentonite also commonly occurs at or near the contact. Both the unconformity and bentonite reflect major regional events that accompanied the beginning of a new Taconian tectophase and resulting changes in cratonic far-field stresses. As a result, by the end of Turinian time, High Bridge deposition had abruptly ended as the Black River Platform (Fig. 15) collapsed along old, basement structural lineaments and generated a new series of structural highs and lows that would become the Lexington Platform, Sebree Trough, and Galena-Trenton Shelf (Fig. 16). These new features would subsequently provide the foundations for overlying Trenton (Lexington) deposition (Ettensohn and others, 2002a).

References Cited

Anderson, W.H., and Barron, L.S., 1995, High-carbonate, low-silica, high-calcium stone in the High Bridge Group (Upper Ordovician), Mason Country, north-central Kentucky: Kentucky Geological Survey, ser. 11, Information Circular 53, 33 p.

Dever, G.R., Jr., Anderson, W.H., Francis, H.E., Davidson, O.B., and Thompson, M.F., 1994, Chemical and statistical analysis of a sampled interval in the Camp Nelson Limestone (Upper Ordovician), Madison County, central Kentucky: Kentucky Geological Survey, ser. 11, Information Circular 51, 19 p.

Ettensohn, F.R., 1991, Flexural interpretation of relationships between Ordovician tectonism and stratigraphic sequences, central and southern Appalachians, *in* Barnes, C.R., and Williams, S.H., eds., Advances in Ordovician geology: Geological Survey of Canada Paper 90-9, p. 213–224.

Ettensohn, F.R., 1992a, Contacts between the Camp Nelson, Oregon, and Tyrone formations—Stratigraphic and environmental implications, *in* Ettensohn, F.R., ed., Changing interpretations of Kentucky geology—Layer-cake, facies, flexure, and eustacy: Ohio Division of Geological Survey Miscellaneous Report 5, p. 28–30.

Ettensohn, F.R., 1992b, Kentucky River Fault System and the Camp Nelson Limestone, *in* Ettensohn, F.R., ed., Changing interpretations of Kentucky geology—Layer-cake, facies, flexure, and eustacy: Ohio Division of Geological Survey Miscellaneous Report 5, p. 29–31.

Ettensohn, F.R., 1994, Tectonic control on the formation and cyclicity of major Appalachian unconformities and associated stratigraphic sequences, *in* Dennison, J.M., and Ettensohn, F.R., eds., Tectonic and eustatic controls on sedimentary cycles: SEPM Concepts in Sedimentology and Paleontology, v. 4, p. 217–242.

Ettensohn, F.R., Fulton, L.P., and Kepferle, R.C., 1979, Use of scintillometer and gamma-ray logs for correlation and stratigraphy in homogeneous black shales: Geological Society of America Bulletin, v. 90, pt. I, p. 421–432, pt. II, p. 828–849.

Ettensohn, F.R., and Hickman, J.B., 2002, Structural framework, *in* Andrews, W.M., Jr., Ettensohn, F.R., Gooding, P.J., and Smath, M.L., eds., Impact of geology on human history at Camp Nelson and Perryville, central Kentucky: Lexington, Kentucky Society of Professional Geologists, p. 11–14.

Ettensohn, F.R., Hohman, J.C., Kulp, M.A., and Rast, N., 2002a, Evidence and implications of possible far-field responses to Taconian Orogeny: Middle–Late Ordovician Lexington Platform and Sebree Trough, east-central United States: Southeastern Geology, v. 41, p. 1–36.

Ettensohn, F.R., Kuhnhenn, G.L., and Andrews, W.M., Jr., 2002b, Stop 3—Shallow-ramp, platform-lagoonal carbonates in the Oregon and Camp Nelson formations, High Bridge Group, *in* Andrews, W.M., Jr., Ettensohn, F.R., Gooding, P.J., and Smath, M.L., eds., Impact of geology on human history at Camp Nelson and Perryville, central Kentucky: Lexington, Kentucky Society of Professional Geologists, p. 71–76.

Fisher, I.S., 1970a, Selective weathering of dolomite bodies from a limestone host: Geological Society of America Bulletin, v. 81, p. 3757–3758.

Fisher, I.S. 1970b, Origin of small irregular dolomite bodies in the pelletal Camp Nelson Limestone (Ordovician) of Kentucky: Southeastern Geology, v. 12, p. 115–120.

Gilreath, J.A., Potter, P.E., and Losonsky, G., 1989, Guide to interpretation of structural features associated with the Kentucky River Fault System along U.S. Highway 27 near Camp Nelson, Kentucky: Kentucky Geological Survey, ser. 11, Map and Chart 1, 1 sheet.

Keith, B.D., 1989, Regional facies of Upper Ordovician Series of eastern North America, *in* Keith, B.D., ed., The Trenton Group (Upper Ordovician Series) of eastern North America, deposition, diagenesis, and petroleum: American Association of Petroleum Geologists Studies in Geology 29, p. 1–16.

Kuhnhenn, G.L., Grabowski, G.J., Jr., and Dever, G.R., Jr., 1981, Paleoenviromental interpretation of the Middle Ordovician High Bridge Group in central Kentucky, *in* Roberts, T.G., ed., GSA Cincinnati ’81 Field Trip Guidebooks, v. 1: Stratigraphy, sedimentology: Falls Church, Va., American Geological Institute, p. 1–30.

Kuhnhenn, G.L., and Haney, D.C., 1986, Middle Ordovician High Bridge Group and Kentucky River Fault System in central Kentucky, *in* Neathery, T.L., ed., Centennial Field Guide, v. 6, Southeastern Section: Geological Society of America, p. 25–29.

Lees, A., 1975, Possible influence of salinity and temperature on modern self carbonate sedimentation: Marine Geology, v. 19, p. 159–198.

Leslie, S.A., and Bergström, S.M., 1995, Revision of the North American late Middle Ordovician standard stage classification and timing of the Trenton transgression based on K-bentonite bed correlation, *in* Cooper, J.D., Droser, M.L., and Finney, S.C., eds., Ordovician odyssey: Fullerton, Pacific Section SEPM, Book 77, p. 49–54.

Miller, A.M., 1905, The lead and zinc bearing rocks of central Kentucky with notes on mineral veins: Kentucky Geological Survey, ser. 3, Bulletin 2, 35 p.

Newell, N.D., Imbrie, J., Purdy, E.G., and Thurber, D.L., 1959, Organism communities and bottom facies, Great Bahama Bank: American Museum of Natural History Bulletin, v. 117, p. 177–228.

Potter, P.E., 1993, Structure on top of the Middle Ordovician High Bridge/Black River groups in the Tristate area of northern Kentucky, southwestern Ohio, and southeastern Indiana: Kentucky Geological Survey, ser. 11, Map and Chart 5, 1 sheet.

Purdy, E.G., 1963a, Recent calcium carbonate facies of the Great Bahama Bank. 1. Petrography and reaction groups: Journal of Geology, v. 71, p. 334–355.

Purdy, E.G., 1963b, Recent calcium carbonate facies of the Great Bahama Bank. 2. Sedimentary facies: Journal of Geology, v. 71, p. 472–497.

Scotese, C.R., 1997, Paleogeographic atlas, PALEOMAP Progress Report 90-0497: Arlington, Department of Geology, University of Texas at Arlington, 45 p.

Shinn, E.A., Lloyd, R.M., and Ginsburg, R.N., 1960, Anatomy of a modern carbonate tidal flat, Andros Island, Bahamas: Journal of Sedimentary Petrology, v. 39, p. 1202–1228.

Stith, D.A., 1986, Supplemental core investigations for high calcium limestones in western Ohio and discussion of natural gas and stratigraphic relationships in the Middle to Upper Ordovician rocks of southwestern Ohio: Ohio Geological Survey Report of Investigations 132, 17 p.

Walker, K.R., 1973, Stratigraphy and environmental sedimentology of Middle Ordovician Black River Group in the type area—New York State: New York State Museum and Science Service Bulletin 419, 43 p.

Wickstrom, L.H., 1996, Play MOf: Middle Ordovician fractured carbonates, *in* Roen, J.B., and Walker, B.J., eds., The atlas of major Appalachian gas plays: West Virginia Geological and Economic Survey Publication V-25, p. 172–176.

