Reports

Trace Fossils from the Athabasca Oil Sands, Alberta, Canada

Abstract. *A diverse and well-preserved ichnofossil suite has been identified from surface exposures of the middle and upper parts of the Lower Cretaceous McMurray Formation. The suite, consisting of representatives of at least ten ichnogenera, is one of the few clues to the original biotic component of the deposit. The distribution and abundance of these biogenic structures present strong evidence that the deep channel complex in which the sediments were deposited was closely associated with a nearby marine shoreline.*

Of the four major Cretaceous oil sands deposits in Alberta (Athabasca, Cold Lake, Wabasca, and Peace River), the Athabasca deposit is by far the largest, with estimated in-place reserves of 922 billion barrels of bitumen (*1*). It is also unique in that it crops out (in places) at the surface as an oil sands reservoir, which facilitates surface mining. Virtually all the bitumen reserves are contained within the Lower Cretaceous McMurray Formation, which comprises 35 to 70 m of uncemented quartz sand and associated shale, with rare interbedded ironstones and coals. In most of the outcrop region the McMurray Formation is oil-bearing from the top to the base (*2*). Porosity in the cleaner sands generally ranges between 20 and 35 percent, and oil saturation of 10 to 18 percent by weight is common (*3*).

Because the sands have suffered very little postdepositional textural change (cementation, clay authigenesis, pressure solution, and so on), the porosity or permeability patterns in the reservoir can be viewed as a direct function of the primary facies distribution of sediments. Therefore, achieving a firm understanding of the depositional environments is the most important step in attempting to map and project zones containing high-grade bitumen. Problems have arisen, however, in interpreting the complex environmental regimes responsible for depositing sediments of the McMurray Formation. During the past several years, numerous independent studies have yielded conflicting conclusions (*2–4*).

One of the major factors contributing to this confusion is the almost total lack of traditional paleontological control. Aside from rare pieces of wood and molluscan shell hash, the formation is virtually barren, inhibiting precise paleoenvironmental reconstructions based on body fossils. We report here a well-preserved ichnofossil suite which represents one of the few strong clues to the biological component of the formation and the associated environmental conditions. Specimens of at least ten ichnogenera have been identified—including *Bergaueria*, *Cylindrichnus*, ?*Dolopichnus*, *Lockeia*, *Monocraterion*, *Palaeophycus*, *Planolites*, ?*Rosselia*, *Skolithos*, *Teichichnus*, and vertical escape structures—as well as numerous units in which distinct forms are difficult to discern because of bioturbation (disruption by the activity of organisms).

In the Fort McMurray area virtually all the surface exposures of the McMurray Formation are located along the banks of the Athabasca River and its tributaries (Fig. 1). These rivers are incised into the surrounding plateau by as much as 120 m, exposing Upper Devonian strata (the Moberly Member of the Waterways Formation) at or about river level, with 35 to 70 m of cliff-forming McMurray Formation strata above, and recessive Clearwater Formation shales on top. A series of excellent outcrop exposures located along the lower portions of the Steepbank River valley provide a good starting point for detailed surface work. Most of these sections exhibit the facies sequence schematically depicted in Fig. 2: (i) thick-bedded to massive sands at the base, characterized throughout by trough cross-stratification; (ii) a central sequence dominated by large-scale solitary sets of inclined strata, up to 25 m thick, referred to by the nongeneric term epsilon cross-strata; and (iii) an upper unit consisting of horizontally bedded argillaceous sands and silts, which gives way to the recessive weathering strata of the Clearwater Formation above (*2, 3*). Ichnofossils are abundant in the middle and upper units of the sequence.

