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Final

GEOLOGICAL AND PETROPHYSICAL CHARACTERIZATION OF THE FERRON SANDSTONE FOR 3-D SIMULATION OF A FLUVIAL-DELTAIC RESERVOIR

(Contract No. DE-AC22-93BC14896)

Submitted by

Utah Geological Survey
Salt Lake City, Utah 84109

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Objective

The objective of this project is to develop a comprehensive, interdisciplinary, AND quantitative characterization of a fluvial-deltaic reservoir which will allow realistic inter-well and reservoir-scale modeling to be developed for improved oil-field development in similar reservoirs world-wide. The geological and petrophysical properties of the Cretaceous Ferron Sandstone in east-central Utah (figure 1) will be quantitatively determined. Both new and existing data will be integrated into a 3-D representation of spatial variations in porosity, storativity, and tensorial rock permeability at a scale appropriate for inter-well to regional-scale reservoir simulation. Results could improve reservoir management through proper infill and extension drilling strategies, reduction of economic risks, increased recovery from existing oil fields, and more reliable reserve calculations. Transfer of the project results to the petroleum industry is an integral component of the project.

Summary of Technical Progress

The technical progress is divided into several sections corresponding to subtasks outlined in the Regional Stratigraphy Task and the Case Studies Task sections of the original proposal. The primary objective of the Regional Stratigraphy Task is to provide a more detailed description and interpretation of the stratigraphy of the Ferron Sandstone outcrop belt from Last Chance Creek to Ferron Creek (figure 1). This regional study will include determining the dimensions and depositional environment of each sandstone boby, and the nature of the contacts with adjacent rocks or flow units. The study will provide a basis for selecting prime outcrops for detailed case studies of the major reservoir types (meander belt, mouth-bar complex, wave-dominated delta front, bar-finger sands, distributary channel, and tidal channels). The morphological framework established from the case studies will be used to generate subsequent flow models for the reservoir types.

The primary objective of the Case Studies Task is to develop a detailed geological and petrophysical characterization, at well-sweep scale or smaller, of the primary reservoir lithofacies typically found in a fluvial-dominated deltaic reservoir. Sedimentary structures, lithofacies, bounding surfaces, and permeabilities measured along closely spaced traverses (both vertical and horizontal) will be combined with data from core drilling to develop a 3-D view of the reservoirs within each case-study area.

Regional Stratigraphy

Surface Mapping/Interpretation of the Outcrop Belt. The Ferron Sandstone outcrop belt within the study area (figure 1) has been obliquely photographed. These photographs (a total of 1,823 depicting 80 miles [130 km] of outcrop) have been digitized and transferred to compact discs (CD). Using image-editing software, photographs from the CDs are being assembled into reproducible photomosaics. Lithofacies, measured sections, vertical and horizontal scales, and other data are being plotted on the photomosaics in the field for both the regional and case-study analysis.

Collection and Interpretation of Existing Surface and Subsurface Data. The Utah Geological Survey (UGS) continues to collect and compile published and unpublished maps, measured sections, well logs, core descriptions, reports, and other data. There are 481 wells in the study area, of which 412 were cored. By September 30, 1994, the UGS had acquired 138 geophysical logs and 1,800 feet (550 m) of core or core descriptions from these wells (table 1). Information from 232 wells has been entered into ASCII files; 305 of the 481 total wells were also entered into the UGS **INTEGRAL** database for the Ferron project (table 1). Interpretations (thickness, type of lithology, and geologic description) have been completed for 343 wells.

Base maps have been digitized for the Willow Springs, Short Canyon, Johns Peak, Mesa Butte, Walker Flat, and Geyser Peak quadrangles. These base maps show drill-hole locations (petroleum exploratory and development wells, and coal core-holes), measured sections, coal outcrops, coal mined-out areas, drainages, and the top and base of the Ferron Sandstone.

Preliminary Regional Stratigraphic Interpretation. Regionally, the Ferron Sandstone consists of up to seven delta-front sandstone bodies or parasequence sets. The focus of our work is two parasequence sets in the lower part of the Ferron. Previous workers have designated these as the Nos. 1 and 2 sets. Recognizable sequences within the sets have been designated with lower-case letters (for example, No. 1a). Most fit the definition of a parasequence, being bounded above and below by transgressive surfaces ("flooding surfaces" in the sequence stratigraphic terminology). In some cases, the divisions may lack transgressive surfaces, yet are recognizable by changes in sedimentary styles. In the Ivie Creek area, the No. 1 a,b, and c parasequences are well exposed and we interprete them as low-wave-energy subdelta deposits. The uppermost carbonaceous mudstone or ash-rich coal is the sub-A coal zone. A flooding surface has been identified at the top of the sub-A. The boundary with the overlying No. 2 parasequence set is drawn at this flooding surface. We have initially interpreted the No. 2 a, b, and c parasequences as low-wave-energy subdelta deposits.