Plate 1


PHOTO SCALE
Photo by Patrick Gooding
CM
IN
1 2 3 4 5
mm

1


PHOTO SCALE
Photo by Patrick Gooding
CM
IN
1 2 3 4 5
mm

2


PHOTO SCALE
Photo by Patrick Gooding
CM
IN
1 2 3 4 5
mm

3


PHOTO SCALE
Photo by Patrick Gooding
CM
IN
1 2 3 4 5
mm

4

Plate 2

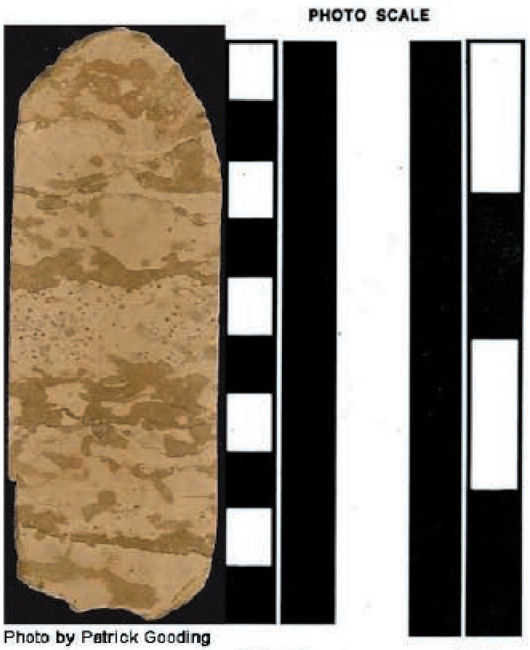


Photo by Patrick Gooding

5 CM IN

1 2 3 4 5 mm

Photo by Patrick Gooding

6 CM IN

1 2 3 4 5 mm

Photo by Patrick Gooding

7 CM IN

1 2 3 4 5 mm

Photo by Patrick Gooding

8 CM IN

1 2 3 4 5 mm

RTE. 3071 LOOP (Road Log Supplement 1)

Total Mileage

0.0	Intersection of AA Highway and Rte. 3071
0.1-0.2	Low outcrop of Grant Lake Formation (Bellevue Ls.)
0.3	Mitsubishi Motors
0.5	Small exposure of Grant Lake limestones
0.7-0.9	Exposure of shaly Corryville Member of Grant Lake Fm.
1.1-1.2	Small outcrops of Bellevue Ls.
1.7-1.9	Large outcrops of Bellevue Ls., including sharp contact between shaly, siltstone-rich Fairview Fm. and thinner-bedded light gray Bellevue Ls.
2.0	Small outcrop in shaly upper Fairview Fm.
2.2-2.5	Large three-tiered outcrop in Fairview Formation; note following features:
2.3	Upper Fairview deformed zone; ball and pillow structure
2.35	Small thrust faults in Fairview appear to die out locally onto bedding planes
2.5	Channel-like feature appears at the same horizon as deformed beds
2.6	Sign for Rte. 8
2.8	Bridge over large creek valley
2.85	Junction Rte. 3056 is at upper end of a huge new roadcut that extends from the middle Kope Fm. at its base upward to the Bellevue and Corryville members of the Grant Lake Fm. at its top
3.15	Bench on top of Grand Avenue submember of Kope Fm.
3.2	Grand Avenue submember; at Dover sign
3.3	Big Shale #5 (base of Grand View submember) seen just above benches
3.6	Sign for Maysville, Rte. 8 near base of section
3.8	Pull off on shoulder; disembark to examine middle Kope Fm. beds

STOP 4: ROADCUTS ON KY ROUTE 3071, MAYSVILLE, KY.

These new roadcuts (late 1990s) provide an excellent and very fresh reference section of the upper half of the Kope Formation, the overlying Fairview and much of the Grant Lake Formation. Approximately 90 meters of section are exposed in this outcrop.

STOP 4A. Lower Exposed Beds Along Route 3071 (Figs. 20-21): Exposures at the lower end of this extended outcrop show the Snag Creek, Alexandria, and Grand View submembers of the middle Kope (Southgate Member). These units were previously examined along the AA Highway at Lower Holst Creek (Stop 1) and Snag Creek East (Stop 2). Through these intermediate outcrops, beds of the Southgate Member exposed along Rte. 3071 can be correlated with equivalents in the Cincinnati area.

Near the base of the outcrop, the upper boundary of the *Sowerbyella*-rich zone occurs in a 40-cm-thick grainstone at the top of Pioneer Valley submember. This is followed by a 1.5-m-thick shale-rich interval, corresponding to Big Shale #3, of the Snag Creek submember. The bundle of limestones overlying this shale form the top of the Snag Creek submember at about the level of the first bench. This is overlain by the thickest shale in the outcrop, Big Shale #4, at the base of the Alexandria submember. This shale is sharply overlain by the next cluster of limestones, which is rich in reddish *Onniella* grainstones and exhibits a characteristic spacing of layers that is traceable to the Cincinnati area; the top of this bundle occurs slightly above the second bench on the east side of the road. The next major shale interval (Big Shale #5) is generally obscured by talus; this forms the base of the Grand View submember, the top of which is identifiable as a "polka-dotted" bryozoan-rich limestone. Higher still, the closely packed thin limestones of the upper Grand Avenue submember form the top of the third bench on the east side.

Note: Rte. 3071 is now Rte. 68/62.

Return to vehicles; turn around and retrace route back south toward AA Highway.

3.8 First bench on west side of Rte. 3071 is on top of Alexandria beds (above Big Shale #4)
4.0 Second platform on top of Grand Avenue submember
4.3 Sign for Rte. 3066
4.35 Third bench is developed on the top of Grand Avenue submember
4.4 Junction of Rte. 3056; upper end of large outcrop; pull off and park just before intersection

Stop 4B. Upper Exposed Beds along Route 3071 (Figs. 20-21): In the upper portion of the roadcut near the road level, the uppermost beds of the Kope are well exposed. Just below the Kope-Fairview contact (in the Taylor Mill submember of the Kope Fm.), note the compact, 50-cm-thick *Onniella*-rich Z bed, which forms the fourth bench near the upper end of the roadcut. This is overlain by about one meter of shale that corresponds with the last bed of the Kope Formation ("Two-Foot Shale") seen elsewhere. At this level, there is an abrupt shift from the underlying shale- and siltstone-dominated Taylor Mill submember of the upper Kope to amalgamated grainstones of the Fairview Fm. Schumacher (1991) placed the base of the Fairview Fm. in this area at or near the base of the overlying compact limestone ledge which is rich in the brachiopod *Strophomena.* Holland (1998) also considered this to be the boundary between the first two sequences of the Cincinnatian Series (C1 and C2). However, recently Holland et al. (this volume) argued that the sequence boundary should perhaps be placed higher, above the *Strophomena*-bearing limestone, at the position of incursion of supposedly shallower water faunas in the "Wesselman shaly tongue." A case could also be made for placing a sequence boundary below the Z bed of the upper Kope. This *Onniella*-rich limestone shows a sharp base and an abrupt change to shallow compact limestone facies from the underlying shales. Fairview Formation beds are especially rich in the brachiopod *Strophomena,* which may represent the abrupt incursion of this species.

If time permits, following a brief examination of these beds we will ascend the southern end of the outcrop along the trail up to the sixth bench. At this location we may examine closely a series of thick siltstones and shales which locally display dramatic evidence of deformation (see Schumacher, this volume). On the opposite, or west, side of the roadcut a large channel-like structure is visible at this level. A series of four bands of siltstone each show ball-and-pillow deformation along the length of the outcrop, although the deformation is laterally discontinuous. These have been interpreted as seismites by Pope et al. (1997).

The seventh bench is just below the relatively sharp lower contact between shaly beds of the upper Fairview (possible Miamitown equivalent) and lighter gray, closely spaced, thin wavy packstone beds of the Bellevue Member of the Grant Lake Formation. About 30 cm below the contact is a distinctive, rusty weathering laminated siltstone with a channeled discontinuity surface along its top; this bed is extensively exposed along higher portions of the bench surface. Local pockets of shale filling hollows on this surface contain very abundant columns and crowns of the crinoid *Glyptocrinus decadatylus.* Basal Bellevue beds, immediately overlying this level, carry a series of hardgrounds with *Trypanites* borings and encrusting holdfasts of *Anomalocrinus.*

The next level of interest occurs about 150 cm below the eighth or second-to-last bench in this roadcut. The highest beds here are rubbly to wavy-bedded packstones and grainstones of the Bellevue Fm. Its basal contact with the Fairview Fm. is rather sharply defined and is located about 8 m above the highest seismites. These beds are full of well-preserved brachiopods, particularly *Platystrophia ponderosa* and *Hebertella.* A number of bedding planes within this interval also show evidence of early lithification as hardgrounds.

Proceeding upward, a small quarried area immediately below the uppermost bench in the outcrop was the site of excavation of a large (~5m^2) hardground surface (see contribution by Sumrall et al., this volume). This hardground was developed on the upper surface of relatively thin packstone beds rich in the brachiopod *Platystrophia ponderosa.* The surface itself was nearly planar with minor relief of a few millimeters. It is marked by large mounded colonies of bryozoans which are clearly cemented to the surface. Both the bryozoans and portions of the limestone surface itself had abundant encrusting edrioasteroids of four different species. Interestingly, the edrioasteroids occur in greatest density in elongate rows a few centimeters wide and up to a meter long; this pattern suggests that narrow portions of the surface were swept clean of mud coating and thereby were accessible to colonization by these crinoids. The hardground itself has been traced to all corners of this outcrop and in the nearby roadcuts potentially correlates also with the previously described hardground on a nearby railroad.

The uppermost beds exposed above the hardgrounds up to the distinct platform of the ninth bench are rubbly limestones. This bench is overlain by light gray, thin, wavy-bedded limestones of the upper Grant Lake Fm. (possible Corryville equivalent). Notable features include a mass of large domal bryozoans at a level of about 2 meters above the platform and a distinctive whitish-weathering amalgamated marker bed. Specimens of cyclocrinitids (small ball-like green algal) have also been obtained from shaly beds slightly below this level.

