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Geology of the Molina Member of the Wasatch Formation, Piceance Basin, Colorado

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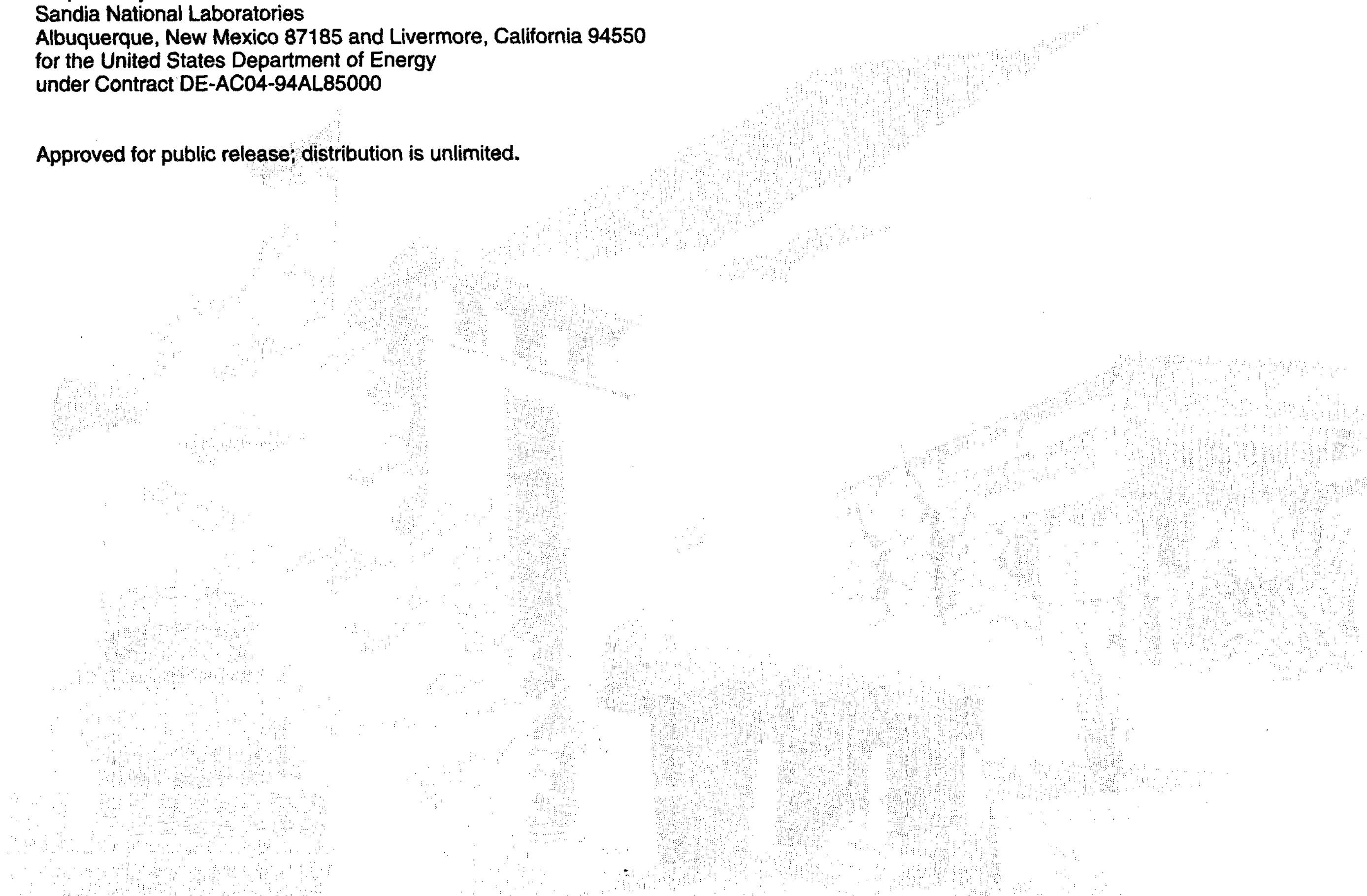

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Geology of the Molina Member of the Wasatch Formation, Piceance Basin, Colorado

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Abstract

The Molina Member of the Wasatch Formation has been cored in order to assess the presence/absence and character of microbial communities in the deep subsurface. Geological study of the Molina Member was undertaken in support of the microbiological tasks of this project, for the purposes of characterizing the host strata and of assessing the potential for post-depositional introduction of microbes into the strata. The Molina Member comprises a sandy fluvial unit within a formation dominated by mudstones. Sandy to conglomeratic deposits of braided and meandering fluvial systems are present on the western and eastern margins of the basin respectively, although the physical and temporal equivalence of these systems cannot be proven. Distal braided facies of planar-horizontal bedded sandstones are recognized on the western margin of the basin. Natural fractures are present in all Molina sandstones, commonly as apparent shear pairs. Core from the 1-M-18 well contains natural fractures similar to those found in outcrops, and has sedimentological affinities to the meandering systems of the eastern margin of the basin. The hydrologic framework of the Molina, and thus any potential post-depositional introduction of microbes into the formation, should have been controlled by approximately east-west flow through the natural fracture system, the geometries and extent of the sandstones in which the fractures occur, and hydraulic gradient. Migration to the well site, from outcropping recharge areas at the edge of the basin, could have started as early as 40 million years ago if the cored strata are connected to the eastern sedimentary system.

Acknowledgment

Reviews by Romeo Flores, Joanne Fredrich, Allan Sattler, and Frank Wobber have improved this manuscript. Discussions with Rick Colwell, Tim Meyer, and T.C. Onstott have helped to clarify the scope of the problem. John Lorenz's part of this work was performed at Sandia National Laboratories, which is operated for the U.S. Department of Energy under contract number DE-AC04-94AL85000.

Contents

Figures

Introduction

Core of the Molina Member of the Wasatch Formation was taken from the 1-M-18 well in December, 1995, and is being assessed for its microbiological content. The origin of the microbes is a primary concern of the U.S. Department of Energy's Subsurface Science Program: have they been in place since deposition, representing long-term in situ survival, or have they been more recently transported into the deep subsurface. A geological characterization of the subsurface system of permeability, or "plumbing", of the Wasatch Formation was undertaken in support of the microbiological aspects of this program, with the intent of affording insights into the potential for post-depositional introduction of microbes, as well as nutrients, into the sandstone from which the core was taken. This report relates preliminary results from the field study that was undertaken in order to characterize the geological controls on the plumbing, and thus the potential for significant fluid flow and microbe migration, within the sandstones of the Molina Member of the Wasatch Formation.

The Molina Member of the Wasatch Formation is a late Paleocene to early Eocene package of strata (Johnson et al., 1994). It consists of sandy to conglomeratic fluvial deposits interbedded with overbank and pedogenic mudstones. It is about 90 m thick at its type section, and is located near the middle of the Wasatch Formation. It is distinguished from the over- and under-lying members of the Wasatch Formation primarily by a significantly higher sandstone content (up to about 50%), and more laterally extensive sandstone bodies.

The geological controls on the plumbing system of the Molina consist of three multifaceted components, onto which the hydrologic gradient(not addressed here) is superimposed. The geologic components include, from broad to fine scale:

1) the overall geometry of the Molina Member across the basin (scale of 100's to 1000's of meters), including thickening and thinning, outcrops and locations of possible recharge, and continuity or lack of it between the "Molina" sandstones at one edge of the basin and those on another,

2) the large-scale geometry of individual sandstones (scale of tens to 100's of meters), including their thicknesses, three-dimensional shapes, axial trends, and the interconnectedness between sandstones, restricting interpretations of the possible and probable flow directions within the formation, and,

3) the internal heterogeneity of the sandstones (scale of meters to tens of meters). This heterogeneity depends primarily on a pervasive system of natural fractures which should provide a distinctly anisotropic horizontal permeability, and thus preferred flow directions. The degree of internal heterogeneity was also controlled by the depositional environment in which the sandstones were deposited.

This report gives the results from two weeks of field work studying the Molina at various outcrops around the edges of the basin (**Fig. 1**). Outcrop study allowed for detailed documentation of the sedimentary heterogeneity, bedding dimensions, and the natural fracture

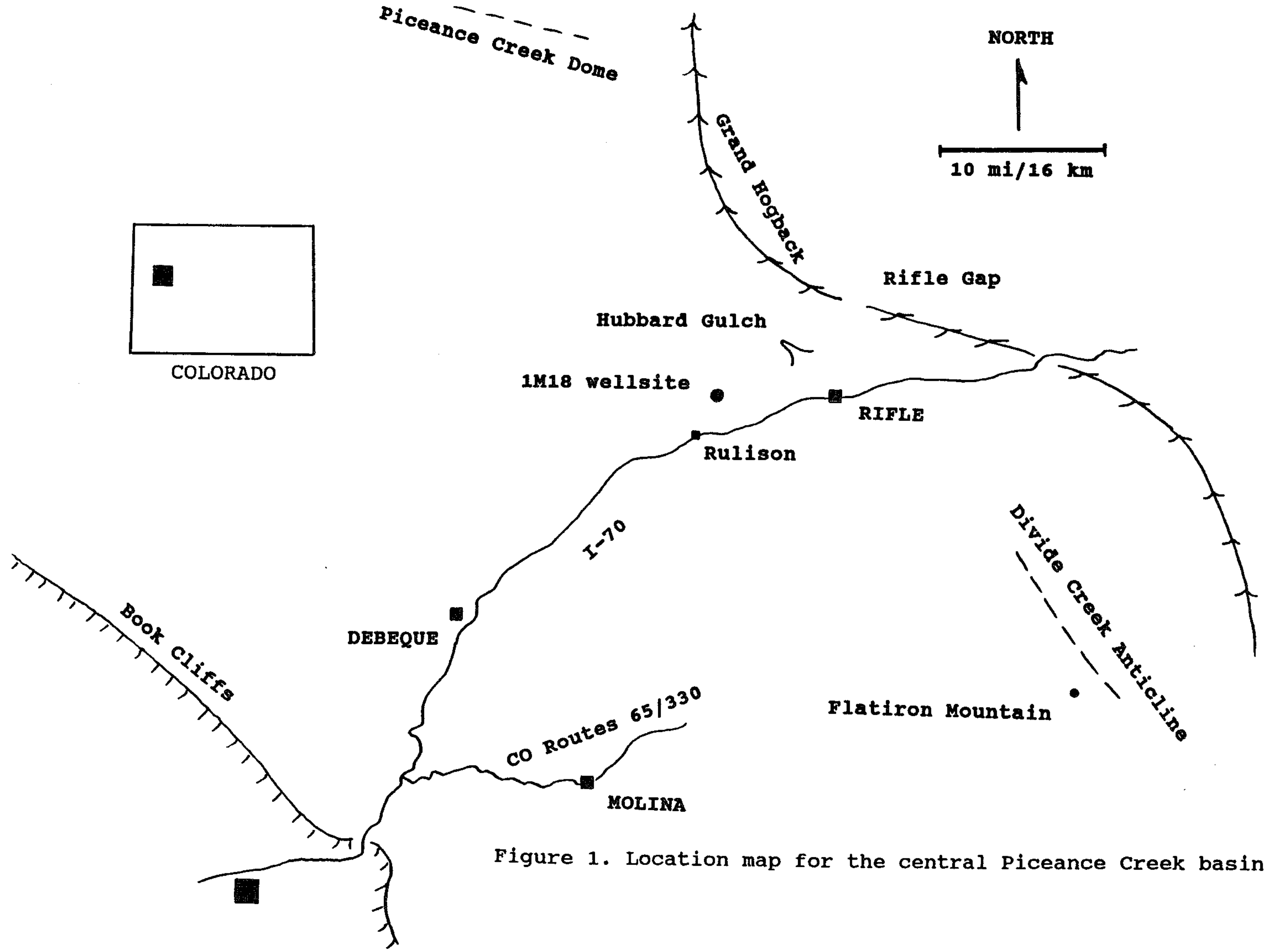

Figure 1. Location map for the central Piceance Creek basin

system. Details of some aspects of the overall geometry of the formation and continuity of individual sandstones should be complemented with a proposed geophysical-log study.