Our regional work in the northern part of the Ivie Creek area (figure 1) has identified a marine sand which developed out of the brackish water lithofacies found to the south in the Ivie Creek case-study area. Stratigraphically, this sand is between the No. 1c and the top of the sub-A coal zone and has been tentatively designated the No. 1d parasequence. This parasequence may emerge to the northeast. In the No. 2c, a large channel system is exposed with a predominantly west-to-southwest-directed paleoflow. We have tentatively interpreted this system to be a tidal channel complex, which flooded back into the bay deposits that are well-defined in the Ivie Creek case-study area. We interpreted the marine sands found proximal to the channel system as deposits of the flood-tidal delta.

Case Studies

Field Work. Forty-six sections have been measured and described in the Ivie Creek and Willow Creek Wash case-study areas. Description of the individual units in the measured sections include the following information: primary and secondary lithologies; rock composition, color, grain size; bed size, shape, degree of induration, sedimentary structures, biologic structures, fossils, bounding surfaces, and depositional environment. Sections were correlated to develop preliminary interpretations of the stratigraphy and lithofacies. Over 500 paleocurrent measurements have been made at these and other localities. Lithologic and paleocurrent data are being entered into the UGS **INTEGRAL** database for use in constructing statistical models,

strip logs, and lithofacies maps.

Eleven core-hole locations have been permitted from the Utah Division of Oil, Gas and Mining in the Ivie Creek area (figure 2); five or six core holes will be drilled. Water use and right-of-way permits have also been obtained. The total depths of the core holes will be approximately 550 feet (150 m). The No. 1 and No. 2 parasequence sets will be cored (approximately 160 feet [50 m]) in each hole. The No. 1 represents a river-dominated delta deposit which changes from proximal to distal (where the sandstone pinches out) from east to west across the Ivie Creek area. The No. 2 contains more and cleaner sand, indicating a more wave-influenced environment of deposition. The core holes will be located down dip 200 to 1,200 feet (60 to 365 m) from the Ferron outcrop. The pattern of the core holes is similar to that in an oil field.

Outcrop Gamma-Ray Measurements. The objectives of outcrop gamma-ray measurements for the Ferron Sandstone in the Ivie Creek case-study area are threefold: (1) to determine variations in clay-mineral content (or sand/shale), (2) to permit detailed correlation among outcrop traverses and between these traverses and drill-hole gamma-ray logs, and (3) to detect possible diagenetic changes associated with precipitation of uranium. The equipment used for field measurements is a portable 256-channel gamma-ray spectrometer, capable of determining total natural gamma counts as well as concentrations of potassium, thorium, and uranium. The spectrometer was tested in the lab and in the field to determine its vertical resolution and replicability. Test measurements in the field were found to be unreliable in rough topography because gamma rays enter the sides of the detector. This problem was corrected by covering the sides of the detector with lead shielding.

Field measurements showed that the total gamma-ray count is not always a reliable indicator of clay content. Potassium and thorium co-vary, probably because they are present primarily in clays. Uranium, however, commonly is not correlated with potassium and thorium. This indicates that uranium is present in minerals other than clays. Consequently, for reliable determination of clay content, potassium and thorium must be measured rather than just total gamma rays. We chose to make one-minute measurements, almost five times as long as is needed for good total-gamma values but barely enough for reliable potassium, thorium, and uranium measurements.

All gamma-ray logging was in the form of vertical or near-vertical (depending on access) traverses. In all, 15 gamma-ray traverses were undertaken, each consisting of 200-400 measurements at 0.5-1.0 foot (0.15-0.3 m) intervals. All traverses included the entire No. 1 parasequence set, and most also included all or part of the No. 2 parasequence set. Most traverses corresponded to measured sections. The traverses are useful for correlation and quantitative determination of sand/shale percentage (figure 3).

Core-plug sampling. The objective of core-plug sampling in the Ivie Creek case-study area was to characterize of vertical and lateral variations of a number of petrophysical properties (velocity, density, porosity, permeability, mineralogy) and to determine the interrelations among these properties. The technique used involved drilling a 1- to 4-inch- (2.5- to 10-cm-) long core plug, 1 inch (2.5 cm) in diameter, with a portable gas-powered motor and diamond bit. The geographic orientation of each sample was determined and the sedimentary structure of the bed was noted or photographed. All core plugging was along vertical or near-vertical (depending on access) traverses. In all, 283 samples were taken from nine traverses. Most traverses

corresponded to measured sections. Various lithofacies from both the Nos. 1 and 2 sandstones were sampled.