The epsilon cross-strata (Fig. 3A) consist of a repetitious sequence of sand and

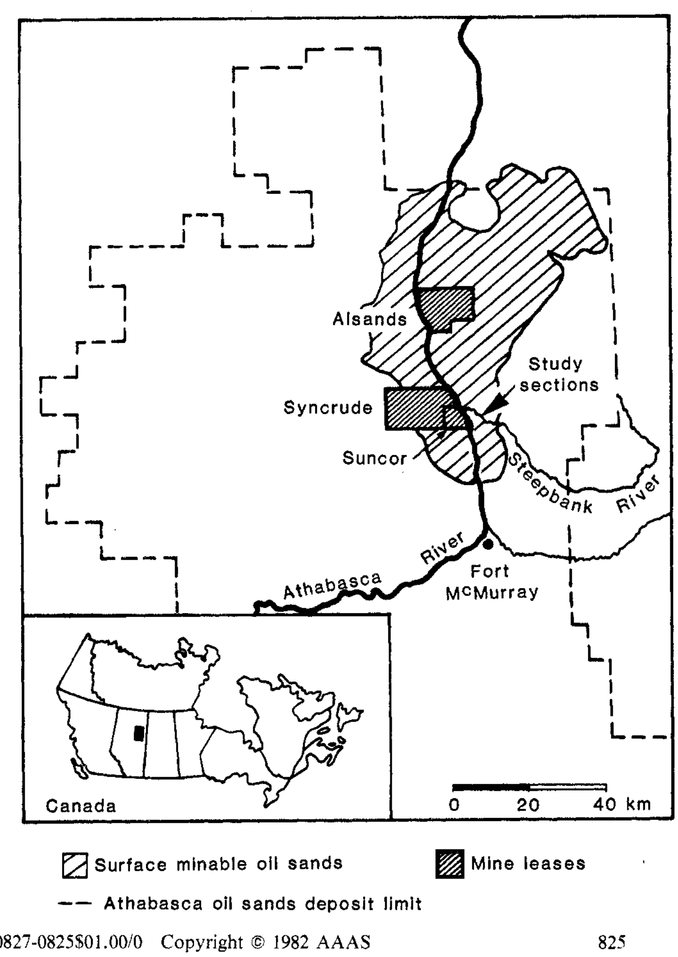

Fig. 1. Location of the Athabasca oil sands deposit, showing the extent of surface minable regions and major mining leases.

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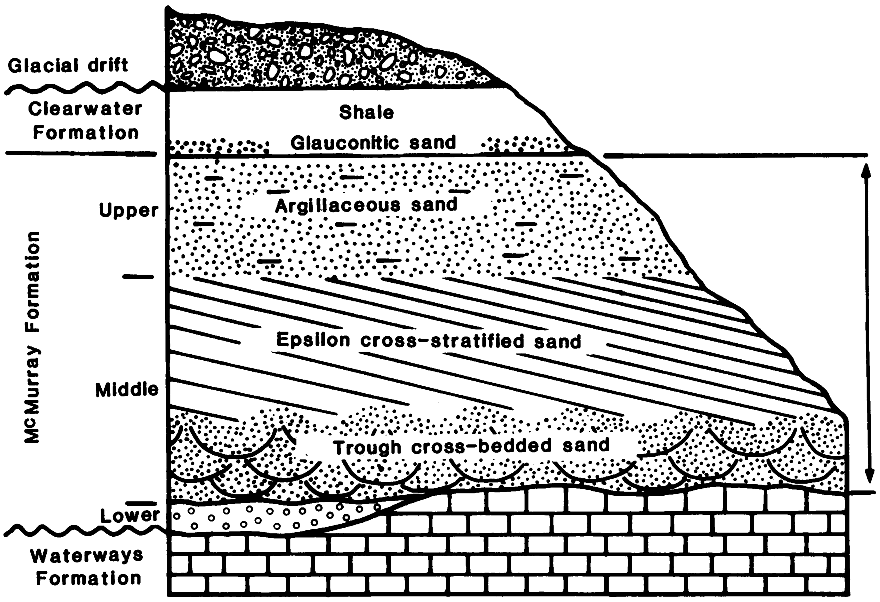
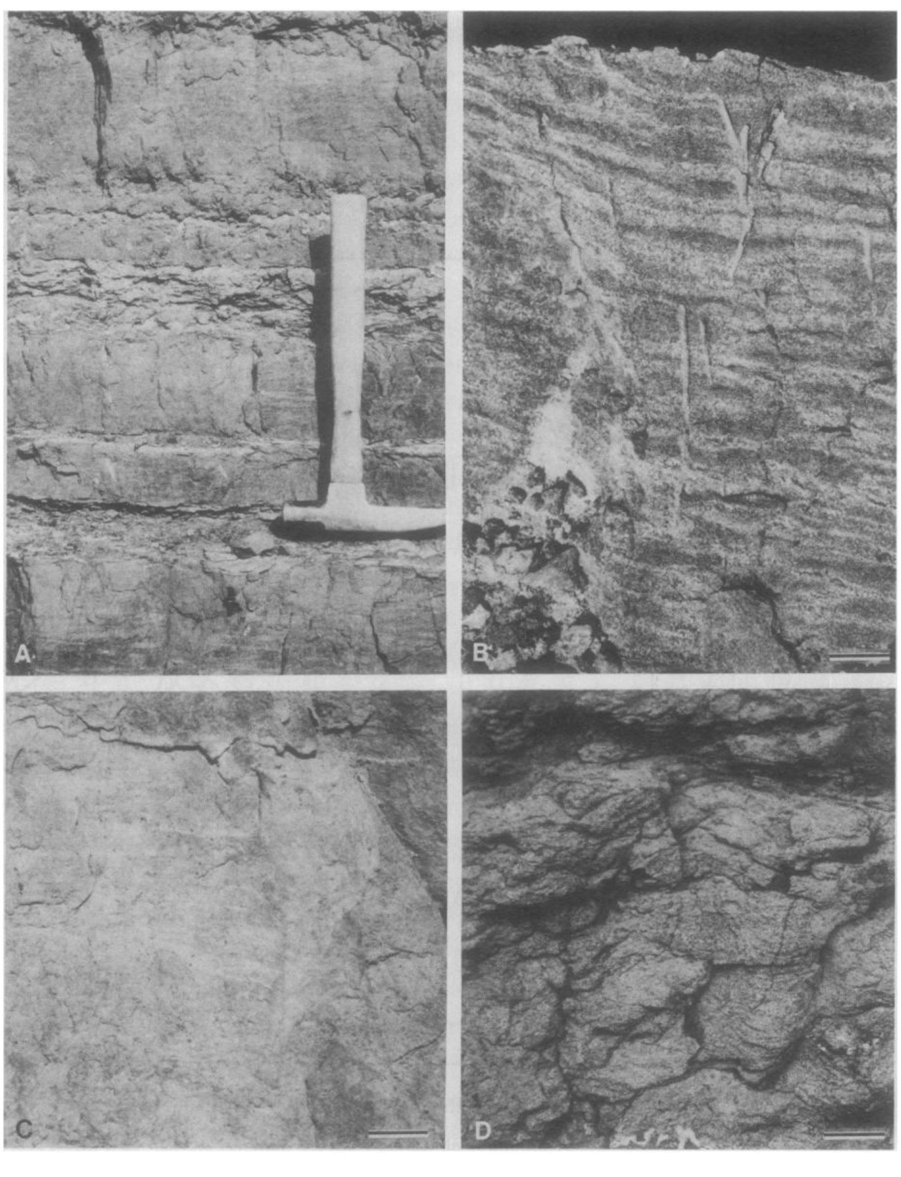


