LANDWARD PINCH-OUT OF CRETACEOUS MARINE NEARSHORE CLASTICS IN THE FERRON SANDSTONE MEMBER OF THE MANCOS SHALE AND BLACKHAWK FORMATION, EAST-CENTRAL UTAH; POTENTIAL PETROLEUM STRATIGRAPHIC TRAPS

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CONTRACT REPORT 91-12 **AUGUST 1991**
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UTAH GEOLOGICAL SURVEY

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Abstract

Nearshore marine sandstone is an important oil and gas reservoir rock. The pinch-out of these sandstone bodies into the seaward marine shales is a well-known exploration target. The landward pinch-out of this same sandstone is more complex stratigraphically and under-explored as a potential stratigraphic play. The landward pinch-out of nearshore marine sandstones have proved their potential for hydrocarbon production. Several examples of production from this type of trap are described.

Wave-dominated shoreline sandstone deposits of the Blackhawk Formation, in the Book Cliffs, and fluvial-dominated shoreline sandstone deposits of the Ferron Sandstone Member of the Mancos Shale, along the Coal Cliffs of Utah, are examined to better understand the nature of the landward pinch-out trap. Drill-hole data and measured sections from the two study areas indicate the fluvial-dominated shoreline deposits (Ferron Sandstone) abruptly pinch-out into coastal-plain deposits. The wave-dominated Blackhawk Formation pinch-out of shoreline sandstone occurred over a quarter- to half-mile. The pinch-out was into sandy facies of marginal marine origin and eventually into finer-grained coastal-plain rocks.

The fluvial-dominated landward pinch-out play is potentially smaller in size due to the discontinuity and heterogeneity of the shoreline deposits. More homogeneous and continuous wave-dominated shorelines provide potential for larger-size reservoirs

associated with a landward pinch-out trap. Down-cutting channels may breach the trap. Only in the Ferron Sandstone area was such a potential breaching channel deposit observed. Coastal-plain deposits are generally fine-grained and lowest in permeability of the entire sediment package, providing excellent trapping characteristics in both depositional systems.

Numerous locations in Utah are potential exploration areas for the landward pinch-out play.

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Introduction

Nearshore marine sandstone is an important oil and gas reservoir rock in the Rockies and around the world. Many large oil and gas fields are found where marine sandstone facies are encased by marine shale and the seaward pinch-out of the sandstone is structurally up-dip. The structural dip in these reservoirs is now in the opposite direction of the original depositional dip. This down-depositional dip (seaward pinch-out) stratigraphic trap is a proven target in exploration.

Nearshore marine sandstone sequences which have a structural dip similar to the original depositional dip often provide good stratigraphic traps. Nearshore marine sands must also pinch out in a landward direction, often into finer-grained rocks landward of the beach, such as lower coastal plain environments (bay, lagoon, or swamp). This type of hydrocarbon trap is more complex than the seaward equivalent because the landward entrapping environments are often more texturally heterogeneous, containing sand bodies (i.e. tidal channels, distributary channels, washover fans, levees, etc.) capable of breaching the trap. There are, however, numerous examples of good production from up-depositional dip or landward pinch-outs of marine nearshore sandstone (see page 4).

Two outcrop examples of non-producing landward pinch-outs of marine nearshore sandstone are examined here. One example is from the Blackhawk Formation in the Book Cliffs and the other from the Ferron Sandstone Member of the Mancos Shale. Both field examples are in central Utah (Figure 1). The Blackhawk Formation was deposited in a wave-dominated delta system (Balsley, 1980), and the Ferron Sandstone in a river-dominated system (Cotter, 1976). The study compares the nature of the landward pinch-out of nearshore marine sandstone in each of the two delta systems.

Outcrop measurements and mapping as well as subsurface data are used to characterize the nature of the landward pinch-out in three dimensions at both locations. Using this information as a model, several areas in Utah are identified as having potential for a similar stratigraphic trap.

General Description of the Depositional Systems

Wave-Dominated Deltas

Modern wave-dominated deltas have been described in the literature by numerous authors (Fisher and others, 1969, Galloway, 1975, and Coleman, 1976). The most important characteristic of this type of delta is the dominance of wave energy at the point of discharge of the river system into the sea. Most of the sediments carried to the coast by the rivers are moved away from the point of discharge into the sea and redistributed along the coast by wave energy. The result is a cuspate shaped geometry (Figure 2). Balsley (1980) has shown the tidal range of the Blackhawk and associated wave-dominated delta deposits to be about one meter (microtidal). Much of the Blackhawk Formation records numerous eastward progradations of wave-dominated deltas into the Mancos Sea. The number of breaks in the littoral progradational sequences (points of sediment influx from rivers, bays or lagoons) is relatively small, leading to the conclusion that the shoreline was fed by several moderate-sized deltas with large areas of strand plain and interdeltaic coastline (Balsley, 1980).

Wave-dominated deltas have an easily identifiable suite of facies which represent a littoral sequence. Figure 3 illustrates a typical vertical section. Individual progradations (members or parasequences) in the Blackhawk Formation have been traced in outcrop up to about ten miles in a depositional dip direction (Balsley, 1980). Depositional strike control on the Blackhawk Formation littoral sequences is limited by the outcrop exposure, but the Star Point Sandstone littoral deposits (partial equivalent to the Blackhawk Formation in the Book Cliffs) extend well over ten miles in a strike direction in exposures along the Wasatch Plateau.

River-Dominated Deltas

As the name implies, river-derived energy dominates over wave and tidal energy in this depositional system (Figure 2). The Mississippi River delta is river-dominated and has been intensively studied. Previous work is summarized in a paper by Coleman and Wright (1975). Fisher and others (1969) refer to the Mississippi River delta as a high-constructive, elongate feature, indicating the dominance of fluvial energy over marine wave energy. The Ferron Sandstone appears to lie in the fluvial-dominated classification of Galloway (1975) but is more lobate in shape (Ryer, 1983), indicating more influence of wave energy on the delta.

The distribution of delta-front sand bodies in the river-dominated delta systems tends to be parallel to depositional dip and somewhat isolated by finer-grained sediments of interdistributary bay deposits. The lateral continuity of these sand bodies along depositional strike increases as the wave energy increases on the system.

Production Examples from Landward Pinch-outs

Stratigraphic traps accounted for 10% of all sandstone oil and gas reservoirs in the U.S. in the late 1950s (Curtis, B.F. and others, 1961). Most (38%) of the stratigraphic sandstone traps were deposited in beach or nearshore environments (op. cit.) and represented 52% of the reserves from sandstone stratigraphic traps in the U.S. Up-depositional dip or landward pinch-out stratigraphic traps were not tallied separately in the study. Several examples of production from landward pinch-out stratigraphic traps from both wave- and river-dominated shorelines are briefly reviewed to show their importance in historic production.

Wave-Dominated Systems

Many of the examples of production from this delta or shoreline system have been more specifically identified as barrier island sandstones. Barrier islands are formed on a coastline with wave-energy dominate over tidal or river influences and, therefore, have been included in this section.

Milbur Field, Texas.

Milbur Field, Milam and Burleson Counties, Texas, is not strictly a wave-dominated delta example, but is interpreted as a barrier island complex by Berg, 1975. The importance of the example is that lagoonal deposits create the trap and marine shoreline facies are the reservoir. Most of the production from the field comes from sand thicknesses of less than 20 feet. In this example the porosities of the lagoonal facies (trapping rock) is about 30 percent less than the reservoir (littoral) and the permeability about 85 to 90 percent less (lagoonal facies: 19-24 percent porosity and 25-153 md permeability). The trap rock is capable of producing water.

Patrick Draw Field, Wyoming.

One of three important producing sandstone bodies from the Patrick Draw Field, located in Sweetwater County, is interpreted to be a barrier bar nearshore marine sandstone (Weimer, 1966). The structural dip and depositional dip of the rocks are presently oriented in the same general direction. Up-dip of the marine sandstone is non-marine swamp and lagoon deposits. These non-marine or lower coastal plain facies provide the trap for large oil and gas accumulations at Patrick Draw.

Frio Formation, South Texas.

The Frio Formation consists of several facies ranging from deep-water marine to coastal plain or lagoonal. The structural position of the formation is relatively unchanged since deposition took place. The greatest oil and gas production comes from barrier island facies, with smaller amounts associated with the delta facies and some washover fans. The oldest and greatest production is in the barrier island facies where the reservoir has been folded into closed anticlines on the downthrown side of growth faults (Burke, 1958). A significant amount of production along the old strandline is, however, from purely stratigraphic traps (Fisher, 1970). The traps are created by the porous barrier island facies pinching out into up-dip non-marine lagoonal facies.

As of 1970, 50 fields in the Frio strandline trend had produced over one million barrels and ten fields had exceeded ten million barrels each.

Atkinson Field, South Texas.

Atkinson Field, in the Reklaw Formation (Eocene) South Texas, produces from a barrier island sandstone (Bulling and Breyer, 1989). The stratigraphic trap consists of lagoonal deposits on the landward side of the barrier island sandstone.

River-Dominated Systems

Lower Wilcox, Texas.

The Lower Wilcox (Eocene) of Texas produces from reservoirs associated with the Rockdale delta system which is classified as a high-constructive delta system (Fisher and McGowen, 1967). The term high-constructive is often used synonymously with fluvial-dominated. As with other delta deposits in south and central Texas, the Rockdale delta system remains in the same general structural orientation now as when deposited, or the structural dip and the depositional dip are in the same general direction.

Many of the fields which produce from the Rockdale delta system tap delta-front deposits and marine-reworked sands from episodes of delta destruction (transgressions). Delta-front sandstone is vertically stacked and intertongues with marine mudstone, resulting in multiple producing zones. The delta-front sandstone is sealed in the up-dip direction by strand plain or lower coastal-plain rocks.

The University of Texas at Austin, Bureau of Economic Geology are presently studying the Ferron Sandstone as an analog to the Lake Creek Field (gas) in Texas. The Lake Creek Field is developed in the Lower Wilcox Group (Rockdale Delta System) and produces from heterogeneous reservoir rocks deposited in a river-dominated deltaic system. Some of the traps are stratigraphic in nature. The depositional dip and structural dip are generally the same at Lake Creek.

Olmos Formation, Texas.

The Olmos Formation (Cretaceous), Texas, contains a series of both wave- and river-dominated deltas with oil and gas production from both delta system deposits (Tyler and Ambrose, 1986). The Big Foot delta system in Frio and Atascosa Counties has reservoirs in deltaic sandstone deposited in river-dominated deltas. Stratigraphic traps account for 51,927,833 billion barrels equivalent production (Tyler and Ambrose, 1986, p. 31), some of which is from landward pinch-outs of deltaic shoreline sands.

Breathitt Formation, Kentucky (non-producing).

Breathitt Formation contains Carboniferous deltaic deposits which are a good analog to the Ferron Sandstone in several respects. However, no production of oil or gas is known from these rocks. The Carboniferous delta deposits are exposed along road cuts in eastern Kentucky and have been documented in the literature (Baganz, B.P. and others, 1975). The similarity of the two river-dominated delta systems is in their setting. The distance from the source area to the delta in the Carboniferous is believed to be 150 to 200 miles, the size of the distributary channels feeding the delta are 600 feet wide and 40 feet deep, the river mouth bar deposits are maximum of 2.5 miles wide and 70 feet thick, and the average grain size in the system is somewhat larger than found in the Mississippi because of the shorter transport distances. The system had numerous points of discharge (deltas) rather than one large point of discharge.

Field Studies

Blackhawk Formation, Book Cliffs, Utah
Wave-Dominated Delta Deposits

Previous work

Coal spawned early workers' interest in the Book Cliffs (Forrester 1893, Storrs 1902, Taff 1906, Richardson 1909, and Clark 1928). Attention was turned to the stratigraphy of the Book Cliffs as the oil and gas industry developed new resources in Cretaceous deposits (Fisher 1960, Hail 1956, Howard 1966, Abbott 1956, Hale 1959, Walton 1944, and Zapp 1960). Some of the first attempts to describe the depositional settings of the

Mesaverde section in the Book Cliffs were by Young (1955, 1957, 1966, 1976). Balsley (1980) refined the earlier interpretations of Young and suggested that most of the sheet sands of the Blackhawk Formation were deposited in a wave-dominated delta system.

Stratigraphic Framework

The Blackhawk Formation is about 1000 feet thick in the field study area (Anderson, 1983) and is Upper Cretaceous (Campanian) in age. Blackhawk deposition took place along the west shore of the Western Interior Cretaceous Seaway (Kauffman, 1977). Figure 4 summarizes the regional depositional systems for the Blackhawk Formation. The chiefly regressive, nearshore deposits of the Blackhawk Formation shown in Figure 4, intertongue with coastal plain and prodelta marine rocks. Generally the source area for the Blackhawk sediments was to the west in the Sevier orogenic highlands. Balsley's (1980) work has shown a more localized depositional dip of northwest, with some variation in individual shoreline deposits or members of the Blackhawk Formation.

A small portion of Balsley's measured sections are reproduced in Figure 5. The correlation of the sections are modified between Dugout and Rock Canyons (Figure 6) from those shown in Balsley (1980). Complete littoral sequences have been informally named to help follow the sequences through the cross section. The Kenilworth member, below, and the Sunnyside member, above, are fully-developed regressive nearshore marine sandstone sequences and found across the entire study area. (Fully-developed meaning they contain a complete suite of facies associated with a regressive wave-dominated shoreline sequence.) This sequence is described in detail in Anderson, 1978 and 1983, and Balsley, 1980.

Stratigraphically between the Kenilworth and Sunnyside members (between Dugout and Bear Canyon sections, Figure 5) are the Rock Canyon, Tank Canyon, and Bear Canyon members or marine nearshore sequences (Figure 7). The names are assigned based on the canyon in which they are most fully developed. These nearshore sequences, stratigraphically between the Kenilworth and main Sunnyside members, indicate a short episode of vertical stacking or aggradation punctuated by the Lower Sunnyside member, which steps in a landward direction. The main Sunnyside member resumes the more typical seaward-stepping regression. Figure 5 indicates that the landward pinch-out of the Rock Canyon, Tank Canyon, and Bear Canyon marine shoreface deposits or members takes place between Rock and Dugout Canyons. The pinch-outs are, laterally, into marginal marine/coastal plain facies. Field work focused on describing the nature of these three landward pinch-outs of marine nearshore sequences.

Outcrop studies

Nine stratigraphic sections were measured along the Book Cliffs escarpment between Dugout Canyon and Rock Canyon.

Balsley's (1980) sections of the Blackhawk Formation measured in Dugout, Pace, and Rock Canyon were also used in the study. Figure 8 shows the locations of the sections used and the outcrop of the top of the Kenilworth and Sunnyside marine sequences. The sections located on Figure 8 can be found in the Appendix.

Figure 9 is a diagrammatic cross section from Dugout Canyon to Rock Canyon. A detailed section of this area can be constructed using the sections in the Appendix. See Figure 8 for the locations of the sections in this area and the orientation of the pinch-outs based on examination of drill-hole and outcrop data.

The position of the landward pinch-outs is gradational taking place over about a quarter- to a half-mile. The end of the distinctive littoral facies is better described as "faded out." As the landward pinch-out is approached from a seaward direction (southeast), the shoreface sequence gradually thins by loss of progressively shallower water facies (from prodelta to lower shoreface). The pinch-outs in Figure 9 are not an abrupt loss of sand thickness but a gradual change of facies within the sandstone body.

The stratigraphic position of the marine rocks is occupied, in a landward position, by rocks which have some marine characteristics (marginal marine or restricted marine), but are definitely not identifiable as part of an organized shoreface sequence. The correlative rocks of the Tank Canyon member showed definite fining in grain size, landward of the pinch-out (see Section #4, Appendix).

In each of the three pinch-outs the encasing rocks were deposited in coastal plain environments. Generally these coastal plain facies are finer-grained than the marine rocks. Fluvial channel sands were present in the section, but no example of down-cutting into the marine facies was seen on the outcrop. Channel cuts into the marine nearshore rocks would, however, be expected in the system.

Van Wagoner and others (1990, figure 13) illustrate a landward pinch-out of a Blackhawk Formation marine sequence in Spring Canyon. At this location the marine sequence is abruptly truncated by flood-tidal delta deposits from a migrating tidal inlet. Such an abrupt pinch out would enhance a stratigraphic trap in the nearshore marine section, but would be small in aerial extent.

The top of the cliff-forming Kenilworth member was used as a datum in analyzing the detailed sections. Moving from east to west, from Rock Canyon to Dugout Canyon, an unfamiliar facies developed atop the foreshore facies. On the east this facies is thin and was included as part of the Kenilworth member. In Dugout Canyon and east to section #4, the top of the Kenilworth member was mapped below this facies, at the top of the foreshore. The coal atop the Kenilworth member in Rock Canyon (Kenilworth coal zone) remains atop this developing restricted marine facies, climbing stratigraphically to the west. As noted by Anderson

(1978), the Kenilworth coal zone in the area of Soldier to Dugout Canyons lies several feet above the Kenilworth marine sequence. The rocks between the coal and Kenilworth member contain brackish water faunas (Anderson, 1978).

Subsurface

Coal exploration drill holes are located along the width of the Flagstaff-North Horn dip slope, above the Book Cliffs escarpment (Figure 8). Sunedco (Soldier Creek Mine) was kind enough to release most of their drill-hole information for this study. Unlabeled drill holes were not released for this study. Selected drill-hole logs are located in the Appendix. Drill holes beginning with K on Figure 8 have a driller's core log of roof, floor, and coal for each major coal zone. These logs were of little help in this study and, therefore, are not included in the Appendix.

Reservoir and Trap Quality

The pinch-out of three marine nearshore sequences in the wave-dominated Blackhawk Formation is gradational and not abrupt. The facies which are laterally equivalent to the pinched-out classic shoreface sequence are generally fine-grained to silty sandstone, thinly-bedded, horizontally-, cross-, and ripple-laminated. These rocks would make a poor reservoir and a poor trap.

The encasing mudstone and siltstone is often fossiliferous, with a suite of brackish water mollusks (Anderson, 1978, p. 85-87). The encasing facies (coastal-plain and interdeltaic rocks) have the lowest porosities and permeabilities in the Blackhawk Formation (Balsley, personal communication, 1989), making them the best trap rocks.

Ferron Sandstone, San Rafael Swell, Utah
River-Dominated Delta Deposits

Previous Work

Numerous authors (Cotter, 1971, 1975a, 1975b, and 1976; Hale, 1972; Hale and Van De Graaff, 1964; Ryer, 1981a, and 1981b; Ryer and others, 1980, 1983, and 1986) have described the depositional framework of the Ferron Sandstone. Cotter and Ryer's work are the most detailed and have laid an excellent foundation. Figure 10 is from Ryer and Lovekin (1986) and shows the stratigraphy, age, and correlation of the Ferron Sandstone. Doelling (1972) describes the coal geology of the area, and Tripp (1989, 1990) studied the Ferron Sandstone in the subsurface.

Stratigraphic Framework

Hale (1972) named the delta associated with the Ferron Sandstone as the Last Chance delta. Cotter (1975a) described the delta as a lobate, high-constructive. He described the facies of the Ferron Sandstone and their environments of deposition

(Cotter, 1975b). Most deposition took place during progradations of the delta system. Ryer (1981) recognizes five major progradations of the Last Chance Delta system, all having sheet-like delta-front deposits. He informally groups these five progradations into the upper Ferron Sandstone. Last Chance delta progradations were generally from southwest to northeast.

Ryer's (1981b) stratigraphy and nomenclature are used in this report. A more comprehensive stratigraphic study of the Ferron Sandstone Member is near completion (Mike Gardner, personal common., 1990). Gardner's work indicates the stratigraphic framework of Ryer has held up well. Ryer (1981a) has interpreted the depositional environment of the marine sandstone of the Ferron Sandstone as chiefly delta-front deposits consisting of distributary channel, river mouth bar, and distal bar deposits (Figure 11).

Outcrop Studies

Two areas of the Ferron outcrop were selected to examine the nature of the landward pinch-out of marine sandstone deposits (delta-front) into non-marine deposits. The first area is in Section 13, T22S, R6E, where Muddy Creek enters the Coal Cliffs and the second is further south in the Willow Springs Wash area in Section 18, T24S, R6E (Figure 12).

Muddy Creek Area (J sandstone)

Figure 13 is a portion of Ryer's (1981b) cross section and shows the stratigraphy and relationships of the delta-front sandstones numbered 1 through 7. The cross section shows the landward pinch-out of the J or No. 6 sandstone. The J coal overlies this sandstone and hence, shall be referred to informally as the J sandstone. Potential trapping rocks of the I coal or swamp are present below the J sandstone and the J swamp rocks (coal) are present above the J sandstone.

Figure 14 shows the Muddy Creek study area with measured section locations, thicknesses, and the landward pinch-out location of the J sandstone. The J sandstone can be followed in outcrop to the southeast (depositional strike) about a mile. In Section 18, T22S, R7E, a tributary to Muddy Creek has eroded the J sandstone. In field checking the east side of this side canyon, the J sandstone is eroded or not present and the No. 5 delta-front sandstone caps the top of the mesa. On the west side of this tributary and seaward of the pinch-out, the J sandstone is difficult to distinguish from the underlying No. 5 delta-front sandstone. Mudstone and siltstone of the underlying I swamp are not present in this area. The landward pinch-out of the J sandstone (Figure 14) is exposed in four locations along approximately a mile of outcrop oriented along depositional strike.

Ryer (1981a) has mapped the location of five landward pinch-outs of delta-front sandstone sequences in his area of study and traced them into the subsurface using drill holes. Figure 15 shows the pinch-outs and their orientation. The similarity in trend of the landward pinch-outs for all of the Ferron marine progradations indicates a uniform trend in the tectonics throughout Upper Ferron deposition. The trend of the pinch-out of the J sandstone mapped in this outcrop study corresponds to the trends of the other landward pinch-outs of marine sandstones mapped by Ryer using drill-hole data and outcrops.

Sections J1, J2, J20, J21, J25, J26, and J27 of the J sandstone measured near the landward pinch-out are in the Appendix. Measured section J1 is representative of the thicker portions of the J sandstone. The base of the sandstone is irregular, with about 1-1.5 feet of local relief. It overlies muddy to sandy coastal-plain deposits of the I swamp. In this area the I coal is very thin to absent. Where the J sandstone is generally thicker than 20 feet, the basal 8 to 12 feet of sandstone is dominantly trough cross bedded, the sets are small- to medium-scale, and the upper surface is generally slightly irregular. Sandstone overlying the troughs is finer-grained chiefly horizontal bedded with some small-scale cross beds and occasionally bioturbated. Overlying the horizontally bedded sandstone, is 2 to 6 feet of coarser sandstone (medium-grained) which is completely devoid of sedimentary structures due primarily to bioturbation. This upper sandstone is normally rooted in the upper one foot. The J coal or associated carbonaceous mudstone overlies the bioturbated facies of the J sandstone. The overlying coal ranges from .05 to 5 feet thick.

As the J sandstone thins to the southwest (landward), the facies sequence becomes less predictable. Normally the stratigraphically lower, horizontal bedded and cross bedded sequences drop out, in the above order, as the pinch-out is approached. The upper bed of structureless medium sandstone has better continuity toward the landward pinch-out. At the pinch-out (Figure 16) the sandstone is medium-grained, poorly-sorted, crudely horizontally bedded to structureless, and contains abundant woody fragments, is rooted and bioturbated.

At section J27 the J sandstone contains rounded to angular intraclasts of very-fine-grain sandstone in a matrix of medium-grained sandstone. This is very near the landward pinch-out.

Available outcrops of the J sandstone show general coarsening upward sequences and contain *Ophiomorpha* (a common marine trace fossil). The interpretation of the J sandstone as marine river mouth bar deposits seems appropriate. Lateral discontinuity of facies associated with delta-front sandstone sequence has been documented by Ryer (1981a) and Cotter (1975b).

One interesting feature of the J sandstone geometry is its rapid change in thickness. This variation occurs both near and away from the landward pinch-out of the sandstone. Figure 17 is a diagrammatic cross section which shows the up-dip pinch-out of the J sandstone and encasing units. Note the thinning of the sandstone just northeast of section J1. Similar features were found in the No. 2 delta-front sandstone in the Willow Springs Wash area (see page 22) and Ryer (p. 2327, 1981a) made note of these features. Local thinning of the J sandstone appears to be related to erosion of the sand prior to the deposition of the overlying unit. Locally, the sediments which in-filled erosional cuts into the J sandstone are poorly exposed (delta-plain mudstone) or often completely eroded away (Figure 18).

Willow Springs Wash Area (No. 2 sandstone)

No. 2 delta-front sandstone is exposed in a large area along the Coal Cliffs and makes a good comparison to the J sandstone, which is aerially limited in outcrop. Figure 19 is from Ryer's (1981b) cross section through the Coal Cliffs. He shows the landward pinch-out of the No. 2 delta-front sandstone just northeast of Willow Springs Wash. On Ryer's map of the up-dip limit of the major delta-front sandstones (Figure 15) he indicates the position of the No. 2 delta-front sandstone pinch-out along the north edge of Willow Springs Wash. Present work confirms this as a good pick for the pinch-out. Figure 20 is a map of the area studied in detail in the Willow Springs area.

Sections W1 through W11 were measured near the landward pinch-out and are in the Appendix. Figure 21 is a cross-sectional profile of the No. 2 sandstone drawn along the outcrop, which approximates depositional dip. The top of the No. 1 delta-front sandstone is used as the datum for the cross sectional profile. The landward pinch-out of the No. 2 sandstone is shown on the section and the irregular thickness of the marine sandstone is well demonstrated.

The base of the No. 2 delta-front sandstone lies atop the sub-A coal zone or delta-plain swamp. This coal zone is correlatable for several miles to the north and south. The non-marine deposits associated with the coal zone thicken in the direction of the landward pinch-out of the overlying No. 2 delta-front sandstone. Section W8, measured near the landward pinch-out of the No. 2 delta-front sandstone has 6 feet of mudstone with a brackish water fauna (*Corbula,s.p.*, *Brachidontes*, *Anomia*, *Ostera*, *Crassostera?*, *Neogastropoda?*) lying just below the No. 2 sandstone. Section W9 also contained brackish-water faunas above the No. 1 sandstone (Figure 20).

The sequence of sedimentary structures found in the No. 2 delta-front sandstone vary along the cross section (Figure 21). In the thicker sections (W6-W8), the lower sequence is dominantly horizontal- to ripple-bedded sandstone which is slightly to intensely bioturbated (*Ophiomorphia)*. Lunate symmetrical ripples (Figure 22) are common as set boundaries in this facies. Their approximate length is 21 cm and height 5 cm, and average crest orientation is N 12°W. The upper sequence is dominantly trough cross bedded with only occasional bioturbation. Ryer (p. 2326, 1981a) describes the thicker delta-front sequences as consisting of a lower horizontally bedded unit and a upper dominantly cross bedded unit. The lower unit being interpreted by Ryer as distal bar and the upper unit mouth bar.

Capping the No. 2 sandstone in most locations is a fine- to medium-grained, intensely bioturbated, often rooted unit. This facies occurs in the thinned areas of the No. 2 sandstone, where it has been channeled. The environment of deposition of this capping facies may be related to subsidence of the delta lobe and transgressive flooding. This subsidence could be caused by local tectonics or more likely early compaction of the delta lobe.

Tens of feet of relief exists on the top of the No. 2 delta-front sandstone, similar to the geometries found in the J sandstone to the north. Abrupt changes in thickness are caused by paleochanneling into the marine mouth bar deposits. Channel-fill deposits vary from sandstone to non-marine delta-plain deposits. Figure 23 is a view of thinned No. 2 sandstone caused by channel scouring near sections W7 and W8. Similar channel cuts are present near sections W3 and W4, where bedding planes in the No. 2 delta-front sandstone are truncated by paleoerosion into the sand (Figure 24).

In Figure 24 the uppermost sandstone bed drapes down the steep channel edge cut into the main body of the No. 2 delta-front sandstone. At this location the uppermost sand was deposited by a local transgressive flooding, is intensely bioturbated and medium-grained, which is usually coarser than the underlying sandstone (mouth bar or distal bar deposits). The uppermost sandstone bed has good lateral continuity but it does vary in thickness. It is believed to be reworked because of its continuity and coarser grain size.

The channeling is believed to be related to local changes in the base level of the river system feeding the delta's progradation. Upstream avulsion sometimes leaves the channels only partially filled with sand, allowing the remainder of the channel to fill with delta-plain deposits. Although prior to the deposition of delta-plain deposits, the water depth over this area of the No. 2 delta was deep enough to cover the topography left by the channels and rework (winnowing and bioturbation) the upper few feet of sand. [To have enough energy to winnow out the medium-grained sand and yet not redistribute the sand and fill the channels is puzzling.] At this point, the fine muds of the delta plain began to cover the older delta-front sands as regression continued.

A spectacular exposure of a channel was found in the north side of Willow Springs Canyon (Figure 25), in NESE 13, T24S, R5E (see Figure 20). The Emery-Sevier county line runs through the channel and hence, it will be called the County Line channel. The channel cuts down through delta-plain deposits and into the No. 1 delta-front sequence. It is approximately 1,500 feet wide and has a maximum thickness of 55 feet. The profile of the County Line channel cut indicates an approximate normal-to-flow outcrop section and denotes a north-south component of flow direction at this location. Across the canyon to the south, another channel is visible in the canyon wall above the No. 1 sandstone. Assuming this is the same channel, the south to north flow direction is further confined.

The top of the County Line channel lies at the same stratigraphic position as the No. 2 delta-front sandstone found just a few hundred feet to the east. The channel cuts about 20 feet down into the No. 1 delta-front sequence and attains a maximum thickness of 55 feet. Modern river-dominated delta systems have distributary channels with depths of around 60 feet near the mouth-bar deposits. The County Line channel probably fed the prograding river-mouth bar deposits of the No. 2 sandstone to the north and east.

In a seaward direction, near measured section W2, the distinctive division of the No. 2 delta-front sandstone into horizontal bedded (distal bar) and dominantly trough cross bedded (mouth bar) facies breaks down. Measured section W1 is about 50% thinner than section W2 and contains complexly interbedded marine sandstone, siltstone and mudstone beds. It represents the edge of the mouth bar sequence and perhaps the edge of a "delta lobe" of the No. 2 marine progradation.

A "white cap" was noted on the top portion of the No. 2 delta-front sandstone in this area. Balsley (1980) has shown that the "white cap" in the Blackhawk Formation is due to the absence of detrital dolomite (and associated iron) in the higher energy portion of the beach (foreshore and upper shoreface). In the Willow Springs Wash area the No. 2 delta-front sandstone "white cap" is generally associated with trough cross bedded, fine- to medium-grained sandstone. Thin section work has not been done on these facies and it can only be suggested that the presence of the "white cap" may be related to winnowing sands by wave action, depleting them of denser detrital iron rich dolomite.

