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A Novel Geotechnical/Geostatistical Approach for Exploration and Production of Natural Gas From Multiple Geologic Strata Phase I - Volume II: Geology and Engineering

Topical Report

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May 1991

Work Performed Under Contract No.: DE-AC21-89MC26026

For
U.S. Department of Energy
Office of Fossil Energy
Morgantown Energy Technology Center
Morgantown, West Virginia

By
The College of West Virginia
Beckley, West Virginia
and
BDM Engineering Services Company
Morgantown, West Virginia

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May 1991

MULTI-STRATA EXPLORATION AND PRODUCTION STUDY

PHASE I - VOLUME II - GEOLOGY AND ENGINEERING

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1.0 INTRODUCTION

This research program has been designed to develop and verify a unique geostatistical approach for finding natural gas resources. The project has been conducted by Beckley College, Inc., and BDM Engineering Services Company (BDMESC) under contract to the U.S. Department of Energy (DOE), Morgantown Energy Technology Center (METC).

This section, Volume II, contains a detailed discussion of the methodology used and the geological and production information collected and analyzed for this study. A companion document, Volume I, provides an overview of the program, technique and results of the study.

In combination, Volumes I and II cover the completion of the research undertaken under Phase I of this DOE project, which included the identification of five high-potential sites for natural gas production on the Eccles Quadrangle, Raleigh County, West Virginia. Each of these sites was selected for its excellent potential for gas production from both relatively shallow coalbeds and the deeper, conventional reservoir formations.

Phase II is scheduled to be initiated in April, 1991, with the drilling of the first of up to three wells planned to confirm the Phase I analyses. Each of the planned wells is scheduled to be dually-completed in the coal seams (for methane production) and the underlying conventional reservoirs (for natural gas production). Each well will be produced through dual strings. The strings will be independently metered and tested for quality before the gas is commingled for ultimate sale into a commercial pipeline. The economics of adding methane from the coal to multiple-strata conventional natural gas resources are expected to be significantly greater than the economics of producing a single interval alone.

Successful application of the methodology developed for this project should lead to reduced exploration times and finding costs for natural gas and methane, and, thus, directly to expanded commercial development in the Raleigh County area and in other areas with combined coalbed methane and conventional natural gas resources. Additionally, the methodology represents a low-cost approach that should be generally applicable to finding oil, natural gas or methane reserves in other producing areas of the United States.

2.0 METHODOLOGY AND TECHNICAL SUMMARY

The material which follows is designed to provide an overview of the methodology developed for this study and to summarize the key findings of the study.

2.1 Resource Analysis

The early phases of this study focused on the conventional natural gas resources because a large data base was readily available (**Figure** 2.1.1), at a very reasonable cost, from West Virginia government

4 QUAD DATABASE

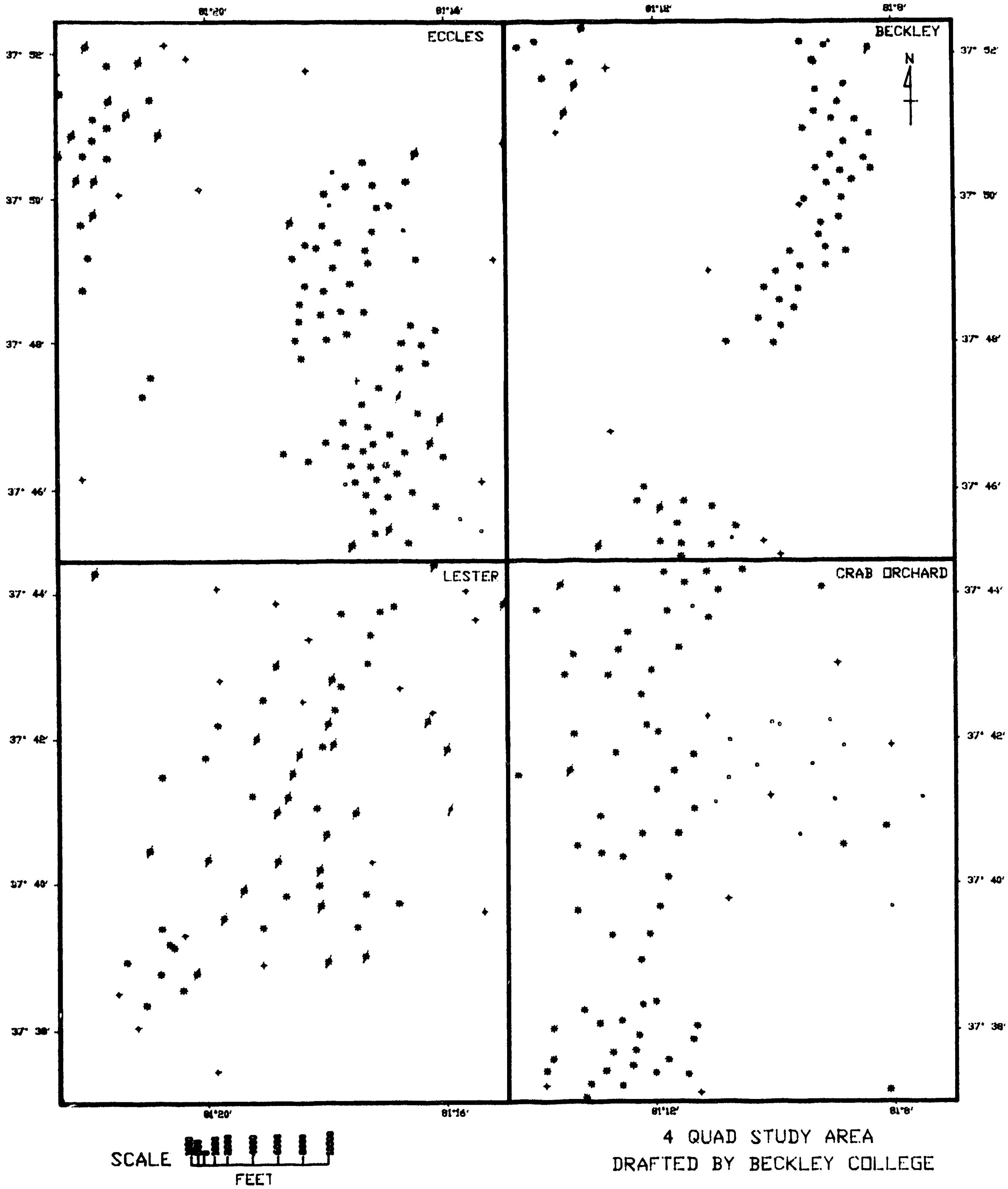


Figure 2.1.1 Location of Database Wells in the Study Area

sources such as the West Virginia Geological and Economic Survey (WVGES), the West Virginia Oil and Gas Conservation Commission and from private industry sources. Formation tops, isopach data, shows, flow information, production numbers, water reports, coal information, ownership records and other key data elements were extracted from the data base and entered in a series of spreadsheets and data sets for manipulation and plotting.

2.1.1 Pennsylvanian-Age Sandstone Natural Gas Resource

Initial data for analyses were obtained from well completion forms (OG-10's) at the WVGES . Forms were obtained for all of the recorded wells that have been drilled and completed on the Eccles, West Virginia, 7.5 minute quadrangle. Computerized sets of data were also purchased from the Survey covering such topics as well completions, location and ownership information, shows, production, stratigraphic and water data. This information was entered into spreadsheets developed for the project. All of the wells that were completed in the Pennsylvanian-aged sandstones, such as the Salt Sands, Ravencliff and Maxton, were listed by permit number. Isopach and structure maps were prepared for each key formation, and large-interval isopachs were made and studied to identify long-term structural trends and areas where thickening and thinning might be tectonically influenced or controlled.

It became obvious that the Salt Sands and Maxton were not significant producing units in the study area. The study therefore focused on the Pennsylvanian-age Ravencliff Sandstone.

A literature and data search was initiated to gather information that would allow the identification of reservoir analogs or models for the most important reservoirs. This search uncovered a Master's Thesis done by Mr. Gregory Wrightstone in 1985 (**Ref.** 6) while at West Virginia University and additional writing by him (**Ref.** 5) concerning the Ravencliff Sandstone. This work provided considerable insight into the depositional environment of the Ravencliff sandstone, identifying its environment of deposition as part of a channel system (**Figures** 2.1.2, 2.1.3). Electric logs were obtained by Beckley College from industry sources to evaluate the log signature of the Ravencliff as a final check on the nature of the sand. This showed a gamma ray signature typical of a fluvial sand system, but the density log showed that diagenesis and invasion by mineral-bearing waters had affected the unit, plugging much of the original porosity.

Isopach and structure maps were made and extensive production and engineering analyses were run and presented in map form. From this data, a Ravencliff Original Reservoir Probability Map was made (**Figure** 2.1.4). A Ravencliff Secondary Porosity Probability Map (**Figure** 2.1.5) was prepared identifying portions of highly fractured areas on the quadrangle which might be expected to act as fracture-enhanced reservoirs within the Ravencliff. The two Reservoir Probability Maps were merged to form a Combined Primary-Secondary Porosity Map (**Figure** 2.1.6). The various probable depositional subenvironments across the study area were thus identified and their diagenetic histories unraveled.

Production maps showed which wells produced from the Ravencliff, alone or in combination with another formation. Initial-open-flow and Final-open-flow-after-stimulation Maps were prepared along with Cumulative Production Maps (**Figures** 2.1.7 and 2.1.8).

Decline curves were prepared for the wells that have produced exclusively from the Ravencliff Sandstone. Cumulative production maps were drafted, projecting this Ravencliff production to the economic limit. The "economic limit' was defined as a decline in the production rate to 100 Mcf of gas per month. Beyond this point it was assumed that well maintenance costs would exceed the income generated from the natural gas.

The original-gas-in-place (OGIP) was calculated and an OGIP map prepared. The economically-recoverable natural gas resource base for the Eccles Quadrangle was calculated and mapped. It was

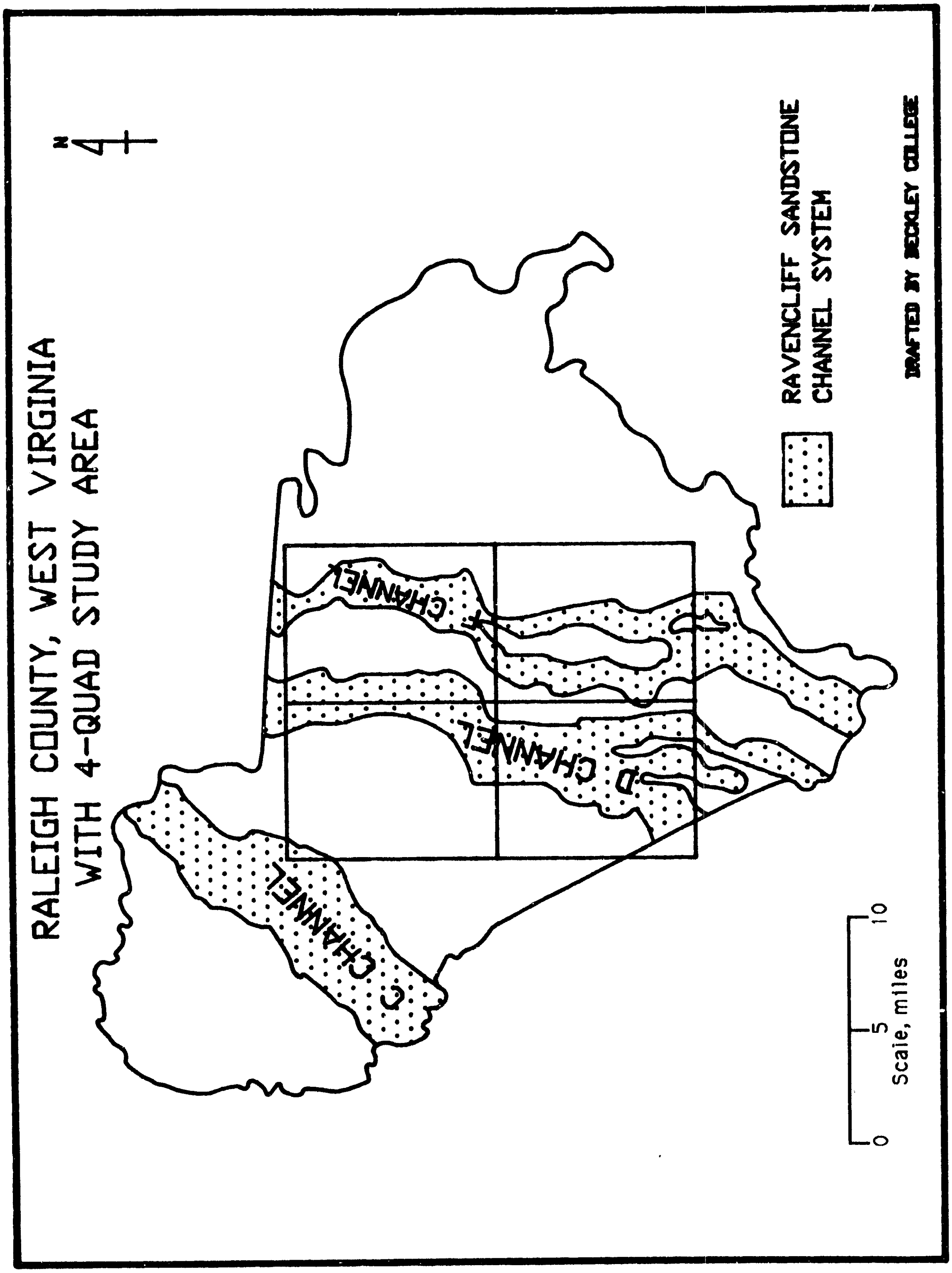


Figure 2.1.2 Ravencliff Sandstone Channel System, Raleigh County

LOCATION OF THE RAVENCLIFF CHANNELS

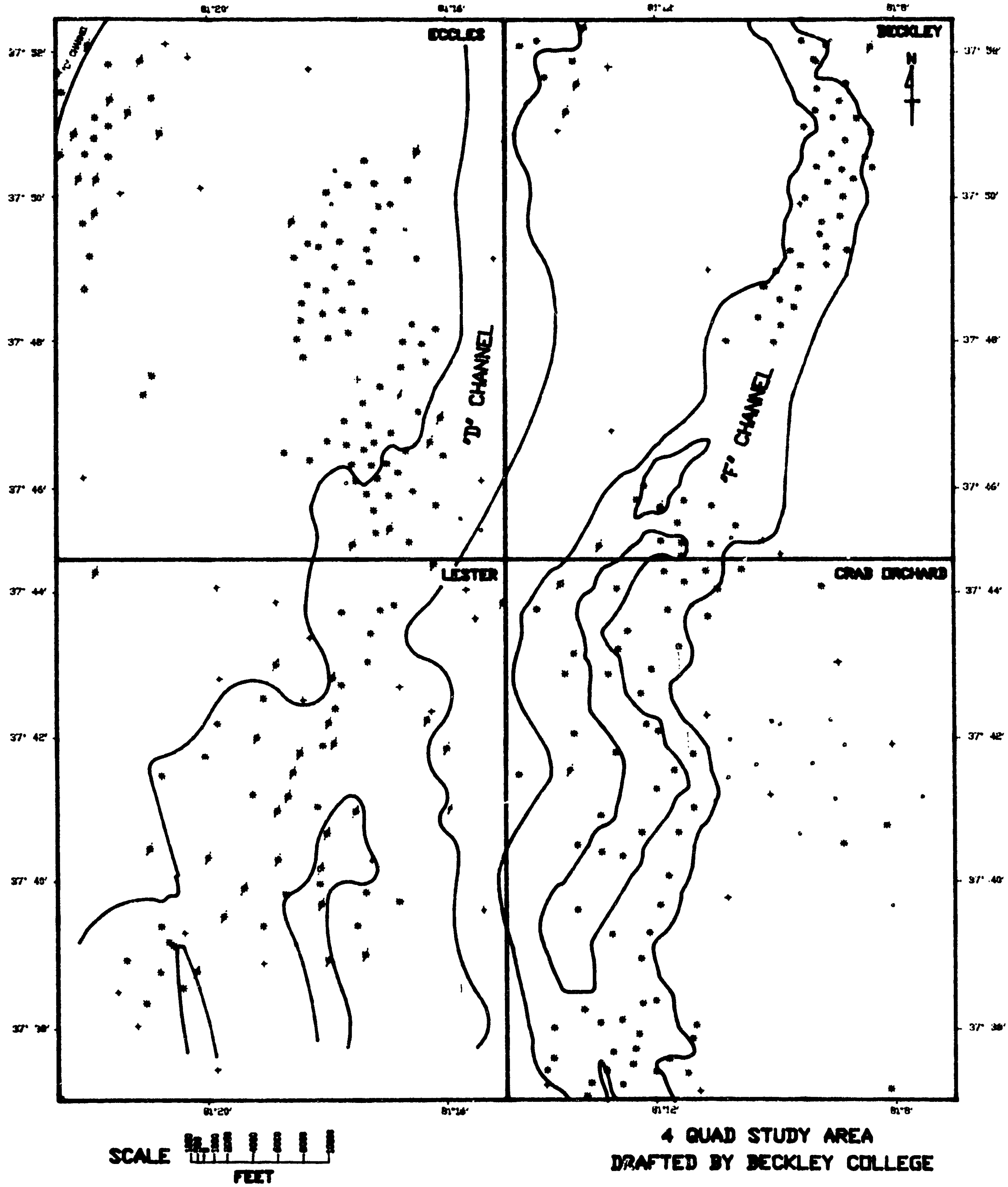


Figure 2.1.3

RAVENCLIFF ORIGINAL RESERVOIR QUALITY PROBABILITY (PRIMARY POROSITY)

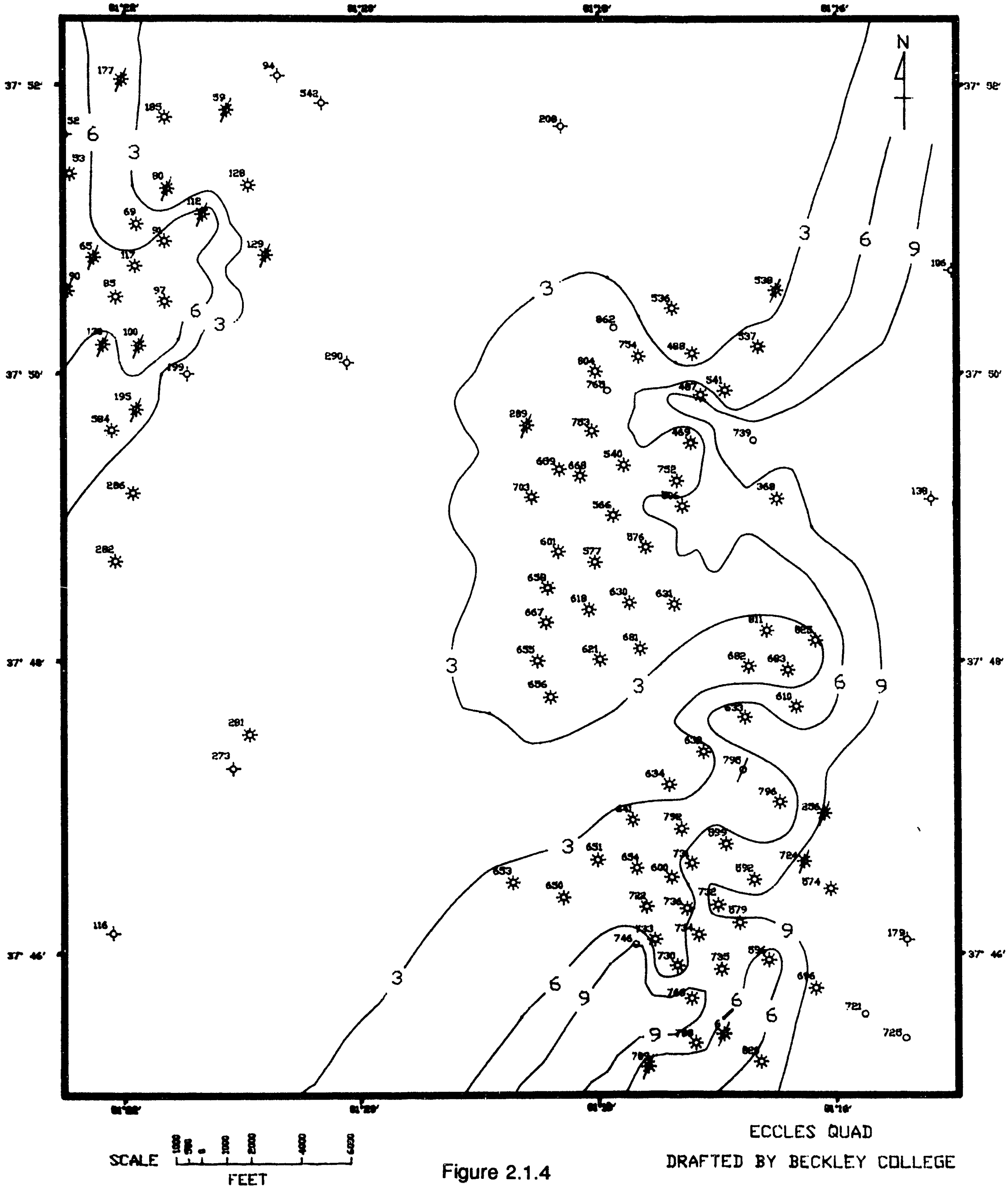


Figure 2.1.4

RAVENCLIFF RESERVOIR
ENHANCEMENT PROBABILITY (SECONDARY POROSITY)

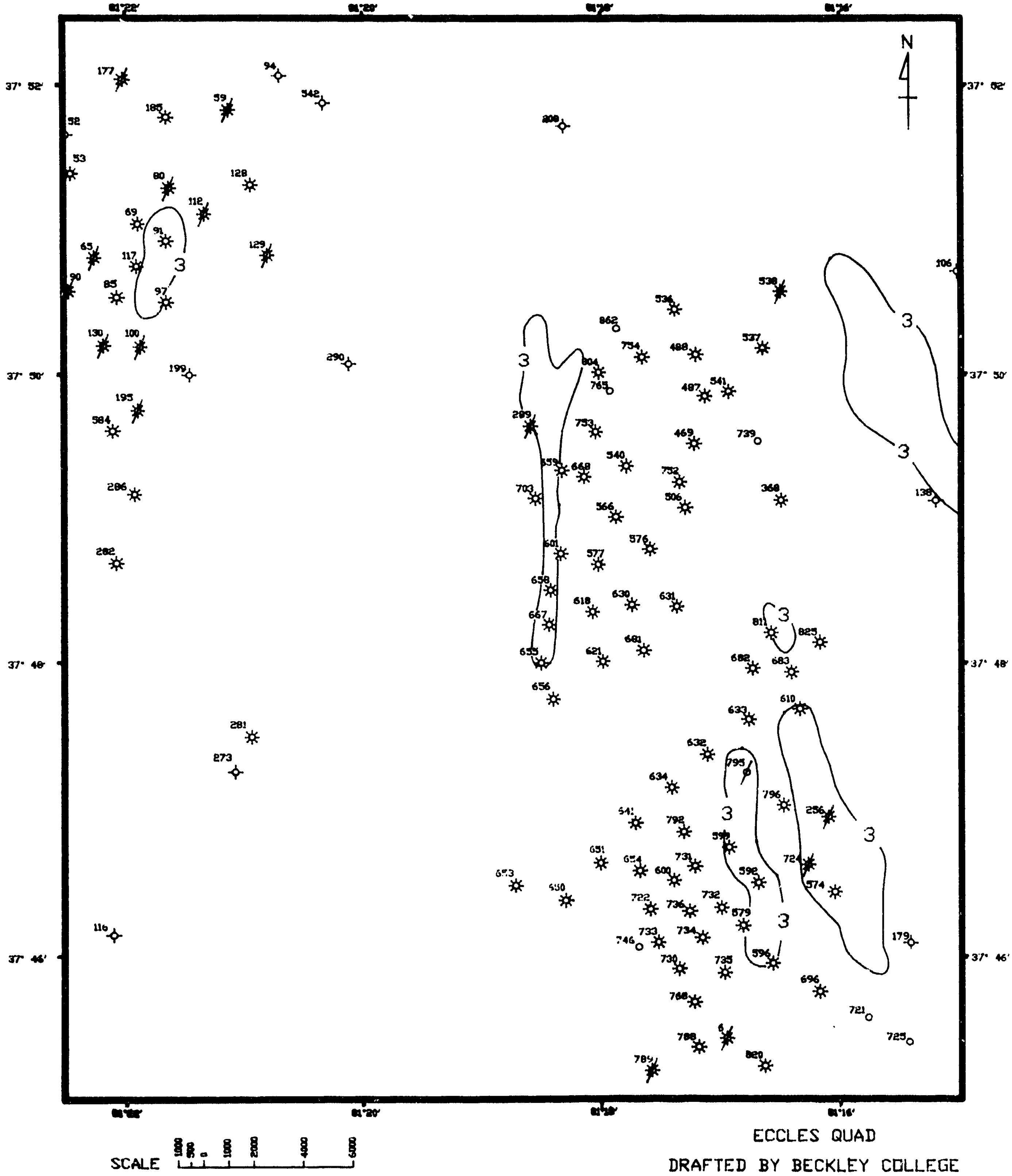


Figure 2.1.5

RAVENCLIFF COMBINED
PRIMARY-SECONDARY POROSITY PROBABILITY MAP

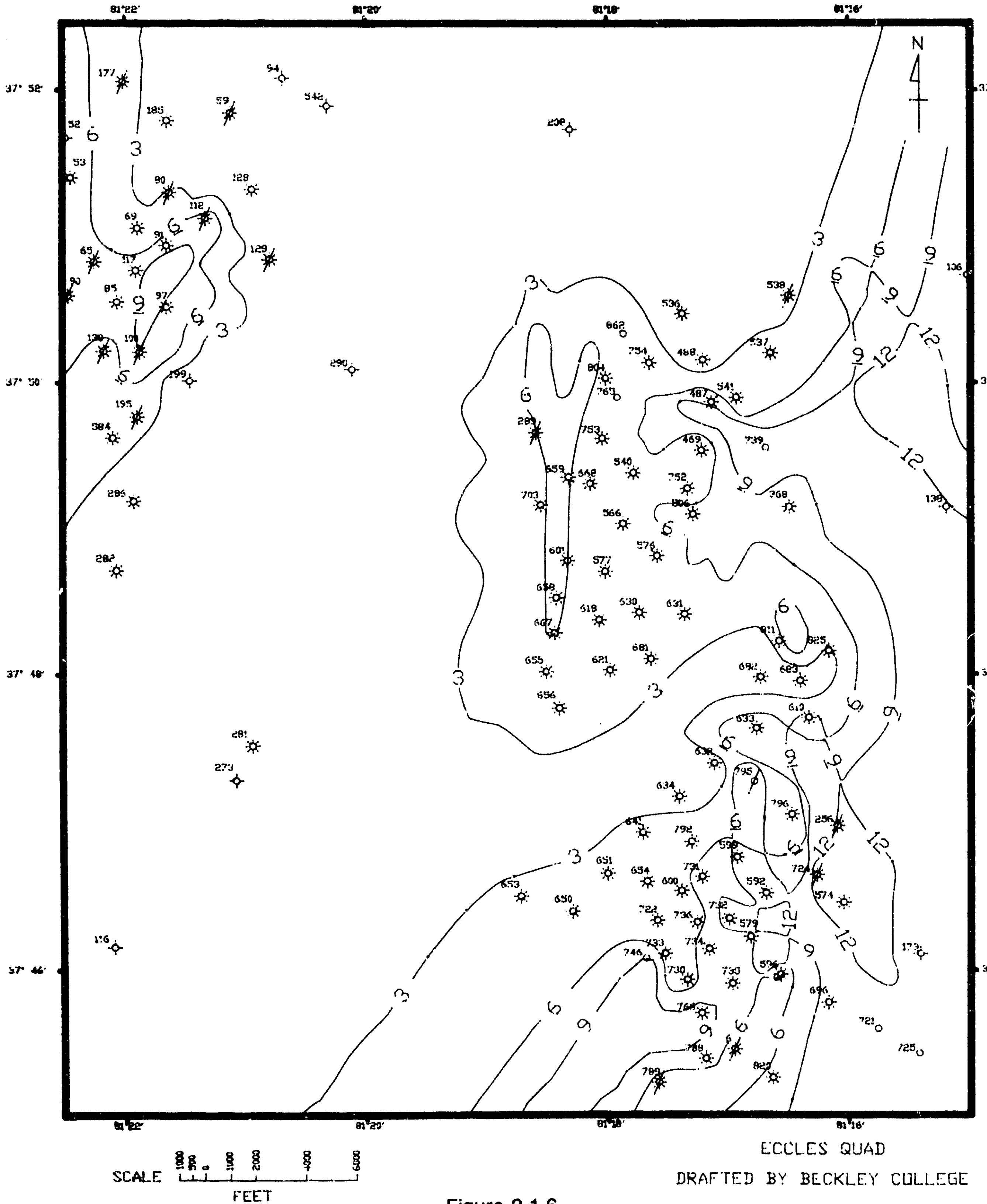


Figure 2.1.6

INITIAL OPEN FLOW BEFORE TREATMENT (MCF/DAY)