Unique features of the sedimentology and the fractures were noted during this study, both of which would seem to allow for relative mobility of fluids and microbes within individual sandstones of the Molina Member of the Wasatch Formation. The fluvial sedimentary environment was such that few mudstones were deposited as drapes and barriers to flow within many of the sandstones. The fracture system consists of apparent shear pairs of fractures that traverse individual sandstones top to bottom. These provide significant vertical and horizontal flow paths along offset asperities, enhancing horizontal fluid migration potential along the preferred orientations of the fractures.

Sedimentology/Stratigraphy

Introduction

The Molina Member is a zone of distinctly sandier fluvial strata within the predominantly muddy, nonmarine Wasatch Formation. Sandstones have a significantly greater potential for fluid flow (i.e., for microbial transport) than do mudstones. The over- and under-lying members of the Wasatch Formation (the Atwell Gulch and Shire members, respectively), consist of infrequent lenses of fluvial-channel sandstones interbedded within thick units of varigated red, orange, purple and gray overbank and paleosol mudstones.

The Molina Member represents a sudden change in the tectonic and/or climatic regimes, that caused an influx of laterally-continuous, fine, coarse and locally conglomeratic sands into the basin. The type section of the Molina is located near the small town of Molina on the western edge of the basin (Donnell, 1969), and is about 90 m thick.

These sandy strata of the Molina Member form continuous, erosion-resistant benches that extend to the north of the type section for approximately 25 km (**Fig. 2**). The benches are cut by canyons or "gulches", from which the Atwell Gulch and Shire Gulch members get their names. The Molina forms the principle target within the Wasatch Formation for natural gas exploration, although it is usually called the "G" sandstone in the subsurface.

Thinner but laterally-extensive sandy to conglomeratic units are also present at several stratigraphic horizons on the eastern margin of the basin. One or more of these horizons have been correlated with the type section (e.g., Donnell, 1969), apparently based in part on the presence of the higher percentage of sandstone in approximately the same stratigraphic interval, and in part on the composition of the conglomerates (Johnson et al., 1994). However, there are few stratigraphic age data to prove this correlation.

Correlations of measured sections of the Molina Member taken along the north-south trending outcrops at the western and southwestern edge of the basin, are presented in **Fig. 2a**.

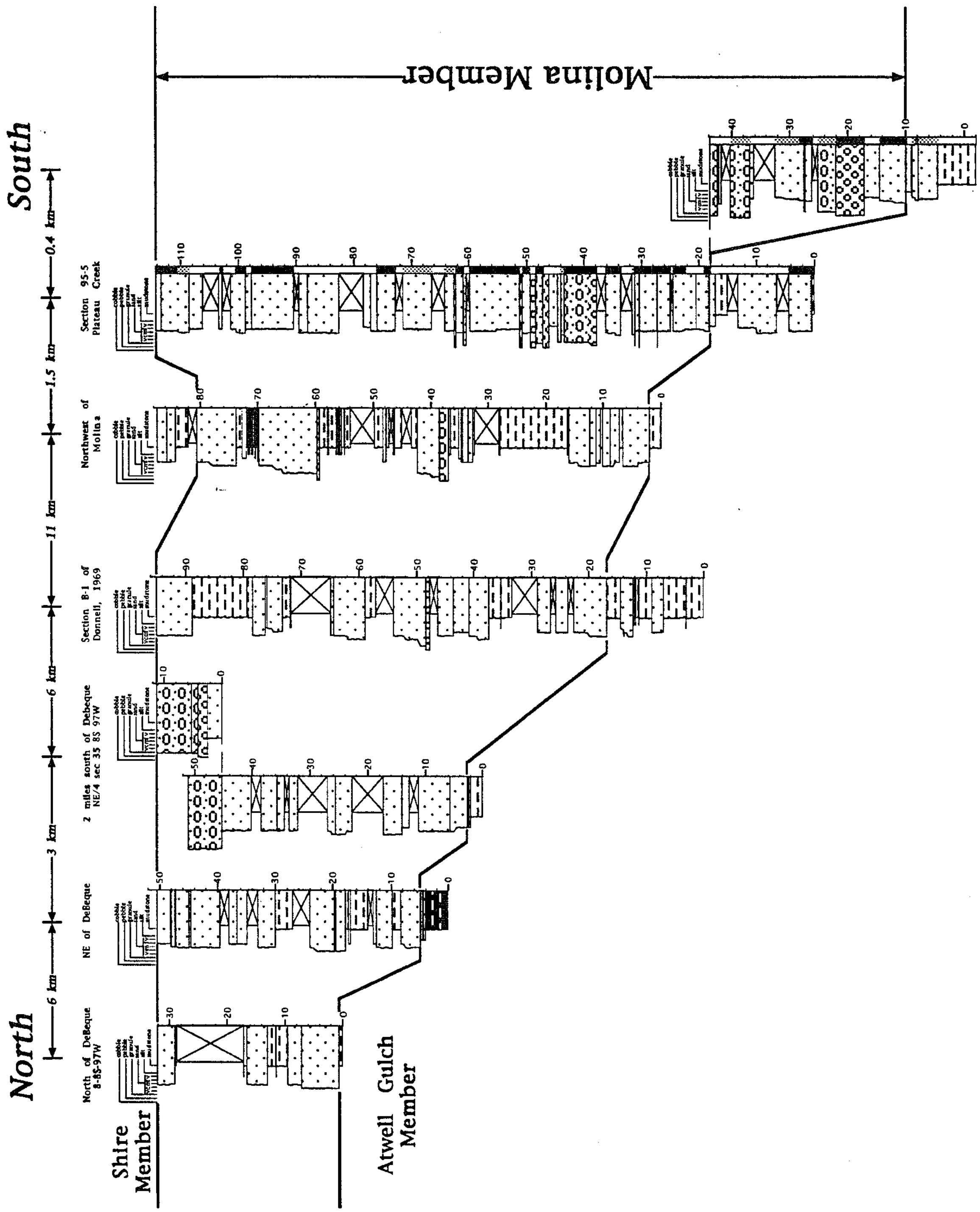

Figure 2a. Correlations of measured sections of the Molina Member, taken along the north-south trending outcrops at the western and southwestern edge of the basin.

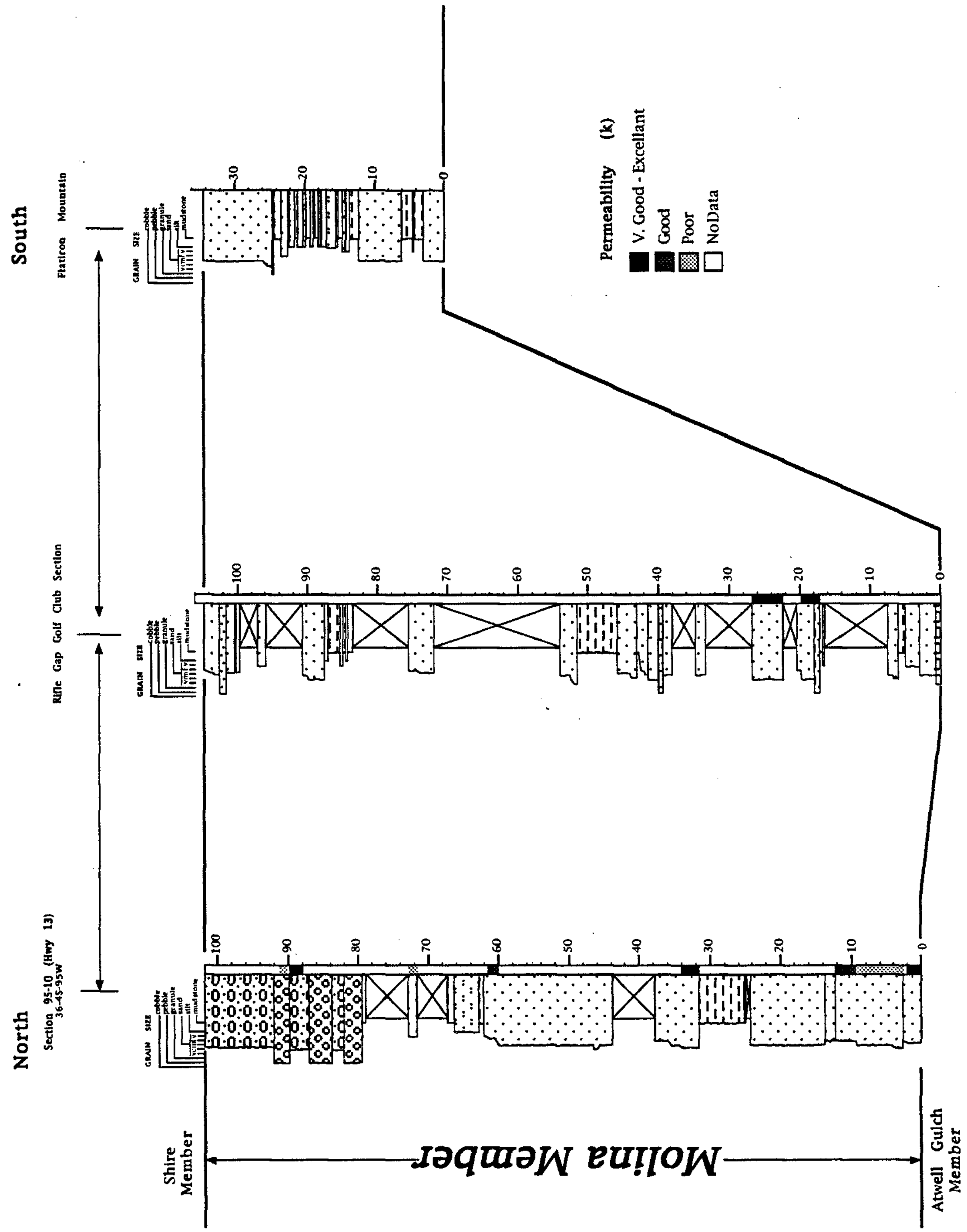

Figure 2b. Measured sections from the eastern edge of the basin, correlating sandstones that are most likely to be the stratigraphic equivalent of the Molina Member.