The pinch-out of the No. 2 sandstone is marked on Figure 20 and shows no distinct bedding features. The unit is fine- to medium-grained and bioturbated, rooted, and pinches out into mudstone and siltstone of delta plain origin (Figure 26).

Subsurface work on the landward pinch-out of the No. 2 sandstone is summarized in Ryer, 1981a and shown on Figure 15. The trend of the pinch-out shown by Ryer cannot be confirmed by outcrop work because of the lack of several exposures needed to delineate a trend.

Reservoir and Trap Quality

The lateral and vertical changes found in the river-dominated delta-front (marine) sandstone provide the sedimentologic framework for dissecting and compartmentalizing a potential reservoir. Ryer (1981a) noted a predominance of river-mouth bar deposits in the delta-front sequences of the Ferron Sandstone. The upper facies (mouth bar) is trough cross bedded, indicating enough energy to winnow out finer fractions and produce a reasonable reservoir. Balsley (1980) found the facies with the greatest porosity and permeability was the upper shoreface, which is dominantly trough-cross bedded and deposited in the surf zone where wave energy winnows out the finer fraction material. Reworking of sediments by wave energy is evident in the Ferron Sandstone by the abundance of cross bedded structures in the mouth bar deposits and the "semi-" sheet-like nature of the delta-front sandstones. These higher energy environments have produced reasonable reservoir rocks, as evidenced by nearby hydrocarbon production (Tripp, 1989).

The size of the potential reservoir should be smaller in the river-dominated system than in the wave-dominated system. The volume of marine trough-cross bedded facies (mouth bar) was limited in the two Ferron areas studied. There was a relatively large area (1-2 square miles) of thick (>10 feet) mouth bar facies found north of Willow Springs, in Rock Canyon in the No. 2 delta-front sequence.

The trap quality, like the reservoir quality, varies considerably. In the Muddy Creek area the J delta-front sandstone is consistenly overlain by carbonaceous mudstone or a few inches to several feet of coal. The coal is overlain by mudstone to sandstone and finally capped by hundreds of feet of marine shale (Blue Gate Shale Member of the Mancos Shale). In the area of the landward pinch-out, below the J sandstone, is sandy to silty mudstone of the I swamp. These deposits are 10 to 12 feet thick. Just seaward (approximately 1/2 mile) of the landward pinch-out the mud rocks of the I swamp are gone and the J sandstone appears to lie on rocks deposited in a distributary channel environment associated with the No. 5 delta-front sequence. The equivalent section of thick (>30 feet) channel sandstone associated with the No. 5 regression or parasequence is well exposed on the west side of Muddy Creek, just south of the landward pinch-out of the J sandstone. Assuming the distributary channel deposits have enough porosity and permeability to leak potential hydrocarbons, the width of the potential trap in the J sandstone at the study area (given the proper structural orientation and burial) would be limited to about 1/2 mile in the dip direction.

Tyler and others (1990) noted a low-permeability (less than five millidarcies) zone at the base of the distributary channel complex above the No. 5 delta-front sequence in Muddy Creek. Distributary channel complexes above delta-front sandstones may not be as "leaky" as previously thought. This fact enhances the potential for traps associated with landward pinch-outs.

In the Willow Creek area the No. 2 delta-front sandstone lies on top of 12 to 30 feet of delta-plain and/or brackish-water interdeltaic deposits. On the north, the marine No. 2 sandstone consistently lies atop a 1 to 3 foot thick coal. Overlying the No. 2 delta-front sandstone is 15 to 50 feet of mudstone, siltstone, and coal, with a few thin lenticular beds of sandstone (delta-plain deposits). Above the delta-plain deposits is a thick section of alluvial-plain (Ryer, 1981a) deposits which consist of dominantly thick lenticular channel sandstone. The only potential breach in a hypothetical trap of the No. 2 delta-front sequence at the landward pinch-out, as exposed on outcrop, was the County Line channel sequence exposed on the north side of Willow Springs Wash (page 23). Recall that this channel sequence occupied a similar stratigraphic position as the pinched-out No. 2 delta-front sandstone and cut into the underlying No. 1 delta-front sandstone. Assuming this channel sequence eventually becomes juxtaposed with the No. 2 delta-front sandstone, further to the north (seaward), the channel sequence could become a spill point into the lower No. 1 delta-front sandstone, limiting the size of the reservoir in the No. 2 delta-front sandstone. Tyler and others' work shows low permeabilities at the base of distributary channels may inhibit migration of hydrocarbons, perhaps eliminating the channel complex as a leak point in the potential trap.

Potential Plays in Utah

A cursory examination for potential targets from landward pinch-outs of marine nearshore facies within Utah was performed. Several possible locations are listed below; their locations are shown on Figure 27.

1. West side of Pine Valley Mountains. A Cretaceous section is probably dipping to the east into the Gunlock Fault. The best possibilities are in the southern area along the Shebit Syncline.
2. Kaiparowits Basin. Numerous small structures exist within the basin. A thick section of Cretaceous rocks is buried in the basin, some may be in the proper structural orientation.

3. West side of the Paunsaungunt Syncline (near Beaver). Here Upper and perhaps Lower Cretaceous sediments should be in the proper structural orientation. It is not clear if the proper facies are present.
4. The area north of the Alstrom Hollow fault to the volcanics of the Circleville area are prospective.
5. John's Valley Anticline, Garfield County. In the northeast quadrant of T34S, R2W, the Straight Cliffs and Dakota formations should be in the proper structural orientation.
6. East-flank of the Upper Valley Anticline. Here the Dakota through Straight Cliffs formations offer some potential.
7. East-flank of the Butler Valley Anticline, T37-38S, R1E.
8. East-flank of the Huntington Anticline (T17S, R8E). The Ferron Sandstone is prospective here and along the east flank of several other structures which have eastward dipping strata in the Cretaceous.
9. Southern flank of the Uinta Basin (Green River and Wasatch formations). Production has been established in this area where the deltaic deposits of the Wasatch intertongue with the lacustrine facies of the Green River Formation. Although these rocks are not marine, many of the processes along the margins of the lake are similar to those in Cretaceous shorelines,

creating similar potential for landward pinch-outs and traps.

Summary

The stratigraphic hydrocarbon trap of the landward pinch-out of marine nearshore or littoral sandstone bodies has proven productive potential. This type of trap is found in both river- and wave-dominated delta systems. By comparing an outcrop example from both depositional systems a better understanding of the detail of the stratigraphy and contrast of potential trap and reservoir quality is developed.

The landward pinch-out in the river-dominated delta system is abrupt, providing a better potential trap. Geometries and facies within the delta-front environments are more heterogeneous in the river-dominated system. The size of the potential reservoir (both as a gross sand body and flow unit) is smaller in the river-dominated system.

The landward pinch-out in the wave-dominated delta system is gradational and is better described as a "fade-out." The nearshore sandstone grades into marginal marine to coastal-plain sandstone and eventually into finer-grained silt and mud rocks. The more laterally continuous nature of the strandlines in the wave-dominated system makes the potential reservoir size larger than in a river-dominated system.

Landward pinch-outs from both depositional systems have been under-explored in the Rockies. Utah has several good exploration areas where this type of play could be found.

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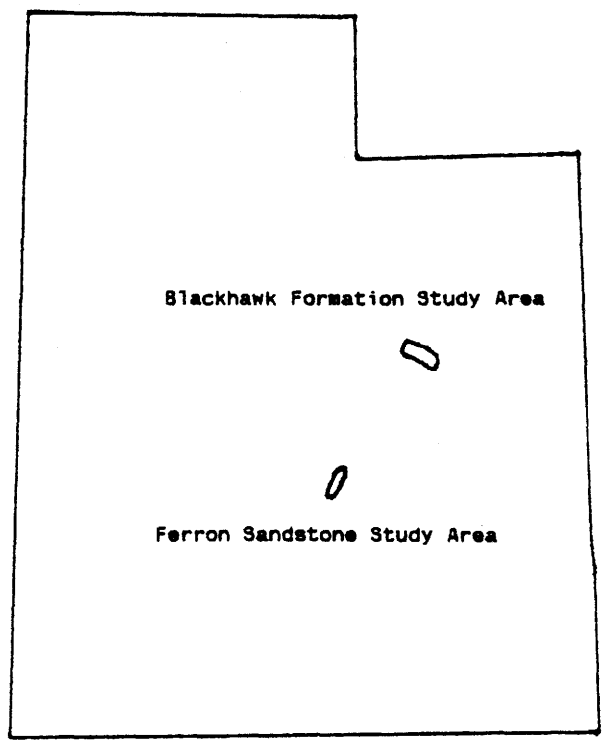


Figure 1 Location map of the two outcrop areas examined in the study.

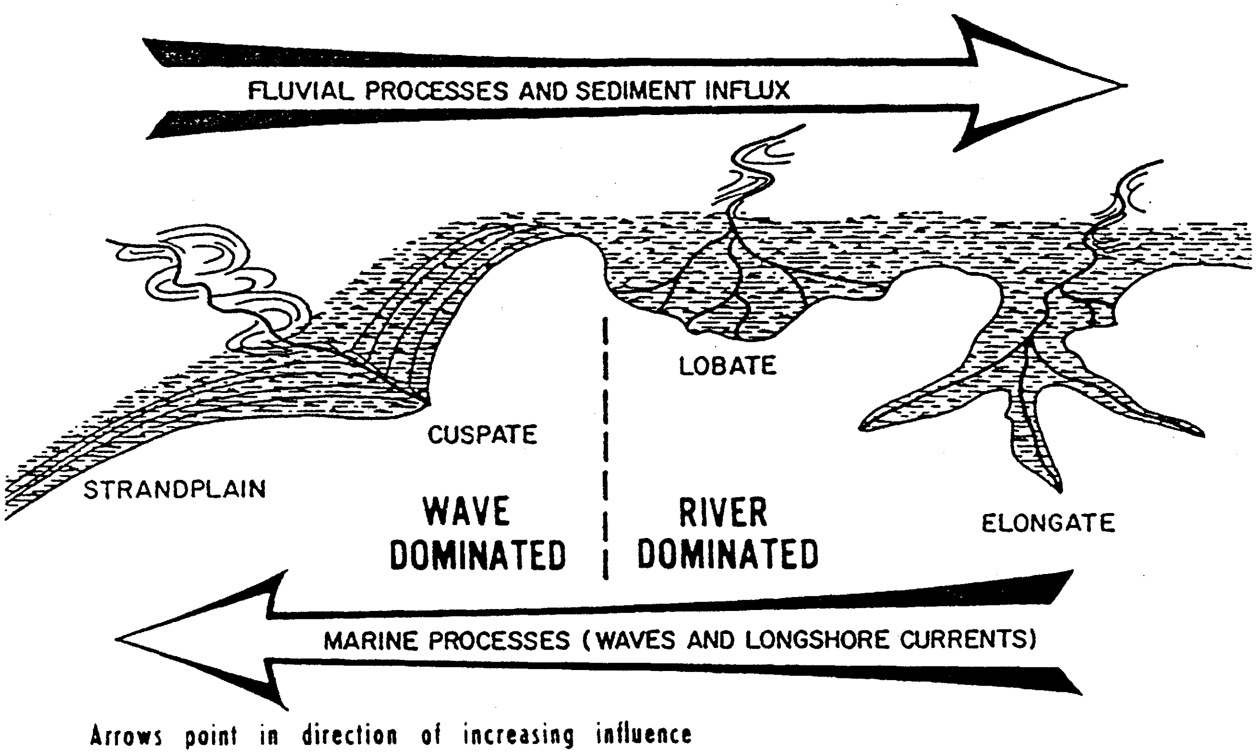


Figure 2 Delta geometries and their relation to wave energy, and sediment influx (Modified after Scott, 1969).

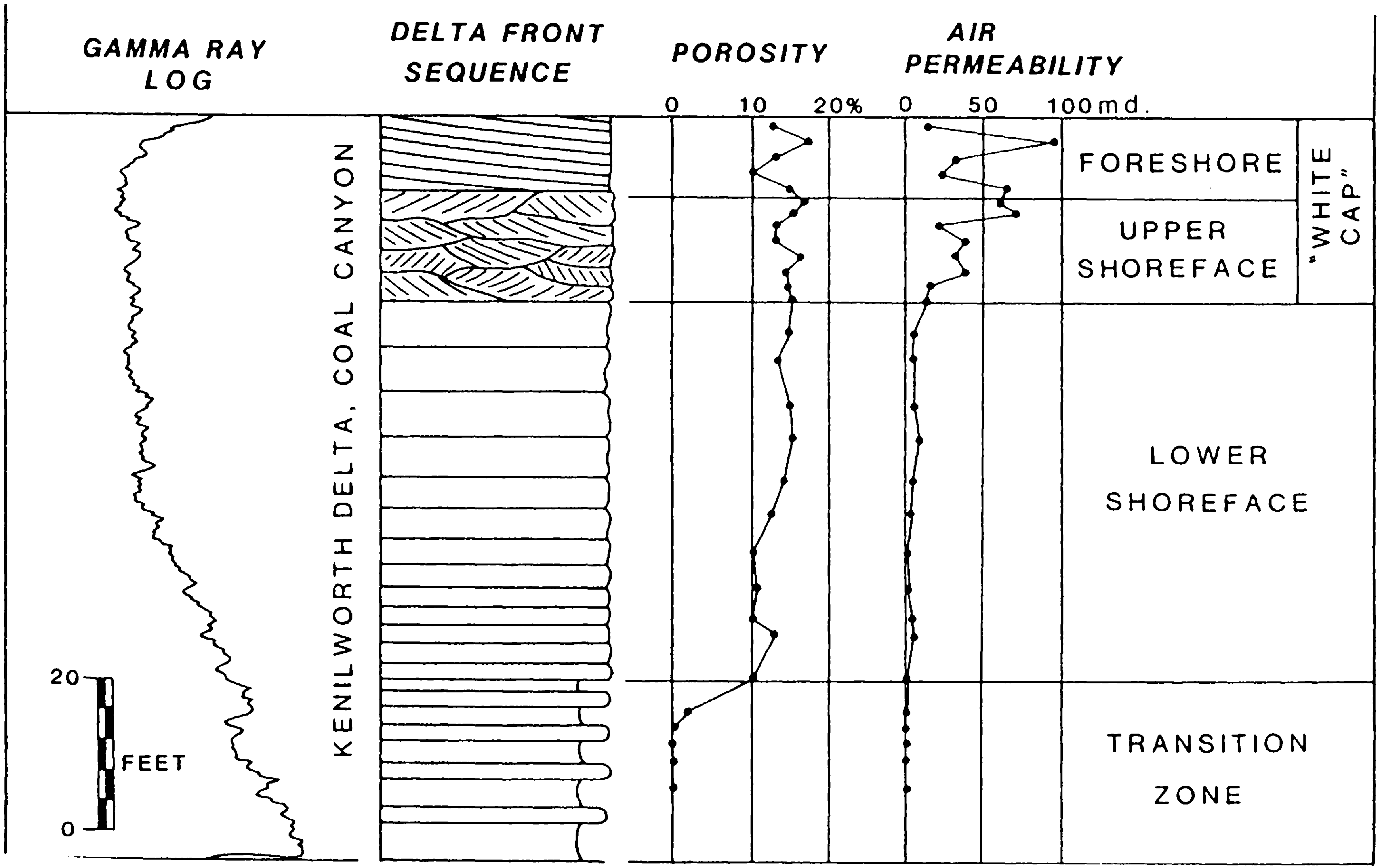


Figure 3 Typical vertical sequence from wave-dominated shoreface in the Blackhawk Formation. The sandstone coarsens upward, showing the greatest porosity and permeability in the forshore and upper shoreface (After Balsley, 1980).

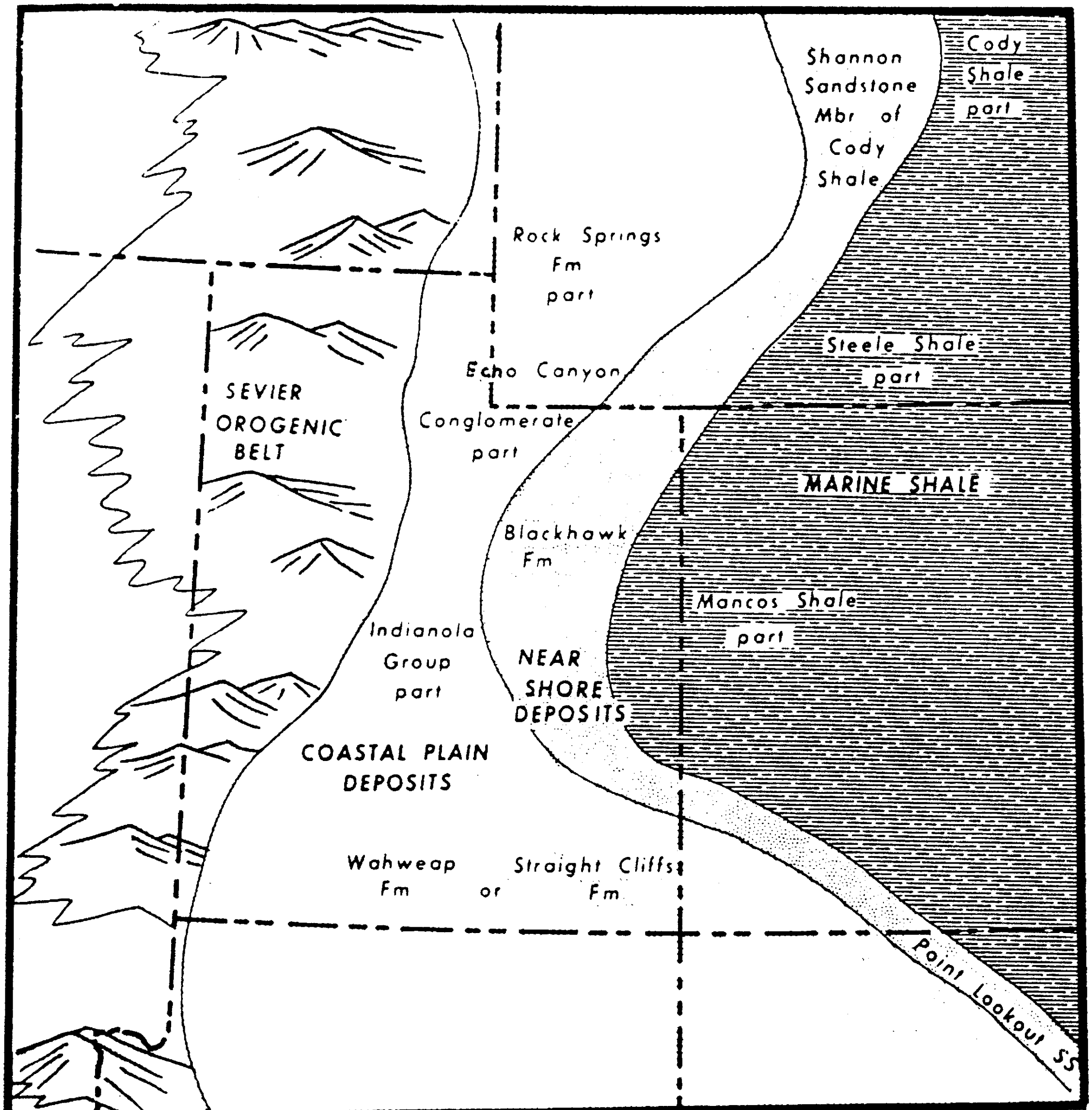


Figure 4 Regional depositional environments during Campanian time and the associated formations (Modified after McGookey et. al., 1972).

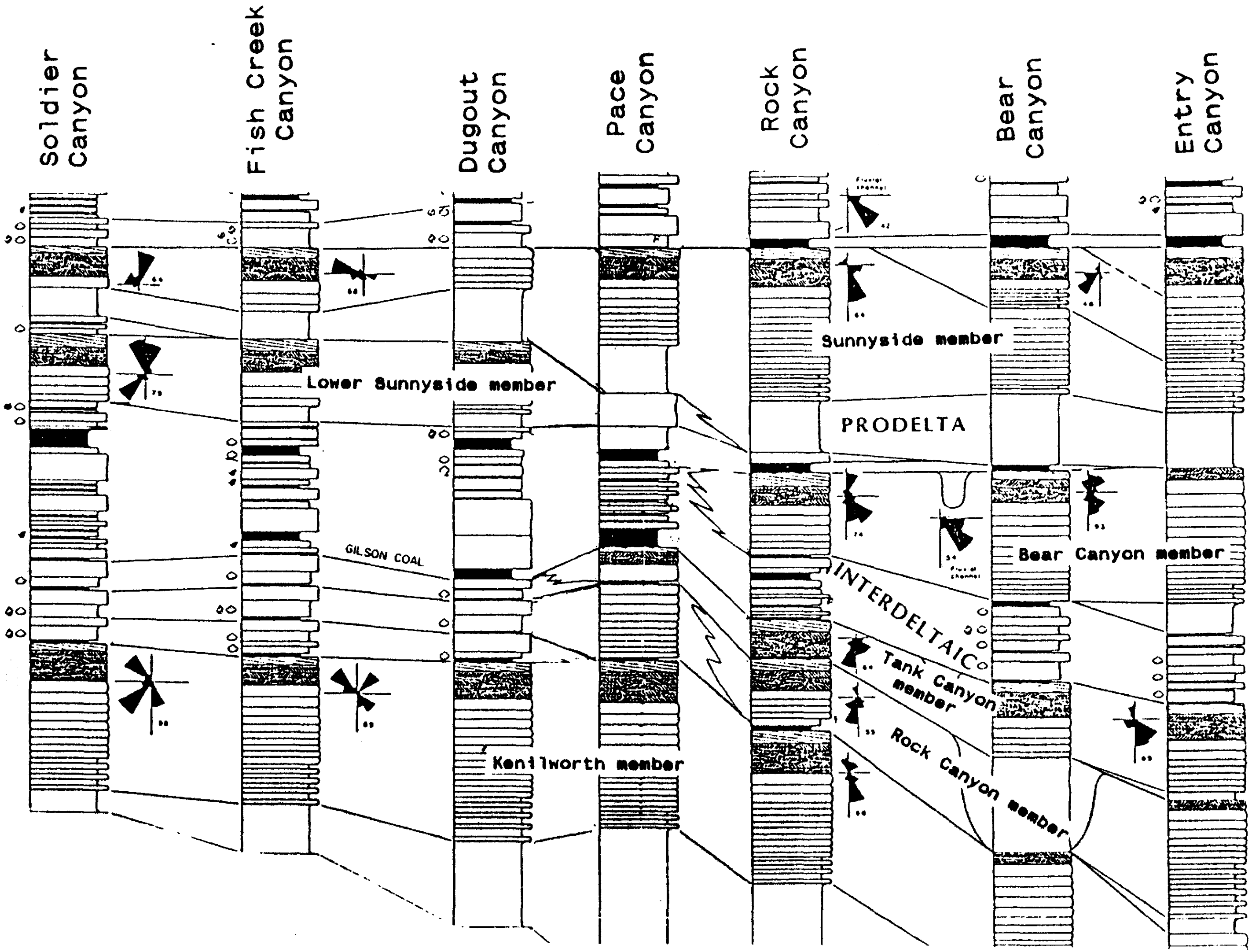


Figure 5 Cross section from Soldier Canyon to Entry Canyon modified from Balsley (1980). Sections measured by Balsley with the correlation of units modified between Dugout and Rock Canyons. Member names are informal units.

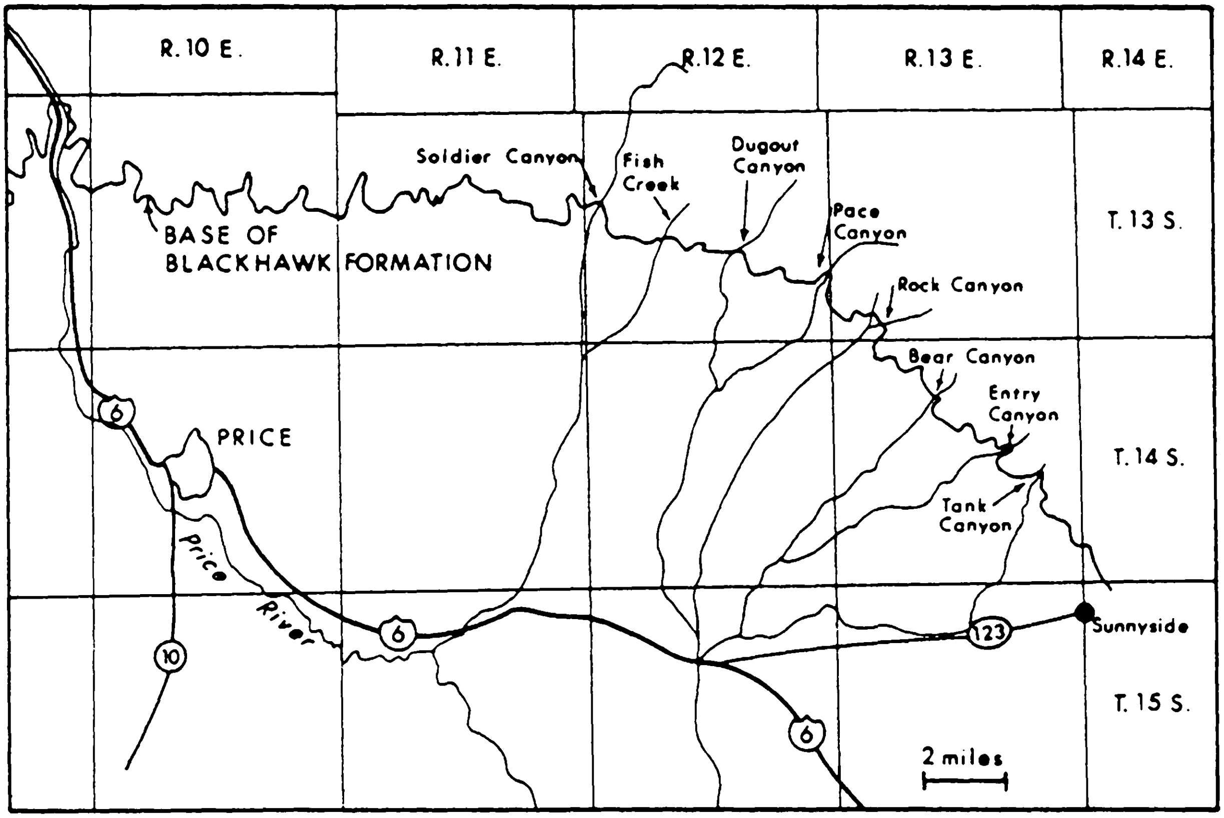


Figure 6 Location of canyons in and adjacent to the study area, Book Cliffs. Base and geology from Stokes and Madsen, (1961).

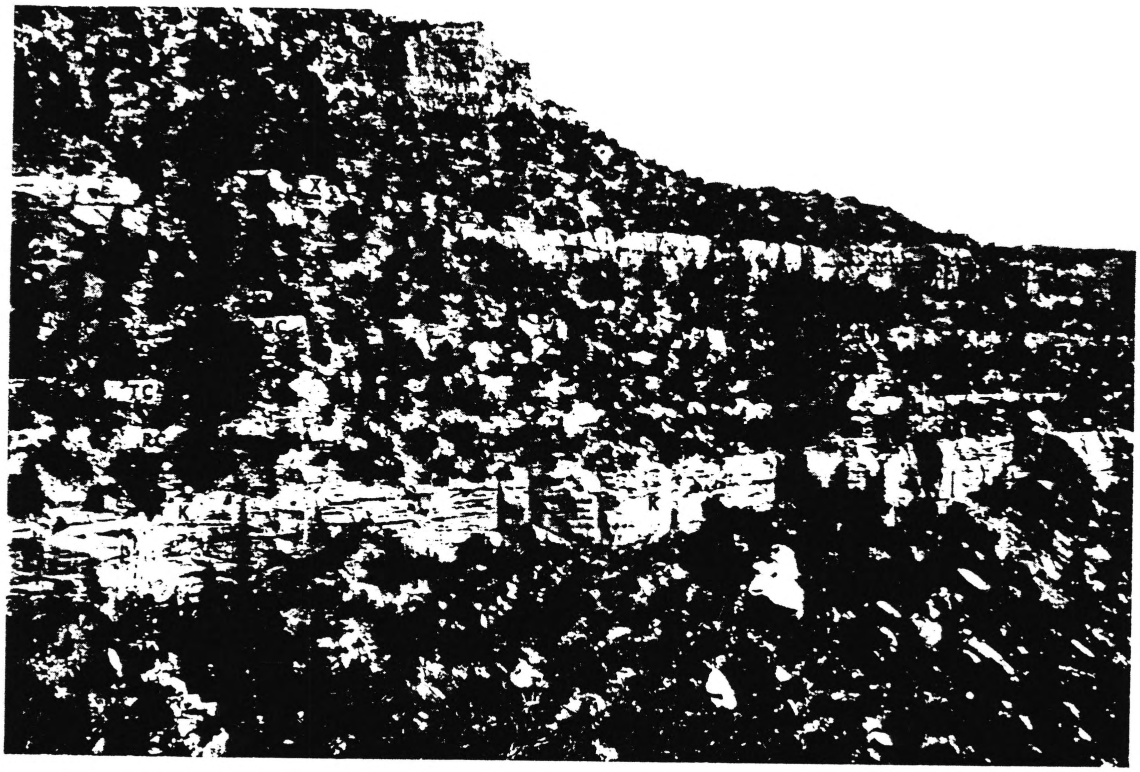


Figure 7 Marine beach sequences in the Blackhawk Formation outcrop as "white capped" sandstones. From bottom to top, the Kenilworth (K), Rock Canyon (RC), Tank Canyon (TC), Bear Canyon (BC), and Sunnyside (X) are shown here. The view is to the northeast, between Pace and Rock Canyons.