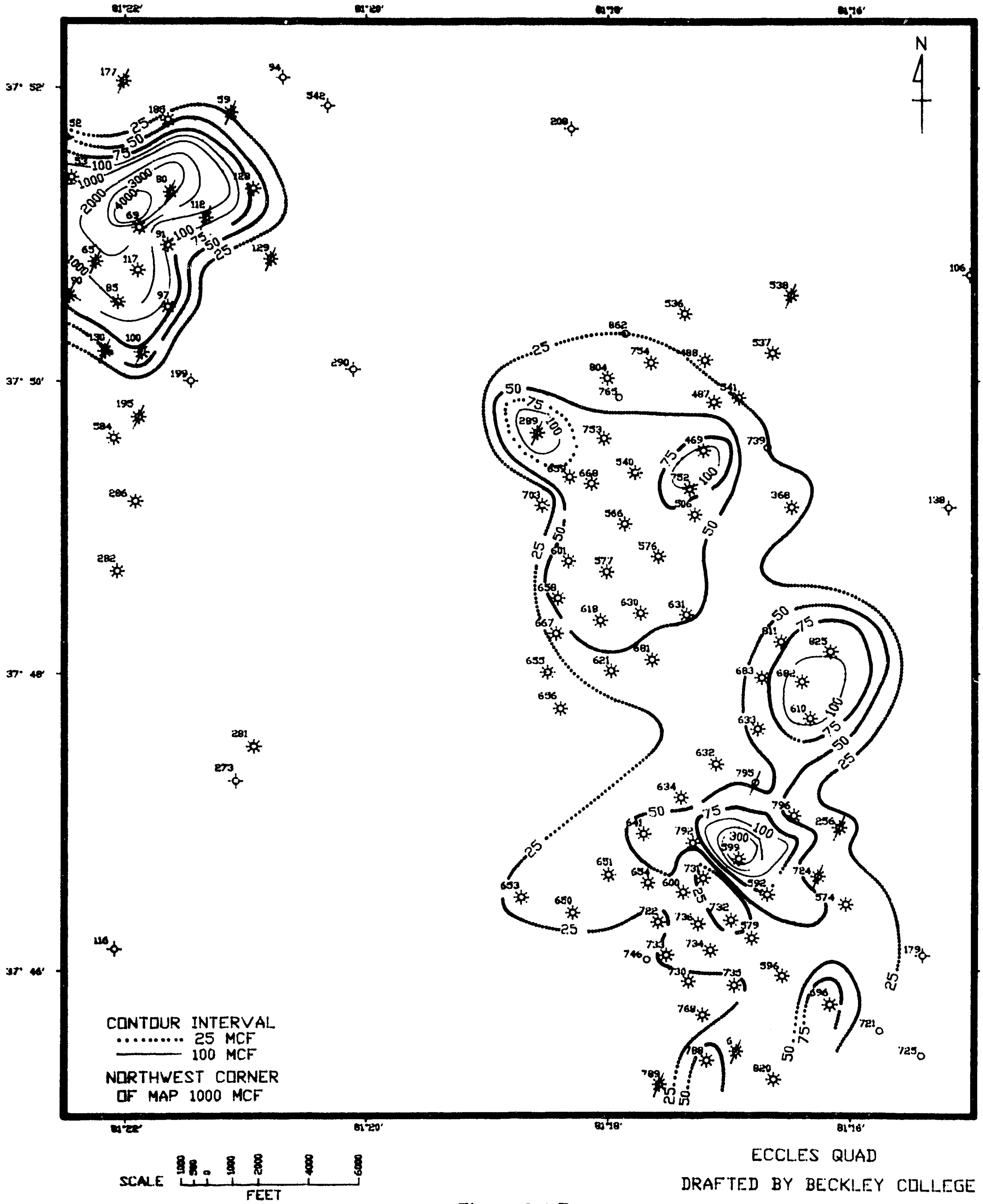


Figure 2.1.7

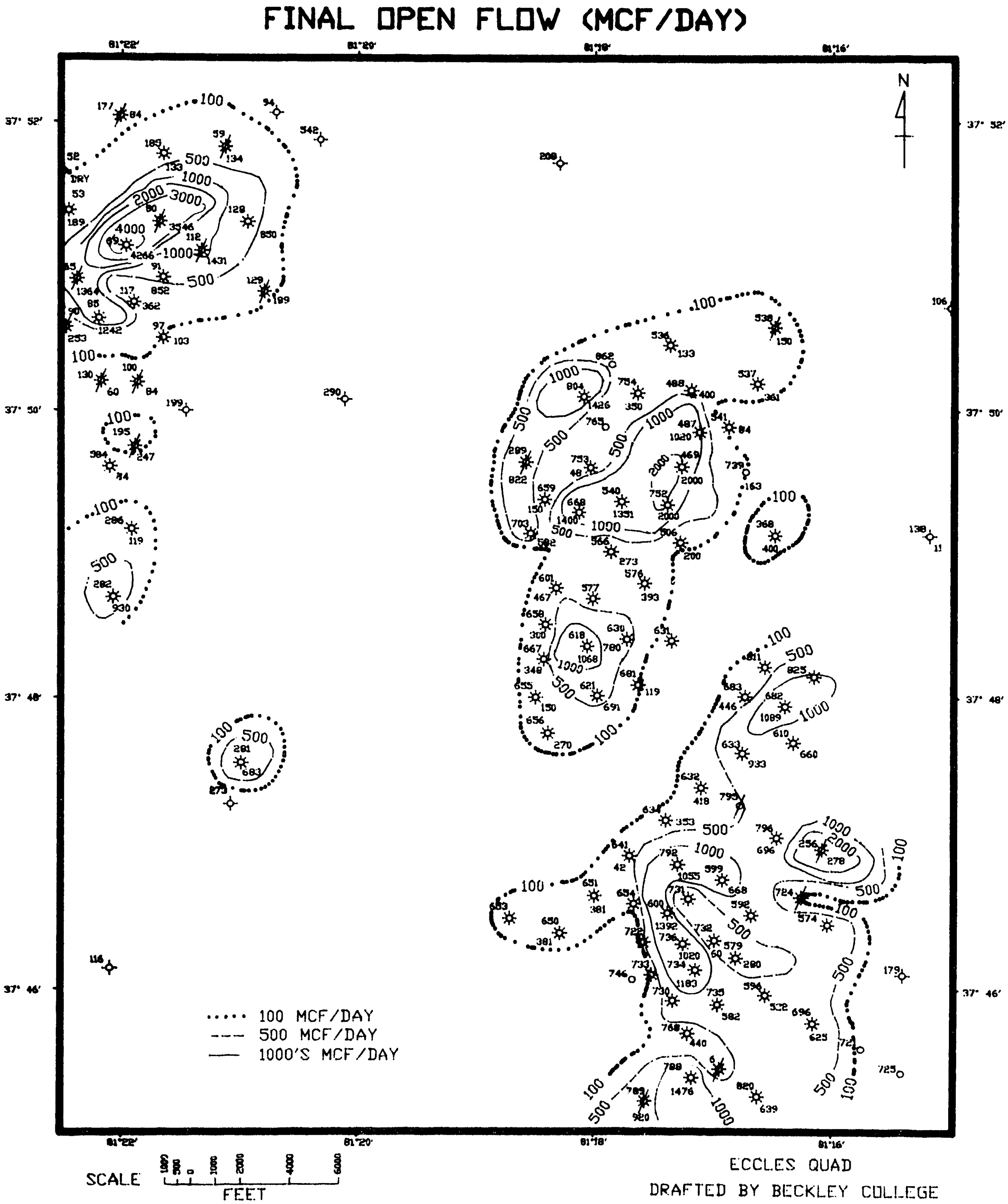


Figure 2.1.8 Final Open Flow After Stimulation, Eccles Quadrangle

assumed that 60% of the OGIP will be produced at the economic limit and a map of the recoverable reserves was prepared.

Spacing between producing Ravencliff wells was measured and the effective drainage radius for each well determined. An average drainage radius was calculated for the Ravencliff wells on the Eccles quadrangle.

Cross-checking the engineering analyses with information developed from well logs and isopach maps allowed areas of diagenetic alteration and reservoir degradation to be identified. A Ravencliff Reservoir Diagenesis Probability Map (**Figure** 2.1.9) was prepared. This was combined with **Figure** 2.1.4, the Original Reservoir Probability Map to produce the final product, a Ravencliff Modern Day Reservoir Probability Map (**Figure** 2.1.10).

Only two or three wells were found producing from supposed Maxton Sands, and even these wells, based on log appearances, may actually be producing from deeply incised basal Ravencliff channel sands that have been misidentified as Maxton. It was concluded that the Ravencliff sand is the only unit that can be considered to be a viable producing, Pennsylvanian-age target on the Eccles Quadrangle.

2.1.2 Mississippian-age Sandstone and Limestone Natural Gas Resource

Mississippian-age resources were approached in a manner similar to that described for the Pennsylvanian-age formations. The analysis revealed that the Chesterian-age Greenbrier limestone, generally referred to by its drillers' name, the "Big Lime," was the primary Mississippian-age producing unit in the study area.

The "Big Injun" sandstone appeared to be dry across the study area and the Weir and Berea sandstones had only very spotty recorded production. Neither deeper Mississippian-age unit produces sufficient gas to merit inclusion in the resource estimates. In addition, the spread in depths between the coals and the deepest Mississippian-age units could have presented difficulties in simultaneous completion and production through a single borehole.

A Masters Thesis, currently in preparation, by Mr. Gregory Kelleher (**Ref.** 3) at West Virginia University, describes the Greenbrier "Big Lime" limestone as an oolitic or pelletoid limestone with most of the porosity being intra-granular. The pellets formed in shallow water by wave action and the porosity occurs primarily between the thin layers of mud within the pellets.

Information in the WVGES database and from private industry sources tended to support this interpretation. In this scenario, ooids and the best porosity tend to occur where the water was shallow. These units are generally deposited on highs or shoal areas within a shallow sea.

The Big Lime structure (**Figure** 2.1.11) and isopach (**Figure** 2.1.12) maps showed an area in the eastern portion of the Eccles Quadrangle that has apparently repeatedly acted as a positive block. This block has been tested by several Oriskany and Tuscarora wells.

Study of electric logs (see **Figure** 2.1.13 for an example) confirmed the oolitic concept. The database was manipulated to perform an analysis of the structure and the tectonic history of the area to identify, geostatistically, other areas with a high probability of similar shoaling and high energy conditions in the mud.

This information was used to construct an Iso-probability Map for the "Big Lime" reservoir, which quantified the likelihood of encountering a similar set of "Big Lime" reservoir conditions.

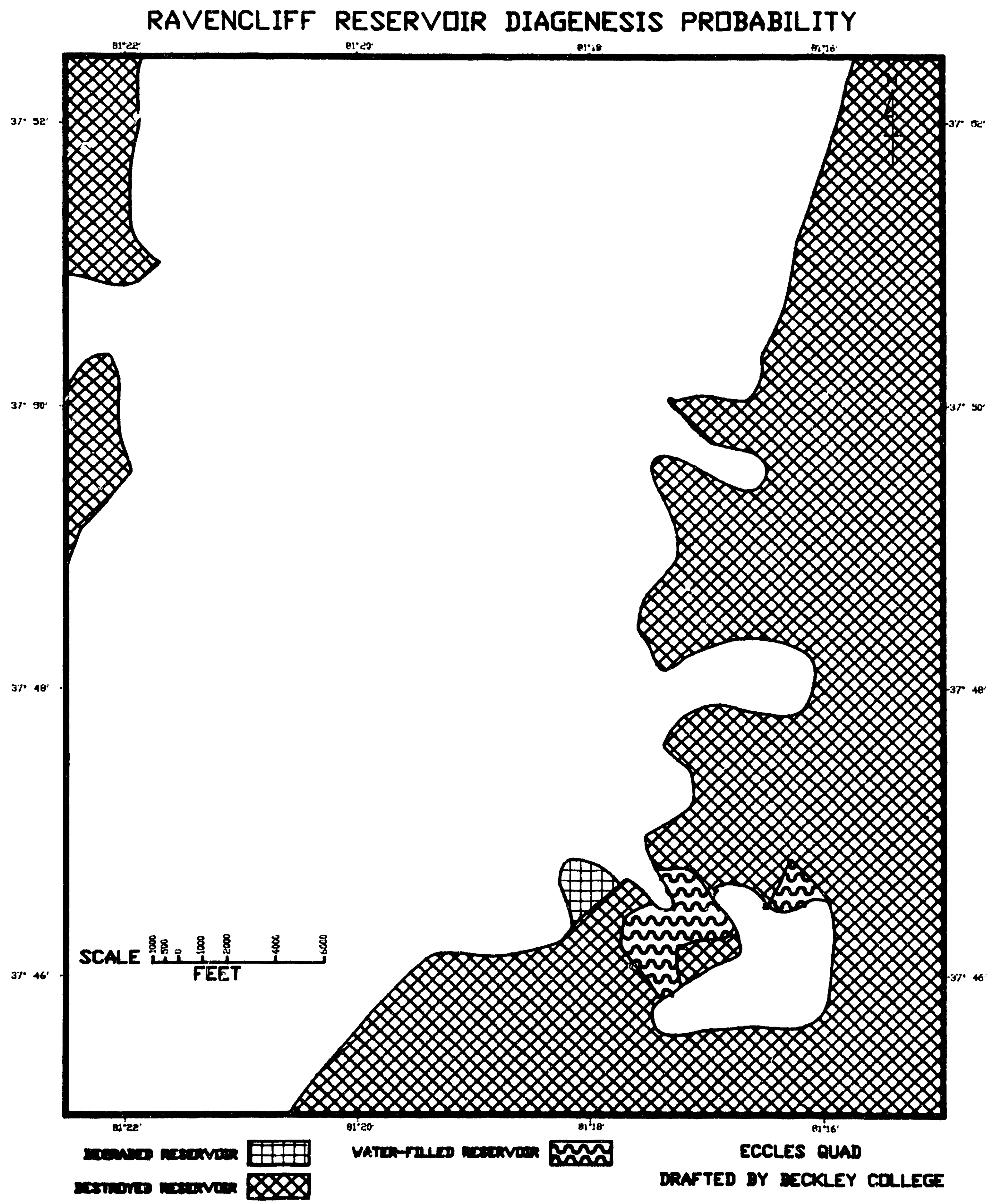

RAVENCLIFF RESERVOIR DIAGENESIS PROBABILITY
81°22'
81°20'
81°18'
81°16'
37° 52'
37° 50'
37° 48'
37° 46'
SCALE
1000
500
0
1000
2000
4000
6000
FEET
WATER-FILLED RESERVOIR
DESTROYED RESERVOIR
ECCLES QUAD
DRAFTED BY BECKLEY COLLEGE

Figure 2.1.9

RAVENCLIFF OPTIMIZED PRESENT DAY RESERVOIR

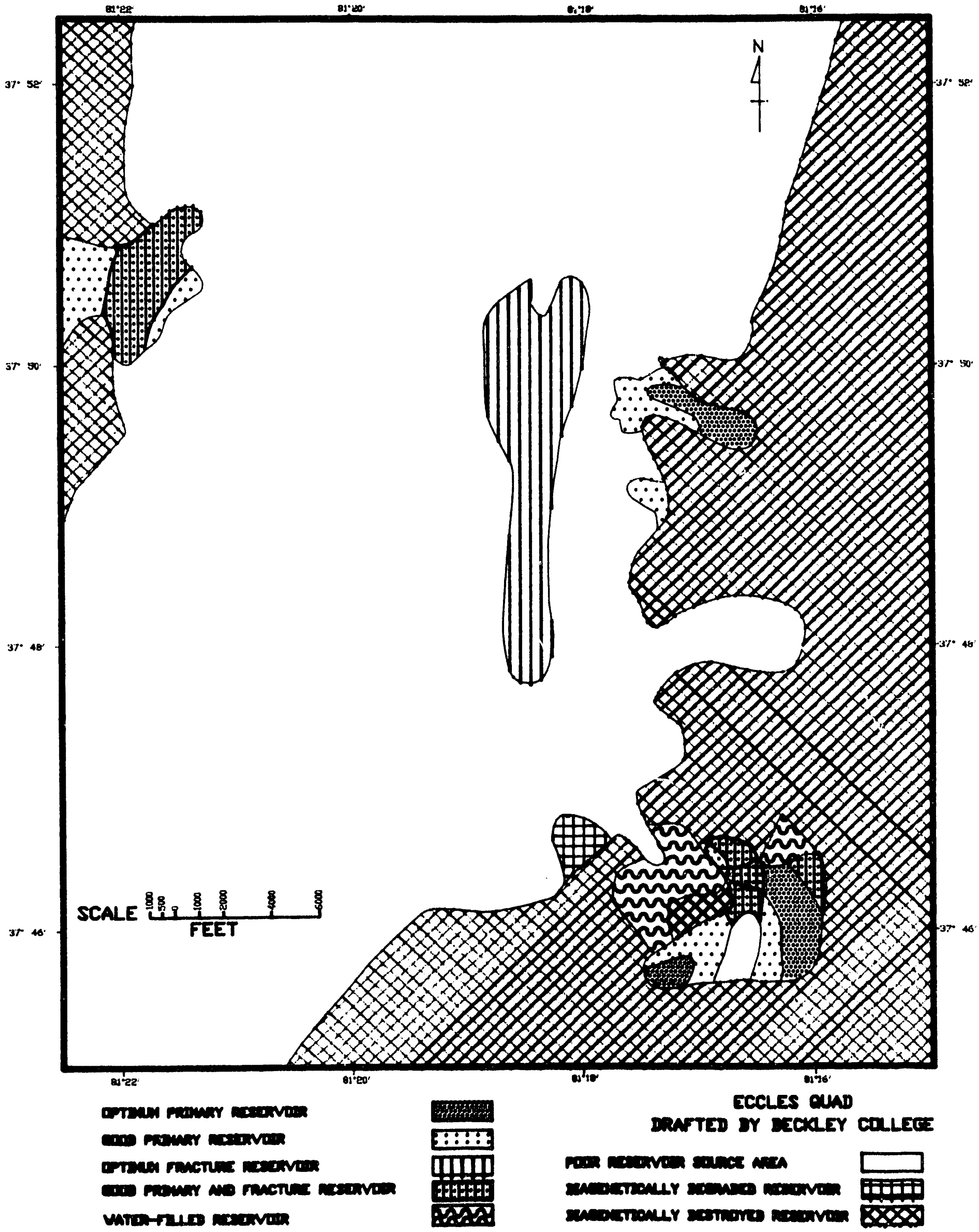


Figure 2.1.10

BIG LIME STRUCTURE MAP

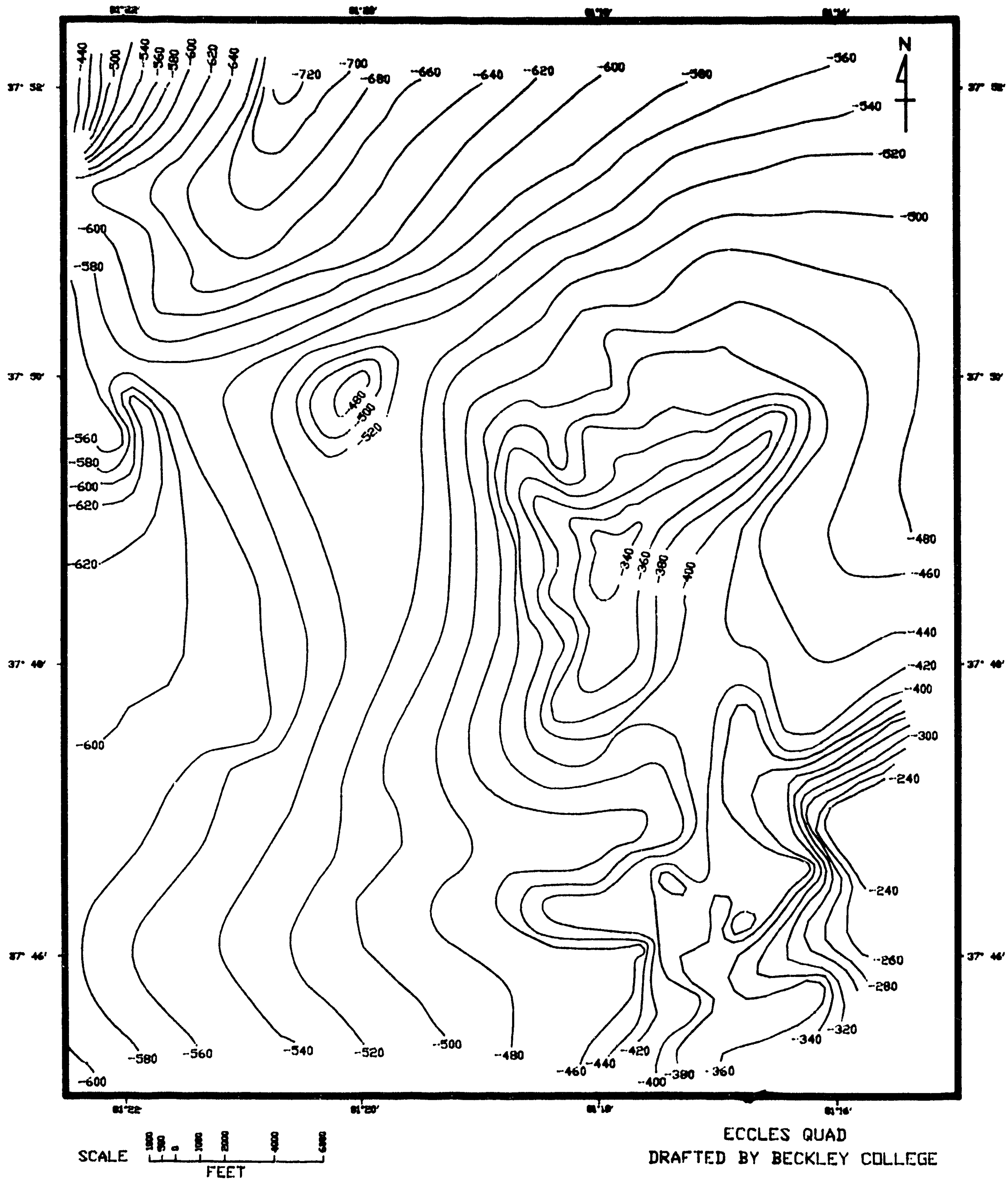


Figure 2.1.11 Structure on Top of the Big Lime, Eccles Quadrangle

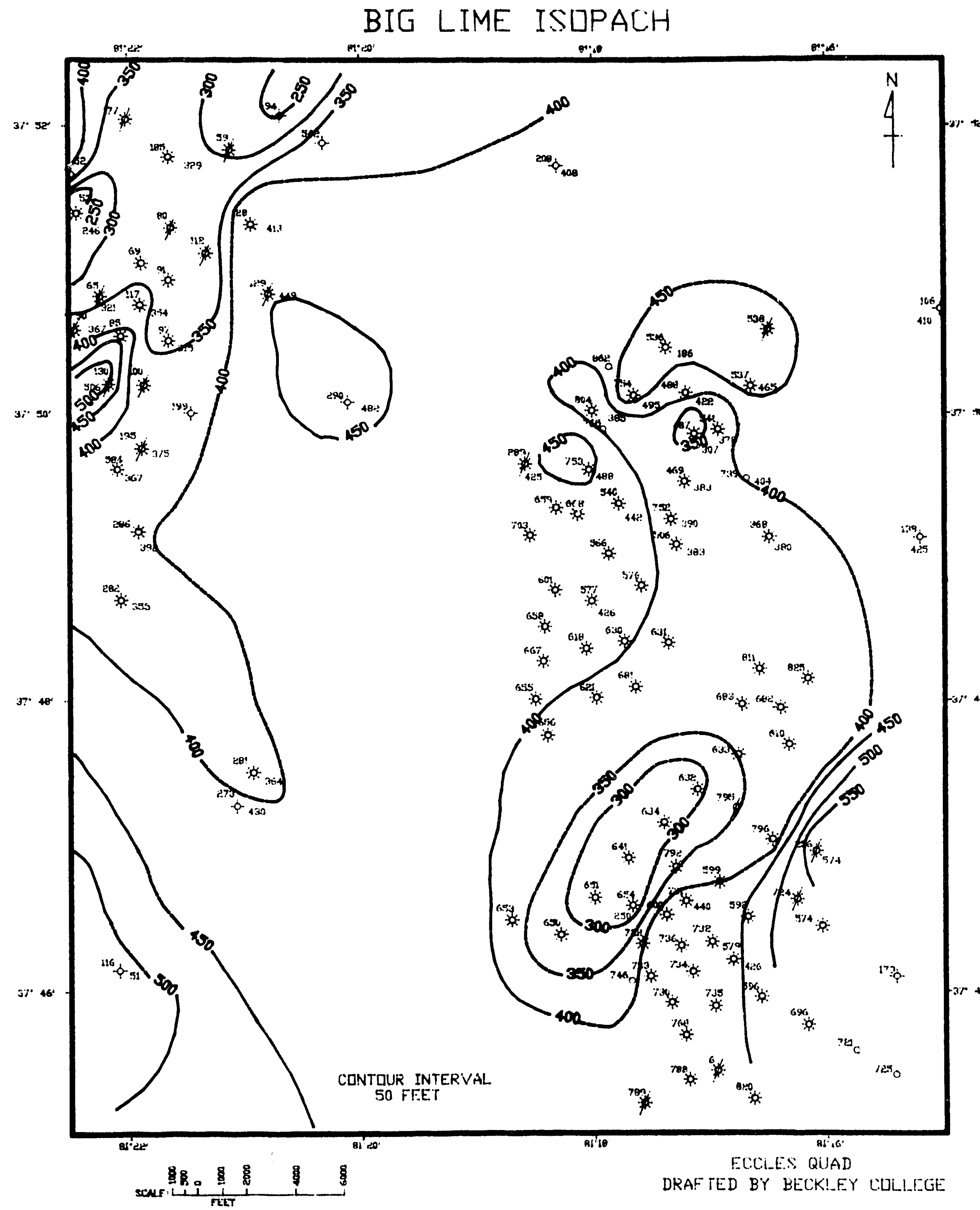

BIG LIME ISOPACH
CONTOUR INTERVAL
50 FEET
SCALE
FEET
ECCLES QUAD
DRAFTED BY BECKLEY COLLEGE

Figure 2.1.12

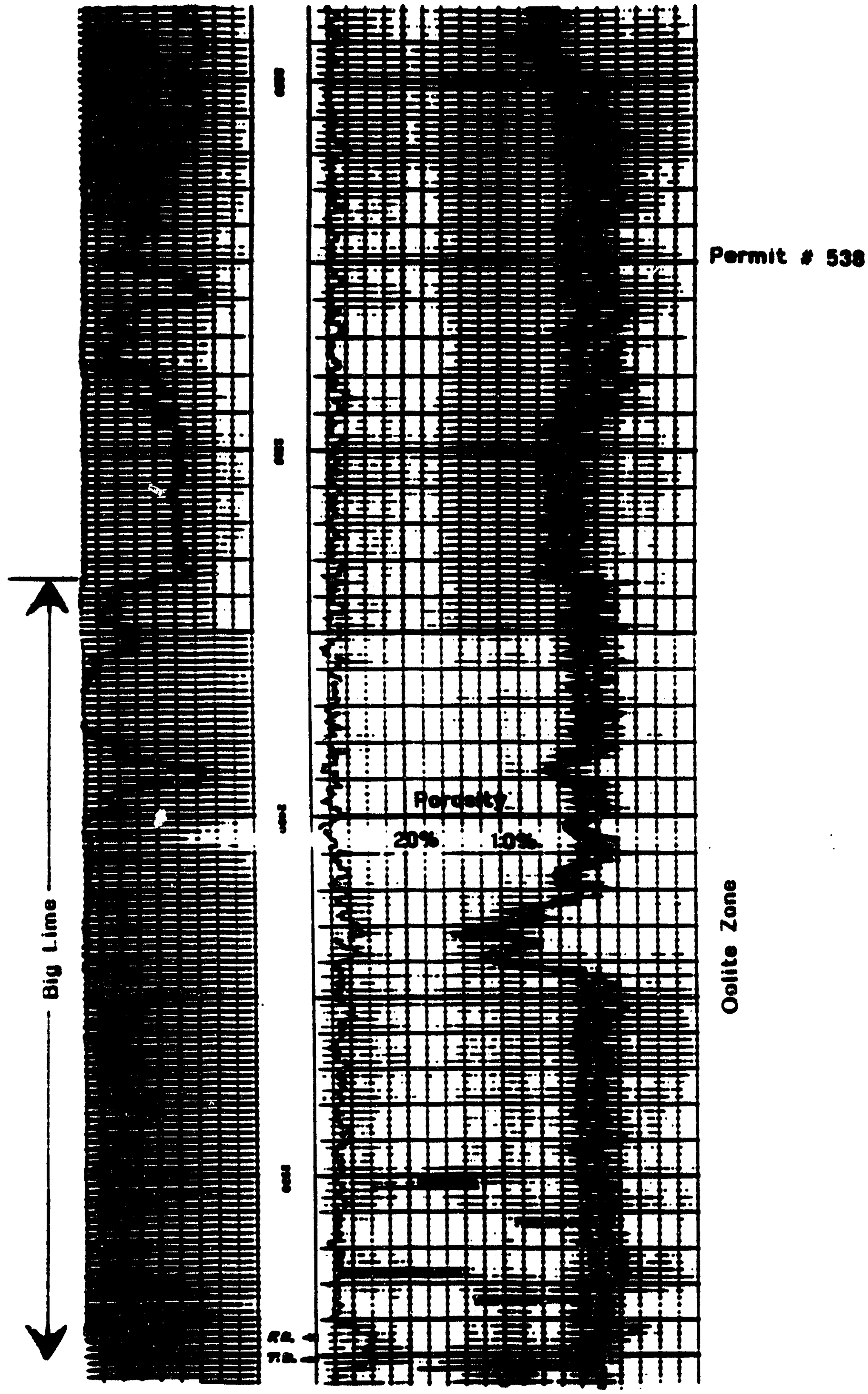


Figure 2.1.13 Sample Gamma-Density Log Showing Oolitic Big Lime Limestone Reservoir

The "Big Lime" resource maps were prepared in a manner similar to that used in the preparation of the Pennsylvanian-age resource maps. The Big Lime Original Reservoir Map (**Figure** 2.1.14) was modified to account for the effects of secondary porosity (**Figure** 2.1.15). The final map in this series (**Figure** 2.1.16) displays the geostatistically probable porosity, primary plus secondary.