Return to vehicles and continue south on Rte. 3071

4.6	Large Fairview outcrop with thrust fault(s)
4.8	Channelized siltstone bed with ball-and-pillow structure
5.0	Outcrop with Fairview-Bellevue contact
7.2	Junction of Rte. 3071 and AA Highway; **END OF RTE. 3071 LOOP**

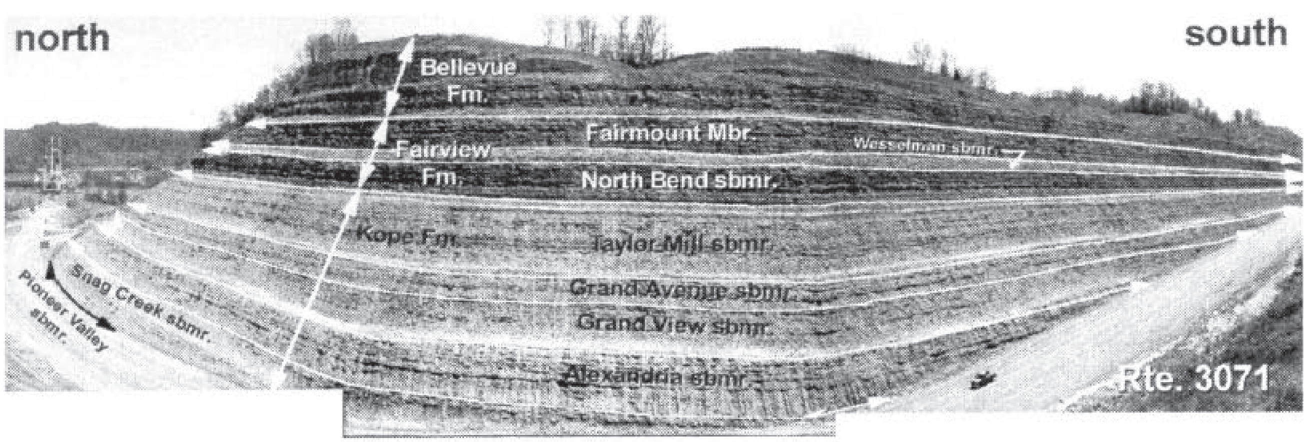


FIGURE 20. Route 3071 outcrop, Maysville, Kentucky. View of section at northern end of highway, looking eastward. The lowest exposed beds, at road level on far left side of photo, are the upper Pioneer Valley beds; these are easily identified by the abundance of *Sowerbyella* contained therein. Overlying this is the full thickness of the Southgate and McMicken members of the Kope Formation, as well as the Fairview, Bellevue, and Grant Lake formations. The main seismite horizons are found in the upper Fairview Formation (Fairmount Member), but these are better seen on the west side of the highway than on the east side (shown here).

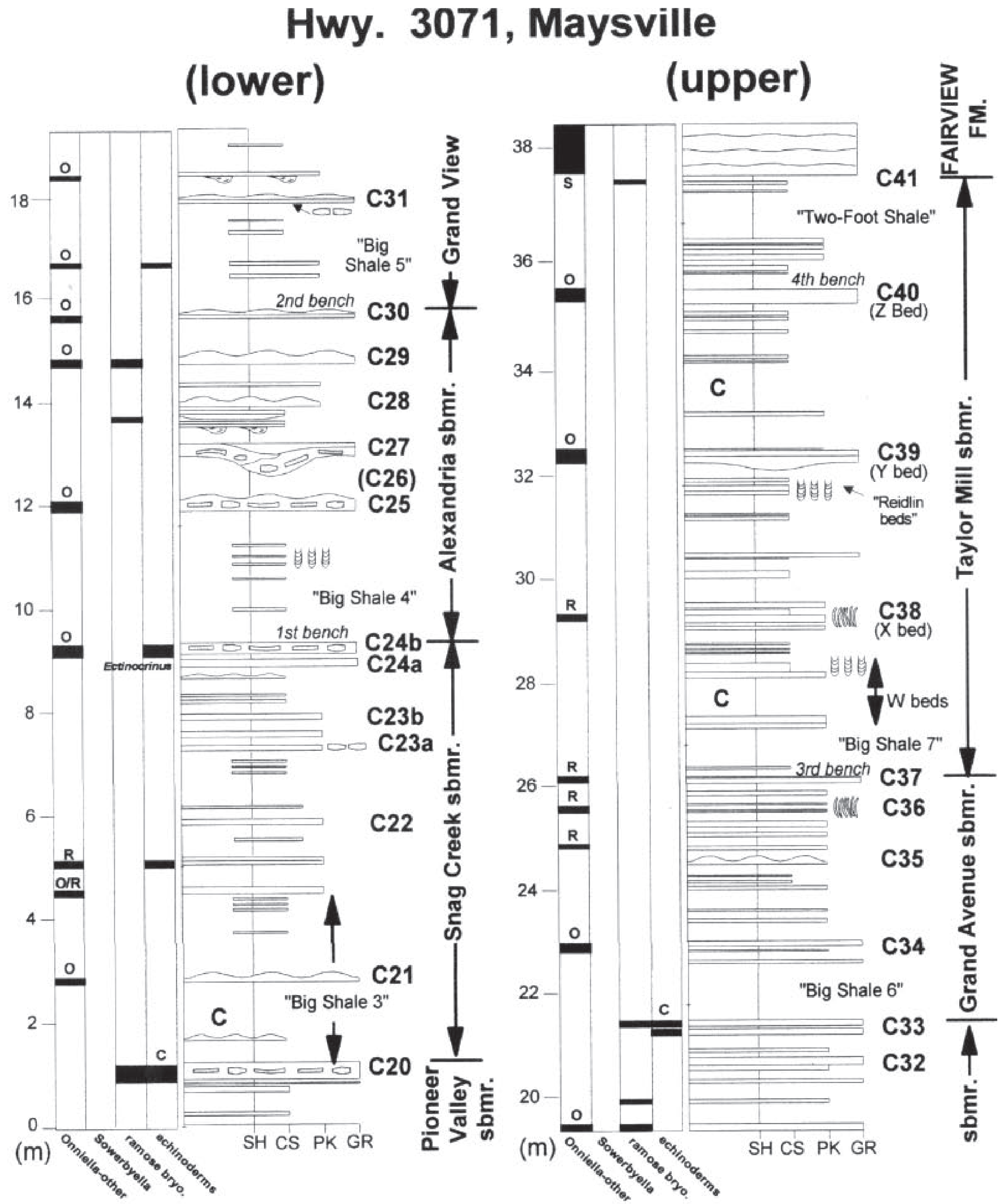


Figure 22. Measured section of Route 3071 outcrop, near Maysville, Kentucky. See p. 12 for general legend to stratigraphic sections. Reprinted from Algeo and Brett (1999) with the permission of the Kentucky Geological Survey. See page 36 for reference to Algeo and Brett (1999).

Discussion of Seismite Features in the Upper Fairview Formation (Upper Ordovician: Maysvillian) at Route 11 near Maysville, Ky.

Carlton E. Brett and James J. Zambito, Department of Geology, University of Cincinnati, Cincinnati, OH 45221-0013

Patrick I. McLaughlin, Department of Geology, Bucknell University, Lewisburg, PA 17837

Introduction

The upper Fairview Formation of the Rte. 11 cut preserves remarkable evidence for synsedimentary deformation that are interpreted as seismites (Schumacher, 2001; McLaughlin and Brett, 2004). Not only does this exposure yield evidence for deformation of beds at or near the seafloor, certain aspects of the deformed beds point to “paleothixotropy”; i.e., that the muds behave initially as semisolids and subsequently became liquefied. This observation, in turn, sheds light on the origin of the deformation.

Description of Deformed Beds

While deformed beds have long been recognized in the rock record, only recently have such features been interpreted as being seismically induced (see McLaughlin and Brett, 2006, and references therein). This study focuses on such beds in the upper Fairview Formation (Upper Ordovician: Maysvillian) near Maysville, Ky. (Figs. 1A, B). The deformed layers consist of plastically deformed ball-and-pillow masses of laminated silt to fine calcarenite, up to 2 m across that show extreme deformation with upturned to overturned laminae, separated by tongues or diapirs of clay (Fig. 1C). Deformed horizons pass laterally into undeformed intervals of laminated siltstone and shale. Deformation appears to be especially concentrated in areas of originally thickened silt. In some instances these are clearly channel fills; sharp lateral boundaries of channel sides truncate older, undeformed tabular beds of siltstone, calcarenite, and shale (Fig. 1C). All of the deformed horizons appear to be sharply overlain by bundles of fine-grained to shelly skeletal pack- and grainstone (Figs. 1C, D). These limestones may rest sharply upon truncated upturned laminae of deformed siltstones and, in turn, they are overlain by intervals of shale. In addition, at least one horizon shows a calcarenite/packstone bed up to 30 cm thick, which is locally broken into blocks that have been slightly rotated from original burial attitude (Fig. 1D).

Well-preserved examples of pillows fallen from the outcrop are available intermittently in the ditches and in a cutting on a small side road that turns off Rte. 11 opposite the main exposures. In several cases, undersurfaces of deformed siltstone masses display deformed sole features; these include distorted burrow molds and tool marks, as well as reticulate patterns of apparent tension fractures. The trace fossils are small, sharply incised, tubular burrows *(Planolites)* up to 10 cm long (Fig. 2). These burrows show varying degrees of deformation from simple, undistorted molds to highly deformed examples that are stretched around the curving contours of the pillows. Likewise, prod and other tool marks on pillow undersides show distortion. In places, pillows also display a ropy surface pattern that appears to be associated with flow of the silt during deformation. This pattern overprints sole marks in places and probably has eradicated some.

In addition to sharp sole marks, the bases of the pillows also display reticulate tension fractures. These form rhombohedral patterns a few centimeters across on the basal surfaces, which are infilled with silt matrix.