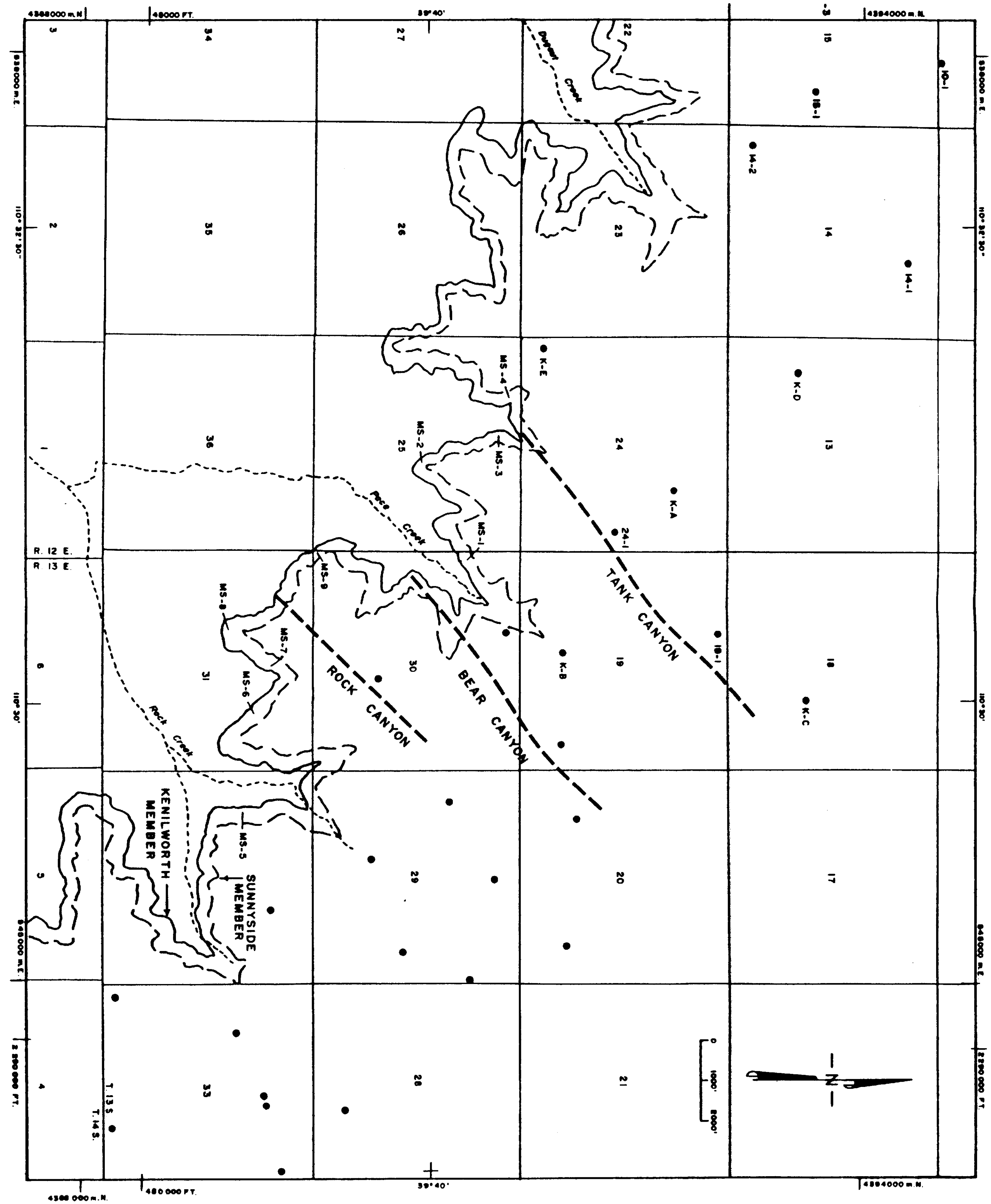


Figure 8 Measured sections and drill hole locations in Book Cliffs study area. Approximate location and orientation of the landward pinch-out of the Rock Canyon, Tank Canyon, and Bear Canyon members of the Blackhawk Formation (heavy black lines).

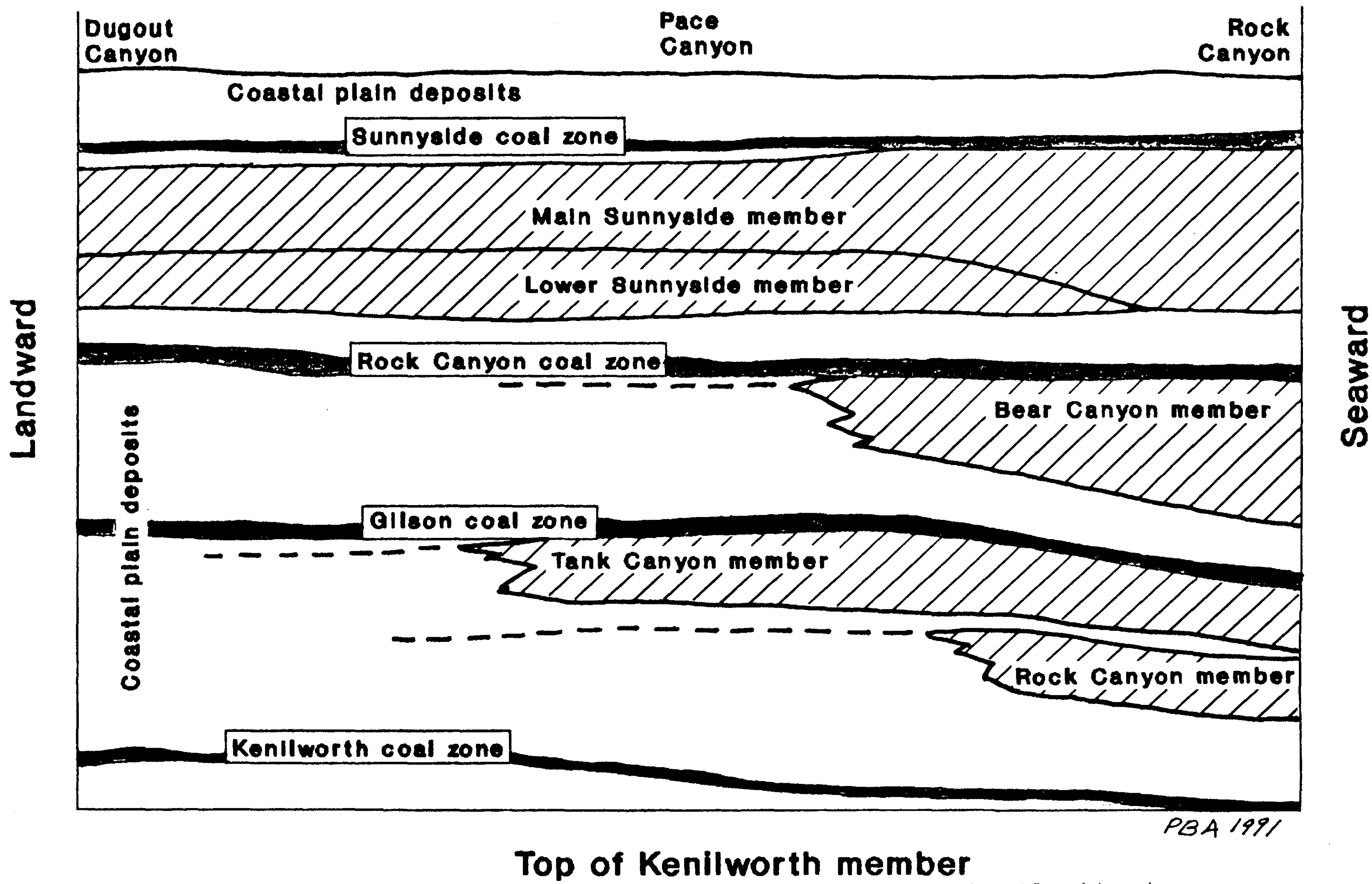


Figure 9 Diagrammatic cross section of the middle Blackhawk Formation between Dugout and Rock canyons. The Rock Canyon, Tank Canyon, and Bear Canyon marine sequences all pinch-out in a landward direction.

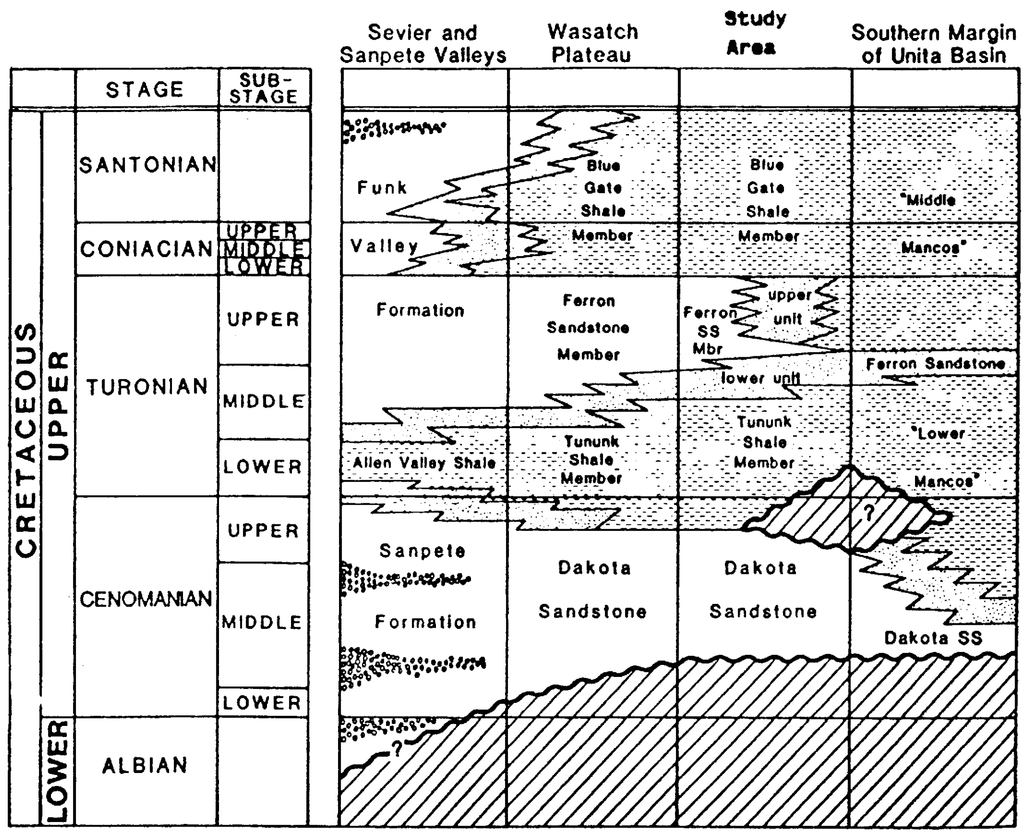


Figure 10 Stratigraphy, age, and correlation of the Ferron Sandstone and associated units in central and eastern Utah (Ryer and Lovekin, 1986).

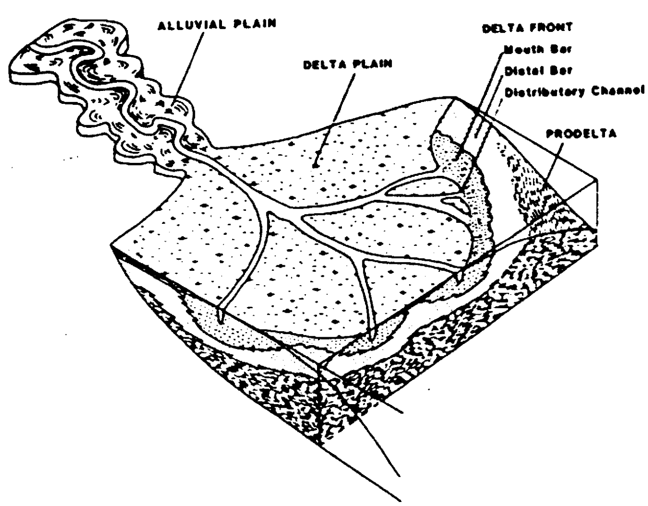


Figure 11 Facies of lobate, river-dominated delta (from Ryer, 1981a).

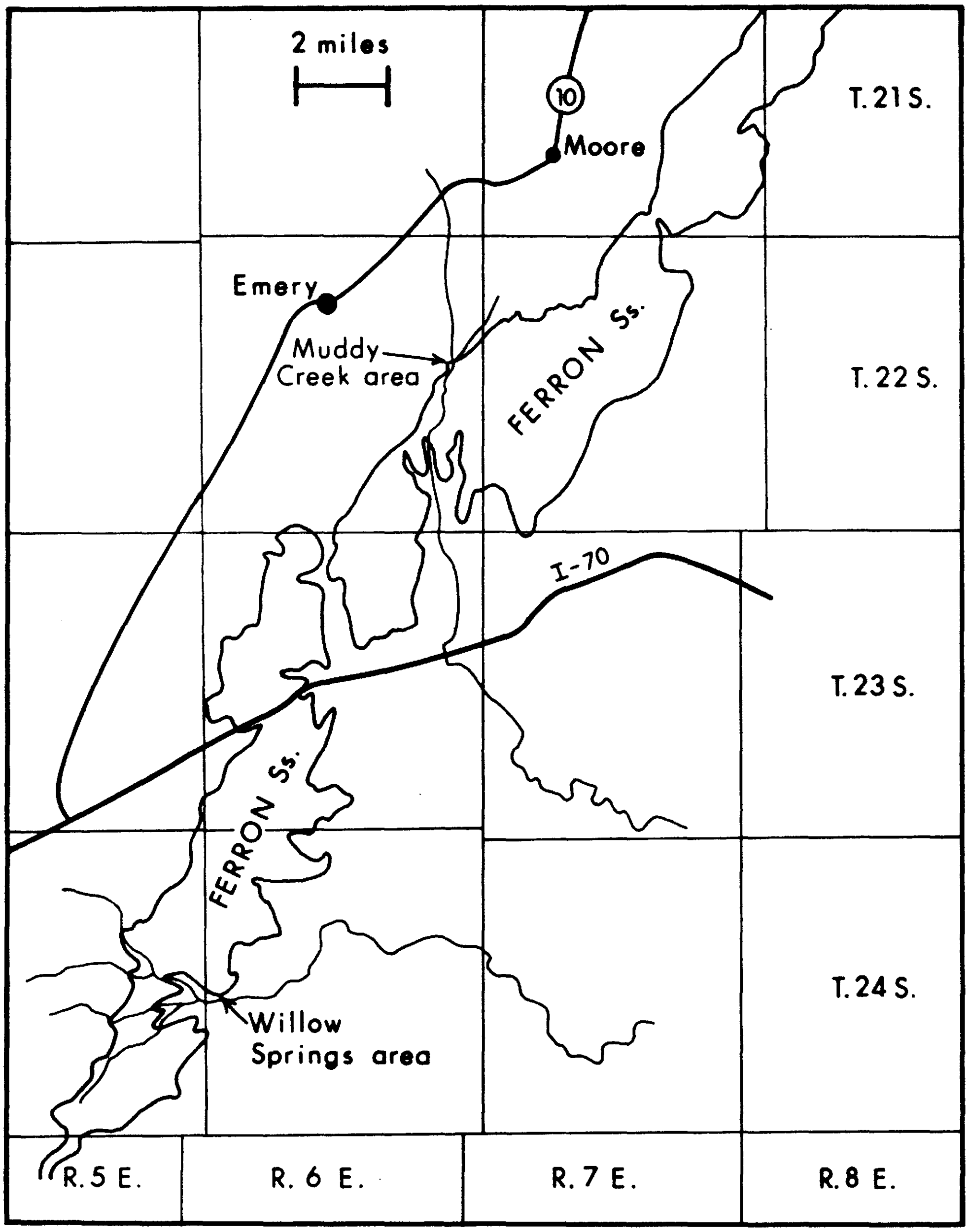


Figure 12 Index map of Ferron Sandstone outcrop study areas (Muddy Creek and Willow Springs Wash areas).

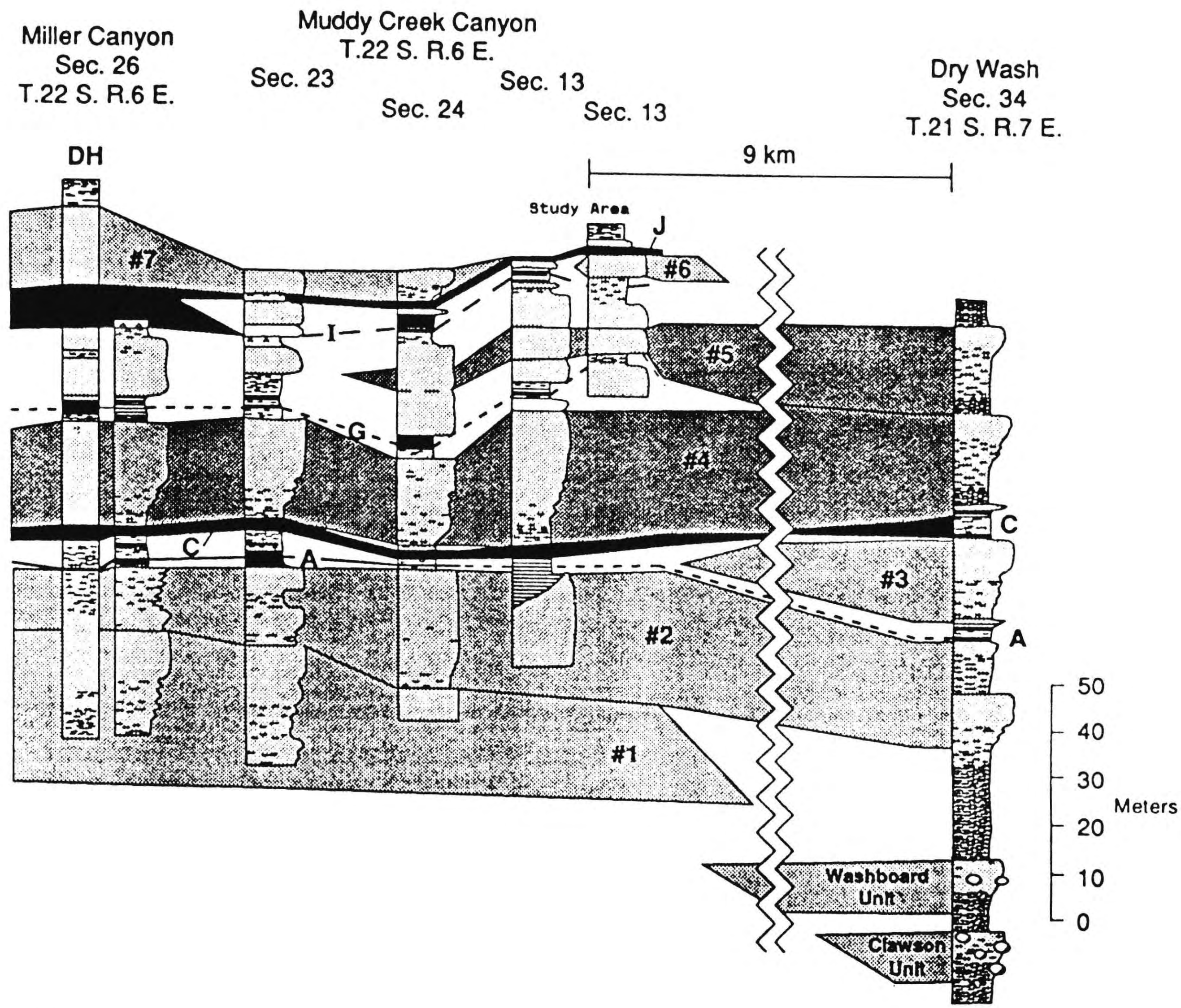


Figure 13 Local stratigraphy and correlations of the Ferron Sandstone, Muddy Creek area, Emery County, Utah. Stippled areas are shallow-marine sandstone (courtesy of University of Utah Research Institute, modidified from Ryer, 1981b).

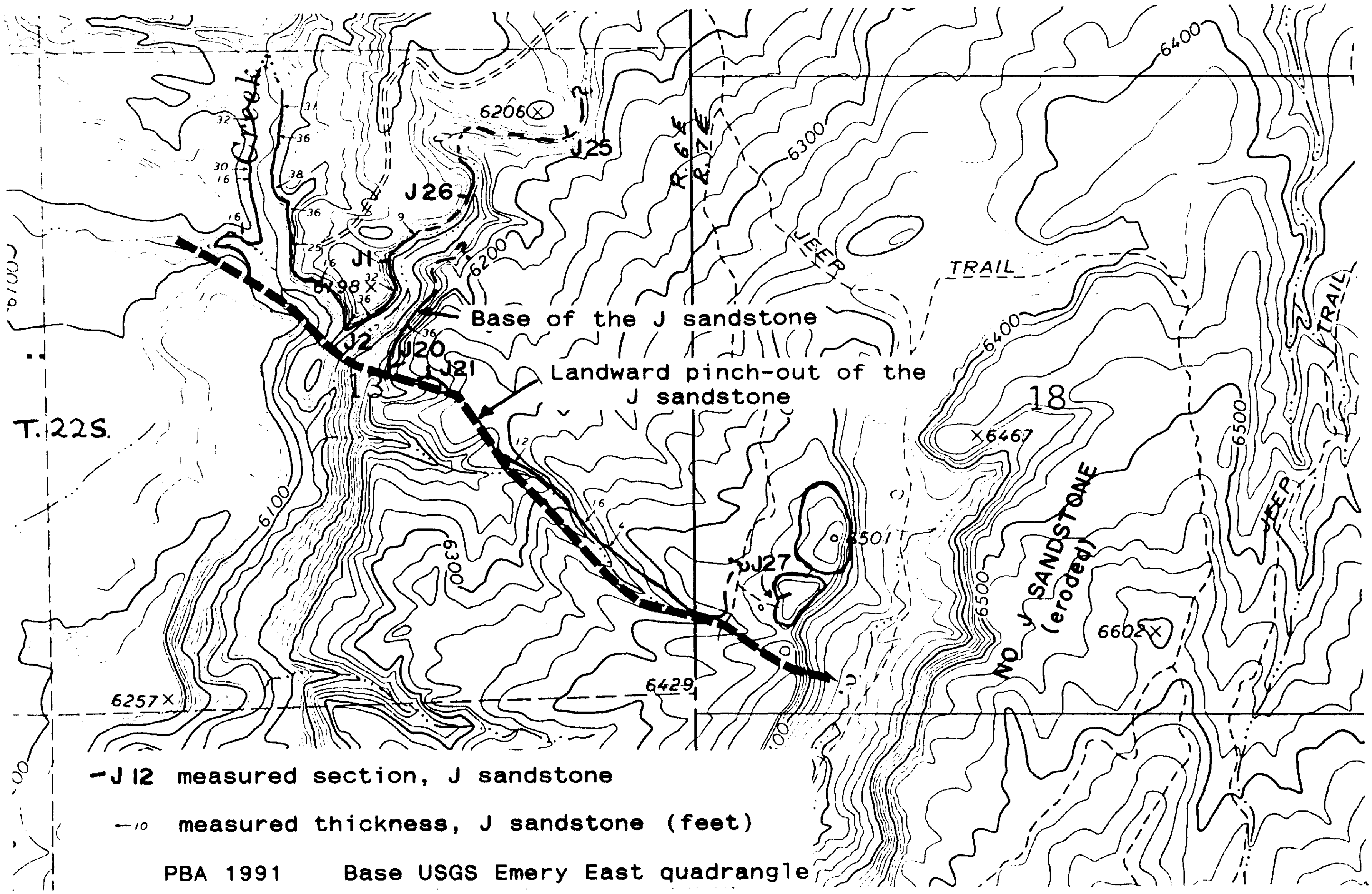


Figure 14 Muddy Creek study area with measured section locations, thicknesses of the J sandstone, and the landward pinch-out location of the J sandstone.

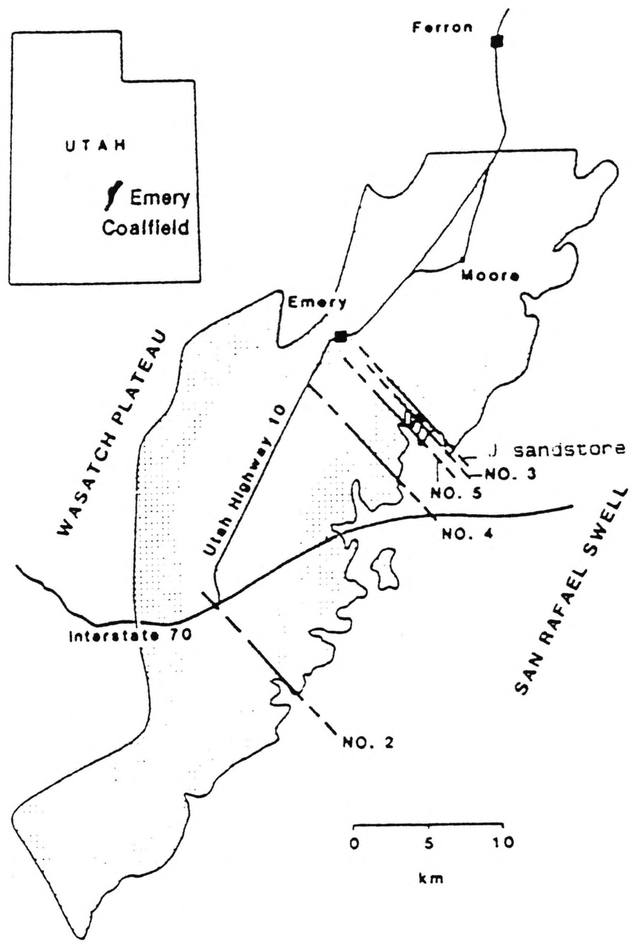


Figure 15 Orientation of landward pinch-out of several marine delta-front sandstones within the Ferron Sandstone (modified after Ryer, 1981a).

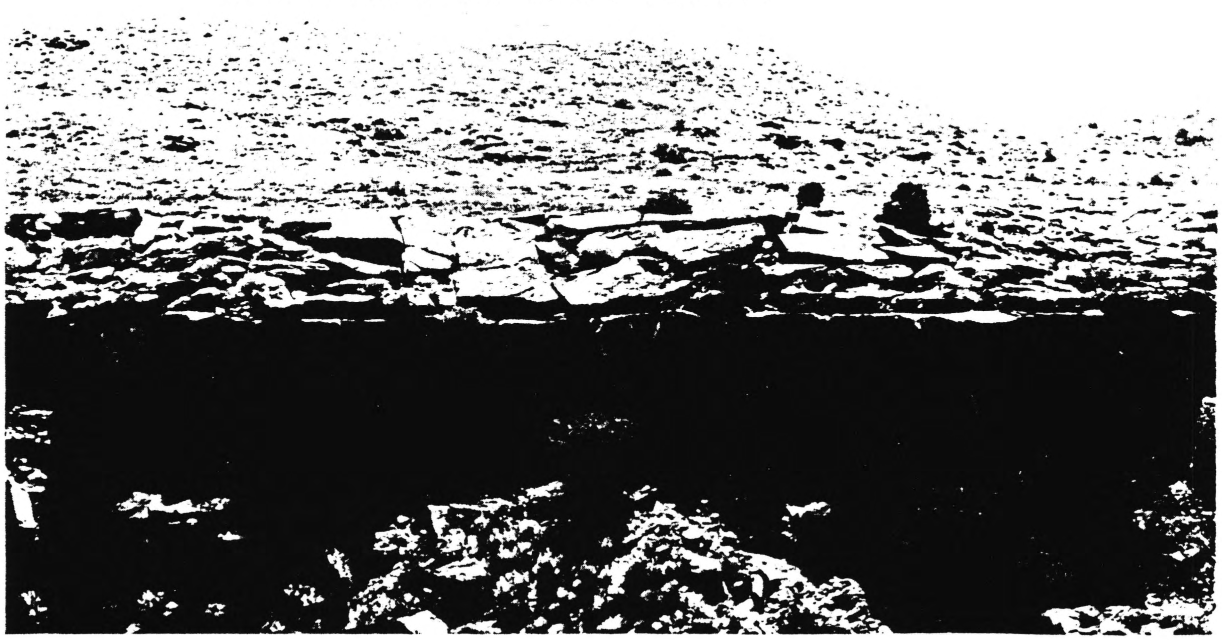


Figure 16 Landward pinch-out of the J sandstone in the Muddy Creek area (on the left side of the photograph).

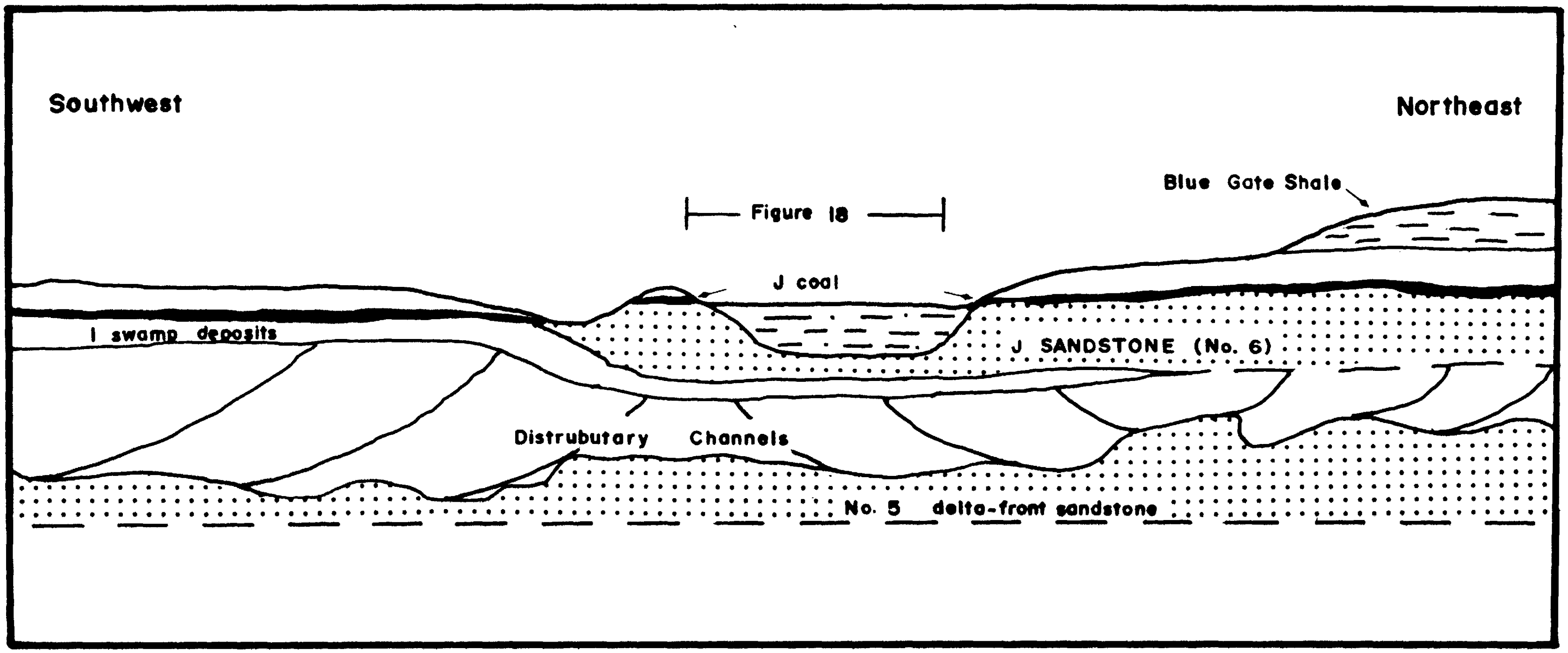


Figure 17 Diagrammatic cross section showing the landward pinch-out and geometry of the J sandstone and the encasing units in the Muddy Creek area.