Diagenetic effects (**Figure** 2.1.17) were identified and used to produce a final Big Lime Modern Day Reservoir Probability Map (**Figure** 2.1.18).

2.1.3 Coalbed Methane Resource

Coal data from the OG-10's proved to be much less accurate and less complete than information on the traditional, deeper, producing-sand units. Drillers apparently pay less attention to the shallow part of the hole than they do to depths where production can be anticipated, since the coals and other shallow units are often described in a very sketchy manner by comparison to the key target beds. When coals are listed on the OG-10's, they are frequently unnamed or misnamed.

For accurate statistical data on the coals, it was necessary to get additional coal information from the West Virginia Geological Survey. A separate database was purchased which included coal tops, thicknesses, and quality information which had been acquired from coal company coreholes. In several cases, detailed core descriptions were available on these holes. In addition to the raw data, the Survey offers mapped interpretations of the structure and coal quality for the most important coal seams. Information was also collected from the U.S. Bureau of Mines, although this information tended to be more generalized, covering broader areas, than the detailed reports and maps prepared by the State Survey.

Extensive coal thickness and seam top data was manipulated to produce structure (**Figures** 2.1.19, 2.1.20) and isopach (**Figures** 2.1.21, 2.2.22) maps for the primary seams in the study area. Several of the seams were found to be quite shallow or very thin. These beds were not of further interest in this project. A guideline of a minimum of 800 feet of overburden (**Figure** 2.1.23) had been set for target coal formations, with 1000 feet preferable.

In addition to individual seam isopachs, a Combined Thickness, Beckley and Pocahontas Coals isopach (**Figure** 2.1.24) was prepared, including all of the coals that should contribute methane to the test hole.

U.S. Bureau of Mines data (**Ref.** 4) was used to determine coalbed methane-per-ton values for the target seams. This was converted to methane-in-place-per-foot-of-coal for each seam. Finally, the effects of mining on the Beckley Coal (**Figure** 2.1.25) were accounted for and a projected Total Methane Resource-per-Acre Map (**Figure** 2.1.26) was prepared.

Once a target area had been identified and a series of specific target sites located, the local coal owner/operator was contacted and additional coal thickness data was obtained. This confirmed the mapping in the target area. However, the data also showed a previously unidentified thinning in the southwestern corner of the Eccles Quadrangle between the New Beckley and Maple Meadow Mines. This thinning has no effect on the target areas, but is noted for the record.

2.1.4 Composite Resource Map

Figures 2.1.10 and 2.1.18, showing conventional Pennsylvanian-age and Mississippian-age natural gas resources, were combined with the Total Methane Resource Map (**Figure** 2.1.26) to produce a Combined Natural Gas and Coalbed Methane Resource Map (**Figure** 2.1.27).

BIG LIME ORIGINAL RESERVOIR
QUALITY PROBABILITY MAP (PRIMARY POROSITY)

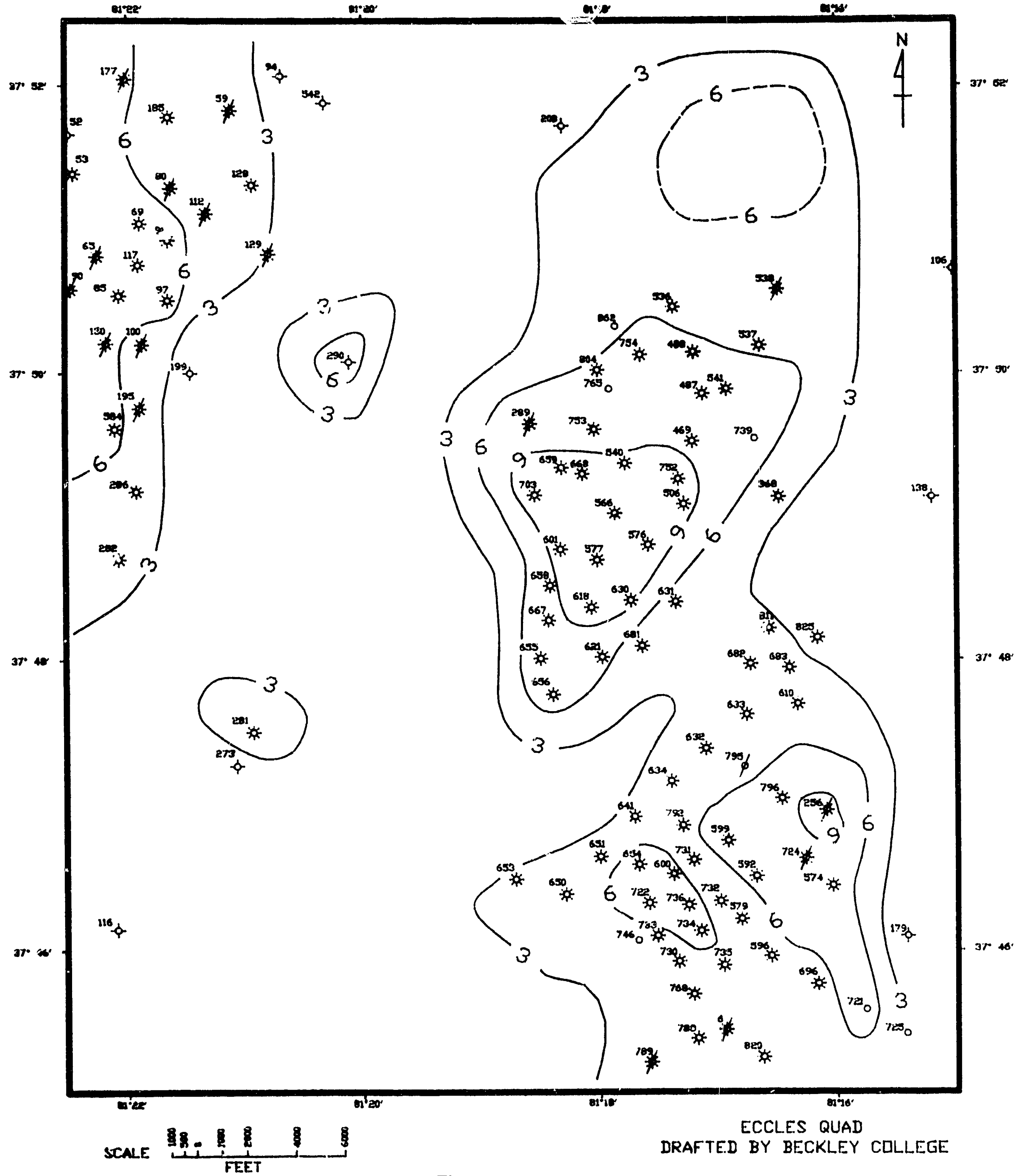
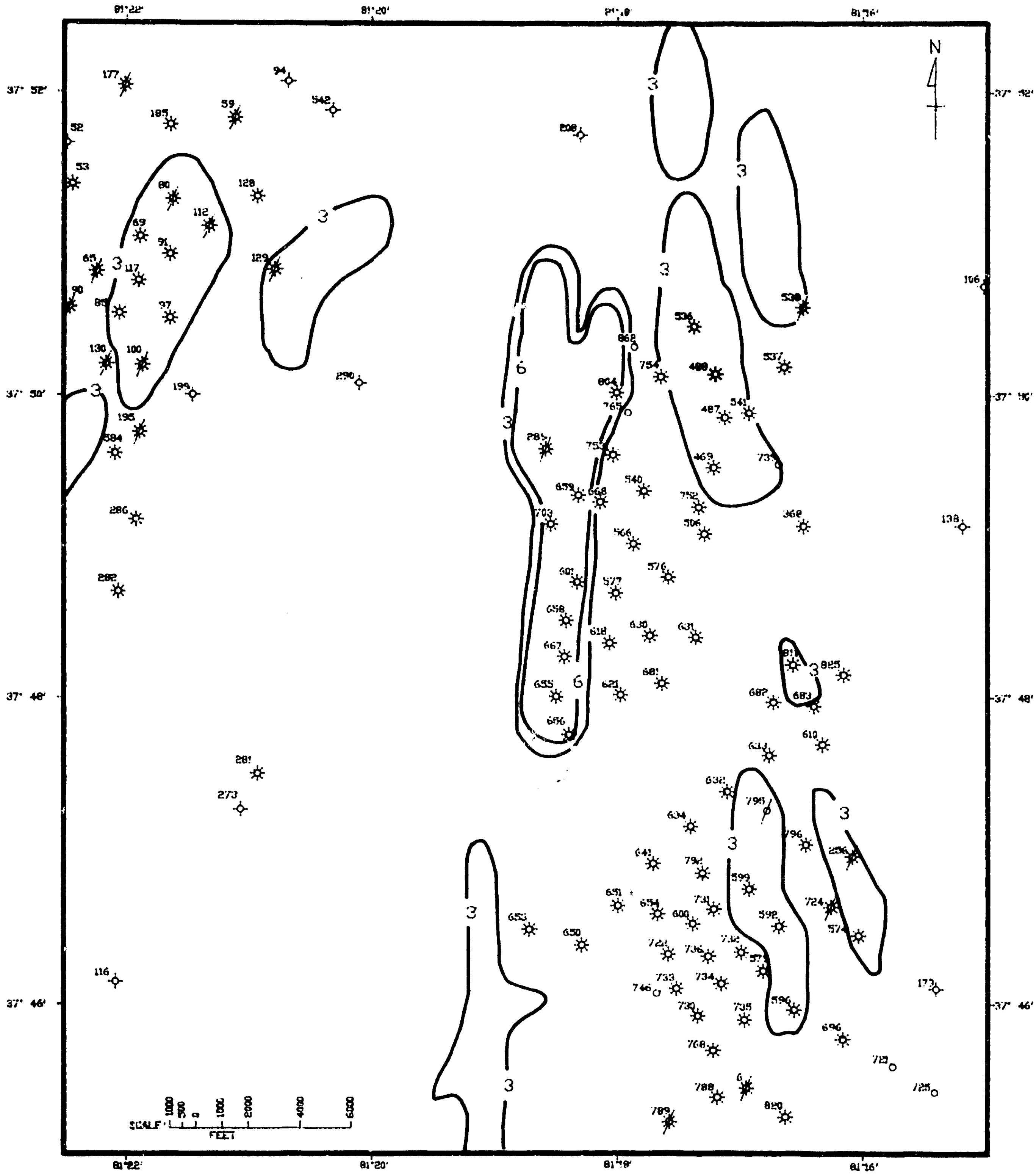


Figure 2.1.14

BIG LIME RESERVOIR ENHANCEMENT
PROBABILITY MAP (SECONDARY POROSITY)



ECCLES QUAD
DRAFTED BY BECKLEY COLLEGE

Figure 2.1.15

BIG LIME COMBINED
PRIMARY-SECONDARY POROSITY PROBABILITY

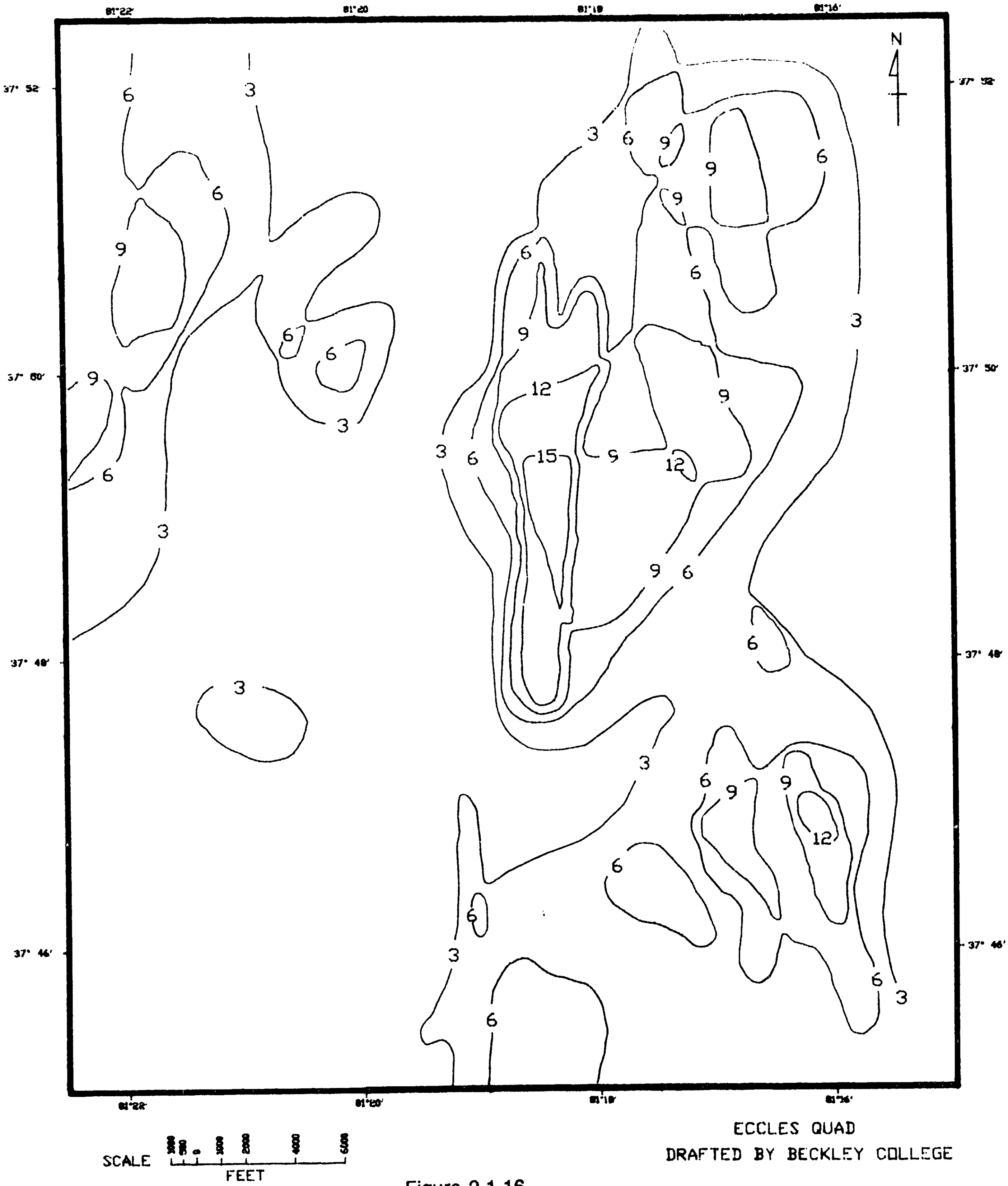


Figure 2.1.16

BIG LIME RESERVOIR DIAGENESIS PROBABILITY MAP

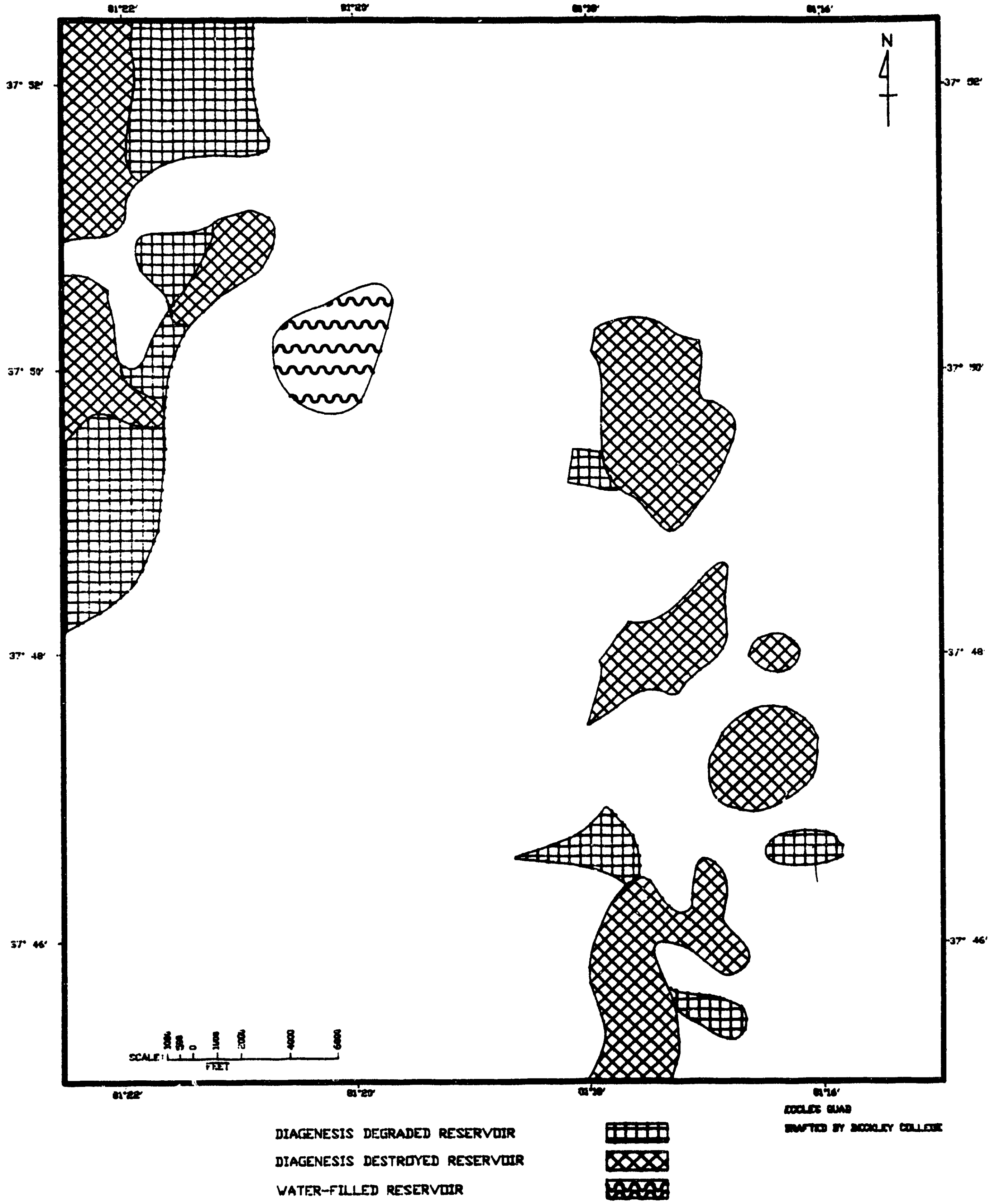


Figure 2.1.17

BIG LIME PRESENT DAY RESERVOIR

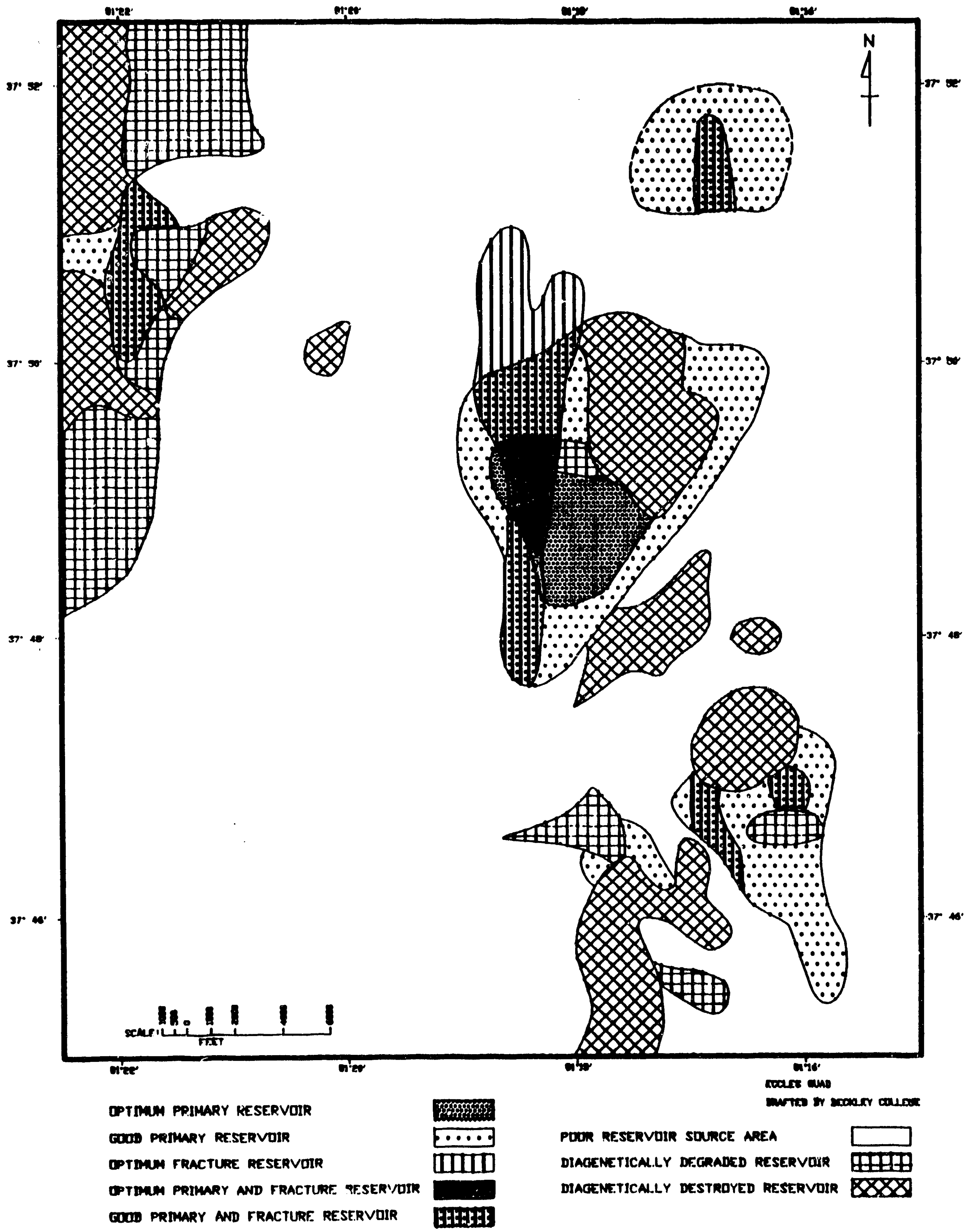
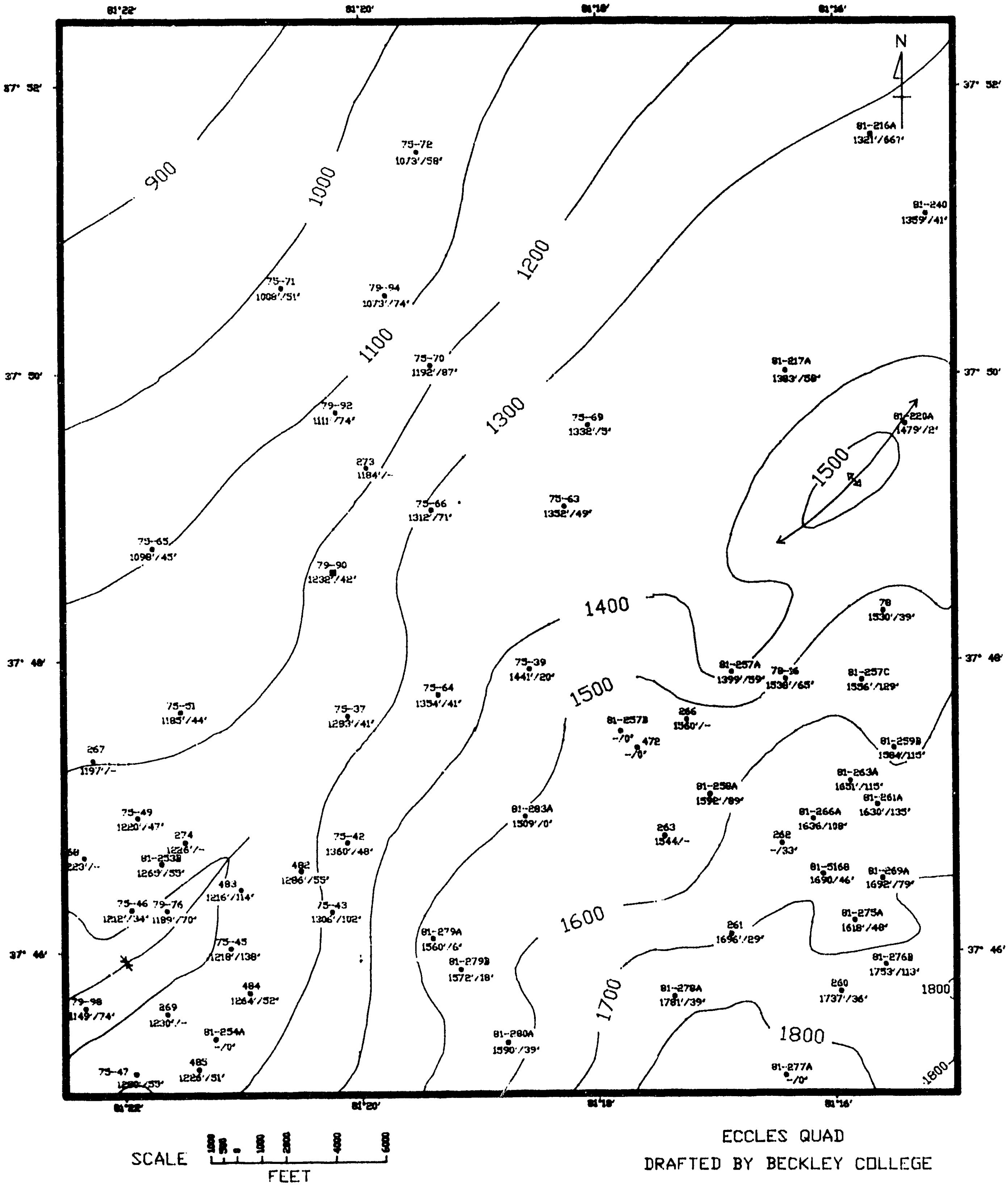