One horizon in the Rte. 11 roadcut shows examples of broken and tilted blocks of fine-grained grainstone (calcarenite)/packstone up to 70 cm long (Fig. 1D). These blocks are partially embedded in a clay matrix such that they can be exposed. Surfaces of these blocks show lamination weathered/eroded

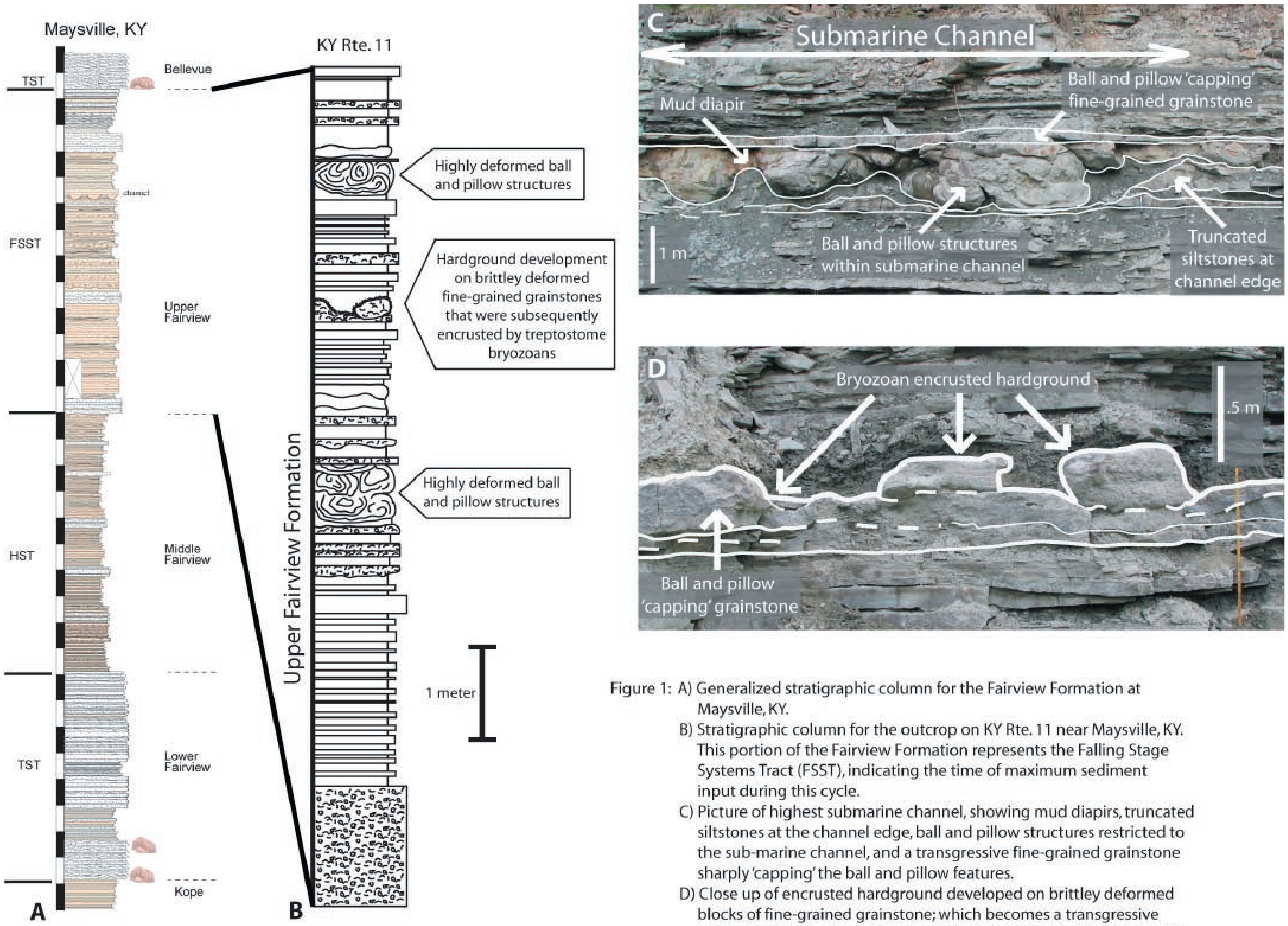


Figure 1: A) Generalized stratigraphic column for the Fairview Formation at Maysville, KY.
B) Stratigraphic column for the outcrop on KY Rte. 11 near Maysville, KY. This portion of the Fairview Formation represents the Falling Stage Systems Tract (FSST), indicating the time of maximum sediment input during this cycle.
C) Picture of highest submarine channel, showing mud diapirs, truncated siltstones at the channel edge, ball and pillow structures restricted to the sub-marine channel, and a transgressive fine-grained grainstone sharply 'capping' the ball and pillow features.
D) Close up of encrusted hardground developed on brittley deformed blocks of fine-grained grainstone; which becomes a transgressive channel 'cap' laterally along the outcrop and truncates ball and pillow structures.

Figure 2: The undersurface of a deformed siltstone bed displaying both deformed sole features and distorted burrow molds (*Planolites*), suggesting the sea floor was firm enough to preserve such features yet still able to behave plastically during deformation events.

out in relief as slight ridges. Blocks rest on a sharp, irregular encrusted hardground with a relief of up to 20 cm. The upper portions of this limestone appear to be similar in lithology to the blocks. Certain blocks, and the hardground itself, are encrusted by bryozoans, especially mat-like treptostomes and the large, fibrous holdfasts of ptilodictyid cryptostomes. The entire hardground and the blocks are covered and surrounded by soft clay-shale.

Interpretations of Process

Sole features demonstrate the firm consistency of the muds at and perhaps somewhat after the time of deposition. This is significant as the muds that originally underlay the siltstones were subsequently deformed and locally injected upward between the pillows to form mud diapirs (flame structures). Thus, evidence that the muds were initially firm, and even perhaps overcompacted, and yet subsequently became liquefied enough to flow, indicates that these muds were thixotropic.

Evidently, the erosive scour, associated with the initial deposition of the silt layers, did not produce liquefication of those muds. Removal of up to a meter of sediment in channels indicates that the channel bases should have been incised into overcompacted muds. Their subsequent liquefaction presumably required a strong disturbance: we postulate that seismic shaking provided the necessary vibration to liquefy the muds. At least one of the mud layers weathers as a sticky clay, suggesting the presence of smectite;

bentonitic composition may have played an important role in the thixotropic character of the muds.

The reticulate fracture structures are either a form of syneresis or perhaps were formed and infilled with silt during the initial shocking of the sediments. In the latter case, it is difficult to understand how the sharp form of the fracture fills was maintained during deformation if the subjacent mud was liquefied; to a lesser extent this is also an issue with preservation of sharp sole marks, although the sediment in the latter could have undergone incipient cementation prior to the deformation. One possibility is that the mud surface was stabilized with biomats prior to silt deposition and these helped to hold sediments in place (A. Seilacher, personal comm., 2007).

The tops of the pillows appear sharply truncated in several cases where they are abruptly overlain by undeformed beds of skeletal debris, including brachiopod valves and fragmentary bryozoans. The latter are apparently time-averaged accumulations, and they represent pauses in sedimentation following deposition and deformation of the silt beds.

It is evident that the deformed silt beds were eroded to nearly planar surfaces during these intervals. In rare cases examples of the peculiar "runzel mark" structure, Kinneyia, have been observed on upper truncated surfaces of the pillows. Such markings have been attributed to gas bubbles trapped between a sediment surface and a biomat (Pflueger, 1999). Thus, possibly mats of microbes were developed at times on the upper surfaces of the deformed sediments.

It is also clear that episodes of deformation produced not only ball-and-pillow type deformation but also brittle fracture of more indurated sediments. The blocks associated with a cemented calcarenite (fine-grained grainstone) above the middle ball-and-pillow deformed interval were apparently broken and slightly rotated. Their external surfaces show coarser skeletal layers in relief, while finer silt laminae are recessive as in modern weathered surfaces of laminated limestones. It is evident, however, that this weathering must have occurred in a submarine environment as the etched-out laminae are overgrown by encrusting bryozoans. What is most remarkable is that these bryozoans occur on all sides of the blocks and overgrow the weathered laminated surfaces of their broken lateral edges. This implies that, following a period of partial cementation, the blocks were broken and rotated somewhat, presumably by seismic shocks. Submarine erosion exposed the blocks, and their surfaces underwent a period of weathering-corrosion. The blocks must have been exposed as hardgrounds for substantial periods on the seafloor, as they were subject to colonization by encrusters. In places the blocks must even have been undercut, as bryozoan colonies sweep around from the upper to lower surfaces. Evidently, the blocks lay loose on a hard pavement during an interval of sediment starvation. Subsequently, the blocks and the hardground itself were buried by clay-rich sediments.