Figure 18 Photograph of thinning in the top of the J sandstone in Muddy Creek area. Section J1 was measured on the left where the sandstone thickens. View is to the west.

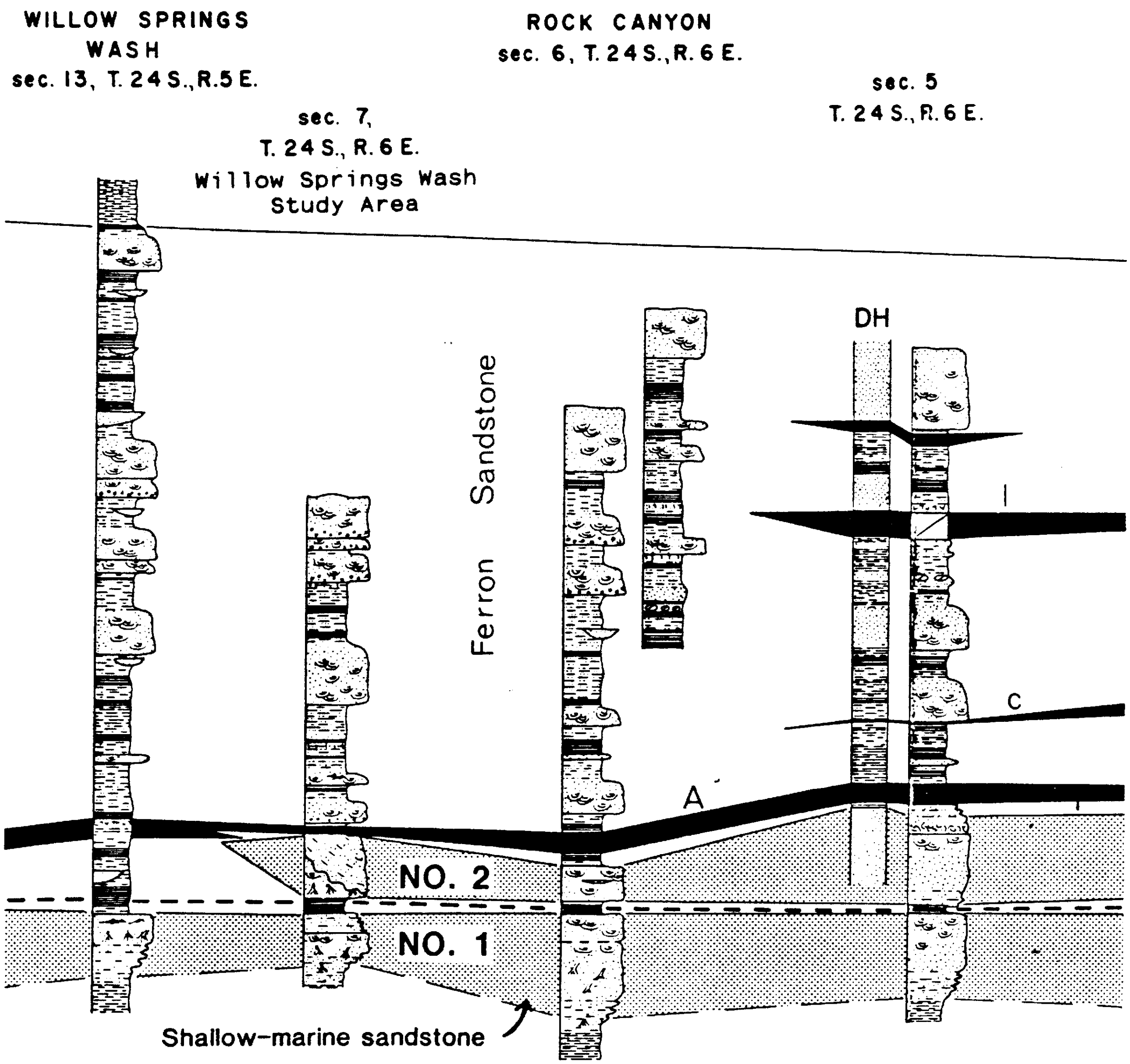


Figure 19 Local stratigraphy and correlations of the Ferron Sandstone, Willow Springs Wash area, Emery and Sevier counties, Utah (Modified from Ryer, 1981b).

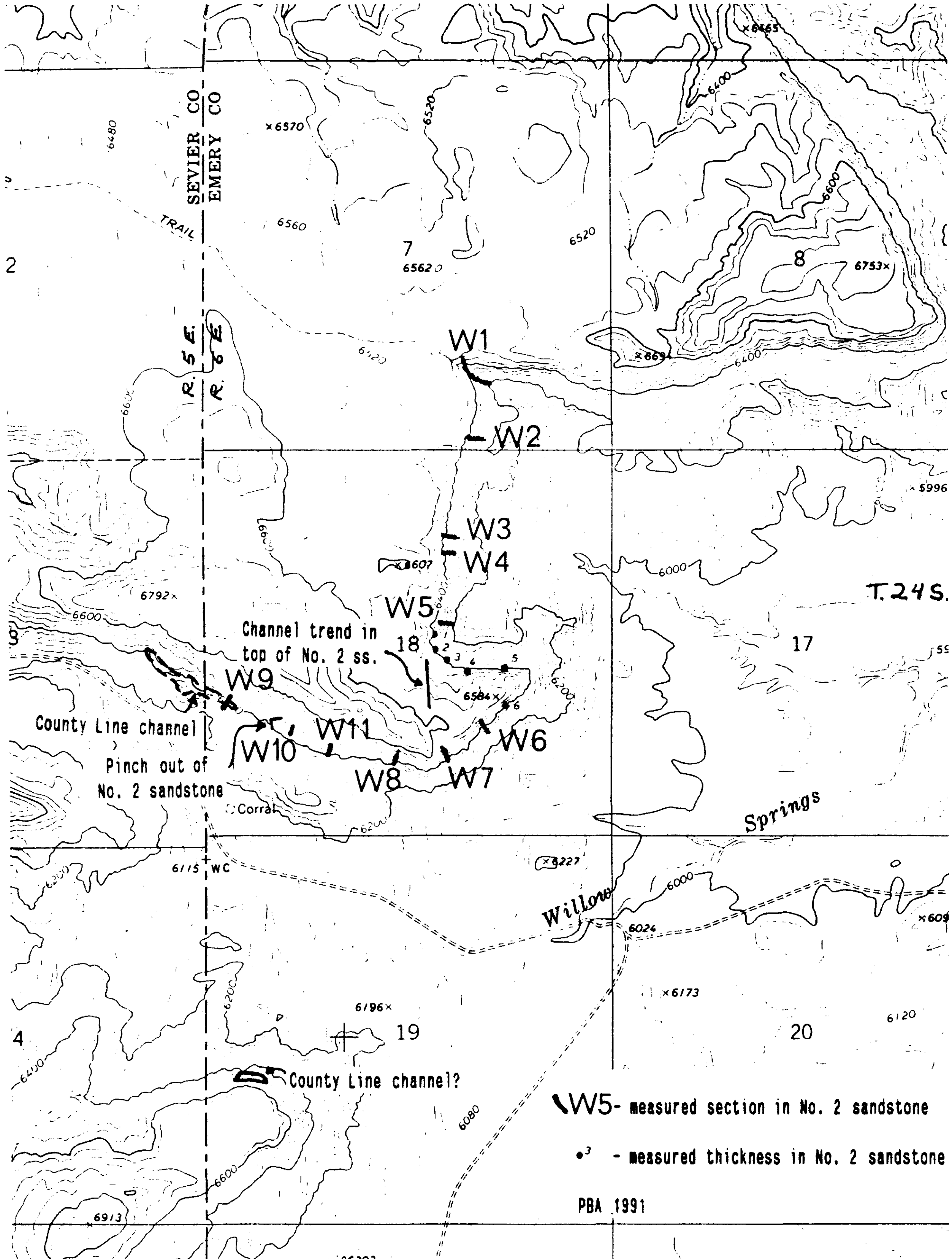


Figure 20 Willow Springs Wash study area with measured section locations, thicknesses, and the pinch-out location of the No. 2 sandstone.

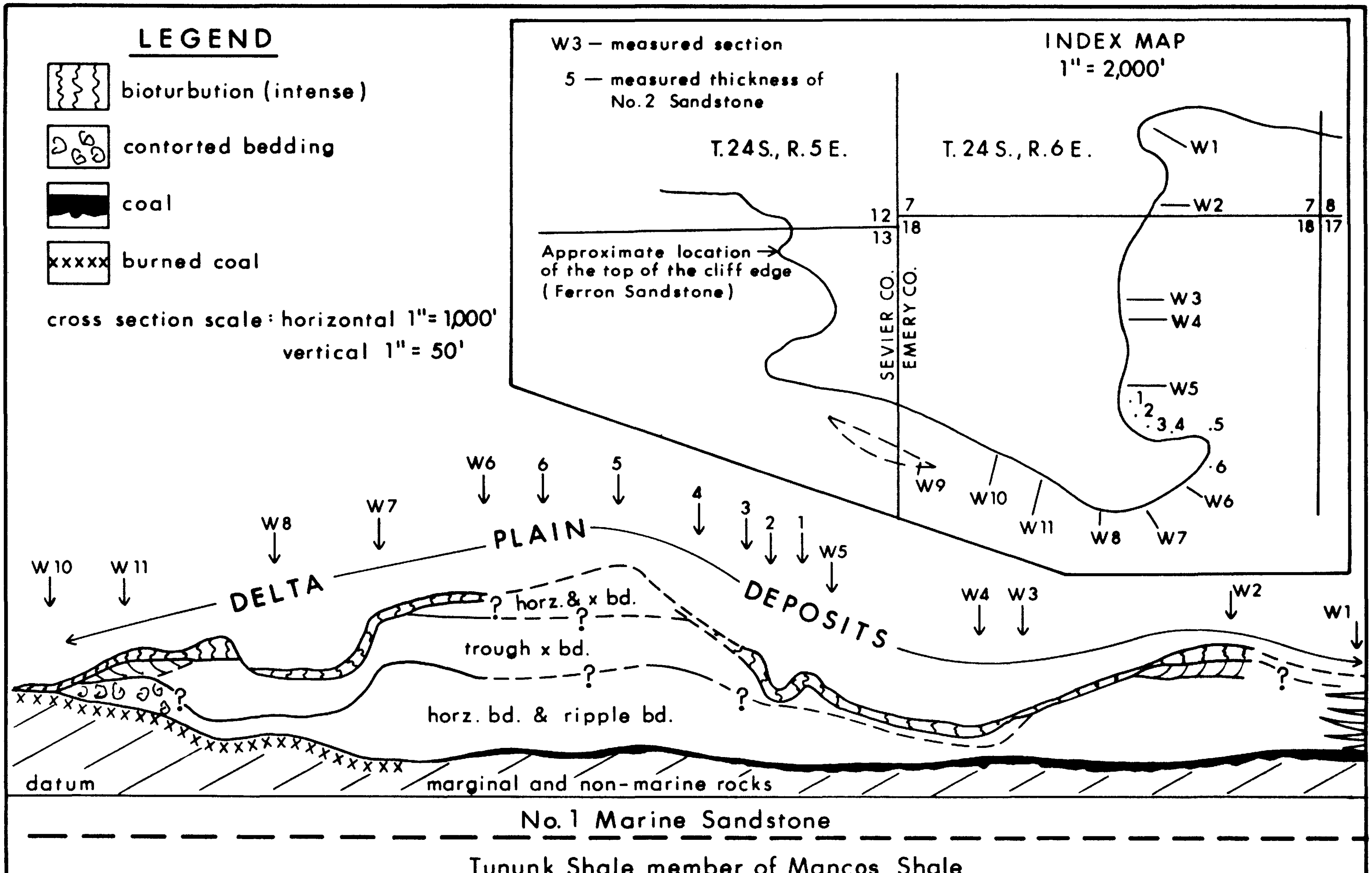


Figure 21 Cross sectional profile along the outcrop of the No. 2 sandstone, north of Willow Springs Wash. From left to right across the section is generally in a landward to seaward direction.

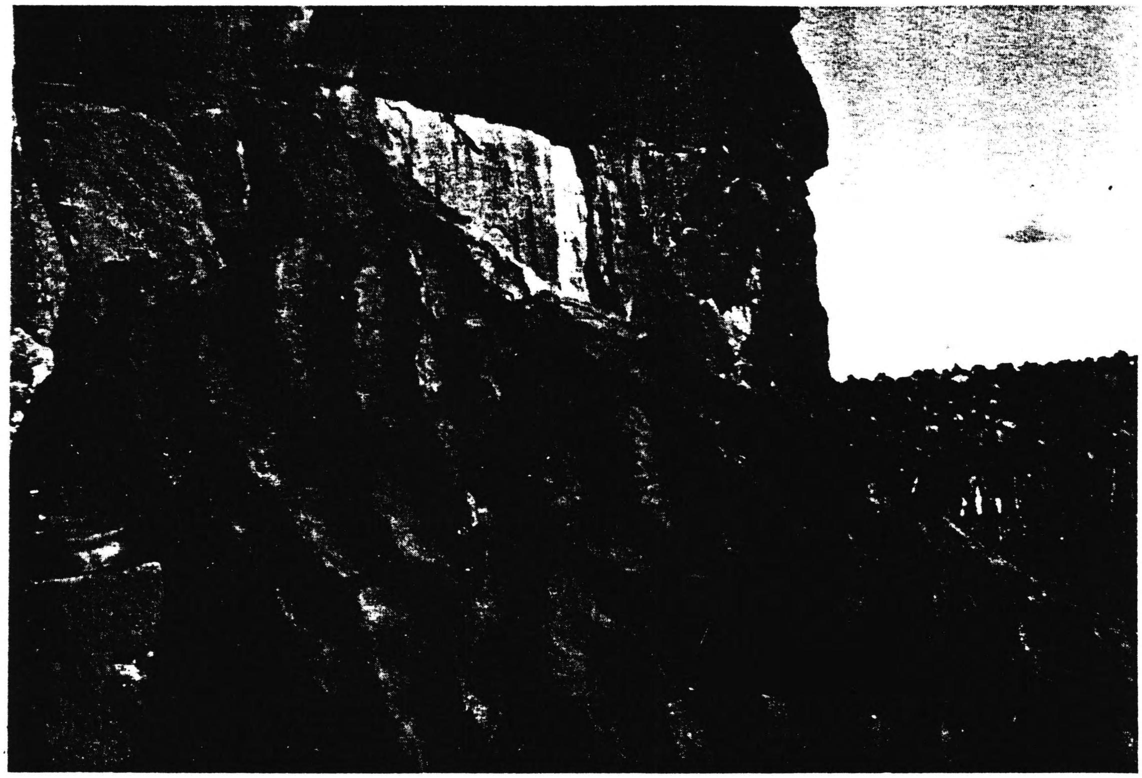


Figure 22 Lunate ripples commonly found in the distal mouth-bar facies in the No. 2 sandstone. This exposure is near section W5.

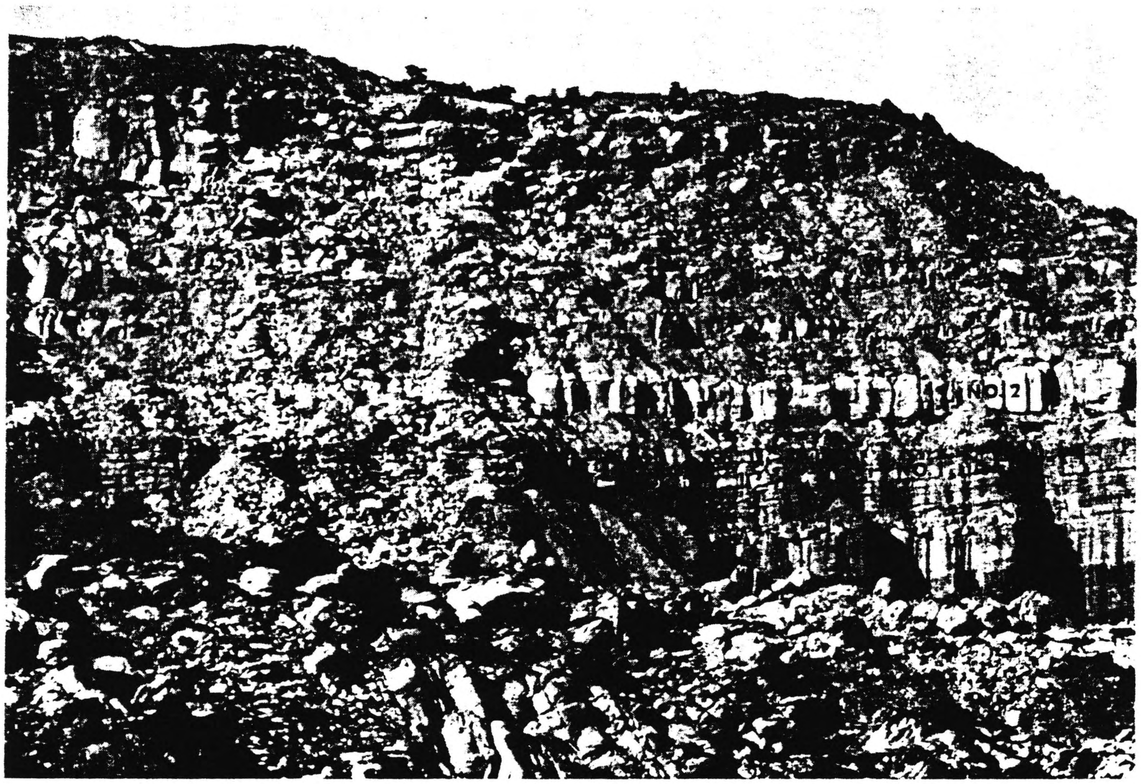


Figure 23 Thinned No. 2 sandstone along the north cliff in Willow Springs Wash. Note the "white-cap" is present through the scour, indicating its relationship to weathering.

Figure 24 Edge of a cut into the No. 2 delta-front sandstone near section W4. Note the drapping bioturbated unit near the shovel.

Figure 25 County Line channel in Willow Springs Wash. The top of the channel complex is at the same stratigraphic level as the No. 2 sandstone which is pinched out a few hundred feet to the east.

Figure 26 Landward pinch-out of No. 2 sandstone into delta-plain deposits at Willow Springs Wash. The pinch-out occurs at the black dot on the photo. (See Figure 20 for its location.)

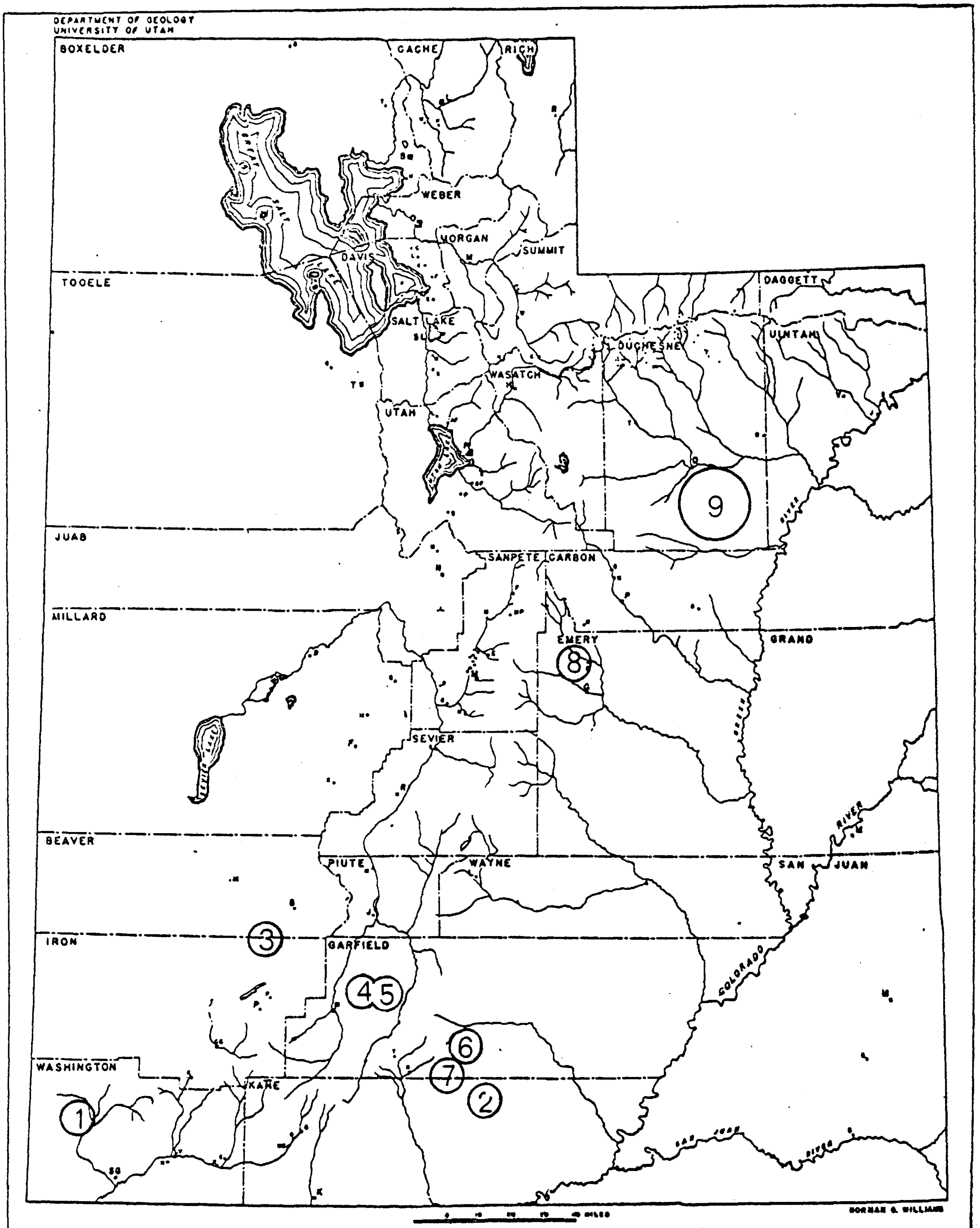
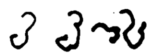
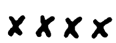


Figure 27 Prospective hydrocarbon traps from landward pinch-outs of marine beach sandstone in Utah.

APPENDIX

Key to the Measured Sections and Logs

PBA 1991

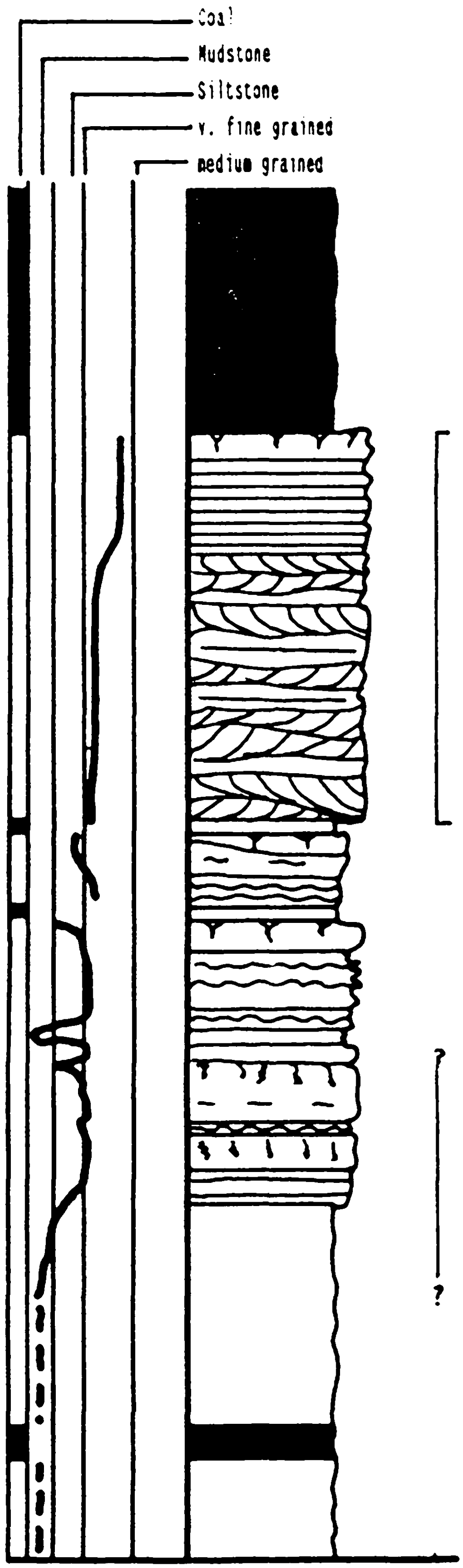
	Horizontal bedding
	Hummocky bedding
	Ripple or wave bedding
	Bioturbation
	Trough-cross bedding
	Body fossils (chiefly mollosks)
	Plant fossils
	Contorted bedding
	Concretions
	Rip-up or intraclasts
	Tabular-cross bedding
	Coal
	Burned coal and overburden
	Rooting

Scale on sections and logs:
1 inch = 10 feet

Measured Sections and Drill-hole Logs

Blackhawk Formation

Section #1, part 1
Book Cliffs, Utah
NWNW 30-13S-13E
Vertical scale: 1 inch = 10 feet
PBA 1991



(continued on #1, part 2)

Gilson Coal

TANK CANYON MEMBER

Foreshore

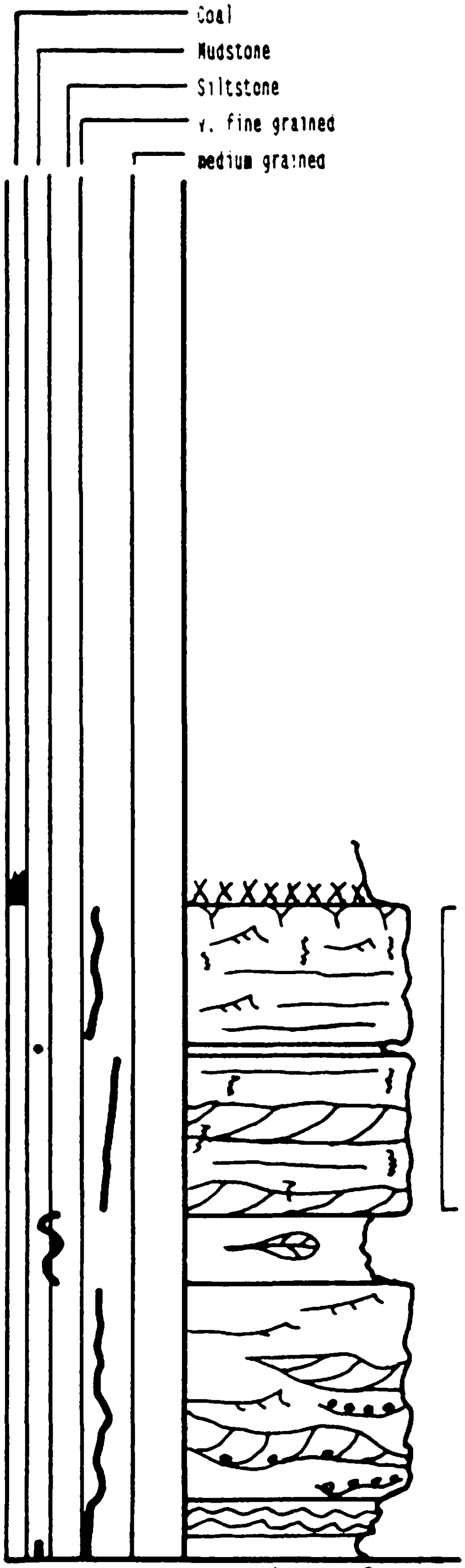
Upper Shoreface?
non-erosional base

erosional base

ROCK CANYON MEMBER
(indistinct, landward of pinch-out)

Top - Kenilworth member

Section #1, part 2
Book Cliffs, Utah
NWNW 30-13S-13E
Vertical scale: 1 inch = 10 feet
PBA 1991



note: The sandstone above the burned Rock Canyon coal zone was trough cross bedded with the basal portions of sets containing mudstone rip-up clasts. The upper portion of the unit is heavily bioturbated (marine) and is similar to the uppermost sandstone unit measured in section #6.