Figure 2.1.18

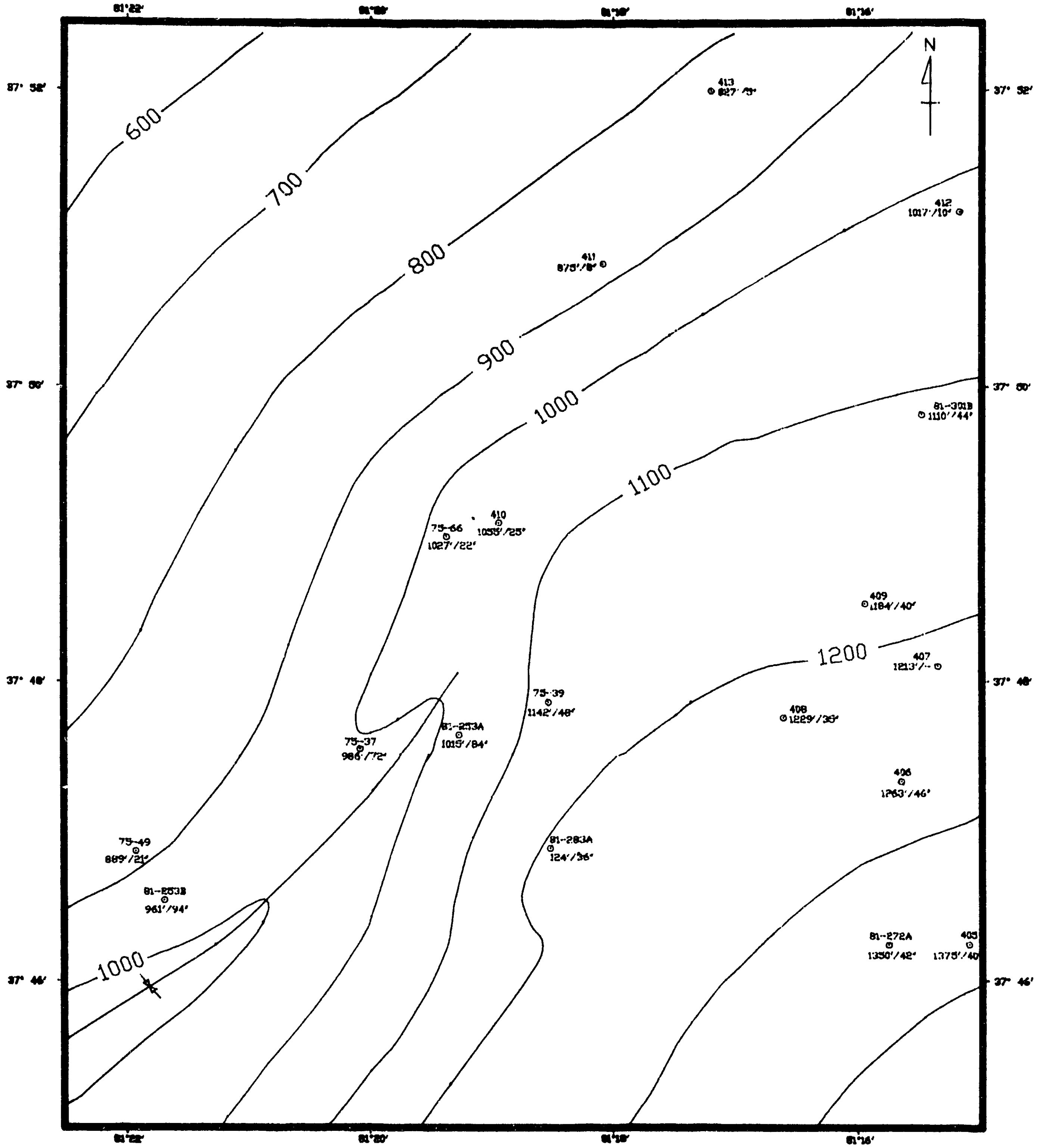
STRUCTURE ON TOP OF THE BECKLEY COAL
(ECCLES QUAD)



ECCLES QUAD
DRAFTED BY BECKLEY COLLEGE

Figure 2.1.19

STRUCTURE ON TOP OF THE POCAHONTAS #3 COAL (ECCLES QUAD)



SCALE FEET

ECCLES QUAD
DRAFTED BY BECKLEY COLLEGE

Figure 2.1.20

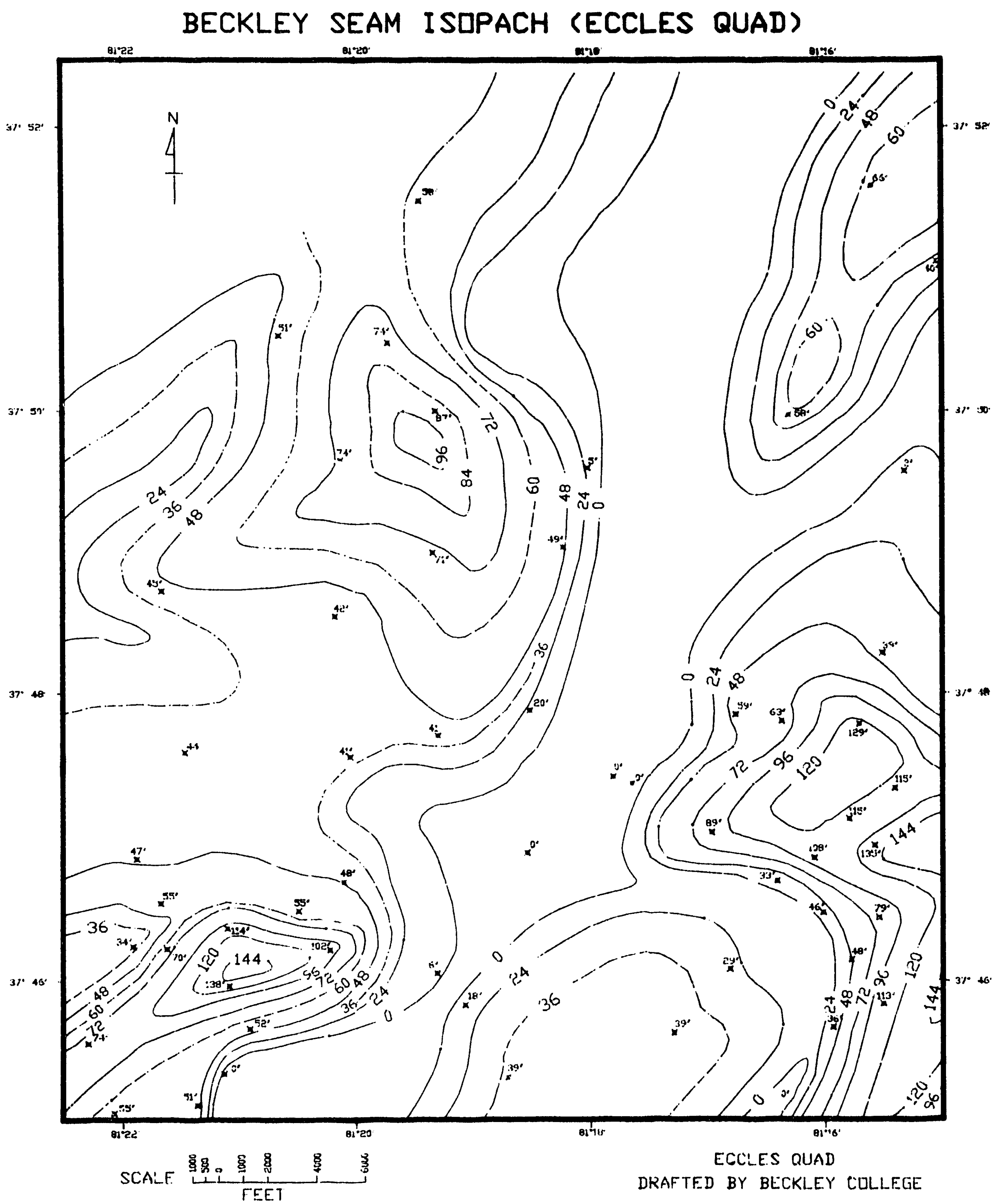
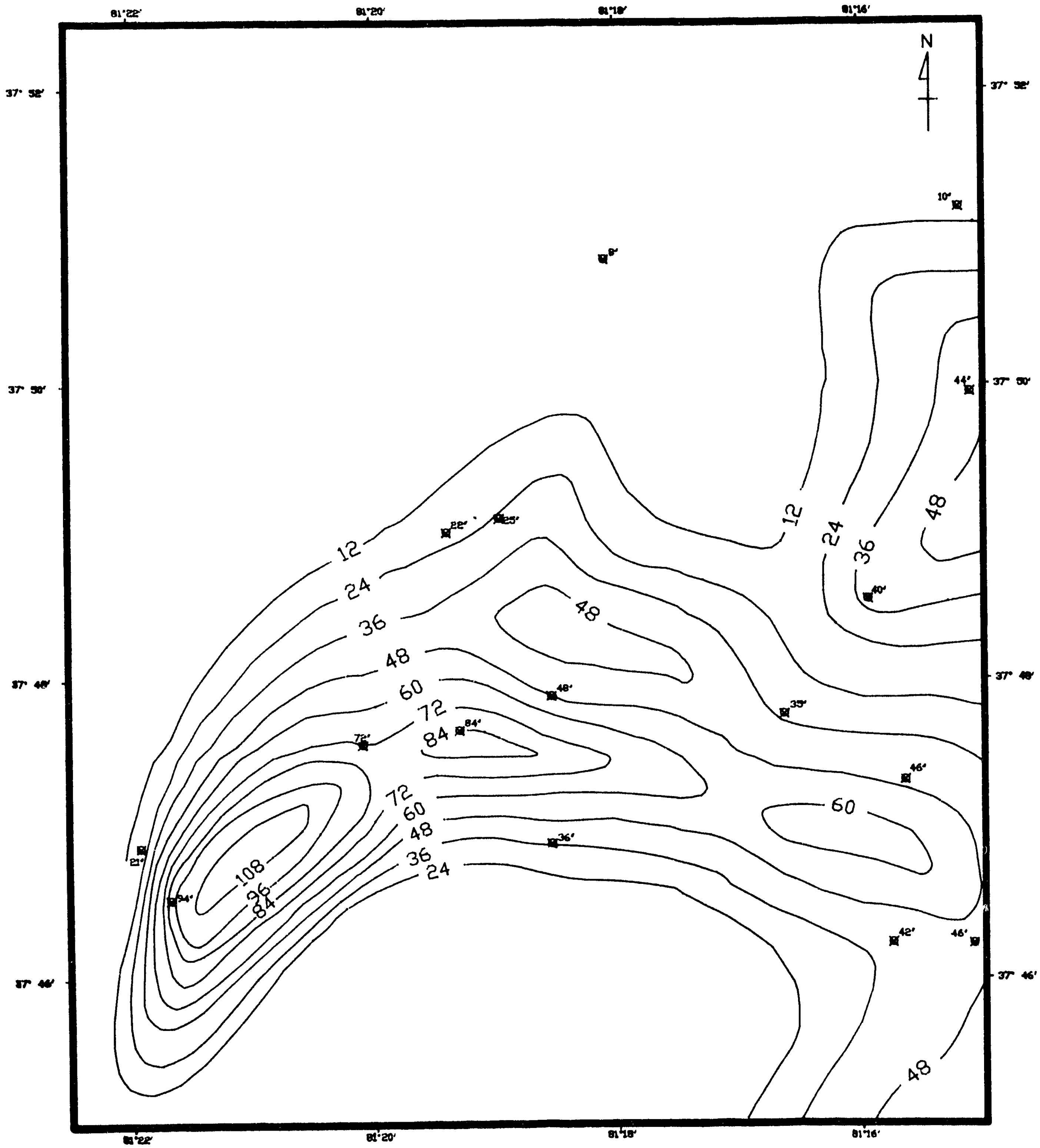

BECKLEY SEAM ISOPACH (ECCLES QUAD)
N
SCALE
FEET
ECCLES QUAD
DRAFTED BY BECKLEY COLLEGE

Figure 2.1.21

ISOPACH OF THE POCAHONTAS #3 COAL
(ECCLES QUAD)



SCALE FEET

ECCLES QUAD

DRAFTED BY BECKLEY COLLEGE

Figure 2.1.22

BECKLEY SEAM OVERBURDEN

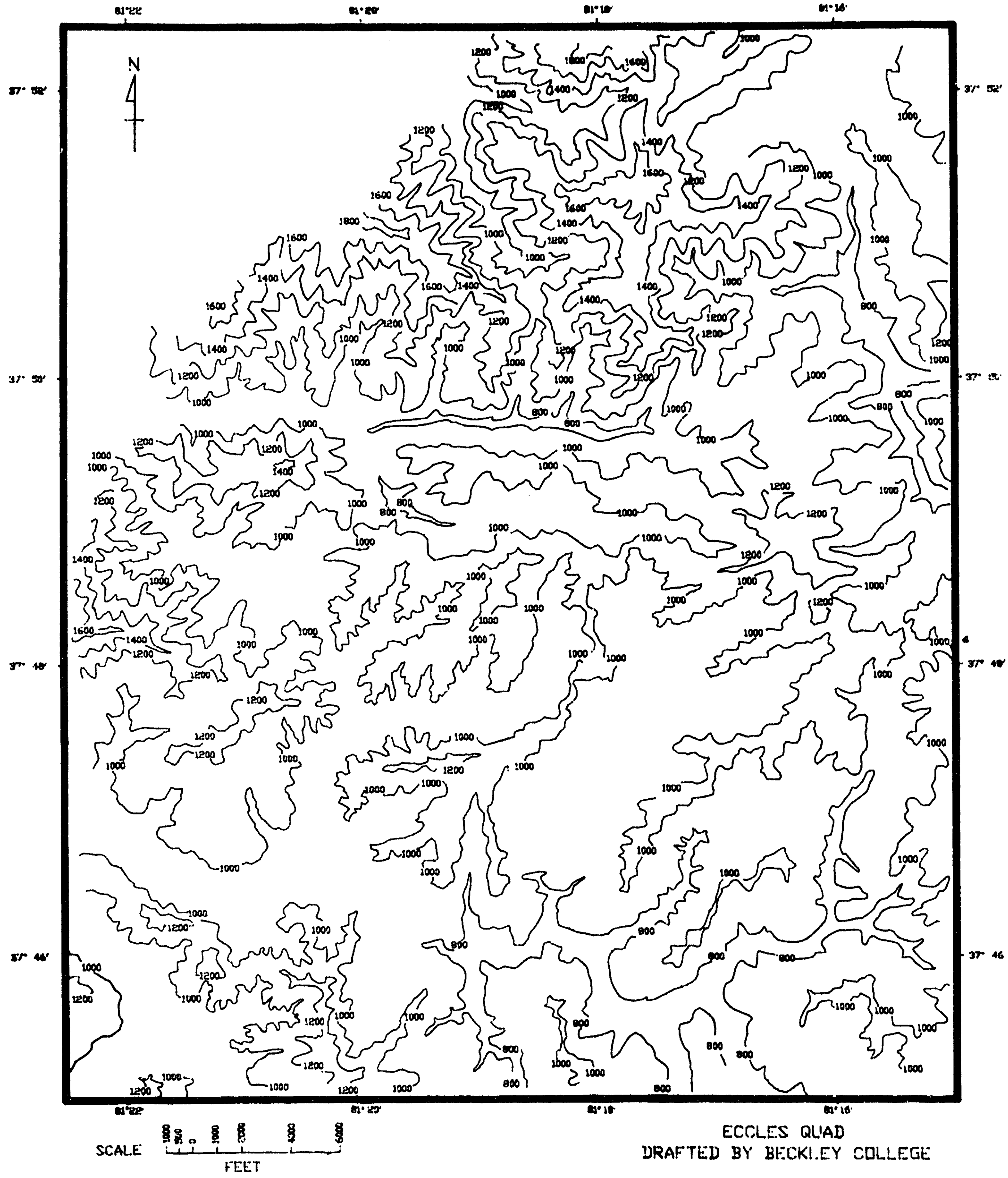


Figure 2.1.23

COMBINED THICKNESS
BECKLEY AND POCAHONTAS #3 SEAMS

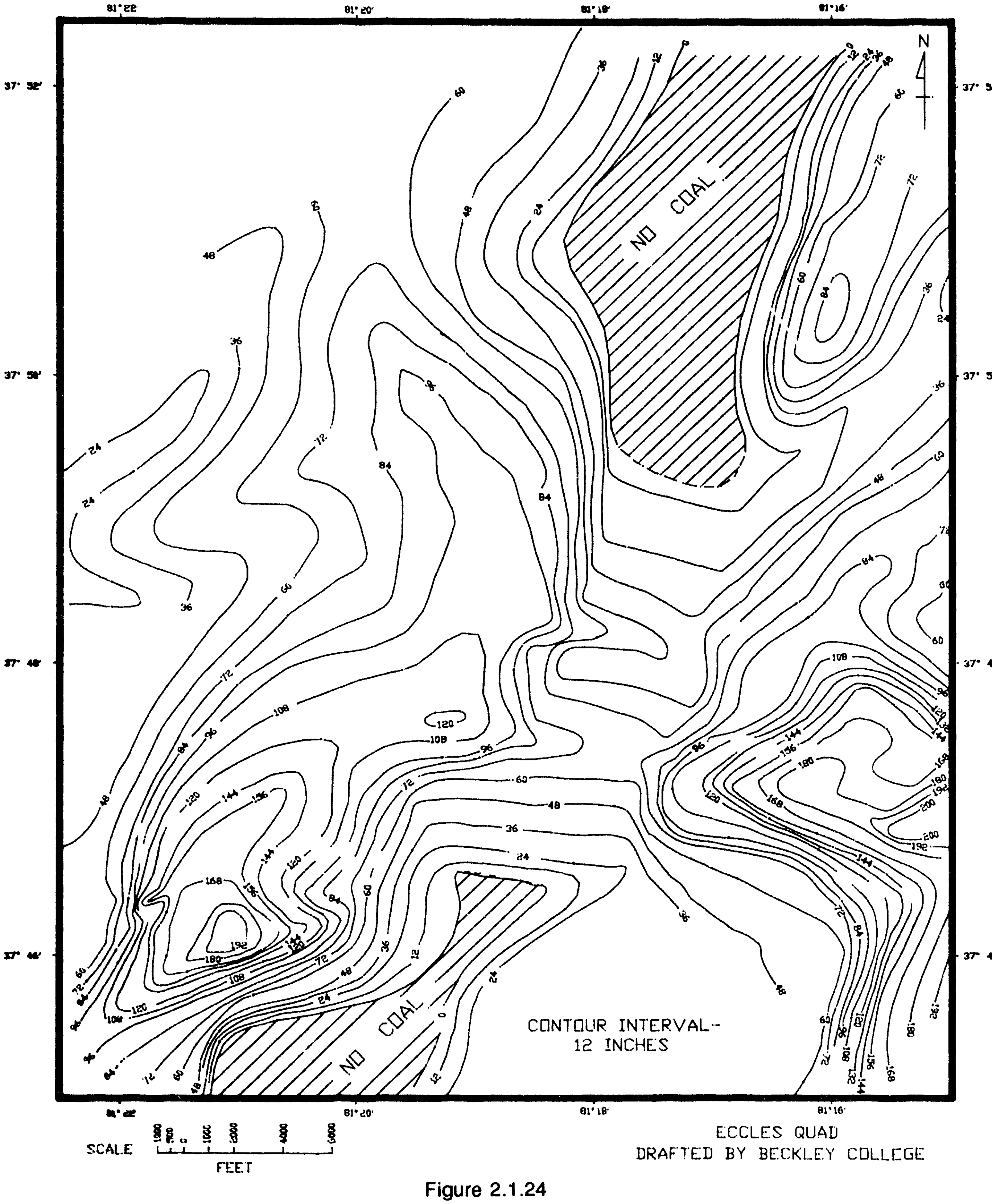


Figure 2.1.24

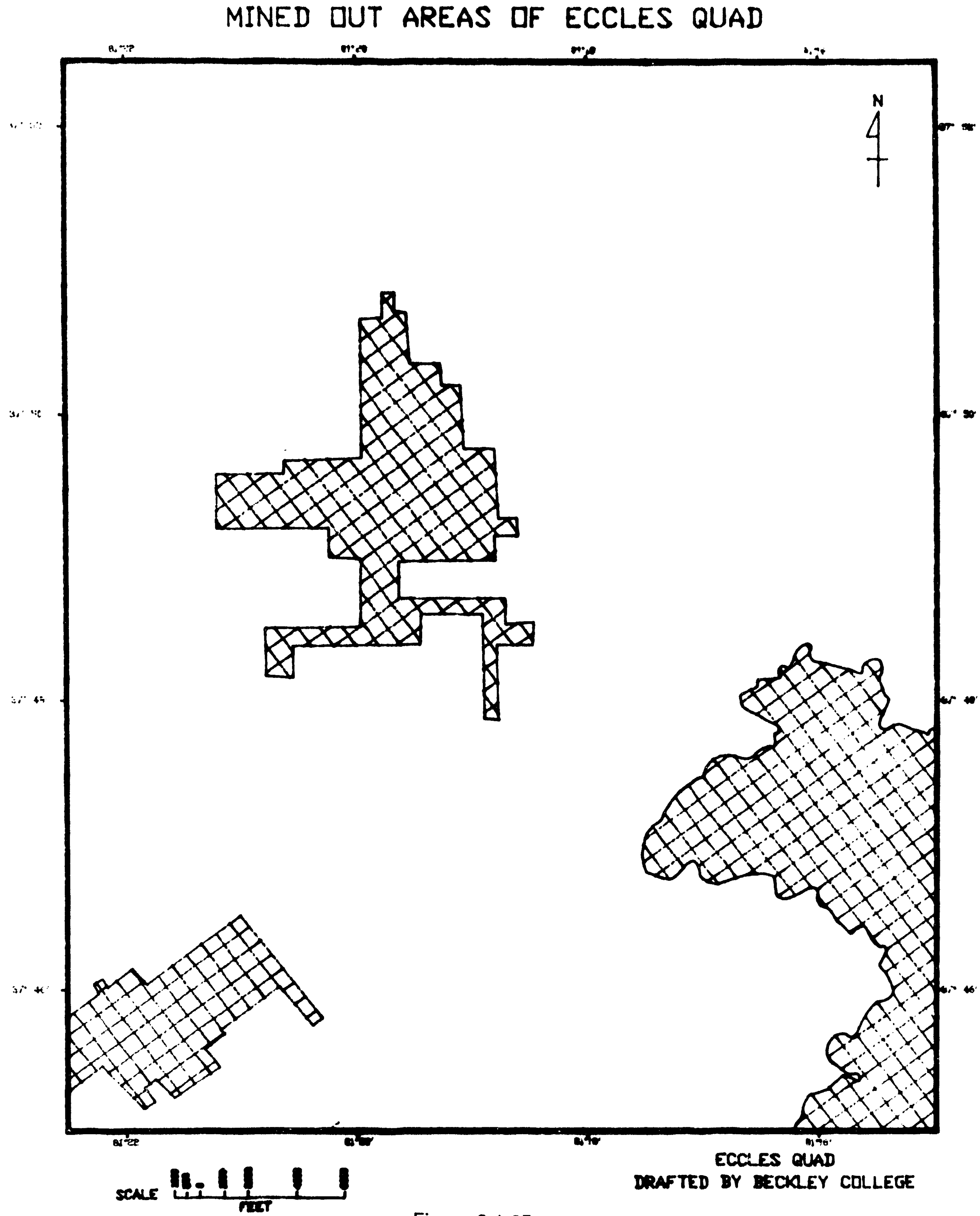

MINED OUT AREAS OF ECCLES QUAD
N
SCALE
FEET
ECCLES QUAD
DRAFTED BY BECKLEY COLLEGE

Figure 2.1.25

TOTAL METHANE IN PLACE (MMCF/ACRE)
BECKLEY & POCAHANTAS #3 SEAM

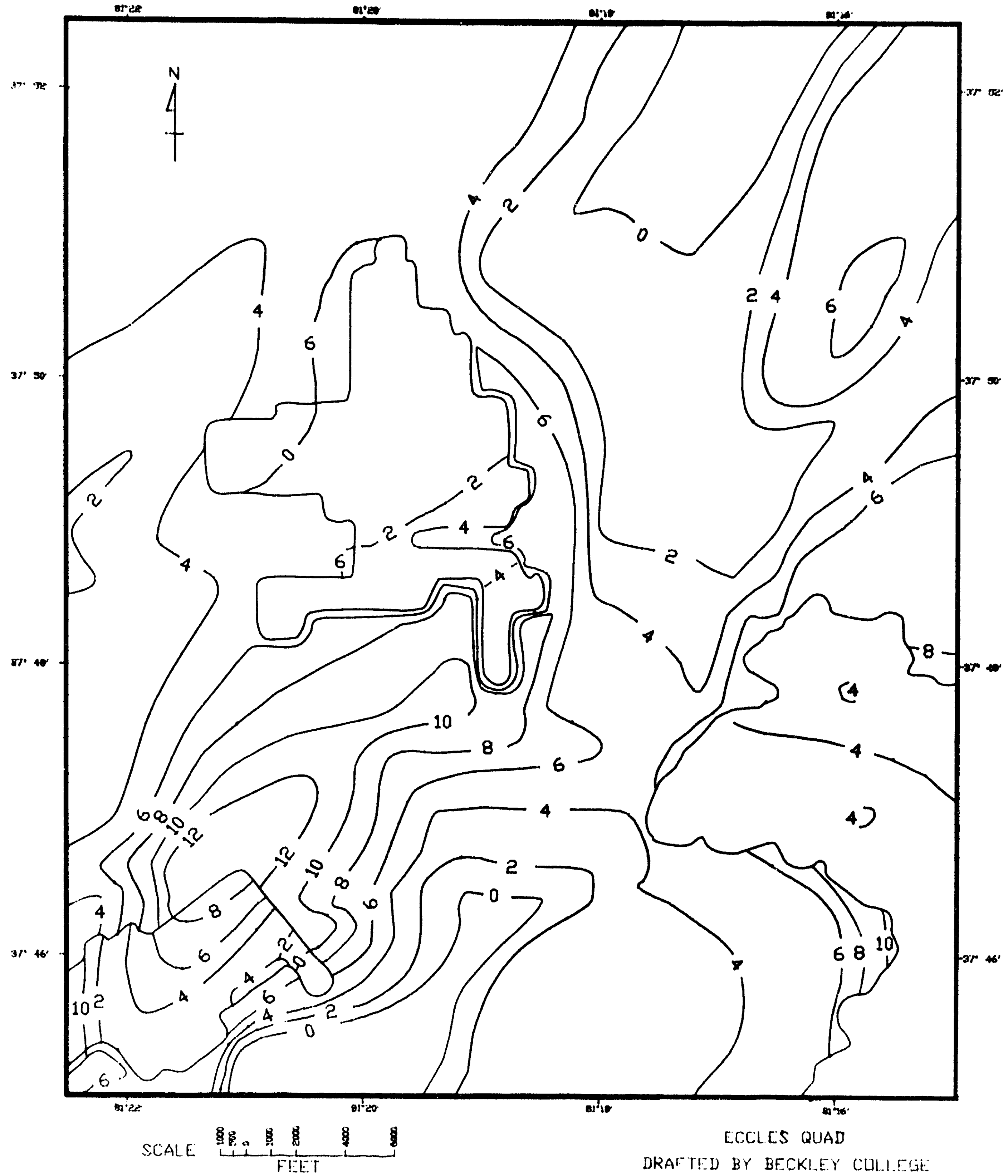


Figure 2.1.26

COMBINED COALBED METHANE AND SHALLOW (PENN. & MISS.) NATURAL GAS IN PLACE (MMCF/ACRE)

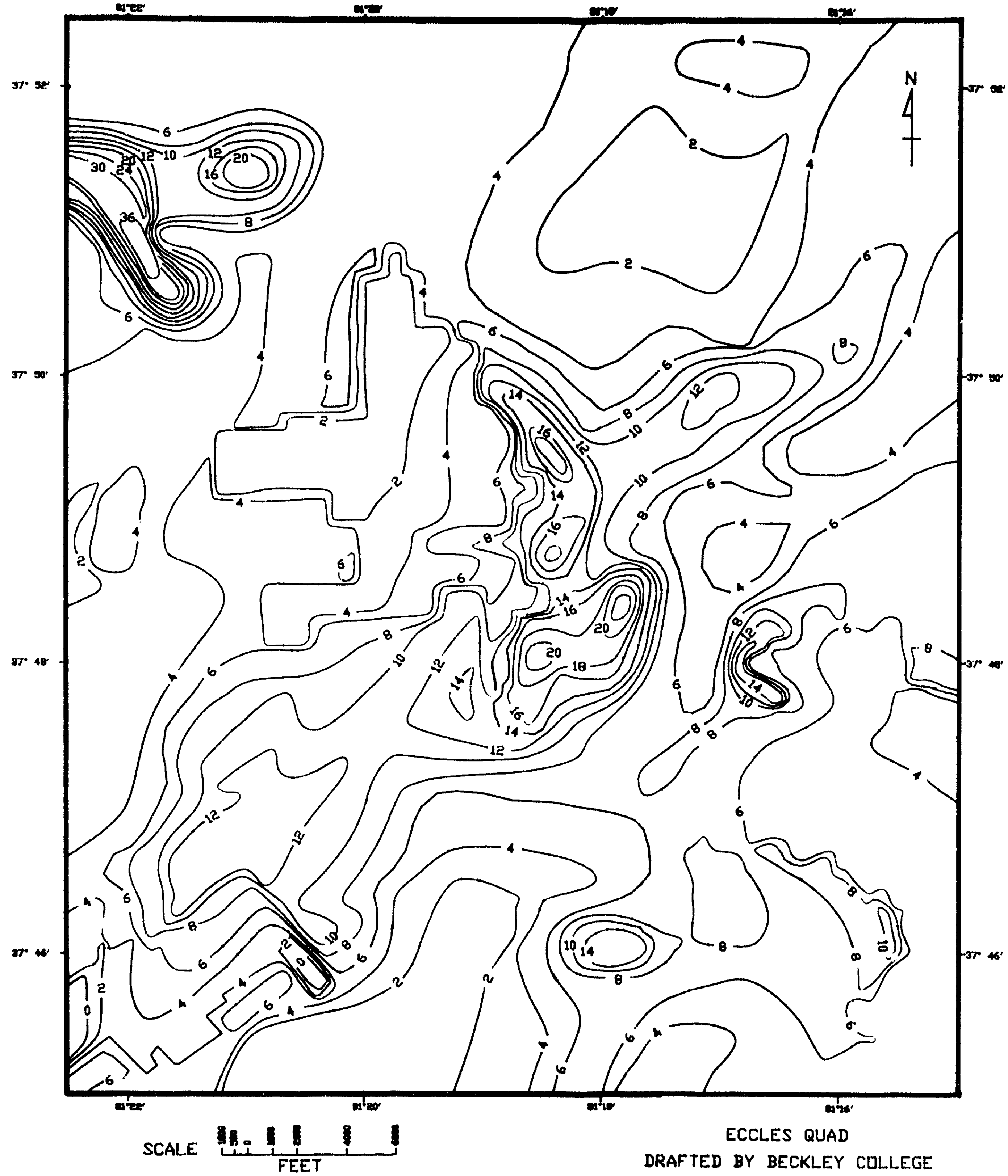


Figure 2.1.27

2.2 Reservoir Analysis

Thesis work at West Virginia University (**Refs.** 3, 6) had covered both of the primary reservoirs in the study area, the Ravencliff Sandstone and "Big Lime" Limestone. As described above, the Ravencliff Sandstone was found to be part of a fluvial system (**Figures** 2.1.2, 2.1.3 and 2.2.1) that extended across the area of several southern West Virginia counties. The Greenbrier "Big Lime" Limestone was deposited as a lime mud on a shallow seafloor, with the reservoir conditions being best developed in shoal areas where wave base churned up the mud.