Fig. 2. Schematic representation of the three facies that characteristically make up the McMurray Formation sequence at outcrop: thick-bedded sands at the base, grading into epsilon cross-strata, overlain by horizontally bedded argillaceous sands.



mud couplets at a depositional dip averaging 12°. A typical set consists of decimeter- to meter-thick beds of fine sand separated by thin partings of argillaceous silt; individual beds are remarkably continuous and uniform from the base to the top of the set, and subtle fining upward within the set is manifest in part by an upward decrease in mean sand size but in greater part by an upward increase in the proportion of silty partings (*2*). These units have been interpreted as representing lateral accretion deposits, laid down on the sloping flanks of channel-margin bars in very large channels (*5, 6*).

The ichnocoenosis of a typical epsilon set is characterized by a relatively consistent association of (i) profuse numbers of vertical to inclined to arcuate shafts up to 20 cm in length and representing at least two distinct morphotypes of *Skolithos* (Fig. 3B); (ii) abundant, vertical, subconical, concentrically lined burrows identified as *Cylindrichnus*; (iii) rare trumpet-shaped burrows identified as *Monocraterion*; (iv) rare to common escape structures, up to 25 cm in length; (v) common, horizontal, branching burrows assigned to *Planolites* and *Palaeophycus*; and (vi) a bioturbated texture in which individual forms are difficult to discern. Ichnofossils are most abundant in the upper parts of the epsilon cross-strata, decreasing in abundance toward the base of the sets, and only very rarely are present in the underlying thick-bedded facies. Burrows are most common in the silt partings and penetrate down into the underlying sand. The distribution of the ichnofossils is consistent with the model of Mossop and Flach (*5, 6*), in which the epsilon cross-strata originated as lateral accretion deposits on the inner bends of channel meanders. Sand deposition occurred only during the higher energy flood events in the channel, with the presence of common escape structures in the sand units indicating that their deposition was relatively rapid. The silty partings accumulated as mud drapes on the bar surface during the remainder of the cycle, and it was during this time of low stage levels that the burrowing organisms flourished.

Fig. 3. Ichnofossils from the Athabasca oil sands. (A) Epsilon cross-strata from the middle McMurray: vertical dwelling burrows and escape structures are associated with the sand beds and a bioturbated texture characterizes the ensuing silty partings. (B) *Skolithos* sp. in unconsolidated sand bed from the middle McMurray; scale bar, 3 cm. (C) ?*Rosselia* sp. from massive sandstone unit in the Upper McMurray; scale bar, 2.5 cm. (D) *Teichichnus* sp. from fine-grained unit in the uppermost McMurray; scale bar, 2 cm.