Rock Canyon coal zone-burned

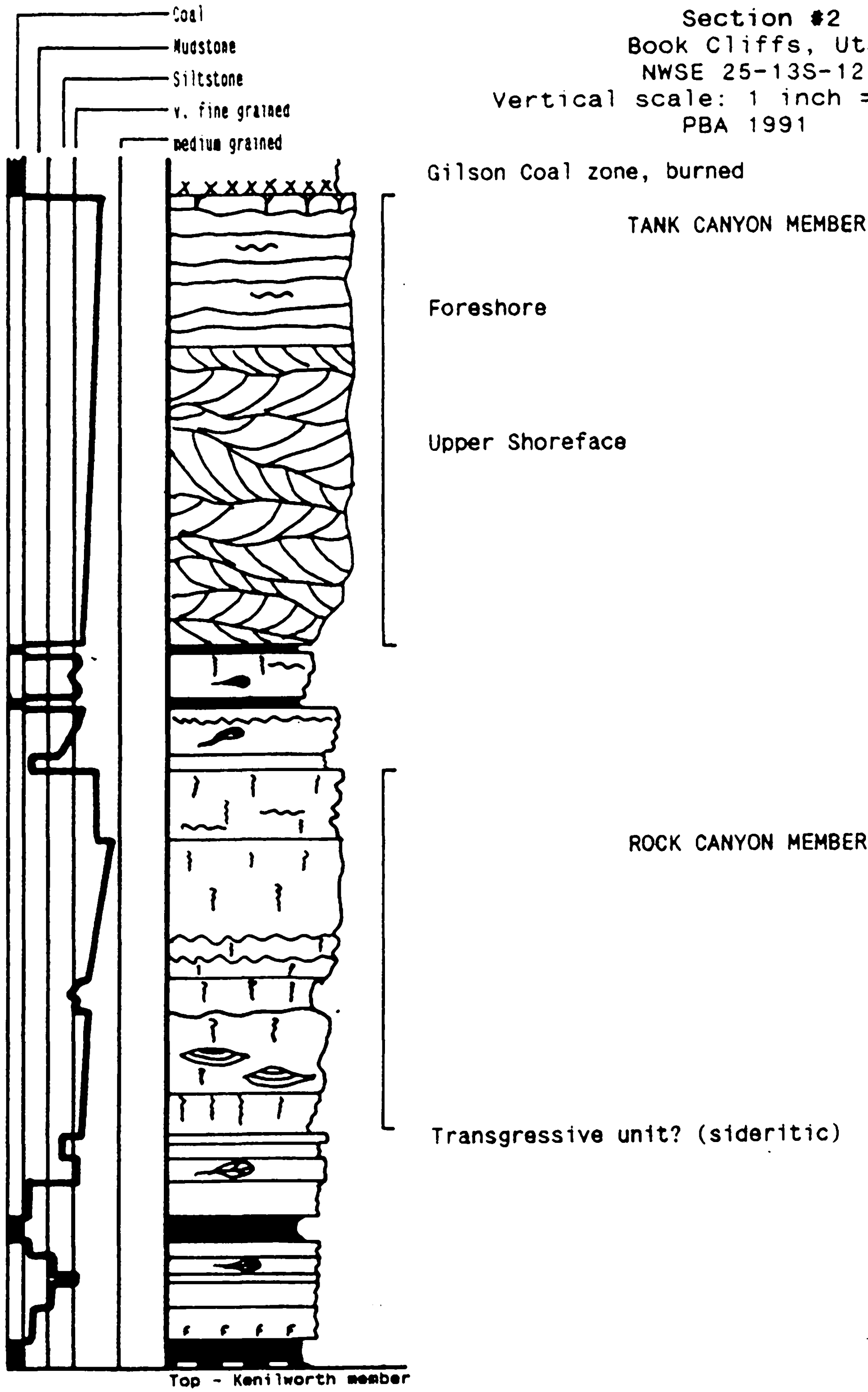
BEAR CANYON MEMBER

Ophiomorpha

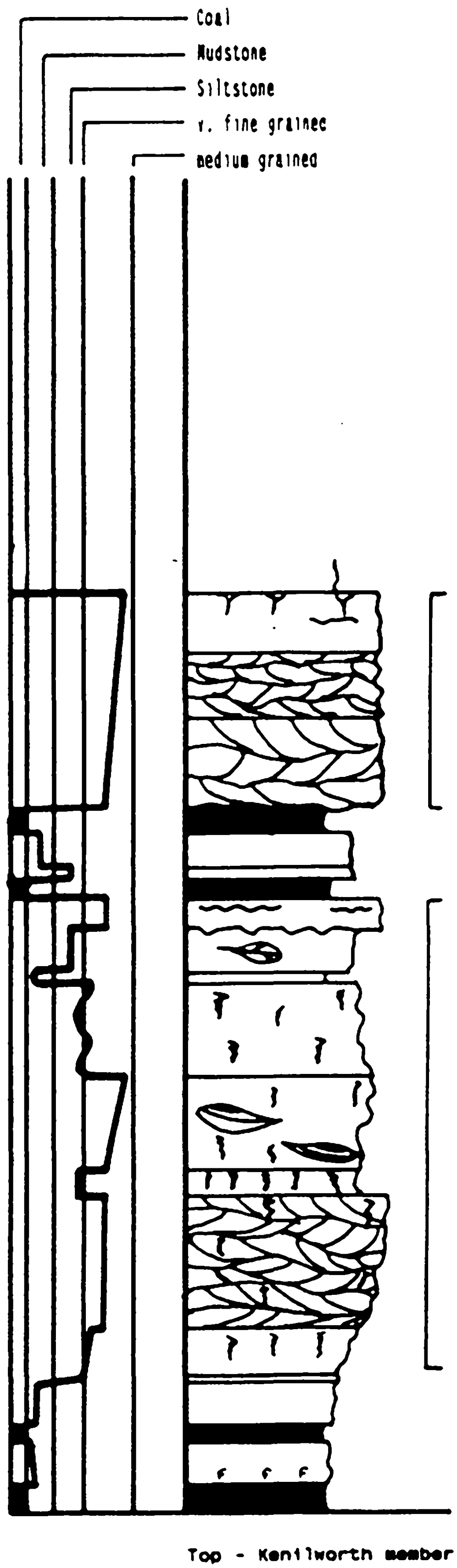
fluvial

(continued from top of part 1)

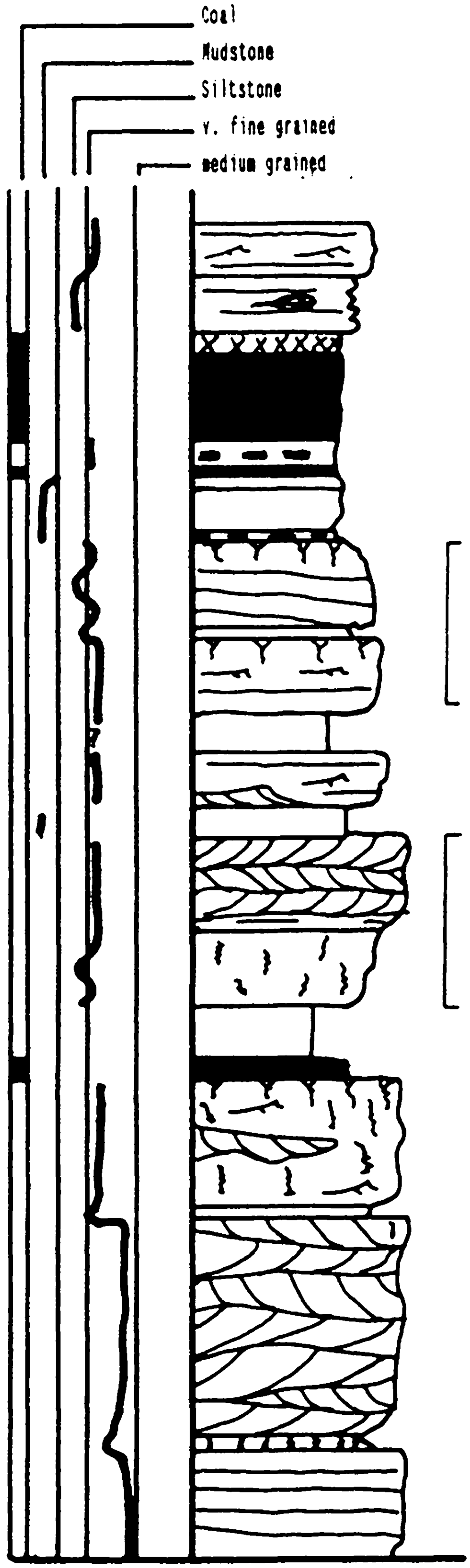
Section #2
Book Cliffs, Utah
NWSE 25-13S-12E
Vertical scale: 1 inch = 10 feet
PBA 1991



Section #3
Book Cliffs, Utah
NWNE 25-13S-12E
Vertical scale: 1 inch = 10 feet
PBA 1991



Section #4
Book Cliffs, Utah
SWSW 24-13S-12E
Vertical scale: 1 inch = 10 feet
PBA 1991



Gilson Coal zone

TANK CANYON MEMBER
(equivalent)
marginal marine

covered

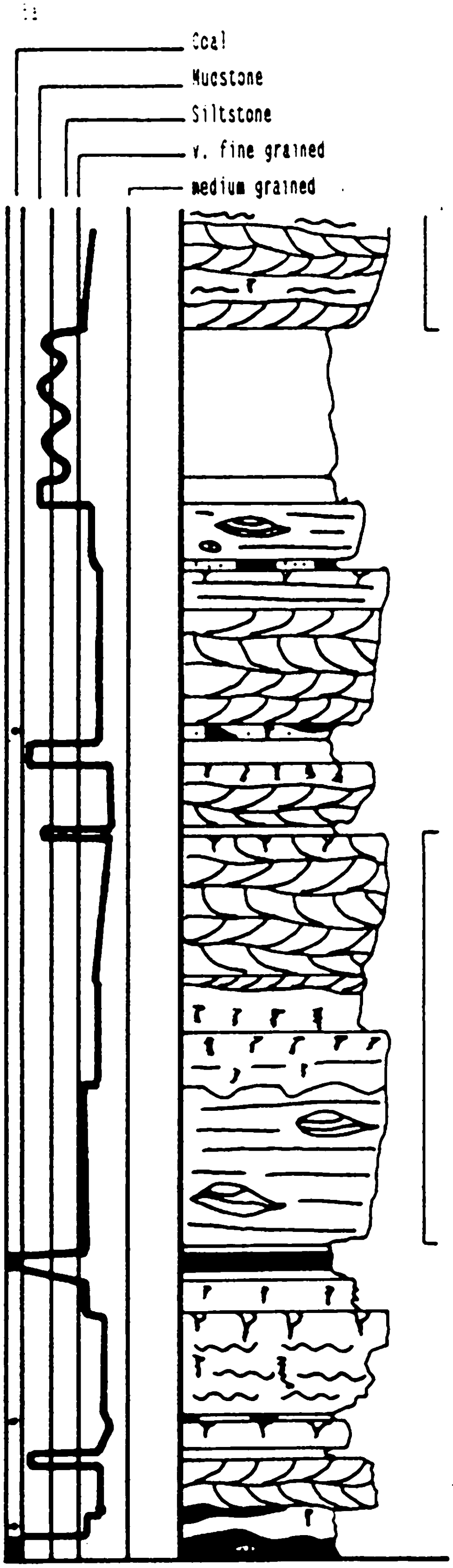
ROCK CANYON MEMBER
(equivalent)
marginal marine

covered

Top of Kenilworth (for correlations)
bioturbation from large pelecypods?

Foreshore (normal top of Kenilworth)

Section #5, part 1
Book Cliffs, Utah
SENW 32-13S-13E
Vertical scale 1 inch = 10 feet
PBA 1991



TANK CANYON MEMBER
(continued on #5, part 2)

poorly exposed, interbd. ss., siltst.,mudst.
non-marine

channel sandstone

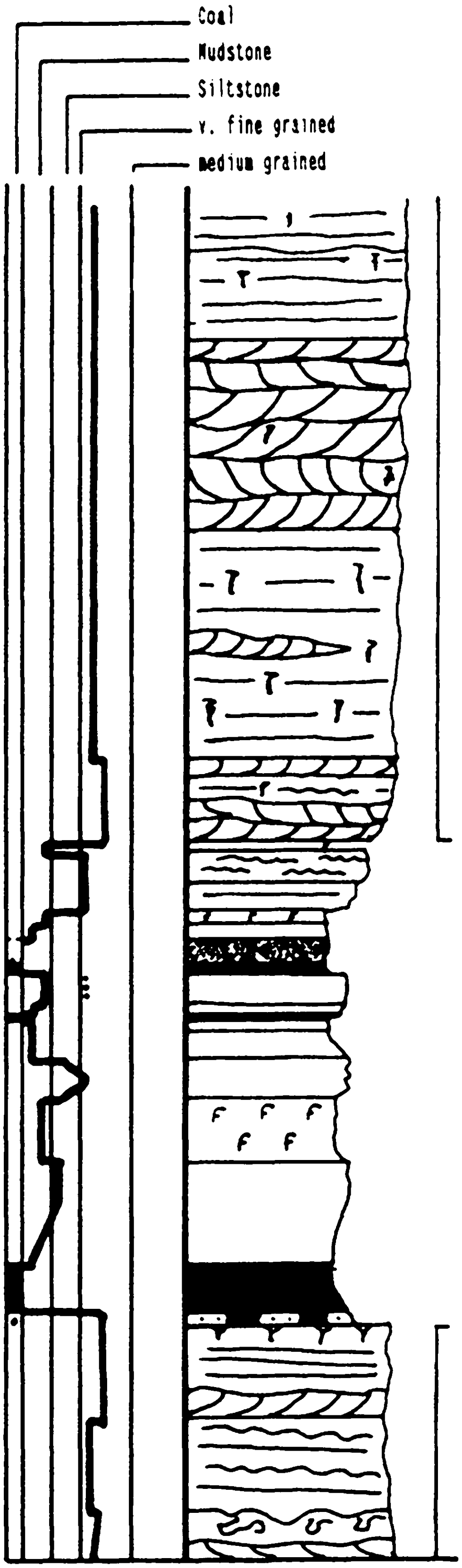
ROCK CANYON MEMBER
Forms "white cap" above Kenilworth member

Ophiomorpha

Lower Shoreface?

Top - Kenilworth Member

Section #5, part 2
Book Cliffs, Utah
SENW 32-13S-13E
Vertical scale: 1 inch = 10 feet
PBA 1991



(continued on #5, part 3)

BEAR CANYON MEMBER

Upper Shoreface

Lower Shoreface

Ophiomorpha

brackish water pelecypods
burned coal-will effect true thickness

poorly exposed-intrbd ss. & mudst.

brackish water pelecypods

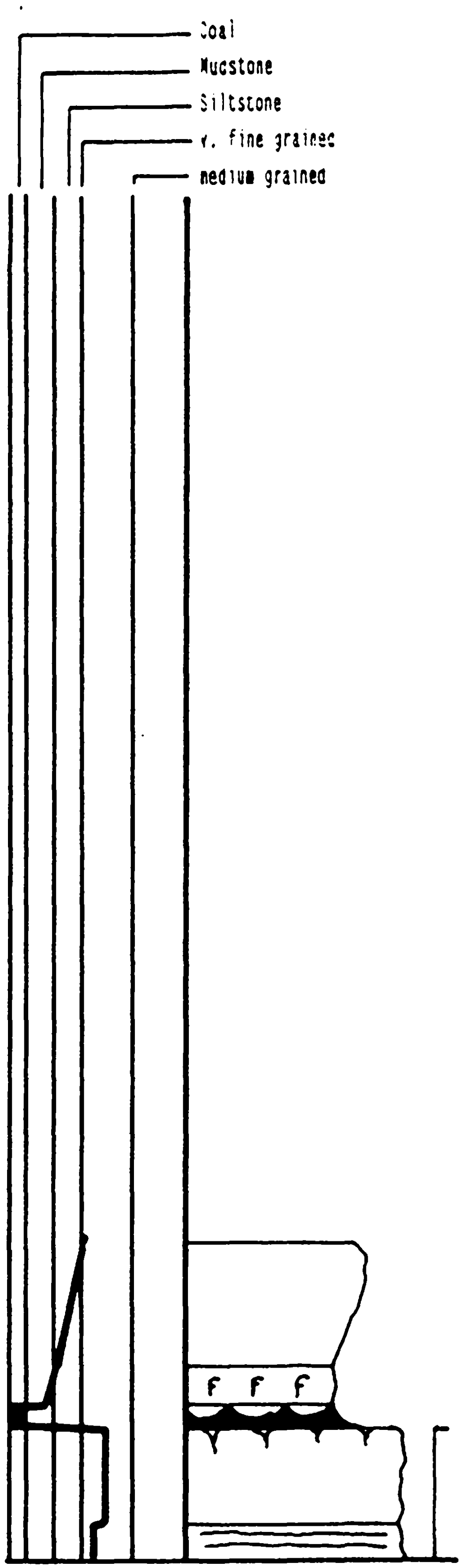
Gilson Coal Zone

TANK CANYON MEMBER

Foreshore?

(continued from top of part 1)

Section #5, part 3
Book Cliffs, Utah
SENW 32-13S-13E
Vertical scale: 1 inch = 10 feet
PBA 1991

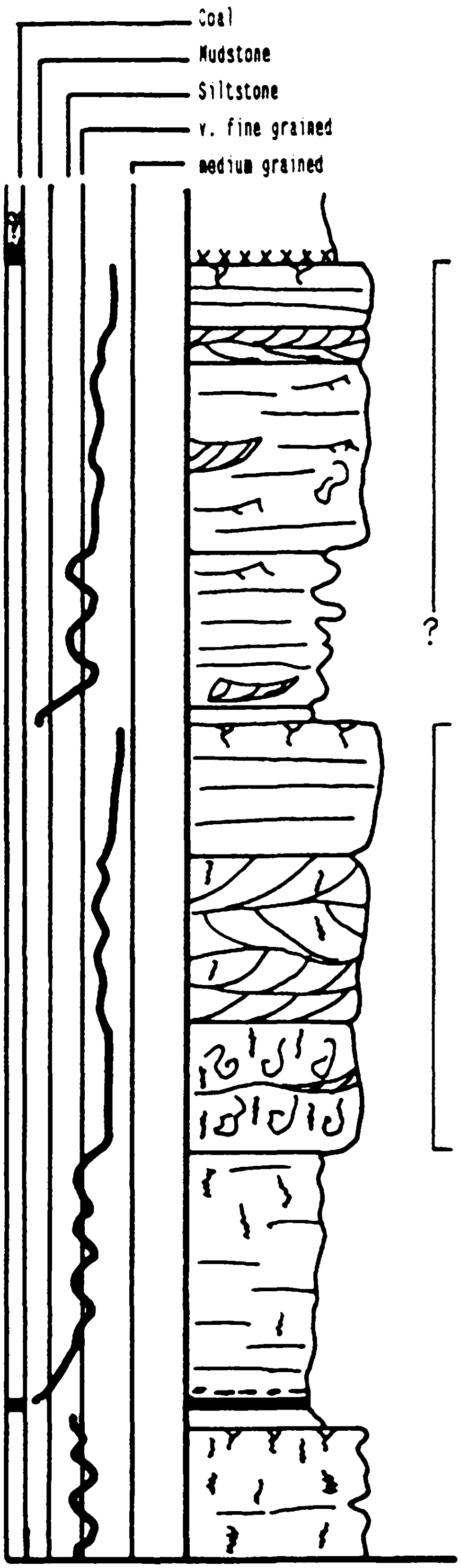


brackish water pelecypods
Rock Canyon coal zone (burned and coal)

BEAR CANYON MEMBER

(continued from top of part 2)

Section #6, part 1
Book Cliffs, Utah
SWNE 31-13S-13E
Vertical scale: 1 inch = 10 feet
PBA 1991



(continued on #6, part 2)
covered, burn-probably Gilson Coal zone

TANK CANYON MEMBER

ROCK CANYON MEMBER

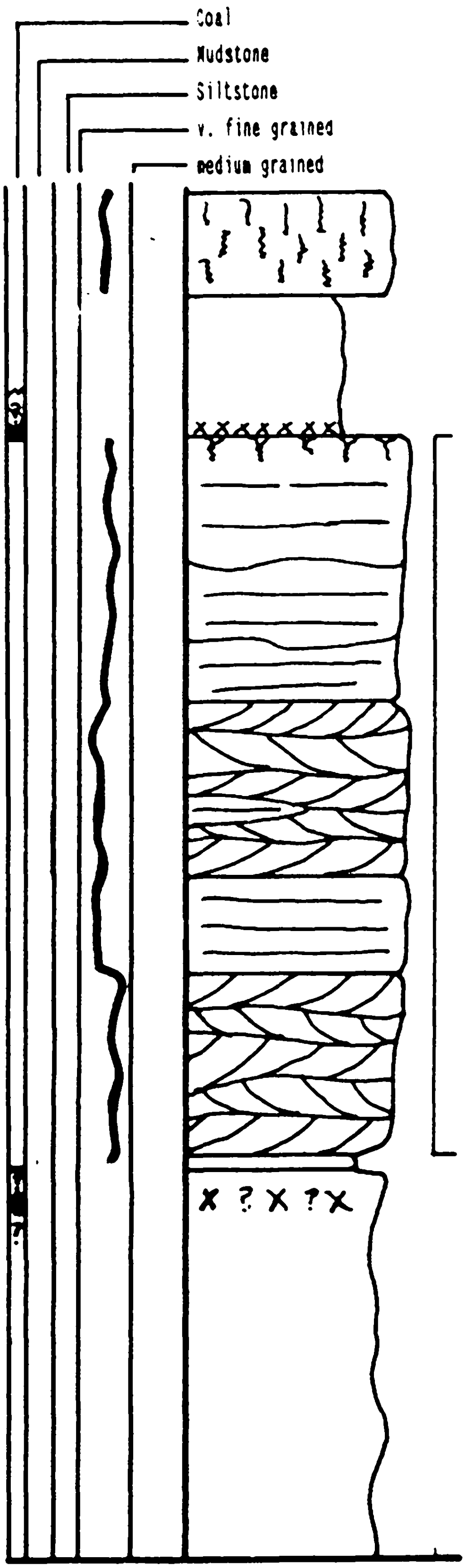
Foreshore

Upper Shoreface

(This unit may be equivalent to the uppermost Kenilworth member in Pace Canyon.)

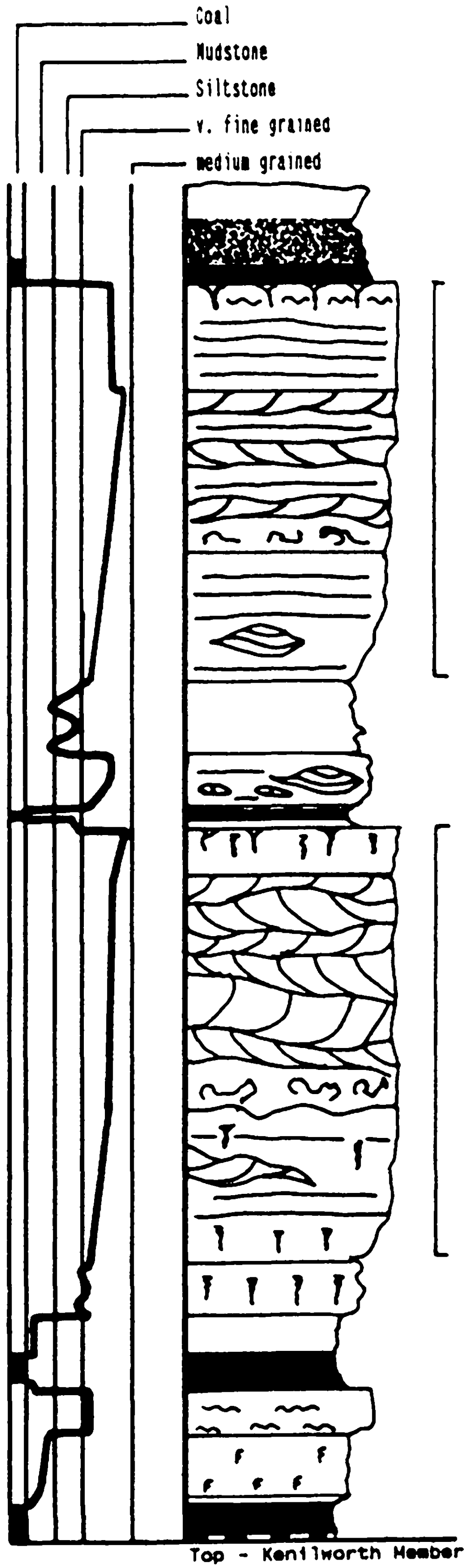
Top-Kenilworth Member

Section #6, part 2
Book Cliffs, Utah
SWNE 31-13S-13E
Vertical scale: 1 inch = 10 feet
PBA 1991

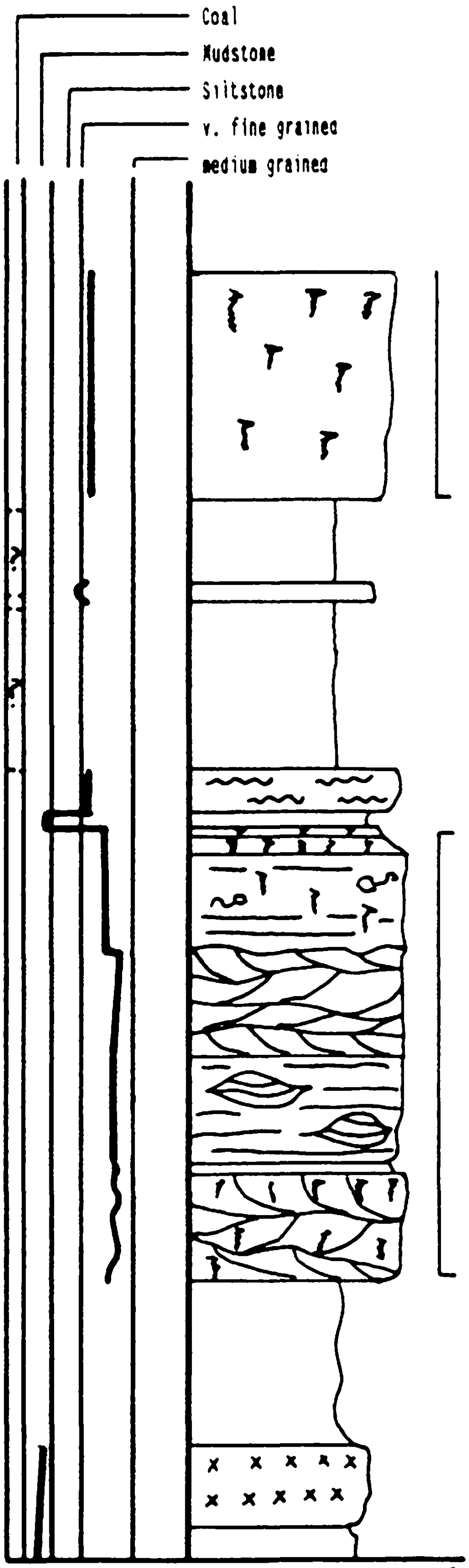


(continued from top of part 1)

Section #7, part 1
Book Cliffs, Utah
NENW 31-13S-13E
Vertical scale: 1 inch = 10 feet
PBA 1991



Section #7, part 2
Book Cliffs, Utah
NENW 31-13S-13E
Vertical scale: 1 inch = 10 feet
PBA 1991



basal Sunnyside member
not main ss. unit
abundant *Ophiomorpha*

mostly covered - mudstone

mostly covered - coal/burn and mudstone

BEAR CANYON TONGUE

Foreshore

Upper Shoreface

Lower Shoreface

??

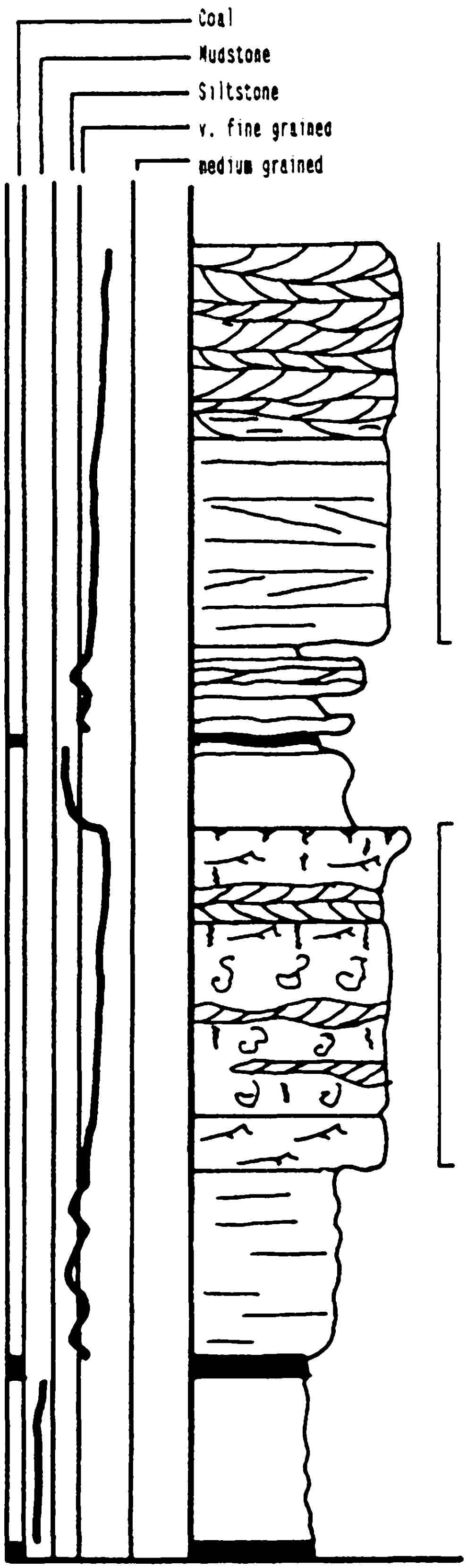
mostly covered - ss., siltst., mudst.
with plant fragments - non-marine

baked mudstone

mudstone - poorly exposed

(continued from top of part 1)

Section #8, part 1
Book Cliffs, Utah
SENW 31-13S-13E
Vertical scale: 1 inch = 10 feet
PBA 1991



(continued on #8, part 2)

TANK CANYON MEMBER
part of "white cap"

Upper Shoreface

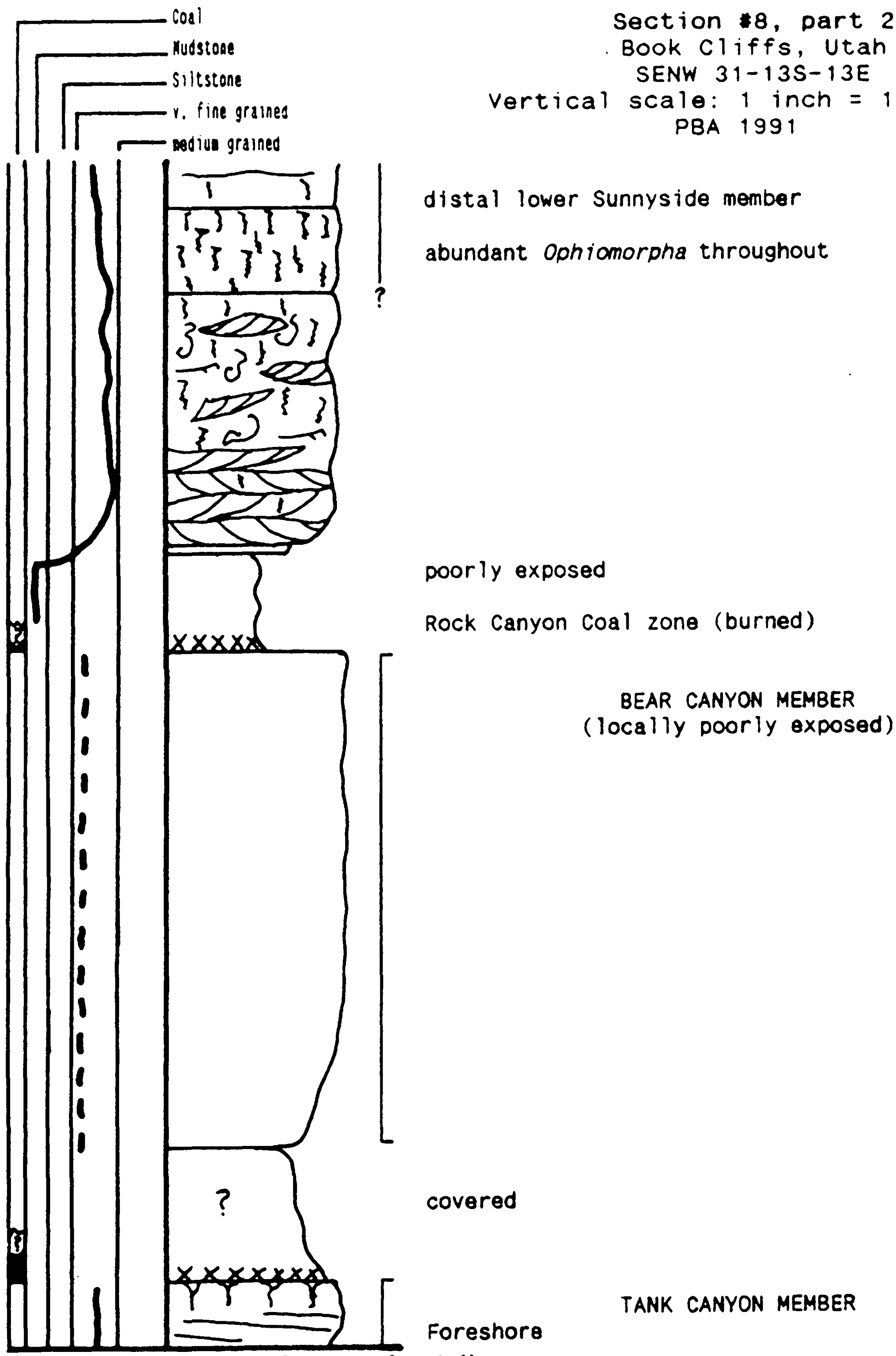
Lower Shoreface

ROCK CANYON MEMBER

covered - mostly mudstone

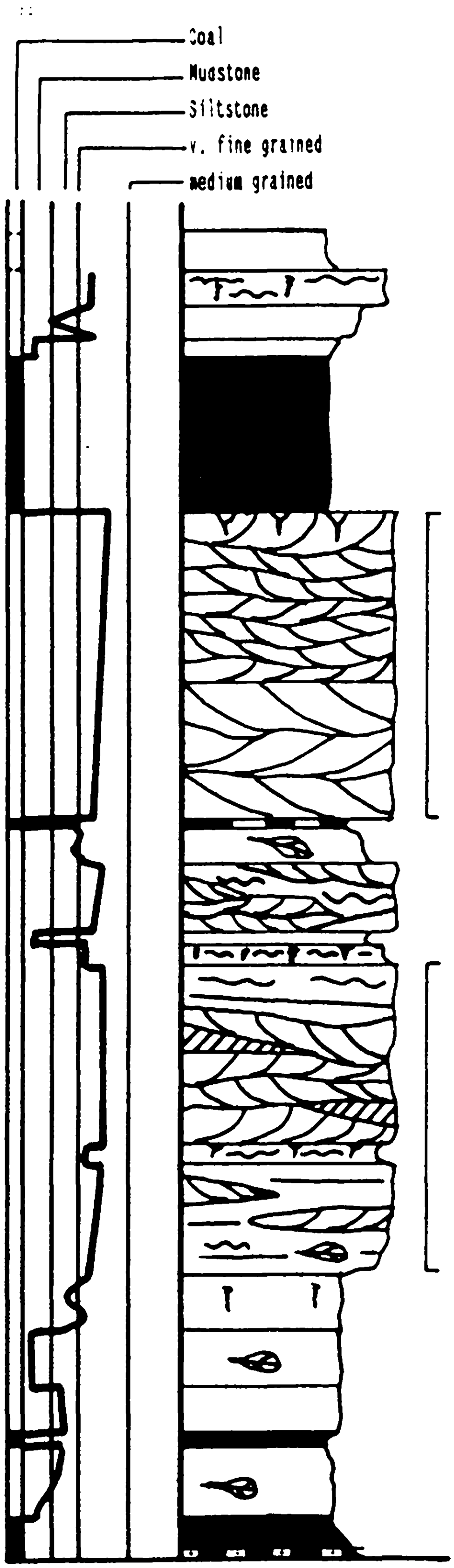
Top-Kenilworth Member

Section #8, part 2
Book Cliffs, Utah
SENW 31-13S-13E
Vertical scale: 1 inch = 10 feet
PBA 1991



(continued from top of part 1)

Section #9, part 1
Book Cliffs, Utah
NWNW 31-13S-13E
Vertical scale: 1 inch = 10 feet
PBA 1991



(continued on #9, part 2)
mostly covered-coal/mudst.