To geostatistically analyze these reservoirs, the structure and isopach maps were studied in detail. Separate maps were prepared for each formation, and, in addition, numerous isopach maps were prepared covering large intervals, representing long periods of time. These isopachs showed recurrent thinning of numerous units in the eastern portion of the Eccles Quadrangle, as well as the existence of a series of deep wells in the same area. This work confirmed that the Big Lime reservoir in this study area matched nearby oolitic Big Lime reservoirs. Logs were obtained from the Survey and from industry sources to confirm this interpretation.

The Ravencliff Sandstone was deposited at a time when the positive block was inactive and locked in place. Isopach and lithologic maps of the study area and surrounding quadrangles and counties seem to show little or no relationship between deeper structural features and the course of the multiple Ravencliff river systems.

Geostatistical analysis alone would not have been able to identify the nature of the depositional environments of the reservoir formations without additional input from literature sources, but the isopach analysis work on the Eccles Quadrangle was crucial in identifying and projecting areas on the map where additional satisfactory Big Lime reservoir conditions are likely to exist.

Once the nature of the reservoirs had been identified, the geostatistical analysis was highly valuable in identifying areas where extensive diagenesis had destroyed original reservoir conditions. The Ravencliff river channels (**Figure** 2.2.1) had all the hallmarks of having been potentially one of the great reservoirs of West Virginia, at one time. Unfortunately, most of the original porosity has been lost to mineral overgrowths and pore clogging. In the thickest channels, which could have been expected to form the best reservoirs, little porosity remains. The remaining Ravencliff reservoirs (**Figure** 2.1.10) appear to be limited to the thinner, less well-developed channels, where original porosity and permeability were not as continuous. Areas with restricted permeability were isolated from the mineralizing fluids which reached the better parts of the system and ruined much of the reservoir. Even in the thicker channels, isolated areas exist where porosity was locally preserved.

The geostatistical approach was aimed at mapping potential target formations and distinguishing areas where diagenetic damage has ruined the reservoir from the pockets where porosity is likely to remain. This involved studying the isopach data and looking for thinner channels, generally under 100 feet thick, and plotting the show and water records to see where the remaining productive areas were. The isopach data and depositional patterns indicated that there were several levee breaks in the mapped area flanked by deposits that seemed to be gas bearing. Most of the main-channel sands seemed to have lost their porosity, although some porosity may have been preserved at forks in the river or where the rivers jumped from one braided channel course to another.

The geostatistical analysis of the Ravencliff Sandstone focused on the diagenetic alteration of the reservoir, while the approach used to study the Big Lime involved a long-term structural analysis and study of the influence of Basement tectonics on the depositional environment during Big Lime time. The

SIMPLIFIED MAP OF RIVER CHANNELS

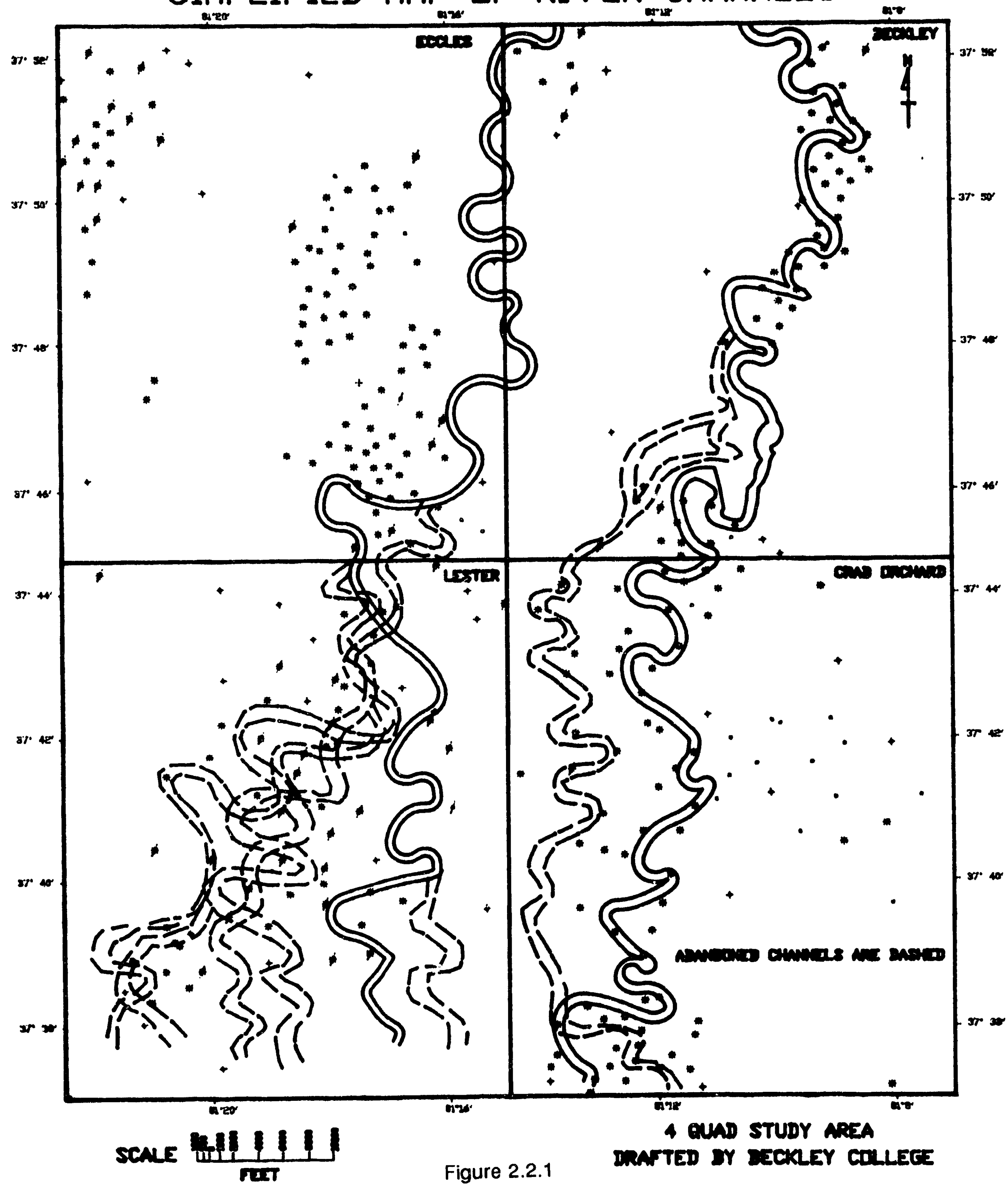


Figure 2.2.1

original Big Lime reservoir (**Figure** 2.1.14) formed above a Basement High. The diagenetic analysis (**Figure** 2.1.17) showed that down-dip areas within the reservoir had been flooded with water, and in other areas, porosity had been destroyed. **Figure** 2.1.18 represents the present day Big Lime reservoir. Most of the Big Lime reservoir was formed on the high or along the western edge of the Eccles Quadrangle, at the limits of the study.

The geostatistical analysis of the coal as a reservoir unit focused primarily on the depositional environment and thickness (**Figure** 2.1.24) of the target coal seams.

Optimized probability maps were also prepared showing the areas geostatistically identified as the best potential reservoir areas for each of the key formations. A composite map was made including all of these units.

2.3 Structure

An understanding of the structural history of the area was important in understanding various depositional environments on this quadrangle through time and their influences on reservoirs, such as the formation of the Big Lime oolites. The deep-seated Basement block (**Figure** 2.3.1) was apparently uplifted again during the deposition of the Beckley Coal seam. The same area that had been a high during Big Lime time was high, once again, when the Beckley Coal was being laid down. The great mass of Beckley Coal was deposited off to either side of this high block.

Structural analysis was important not only in the identification of paleo-highs, but in the location of secondary fracture porosity. Such fractures were considered to be a key potential reservoir element. A remote sensing study was conducted that was closely tied to the geostatistical analysis of structure. This remote sensing study was also used to help select the areas for the geoscience resistivity and geochemical surveys. These studies were designed to test for zones of increased shallow fracturing. Structure mapping also helped explain some wet Big Lime data in a down-dip area where reservoir conditions had once existed, but had been flooded.

The geostatistical approach to structure involved an intense use of isopach maps over a variety of intervals, multiple as well as of single formations, to identify long-term movements and trends; as well as the study of modern surface features to recognize fracture trends that may still be active, open and gas-charged.

A Lineament Density-Fracture Trend Map (**Figure** 2.3.2) was prepared for the Eccles Quadrangle showing all the areas with remote sensing, resistivity, geochemical or topographic indications of fracturing or faulting. Separate maps were then made showing where the key features were located that had affected each of the primary reservoirs. These were used to prepare optimized fracture zone/secondary porosity for each unit (**Figures** 2.1.5 and 2.1.15).

2.4 Summary

Extensive data manipulation and geostatistical analyses and displays were key to this study. The geologic and production engineering datasets were tightly interwoven to produce the final results.

Both small intervals (single formations) and large intervals (formation groups) were isopached to aid in the identification of specific depositional environments which controlled sedimentation at key points in time and to integrate this information with longer term trends and the evolution, development or reactivation of significant structural features, shifting basement blocks, and high or low areas on the seafloor, shore, floodplains or swamps. The thickness data were considered to be the key factors in the

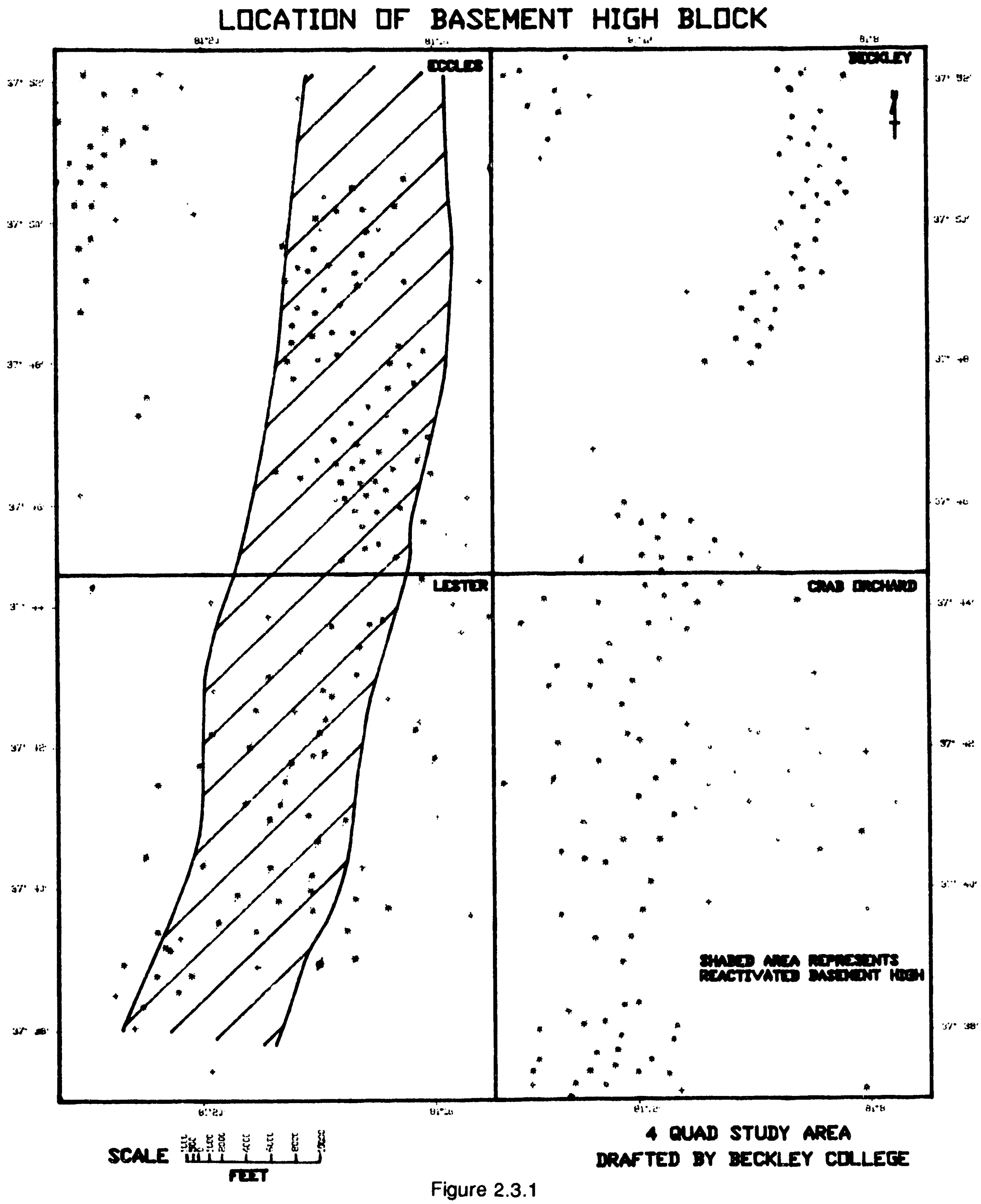
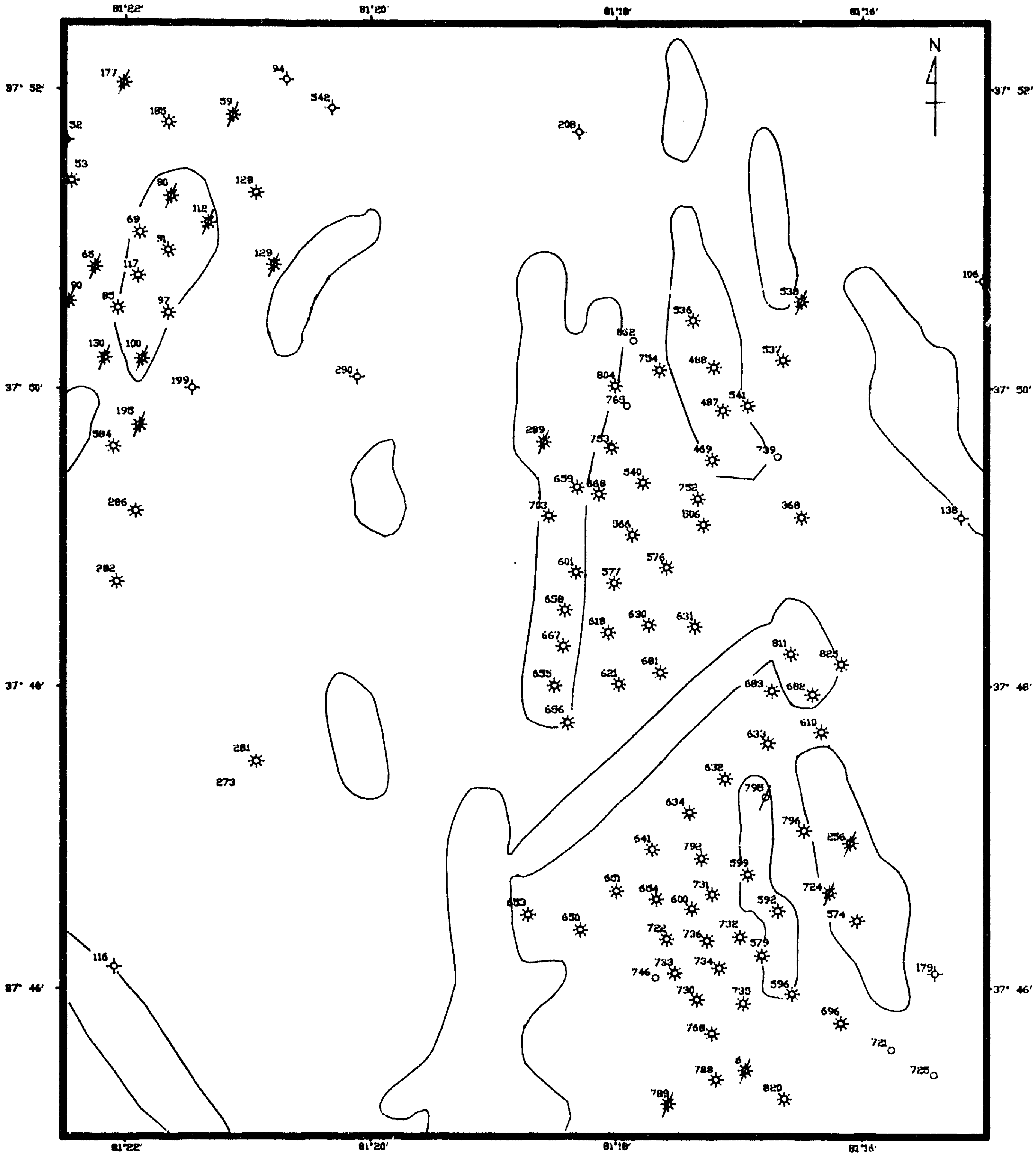

LOCATION OF BASEMENT HIGH BLOCK
ECCLES
BECKLEY
LESTER
CRAB ORCHARD
SHADED AREA REPRESENTS
REACTIVATED BASEMENT HIGH
SCALE
FEET
4 QUAD STUDY AREA
DRAFTED BY BECKLEY COLLEGE

Figure 2.3.1

LINEAMENT DENSITY TREND MAP



SCALE 1000 500 0 1000 2000 4000 6000
FEET

ECCLES QUAD
DRAFTED BY BECKLEY COLLEGE

Figure 2.3.2

calculation of the methane resource for the coal seams. The greatest methane resource is located where the coal seams are thickest.

Structure maps were prepared for approximately thirty formations. These structure maps were then related to the gas show, production and water data. Trend surfaces were contoured for key formations and residual structural anomalies were identified. This information was then crossed checked against the production engineering data for the same formations to see if structure was a controlling influence on production for these units.

Fractured areas were identified by remote sensing, lineament analyses and direct geochemical and geophysical surveys, including resistivity work, and confirmed by seismic lines and cross checked against production data.

In addition to the geologic analyses, computerized geostatistical/geotechnical engineering programs were run to generate decline curves and perform reserve calculations. Logs were used to synergistically identify additional key areas for further geologic study.

The interactive use of simultaneous geologic and engineering input with computer analyses quickly and inexpensively allowed a large number of data sets to be manipulated. Optimized well sites were picked with a minimum of time expenditure.

In the final stage of site selection, the various optimized maps were overlain and combined to produce a composite Component Optimization Map (**Figure** 2.4.1) showing where the best reservoirs exist. These areas contain optimized multiple resources, where structure stands a good chance of enhancing the reservoir quality.

A series of three optimized locations (**Figures** 2.4.2, 2.4.3) were found along the western edge of the Basement high. Two additional optional holes are nearby. All of these locations lie in areas with good reservoir, resource and structural qualities.

3.0 ANALYSIS OF GEOLOGIC AND PRODUCTION DATA AND DEVELOPMENT OF PRODUCTION ANALOGS

The computerized data bases and other information were manipulated extensively in several ways for detailed geologic and engineering analyses.

3.1 Analysis of Structural Data

Information available from the WVGES was entered into the database, manipulated and computer plotted, then extensively hand modified, to produce structure, single formation isopach, and large interval isopach maps to decipher the structural history of the study area.

3.1.1 General Geologic Setting

The Eccles Quadrangle has several small folds overprinted on generally northwest dipping sediments. Pennsylvanian-age sandstones, shales, siltstones, limestones and coals are exposed at the surface. Relief is rugged, with hills generally rising between four- and five-hundred feet above deeply incised stream valleys. Resistant sandstone cliffs are common in the area.

COMPONENT OPTIMIZATION MAP

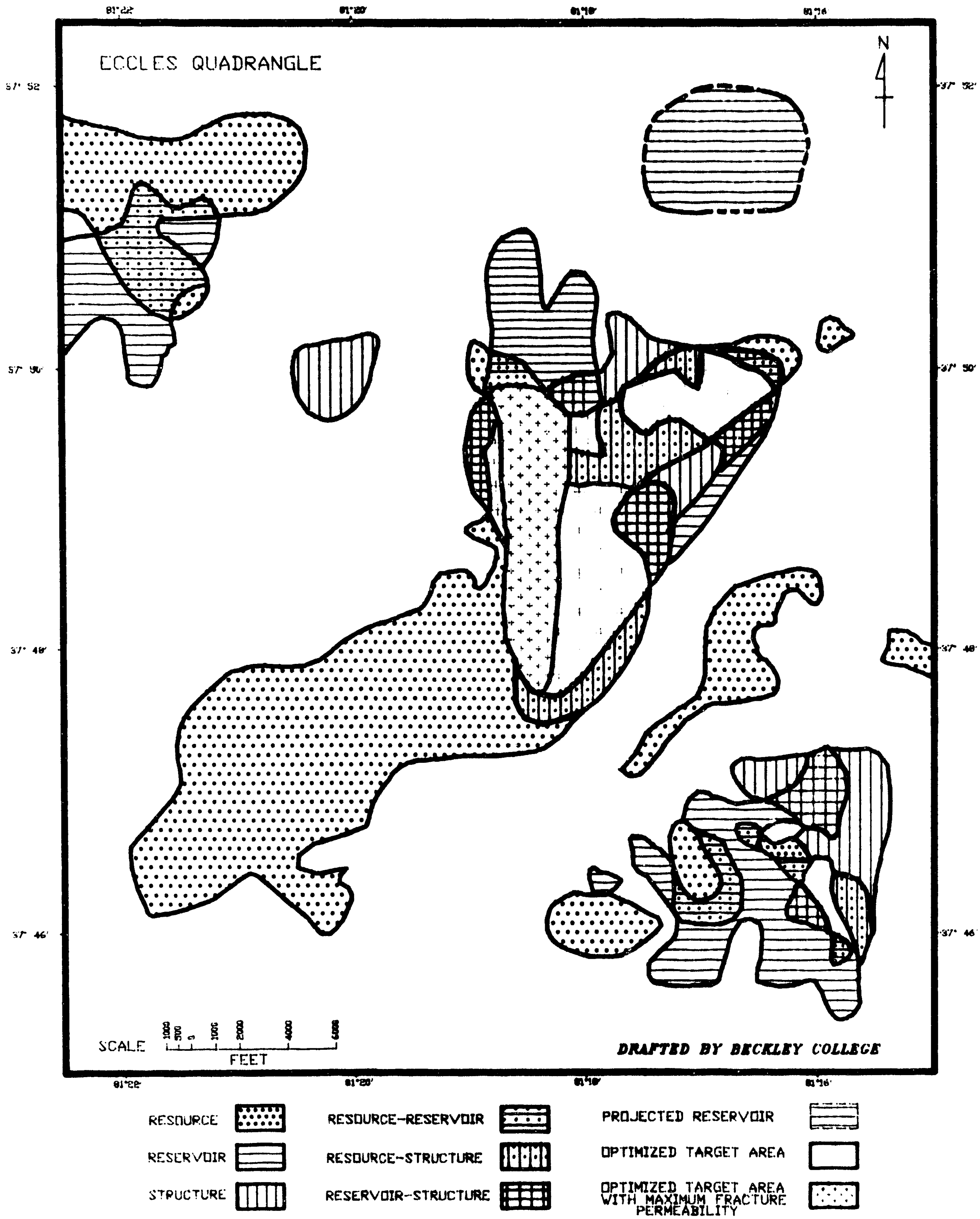


Figure 2.4.1

COMPONENT OPTIMIZATION MAP

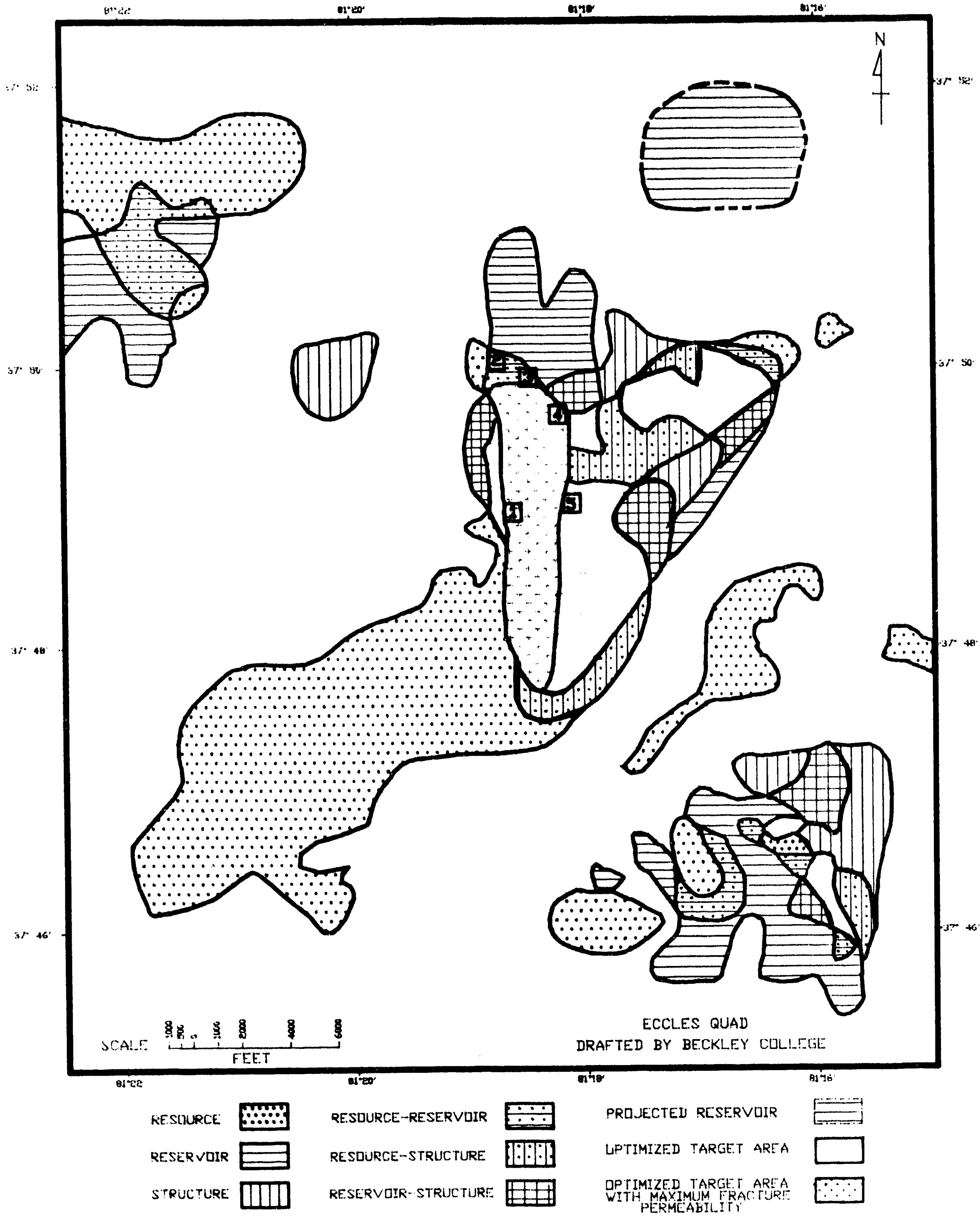
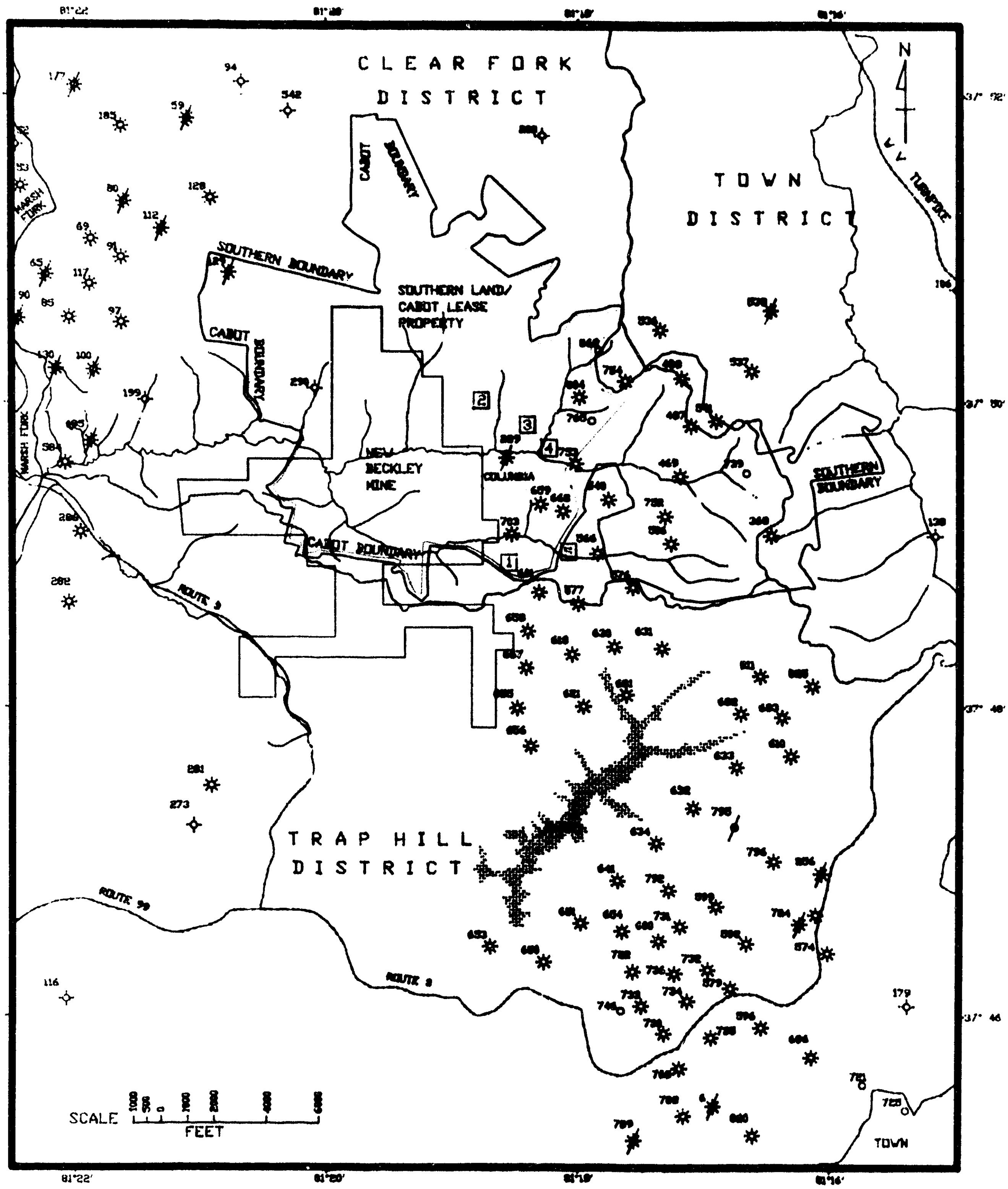


Figure 2.4.2

PROJECTED TARGET DRILLING SITES



NUMBERED SQUARES
REPRESENT PROPOSED TARGET
SITES FOR DRILLING

ECCLES QUADRANGLE
RALEIGH COUNTY, WV
DRAFTED BY BECKLEY COLLEGE

Figure 2.4.3

3.1.2 Regional Structure and Tectonic History

The study area is in a structurally uncomplicated section of southern West Virginia on the midportion of the Central West Virginia Massif. This "massif" was a stable Basement block that remained high with relatively little internal deformation during the late Precambrian and early Paleozoic eras, the period when the basic framework of the Appalachian Basin was being established. As extensional features formed to each side of the massif and Raleigh County, the massif remained relatively high and in place, tilting gently to the north.