Data presented below suggest that these Molina-like units represent strata derived locally from a proximal basin margin, and need not be temporally or physically correlative to the Molina of the type section. There are, in fact, other localized sandy intervals within the Wasatch Formation (i.e., near the top of the Shire Gulch Member east of Molina, and near the base of the same member east of DeBeque), thus stratigraphic units with a high percentage of laterally extensive sandstones are not exclusive to the Molina.

This distinction is important. If the "G" sandstone in the subsurface is a distal facies of the type section, specifically the sandstone cored in the 1-M-18 well, it might reasonably be expected to consist of uniformly planar-bedded, well-sorted sandstones, similar to those found north and east of DeBeque. It should thin to the north and east, and might therefore have better hydraulic connection with meteoric waters derived from the west. On the other hand, if it is equivalent to the coarse, meandering fluvial systems of the eastern basin margin, it would be hydraulically connected to the much closer outcrops along the Grand Hogback and would be a predominantly crossbedded unit.

The distinction is complicated by the fact that there are a number of sandstone beds that comprise the subsurface "G" sandstone package: it is not unlikely that the package at this location near the deeper parts of the basin may represent overlapping or amalgamated units derived from both systems.

Molina Member at the Type Section and Nearby Areas

Description: The type "locality" of the Molina Member of the Wasatch Formation was designated by Donnell (1969) as the exposures on a "prominent hill" north of Plateau Creek, just west of the town of Molina. However, Donnell did not publish a description of a measured section at this type location.

Two sections were measured at Donnell's type locality during this study. The sections are about 1.5 km apart, and highlight considerable lateral variability within the member as well as between and within the individual beds that comprise the unit (southern two sections shown in **Fig. 2**). Individual sandstone beds up to 10 m thick pinch out into overbank mudstones within 100's of meters. Some of the thicker sandstones consist of amalgamated, disconformable beds.

Fluid flow and microbial transport should have been relatively easy through these thick, homogeneous sandstone beds. The introduction of fluids and secondary microbes into the beds would have been especially easy after they had been exposed in outcrop at the edges of the basin during uplift and erosion, probably less than 10 million years ago.

Some sandstones, especially near the base of the member, consist of fine-grained, well-sorted sands deposited entirely as plane-parallel, horizontal beds (**Fig. 3**). Many of these beds have so little differentiation in grain size and composition that they appear to be massive, structureless beds. Locally, compaction and soft-sediment deformation features are common.

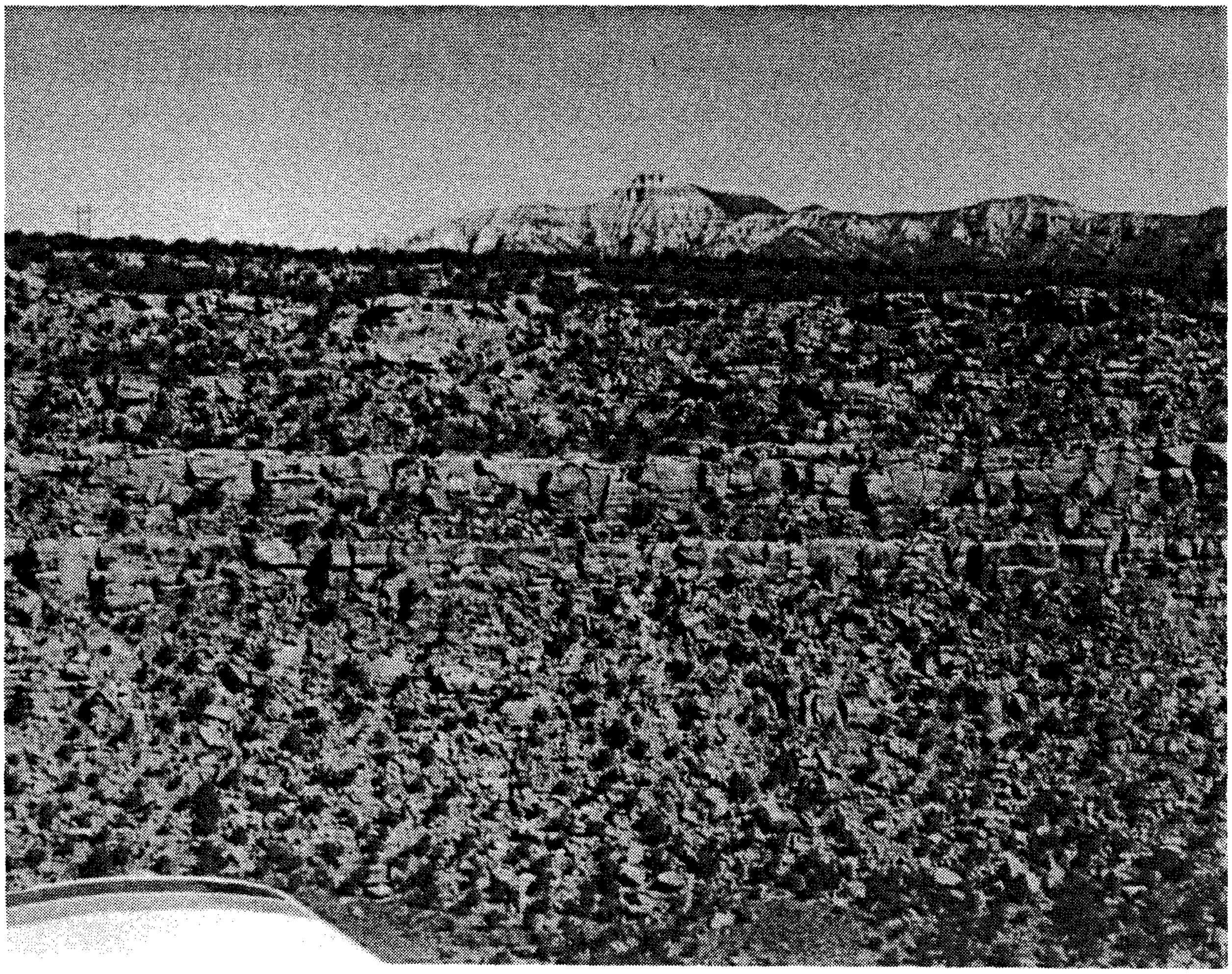

Figure 3a. Sandstones of the Molina Member of the Wasatch Formation near its type section.

Paleocurrent indicators are rarely apparent in these units, although parting lineation is common in slump blocks. Trough crossbeds seem to be the dominant bedform higher in the sections, commonly associated with the coarser to conglomeratic units. Lateral accretion structure is also apparent in some of these coarser beds.

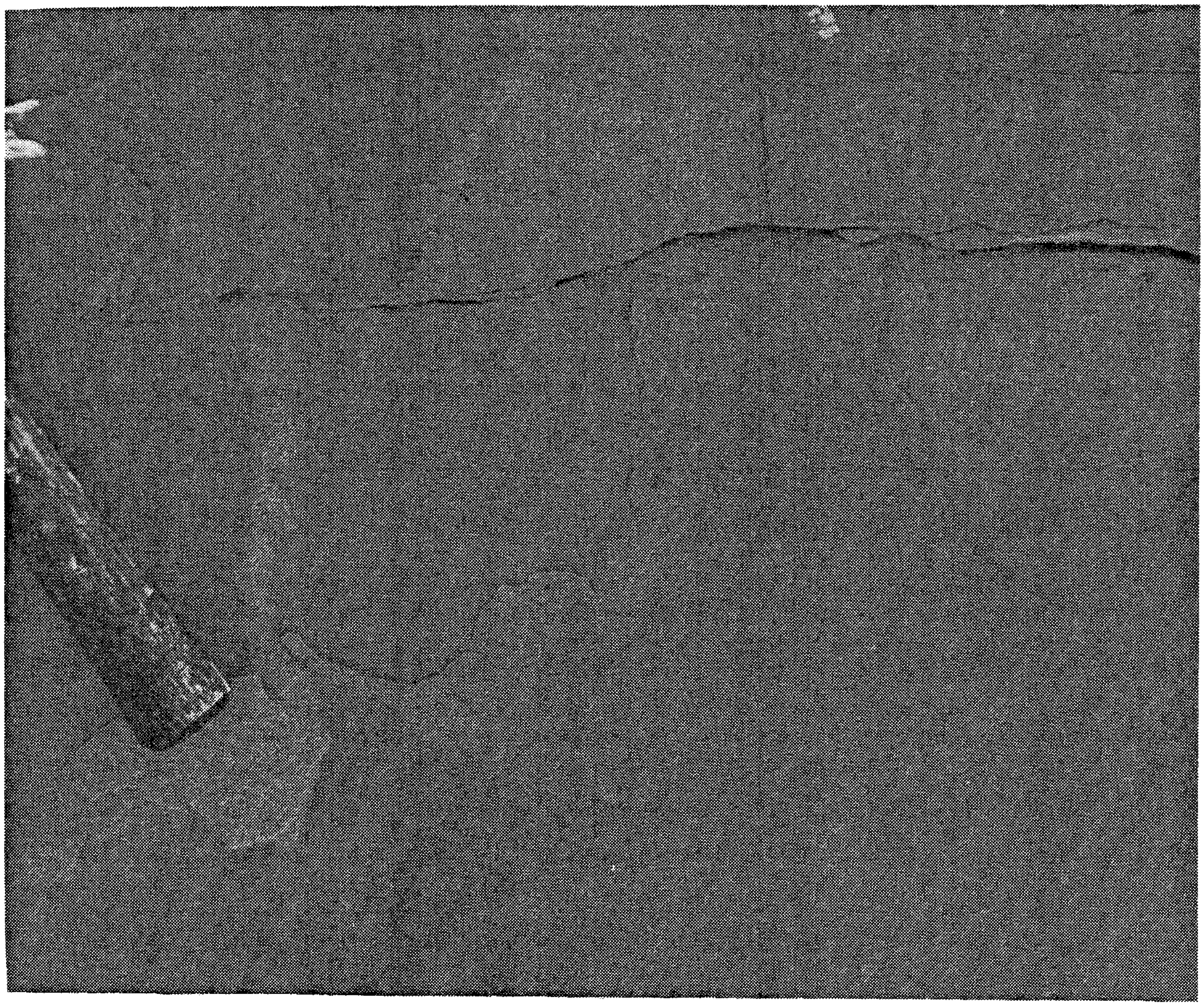

Figure 3b. Parting lineation on bedding planes from the planar-horizontal bedded facies of the type-section Molina Member.