Summary and Environmental Implications

Synopsis of evidence for sedimentation, erosion, and paleothixotropy helps to elucidate the mechanism of deformation. Evidently, deposition of the upper Fairview pulses of mud sedimentation alternated with abrupt influxes of laminated silt, some of which appear to have been carried and deposited in submarine, storm-scour channels, as evidenced by the lense-like shape of such beds. Loading of this silt was not initially sufficient to cause deformation of the underlying muds, and indeed those muds were firm enough during deposition to sustain sharp scour marks and preserve burrows. The stacking of these denser siliciclastic and carbonate silt and sand on muds set up a density inversion that was potentially unstable. In the face of subsequent major seismic shocks the thixotropic mud supporting the heavier silt became liquefied and, particularly in areas of heavy loading, such as storm surge channels, this led to failure of the muds and their injection upward as local diapirs while the silt and sand beds foundered. Depending upon their consistency, these sediments either deformed plastically, if in a semi-indurated, state, or brittlely if in an indurated condition. The set-up for deformation occurred repeatedly in small-scale cycles during minor episodes of greatly increased sedimentation when the silt layers were deposited rapidly. We suggest that these record falling stages or regressions. These were followed by intervals of relative quiescence and sediment starvation and/or winnowing, possibly during minor transgressions. At these times the deformed beds were exposed on the seafloor, physically eroded and truncated, and finally covered by time-averaged skeletal debris. In the case of indurated hardground blocks, these remained more stably on the seafloor and were exposed to encrustation during the sediment-starved intervals. Finally, as siliciclastic sedimentation resumed, the eroded seafloors were blanketed by muds.

References Cited

McLaughlin, P.I., and Brett, C.E., 2004, Eustatic and tectonic controls on the distribution of marine seismites: examples from the Upper Ordovician of Kentucky, USA: Sedimentary Geology, v. 168, p. 165–192.

McLaughlin, P.I., and Brett, C.E., 2006. Widespread soft-sediment deformation horizons in Lower Silurian strata of the Appalachian Basin: Distal signature of orogeny: GFF (Geological Society of Sweden), v. 128, p. 169–172.

Pflueger, F., 1999, Matground structures and redox facies: Palaios, v. 14, p. 25–39.

Schumacher, G.A., 2001, Probable seismites in the Upper Ordovician Fairview Formation near Maysville, Kentucky, *in* Algeo, T.J., and Brett, C.E., eds., Sequence, cycle, and event stratigraphy of Upper Ordovician and Silurian strata of the Cincinnati Arch region: Kentucky Geological Survey, ser. 12, Guidebook 1, p. 112–116.

TAPHONOMY AND PALEOECOLOGY OF AN EDRIOASTEROID ENCRUSTED HARDGROUND IN THE LOWER BELLEVUE FORMATION AT MAYSVILLE, KENTUCKY

Colin D. Sumrall[1], Carlton E. Brett[2], Paula T. Work[1], and David L. Meyer[2]

[1]Geier Collections and Research Center, Cincinnati Museum Center, Cincinnati, OH 45202;
[2]Department of Geology, University of Cincinnati, Cincinnati, OH 45221-0013

INTRODUCTION

Hardgrounds provide unique opportunities to conduct *in situ* census-like assessments of non-transported fossils (Wilson and Palmer, 1992). A new hardground community from the Maysvillian (Upper Ordovician) offers a glimpse into hard substrate communities on the eastern flank of the Cincinnati Arch. In this paper, we will describe the taphonomic implications of faunal components and the utilization of surface area for colonization by an edrioasteroid dominated hardground community preserved at the time of burial.

Recently, a heavily encrusted hardground horizon, whose unique terminal community includes four species of edrioasteroids (Echinodermata) and several species of large encrusting bryozoans, was discovered in the rubbly limestones about seven meters above the base of the Bellevue Member of the Grant Lake Formation in a set of new roadcuts along State Rte. 3071 near Maysville, Mason County, Kentucky. Subsequent search showed that the same hardground occurred in several nearby outcrops within two kilometers of the original discovery site. It has not been traced further, although occurrence of similar rare species of edrioasteroids in a railroad cut near Maysville (Bassler and Shideler, in Bassler, 1936) suggests that the surface may be exposed there as well.

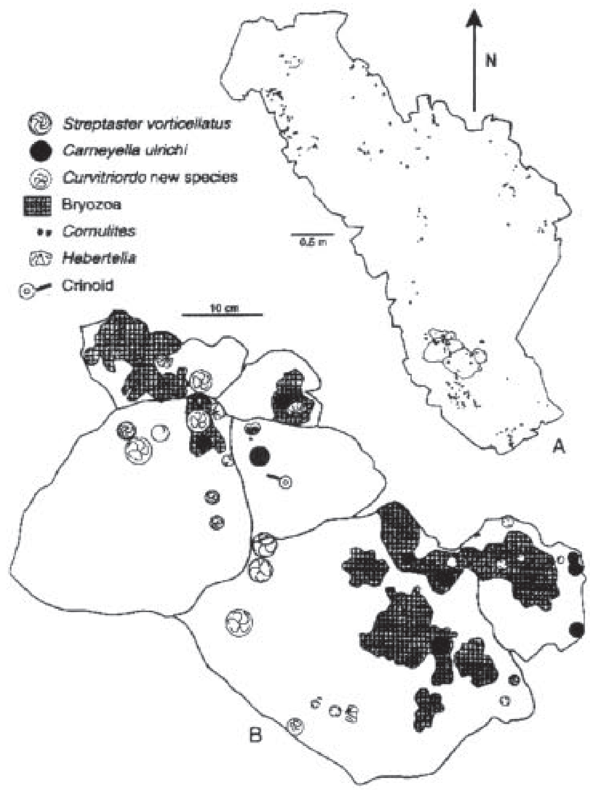


Figure 1. (A) Mapped distribution of edrioasteroids on the slab surface; individual pieces of slab are shown as polygons. Note that small pockets of edrioasteroids are vaguely aligned along N-S trends. (B) Detail of hardground surface illustrating the distributions of the members of the terminal community. Note that *Carneyella ulrichi* and *Curvitriordo* nov. sp. are attached to both bryozoans and the hardground surface and that there is no preferred orientation of specimens.

MATERIALS AND METHODS

During the fall and winter of 1998-1999, some five square meters of the hardground surface were excavated and collected for laboratory preparation (Fig. 1). Recovered slabs were oriented, cleaned and reassembled so that the surface spatial relationships of the hard substrate fauna could be studied. All edrioasteroid specimens were identified, located on a grid, and measured. The surface was also mapped to determine distribution patterns of the edrioasteroids and other fossils and this buried fauna or "terminal community" was compared with the "background community" represented by variably disarticulated and corroded material on and embedded in the hardground surface. These observations provide significant insights into the nature and distribution of an Upper Ordovician hard substrate community.

GEOLOGIC SETTING

The hardground horizon occurs about seven meters above the base of the Bellevue Formation exposed on the second highest bench in the road cut (Fig. 2). It occurs on the top of a series of beds between 10 and 25 cm in thickness that range from clay-rich, rubbly skeletal packstones to grainstones interbedded with thinner, more compact beds of grainstones and packstones. Most have sharp bases and sharp, irregular tops. A number of bed tops exhibit features such as sharp, irregular relief, staining, borings and/or encrusting organisms, indicative of firmground or hardground development.

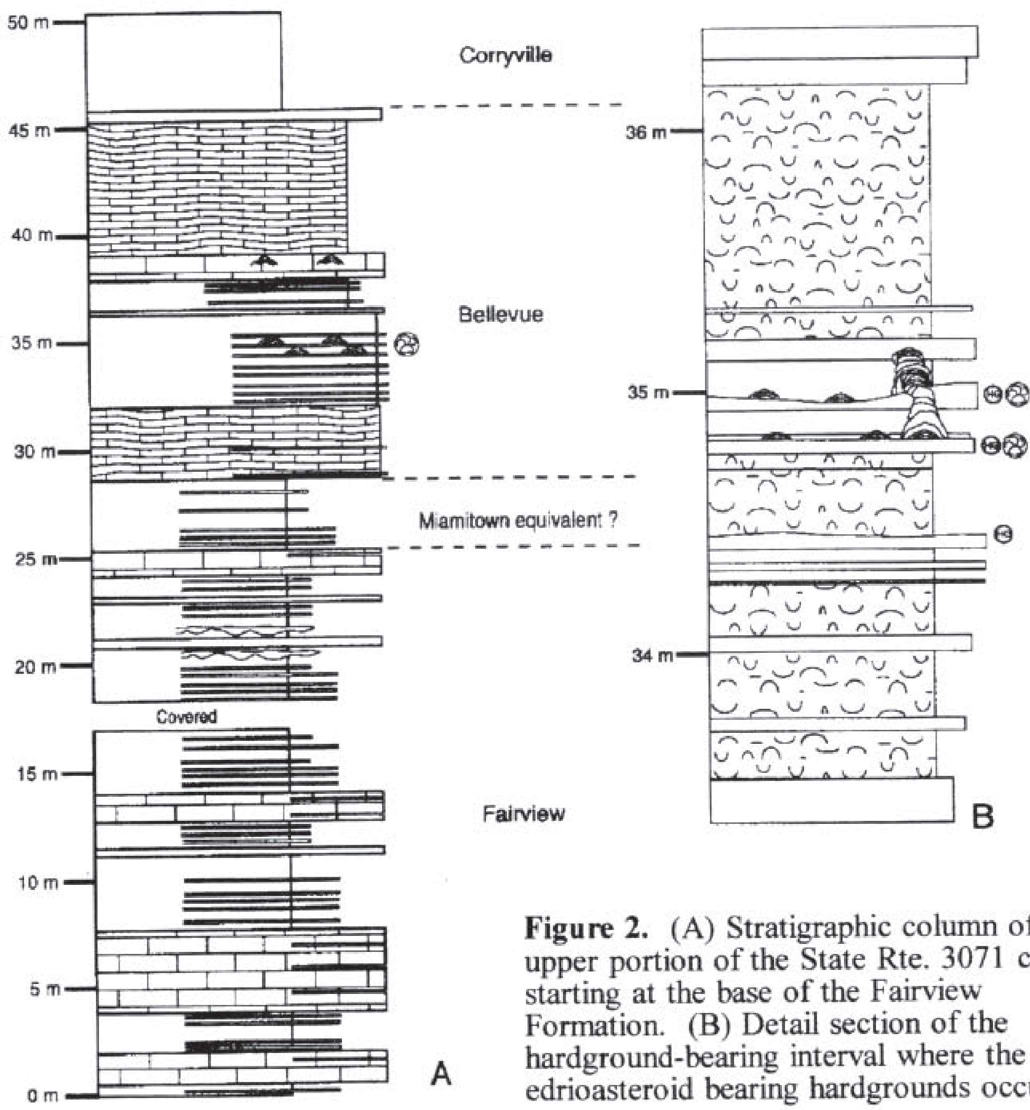


Figure 2. (A) Stratigraphic column of the upper portion of the State Rte. 3071 cut starting at the base of the Fairview Formation. (B) Detail section of the hardground-bearing interval where the two edrioasteroid bearing hardgrounds occurred.