Immediately overlying the epsilon cross-strata are the horizontally bedded, argillaceous sands and silts of the upper unit. The ichnofossil suite, although somewhat more abundant, is essentially similar to the one described for the middle McMurray but is characterized more by a bioturbated texture in which individual burrow forms are difficult to recognize. The intensity of the burrowing is such that primary sedimentary structures and bedding are commonly indistinct. Two notable exceptions to this pattern have been recognized near the top of the unit. The first consists of a distinct sand horizon (approximately 120 cm thick) grading from bioturbated argillaceous sands at the base to more well-sorted sand at the top characterized by parallel laminations, wave ripples, contorted bedding, and ball-and-pillow structures. The ichnofossil suite at the top of this unit (Fig. 3C) consists of ?*Dolopichnus*, *Bergaueria*, and vertical escape structures (a single specimen of a possible *Rosselia* has also been found). *Dolopichnus* and *Bergaueria* have been interpreted as the dwelling burrows of sea anemones (*7*), which are often associated with low-energy beach deposits. Second, at the top of the upper unit, near the contact with the overlying Clearwater Formation (Wabiskaw Member), there is a highly bioturbated unit containing profuse numbers of the wall-like, feeding burrow *Teichichnus* (Fig. 3D), which is generally considered to be a marine form. The retrusive nature of the associated spreiten generally is indicative of low sedimentation rates.

At present there is some controversy about the depositional interpretation of the epsilon-dominated McMurray Formation, with different investigators suggesting environments ranging from fluvial to estuarine to deltaic (*2–4*). Although Mossop and Flach (*5, 6*) have shown that sedimentation was dominated by deep channel and associated depositional processes, the physiographic setting of the channels remains enigmatic. Mossop and Flach envisage a basically fluvial channel system associated with, and in places prograding into, a mosaic of lakes and fresh to brackish bays with limited links to the sea. Although the indigenous palynofloral assemblage is dominantly continental, with local brackish water dinoflagellates (*8*), the overall trace fossil assemblage presents strong evidence that marine environments were also involved, particularly in the deposition of the upper McMurray sediments. The distribution of the trace fossils is consistent with a channel origin for the epsilon-dominated sequence, but shows that saltwater conditions must have been important at least locally, perhaps as salt wedges in the channels or as marine to brackish interchannel bays. In any event the trace fossil assemblage demonstrates that, at the time of deposition of the channel sequence, the marine shoreline must have been very close.

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9. Typing, drafting, and photography were carried out by the Alberta Research Council staff. Acknowledgment is made to the donors of the Petroleum Research Fund, administered by the American Chemical Society, for partial support of this research through a grant to S.G.P.

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Magnetostratigraphy of Sediments in Mammoth Cave, Kentucky

Abstract. *Clastic sediment deposits found within the caves of Mammoth Cave National Park have yielded a magnetostratigraphic pattern of magnetic polarity reversals which indicates that they were deposited over a range of at least 1 million and most likely 2 million years.*

Caves, being voids, are peculiarly difficult to date. As far as the cave passage itself is concerned, about the only technique that offers much hope for success is correlation with river terraces (*1*), although the ages of the terraces may not always be reliably determined. Dating the contents of the cave passages is more promising, but this provides only a lower bound.

Dating techniques which have been applied to cave sediments include faunal correlation (*2*), uranium disequilibrium series dating of calcitic deposits (*3, 4*), and magnetostratigraphy. Most cave sediments distant from an entrance are paleontologically sterile, while the uranium isotope methods yield satisfactory results back to no more than 350,000 years before present.

The chronology of polarity reversals of the earth's magnetic field during the past several million years has been worked out in considerable detail and precision during the past two decades (*5*). Although reversely magnetized clastic cave sediments were reported (*6*) as early as 1969, interest in the magnetic remanence record of these ubiquitous sediments has been fairly recent.

Previous studies (*7–11*) have been concerned with the correlation of minor changes in the direction and magnitude of the local magnetic vector (termed secular variation) with regional reference curves, derived mainly from lake sediments. As a result, previous magnetostratigraphic studies of cave sediments have not addressed ages much greater than about 20,000 years.

The first reversely magnetized clastic sediments from Mammoth Cave were discovered in late 1978, and intensive sampling from caves in the National Park has been carried out since then, yielding a regional pattern of striking consistency. More than 500 oriented sediment samples have been collected to date. A cubical pedestal was carved into the sediment and a 2-cm plastic box was then pressed over the pedestal. After orienting the base and one edge of the box, the pedestal was cut off at its base and the box was capped. Measurements were made with a cryogenic magnetometer at the University of Pittsburgh rock magnetism laboratory.

Nearly all the cave sediments collected have proved to be amenable to magnetic measurement. Only dry loose sands and powders have given erratic results, due to mobility of the grains within the sample boxes. Almost without exception, clay, silt, and sand samples

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