The associated mudstones make up between about 20 to 40% of the section, but are commonly obscured. These units are relatively impermeable, and should have provided significant vertical barriers to flow within the system. Thus, bedding-constrained, lateral fluid flow, and the associated potential for microbial transport, is more likely to have occurred than vertical transport, except possibly in the vicinity of the relatively rare faults that cut the strata.

Figure 3c. Trough crossbed nested within planar-horizontally bedded sandstone, near the type section of the Molina Member.

The mudstones are usually gray and structureless, commonly with interbedded siltstones and sandstones a few tens of centimeters thick. The interbedded silts and sands commonly preserve traces of abundant burrowing and local rooting. They display current ripples where they are not completely bioturbated. Locally the mudstones are mottled red-orange to purple, with well developed soil textures and rooting.

The Molina Member thins northward to about 30 m thick at its northern outcrop exposures **(Fig. 2)**. Sparse paleocurrent measurements suggest a generally northerly flow **(Fig. 4)**. Conglomerates are rarer and appear higher in the section northward, and a higher percentage of the section consists of the plane-parallel, well-sorted sandstone facies.

Interpretation: The Molina Member at its type section was probably deposited by a system of braided streams (Johnson et al., 1994) that flowed in a generally northerly direction. These streams formed a low-gradient alluvial fan that tapered to the north, and possibly to the northeast and northwest as well. Distal facies of the fan consisted of plane-parallel bedded sands, deposited at the base of the type section as the system prograded northward, and at the northern edges of the system. This facies was deposited during ephemeral, irregular flow, in shallow, unconfined, sandy-bedded channels.

Coarser, conglomeratic deposits also prograded northward in this system, occurring near the base and middle of the section proximally, but were deposited near the top of the section in the distal areas. Meandering streams occurred locally, especially during the latter stages of deposition. Overbank facies consisted of muds, silts and sands, probably deposited in marshy environments. Recurrent pauses in deposition and associated lengthy subaerial exposure allowed soils to form within the overbank mudstones.

The source area for the relatively clean sandstones and cherty to quartzitic conglomerates is enigmatic. Paleoflow suggests an area to the south. Well rounded, well sorted sand grains occur in many of the beds, and locally comprise entire units. These suggest reworked eolian sandstones. Jurassic and Triassic eolian deposits are present over the Uncompahgre Uplift to the southwest, but are missing over much of the Precambrian in the Black Canyon of the Gunnison area. Paleocene to Eocene uplift in that area, approximately 100 km to the south-southeast, could have uplifted and exposed these eolian strata as source rocks for much of the Molina. Petrographic study of the Molina sandstones may shed more light on this possibility.

Fluid flow laterally within this system was restricted only by the permeability of the sandstones (enhanced by natural fractures as discussed below), and by the shapes and trends of the sandstone bodies. Vertical flow, however, was severely restricted by the relatively impermeable shale/mudstone beds that are intercalated within the sandstones. However, significant flow was probably not possible until exposure of the sandstones at the margins of the basin, due to uplift and erosion associated with the uplift of the Colorado Plateau, made the beds a potential area of ground water recharge. This uplift did not begin until about 9 million years ago.

Molina-like Deposits at the East Edge of the Basin

Description: Coarse-grained to conglomeratic, laterally-extensive sandstones are present at at least two stratigraphic horizons at the eastern edge of the Piceance basin. These sandy horizons are several tens to about 100 meters thick. Donnell (1969) suggested that a 130-m thick unit of sandstones that is up-ended to vertical at the southern entrance to Rifle Gap is correlative to the Molina Member. This sandy horizon can be traced through intermittent exposures for a few tens of kilometers along the Grand Hogback. Another sandy horizon, probably slightly stratigraphically higher within the Wasatch, forms aligned but separated cuestas for a few tens of kilometers south of the Colorado River as far south as Flatiron Mountain west of the Divide Anticline.

Similar laterally extensive, sandy deposits occur higher in the Wasatch section east of Divide Creek, and in the Hubbard Gulch area north of Rifle. It is conceivable that the first two units described form one stratigraphic horizon, and that the last two form a second horizon, but time-equivalence and physical continuity between any of these deposits, or between any of these sandy units and those of the Molina of the type section, cannot be proven.

These sandstones are typically crossbedded. Crossbedding suggests a general paleoflow to the west, away from the nearby basin margins (**Fig. 4**). Lateral accretion bedding is present locally, as well as common intraclasts of adjacent overbank mudstones up to a meter in diameter. Thick paleosoil horizons are commonly superimposed on the associated overbank muddy facies (**Fig. 5**).

Conglomerate content varies from a few pebbles to thick units with clasts up to 20 cm. Charcoal fragments are a common component of the basal crossbedded sandstones. This component is rare to absent in sandstones of the type section, as are the 1-cm scale, well-rounded fragments of Inoceramus shell, at least three of which were noted at Hubbard Gulch.

Interpretation: These deposits probably record local meandering fluvial systems. Conglomerate composition and clast size, crossbedding/paleoflow vectors, and facies all suggest that these sandy horizons within the Wasatch were derived from nearby sources. We suggest that they were not a distal facies-equivalent of the Molina type-section sandstone/conglomerate sequence.

Many of these deposits seem to represent local, smaller fluvial systems that flowed into the edge of the basin from the adjacent highlands, bringing conglomerate clasts of local composition. The Inoceramus shell fragments found at Hubbard Gulch indicate local, reworked Cretaceous strata: they are very fragile clasts, and are rare in reworked strata. They certainly would not have survived transport across the entire basin. Reworking of Cretaceous strata as source material for some of the upper Wasatch strata is consistent with recent, unpublished data on clay mineralogy (R. Flores, USGS, oral communication, September, 1995). Thick conglomerate units such as that about 10 km west of Rifle Gap probably represent a local, steep-gradient alluvial fan, built by streams flowing from a point source in the nearby highlands of the emerging White River Uplift.

Ground water flow through these units would be similar to that within the type section: i.e., little restriction to lateral flow except by the lateral limits of the sandstones, but severely restricted vertical flow (except possibly locally in association with faults). Most of the sandstones would be expected to have axes approximately normal to the margins of the basin, facilitating flow in the generally east-west direction, but with the natural fracture controls superimposed as discussed below.

Significant flow would not be expected until after the beds were exposed to ground water near or at the surface. Since this margin of the basin is associated with the Laramide uplift, however, flow may have begun much earlier than at the western margin of the basin, possibly beginning as early as about 40 million years ago.

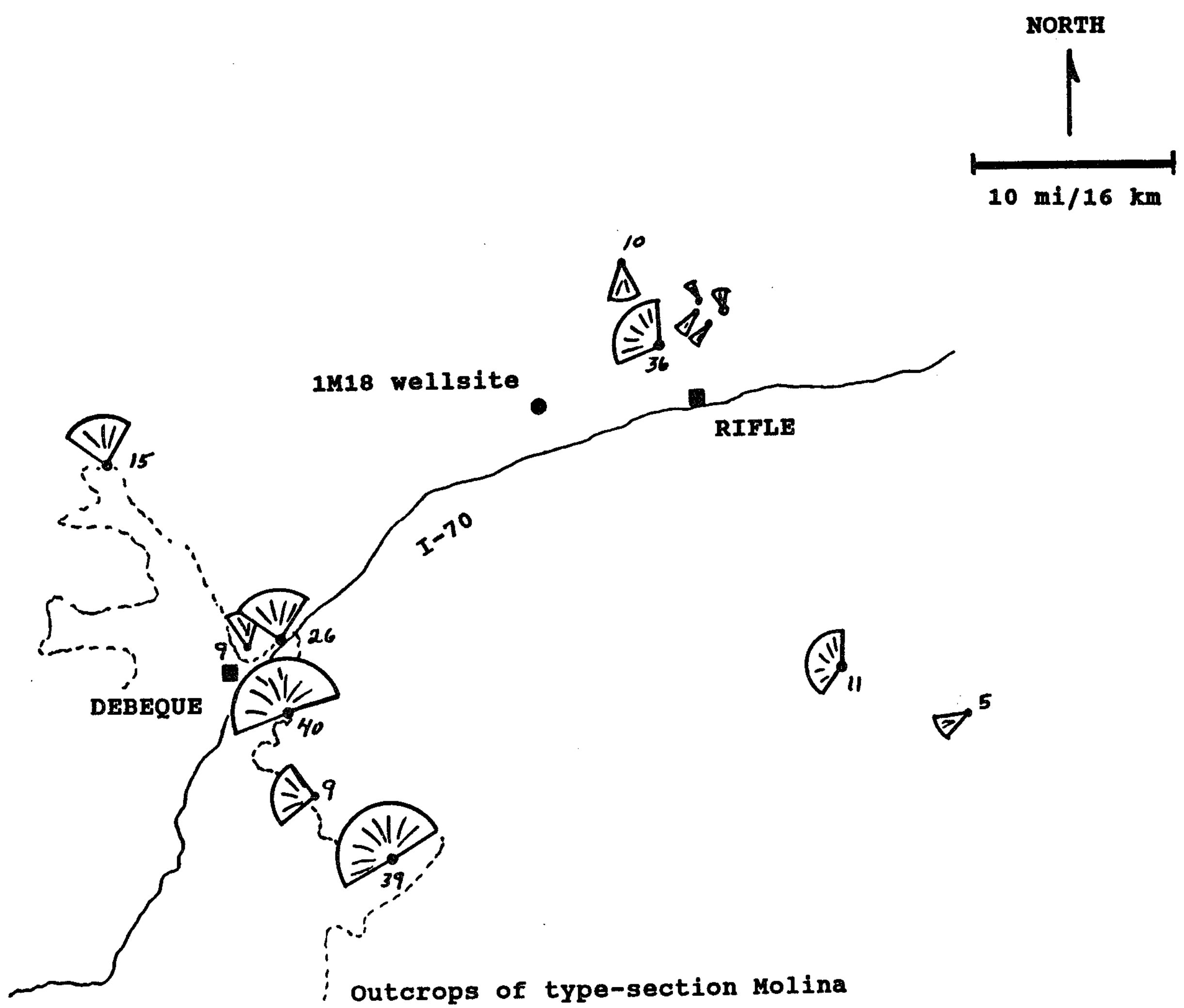

Figure 4. Generalized paleoflow directions in the Molina and related sandstones, based on parting lineation, crossbedding, and channel axes. Numbers associated with roses indicate the size of the data set at that location.

Figure 5a. Fluvial channel that cut down into a soil horizon. Note the anticlinal forms in the mudstones, indicative of vertisols, under the "wing" of the channel sandstone. Sandstone is about three meters thick at the left edge.