Using the stratigraphic definitions of Schumacher (1992, 1998), these beds are assigned to the lower Bellevue Member of the Grant Lake Formation. They abruptly overlie a series of shales and thin to medium bedded limestones typically referred to the upper Fairview, but possibly correlative with the Miamitown Shale of Ohio. The Bellevue contact, in turn, occurs about 10 m above the base of an interval of distinctive ball-and-pillow deformation (possible seismites) in the upper Fairview Formation (Schumacher, 1992). The hardground interval falls within the middle of the Maysvillian Stage of the Cincinnatian series; its age is thus estimated to be about 440 Ma.

During Maysvillian time, the region of the eastern flank of the Cincinnati Arch is thought to have been a gently north sloping ramp flanking the Lexington Platform, a relatively positive area, possibly associated with a forebulge produced by load induced flexure (see Ettensohn, 1992). To the south, the Bellevue grades into very shallow subtidal shoal deposits of the Calloway Creek Formation in the area of the Lexington Platform; to the northwest relatively deeper conditions are recorded by the appearance of shaly tongues within the Bellevue. The Bellevue grades laterally into thin, shaly, nodular limestones and shales in the subsurface about 40 km north of Cincinnati. This suggests that a remnant of the Sebree Trough, a narrow northeast-southwest trending deep water area developed during Edenian time, was still present at this time (Hay, 1998; Dattilo, 1998). During the Maysvillian, continued tectonism associated with the Taconic Orogeny affected eastern Laurentia. Taconic uplifts supplied muds and silts to the interior seaway. This region lay about 0-25° south of the paleoequator (Scotese, 1990). Abundant tempestites of various types (see Tobin and Pryor, 1981; Jennette and Pryor, 1993) indicate that the region was affected by episodic large tropical storms that reworked sediment and in some instances resuspended muds. Silts and muds were transported downslope and rapidly deposited as mud tempestites. Substantial times of non-deposition are recorded at the sharp diastemic contacts of many shell-rich beds, including the hardgrounds described herein. The Bellevue facies was probably deposited slightly below normal wavebase (~5-10 m) but well within reach of storm waves. The preservation of thin muddy layers, such as that which buries this hardground, suggests normally low energy conditions, but interbedded graded pack- and grainstone beds, some with wave ripples, indicate occasional high energy stirring of sea floor sediments (Schumacher, 1992). Occurrence of cyclocrinitids (dasycladacean green algae; Beedle and Johnson, 1986; Beedle, 1988; Brett et al., 1993) in the Fairview and Bellevue (some found about 2.7 m above the hardground; S. Felton, pers. comm.) indicates deposition of these sediments in the upper part of the photic zone, probably in about 10-20 meters of water.

HARDGROUND CHARACTERISTICS AND FAUNA

The Maysville hardground is developed on the upper surface of a brachiopod-rich packstone bed that ranges from at least two to ten centimeters in thickness and may pinch out completely in one area. The limestone contains abundant, large valves of *Platystrophia ponderosa,* in varied stages of preservation from complete and unaltered to heavily corroded and bored remnants. Most of the hardground surface itself shows relatively minor relief although a small scarp about 2 cm high is present along the edge of the excavated slab. The entire surface is irregular on a centimeter high scale with lots of irregular anastomozing raised areas suggestive of interference ripples. Edrioasteroids and other encrusting fossils occur on a small fraction (less than 1 percent) of the total surface area and yet are clustered primarily into vaguely elongate north-south oriented patches along the surface (Fig. 1). Bryozoans on the surface are generally encrusting forms which in some areas form lips where they apparently overgrew mud on the surface of the hardground. Some surface areas are riddled with *Trypanites* type borings. These borings are generally associated with areas colonized by bryozoans and typically penetrate the bryozoan and extend through the hardground bed.

The Maysville hardground was overlain in places by yellowish-weathering calcisiltite up to 5 mm thick. This material includes buried edrioasteroids and other members of the terminal community (Fig. 3). Edgewise brachiopod valves also occur in this matrix, indicating stirring of coarser sediments in the final burial event. This calcisiltite bed is overlain by 2-5 cm of clay shale. Some portions of this shale have proven to be more or less barren, while other shale samples yielded abundant brachiopod valves and a phosphatic microfauna (mainly steinkerns of tiny gastropods and conodonts) and an exceptionally rich assemblage of scolecodonts including 52 form taxa (R. Fuchs, pers. comm.). This mudstone layer shows indistinct burrows, which in a few instances penetrated down to and disrupted plates of buried edrioasteroids and in other cases encircled them (Fig. 3.9).

The hardground fauna is dominated by about three species of trepostome bryozoans. The bryozoan colonies are large (1 to 40 cm across) irregular mounds, some of which have flat sided carinae (keels) that may project several centimeters above the hardground surface (Fig. 3.6). Other faunal elements include: brachiopods *(Hebertella occidentalis, Platystrophia ponderosa, Petrocrania scabiosa)*, cyclostome bryozoans *(Cuffeyella* sp.), annelid worms *(Cornulites* sp.), crinoids *(Cincinnaticrinus* sp.), and edrioasteroids *(Carneyella ulrichi, Carneyella pilea, Curvitriordo* new species? and *Streptaster vorticellatus)*.

The four species of edrioasteroids, although locally abundant (up to 50 individuals per square meter), comprise a unique community dominated by rare forms, both in terms of species composition and specimen size (Table 1). *Carneyella ulrichi* (Fig. 3.1) was previously known from a single specimen. The species of *Curvitriordo* (Fig. 3.2) is new and several specimens of *Streptaster vorticellatus* (Fig. 3.3) are among the largest known for their species reaching 25 mm in thecal diameter. Large and small edrioasteroids are attached to bryozoans and

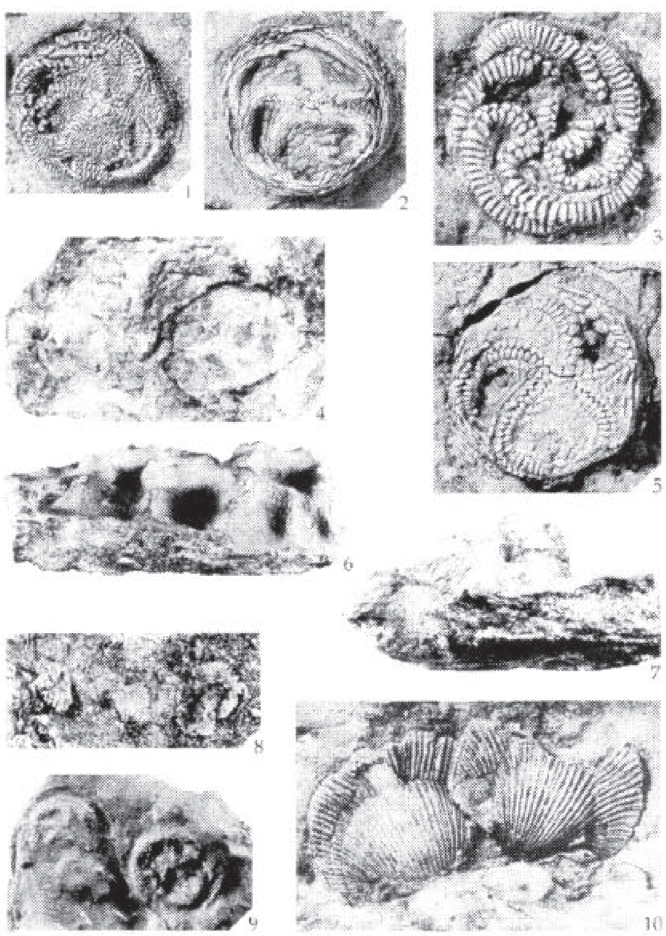


Figure 3. Edrioasteroids and other fauna of the Maysville Hardground. (1) Mature specimen of *Carneyella ulrichi.* Note surface covered with large pustules and wide abulacra, X2. (2) Mature specimen of *Curvitriordo* n. sp. Note narrow ambulacra, X1.25. (3) Mature specimen of *Streptaster vorticellatus.* Note extremely wide and high ambulacra, X2.25. (4) Slab surface showing corroded skeletal debris and a *Cincinnaticrinus* holdfast, X0.5. (5) Mature specimen of *Carneyella pilea.* Note wide ambulacra and lack of large pustules, X3. (6) Oblique view of carinate bryozoan colony, X0.5. (7) Oblique view of bryozoan colony overgrowing broken edge of hardground, X1. (8) View of a cryptic assemblage in a cavity. *Carneyella ulrichi* left, small bryozoan center, *Petrocrania scabiosa* right, X2. (9) Two specimens of *Carneyella ulrichi* encircled by burrow, X0.75. (10) Two specimens of *Hebertella* articulated and in life position attached to a bryozoan. Both specimens have epifauna encrusted on them, X2.

less commonly directly to the hardground. Several juvenile edrioasteroids, however, are attached to brachiopods in life position. A cryptic fauna occurs beneath an overhang formed by the binding of skeletal debris by a large encrusting bryozoan, with an edrioasteroid, bryozoan, and *Petrocrania* all growing into the cavity (Figure 3.8).