Gilson Coal zone

TANK CANYON MEMBER

Upper Shoreface(?)

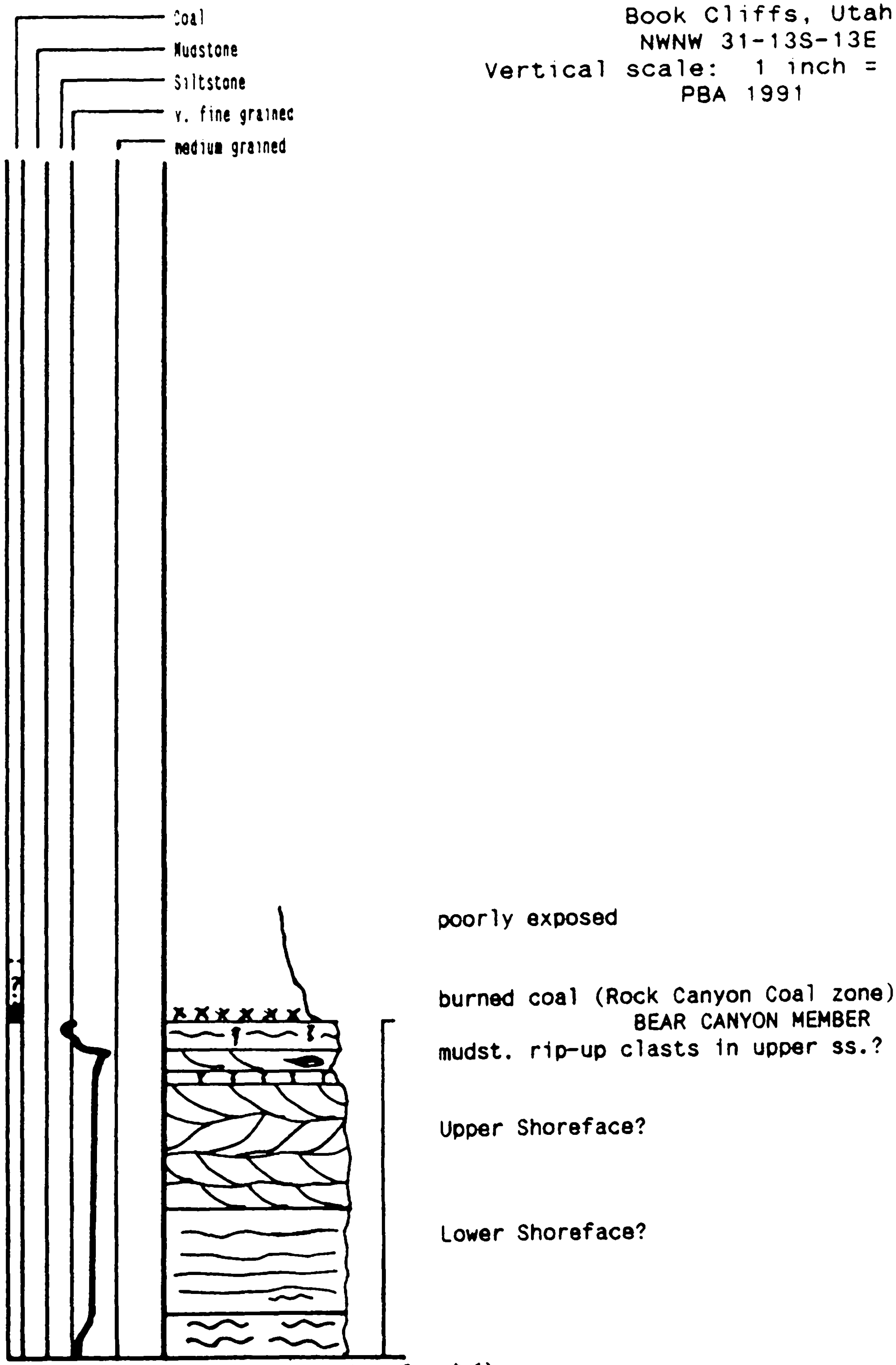
ROCK CANYON MEMBER

Transgressive unit

iron stained

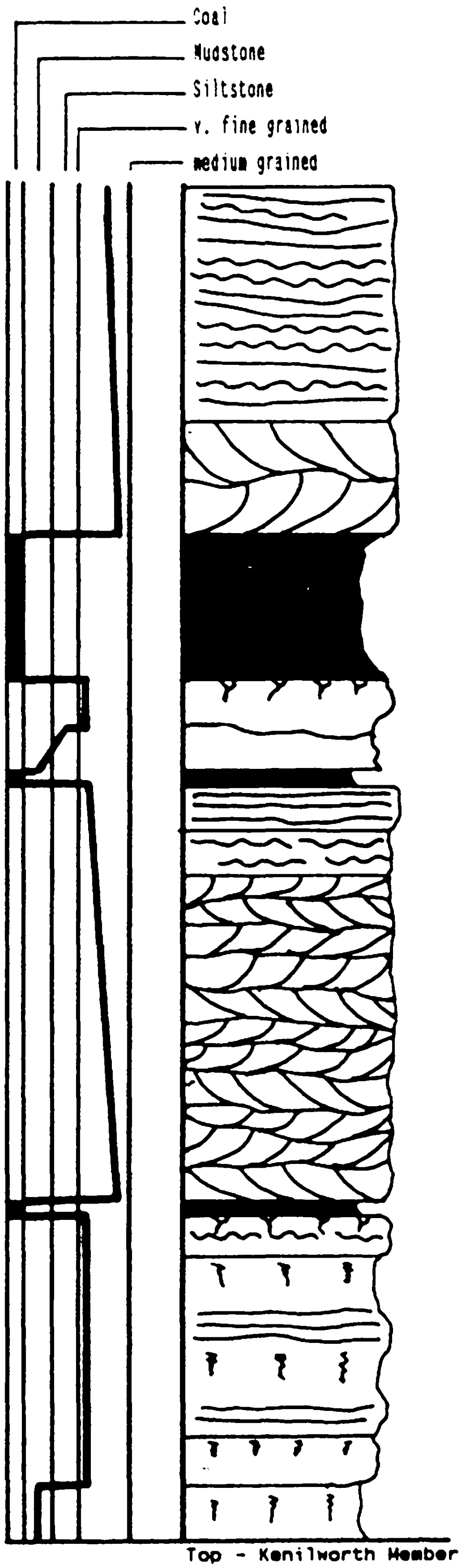
Top - Kenilworth Member

Section #9, part 2
Book Cliffs, Utah
NWNW 31-13S-13E
Vertical scale: 1 inch = 10 feet
PBA 1991



(continued from top of part 1)

Dugout Canyon-Balsley, part 1*
Book Cliffs, Utah
23-13S-12E
Vertical scale: 1 inch = 10 feet
PBA 1991



(continued on Dugout-Balsley, part 2)
point-bar sequence

Gilson coal zone

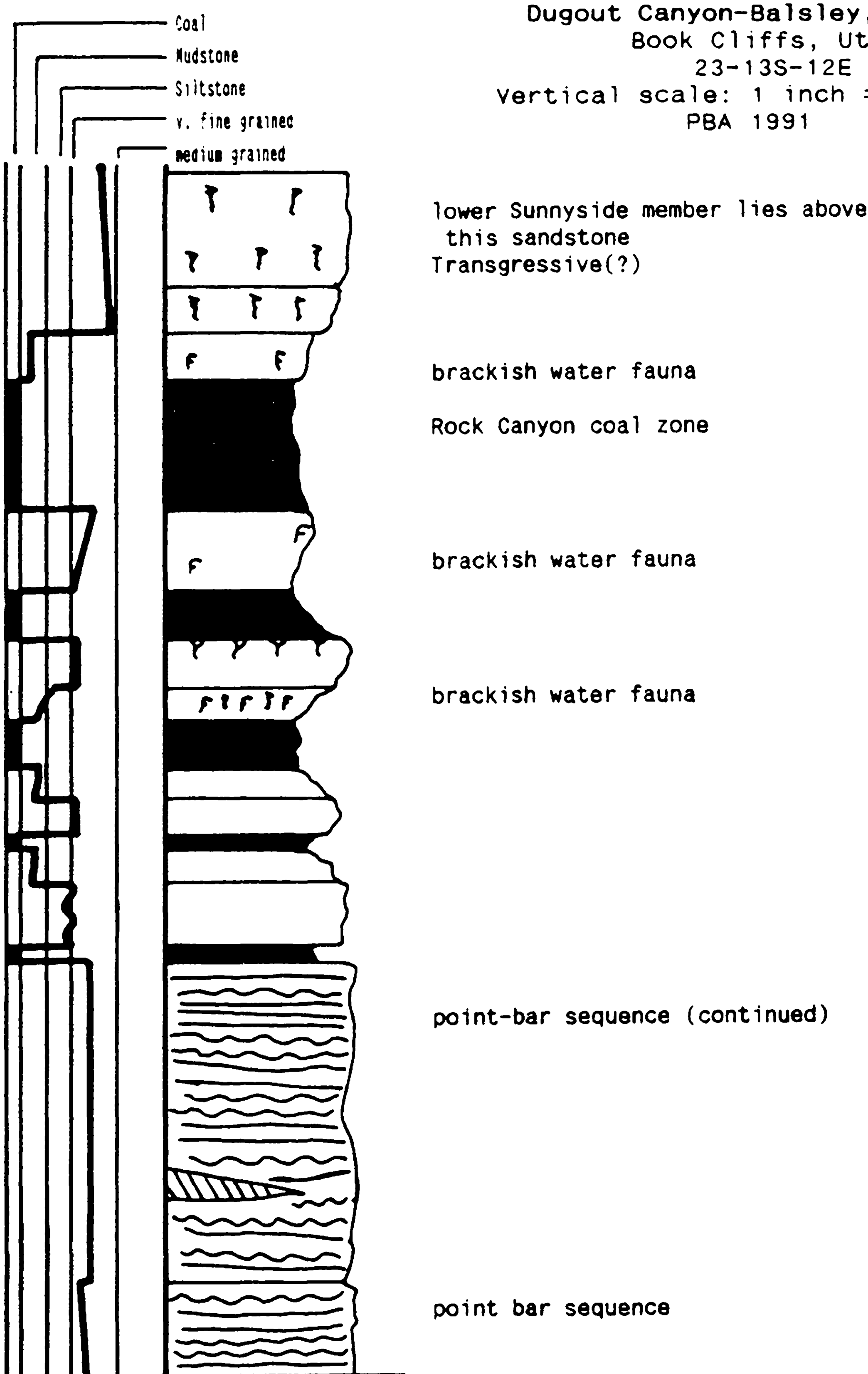
lagoon fill (lateral equivalent of Tank member)

point-bar sequence

restricted marine (lateral equivalent of Rock Canyon member)

*modified from Balsley

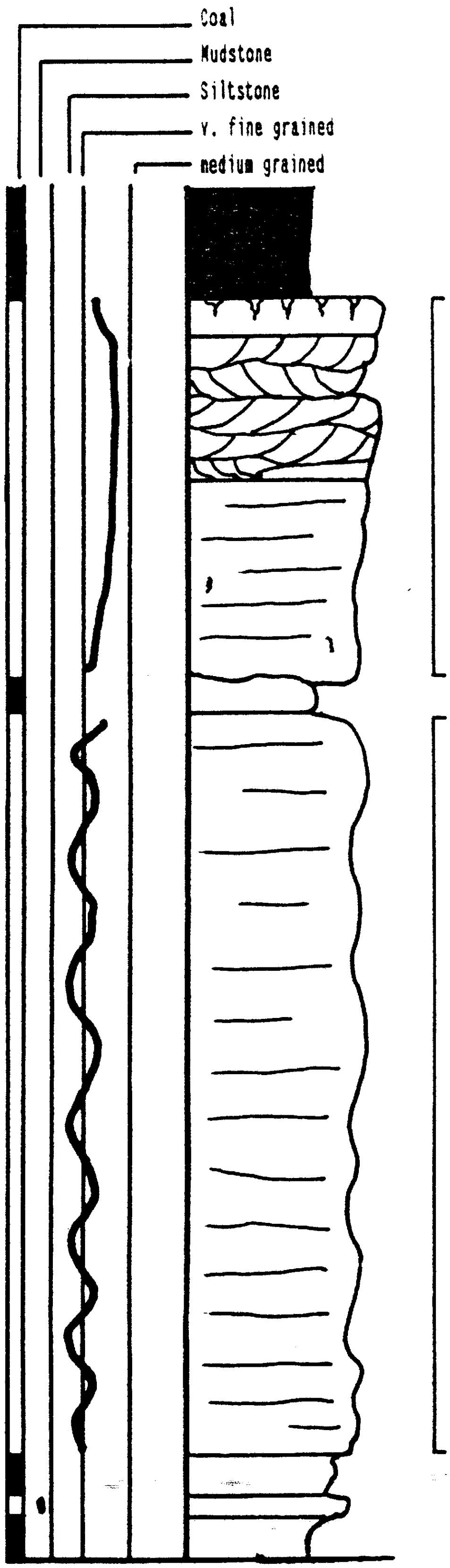
Dugout Canyon-Balsley, part 2*
Book Cliffs, Utah
23-13S-12E
Vertical scale: 1 inch = 10 feet
PBA 1991



(continued from top of part 1)

*modified from Balsley

Pace Canyon-Balsley, part 1*
Book Cliffs, Utah
30-13S-13E
Vertical scale: 1 inch = 10 feet
PBA 1991



continued on Pace-Balsley, part 2)
Gilson Coal Zone

TANK CANYON MEMBER

Upper Shoreface

Lower Shoreface

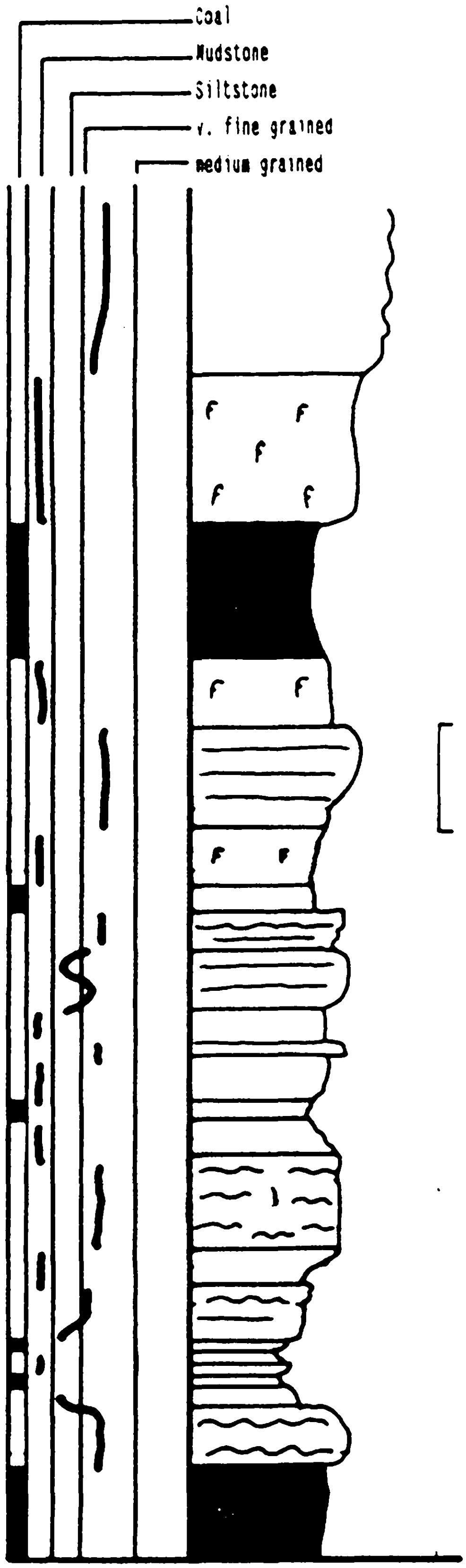
Part or all(?) of this sandstone is equivalent to the Rock Canyon member

Ophiomorpha and smooth tubes were noted

Top-Kenilworth Member

*modified from Balsley, 1976

Pace Canyon-Balsley, part 2*
Book Cliffs, Utah
30-13S-13E
Vertical scale: 1 inch = 10 feet
PBA 1991



distal lower Sunnyside member

fresh water fauna
(at Pace Canyon Mine coal is overlain by approximately 30' of fluvial sandstone)

Rock Canyon coal zone

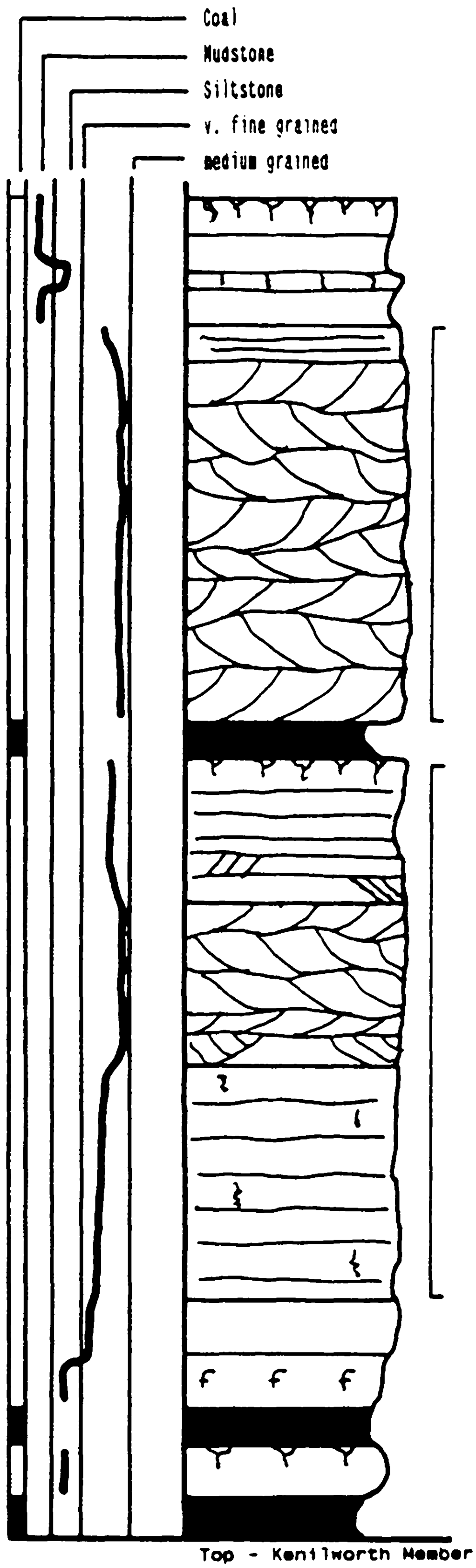
brackish water pelecypods

lateral equivalent of
BEAR CANYON MENBER
interdeltaic or bay deposits

Gilson Coal zone

(continued from top of part 1) *modified from Balsley, 1976

Rock Canyon-Balsley, part 1*
Book Cliffs, Utah
32-13S-13E
Vertical scale: 1 inch = 10 feet
PBA 1991



(continued on Rock Canyon-Balsley, part 2)

TANK CANYON MEMBER

Upper shoreface

ROCK CANYON MEMBER

Forshore

Upper shoreface

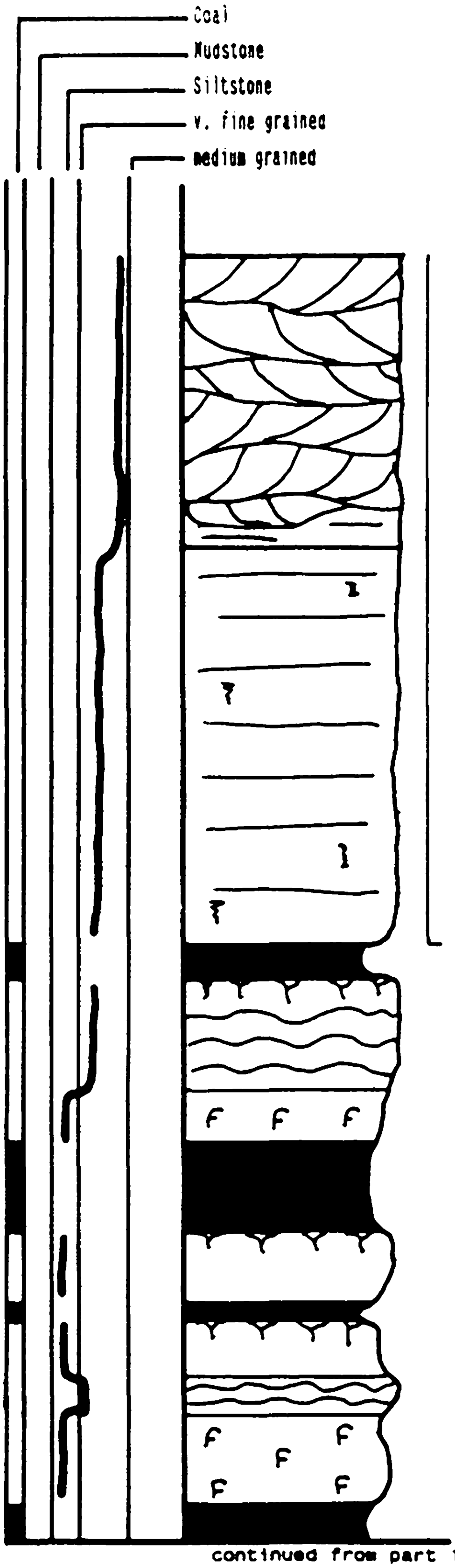
Lower shoreface

transgressive unit (?)

brackish water pelecypods

*modified from Balsley, 1980

Rock Canyon-Balsley, part 2*
Book Cliffs, Utah
32-13S-13E
Vertical scale: 1 inch = 10 feet
PBA 1991



(continued on Rock Canyon-Balsley, part 3)