Mini-permeameter Measurements. A total of seven permeability transects, four vertical and three sub-horizontal (parallel to bedding), were made on the outcrop at the Ivie Creek case-study site (figure 4). The transects span the proximal, middle, and distal portions of the delta-front rocks of the No. 1 sandstone. Transect locations, jointly established by the geological and engineering teams, were designed to encompass the majority of the lithofacies present in the delta-front sequence. Data from these transects will be used to determine the statistical structure of the spatially variable permeability field within the delta front, to investigate how geological processes control the spatial distribution of permeability, and to evaluate permeability measurement techniques.

The four vertical transects were approximately 600 feet (200 m) apart and 100 to 200 feet (30 to 60 m) long. Measurement intervals (station spacing) along all of the vertical transects was 0.3 feet (0.1 m). From west to east (distal to proximal), the transects were: T-2, T-1, T-3, T-4. The three sub-horizontal, bed-parallel transects are approximately 50 feet (15 m) long. From west to east the transects were T-7, T-6, and T-5. Station spacing on the bed-parallel transects was 0.5 feet (0.2 m). After general sedimentologic and stratigraphic interpretation of the area encompassing the vertical transects, a "window" approximately 300 feet (90 m) wide was selected for detailed geologic description. Three stratigraphic sections (at the center and two ends of the window) were measured in detail noting lithologies and grain size, primary and secondary sedimentary structures, and bed thicknesses. Lateral and vertical variation of these parameters within units were also desribed. Units as thin as 0.01 feet (0.2 cm) were described. Within the window, a representative succession of several adjacent clinoforms in the No. 1a was chosen to expand documentation of lateral variation of these parameters within individual clinoforms. Clinoform characterization was continued past the proximal window boundary to incorporate additional variation. Locations along the clinoforms, termed "mini-windows", at approximate 50-foot (15 m) intervals were photographed to document lateral variation in lithology, bed thickness, and sedimentary structures along clinoforms. Several mini-windows outside the window were also interpreted. These were in a more proximal position and allowed documentation of additional change in clinoforms. The demensions of the mini-windows were approximately 4 feet (1 m) high by 6 feet (2 m) wide at the distal ends of the window and approximately 10 feet (3 m) high by 6 feet (2 m) wide at the proximal end of the clinoforms. This detailed geologic information will allow the reservoir modeler to develop rules and constraints on lateral variation within the delta front.

Core plugs roughly 0.75 inches (0.3 cm) in diameter and 1 to 3 inches (2.5 to 7.5 cm) long were drilled from the outcrop at each transect station (where possible) to ensure that permeability measurements could be made on fresh, unweathered rock surfaces. Drilling experience and examination of the core plugs indicates that chemical weathering extends into the rock less than 0.5 inches (1.3 cm). Whole plugs were typically recovered only from sandstone beds greater than 2 inches (5 cm) thick. Useful plugs could usually not be obtained from thinner sandstone beds or from thinly bedded sandstones, siltstones, and mudstones. Core-recovery rates range from 50 percent to nearly 100 percent. Where core plugs could not be recovered, small rock samples were taken, except where the outcrop is buried under colluvium.

We measured permeability in the laboratory on the unweathered end of the core plugs after the unweathered end of the plug was trimmed flat with a rock saw. The thin disks trimmed

from the plug ends were saved for possible future petrographic analysis. At those stations where a good hole was drilled but a broken core was recovered, permeability was measured in the hole. Prior measuring field permeability measurement in a core hole, the back of the hole was prepared using a screwdriver and a rock hammer to chip away rough spots, providing a flat surface for the mini-permeameter probe tip. The hole was sprayed out with water and allowed to dry for at least 24 hours prior to permeability testing. The hole was also cleaned by a blast of compressed gas immediately before testing.

An electronic miniprobe permeameter (EMP) supplied to the project by Mobil Research and Development was used to make laboratory permeability measurements on the trimmed, whole core plugs and field measurements in core holes (figure 5). This instrument has an accuracy of 1 to 12 percent and a precision of 1 to 3 percent on homogenous core plugs with permeabilities ranging from 1 to 4,500 millidarcies (md). A rack was used to secure the probe in the laboratory; an expansion packer was used to secure the probe in a core hole in the field. In both cases, an air-actuated piston pushes the probe tip against the center of the sample, providing a consistent coupling between the probe tip and the rock.