Table 1. Numbers of edrioasteroid species present on main hardground.

Streptaster vorticellatus	9
Carneyella ulrichi	107
Carneyella pilea	2
Curvitriordo n. sp.	92

DISCUSSION

Taphonomic aspects: Hardgrounds are diastemic surfaces whose very existence indicates prolonged breaks in sedimentation. The taphonomy of the fossils immediately overlying the Maysville hardground support this. The abundance of phosphatized fossil steinkerns, conodonts, and chitinous scolecodonts in some samples of shale directly adherent to the hardground suggest that the surface was partially overlain by a thin, condensed lag deposit of worm jaws and other geochemically resistant debris which gradually accumulated on the hardground surfaces. Barren shale samples, also recovered from the site, may represent rapidly deposited obrutionary muds.

Hardground cementation is thought to occur somewhat below a sediment-water interface in the zone of sulfate reduction where alkalinity buildup promotes precipitation of carbonate cements (Wilson and Palmer, 1992). The exposure of a hardground pavement, therefore, requires erosional removal of at least a few centimeters of sediment. The rarity of encrusted hardgrounds in the Cincinnatian as a whole may reflect rates of mud accumulation that were typically too high for prolonged exposure. Even in this example, there is evidence that for much of the time, the surface was not fully exposed, despite low net rates of accumulation. Most surface areas are nearly planar, though uneven, with few pockets or corrosion pits. The surface does not show dark staining and *Trypanites* borings are rare in most areas, suggesting that the surface may have been covered by a thin film of sediment much of the time. Furthermore, many edrioasteroids occur on the slightly elevated sides of the bryozoan colonies, not directly on the paleo-sea floor, and the occurrence of juvenile edrioasteroids (late recruits) on brachiopods and bryozoans may indicate that the hardground itself was at least partially mud covered prior to its final burial. That these newly settling edrioasteroids attached to small, suboptimal hard substrates while most of the hardground itself is clean of epibionts strongly suggests that a mud blanket covered much of the surface.

Emplacement of the final mud layer was obviously rapid. Fragile imbricated skeletons of edrioasteroids clearly could only be preserved if they were buried very rapidly after death or were buried alive by sediment (Brett et al., 1997). We surmise that the final depositional pulse probably came in the form of a suspended flow of mud or mud tempestite. SEM studies of similar muds enclosing fragile fossils have shown that in most cases the muds were flocculated and therefore settled as rapidly as silt or even fine sand-sized particles (of clay density) (O'Brien et al., 1994, 1998). It is clear that the burial mud blanket was not particularly thick, probably not more than about ten centimeters uncompacted. Post burial burrowing organisms were able to penetrate downward to the hardground and slightly disrupt some of the entombed carcasses or pass around the perimeter of others.

Biological aspects: As noted, the bryozoans form large mound-like and often carinate (keeled) colonies, that may extend upward for over eight cm above the hardground surface. In several instances a bryozoan colony appears to have survived the burial event and extended upward from a lower hardground 11 centimeters below the one described here in detail, and continued through the deposition of the sediment that comprises the main hardground and upwards into the overlying thin shale and fossil packstone layer. Morphology of these bryozoan colonies shows that they cantilevered outward onto the packstone or mud layers indicating that they survived episodes of partial burial and regrew. Such evidence not only

Table 2. Comparison between *Platystrophia* and *Hebertella*. Note that *Platystrophia* valves show nearly a 5:1 ratio between pedicle and brachial valves whereas *Hebertella* exhibits roughly a 1:1 ratio. The anomalously high number of uncorroded brachial valves for *Hebertella* may reflect a misidentification of articulated specimens in life position.

	Platystrophia			*Hebertella*		
	pedicle	*brachial*	*life pos.*	*pedicle*	*brachial*	*life pos.*
broken and corroded	18	3	--	5	1	--
broken not corroded	4	0	--	14	10	--
corroded	60	4	--	18	2	--
slightly corroded	19	5	--	22	12	--
not corroded	6	10	--	17	53	--
	-----	----	----	----	----	----
Total	107	22	19	76	78	26

attests to the persistence of colonies through adverse conditions but also help to bracket the approximate duration of beds immediately overlying the hardground (only a few centuries at most). It also suggests that the keeled growth form of the colony may have been adaptive in preventing complete smothering by mud layers. As it seems unlikely that organisms could adapt to infrequent and unpredictable obrutionary events, we suggest that this was an adaptation to life in environments that were normally prone to some mud deposition.

Edrioasteroids and other encrusters are not evenly distributed on the slab surface, rather they are highly clumped and aligned following a vaguely north-south trend (Fig. 1A). Distributions of other faunal elements smothered by the same obrutionary event are highly correlated with edrioasteroid placements. We surmise that these may follow very shallow, gutter-like scours which stripped silt and mud off the hardground and provided elongate areas of exposed hard pavement for colonization. The N-S trend of colonized areas is consistent with the direction of gutter casts measured in the Upper Kope Formation and may reflect the direction of paleoslope (Jennette and Pryor, 1993). Other nonencrusted portions of the surface may have been covered by sediments which precluded colonization. The morphology of the bryozoans which over-grew the mud confirms this supposition (Fig. 3.7).

Preservational differences of fossils allow "live vs. dead" counts of skeletonized organisms on the surface (Table 2), and may also point to prolonged sediment starvation and reworking of skeletal material. For example, articulated, spar-filled, and *in situ* brachiopods (Fig. 3.10) are assumed to come from the terminal community, i.e., the population that encrusted the surface immediately before burial; whereas variably disarticulated, fragmented, and corroded specimens may be counted among the background, time averaged death assemblage. Comparison of counts of these two constituents of the fossil assemblage, suggest that the time-averaged death assemblage was much richer in *Platystrophia* than the terminal community found articulated and/or attached directly to the hardground at the time of burial. This terminal community appears to have been dominated by *Hebertella* with slightly lesser numbers of *Platystrophia*. The death assemblage, however, is enriched with the more robust pedicle valves of *Platystrophia* to nearly a 5:1 ratio. Since in life the ratio of pedicle to brachial valves is 1:1, this enrichment suggests a strong bias due to prolonged mechanical reworking. This sharply differs from the 1:1 ratio of disarticulated *Hebertella* valves suggesting that the thinner *Hebertella* valves are more subject to fragmentation and therefore underrepresented in the death assemblage. This too points to a period of little or no sediment aggradation and low burial rates, prior to the final obrutionary event. It also suggests that conditions were not entirely "low energy" as most of the more fragile skeletal remains have been fragmented and corroded to form debris.

A number of edrioasteroid beds have been reported previously from the Cincinnatian of the Cincinnati Arch region (Kesling and Mintz, 1960; Meyer, 1990; Datillo, 1998). However, the Maysville occurrence is distinct from the others in several aspects. Most previously reported edrioasteroid occurrences have been derived mainly from the Miamitown and Corryville shaly intervals, which lie respectively slightly below and above the present horizon. These assemblages were dominated by the edrioasteroids *Isorophus,* and *Carneyella* while *Streptaster* occurs only very rarely. *Curvitriordo* is virtually absent from these faunas. Previously described Cincinnatian edrioasteroid beds were mainly associated with pavements of *Rafinesquina* brachiopods rather than true hardgrounds (Meyer, 1990). Such pavements may have been stabilized by early cementation (Rassman, 1981) but in no cases were edrioasteroids found directly encrusting limestone surfaces.

For the *Carneyella-Curvitriordo* assemblage, all species were spatially intermingled, with no species demonstrating a preference for type of substrate attachment or height above substrate (Fig. 1B). This suggests that there was little interspecific competition among them. Indeed, all three genera belong to different edrioasteroid families and all show substantially different abulacral morphology suggesting distinct food gathering techniques. The community, however, appears to have been spatially limited, this despite the fact that more than 99% of the hardground surface is clean of encrusters. The same appears to be true for juvenile recruitment. Although juveniles were not found for all species, those which were present showed no selective substrate preference, occurring on brachiopods, bryozoans and in one case on the hardground surface.