3.1.2.1 Internal Structure of the Central West Virginia Massif

The "massif" was probably a relatively stable crustal block that retained, more or less, its original elevation during a late Pre-Cambrian-Eocambrian period of continental breakup and tension, as the late Precambrian continental landmass began to fragment prior to the opening of the Proto-Atlantic Ocean. In North America, a rift system opened, stretching from Oklahoma to the Northern Appalachians. Subsequently, the main area of tension shifted and a continental margin and true ocean formed to the east of the study area. The Raleigh County area remained relatively unaffected by this activity.

The rift system to the west of the study area is known as the Rome Trough in West Virginia. It runs through Logan, Boone, Kanawha, and the counties to the north and west, and may be associated with enhanced fracture porosity in extreme northwestern Raleigh County, but did not produce any noticeable effects in the reservoirs in the study area.

The stable block remained highest in southern West Virginia in the area of the "Southern West Virginia Arch" of Kullander and Dean. In central West Virginia, the block dips to the north.

Seismic evidence shows little relief on the Basement reflector within the massif. While no seismic lines were available directly across the study area prior to the initiation of this project, nearby data in southern West Virginia indicates a generally featureless Basement surface with minor discontinuities, generally at the limits of reliable interpretation. Such minor offsets or breaks on deep reflectors could be genuine small relief fault structures or could be spurious discontinuities produced by velocity changes in the shallow section that processing failed to resolve.

Although there is minimal relief on the present-day Basement surface, the Central West Virginia Massif is theoretically composed of highly disturbed, badly broken crust. It was part of the old Grenville Continent that had been thoroughly shattered during the Grenville Orogeny. During that tectonic episode, circa one billion years, BP, the core of the North American Continent collided with the Grenville Continent. The result was an obductive orogeny, with the Grenville Continent riding up and over the southeastern margin of the "Central Province" portion of the crust of North America. Massive, through-crustal faults stacked the edge of Grenvillia on itself like shingles, forming a Himalaya-style mountain range through the Appalachian states. The results probably formed one of the greatest mountain ranges in the history of the world.

The Grenvillian faults appear to have cut completely through the crust to mantle level. The deformation and faulting were most extreme near the front of the collision zone through Kentucky, Ohio and Canada, but numerous through-crust faults apparently exist in the Basement beneath eastern Kentucky, West Virginia, Pennsylvania, New York and eastern Canada, east of the Grenville Front. Seismic lines with good data quality displaying features within the Basement in these areas indicate the possible presence of great fault planes dipping to the east below the Paleozoic sediments in much of the Appalachian area.

3.1.2.2 Effects of the Grenville Faults on the Shallow Section

At the close of the Grenville Orogeny, these faults tended to lock in place, but they have continued to be the sites of zones of weakness up through modern times. Any break that has penetrated through the entire crust will offer an opportunity for relief when the crust is later subjected to regional tensional or compressive stresses.

As a shattered, imbricated crust is subjected to compression, the hanging walls (Basement blocks to the East) will tend to rise, causing slight shortening and crumpling or fracturing in the sediments above the break. A seafloor above such a compressive zone would be expected to arch or shoal. Small thrusts or folds may even form in the sedimentary cover if the stress is sufficiently great. Under tension, the hanging wall will tend to relax, creating sags or lows, deeper-water facies, local depocenters and forming or reopening fractures above the Grenvillian break.

Alternating periods of local compression and relaxation along a Grenvillian feature can create a complicated picture of sedimentary thicks and thins through time above the fault. For the duration of a compressive period, the east side (hanging wall) would appear as a high and would generally tend to accumulate a thinner clastic sedimentary section or might even experience erosion. In a carbonate environment, the east side of the fault could show up as a shoal area where oolitic banks, reefing, or karst features might form.

Under a local tensional episode, the hanging wall would tend to subside, leaving the west side of the fault as a subtly higher block with depo-trends reversing to the alternate side of the crustal break. In this manner, through time, a series of alternating features could form, concentrated along the fault trace, possibly switching sporadically from thicks to thins back and forth from one side to the other of the Basement break.

Over the great span of geologic time from the Paleozoic to the present, movements on the Grenville breaks have been recurrent, and occasionally may have been frequent. The Rome Trough opening indicates that a great tensional episode occurred several hundred million years after the Grenville Orogeny. The Taconic, Acadian and Alleghenian collisions along the East Coast probably produced compression along these features, elevating the hanging wall (east) block slightly. These subtle movements seem to have controlled drainage features or current patterns locally in the Appalachian Basin at various times during the Paleozoic and could cause a stacking of drainage courses or shoreline standstills in the same areas at different periods.

Relaxation in the intervals between the collisional episodes and during the Mesozoic, when rifting affected the east coast, could have caused tension at the same locations, dropping the wall slightly, and tending to produce unusually thick sediment accumulations on the east side of the faults. Some of the Mesozoic intrusives in the area seem to occur along fracture systems that date back to the Grenvillian events, and many modern drainage patterns follow a "Grenvillian" trend.

Such shifts allowed the Appalachian Basin area to adjust to changing stress fields on a continental, as well as local scale, and produced concentrations of unusual lithologies and fracture zones in the sediments above the fault zones in the massif. The minimal relief at the Basement level in Raleigh County indicates that cumulative movements during the Paleozoic produced only minor offset. This may be due in part to compressional effects being largely offset by tensional subsidence over the long period of time, with an overall negligible net effect.

Although the net offset is minor, individual movements on these through-crust faults may have been significant at various times, and the recurrence of movement had a tendency to fracture and then refracture the sediments which accumulated above the zones of weakness. The episodic nature of the reactivations ensured that the fracture systems would stay open over long periods of time.

Most of the Grenvillian features in this area tend to run North-South, parallel to the Grenville structure zone. Extensive North-South oriented drainage east of the Grenville Front through much of Southern West Virginia testifies to the persistence and effectiveness of the Grenvillian-related fracturing. Many of the faults have moved recently enough to have fractured the shallower beds, exerting control on modern drainage. In addition, a significant number of oil and natural gas fields in West Virginia, Pennsylvania and Ohio run essentially North-South, often with sharp western boundaries, presumably along Grenville-related fracture trends.

3.1.2.3 Interaction of the Basement and Shallow Section

Despite the lack of seismic data for this project, the presence of a Grenville-oriented Basement block in the study area (**Figure** 2.3.1) can be inferred through several lines of evidence. A narrow positive structural feature appears to run nearly North-South from the southwestern portion of the Lester Quadrangle through the central area of the Eccles Quadrangle.

This Basement block seems to have acted as a positive feature at various times during the Paleozoic, and to have caused recurrent shallowing on the Paleozoic sea floor. The deep targets in this area display closure over the high, with several tests to the Tuscarora or Oriskany levels along the trend on the Lester and Eccles Quadrangles. This closure is apparently due to early movements of the Basement. In the absence of seismic data, this is the deepest, earliest indicator of structure at depth. Several later Paleozoic features follow the same trend as the Silurian and Lower Devonian features.

Most of the Paleozoic tectonic history of Raleigh County was very quiet. There was little obvious structural disturbance created locally during the opening of the Rome Trough or during the Taconic or Acadian Orogenies. The most significant change was coarsening of the sediment influx during the orogenic events. The Basement block may have been reactivated during these orogenies, but no major movements are detectable.

Following the deposition of the shallowest coal/clastic units at the surface, the geologic history of the area remains a blank until the Alleghenian Orogeny. During that orogeny, the stress regime changed significantly, and a series of Southwest-Northeast folds formed at approximately N35E, an orientation quite different from the Grenvillian trend that had previously dominated the area.

A significant broad-topped anticline crosses the Lester Quadrangle on top of the Basement high, but dies out to the northeast off the Basement trend (**Figure** 3.1.1). North of this anticline, two small domes follow the Basement trend across the Eccles Quadrangle. A second anticline extends from Beckley onto the Crab Orchard Map, but this structure also dies out into a low.

It appears that the Paleozoic cover in the area has detached and slid relatively freely across the areas where the shales and decollement units are thickest. The allochthonous sheet piled up over the Basement high where the beds thinned. Since the Grenvillian features were at a sharp angle to the direction of Alleghenian transport, the resultant folds were discontinuous with the axes dying out in the low areas.

The Basement was not directly involved in the Alleghenian folding, and does not appear to have been rising or falling as the anticlines formed. The deep influence on the Alleghenian anticlines was a

STRUCTURE ON TOP OF THE BEREA

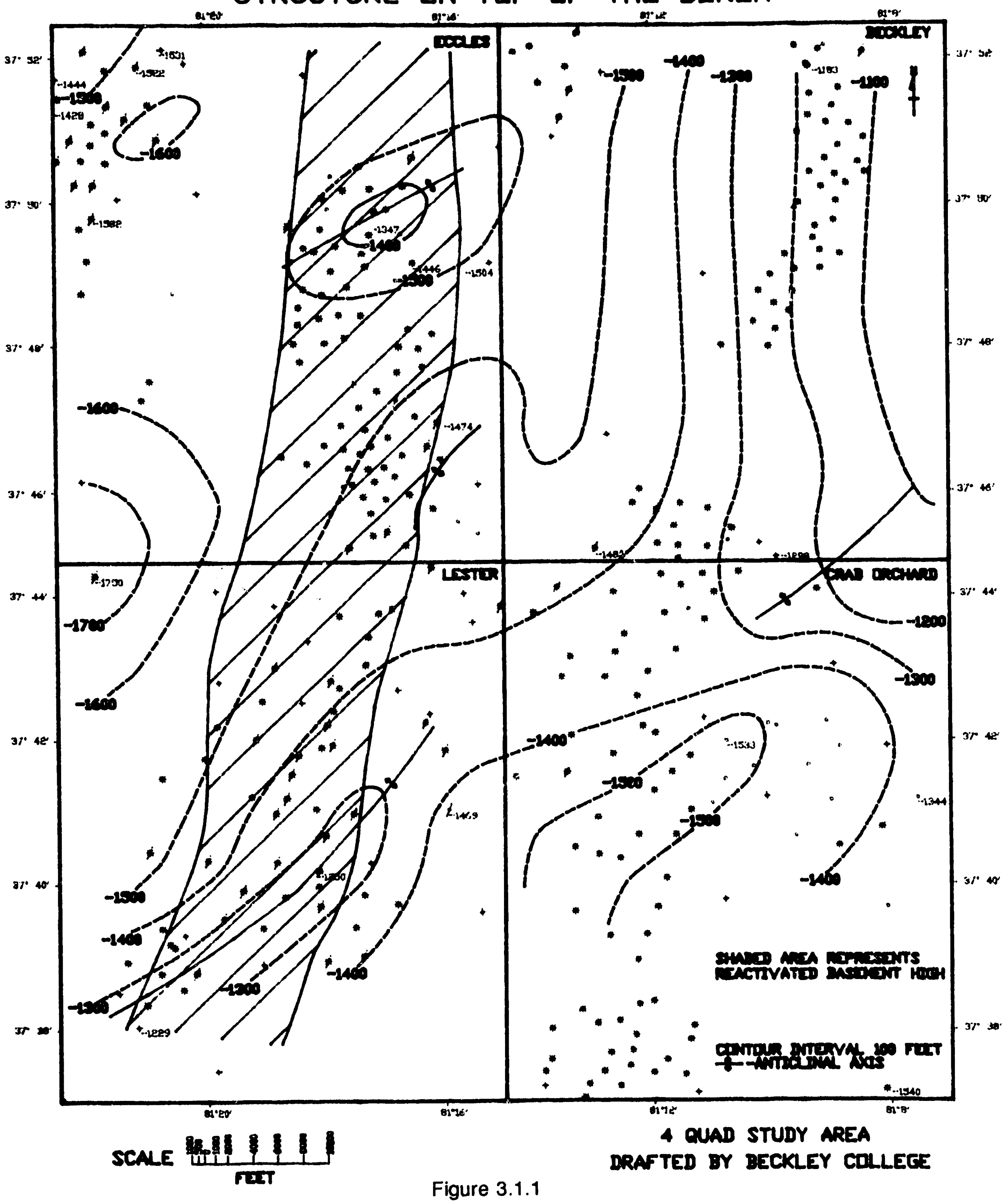


Figure 3.1.1

subtle one, probably reflecting the difficulty of folding thick beds in the lows versus thin beds over the crest of the paleo-highs. The shallow folds are best developed across the paleo-highs. The difficulty of folding thicker beds in the basins caused some unusual features, including possible faulting, in those areas.

Following the Alleghenian Orogeny, this area, along with most of the rest of West Virginia, has traditionally been considered to have been stable and tectonically quiet; however, complex local structural features, fracture patterns and drainage trends indicate that many of the Grenvillian features have periodically been reactivated.

3.1.3 Structure Mapping

Structure and isopach maps were prepared from the Berea formation up, showing a series of structural highs, breaks in slope and thins on the isopach maps across the Basement block. Lithologic studies show facies changes in the same area.

These shallow data imply the existence of a persistent positive area through the Lester and Eccles Quadrangles throughout much of the Paleozoic. The location coincides with the area of closure in the Silurian and Lower Devonian targets.

There are hints in the data base that another active Basement block may cut along the east edge of the Beckley and Crab Orchard maps,however, this cannot be stated as a certainty without additional study and an expanded data base to the east.

3.1.3.1 Structure At The Berea Level

Figure 3.1.1 shows the structure at the Berea level for all four study area quadrangles. Structure contours indicate a regional dip to the northwest complicated by the influence of the Basement high. A depression shows up to the east of the high. The Berea structure contours run southwest-northeast until they reach the high, at which point they bend to the north, then cut across the high and drop to the south into the low, east of the positive block.

Small domes occupy the southeast corner of the Eccles Quadrangle and the east-central portion of the Eccles map. These same highs will show up with slight variations on several other formations. A low exists on the southwest corner of the map. Around the Irish Lick Knob area in the northwest corner of the Eccles map, the beds are disturbed, apparently tightly crinkled.

North-South structure contours showing a steep dip to the west dominate the east edge of the Beckley Quadrangle. At the Berea level, the low in the southwest corner of the Beckley Quadrangle is quite evident.

An anticlinal axis extends into the northeast corner of the Crab Orchard Quadrangle. Most of the southern two-thirds of that map is dominated by a syncline, possibly explaining why there has been very little production from anything other than the Ravencliff in that area. Most of the deeper well tests there have had no gas. The beds through that area may be filled with water, if there is any porosity preserved. The Ravencliff channel system which crosses the study area appears to be more productive on the Eccles and northern Crab Orchard Quadrangles than it is south of the town of Crab Orchard, where structure is lower and water is more likely.

The Lester Quadrangle structure is dominated by the Basement high. Two domes in the eastern half of the map lie on the fault block.

3.1.3.2 Structure At The Big Lime Level

The Big Lime structure, **Figure** 3.1.2, resembles that at the Berea level. The same domes show up, although the shape and high point on the northern dome on the Eccles Quadrangle has shifted somewhat and the crinkled pattern around Irish Lick Knob is quite different. The sag between the two domes on the Eccles map is marked by a synclinal axis.

The Big Lime lithology indicates there was shoaling above the Basement block during Big Lime time indicating that this structural feature was active at the time of Big Lime deposition.

3.1.3.3 Structure at the Ravencliff Level

Figure 3.1.3 shows the Ravencliff structure for the four maps. This structure is similar to that for the deeper Big Lime and Berea formations.

3.1.3.4 Structure On The Coals

Detailed coal structure maps were prepared for the Beckley and Eccles Quadrangles. **Figure** 2.1.20 shows the Pocahontas #3 Coal Structure. The regional strike shows up clearly, however, the effects of the Basement high can be seen in the eastern Eccles area where the contours first swing toward the north on the west flank of the structure, then swing around toward the east over the crest of the structure.

The data on the Pocahontas Coal is limited. The depth of the seam has generally inhibited plans to mine this seam on the Eccles Quadrangle. The control is much better on the shallower Beckley Coal which is shown in **Figure** 2.1.19. This seam shows a much more complex structure which probably simply indicates the increase in control, rather than a real increase in structural complexity. If the control was as complete for the Pocahontas #3 Seam, that structure would probably appear just as complicated.

The Beckley Coal also shows the obvious regional strike, but the contours contort in the eastern portion of the Eccles Quadrangle over the Basement high and along the eastern edge of the Beckley Quadrangle where the existence of a second Basement high can be inferred.

The coal structure maps were prepared by Ed Rehbein, consultant to the project, without any prior knowledge of the Basement features or structure on the deeper formations. Nevertheless, his maps show many of the same features recognized at deeper levels. The Beckley Coal structure map even shows a dome along the eastern side of the map, near the domes at the Berea and Big Lime levels, but slightly further east. Individual quadrangle maps of the coal structure are presented in **Appendix A**.

3.1.4 Trend Surface Analysis Of Structure Mapping

Big Lime production is especially dependent upon structural features which were highs or shoal areas at the time of deposition. To assist in deciphering the location of these original Big Lime shoals, a trend surface analysis was performed on the Big Lime structural data for the Eccles Quadrangle. The Big Lime structure map for the Eccles Quadrangle was used as a base for the study.

The detailed Big Lime structure map was converted to a first order trend surface by deriving a simplified plane surface representing the regional Big Lime strike and dip. This plane was projected across the Eccles map and actual structure contour data points were compared to the regional trend surface. Control well formation tops that stood above the regional plane were assigned positive values

BIG LIME STRUCTURE (FEET BELOW SEA LEVEL)

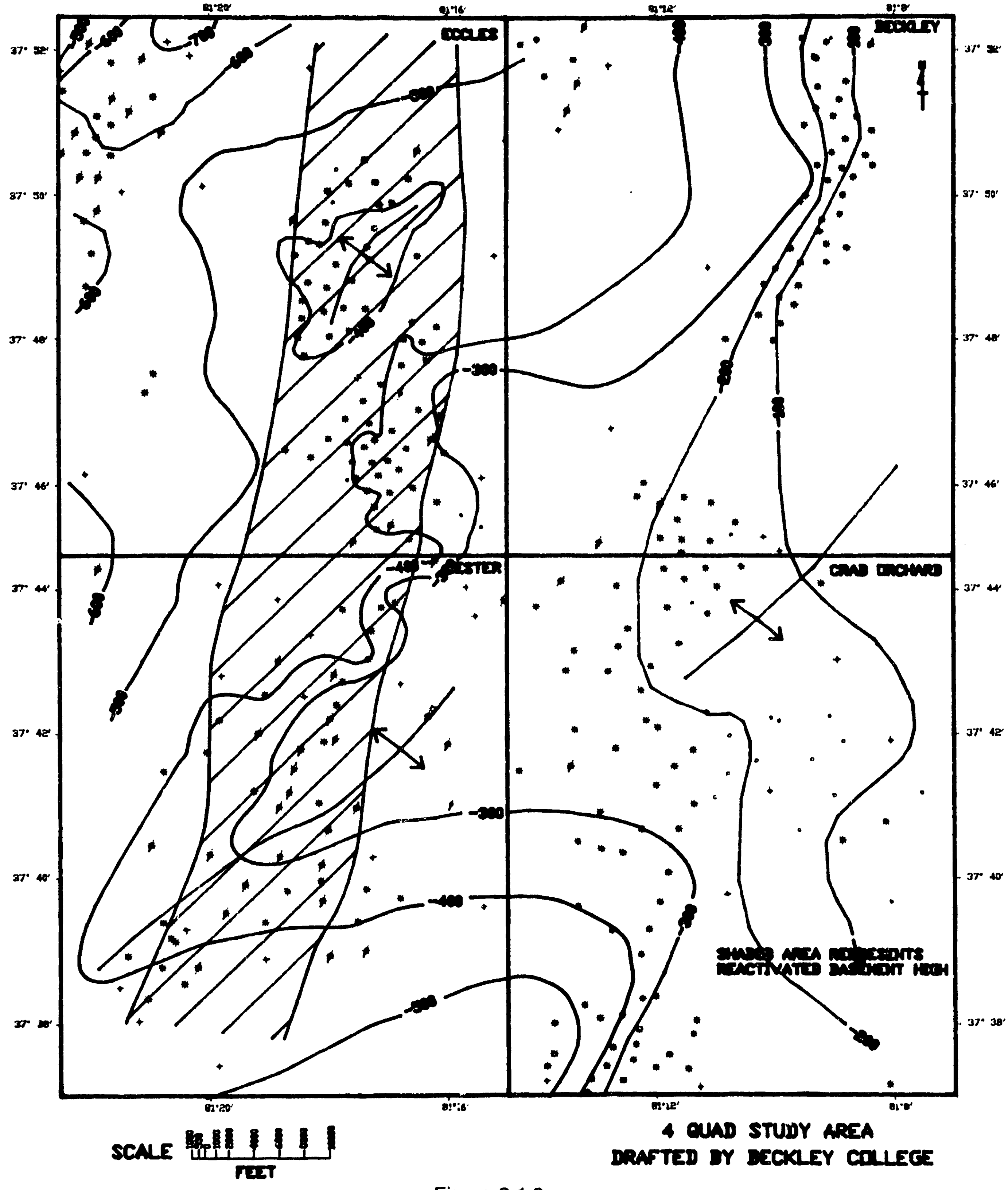


Figure 3.1.2

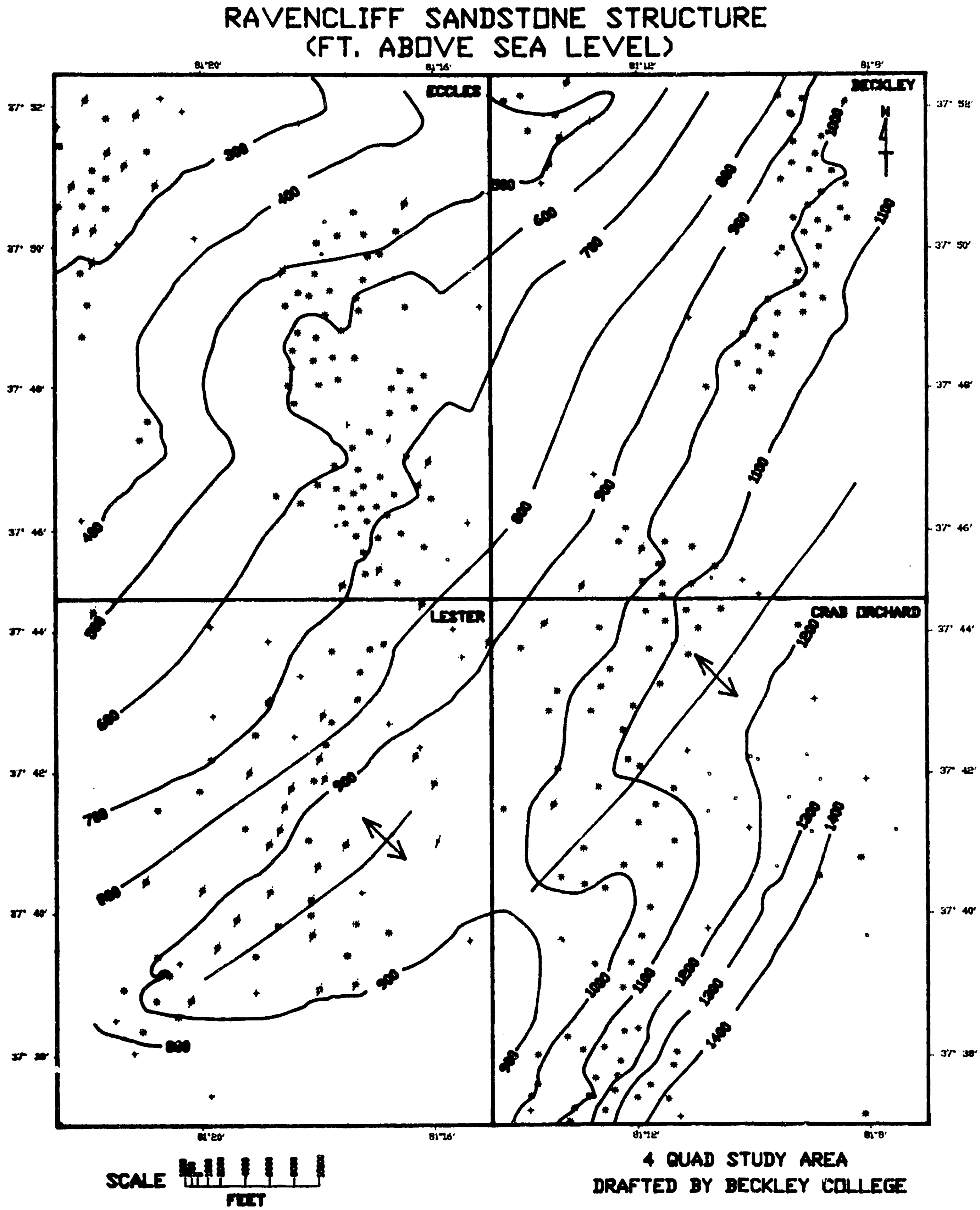

RAVENCLIFF SANDSTONE STRUCTURE
(FT. ABOVE SEA LEVEL)
ECCLES
BECKLEY
LESTER
CRAB ORCHARD
SCALE
FEET
4 QUAD STUDY AREA
DRAFTED BY BECKLEY COLLEGE

Figure 3.1.3

and their elevation above the regional base was noted. A large anomalously high area in the region of the recurrently positive Basement block stood out and was interpreted as a probable area where shoals had formed and where oolites may have developed.

Areas near the shoals with depths below the regional trend were interpreted as possible channels between the shoal banks that could have fed fresh water and channeled energy into the area. Currents moving through these channels would have agitated the oolites and led to the enhanced porosity on the shoal areas.