The seven transects contain a total of 1,236 stations; of these, 1,000 were drilled and 900 whole core plugs were recovered for laboratory permeability testing. as of October, 1994, the permeability measurements made so far are too sparse to make any definitive statements about the spatial pattern of permeability in the delta front of the No. 1 sandstone. The early data suggest that a substantial fraction of the rocks are low permeability, less than 10 md. This holds true for both the mudstones and siltstones as well as the sandstones. However, the majority of the permeabilities obtained thus far are field measurements made in transects T-1 and T-2, situated in the middle and distal portions of the delta front, where siltstones and mudstones are common and lower permeabilities expected. Less than 50 permeability measurements have been made thus far in the laboratory. The majority of these samples are more proximally located, fine-grained, well-cemented sandstones; permeability of these sandstones is usually less than 10 md. At a few stations, however, permeabilities greater than 100 md have been measured in coarser grained, poorly cemented sandstones.

Several stations were occupied multiple times in the field in order to obtain statistics to verify the precision of the mini-permeameter. In addition, several stations from which good whole core plugs were recovered were also field tested in the core hole to provide a comparison between field and laboratory measurements of permeability. The permeability of these core plugs will also be measured using conventional Hassler sleeve techniques to evaluate the accuracy of the mini-permeameter.

Next Quarter Planned Activities

Planned activities for the next quarter include:

1. Continue collecting published measured sections, well logs, core descriptions, mini-permeameter values, and other data. Enter this information into the database and prepare strip logs.
2. Catalog and continue to laser print aerial photos from CDs, and construct photomosaics for regional stratigraphic and case-study analysis.

3. Drill, log, and core six to eight holes in the Ivie Creek case-study area. Cores and geophysical logs from these wells will provide data for 3-D morphology interpretation of individual lithofacies. Cores will be cut in the delta-front sandstones in the lower part of the Ferron Sandstone. The changes in these units across the Ivie Creek area will provide excellent data for the reservoir model. Core plugs (200) will be obtained for petrophysical analyses from these cores.

4. Continue regional outcrop mapping and interpretation. Some mosaics in the vicinity of the Ivie Creek case-study area have been interpreted in the field. A preliminary interpretation of all other mosaics will be done in the office. These preliminary interpretations will be field-checked and modified if necessary next field season. Parasequence sets, parasequences, and facies will be differentiated on the mosaics. Locations of stratigraphic sections to be measured next field season will be chosen based on the preliminary mosaic interpretations. Correlations will also be made based on the mosaic interpretations.

5. Continue measuring sections, writing lithologic descriptions, and obtaining paleocurrent data for the case studies of the Ivie Creek and Willow Springs Wash areas. Enter this data into the database. Complete mini-permeameter measurements, outcrop core sampling, and gamma-ray work on selected lithofacies in the Ivie Creek case-study area.

6. Obtain additional software to develop a 3-D-gridded database.

7. Begin quantifying sedimentary and petrophysical data to develop statistical models.

8. Complete data for window and detailed characterization of the No. 1 sandstone in the Ivie Creek case-study area. The data will be compiled for future reservoir modeling tasks.

Table 1. Summary of well, geophysical log, and core data collected for the Ferron Sandstone study area.

Source of wells	No of wells with geophysical logs	No of logs obtained by the UGS[1]	No of wells cored/ footage cored	Core obtained by the UGS[1] (in feet)	No of wells recorded in ASCII files[1]	No of wells recorded in INTEGRAL[1]
Oil and Gas						
UURI[2]	2	2	2/800	800	0	0
ARCO[3]	7	7	7/3,527	descriptions only	0	0
BP[4]	5	5	5/1,000	1,000	0	0
other	58	41	0	0	0	0
Coal						
CONSOL[5]	357	62	356/unknown	descriptions only	232	305
USGS[6]	33	15	29/1,402	descriptions only	0	0
BLM[7]	0	0	6/1,156	descriptions only	0	0
WSMC[8]	12	0	0	0	0	0
HVCC[9]	7	6	7/463	descriptions only	0	0
TOTAL	481	138	412/8,348	1,800	232	305

[1] as of September 30, 1994
[2] University of Utah Research Institute
[3] ARCO Oil and Gas Company
[4] British Petroleum
[5] CONSOL Inc
[6] U S Geological Survey
[7] Bureau of Land Management
[8] Western States Mineral Corporation
[9] Hidden Valley Coal Company