BEAR CANYON MEMBER

Upper shoreface

Lower shoreface

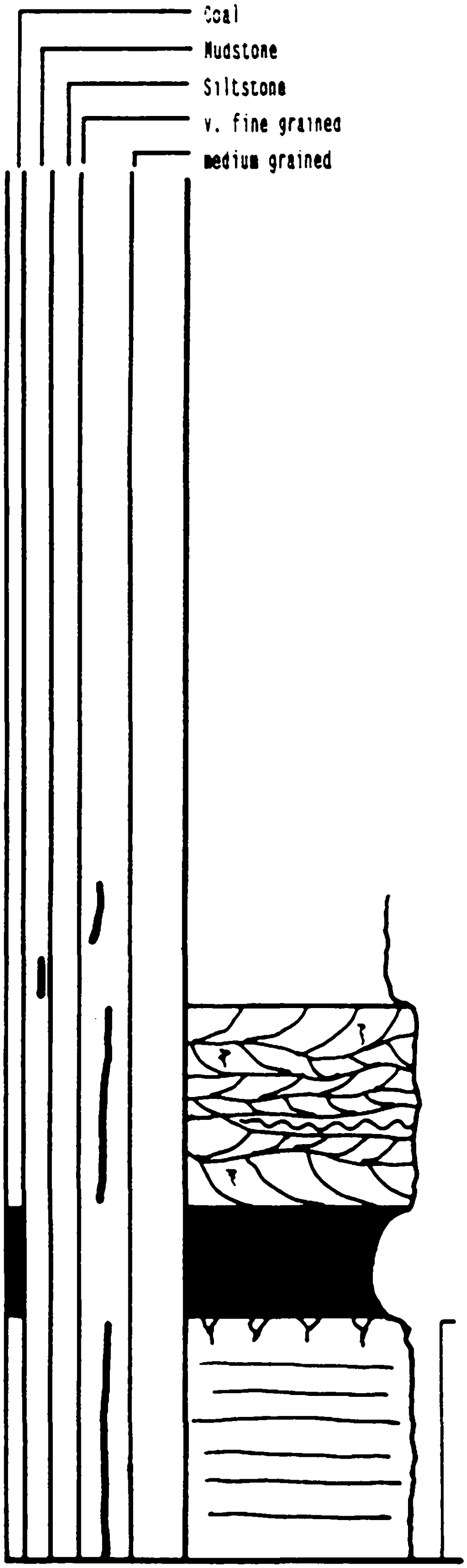
Top of coal eroded

Gilson Coal Zone

Pelecypod and oyster fauna

*modified from Balsley, 1980

Rock Canyon-Balsley, part 3*
Book Cliffs, Utah
32-13S-13E
Vertical scale: 1 inch = 10 feet
PBA 1991



restricted marine deposits

Rock Canyon Coal

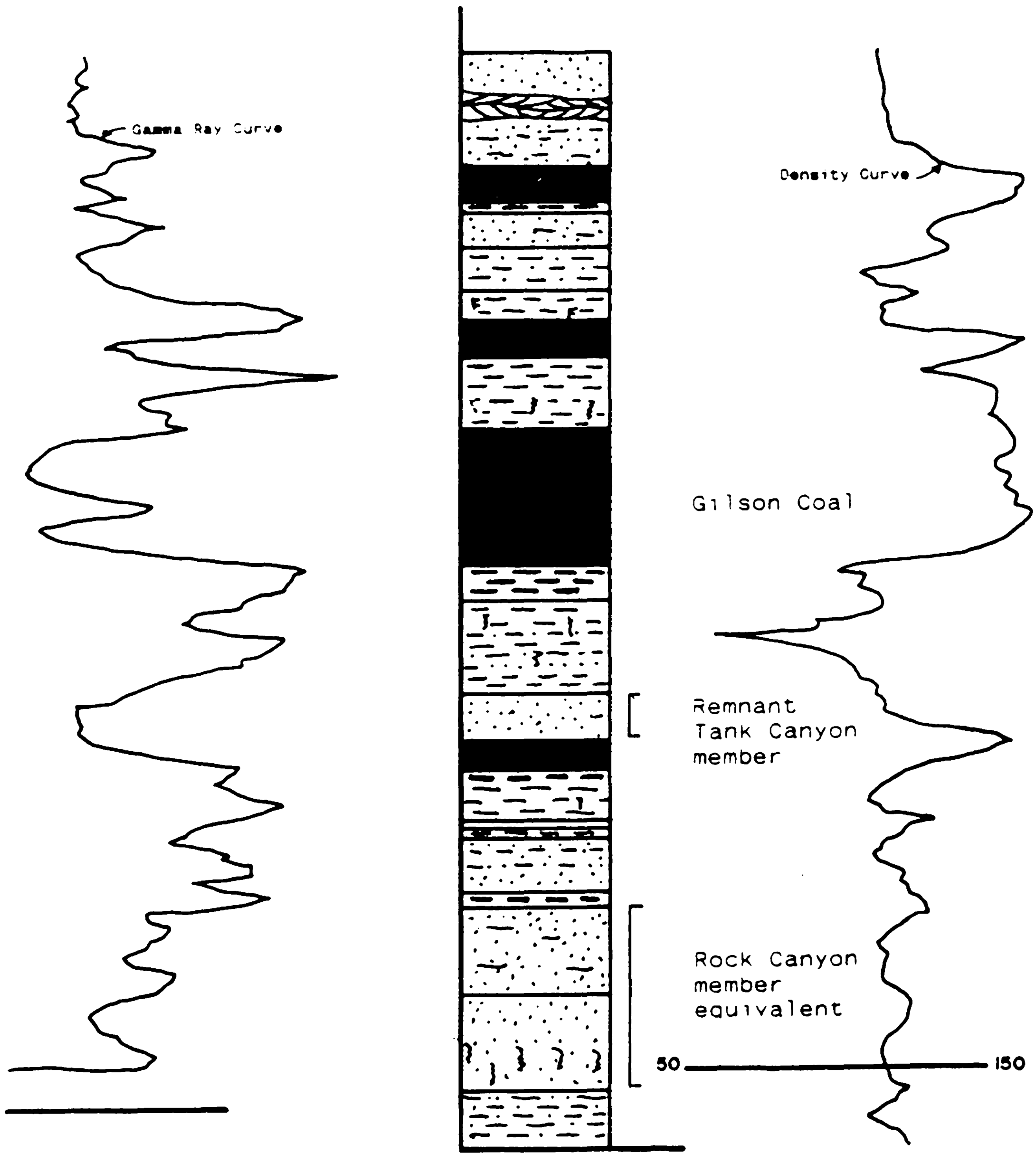
BEAR CANYON MEMBER

Foreshore

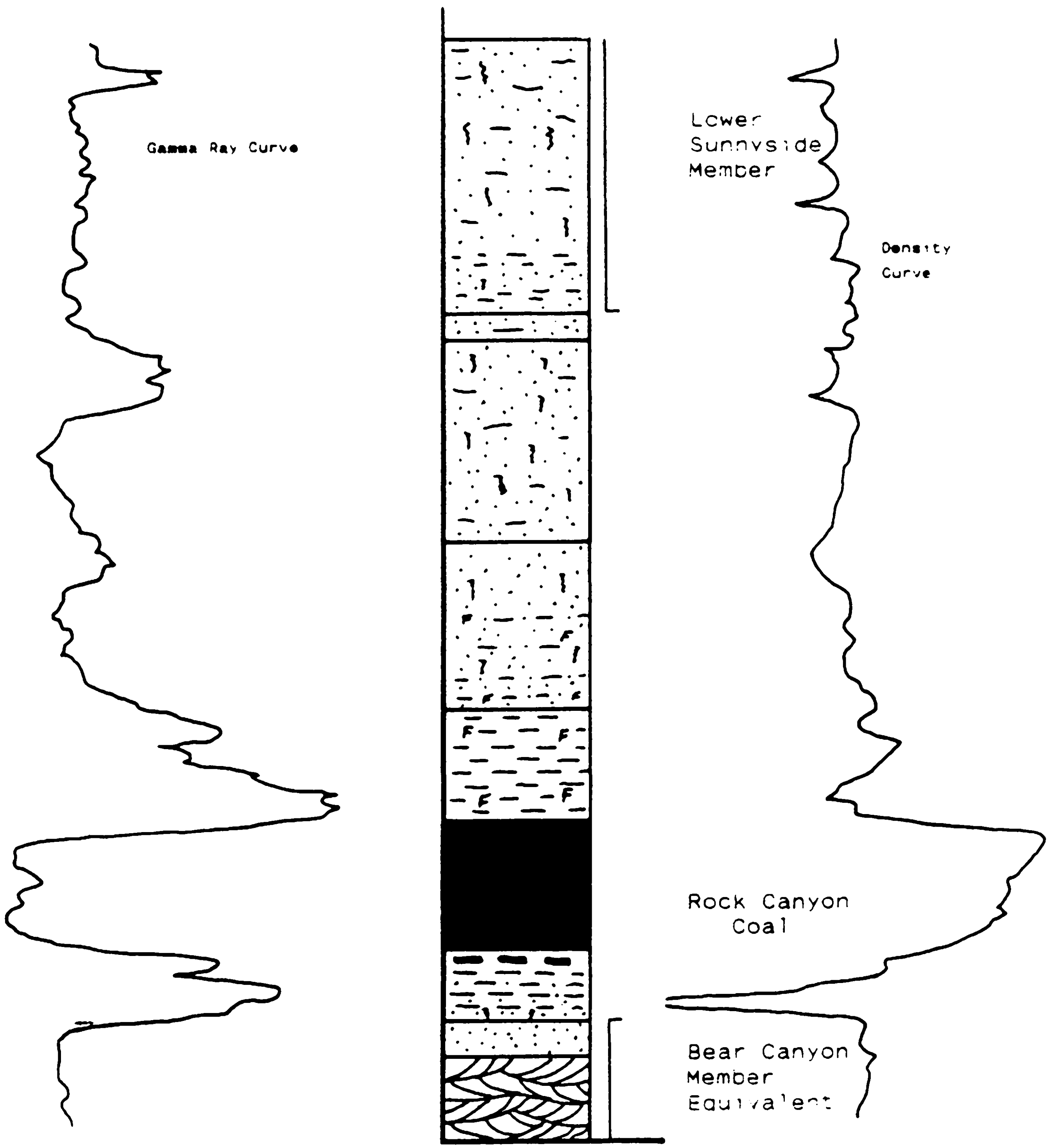
continued from part 2

*modified from Balsley, 1980

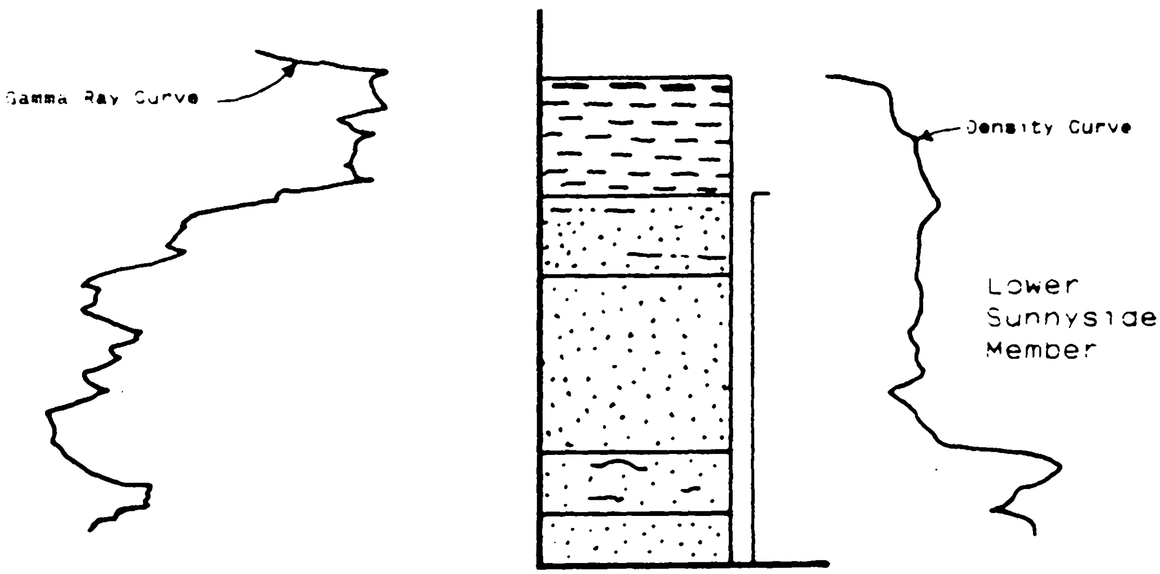
Drill hole #24, part 1
Book Cliffs, Utah
NESE 24-13S-12E
Vertical scale 1 inch = 10 feet
(from core)
PBA 1991



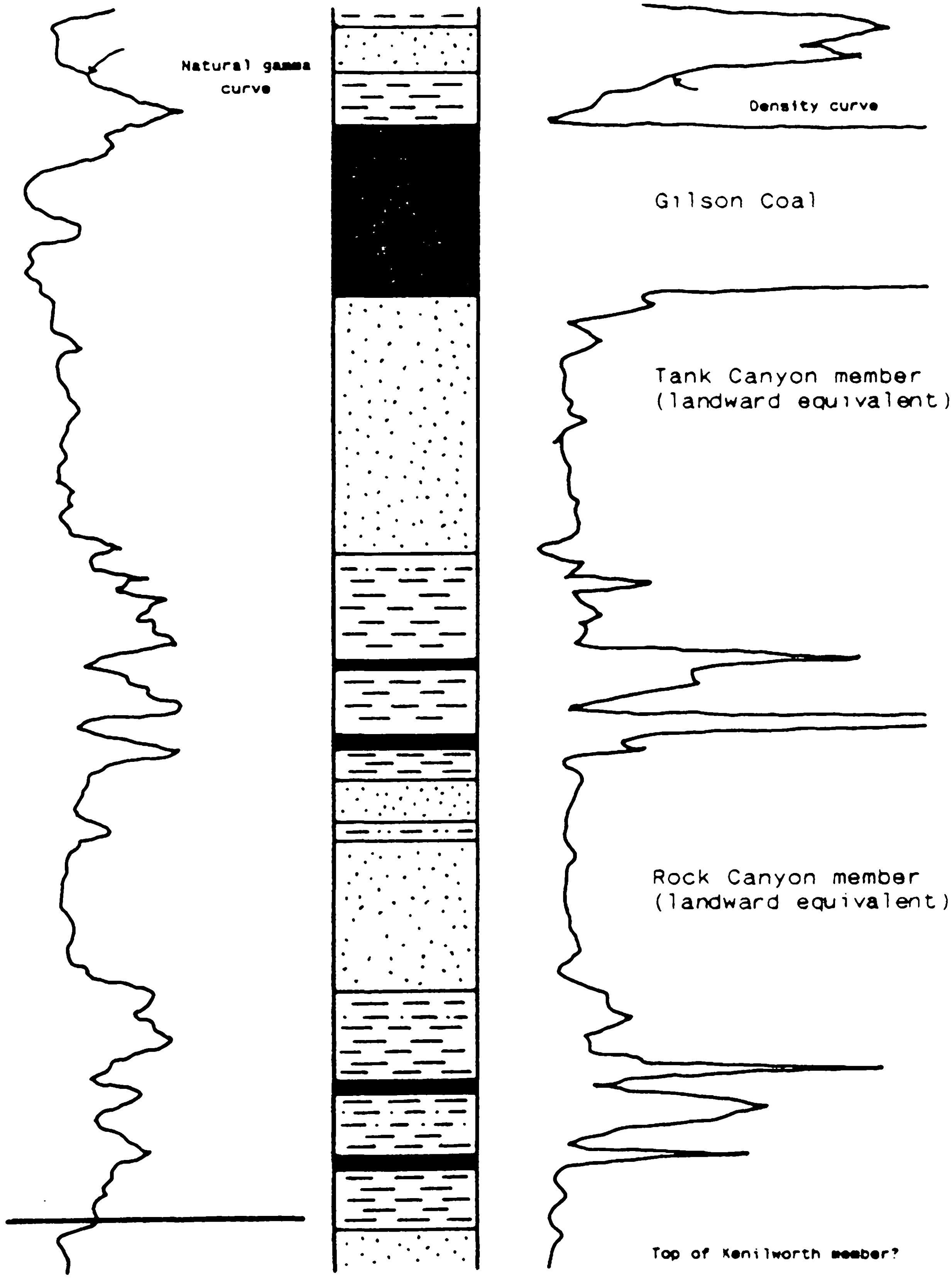
Drill hole #24, part 2
Book Cliffs, Utah
NESE 24-13S-12E
Vertical scale 1 inch = 10 feet
(from core)
PBA 1991



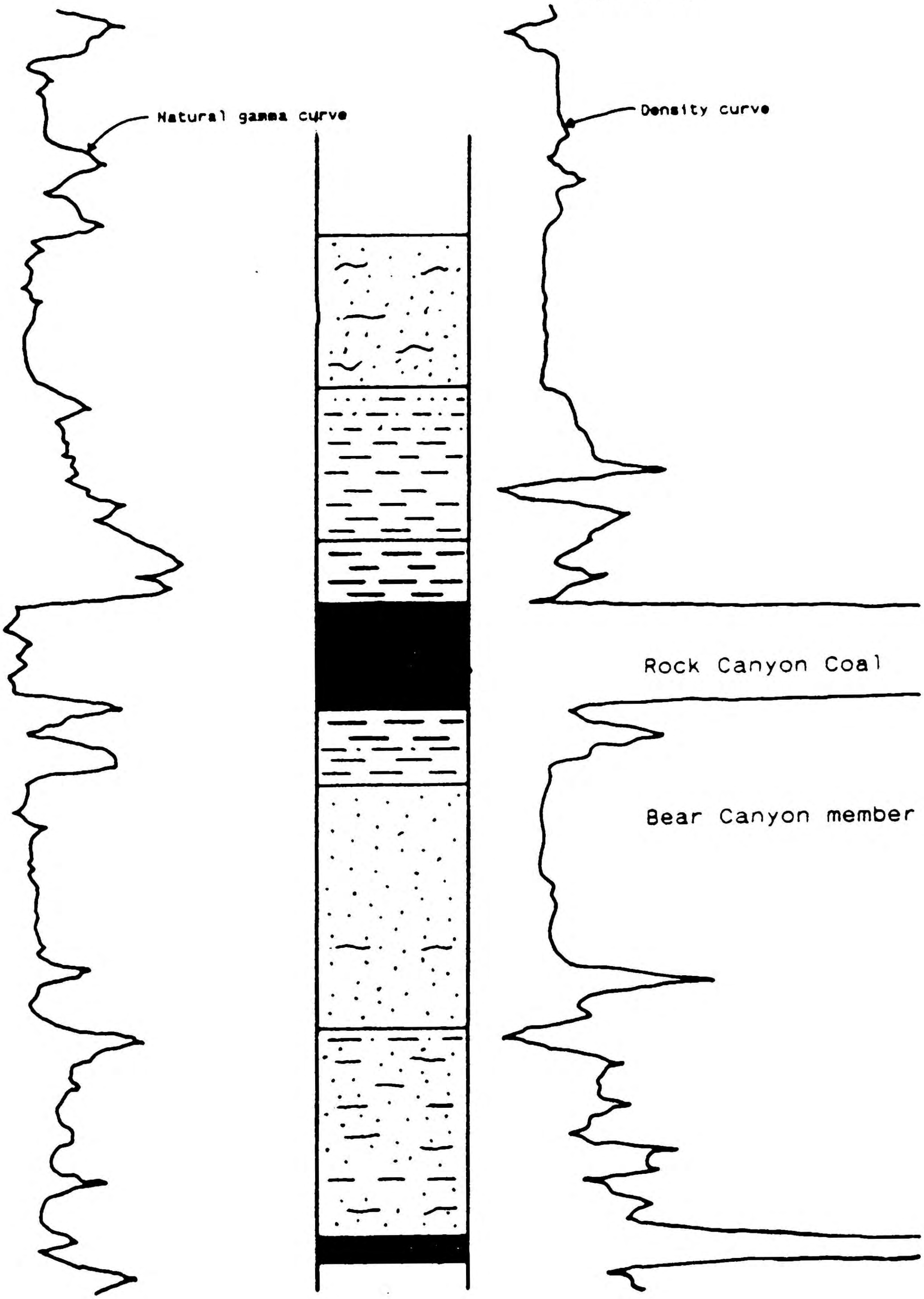
Drill hole #24, part 3
Book Cliffs, Utah
NESE 24-13S-12E
Vertical scale 1 inch = 10 feet
(from core)
PBA 1991



Drill hole #19-1, part 1
Book Cliffs, Utah
NENW 19-13S-13E
Vertical scale 1 inch = 10 feet
PBA 1991

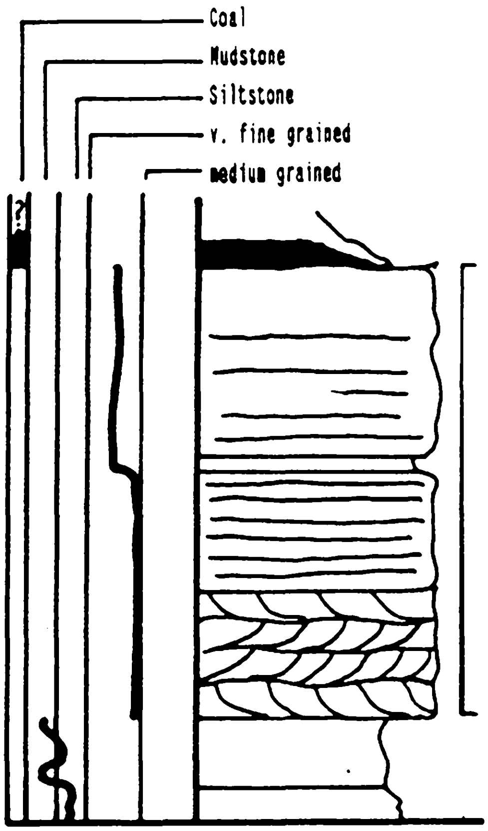


Drill hole #19-1, part 2
Book Cliffs, Utah
NENW 19-13S-13E
Vertical scale 1 inch = [illegible] feet
PBA 1991



Measured Sections - Muddy Creek Area

Section #J1
Muddy Creek Area, Utah
SWNE 13-22S-6E
Vertical scale: 1 inch = 10 feet
PBA 1991

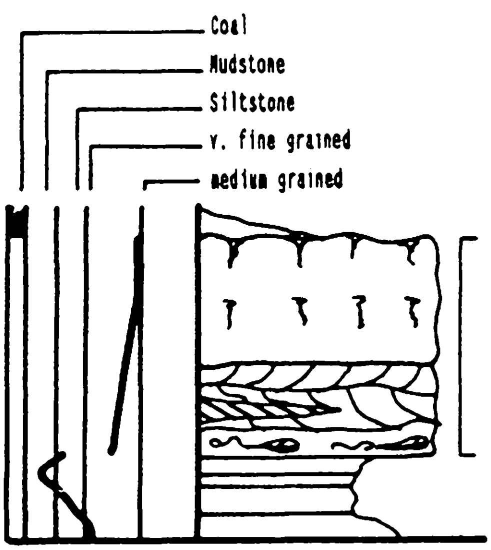


J coal zone

J SANDSTONE

I swamp or delta-plain deposits

Section #J2
Muddy Creed Area, Utah
SENW 13-22S-6E
Vertical scale: 1 inch = 10 feet
PBA 1991

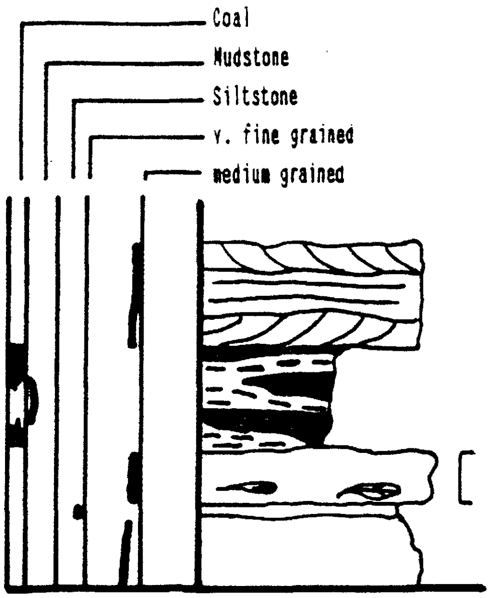


J coal zone

J SANDSTONE

I swamp or delta-plain deposits

Section #J20
Muddy Creek Area, Utah
SWNE 13-22S-6E
Vertical scale: 1 inch = 10 feet
PBA 1991

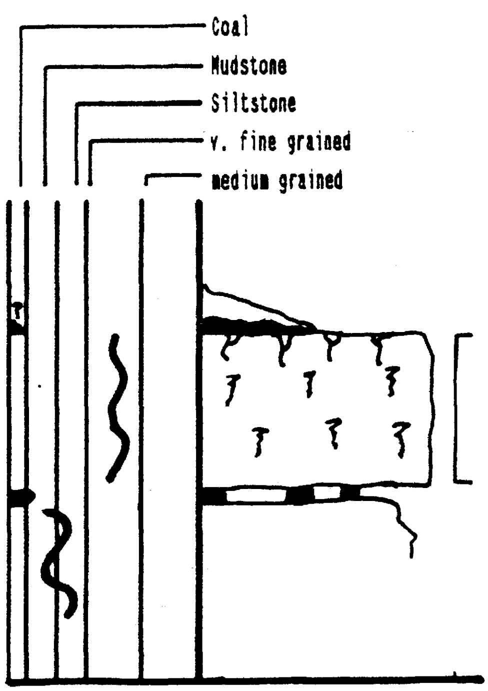


J coal zone (coal & carbonaceous mudstone - poorly exposed)

J SANDSTONE

poorly exposed I swamp or delta-plain deposits

Section #J21
Muddy Creek Area, Utah
SWNE 13-22S-6E
Vertical scale: 1 inch = 10 feet
PBA 1991

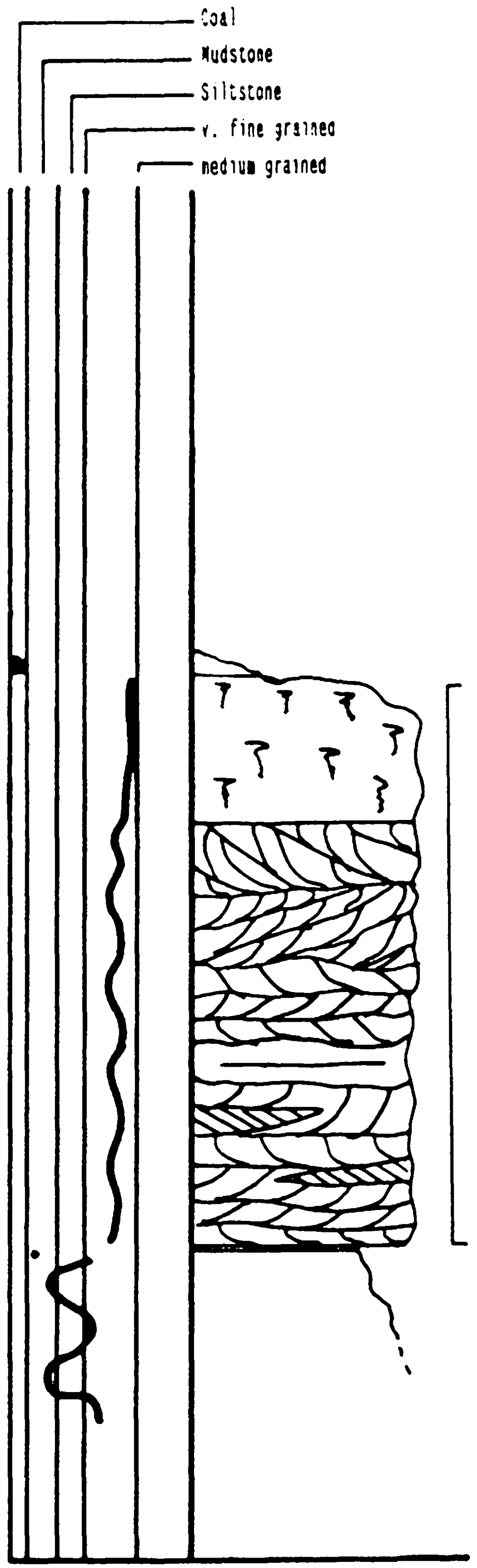


J coal zone

J SANDSTONE

I swamp
coal, mudstone, siltstone, carbonacous mudstone

Section #J25
Muddy Creek Area, Utah
NENE 13-22S-6E
Vertical scale: 1 inch = 10 feet
PBA 1991

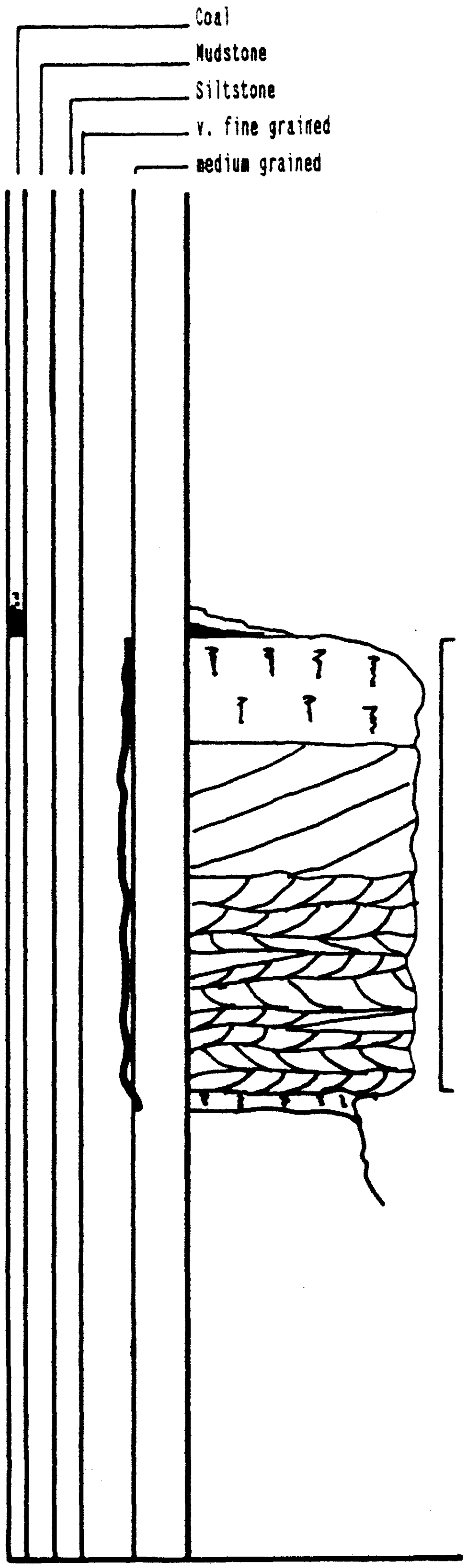


J coal zone

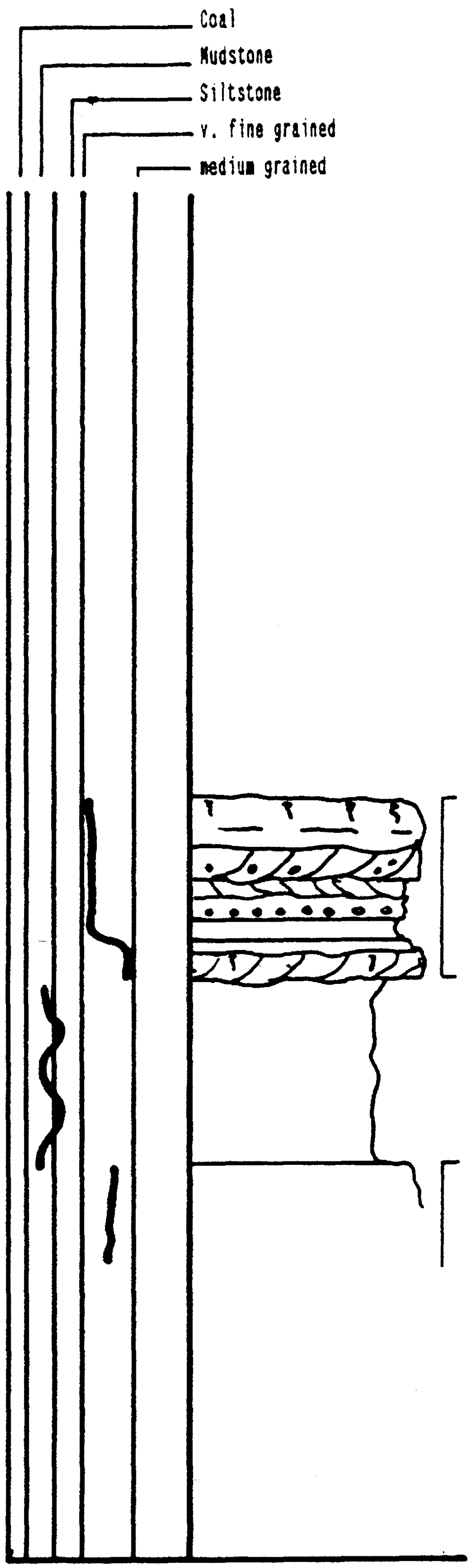
J SANDSTONE

I swamp or delta-plain deposits

Section #J26
Muddy Creek Area, Utah
NWNE 13-22S-6E
Vertical scale: 1 inch = 10 feet
PBA 1991



Section #J27
Muddy Creek Area, Utah
SWSW 18-22S-7E
Vertical scale: 1 inch = 10 feet
PBA 1991