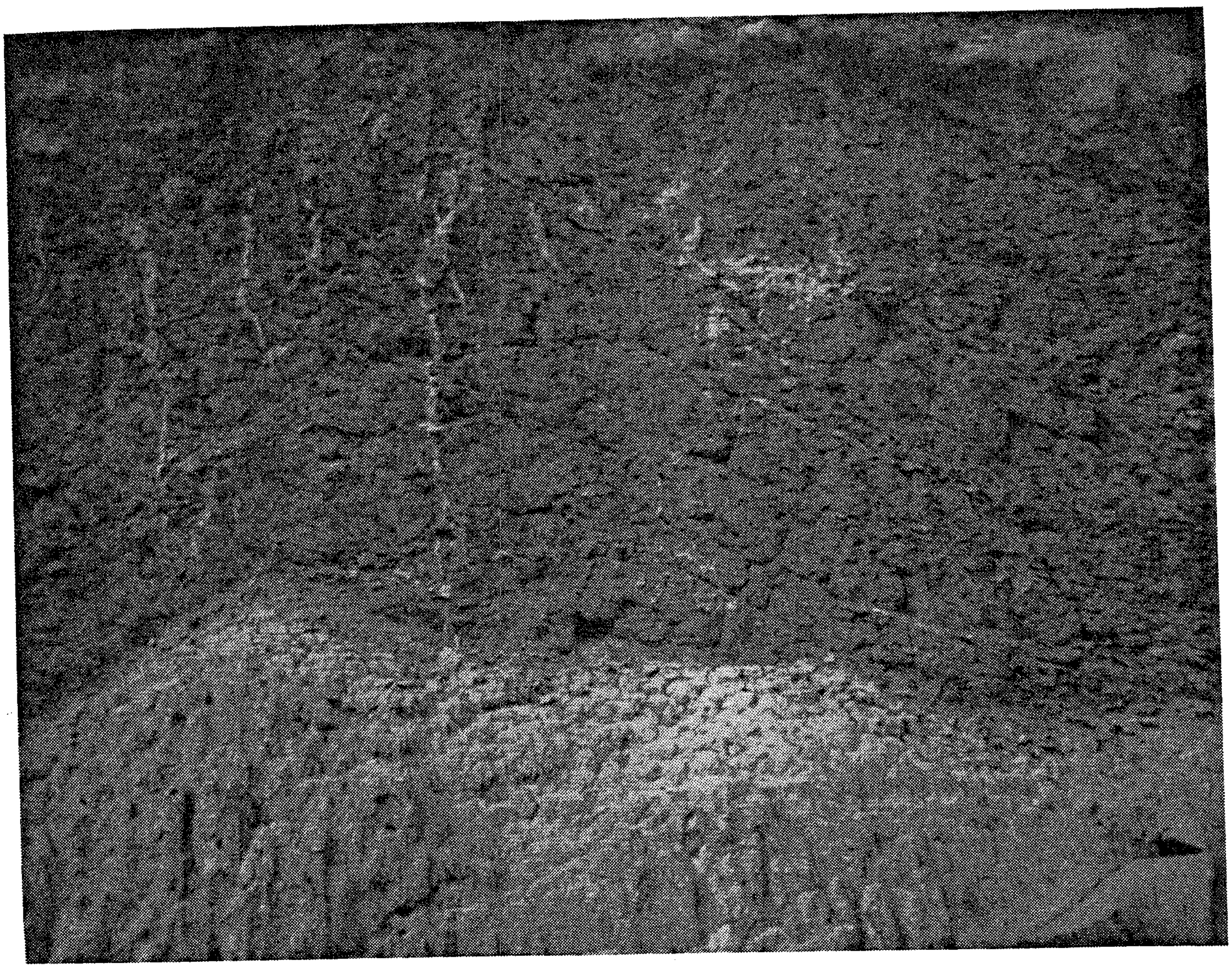

Figure 5b. Closeup of anticlines in a mottled purple mudstone horizon that is laterally equivalent to the anticlines in the previous figure. The mudstone shown is approximately 1.5 meters thick.

Description and Interpretation of Core from the 1-M-18 Well

A core approximately 20.5 ft (6.3 m) long was recovered from the Wasatch Formation in the "G" sandstone interval (**Fig. 6**). [Core depth and length were originally measured in feet, and will be reported that way here, with metric conversions. The '"G" sandstone' is the common name given by the oil and gas industry to the sandy subsurface horizon that has been correlated to the outcrop Molina Member.] The top of the 1-M-18 core is 2808 ft (855.9 m) below the Kelley Bushing of the drilling rig (used as a reference datum during coring and most--but not all--of the logging), or 2792.5 ft (851.2 m) below the local ground surface.

The core was taken from a sandstone bed near the top of the "G" package of sandstones (**Figs. 6,7,8**). The core contains a complete fluvial-channel sandstone, along with good examples of the associated overbank facies that over- and underlie the channel. This description starts at the base of the core, following the depositional sequence.

The basal several centimeters of the core consist of a black, laminated claystone, probably deposited in a lacustrine environment on the floodplain. The overlying three ft (0.9 m) consist of a black, silty, apparently massive mudstone, the top third of which becomes vaguely laminated and contains cm-scale nodules of what is probably the siderite, an iron carbonate. Tracks and trails of invertebrate fauna occur on the obscured bedding planes. This facies may record the development of a marsh during infilling of the earlier lacustrine environment. Overlying this is a thin interval (0.95 ft/0.29 m) of laminated, black, claystone/mudstone similar to that at the base of the core, indicating a return to the lacustrine facies. These organic-rich facies could be sampled for palynology if age dating or further environmental analysis is desired.

A few centimeters of black silty sandstone mark the first influx of fluvial sediments into the lake. They are abruptly overlain by medium-grained, gray sandstones that were deposited at the base of a fluvial channel. Ripup clasts of claystone from the underlying sediments suggest that the basal channel sandstone contact is erosional. The lower 6.5 ft (2.0 m) of this 14 ft (4.3 m) thick channel sandstone are crossbedded, with local inclusions of coalified plant debris up to several centimeters in diameter. A long calcite-mineralized natural fracture (discussed below) is also present in this part of the sandstone.

Sedimentary structures are obscured in the overlying five ft (1.5 m) of the channel sandstone, and the included plant debris becomes smaller. Several artificial fractures, induced by the coring and recovery process, are present in this interval. The grain size fines gradually upward above this to a 1.5 ft (0.46 m) thick interval of fine-grained sandstone to siltstone, marking the shallower depositional environments in the fluvial channel. The overlying one-ft (0.3 m) thick, coarser (medium-grained) sandstone is the last of the fluvial facies in this core, and probably represents an overbank/levee environment recording the lateral migration of the fluvial channel out of the area. This thin sandstone contains a calcite-mineralized natural fracture that terminates abruptly, top and bottom, at the contacts with the adjacent lithologies.

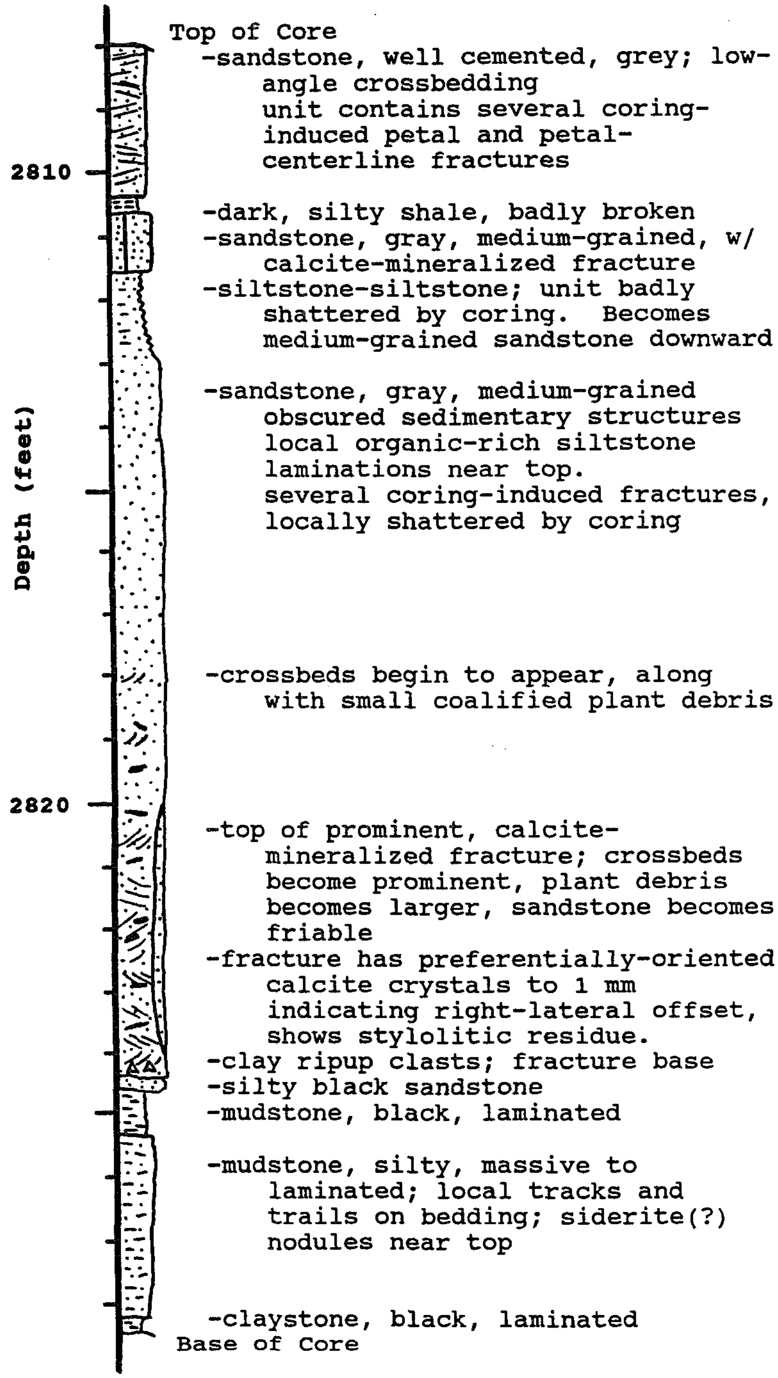

Figure 6. Lithology log from the DOE 1-M-18 well, Section 18, T6S, R94W.