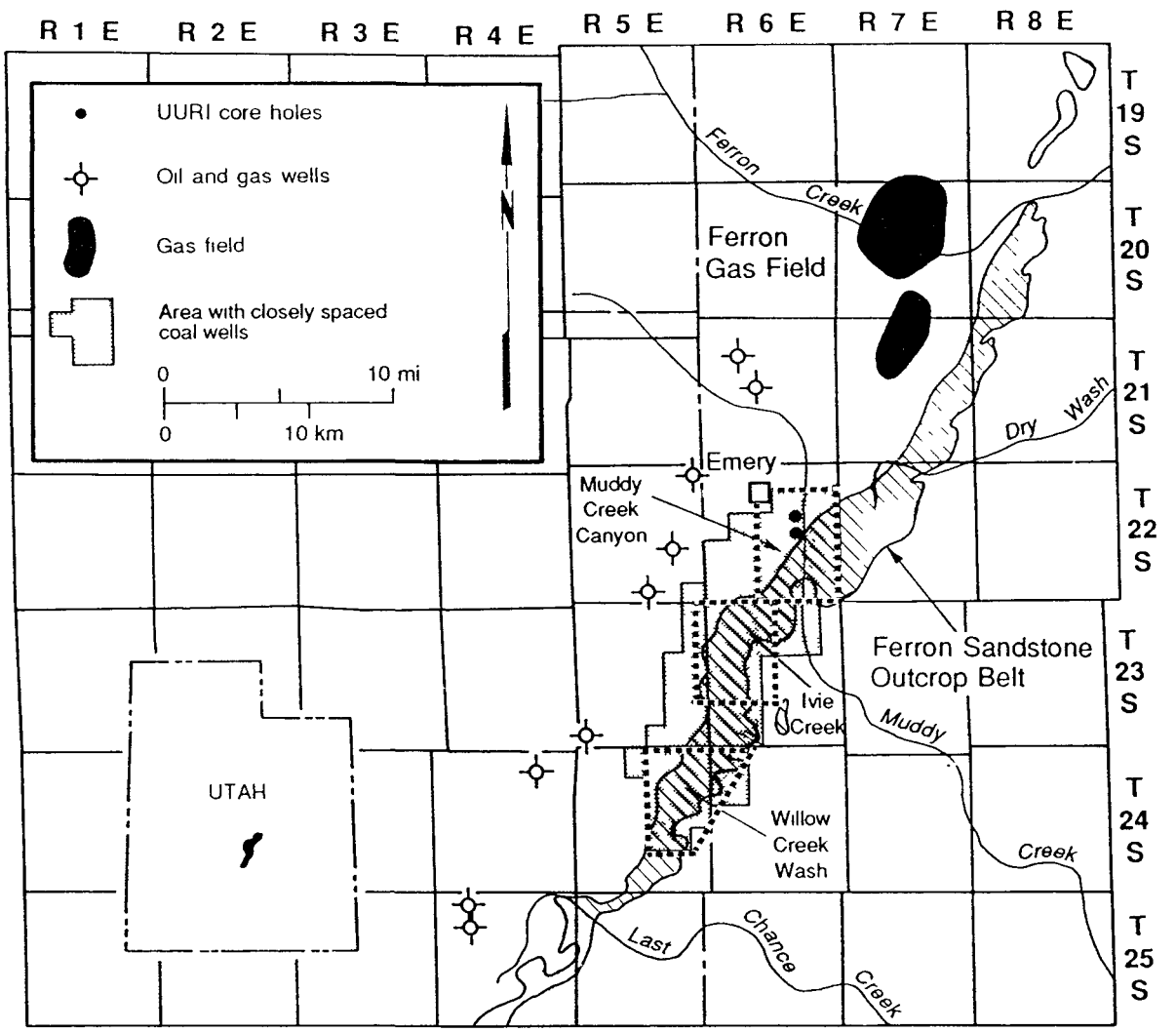

Figure 1. Location map of the Ferron Sandstone study area (cross-hatched) showing detailed case-study sites (outlined by heavy dashed lines).