J coal zone - eroded off

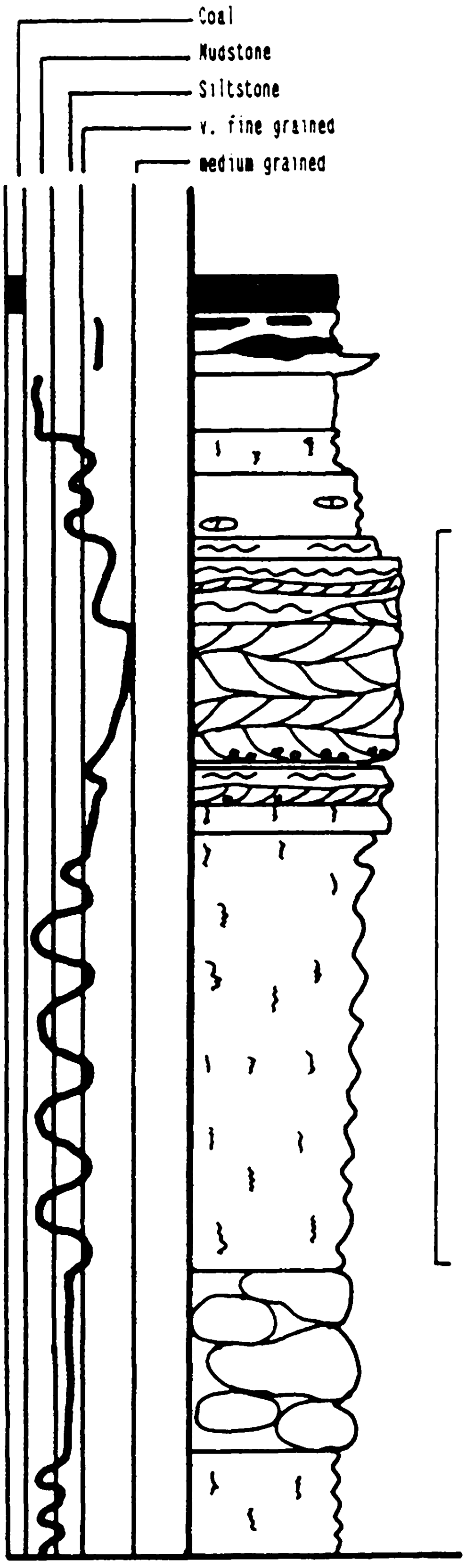
J SANDSTONE

I swamp or delta-plain deposits

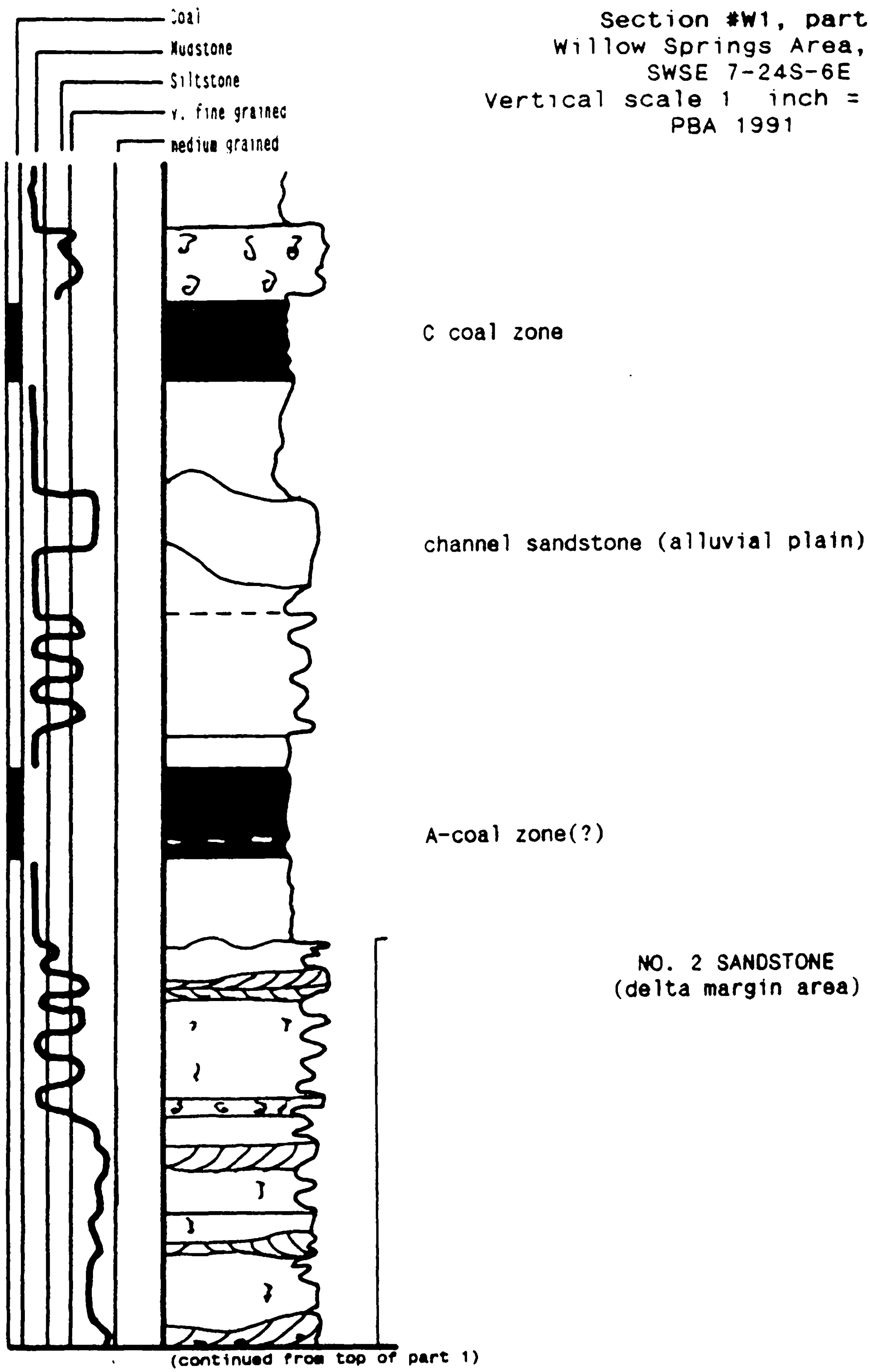
NO. 5 SANDSTONE

Measured Sections - Willow Springs Area

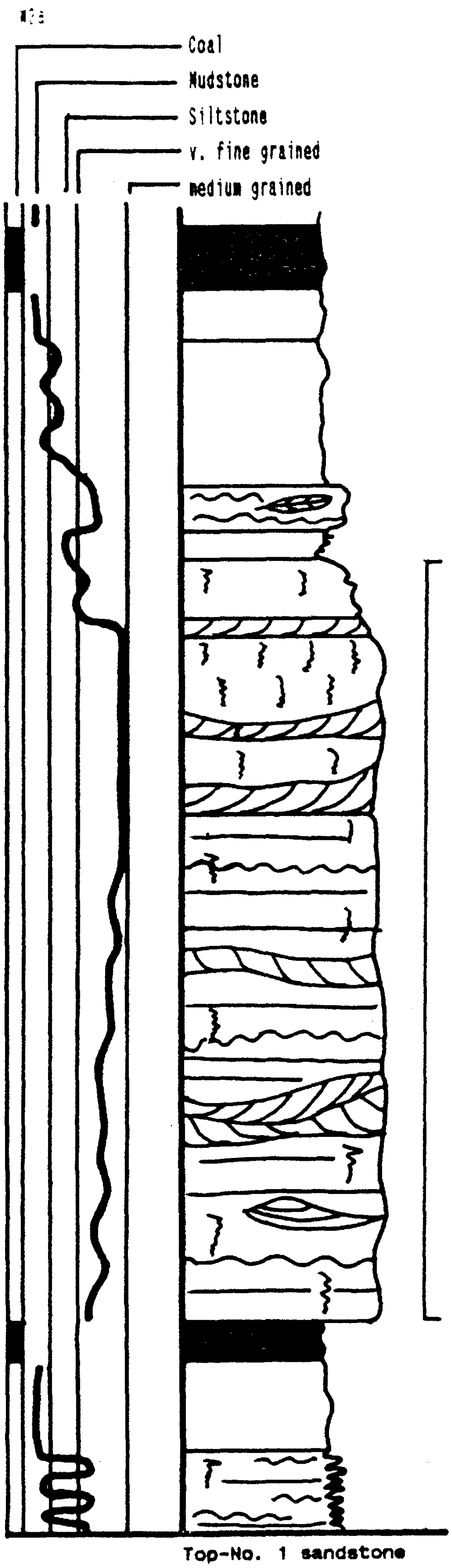
Section #W1, part 1
Willow Springs Area, Utah
SWSE 7-24S-6E
Vertical scale 1: inch = 10 feet
PBA 1991



Section #W1, part 2
Willow Springs Area, Utah
SWSE 7-24S-6E
Vertical scale 1 inch = 10 feet
PBA 1991



Section #W2
Willow Springs Area, Utah
SWSE 7-24S-6E
Vertical scale 1 inch = 10 feet
PBA 1991



A-coal zone(?)

NO. 2 SANDSTONE

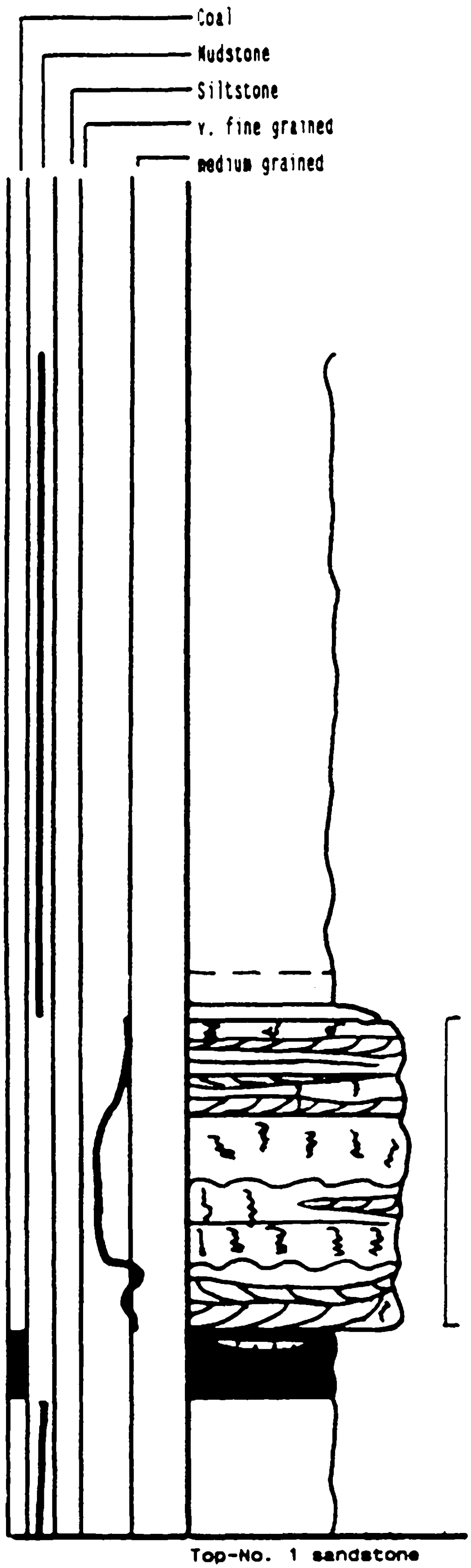
Ophiomorpha

coarsens up

sub-A coal zone

9 feet of fine-grain sandstone, cross bedded

Section #W3
Willow Springs Area, Utah
NWNE 18-24S-6E
Vertical scale: 1 inch = 10 feet
PBA 1991



poorly exposed - 30-50 feet of carbonaceous mudstone to siltstone, with some coal beds - delta plain facies

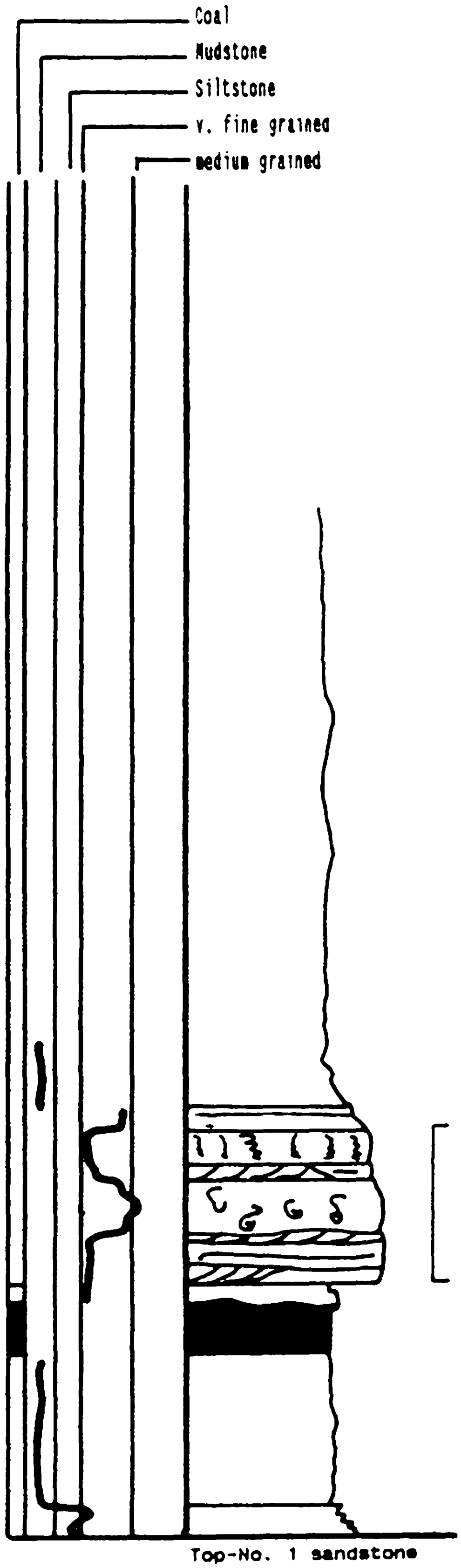
NO. 2 SANDSTONE
"white cap" (mouth bar)

distal bar

sub-A coal zone

15 feet thick, sandstone, very-fine-grain to fine-grain, thin to medium bedded

Section #W4
Willow Springs Area, Utah
SWNE 18-24S-6E
Vertical scale: 1 inch = 10 feet
PBA 1991



poorly exposed, mudstones of the delta plain - some coals

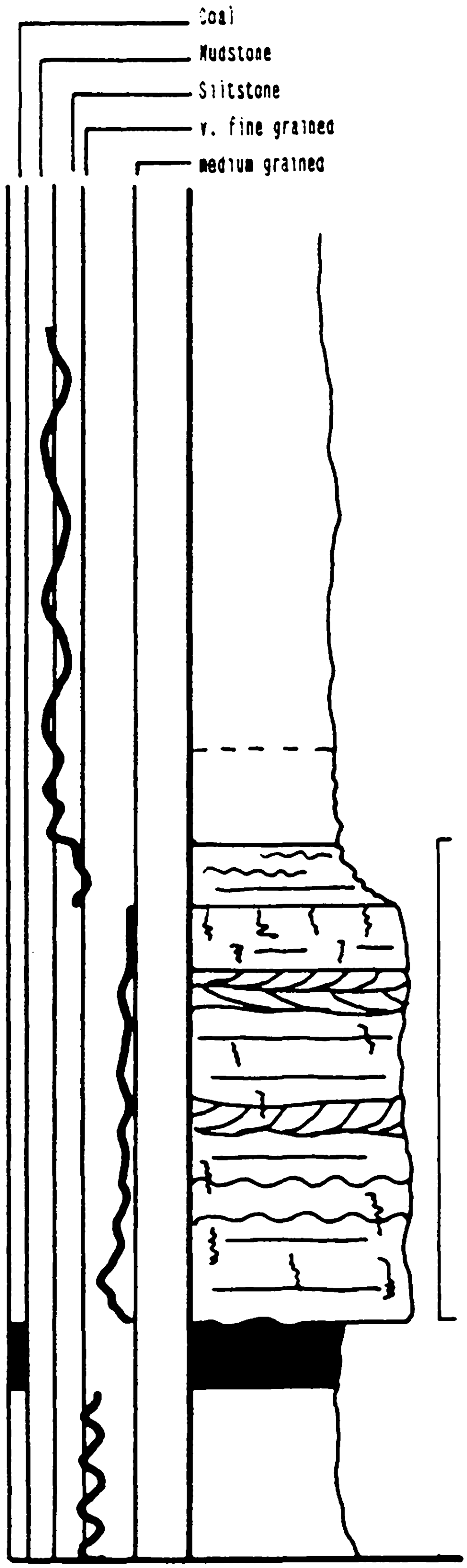
NO. 2 SANDSTONE

"white cap"

sub-A coal zone

15 feet thick sandstone, very-fine-grain to fine-grain, thin-to medium-bedded

Section #W5
Willow Springs Area, Utah
SWNE 18-24S-6E
Vertical scale: 1 inch = 10 feet
PBA 1991



30-40 feet of delta plain rocks overlain by 10-15 feet of channel sandstone

NO. 2 SANDSTONE

mouth bar ("white cap")

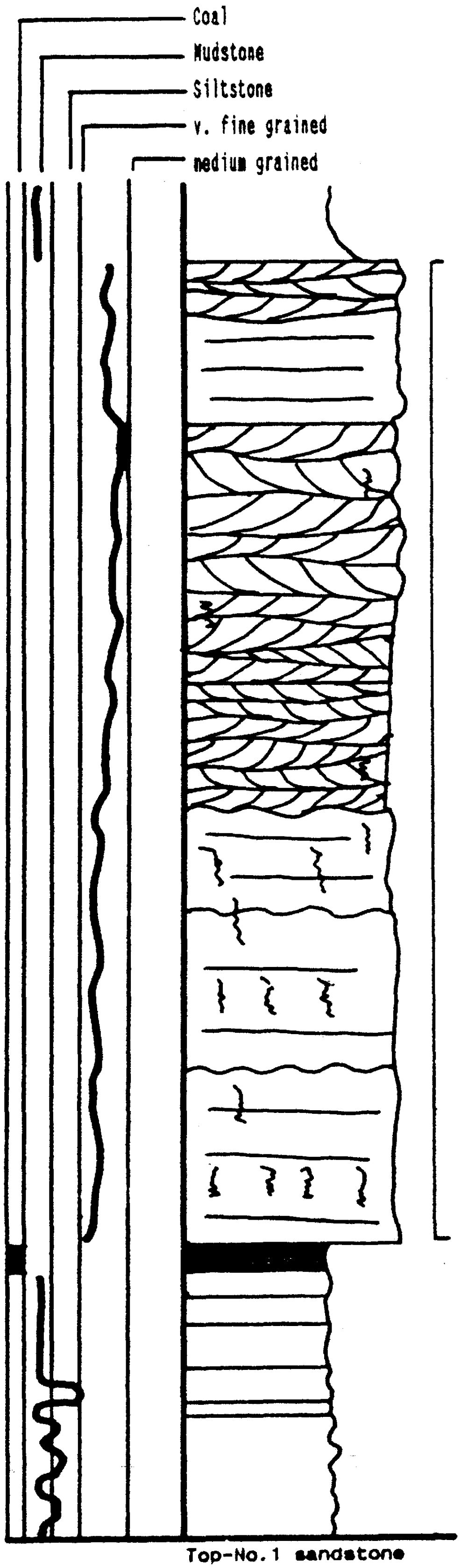
distal bar - large lunate ripples and *Ophipmorpha*

sub-A coal zone

Top-No. 1 sandstone

15 feet sandstone, very-fine-grain to fine-grain, thin- to medium-bedded

Section #W6
Willow Springs Area, Utah
NWSE 18-24S-6E
Vertical scale 1 inch = 10 feet
PBA 1991



NO. 2 SANDSTONE

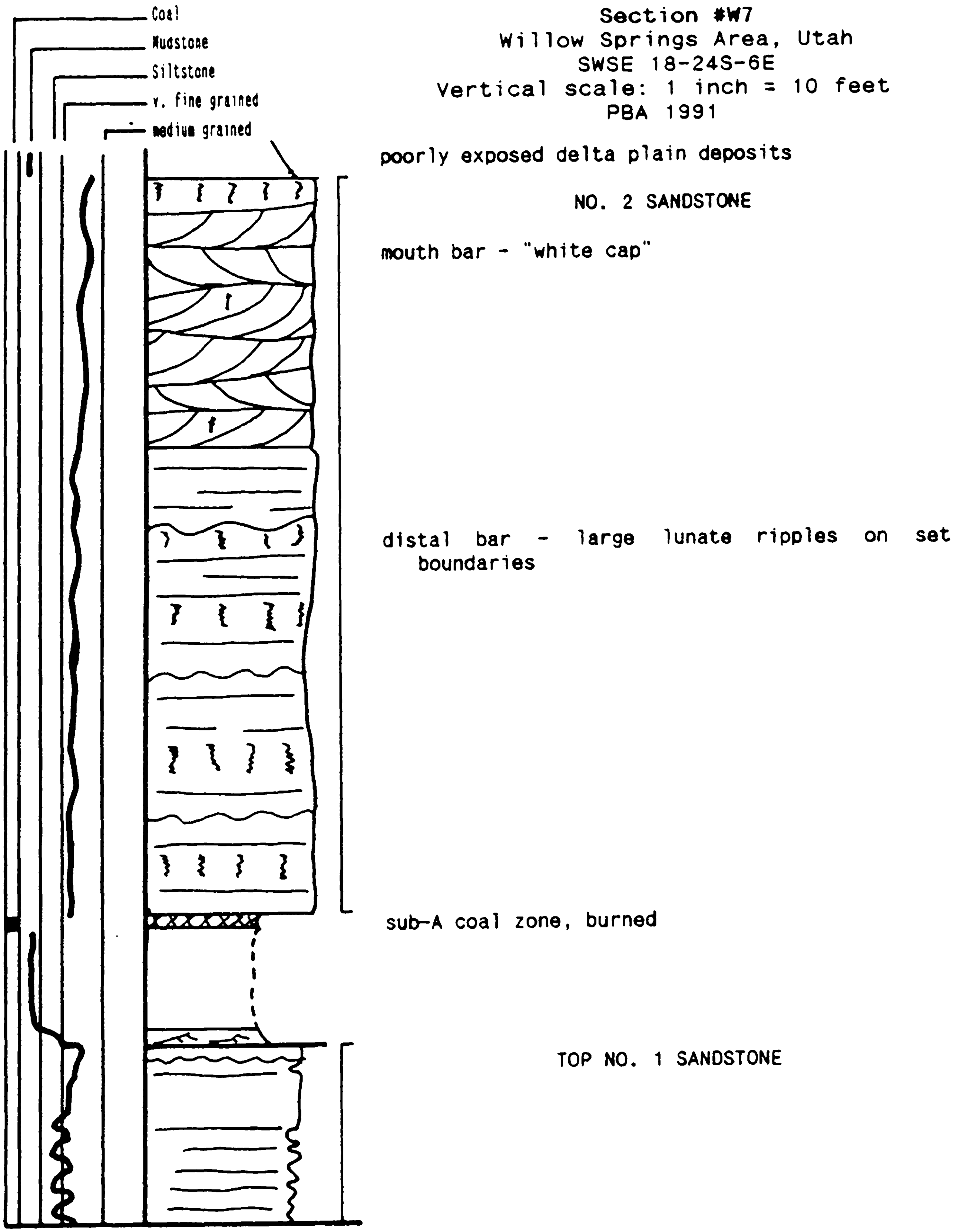
mouth bar

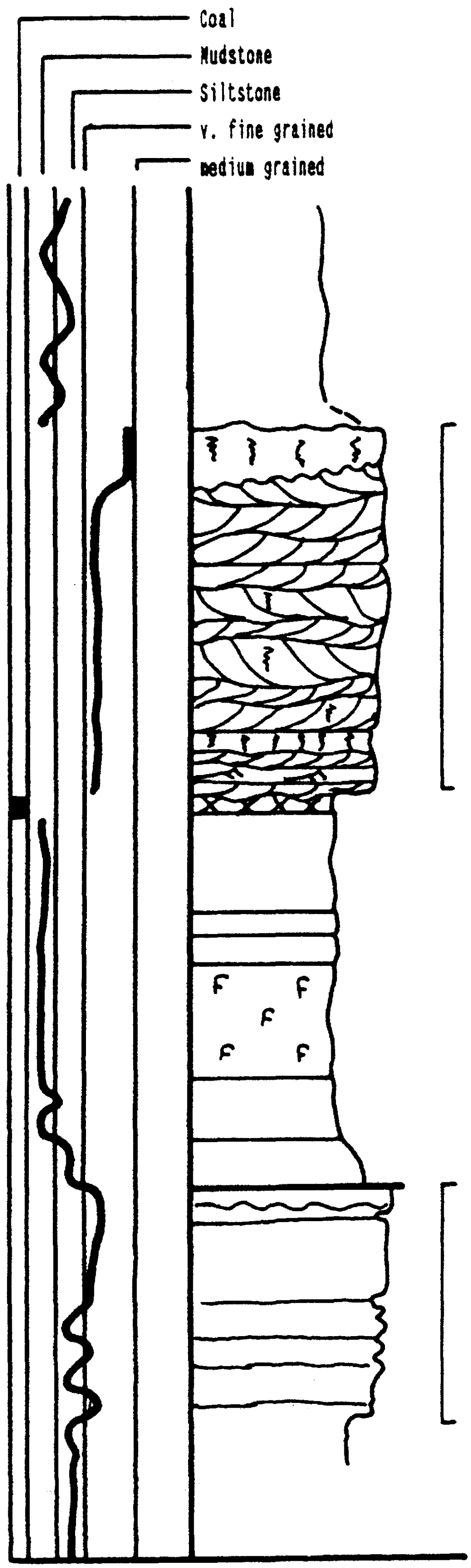
distal bar - large lunate ripples on set boundaries, *Ophiomorpha*

sub-A coal zone

10 to 15 feet of sandstone, thin- to medium-bedded

Section #W7
Willow Springs Area, Utah
SWSE 18-24S-6E
Vertical scale: 1 inch = 10 feet
PBA 1991





Section #W8
Willow Springs Area, Utah
SESW 18-24S-6E
Vertical scale: 1 inch = 10 feet
PBA 1991

30 to 50 feet of poorly exposed delta-plain deposits

NO. 2 SANDSTONE

"white-cap"

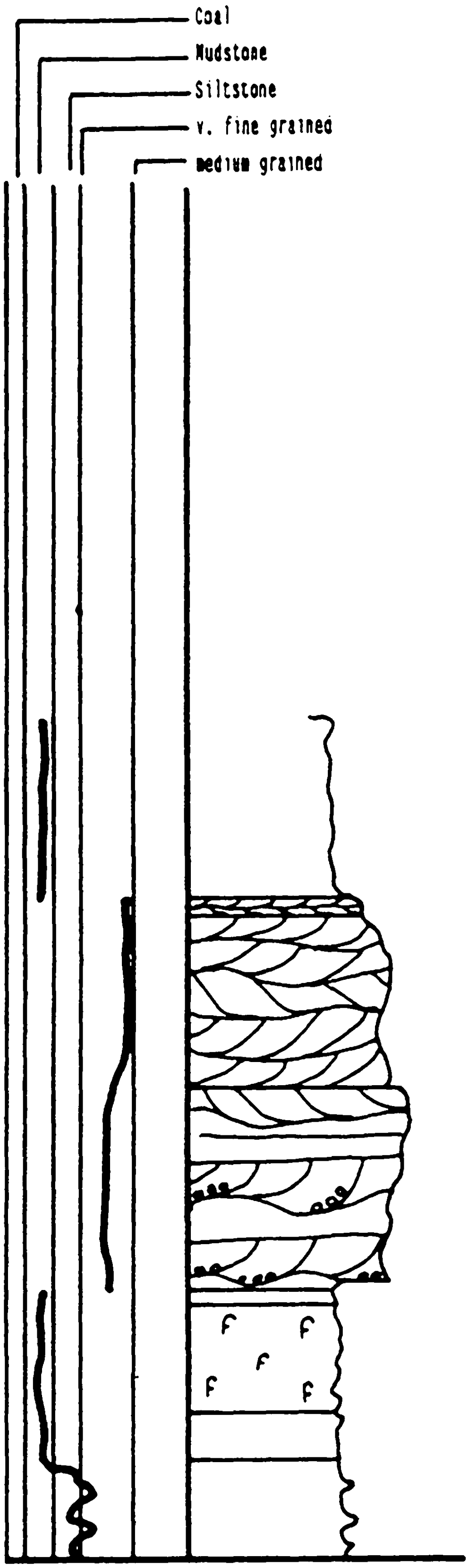
mouth bar

distal bar?
sub-A coal zone, burned

Corbula, *Brachiodontes*, *Anomia*, *Ostera*, *Crassostreal(?)*, *Neogastropoda(?)*

TOP NO. 1 SANDSTONE

Section #W9
Willow Springs Area, Utah
NWSW 18-24S-6E
Vertical scale: 1 inch = 10 feet
PBA 1991



delta-plain deposits, some burned coal

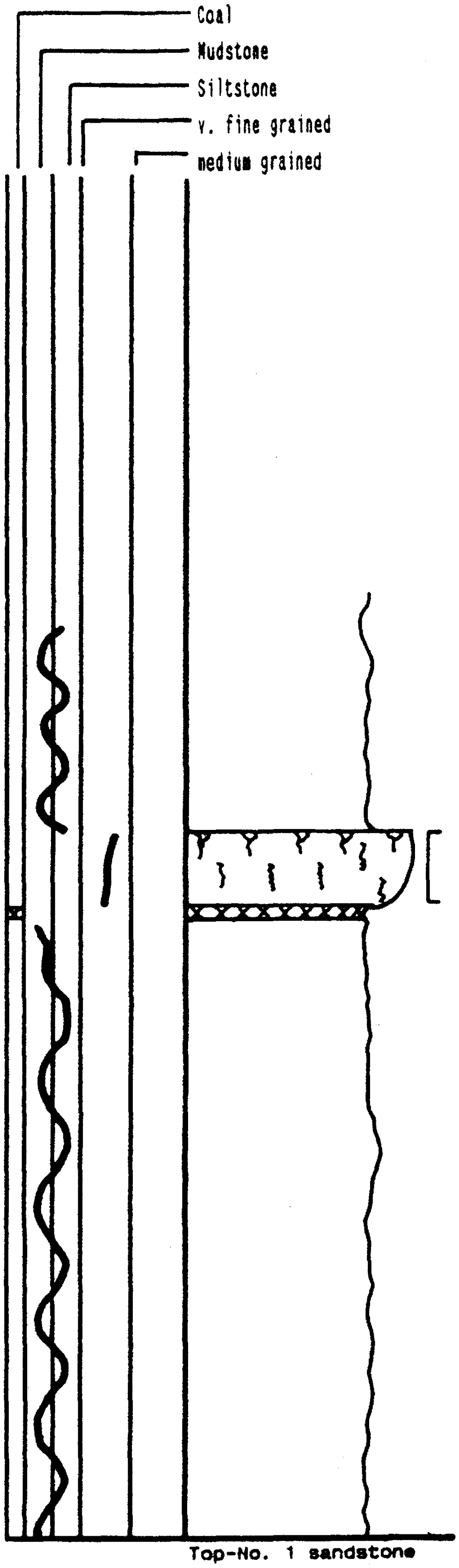
channel complex

(The channel top is at the same stratigraphic position as the top of No. 2 Sandstone to the east)

brackish water fauna (see section #w8)

Top-No. 1 sandstone

Section #W10
Willow Springs Area, Utah
NWSW 18-24S-6E
Vertical scale: 1 inch = 10 feet
PBA 1991



delta-plain deposits - mudstone and siltstone

NO. 2 SANDSTONE

(nearest landward pinchout)

poorly exposed - mostly mudstone

Section #W11
Willow Springs Area, Utah
SESW 18-24S-6E
Vertical scale: 1 inch = 10 feet
PBA 1991