There are two apparent domes at the Big Lime level, but only one of these, the northern dome, clearly stood well above the regional trend surface. This may explain why the northern dome appears to be far more productive than the southern feature.

Figure 3.1.4 shows the Big Lime Positive Residual Anomaly Map, a graphic representation of the recurrently tectonically active areas on the Eccles Quadrangle. Isolated spots have values almost two hundred feet above the regional trend. Most of the northern dome is in excess of one hundred feet above the regional surface. The southern dome, by contrast, rarely reaches 100 feet above the trend surface. This helps to explain the greater productivity on the northern feature where the water was apparently shallower and the oolites would have been tossed around with greater intensity. Some of the most productive wells on the southern dome are located at the north edge of the high where the highest point on the dome occurs.

Anomalies can only be mapped at data points. It is possible that a third high exists in the northeastern corner of the map. It has not have been identified on this map since there is no well control in this area so far. The apparent shape of the Basement block and the pattern of the positive anomalies suggests a high likelihood that there may be another such feature on the north portion of the Grenvillian-trend Basement high.

3.1.5 Analysis Of Structural Control On Gas Production

As shown in **Figure** 3.1.5, many subelements contribute to the influence that structure can have on oil or gas production. Several units in this area like the Tuscarora, Oriskany and Big Lime produce on top of paleohighs. Successful prospecting for these units involves a good understanding of structure.

Structure at the Berea and Weir levels shows two highs at an angle to the Alleghenian-age folds in approximately the same position as the Tuscarora and Oriskany highs. Large-interval isopachs from these formations to shallower beds with extensive control confirms that these areas were positive during Upper Devonian time. Deeper basinal areas lie along the boundary area between the Eccles and Beckley Quadrangles and between Lester and Crab Orchard. The town of Crab Orchard is located at one of these depocenters. The Berea has not been productive in the study area, and the Weir production is too limited to relate to structure.

Structure was critical for reservoir formation in the Big Lime Limestone. The reservoir in this unit owes its existence to shoaling during the deposition of the Big Lime. These shoal areas allowed the lime muds to be tossed around and rolled into oolites or pellets. As described by Kelleher (**Ref.** 3), the pellets contained aragonite, which subsequently was altered to calcite. The alteration resulted in the formation of intragranular porosity which has since formed a significant reservoir on the paleohighs. Intergranular porosity also contributes to the quality of the Big Lime reservoir.

The oolites on the Big Lime shoals appear to form the best reservoirs on the Eccles Quadrangle. Other units like the Ravencliff are predominantly stratigraphic plays. There is no obvious relationship

BIG LIME STRUCTURE ANOMALY

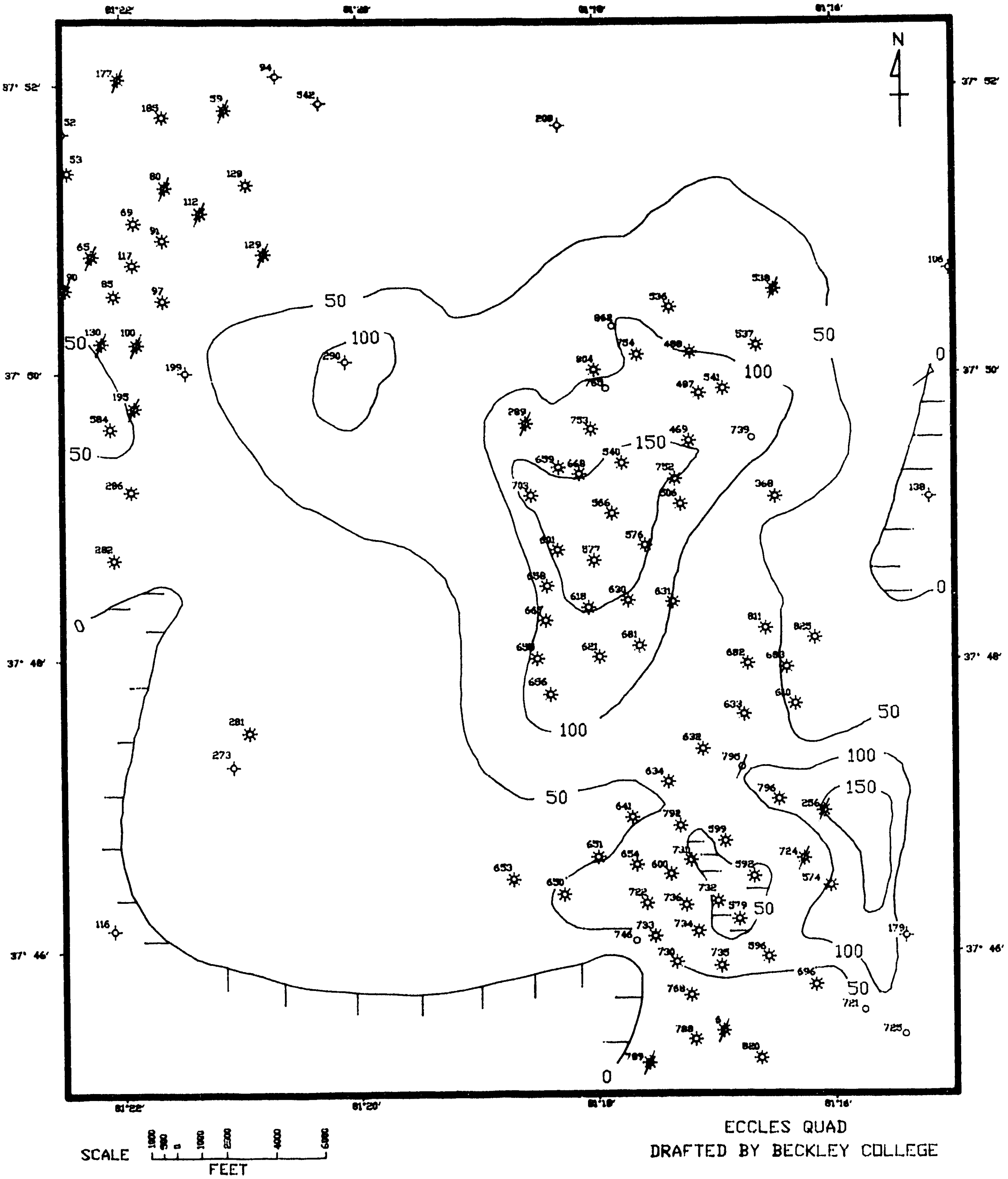


Figure 3.1.4

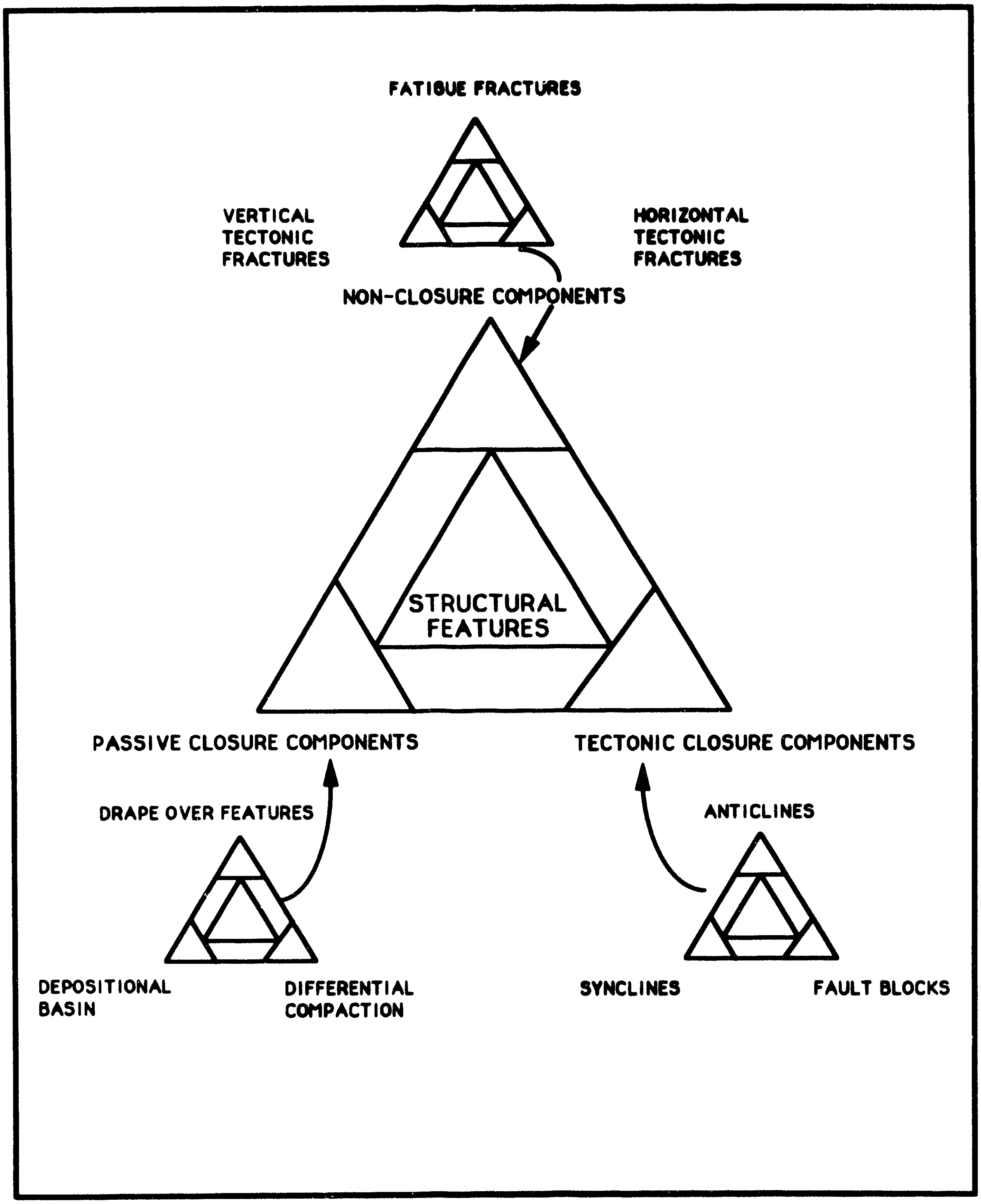


Figure 3.1.5 Ternary Diagram of Components of "Structure"

between Ravencliff or Maxton production and paleo or modern structures. The largest Ravencliff gas field in the study area is in the "F" Channel (see **Figure** 2.1.2), on a midslope area, not related to any structural feature. Gas accumulation in these units was controlled by lithology. Migration through hese units and the formation of traps apparently was influenced primarily by lithologic factors, rather than by Appalachian or earlier folding or faulting.

The Maxton units are not well understood. This family of sands does not seem to form a good reservoir throughout most of this area and has not been extensively explored or even accurately correlated. Many so-called "Maxton" units may actually be deep portions of incised Ravencliff channels. The Maxton may have had good porosity locally and lost it during cementation, clay filling, recrystallization and mineralization.

3.2 Analysis Of Reservoir Isopach Data

Lithologic and isopach data provide clues to periods when Grenvillian-age Basement blocks moved and to when they were quiescent. The evidence strongly implies that activity was episodic and that the area was not under continuous compression.

Lacking seismic evidence, much of the data on early movements of the Basement is based on isopach evidence. Wells penetrating the formations below the Big Lime were too sparse to isopach meaningfully, other than to identify the general area of the Basement high.

3.2.1 Isopach Information For The Big Lime

The interpretation of the Big Lime depositional environment is based on both lithologic and isopach evidence.

Production from the Big Lime in West Virginia has typically been explained as coming from limestones laid down in very shallow water. At shallow depths near wave base, the energy level is higher and lime muds can be rolled up into oolite pellets with the chance for porosity development between grains, or within the rolled up ooids. In other cases, organic mats or low reefal growths may build up in a third model, the shallow-water limestones were dolomitized with the development of significant, sometimes cavernous, porosity.

In southern West Virginia, the model for Big Lime production is from oolites. Kelleher (**Ref.** 3) has recently completed an unpublished Masters Thesis at West Virginia University documenting the Big Lime environment of deposition for a nine quadrangle area immediately south of the Lester and Crab Orchard Quadrangles.

In the area of Kelleher's (**Ref.** 3) work, the Big Lime is productive along the crests of a series of paleohighs on the seafloor. The pattern of deposition swings around to a different orientation to the north and the highs die out or merge into a single high trend. A broad shoal area trends across both the Lester and Eccles maps. This formed as the Basement shifted during Big Lime time, reactivating a recurrently positive area (**Figure** 2.3.1). Isopach work on the Big Lime (**Figure** 2.1.12) shows thinning along the high.

Isopach information implies that the high persisted for some period of time after Greenbrier/Big Lime deposition ended. The feature continued to have a subtle expression, but the Little Lime and Pencil Cave units both appear to thin cross this structure.

3.2.2 Isopach Information For The Maxton

Isopach maps for the Maxton family of units (the Upper Maxton, Maxton proper and Lower Maxton) are difficult to decipher, due to extensive correlation problems and misidentification of the three units in the data base. It is not obvious if the three units are affected by the deeper structures.

3.2.3 Isopach Information For The Ravencliff

By Ravencliff time, the Basement seems to have stabilized. The Ravencliff fluvial channels (**Figures** 2.1.2, 2.1.3, and 2.2.1) follow essentially straight paths from the north directly through the study area without any deviation as they cross the mapped quadrangles. The largest river channel in the mapped area, Wrightstone's "D" Channel (**Refs.** 5, 6), shows no twisting, turning or broadening as it reaches the area of the positive Basement high. An isopach map (**Figure** 3.2.1) does not indicate any thinning over the central area of the maps.

The path of the "D" Channel seems to parallel the much smaller "F" Channel, which lies to the east and which also seems to follow an essentially straight course across the maps, disregarding the presence of features that should have influenced the drainage if the structures had been active at this time.

While the "D" Channel sands were presumably deposited by a large river that might have had the power to cut across minor structural features, the "F" Channel was deposited by a much smaller and less powerful stream and could have been expected to deviate around any subtle positive blocks or features. The straightness of the "F" Channel locally, as well as the long, straight courses of all the channels on a regional basis, cutting directly across the Grenville trend, strongly suggests that the Basement was stable during the period when the Ravencliff was deposited.

3.2.4 Isopach Information For The Coals

The Basement block seems to have been reactivated during the period of the coal deposition. The Beckley Coal isopach thins to zero over the area of the Basement, Tuscarora, Oriskany and Big Lime highs (**Figure** 2.1.21). The Pocahontas #3 Coal (**Figure** 2.1.22) has not been cored in this critical area, but it too may pinch out across the high. It appears that the basins on the flanks of the Big Lime high had been a flat floodplain during Ravencliff time, but then dropped again, becoming the locus for major, rapidly subsiding swamps during the Carboniferous coal period.

The Beckley Coal thickness decreases from between ten or twelve feet to zero in just a few thousand feet at the edge of the high, implying a relatively rapid subsidence of the swampy areas or a rise of the high block as the coal accumulated.

Following the end of the period of coal deposition, the geologic history of Raleigh County is a blank until the Alleghenian Orogeny. This episode of deformation produced a set of folds at a new angle, roughly N35E. The Alleghenian structures cut across, and seem to ignore the Grenville-related Basement trends.

There do seem to be some twists, turns and offsets on the shallow Alleghenian structures as they cross the deeper trends. It becomes difficult to identify single, obvious shallow Alleghenian axes as the younger folds cross the paleobasins along the Lester-Crab Orchard boundary or in the western portion of the Beckley Quadrangle. (See the Isopach and structure maps on Eccles and Beckley Quadrangles in **Appendix B**).

RAVENCLIFF ISOPACH

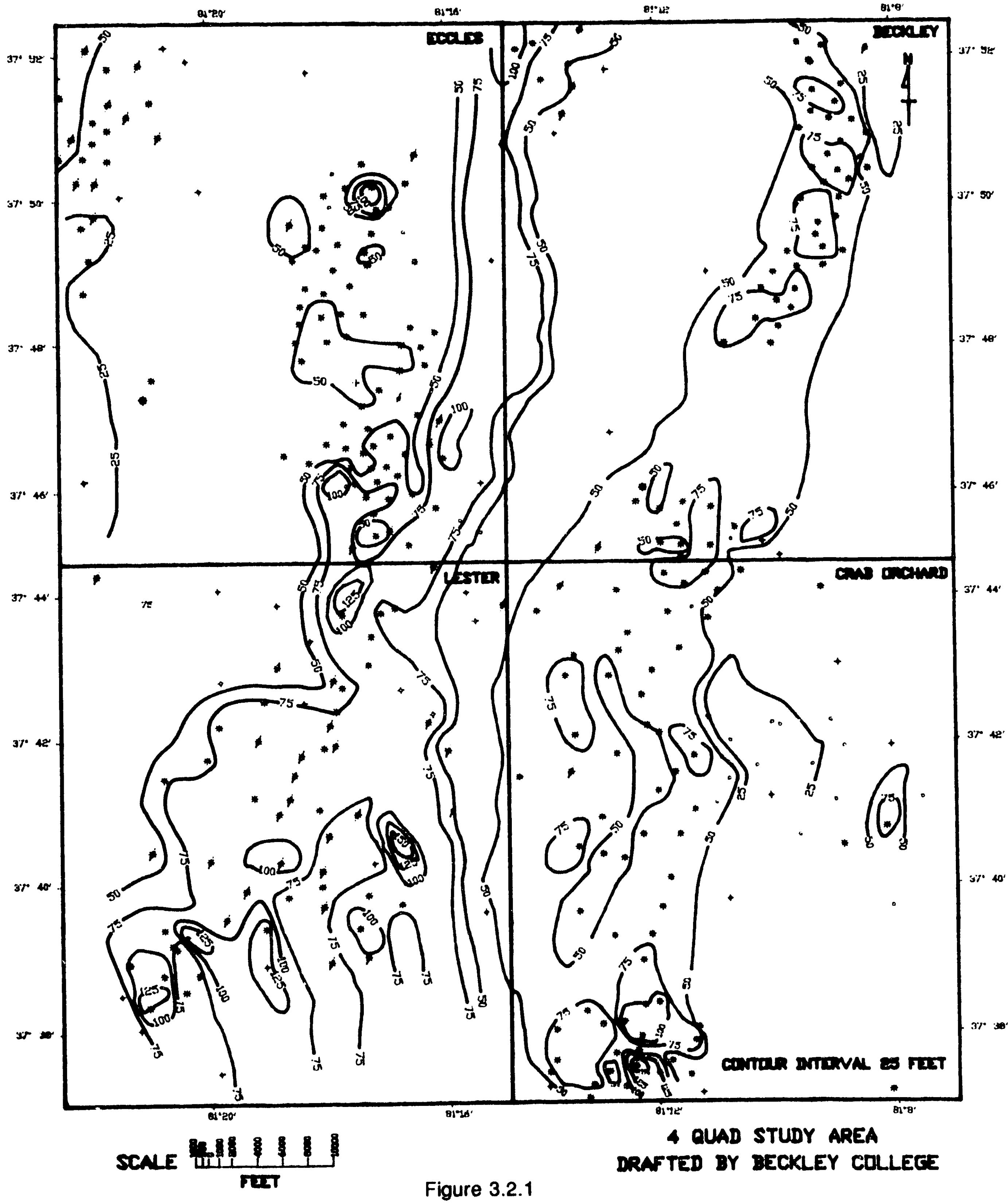


Figure 3.2.1

The Basement was not involved in the Alleghenian folding, and does not appear to have been rising or falling as the anticlines formed. The influence of deep structure on the Alleghenian anticlines was a subtle one, probably reflecting the difficulty of folding thick beds in the lows versus thin beds over the crest of the paleohighs. The shallow folds are best developed across the paleohighs. The difficulty of folding thicker beds in the basins caused some unusual features, including possible faulting, in those areas.

Following the Alleghenian Orogeny, this area, along with most of the rest of West Virginia, has traditionally been considered to have been stable and tectonically quiet, however, complex local structural features, fracture patterns and drainage trends indicate that many of the Grenvillian features have periodically been reactivated since the end of the Paleozoic.

3.3 Analysis Of Reservoir Lithology

The potentially productive reservoir units for the test well are discussed below.

3.3.1 Berea Formation Lithology

The Berea is a wide-spread sand that sits atop an unconformity surface at the top of the Devonian Shale section. The Berea is productive across much of West Virginia, but has not even had a show reported on the quadrangles studied for this report. It is a fine to very fine grained, tightly cemented sandstone.

Twelve unsuccessful holes were drilled on the Eccles Quadrangle targeted to the Berea. Seven of these were located in a complexly folded or faulted area around Irish Lick Knob in the northwest corner of the quadrangle. None reported any shows or flows.

The Lester Quadrangle has five dry Berea wells. These are spread across the map, including sites on the Grenville-related high, on the Alleghenian fold and in structural basins. This lack of success with such a mix of tests tends to discourage additional Berea exploration in this area.

One test well was specifically targeted for the Berea on the Crab Orchard Quadrangle, south of Beckley. The Berea was apparently too tight to serve as a reservoir at that location.

With this poor drilling success record and in light of the depth spread between the Berea and the coals, the Berea was not considered as a major target for this Multi-Strata Test program.

3.3.2 Weir Sandstones And Siltstones Lithology

The Weir units are another widespread series of sandstones that are productive across much of West Virginia. In the eastern counties, they mark part of the great deltaic complex (Boswell and Jewell, **Ref.** 1) that extended out to the west from the Acadian-age mountains that were rising in Maryland and Virginia. Similar deltas lay to the north and south, fronting mountains from Pennsylvania on into New England and from the Carolinas to the south.

In western West Virginia, Boswell and Jewell (**Ref.** 1) have identified the Weir as a deeper-water, submarine fan deposit. The Weir units vary from very fine to fine grained, tightly cemented sandstone to coarse grained siltstones.

The work of Boswell and Jewell (**Ref.** 1) does not extend into Raleigh County, but the Weir sands in this county probably belong to their "western Weir," deep-water facies. These sands represent various deep water fan and turbidite complexes. Similar deeper-water units are productive in several of the western counties of the state.

The Weir has been productive at a number of locations across the quadrangles investigated in this report. Weir shows and producing wells are located on every quadrangle except Beckley.

The Beckley Quadrangle has had three wells drilled specifically to test the Weir, as well as four deeper holes through the Weir that were drilled to the Berea or deeper targets. None had shows at the Weir level.

The Eccles Quadrangle has had Weir shows or production from two wells in the Irish Lick Knob area, along with ten dry holes in the formation in that corner of the map. In addition, four holes had gas in the Weir on the crest of the Grenville-related high on the Eccles Quadrangle. Eleven wells, presumably lower on the flanks of the structure, had no shows.

Two wells in the trough along the border between the Beckley and Eccles Quadrangles were dry at the Weir level, but one of two wells in the low basin in the southwest corner of the quadrangle had a Weir gas show.

On the Lester Quadrangle, the "Chert" well had a Weir show on the west flank of the Grenville-related high. Weir gas was also encountered on the east side of the quadrangle.

Ten other wells had no reports of Weir gas on this quadrangle. These test failures were scattered along the Grenville high and the Alleghenian fold, as well as in the basin in the northwest corner of the map.

The Crab Orchard Quadrangle had nine dry holes through the Weir and two wells with shows or production in the southwest corner of the map. An additional two holes near the eastern edge of the map had gas in the Weir.

3.3.3 Big Injun Lithology

Although the Pocono "Big Injun" Sandstone is a major reservoir unit across much of West Virginia, it is not gas productive in this portion of Raleigh County. No shows have been reported in the Big Injun in any of these Quadrangles.

As best as can be determined from the WVGES data base, none of the wells in the area were originally targeted for the Pocono Big Injun. Some of the early Big Lime wells reached a total depth in the Big Injun, but the penetrations were minimal and probably indicate the drilling of a deeper than normal pocket as a safety margin to be sure that the basal Big Lime would be included in the well completion. Most of the later wells stopped further uphole within the Big Lime once better well control became available and an understanding was gained of the Big Lime structure and the lithology of the producing interval. The Big Injun is a fine to medium grained, argillaceous sandstone containing glauconite and iron-rich cements.

3.3.4 Big Lime Lithology

The Chesterian-Age Greenbrier section, locally and in this paper referred to by the drillers' name "Big Lime," is the deepest unit in the Beckley area with significant production. There is a very close correlation between the pattern of wells with gas in the Big Lime and the Natural Gas Reserves map for the Eccles Quadrangle. All of the best wells on the map have produced from the Big Lime. Comparing the

Reserve maps with the show and producing patterns for the shallower formations demonstrates that no other formation is consistently productive on the Eccles Quadrangle. On this quadrangle, drilling an exceptional well seems to require good to excellent results in the Greenbrier Big Lime.

Most of the Big Lime gas has been found along the crest of the postulated Grenville-related high (**Figure** 2.3.1). A series of pools stretches along the structure through Raleigh County from the southwest corner of the Lester Quadrangle, extending to the north through the center of the Eccles Quadrangle.

Extensive drilling in the best Big Lime area around Eccles has been conducted by the Peake Operating Company. Their studies led them to consider the Big Lime as the primary objective for development there. Peake feels that the Big Lime deposition here fit the Greenbrier pattern that is well known in other areas of West Virginia where a porous oolitic, pelletal, and sometime biohermal limestone is productive.

During Greenbrier time, a very shallow inland sea stretched across much of West Virginia. Lime muds floored most of the sea. Within the shallow water, shoal areas projected above wave base. These shoals marked localized higher energy environments. At these high energy locations, the lime muds were tossed back and forth, rolled up and formed into oolite pellets. Oolitic bars built up with very high natural porosities. This is the type of reservoir that forms the best productive pools on the Eccles Quadrangle.

In many places in the state, the porous oolitic zones allowed fluids to move through the limestone as it was lithified, and porous zones in the Big Lime became dolomitized. The conversion from limestone to dolomite involves the substitution of small magnesium atoms for larger calcium atoms, causing a reduction of volume within the rock, enhancing its porosity.

At some locations in West Virginia, Big Lime porosity has also been increased on highs by the buildup of biologic "mats" or very low reefs or bioherms. The Big Lime reefs were not the sort of high pinnacle reefs that are prolific producers in Michigan and New York and which can be identified on seismic sections. The Greenbrier "reefs" were very low relief, flat growths, but they had very good interstitial porosity and in some areas are very good producers by West Virginia standards.

3.3.5 The Maxton Sands Lithology

The Maxton (often spelled Maxon in southern West Virginia) sediments, a mix of small, localized sand bodies within a mass of shales and silts, were deposited as the sea that had been covering Raleigh County during Big Lime and Little Lime time was finally overwhelmed by an influx of sediments from the east. A deltaic complex spread across the county during Maxton time.

The Maxton is generally divided into three main units: the Upper Maxton, the Maxton proper, and the Lower Maxton unit. This simple classification system only hints at the complexity of sand lenses and pods, and names have often been misapplied in Raleigh County. Different names have frequently been assigned to a single sand body in adjacent wells. The "Lower Maxton" name has not been as extensively utilized in Raleigh County, therefore, it is not involved in as many errors.

This project involved extensive work with the original OG-10's as well as with the computerized data base. Comparison of the OG-10's and the data base indicated that many of the wells had four or five sands in the Maxton interval, of which only one or two had been assigned a name by the well operator. In many wells, only the thickest one or two sands around the anticipated "Maxton" depth were assigned a name. The thin fringes of lens-shaped sands were usually mentioned on the OG-10, but had been ignored in favor of another thicker sand when it came time to assign a name for record purposes in a given well. Unnamed sands are not coded or entered in the computerized data base, even though they may be part of an identifiable, significant, relatively extensive Maxton or Upper Maxton sand body. This makes it almost impossible to refine, correct or expand the Maxton information by analysis of the computerized data alone. This situation emphasizes the importance of operators doing careful correlations and naming as many units as possible on their OG-10's for submissions to the WVGES.

3.3.6 Ravencliff Lithology

The Ravencliff Sandstone has been reported on in detail by Wrightstone (**Refs.** 5, 6) and others (Kamm and Heald, **Ref.** 2). This work has established that much of southern West Virginia was a river floodplain during Ravencliff time. While Wrightstone (**Refs.** 5, 6) did not include Raleigh County in his study area, mapping of the Ravencliff across the four quadrangles referenced in this report (**Figures** 2.1.2, 2.1.3, 2.2.1, and 3.2.1) makes it obvious that the river systems extended across the study area.

A long, sinuous channel system entered the study area near the northeastern corner of the Beckley Quadrangle and flowed to the south through the town of Beckley. Just southwest of Beckley, the river forked or shifted through time with two courses having been preserved.

This Ravencliff channel includes sandy deposits which generally range from 60 to 80 feet in thickness and around 6,000 to 8,000 feet in width. This is consistent with Wrightstone's descriptions (**Refs.** 5, 6) of Ravencliff channels in counties further to the south.

To the west, on the Eccles and Lester Quadrangles, another Ravencliff channel system is present, but that bed is much more irregular with many wells showing sand thicknesses exceeding 100 feet, even 190 feet in one well (**Figure** 3.2.1). The sand is quite widespread on these quadrangles, but displays no linear trends. Wrightstone (**Refs.** 5, 6) notes the occurrence of similar thicker Ravencliff sands in his study area, and says that these bodies seldom form good producing reservoirs. This description fits the Raleigh County study area. The Ravencliff has had few shows and little production on the Lester Quadrangle where the Ravencliff is thickest.