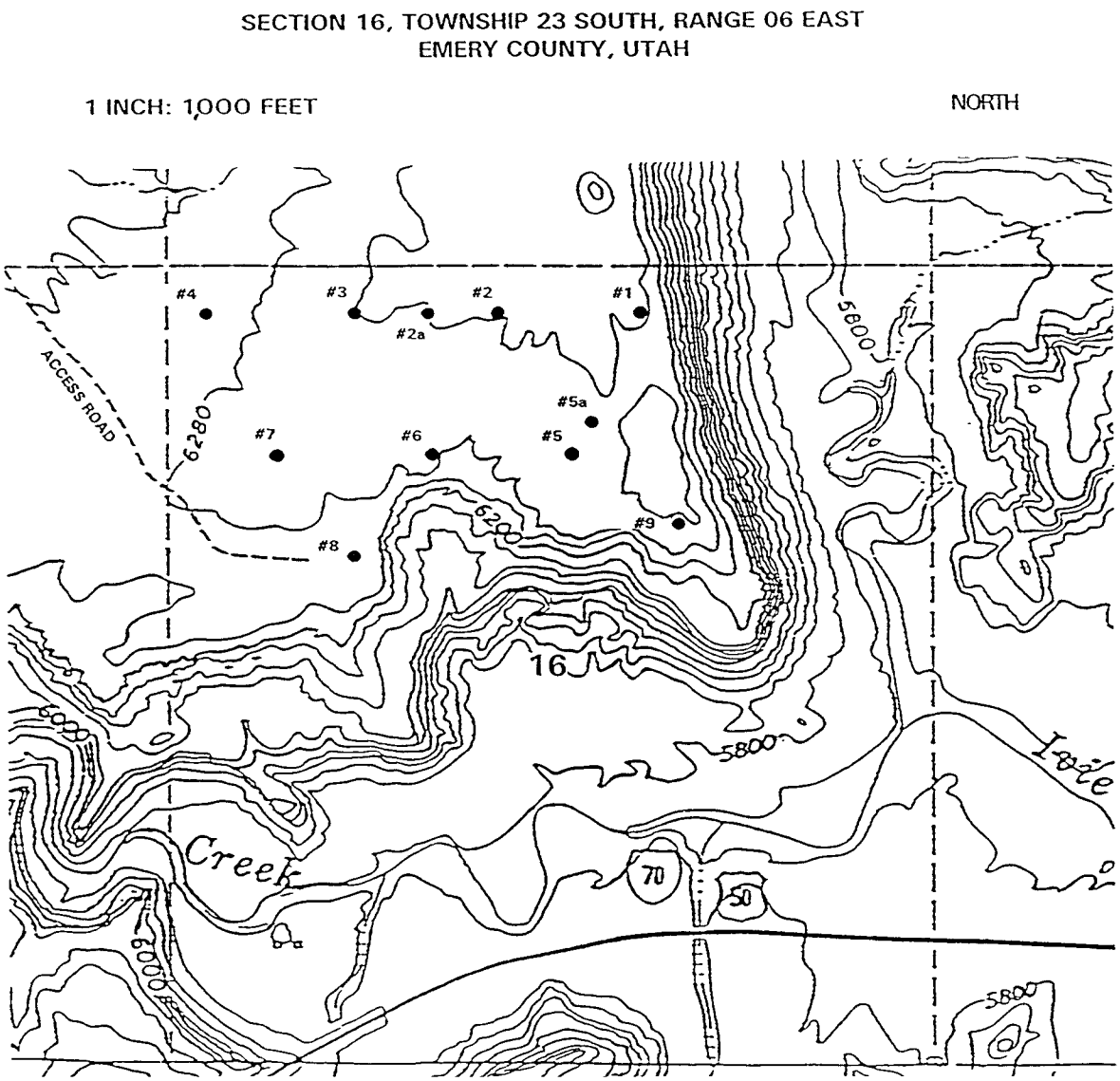

Figure 2. Location of eleven proposed core holes permitted in the Ivie Creek case-study area, section 16, T. 23 S., R. 6 E., Emery County, Utah to core the Nos. 1 and 2 sandstones. Base map from U.S. Geological Survey topographic maps Mesa Butte and Walker Flat; contour interval is 40 feet (12 m).