The *Carneyella-Curvitriordo* assemblage may have been specifically adapted to encrusting hard, relatively smooth surfaces as opposed to brachiopod shells. Although a few specimens were found attached to brachiopods, the majority were either on bryozoans or directly on the hardground. The prevalence of these species on the Maysville hardground records both a taphonomic and an ecological epibole (*sensu* Brett et al., 1997). Obviously, specific occurrences of any edrioasteroid assemblage reflects rapid smothering by muds. However, this cannot explain the difference in taxonomic composition nor substrate behavior of the Maysville vs. other Cincinnatian edrioasteroid occurrences. We suggest that this assemblage represented a suite of opportunistic species adapted to shallower water hardgrounds. The brachiopod pavements occurring in the Miamitown and Corryville developed in somewhat deeper water below common storm wavebase. Here pavements of larger shells evidently provided sufficient stability for survival of isorophids. In shallower, somewhat agitated settings represented by the Bellevue, attachment to dead skeletal material may not have afforded adequate stability. Thus, edrioasteroids being relatively sensitive to reorientation, would have required larger surfaces, such as bryozoans, hardgrounds, or firmly attached live brachiopods for stable settlement. *Platystrophia* and *Hebertella* were probably rather nonselective, heavier, pedically attached hard substrate forms that could have attached to a variety of substrates from shells to hardgrounds or even have been free resting at times (Richards, 1972). Their thickened umbones may have given these organisms a low center of gravity with a stability akin to weebles (A. Seilacher, pers. comm.).

In any case, these edrioasteroids may have been adapted to life on hardgrounds that developed more commonly in other, shoal-marginal environments; such environments probably had much poorer preservation potential. Thus, the very conditions (e.g., higher energy, low sedimentation rate) which favored this suite of edrioasteroids, also may have mitigated against their preservation and only rare (but sometimes dense) outlier populations such as this one are preserved.

In this instance, erosional exposure of a hardground/bryozoan ground substrate provided a narrow window of opportunity for colonization maturation and perhaps minor recruitment of a new generation. The brief colonization episode was abruptly terminated by a pulse of mud sedimentation that smothered the hardground and its faunas over an area of at least a few square kilometers.

ACKNOWLEDGMENTS

We would like to thank D. Cooper, S. Felton, and T. Bantell of the Dry Dredgers and S. Cornell, F. Gahn at the University of Cincinnati for their help in the field. R. Fuchs of the Dry Dredgers identified the scolecodont assemblage that was recovered from the obrutionary mud.

REFERENCES

Bassler, R.S., 1936, New species of American Edrioasteroidea: *Smithsonian Miscellaneous Collections,* v. 95, p. 1-33.

Beadle, S.C., 1988, Dasyclads, cyclocrinitids, and receptaculitids: Comparative morphology and paleoecology: *Lethaia,* v. 21, p. 1-12.

Beadle, S.C., and Johnson, M.E., 1986, Paleoecology of Silurian cyclocrinitid algae: *Palaeontology,* v. 29, p. 585-601.

Brett, C.E., Boucot, A.J., and Jones, B., 1993, Absolute depths of Silurian benthic assemblages: *Lethaia,* v. 26, p. 25-40.

Brett, C.E., and Baird, G.C., 1997, Epiboles, outages, and ecological evolutionary bioevents: Taphonomic, ecological, and evolutionary factors. In: Brett, C.E., and Baird, G.C., eds., *Paleontological Events: Stratigraphic, Ecological, and Evolutionary Implications:* New York, Columbia University Press, p. 249-285.

Brett, C.E., Moffat, H.A., and Taylor, W.L., 1997, Echinoderm taphonomy, taphofacies, and Lagerstätten. In: Waters, J.A., and Maples, C.G., eds., *Geobiology of Echinoderms:* Paleontological Society Papers, v. 3, p. 147-190.

Dattilo, B.F., 1998, The Miamitown Shale: Stratigraphic and historic context (Upper Ordovician, Cincinnati, Ohio, region). In: Davis, R.A., and Cuffey, R.J., eds., *Sampling the Layer Cake That Isn't: The Stratigraphy and Paleontology of the Type-Cincinnatian:* Ohio Division of Geological Survey, Guidebook No. 13, p. 49-59.

Ettensohn, F.R., 1992c, General Ordovician paleogeographic and tectonic framework for Kentucky. In: Ettensohn, F.R., ed., *Changing Interpretations of Kentucky Geology: Layer Cake, Facies, Flexure, and Eustasy:* Ohio Division of Geological Survey, Miscellaneous Report 5, p. 19-21.

Hay, H.B., 1998, Paleogeography and paleoenvironments, Fairview through Whitewater formations (Upper Ordovician, southeastern Indiana and southwestern Ohio). In: Davis, R.A., and Cuffey, R.J., eds., *Sampling the Layer Cake That Isn't: The Stratigraphy and Paleontology of the Type-Cincinnatian:* Ohio Division of Geological Survey, Guidebook No. 13, p. 120-134.

Jennette, D.C., and Pryor, W.A., 1993, Cyclic alternation of proximal and distal storm facies: Kope and Fairview formations (Upper Ordovician), Ohio and Kentucky: *Journal of Sedimentary Petrology,* v. 63, p. 183-203.

Kesling, R.V., and Mintz, L.W., 1960, Internal structures in two edrioasteroid species, *Isorophus cincinnatiensis* (Roemer) and *Carneyella pilea* (Hall): *University of Michigan Museum of Paleontology Contributions,* v. 15, p. 315-348.

Meyer, D.L., 1990, Population paleoecology and comparative taphonomy of two edrioasteroid (Echinodermata) pavements: Upper Ordovician of Kentucky and Ohio: *Historical Biology,* v. 4, p. 155-178.

O'Brien, N.R., Brett, C.E., and Taylor, W.L., 1994, Microfabric and taphonomic analysis in determining sedimentary processes in marine mudstones: Example from the Silurian of New York: *Journal of Sedimentary Research,* v. A64, p. 847-852.

O'Brien, N.R., Brett, C.E., and Woodard, M.J., 1998, Shale fabric as a clue to sedimentary processes: Example from the Williamson-Willowvale Shales (Silurian), New York. In: Schieber, J., Zimmerle, W., and Sethie, P.S., eds., *Shales and Mudstones, Vol. 2: Petrography, Petrophysics, Geochemistry, and Economic Geology:* Stuttgart, E. Schweizerbart'sche, p. 55-66.

Rassman, B., 1981, *A Sedimentological Comparison of Two Dissimilar Ordovi-*

cian Edrioasteroid Pavements (Hardgrounds): M.S. thesis (unpubl.), University of Cincinnati, 224 p.

Richards, R.P., 1972, Autecology of Richmondian brachiopods (Late Ordovician of Indiana and Ohio): *Journal of Paleontology,* v. 46, p. 386-405.

Schumacher, G.A., 1992, Lithostratigraphy, cyclic sedimentation, and event stratigraphy of the Maysville, Kentucky area. In: Ettensohn, F.R., ed., *Changing Interpretations of Kentucky Geology: Layer Cake, Facies, Flexure, and Eustasy:* Ohio Division of Geological Survey, Miscellaneous Report 5, p. 165-172.

Schumacher, G.A., 1998, A new look at the Cincinnatian Series from a mapping perspective. In: Davis, R.A., and Cuffey, R.J., eds., *Sampling the Layer Cake That Isn't: The Stratigraphy and Paleontology of the Type-Cincinnatian:* Ohio Division of Geological Survey, Guidebook No. 13, p. 111-119.

Scotese, C.R., 1990, *Atlas of Phanerozoic Plate Tectonic Reconstructions, International Lithophase Program (IUGG-IUGS):* PaleoMap project technical report no. 10-90-1.

Tobin, R.C., and Pryor, W.A., 1981, Sedimentological interpretation of an Upper Ordovician carbonate-shale vertical sequence in northern Kentucky. In: Roberts, T.G., ed., Geological Society of America, *1981 Annual Meeting Field Trip Guidebooks. Vol. I: Stratigraphy and Sedimentology:* Falls Church, Virginia, American Geological Institute, p. 1-10.

Tobin, R.C., and Pryor, W.A., 1985, Cincinnatian Series: Model for cyclic and episodic deposition of carbonates and shales on a storm-dominated ramp (abstract): *American Association of Petroleum Geologists Bulletin,* v. 69, p. 311-312.

Wilson, M.A., and Palmer, T.J., 1992, Hardgrounds and hardground faunas: *University of Wales, Aberystwyth, Institute of Earth Studies Publications,* v. 9, p. 1-131.

Preceding paper reprinted from Algeo, T.J., and Brett, C.E., eds., 1999, Sequence, cycle, and event stratigraphy of Upper Ordovician and Silurian strata of the Cincinnati Arch region (field trip guidebook in conjunction with the 1999 field conference of the Great Lakes Section SEPM-SSG (Society for Sedimentary Geology) and the Kentucky Society of Professional Geologists, October 8–10, 1999): Kentucky Geological Survey, ser. 12, Guidebook 1, 152 p. Reprinted with the permission of the Kentucky Geological Survey.

John Filson was a pioneer and explorer, born in Chester County, Pa., in 1747. He purchased a one-third interest in the site of Cincinnati, which was later called Losantiville. While exploring the area in 1788, he disappeared and was reported killed by hostile Indians.

The entire map made in 1793 has been reproduced by the Kentucky Geological Survey to accompany "John Filson of Kentucke" by John Walton, published by the University of Kentucky Press, 1956. A copy is stored in the Map and Archive Library, M.I. King Library, University of Kentucky, Lexington, Ky.

It can also be viewed at www.goldbug.com/digitalmaps.html.

Reproduction courtesy of the Kentucky Geological Survey. To accompany "John Filson of Kentucke" by John Walton, Published by the University of Kentucky Press, 1956.