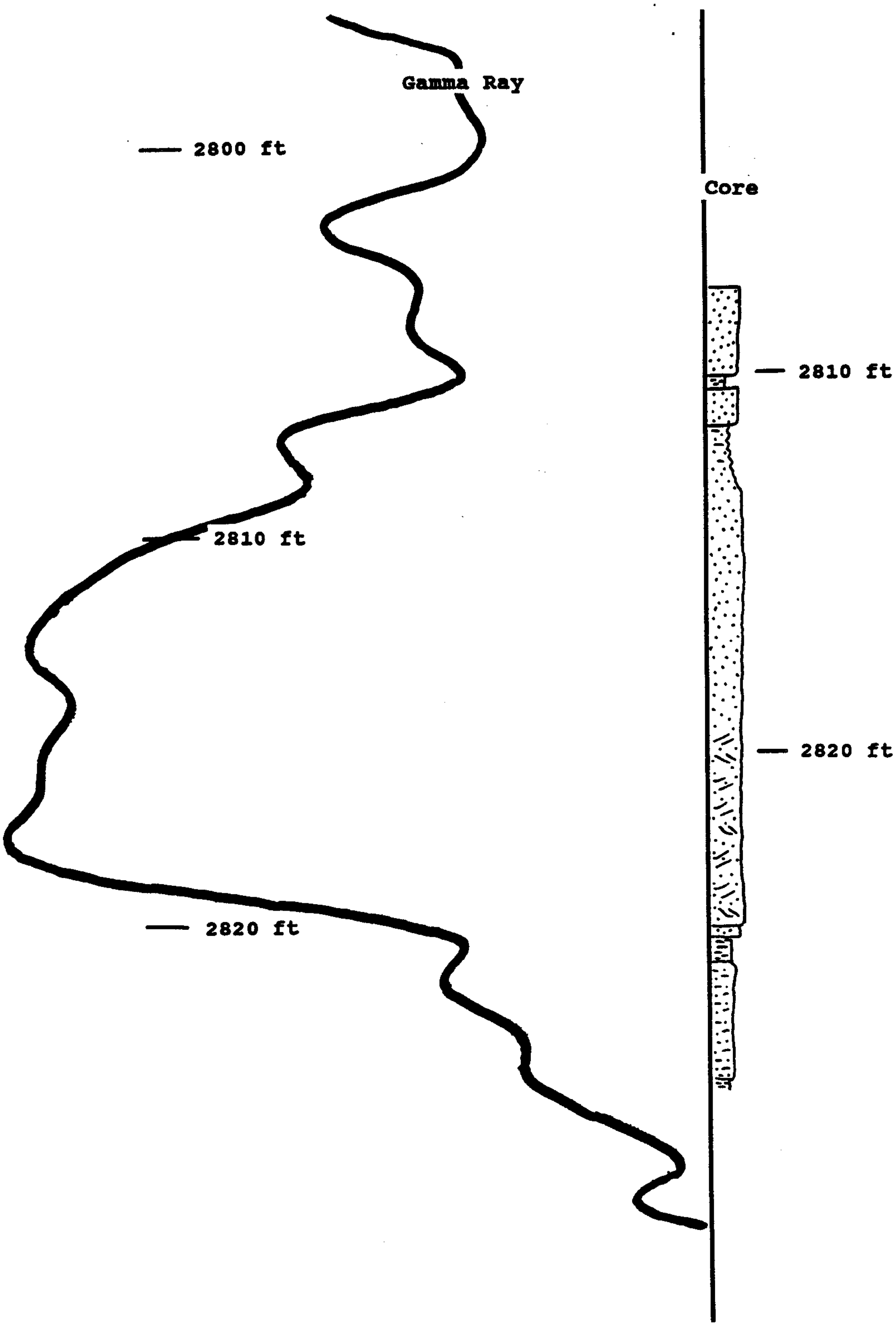

Figure 7. Relationship between the profile of the gamma ray log and the lithology of the core in the 1-M-18 well. A four-foot offset between the depth of the core and the log depth was necessary in order to make this correlation.

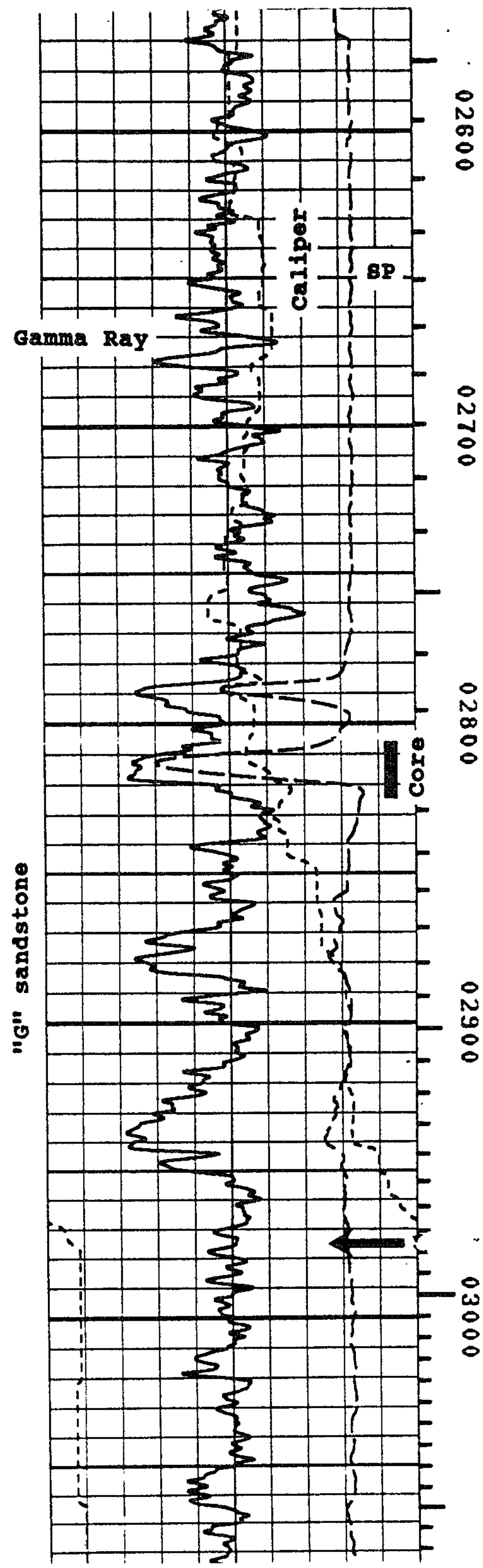

Figure 8. Geophysical log showing the location of the SSP core within the sandier "G" interval of the Wasatch Formation.

Above this channel sandstone, a few centimeters of dark, silty shale, record a marshy environment, and are overlain by 2.5 ft (0.76 m) of well cemented, fine to medium-grained gray sandstone with some preserved low-angle crossbedding. The sandstones probably record the proximal levee of a different, younger fluvial system. Several drilling-induced fractures mark the well-cemented sandstone.

The 14-ft (4.3-m) thick fluvial-channel sandstone probably records the presence of a meandering fluvial system. The sandstone does not contain repeated internal channel scours as might be expected in a braided system. Nor does it contain the repetitive planar-horizontal bedding that are associated with the braided Molina deposits at the type section. The associated dark, organic-rich facies suggest high water tables in reducing, swampy and lacustrine environments adjacent to a well adjusted (rarely flooded) meandering stream. This suggests that that part of the "G" sandstone that was cored at the 1-M-18 well has stronger affinities to the fluvial systems derived from the eastern margin of the basin than to the type-section strata. The affinities of the associated "G" sandstones penetrated in this well, however, are not constrained by this interpretation of one sandstone from the package.

Geologic Constraints on Molina Hydrology

The sedimentologic data suggest that the strata that form the type section of the Molina Member probably form a radial wedge that originated in the south-central part of the basin, and thins northward along the axis of deposition. It probably also thins and/or fingers eastward into the basin, and thins westward beyond the present-day erosional limits. Strictly based on the geometry of the wedge, hydraulic transport within these type-section sandstones should be least restricted along the north-south depositional axis and most restricted vertically. However, the locations of recharge, hydraulic gradients, and fracture-enhanced permeability, as discussed below, will be controlling factors.

The sandy to conglomeratic Wasatch strata that were deposited at the eastern margin probably form a sandy fringe an estimated 5-15 km wide along that edge of the basin, with fluid transport least restricted in the east-west direction and most restricted vertically. Local fingers of sandstone may penetrate farther west and northwestward to join a northerly, basin-axis paleoflow. These fingers may overlap or even amalgamate with the northward tapering Molina clastic wedge coming up from the south; well-log correlations may help to decipher this interaction. Areas of recharge, timing of exposure to recharge, hydraulic gradients, and fracture patterns will dominate the actual subsurface hydraulic transport directions in the horizontal planes, and their rates.

Natural Fractures

Introduction

Natural fractures, in both ground-water and hydrocarbon reservoirs, can provide permeability and conductivity enhancements of several orders of magnitude over the permeability of the associated matrix rock. Fracture enhancement may be local, associated with particular structures, or may be more pervasive, related to a regional system of systematic fractures. The well developed Wasatch fracture system represents a significant potential for fluid transport and thus for microbial migration. Permeability enhancement due to natural fractures occurs in the Molina Member of the Wasatch Formation, where matrix permeabilities are in the range of tenths or even hundredths of millidarcys. In contrast, reservoir permeabilities of tens of millidarcys are required to support the measured production of natural gas from most wells completed in this formation. A similar magnitude of enhancement, modified for differences in capillarity and viscosity of the fluids, might be expected to apply to the migration of water and/or microbes through these strata.

A set of pervasive sub-parallel, regional, extension fractures are present in the Mesaverde Formation that directly underlies the Wasatch Formation in the Piceance basin. Near-orthogonal cross-fractures commonly connect these regional fractures in outcrop, and fractures terminate vertically at minor lithologic discontinuities within the reservoir sandstones. These fractures have been studied and are well characterized (Lorenz and Finley, 1991). Sandstones of the Molina Member are also invariably fractured in outcrop, and the rare cores of rocks from natural gas wells in the basin contain local natural fractures.

Fractures similar to those documented in the Mesaverde were expected to be present in the Molina, but such is not the case. Instead, natural fractures in outcrops of the Molina sandstones occur most commonly as paired oblique sets, and fracture heights are commonly equivalent to bed thicknesses (meters to a few tens of meters). The fracture system represents a significant potential for the enhancement of fluid flow laterally through the strata (the vertical component is still constrained by poorly fractured mudstones and shales), and thus a potential mechanism for the introduction of transported, post-depositional microbial communities.

General Fracture Characteristics of the Molina Member

Intersecting at angles between 30 to 60 degrees, the Molina fracture pairs are suggestive of shear pairs (**Fig. 9**). In fact, the surfaces of about 20% of these fractures display small steps indicative of shear motion. They also locally contain oriented crystals of mineralization ("slickencrysts", usually calcite) that filled in void spaces left by mm- to cm-scale offsets of the asperities on irregular fracture surfaces. The sense of motion recorded by mineralization and steps is consistent with shear pairs, although 1) the angle of intersection is locally less than the 60-degree intersection angle commonly ascribed to ideal "conjugate shear pairs", and 2) only one set of the fracture pair is present in many outcrops. The virtual absence of true slickensides of comminuted rock, combined with the small fracture intersection angle, suggest that confining stresses were small at the time of fracture origin and offset. Locally, quartzite clasts larger than 5 cm within conglomerate beds are fractured parallel to the local fracture trend; these fractures do not extend beyond the clasts into the matrix, suggesting that they formed in extension.