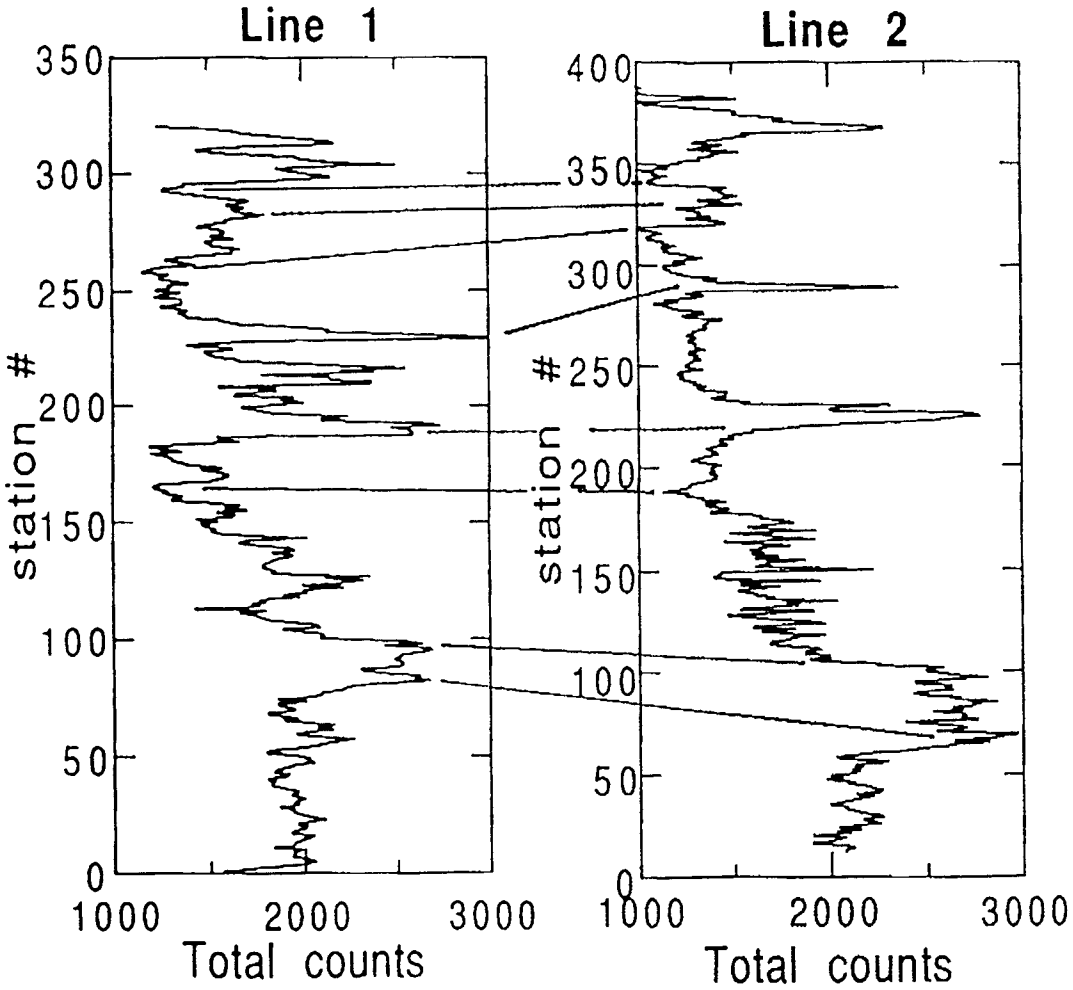

Figure 3. Typical gamma-ray profiles from traverses in the Ivie Creek case-study area. Preliminary correlations are shown.