Although it does not effect fluid flow, it is a question of some scientific interest as to whether the fracture pairs in fact formed synchronously as shear pairs, or whether they formed as successive, superimposed sets of extension fractures. Among the few outcrops where relative age relationships can be determined, there is, in fact, evidence for both interpretations.

1. At Hubbard Gulch north of Rifle, a single sandstone pavement contains intersections of 80-degree and 110-degree fracture sets. Several of the exposures of fracture intersections indicate that the 80-degree set formed first, yet equal numbers of intersections within the same pavement indicate the opposite relative age relationship (**Fig. 10**). This suggests that the fractures of both sets were forming contemporaneously yet independently; it is not a relationship between fracture shear pairs that is commonly reported or expected.

2. Evidence for nonsynchronous fracture set formation is present in a spectacular outcrop of Wasatch sandstones that occurs stratigraphically below the Molina Member, at the southern entrance to Rifle Gap. Fractures of the 110-degree set appear to have formed first in many of the sandstone lenses exposed here, with the later, 80-degree set having been superimposed on them only locally. Differing rock properties, caused by variable conglomeratic to sandy compositions, probably account for the different fracture patterns. The conglomeratic units were apparently less susceptible to the initial episode of fracturing, as they do not contain the early 110-degree set. They did, however, fracture later with the 80-degree orientation, at the same time that the 80-degree set was superimposed on sandy units containing the 110-degree set.

Southwest across the basin at the type section outcrops, the fracture pairs have different trends (commonly northeast east-southeast), and the intersection angles are typically larger, closer to the ideal 60-degree angle. A third, north-northwest trending set is locally present in some of the northern outcrops in this area (**Fig. 11**). These fractures are oblique to the five normal faults mapped in this area (Tweto, 1979). Because of the oblique relationship, and because the fractures probably represent compressional features whereas the faults record extension, the fractures are inferred to be unrelated to faulting.

Relatively uniform grain sizes and the rarity of clay drapes have produced a relatively homogeneous internal lithology within most of the 2- to 12-meter thick sandstone beds (**Fig. 12**). This lack of significant sedimentary heterogeneity allowed uninterrupted vertical propagation of fractures, resulting in fractures heights that are commonly of similar dimensions to bed thicknesses. Vertical permeability is virtually unlimited <u>within</u> individual sandstones.

It does not appear, however, that these fractures extended across the mudstones between sandstone beds to provide conductive pathways between adjacent reservoirs: vertical permeability <u>between</u> beds is poor. Although the mudstones are commonly fractured, their most common fractures are pedogenic and surficial features. The latter features are diagnostic of vertisols (Wilding et al., 1988), and consist of nested, concave-upward shear planes, without preferred strike (**Fig. 5**). They formed in soil horizons by expansion and contraction during seasonal wet-dry cycles at the Eocene depositional surface. Assuming that the muddy horizons in which they occur are relatively ductile, these features are probably squeezed shut under the compressive stresses found in the subsurface and thus do not provide significant permeability pathways.

Figure 9. Intersecting (shear?) fractures on a sandstone pavement at the type section of the Molina: boot for scale.

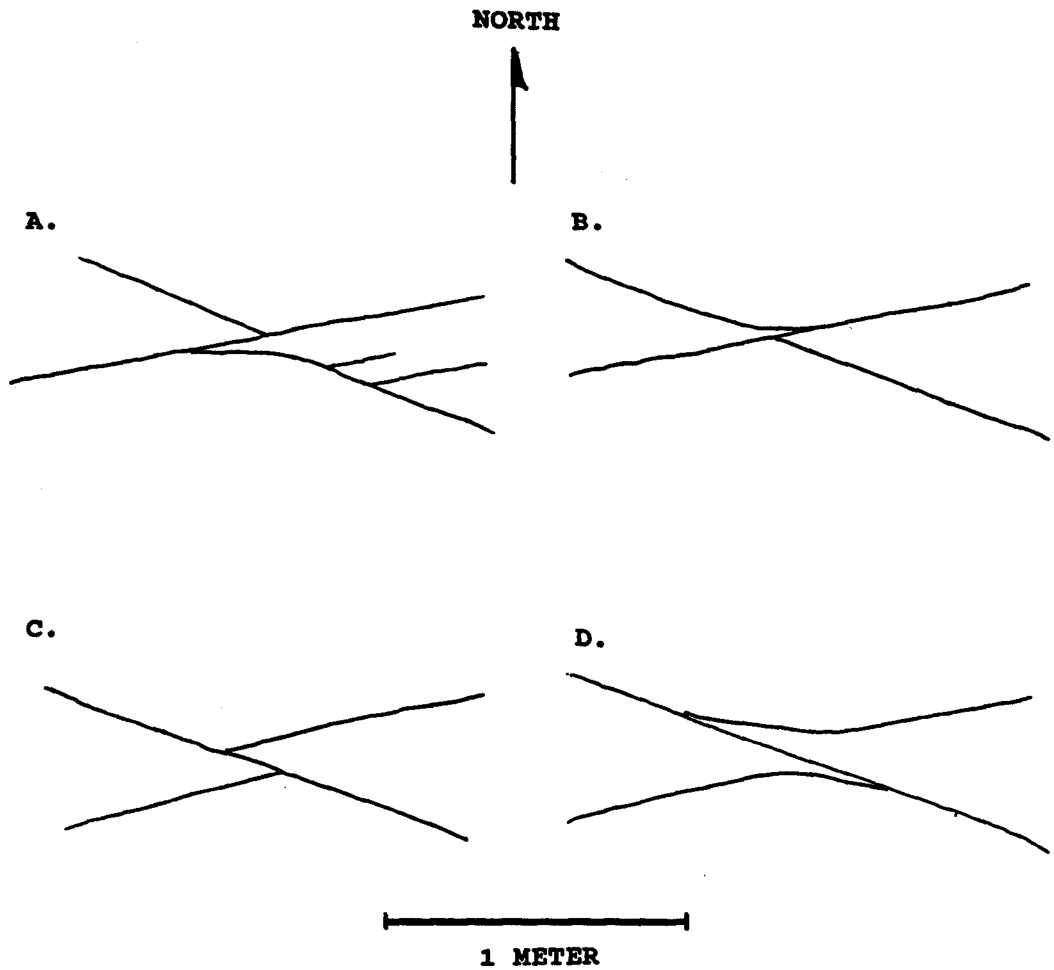

Figure 10. Field sketches from a single sandstone pavement at Hubbard Gulch, north of Rifle, showing relative ages of fracture sets. A and B show an 80-degree set predating fractures that strike 110 degrees, whereas the reverse age relationship is indicated by C and D. This suggests that the two fracture sets were forming contemporaneously.

Figure 11. Generalized trends of natural fractures in the Molina and related sandstones

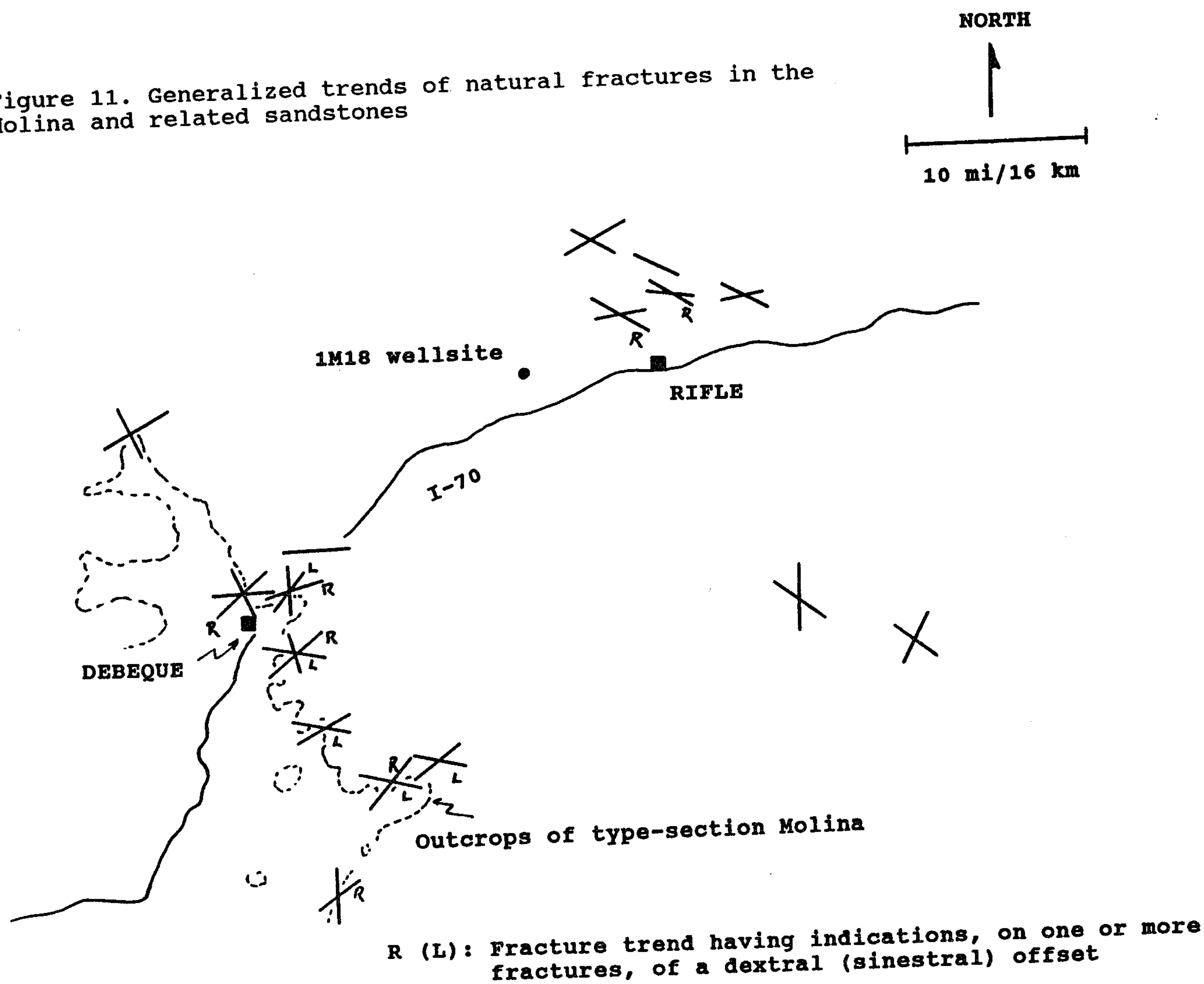

Figure 11. Generalized trends of natural fractures in the Molina and related sandstones.

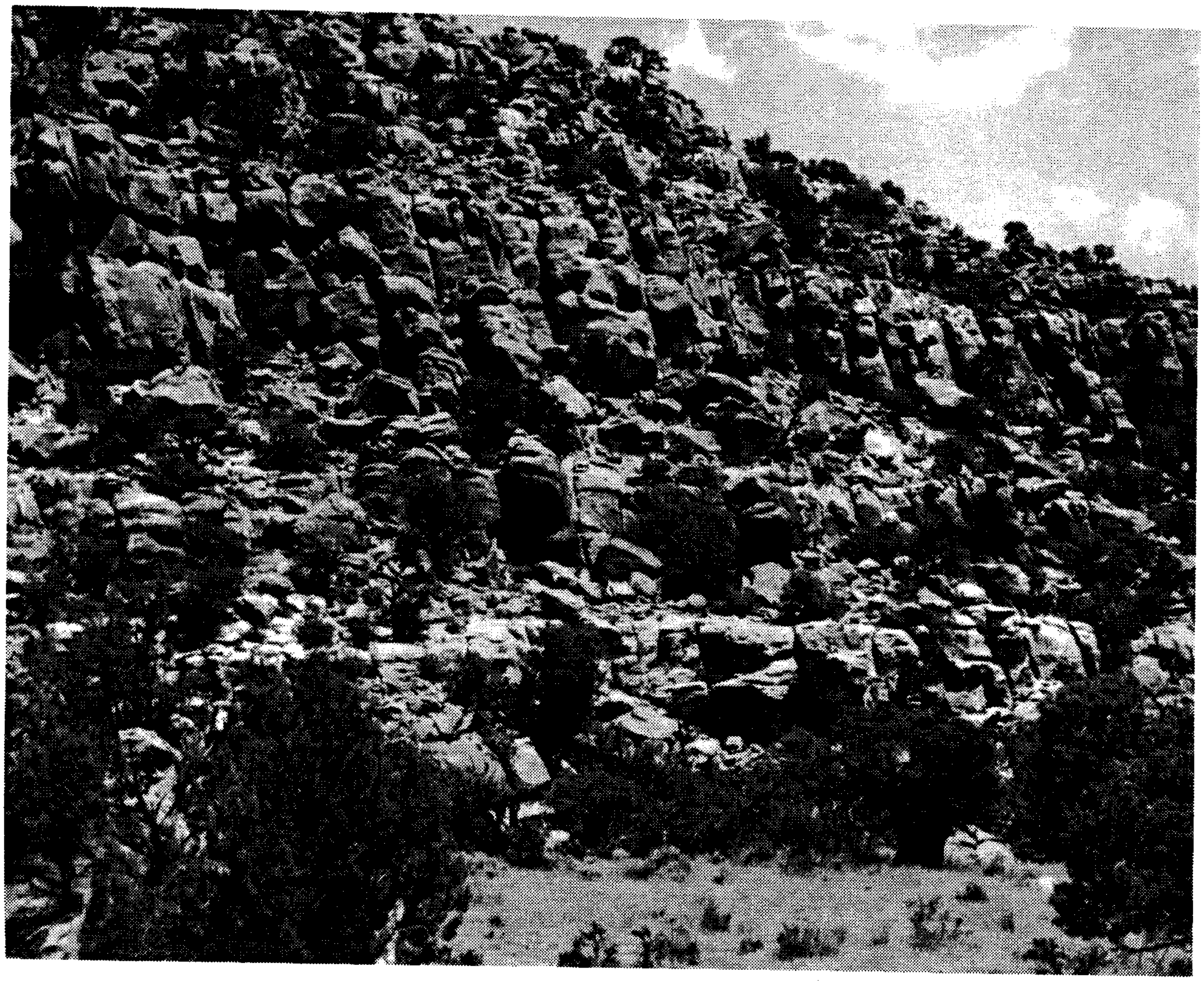

Figure 12. Highly fractured sandstone beds of the Molina Member at the type section.

Fractures in Core from Well #1-M-18

Two mineralized natural fractures (**Fig. 6**) are present in the approximately seven meters of core taken from the "G" Sandstone interval. These fractures are similar to the fractures studied in outcrop. The upper fracture is mineralized with calcite, is about 30 cm in height, and is confined by an overlying shale and an underlying siltstone to a sandstone bed of the same thickness.

The lower fracture is also mineralized with calcite. It is about 1.5 meters in height and occurs within a gray, medium-grained sandstone. It's top and basal terminations are unknown since the fracture is sub-parallel to the core axis and exits the core before terminating. However, it traverses at least 60% of the height of the sandstone bed and probably extends top to base as do most outcrop fractures. This fracture contains oriented calcite crystals suggesting right-lateral, mm- to cm-scale offset. Assuming that it has the same strike as right-lateral fractures in outcrops 15 km to the east, this fracture should have an east-southeasterly strike.

Mobil Exploration and Production U.S. has recently taken core from the Wasatch Formation over the Piceance Dome, about 35 km north of the 1-M-18 well. Fractures in core from this well trend east-southeast and are mineralized with dickite, a polymorph of kaolinite (R. Hager, Mobil, personal communication, September, 1995).

The 1-M-18 well is located southeast of several small magnetic anomalies. The anomalies are similar to a subtle anomaly associated with a 2-meter wide, several-hundred-meter long basaltic dike 15 km to the southwest of the wellsite. The inferred local fracture-enhanced permeability trend is approximately west-northwest, aligned to provide possible conductive pathways between the wellsite and the magnetic anomalies. This direction is also nearly parallel to the local structure contours. Whether or not communication actually occurred between the well site and the location of the magnetic anomalies would have depended on the local hydraulic gradient.

Probable Effects of Fractures on Fluid Flow

While fractures enhanced vertical flow within sandstones, vertical flow between sandstones probably was and is severely restricted by the intervening muddy intervals. Thus fluid migration was channeled within horizontal planes defined by fractured sandstone beds.

Directions of rapid fluid migrations were further restricted by fracture orientations. The maximum permeability due to fracturing should be in the direction of the bisector of the orientation of the local fracture pairs, **assuming** that 1) both fracture sets have equal development in the subsurface (reasonable, based on outcrop observations), and 2) that the in situ stresses are oriented such that neither fracture set is preferentially squeezed shut (reasonable, assuming that little stress has been added to the strata since fracturing). Flow in response to any hydraulic gradient or head could have been substantially diverted parallel or sub-parallel to the preferred permeability anisotropy provided by the fractures once they formed. The fractures probably formed in response to Laramide tectonics at the margins of the basin, thus their age is probably about 40-50 million years. They were available for fluid transport by the time the sandstones were exposed during erosion at the basin margins.

This direction of maximum permeability must also be correlated with outcrop/recharge areas and with the geometric trends of the sandbodies. The fracture-enhanced permeability direction is approximately east-northeast in the southwestern and western parts of the basin, orthogonal to the general trend of the Molina outcrops and sub-parallel to structural dip. Thus the type-section outcrops represent an area of significant potential for meteoric water recharge into a permeability system that has its maximum permeability leading directly down-dip, albeit at only a few degrees, into the center of the basin.

However, facies and paleocurrents suggest that the sandbodies of this system have their long axes striking nearly north-northwest, normal to the high-permeability trends. Although a sandy interval can be traced on well logs northeastward across the basin, individual sandstones of this system are probably more discontinuous laterally in this direction, across depositional strike, than they are north-south, parallel to depositional strike. (Detailed study of the subsurface well logs is suggested in an effort to resolve the degree of discontinuity.) Thus the plumbing system in the east-northeast direction is probably discontinuous despite fracturing, and an influx of meteoric water to the 1-M-18 well site from this source may not be the most probable scenario. This is especially so given that the Molina Member is thinnest at its northern outcrop extent, where the east-northeast permeability trend is best aligned between outcrop and wellsite.

As discussed in the sedimentology section, the type-section sandstones may not correlate directly to sandstones usually considered to be "Molina" at the eastern edge of the basin, and rim-to-rim hydraulic connectivity across the basin is unlikely. Nevertheless, the laterally-continuous sandy intervals north and southeast of Rifle represent outcrops with their own recharge potential, especially where they have been up-ended into vertical flatirons along the Grand Hogback. Fracture orientations, however, trend nearly transverse to the steep structural dip, thus invasion of water at this margin of the basin would not have been significantly aided by fracture permeability to the south of the Grand Hogback, but could have been enhanced west of the dogleg (hogleg?) in the hogback, in the general direction of the 1-M-18 well.

Paleocurrent and grain-size data suggest irregular, probably generally east-west depositional axes for these sandstones, but the data are not conclusive. We prefer not to speculate on the interaction of fracture trends, sandstone geometry, and flow in this part of the basin at this time. Correlation of subsurface well logs may shed more light on this aspect of the problem. However, the smaller thrust and normal faults that are now being discovered during industry drilling may prove to be a major control on the local movements of ground waters.

Conclusions

One of the primary concerns of the U.S. DOE's Piceance Basin Subsurface Science Program is the discrimination between a transported origin and an in situ, long term survival origin for the microbial community in the Wasatch core from the 1-M-18 well. Geologic field studies have provided certain constraints on the potential for fluid flow, and thus on possibility for microbe migration or transportation, through the Wasatch Formation (specifically through the Molina Member of the formation). These constraints suggest that lateral migration through the formation was possible, even probable, if a hydraulic gradient existed after fracture formation, about 40 million years ago. Thus the microbes found in the 1-M-18 core could conceivably be a transported microbial community rather than a long term, in situ survival community, remnant from the primary depositional system and time.

The Molina consists of sandy to conglomeratic deposits of braided and meandering fluvial systems, which are present on the western and eastern margins of the basin respectively. The physical and temporal equivalence of these systems, however, cannot be proven. They may become amalgamated along the depositional axis of the basin.

Natural fractures are present in all Molina sandstones, commonly as apparent shear pairs. Hydrologic continuity through the sandstones of the Molina Member of the Wasatch Formation is dominated by the potential for east-west flow in the natural fracture systems, but this flow is confined within sandstones that trend generally north-south (east-west at the eastern edge of the basin). Any preferred hydraulic gradient would have to contend with this system of horizontally anisotropic permeability in the formation. A hydraulic gradient probably could not have existed prior to the exhumation of the sandstones at the edges of the basin, and their exposure to recharge conditions, at 40 million years ago (eastern edge of the basin) or 9 million years ago (western edge of the basin). Fracture-enhanced flow probably does not occur vertically across the formation or between sandstones, since the intervening mudstones are not fractured in the same manner.

Core from the 1-M-18 well contains natural fractures similar to those found in outcrops, and has sedimentological affinities to the meandering systems of the eastern margin of the basin. Microbes from this core could have been transported into the local formation by lateral migration and/or fluid transport through natural fractures in the sandstones, from the nearby eastern edge of the basin, beginning about 40 million years ago.

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