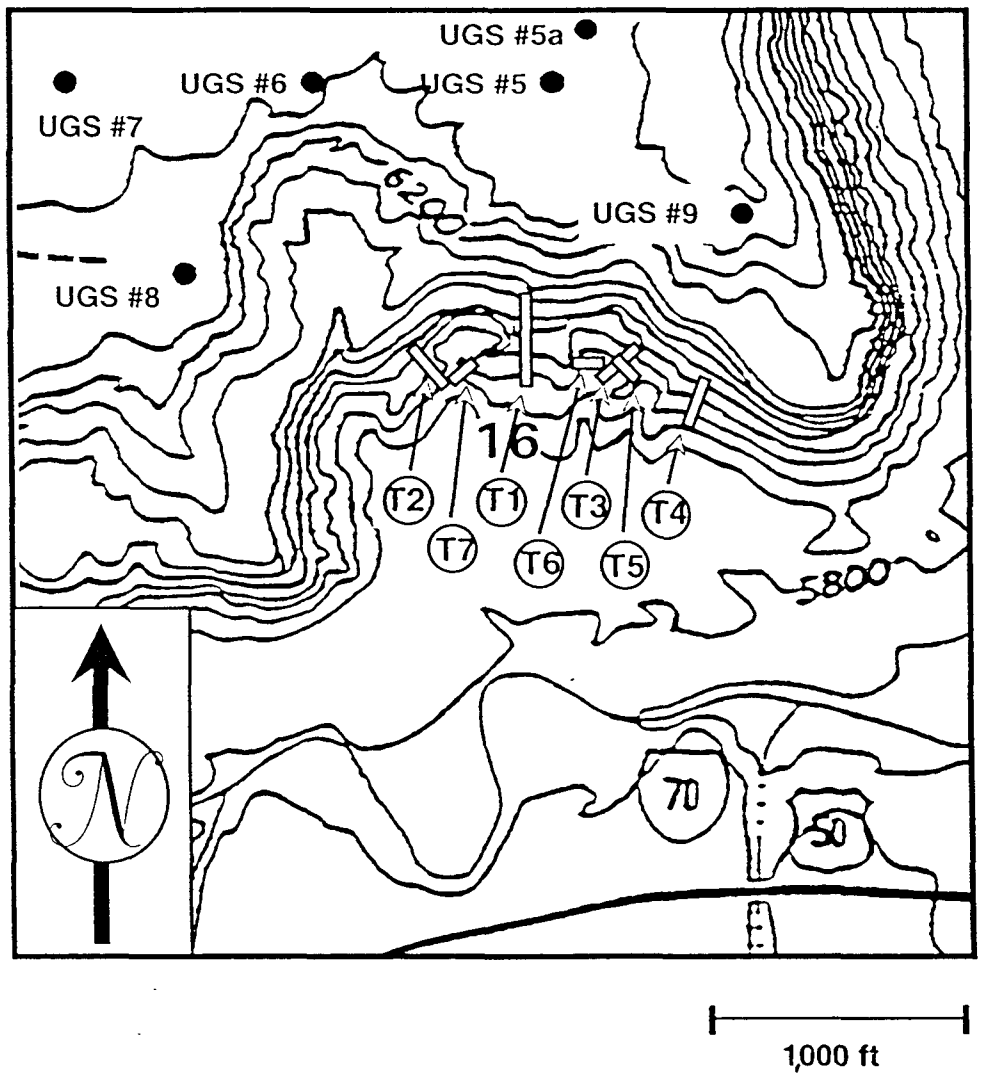

Figure 4. Location of seven permeability transects (vertical and parallel to bedding) in the Ivie Creek case-study area, section 16, T. 23 S., R. 6 E., Emery County, Utah. Proposed core-hole sites are shown by heavy dots. Base map from U.S. Geological Survey topographic maps Mesa Butte and Walker Flat; contour interval is 40 feet (12 m).

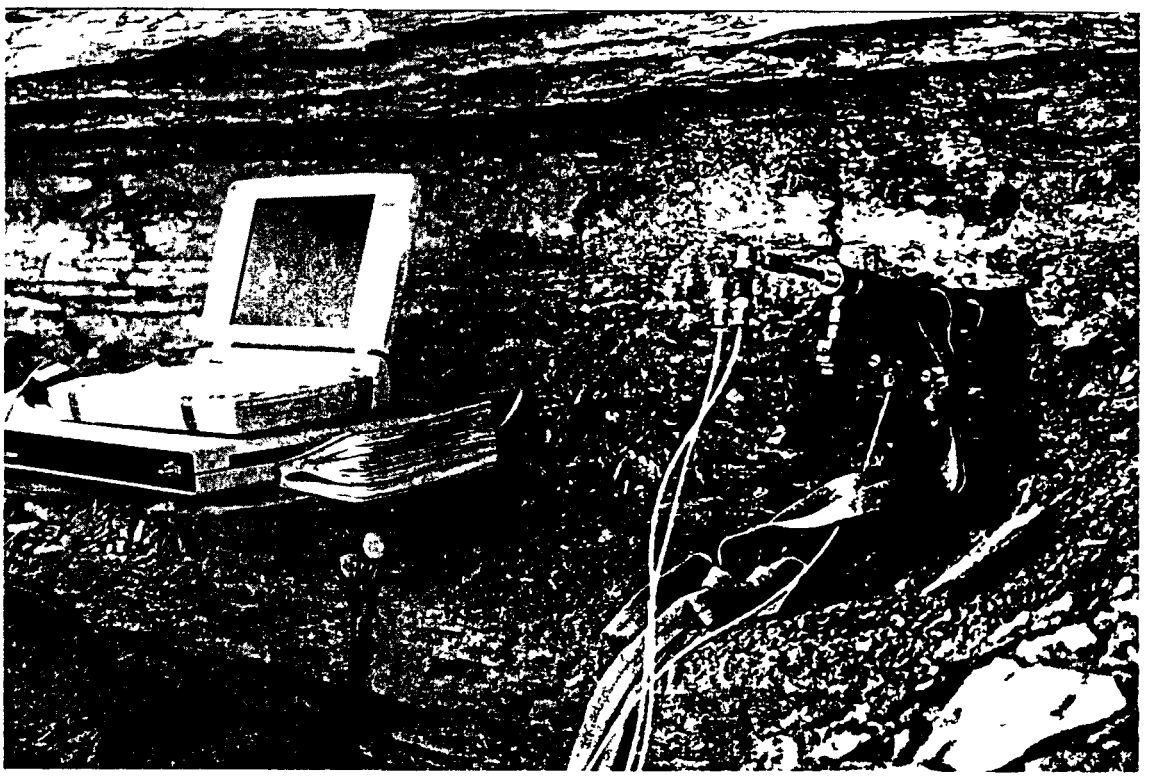

Figure 5. The electronic miniprobe permeameter shown measuring permeability at a core hole in the Ivie Creek case-study area.