On the Lester Quadrangle, neither a favorable structural position nor thick sediments seem to have helped the Ravencliff. Most of the wells along the shallow structural high were dry or had only small shows that were apparently not even worth testing, according to the data base. Only eight or nine out of almost fifty wells along the Basement high had shows of gas in the Ravencliff. Even the local domes which have Big Lime production are dry in the Ravencliff.

On the flanks of the Basement feature, there are occasional low wells that had gas in the Ravencliff, but some of these reported no test flow or pressure values, indicating that the shows were minimal. The wells farthest off structure were all dry in the Ravencliff. Several of the wells near the north edge of the Lester Quadrangle had water in the Ravencliff, even though they were high on structure.

Pure sand thickness is not a useful predictor of Ravencliff production in the Lester area. Many of the holes with no Ravencliff gas had wells over 100 feet of sand. Most of the Ravencliff gas comes from wells with much thinner Ravencliff sands.

3.4 Analysis Of Resource Production Data

Production data was obtained as part of the computerized data file from the WVGES. The production data obtained was limited to monthly production reported to the WVGES from wells in Raleigh County. This information was woefully incomplete. For a few newer wells, complete production histories were available, but for many holes, including for all wells drilled prior to 1979, data was incomplete.

Beckley College personnel contacted the major operators in the area and obtained more complete production data for some of the wells. This data, along with OG-10 data, was used to help develop the production analogs discussed in the following sections. Decline curve analyses were run on the data available. While the incomplete nature of the records casts some doubt on the accuracy of the results, BDMESC believes they are reasonably accurate.

3.4.1 Big Lime Geology and Production

The Big Lime has been the main producing unit on the Eccles map. The best Big Lime production occurs on two highs on the east side of the quadrangle. Eighty percent of Big Lime wells in that area have been productive, although several wells along the fringe of the fields have been sub-economic.

The details of the structure along the crest of the highs are quite complex, with numerous small domes and saddles. The best production appears to be concentrated on the localized highs. However, on at least one high area, the porous oolitic reservoir beds appear to have been scoured and eroded after deposition, resulting in several dry holes in one very high area.

In addition to the production on the domes, a second significant area of Big Lime production occurs in the northwest corner of the Eccles Quadrangle, around Irish Lick Knob. There, three small, two- or three-well pools mark another structural feature with small local highs. Eight of eighteen tests had shows of gas in the Big Lime in that area. However, this success ratio may be an overly pessimistic statistic for the Big Lime potential in that corner of the map. Eleven of the eighteen holes were targeted to deeper formations, not to the Big Lime. Some of the younger, deeper tests were likely drilled well after the Big Lime was already depleted, at spacings that would not have been considered if the Big Lime reservoir was to be fairly evaluated in the test.

There is a relatively little Greenbrier gas elsewhere on the four maps. A cluster of wells in the northeast corner of the Beckley Quadrangle suggests the presence of another paleo-structure in that area. Ten wells have been drilled to the Big Lime in a trend north and slightly east of the town of Beckley. Three of these tests, grouped near each other, had gas in the Big Lime. The producing wells are near the corner of the map. This may indicate the presence of a larger pool or group of pools at the northeast corner of the Beckley Quadrangle and implies the existence of structural features along, or perhaps just beyond the edge of the study area.

Three additional Big Lime tests are scattered around the Beckley Quadrangle. Two of these were dry, while one, immediately southeast of the town, showed gas in the Big Lime. This latter hole apparently quickly blew down or had a very small show. The well was never produced.

There is no record of any gas having been produced from the Big Lime anywhere on the Crab Orchard Quadrangle. Thirteen tests have been drilled through the Big Lime here without any recorded shows. This lack of production tends to confirm the analog for production on the Eccles Quadrangle. There are no structural clues or indications that there were any significant highs or shoal areas developed in that area during Greenbrier time. The model dictates that such shoals were necessary for commercial production in this region.

Big Lime production has been extensive on the Lester Quadrangle. Twenty-nine wells have had Big Lime gas shows or production across the area of the Basement high which runs through the center and down to the southwest corner of the map.

The pattern of production throughout the study area indicates that the Big Lime play is very strongly related to paleo-structure. The best Greenbrier wells on the four maps are all associated with highs that caused shoaling during Big Lime time. Additional Big Lime discoveries are a good possibility on the Eccles and Lester Quadrangles.

3.4.2 Maxton Sands Geology and Production

The Maxton units are not very important reservoirs on a regional scale in this portion of Raleigh County. In the area with many of the best wells, Maxton shows are rare (although the best well on the Eccles Quadrangle does include possible Maxton gas). The Maxton has been dry in a large number of holes, including many of the best wells. At the same time, a large number of poor and mediocre wells have included Maxton reserves. Getting production from the Maxton has not been important in locating the best wells on the Eccles or adjacent quadrangles.

On the Eccles Quadrangle, the Grenville-related high has been tested extensively through the Maxton sands, with results very different from those in the Big Lime. The large, prolific, Big Lime-producing area at the north end of the high has been almost totally devoid of Maxton gas. Of twenty-nine penetrations through the Maxton on this high, only two showed any gas from the Maxton. One of these two producers is the best well in the area, PN 659. The other is a newer well on the flank of the structure. None of the other good wells or structurally high wells in the data base had any gas in the Maxton.

On the dome to the south, a feature which has been less productive than the northern high, twenty-two wells have recorded Maxton shows (although four of these were too small to even warrant testing), while thirteen holes had no reports of gas. There does not appear to be any strong correlation between the Maxton shows and the limited production data available for this high. Many of the better producing wells had no Maxton shows, while other, poor wells on the periphery of the structure or in saddles had gas in the Maxton. Adjacent wells on the high include dry holes and Maxton production with little apparent rhyme or reason to the patterns.

The lows to the east and west of the high on the Eccles Quadrangle have been tested by seven holes, all of which were dry at the Maxton level, or had water in those sands.

In the area of Irish Lick Knob, nine out of nineteen wells in the data base had gas shows in the Maxton sands. Once again, the dry holes are closely interspersed with producers.

3.4.3 Ravencliff Geology and Production

Ravencliff production has been influenced by both the depositional environment and structure. On the Eccles Quadrangle, every well drilled off structure produced no gas or was wet in the Ravencliff.

In the northwest corner of the map, near Irish Lick Knob, nine out of twenty wells in the data base had Ravencliff gas reported. These wells were all along the edge of the map, clustered in one small pool, hinting at the presence of another Ravencliff channel to the west, beyond the limits of this study.

On the two domes, west and northwest of the town of Eccles, there has been Ravencliff production, but the production patterns are quite distinct and different on the two domes, and neither has a pattern which resembles closely the Total Reserve Map pattern, indicating that the Ravencliff is not a dominant producing unit on this quadrangle.

The northern dome on the Grenville-related Basement high has had Ravencliff gas in every well except for four fringe wells at the extreme northeast end of the structure and two wells in the hollow of

Sandlick Creek. The Ravencliff Sandstone has contributed to many wells on this structure, but where it has been the only producing unit, or where it has shared production with only the Maxton, the wells have been very poor. The Ravencliff here may contribute gas to the better wells, but in holes where the Big Lime has not produced, the Ravencliff or Ravencliff and Maxton Sandstones alone have not had sufficient reserves to support an economic well.

On the southern high, just west of Eccles, the Ravencliff has produced in thirteen wells and been dry in another twenty-one data base wells. Eight wells in the center of the high have had water in the Ravencliff. Several of these eight wells were productive, others were dry. The patterns of gas and of water production from the Ravencliff do not resemble the Total Reserve Map pattern for this area. On both domes it seems that Big Lime production has been far more important than the Ravencliff and Maxton reserves.

At the northern end of the Grenville-related high on the two western quadrangles, the Ravencliff Sandstone produces gas in virtually every well. The wells begin to pick up occasional water to the south and eventually dry holes become common. On the Lester Quadrangle, the majority of the holes are dry in the Ravencliff.

Sand thickness is not the key to Ravencliff productivity on the Eccles or Lester Quadrangles. The exceptionally thick Ravencliff sands (**Figure** 3.2.1) on the Lester Quadrangle have had almost no gas shows, while many of the non-productive Ravencliff wells on the Eccles map have had the thickest reported Ravencliff sections on that map.

These sands appear to be part of Wrightstone's "D" Channel (**Refs.** 5, 6). Kamm and Heald's 1983 work (**Ref.** 2) and Wrightstone's studies have shown that the thickest Ravencliff channel sands do not form reliable reservoirs. All of the ultra-thick Ravencliff channels that Wrightstone studied showed very spotty porosity and productivity. He attributed this low porosity to some quirk of the petrography or mineralogy of these thicker sands.

References 5 and 6 suggest that these massive channels may have been too thick and too clean. Wrightstone has hypothesized that the open porosity allowed the entry of clay- or mineral-bearing waters during diagenesis which ultimately clogged or cemented the pore spaces.

The preservation of primary porosity in Paleozoic reservoirs is a very chancy process. In the thinner Ravencliff channels, Kamm and Heald (**Ref.** 2) noted that the quartz grains in some of the coarser grained layers have a thin coating of clay which they believe prevented the growth of secondary minerals in the pore spaces. There has been a very subtle balance between the "dirty" units where a fine clay content inhibited fluid movements and shielded the matrix grains, protecting them from chemical reactions with mineral-rich waters, and very "clean" units where the porosity was so open that fluids readily entered the sands, depositing fines and exposing the grain surfaces to secondary mineralization and alterations which closed the pores. Porosity preservation has been limited to the coarser sections of moderately dirty beds with just enough clay coating material to act as a shield, but not so much as to clog the intergranular openings.

In the case of the Ravencliff, the thinner Ravencliff channels seem to have met the requirements of this delicate balance. On the Eccles and Lester Quadrangles, the Ravencliff is not a viable target by itself, but it should be planned for as a possible extra completion zone in any well being drilled to the Big Lime, especially on the northern dome northwest of Eccles.

On the Beckley and Crab Orchard Quadrangles, the picture is quite different. Here one of Wrightstone's thinner Ravencliff channels, apparently the "F" Channel, as identified in his 1984 article

(**Ref.** 5), has been identified. The Ravencliff is a viable target on these maps with sufficient reserves to support the cost of drilling a 2,000 foot hole. Few of the recent wells drilled on either of these quadrangles have gone much below the Ravencliff.

Several older wells which had been targeted to the Berea and Weir penetrated the Ravencliff across these two quadrangles. However, this drilling was done prior to Wrightstone's work and the current understanding of the nature and production potential of these channel sandstones. The Ravencliff shows or flows were apparently not high enough in the earlier drilling to attract commercial interest. The channels are narrow, discrete bodies, not likely to be hit at random by drilling targeted for the geology of other formations. The Ravencliff become a major target in Raleigh County once the sedimentary environment had been unraveled to the southwest in Wyoming and McDowell Counties. The "F" Channel was "discovered" in the late 1970's and most of the drilling on the Beckley and Crab Orchard maps has postdated this discovery.

On the Beckley Quadrangle, only three of the recent wells, all along the eastern edge of the channel, appear to have missed the sand. The production data shows that the quality of the reservoir does vary along the channel, but that overall, most wells are economically viable.

Two older holes, one north and one south of the town of Beckley, have missed the sand and had no gas in the Ravencliff. Six wells in the northeast corner of the map have also encountered Ravencliff gas and may represent fringe production along the margin of the "D" channel.

The geometry of the Ravencliff channels (**Figures** 2.1.2, 2.1.3, 2.2.1 and 3.2.1) fits a classic fluvial point bar pattern that can be contoured in the style propounded by Don Swanson. Swanson has done extensive work with modern and ancient river meander patterns and conducted detailed studies of how point bars develop. He does not contour fluvial deposits as long strings of sand, but instead as a system of thick, circular pods of sand with relatively uniform thickness that quickly taper off at the edges, and that usually are covered with a clay drape layer which can form a good seal or cap, producing good reservoir units. This picture becomes more complicated as a floodplain builds up and later channels migrate, cutting into earlier sand bodies, partially reworking them.

Swanson's work has shown that a channel's sand pods are generally uniform not only in thickness, but in diameter and spacing (i.e., there is a regularity in the periodicity of river meanders). This regularity produces a standardization of features in fluvial depositional systems. This uniformity and regularity can be seen in the mapping of the Ravencliff channels.

3.4.4 Shallow Sands Geology and Production

The data base shows scattered records of production from shallow units like the Salt Sands, but little information is available on these formations. In many parts of West Virginia these shallow sands were developed decades before formal record filing began. Raleigh County did not have the major oil and gas drilling industry seen in some other parts of the state, in part because these shallow units are not as productive in this area as they are further to the north and to the west.

The only shallow shows reported in the WVGES data available for this project were small and widely scattered. The information available only includes data on recent wells, so there could have been a number of productive older shallow holes for which no record exists. There have been no multi-well pools reported in the very shallow section identifiable in the information available for this study. At this point, the shallow Salt Sands and similar units are not considered to be major targets in this area.

3.4.5 Coalbed Methane

In resource terms, the distinctive feature of this research project is the consideration of the methane resources in the coal along with the natural gas in the conventional reservoirs, with both to be completed and produced in the same hole. Methane potential is largely overlooked by most oil and gas producers as a resource in evaluating the natural gas potential of an area.

In this study, the methane content of the Beckley and Pocahontas #3 coals were considered to be economically attractive targets, with depths ranging form 800 to 1200+ feet for the Beckley Coal (**Figure** 2.1.23) and from 900 to 1300+ feet for the Pocahontas Coal on the Eccles Quadrangle. The Beckley Coal ranges up to 12 feet (**Figure** 2.1.21) and the Pocahontas up to 9 feet in thickness (**Figure** 2.1.22) in the Eccles area.

There were 103,307 acre-feet of Beckley Coal and 40,632 acre-feet of Pocahontas #3 on the quadrangle, which translated to 160 BCF of methane available prior to mining of the Beckley seam. The Pocahontas Coal has not been mined in the study area.

Mining has removed much of the thickest Beckley coal (**Figure** 2.1.25) with the probable venting of at least 44 BCF of methane during the active part of the mining operation. In addition, the mining activity has upset the equilibrium of the coal-water-methane system. In addition to draining methane into the mine, large quantities of water been produced from the coal, especially on the updip side of the coal seam. Most of the coal seam water remains in place downdip from the mine, with the methane on that side of the operation being much less disturbed than on the updip side.

As water is removed from a coal-water-methane system, the methane is under much less pressure and tends to desorb from the coal. The cleats, a system of fractures through the coal, provide a migration route for the methane to move toward low pressure areas, such as mines. The same cleat system route is used in producing methane from the coal in degassification wells. Removing water and reducing the pressure on the coal allows the methane to be desorbed and produced from the surface of the coal. In addition to production through the cleat fractures, coalbed methane productivity can be enhanced by hydraulically fracturing a coal and extending the effective drainage radius.

Several of the mines in the Beckley and Eccles area have shut down and have been, or are being, abandoned and flooded. Methane desorption continues in the coal surrounding a mine even after the cessation of mining. With a dewatered, reduced-pressure situation extending well back into the coal around a mine, methane continues to desorb and leak through the disturbed and open cleats for some distance back from the mine.

In the abandoned mines, the ventilation systems are turned off and water continues to seep into the mines until the system is flooded. Methane will continue to desorb from the coal until a pressure equilibrium is reestablished at some point, usually years in the future.

For this study, the area of greatest interest was in the immediate vicinity of a mine that has just shut down, so no assumptions had to be made about long-term drainage and eventual stability pressure. Since the mine will have only been closed for a matter of months when the well is drilled, it can effectively be considered to be an active mine.

In addition to the Beckley and Pocahontas #3 seams, there have been several other coals in most of the wells drilled on the Beckley and Eccles Quadrangles, but these are usually thinner and do not display the broad regional extent of the two main coal bodies. Due to this limited size and shallower burial depth for many of the minor coals, they were not factored into the reserves for the area, but a given minor coal might be a methane contributor to wells in the northwest corner of the Eccles Quadrangle where depths of burial of the coals are greatest.

The Beckley Coal swamps formed two active depocenters, one just east and one just west of the Basement high block (**Figure** 2.1.21). Mining maps and several core tests show that the coal pinches out rapidly and is absent along the crest of the Basement trend. Coal thickness can decrease from 4 feet to zero feet in only 1200 feet along the flanks of the high.

While the Pocahontas #3 has been contoured as an east-west body extending across the Basement trend (**Figure** 2.1.22), control is absent at the critical area on the high, and this coal could also thin or even pinch out across the axis.

There is very close correspondence between the high points on the Big Lime domes and the limits of the Beckley Coal, supporting the concept of strong, long term Basement control of Paleozoic depositional patterns.

3.4.6 Production Data Maps

The production data from the WVGES "Production" computerized file were combined with data gathered by Beckley College personnel from industry sources to give an expanded set of completion and production numbers for the Eccles Quadrangle. The resulting information was computer processed to derive production data for the preparation of maps.

Figure 2.1.7 shows the reported Natural Open Flows for wells in the study area. **Figure** 2.1.8 is a much more complete data set showing Final Open Flow values for a larger number of wells. The two shoal areas which affected Big Lime production are readily identifiable on this map, clearly showing the importance of Big Lime gas to total productivity in this area. Several "peaks" can be identified on each of these domes.

Areas with poorer open flow results flank the highs. The poor open flows coincide with production numbers which show that the paleo-lows coincide with relatively tight, unproductive areas. In one of the paleo-low areas with low flows and poor production, the Big Lime is abnormally thin. The extremely thin limestones may mark the location of a deeper channel cutting between the domes. Such channels would localize currents that swept the bottom, inhibiting sedimentation. The domes flanking this channel were covered with shallow water. While waves on the shoals rolled the muds there into oolitic pellets with good porosity, the deep currents prevented the accumulation of any type of sediment, so no reservoir formed. The broad, unproductive area on the western half of the map probably reflect a combination of very tight, very fine-grained micritic muds deposited in deeper water and wet areas which may have some porosity, but which have filled with water in the modern-day structural low.

Open flow patterns in the northwest corner of the map are more difficult to interpret since several different producing formations are involved in that area. Some of this production comes from a possible overbank splay east of the Ravencliff "C" channel. Other production includes gas from the Maxton, Big Lime, and Weir formations.

Figure 3.4.1 shows the Rock Pressure, measured after stimulation. It is obvious that these pressures vary greatly, but many of the better wells had somewhat higher pressures. The reported pressures are somewhat difficult to interpret. As a rough rule of thumb, Appalachian gas reservoir pressures can often be estimated, in pounds per square inch, by multiplying the depth of the reservoir by 0.33. The Eccles Quadrangle, however, shows an average rock pressure value equal to about 0.15 times depth, or about half of the expected value. This means that the entire area is severely underpressured.

ROCK PRESSURE AFTER STIMULATION (PSI)

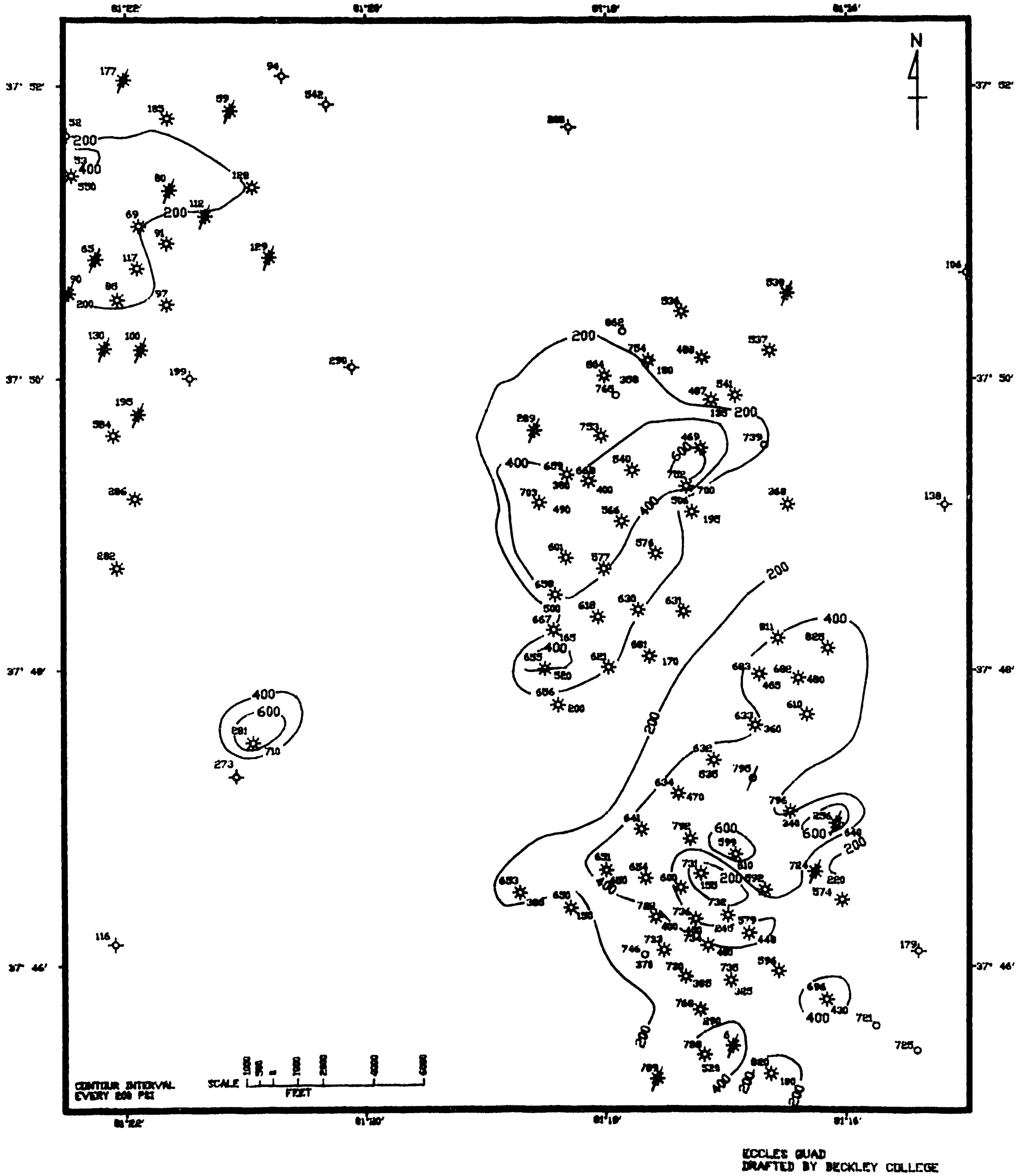


Figure 3.4.1

All available completion and production data were analyzed, and a number of projected production and reserve maps were generated. **Figure** 3.4.2 is a representation of the Initial Production Rate, the rate, in Mcf per month, at which the wells actually produced when initially turned in line. This value is a computer projection and may be conservative in some cases, since it was based on an exponential production decline analysis.

A decline curve analysis was also used to project the anticipated production for various time periods. **Figure** 3.4.3 shows the Three Year Projected Cumulative Production expected after thirty-six months in line. Several areas of superior production can be identified. These generally coincide with the shoal areas in the Big Lime.

On **Figure** 3.4.3, a break-even point, economically, would approximate the 100 MMcf contour. The exact value will vary with the price of gas, but 100 MMcf is a useful number for a quick approximation. Wells inside this contour should be economic producers. Some economic wells may exist outside the contour in areas that could not be contoured due to a lack of data.

A Projected Cumulative Production At The Economic Limit Map was prepared showing the total production anticipated by the time each well reaches its "economic limit" (**Figure** 3.4.4). "Economic Limit" was defined, for this report, as the point at which production declined to 120 Mcf per month. Below this level, well tending costs, at present, would exceed the revenues from production. A graph showing the number of months a well can produce before it reaches the economic limit is included in **Appendix B**. These economic projection maps are highly sensitive to gas prices and labor and equipment costs, so the economic limit will shift over time as prices and expenses change.

The contoured values in **Figures** 3.4.3 and 3.4.4 resemble the pattern from **Figure** 2.1.8. The form of the Big Lime shoals dominate all these maps, showing a strong influence of the Big Lime reservoir on both the open flow and production patterns, indicating that the Big Lime is the most important reservoir mapped.

Finally, all the production data were assessed and total reserves were estimated for the quadrangle, based on exponential decline curve analyses. The total projected reserve for each location was divided by the well's producing area (well spacing). This provided data for a calculation of the gas reserves in place, in MMcf/acre, for all producing reservoirs combined. A 60% recovery factor was assumed, and the total reserve values were divided by 0.6 to develop **Figure** 3.4.5, the Projected Natural Gas Resource Map for the Eccles Quadrangle.

4.0 IDENTIFICATION OF CRITERIA USED FOR DETERMINING GAS RESOURCE RICHNESS AND PREDICTING SUCCESSFUL DRILLING TARGETS

The geotechnical-geostatistical approach has been predicated on several beliefs, including that:

hydrocarbon production requires the presence of three key elements; resource, reservoir, and structure;

the elements consist of subelements (see **Figure** 3.1.5);

these elements can be analyzed and described in numerical or statistical terms.

INITIAL PRODUCTION RATE (MCF/MONTH)

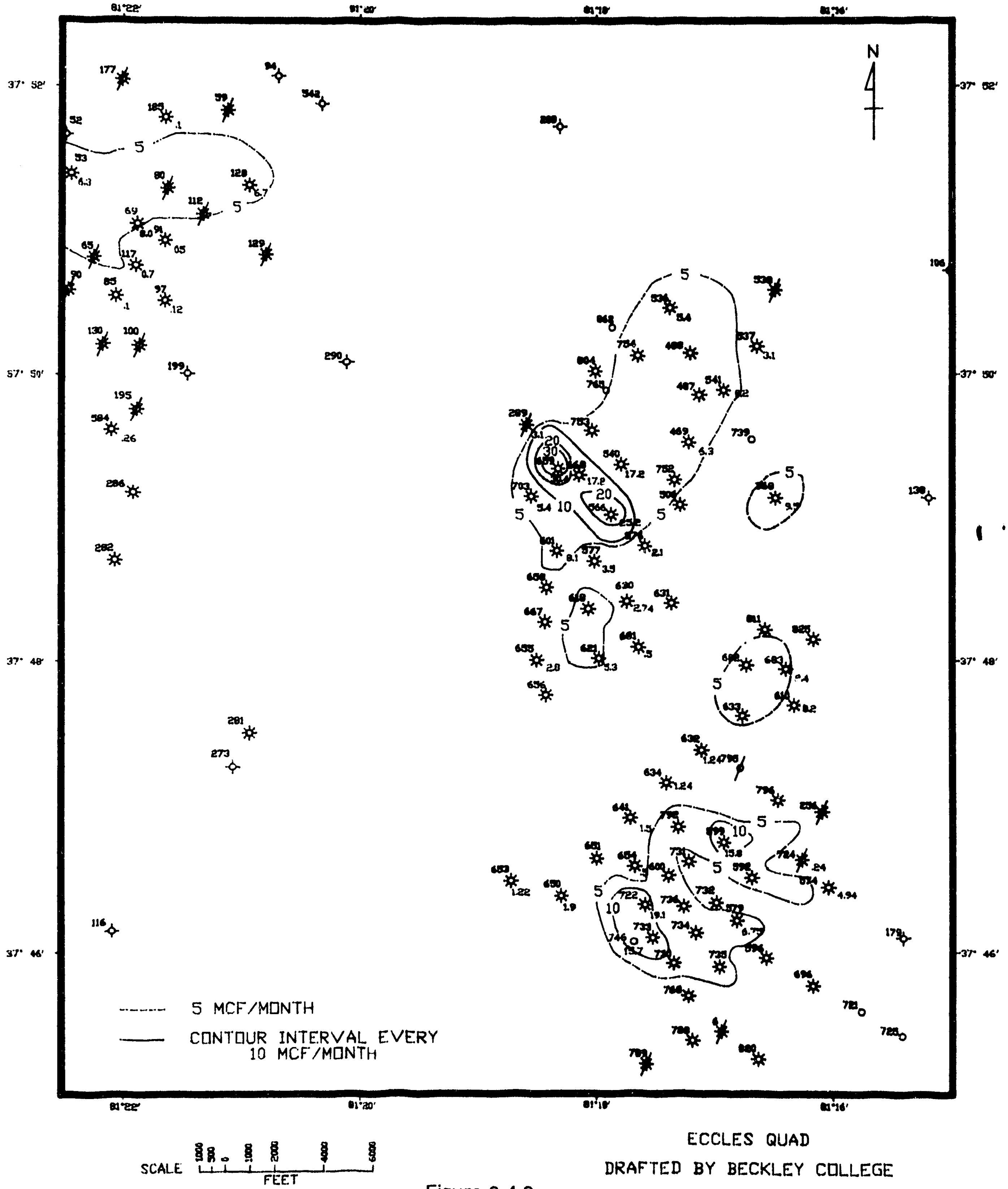
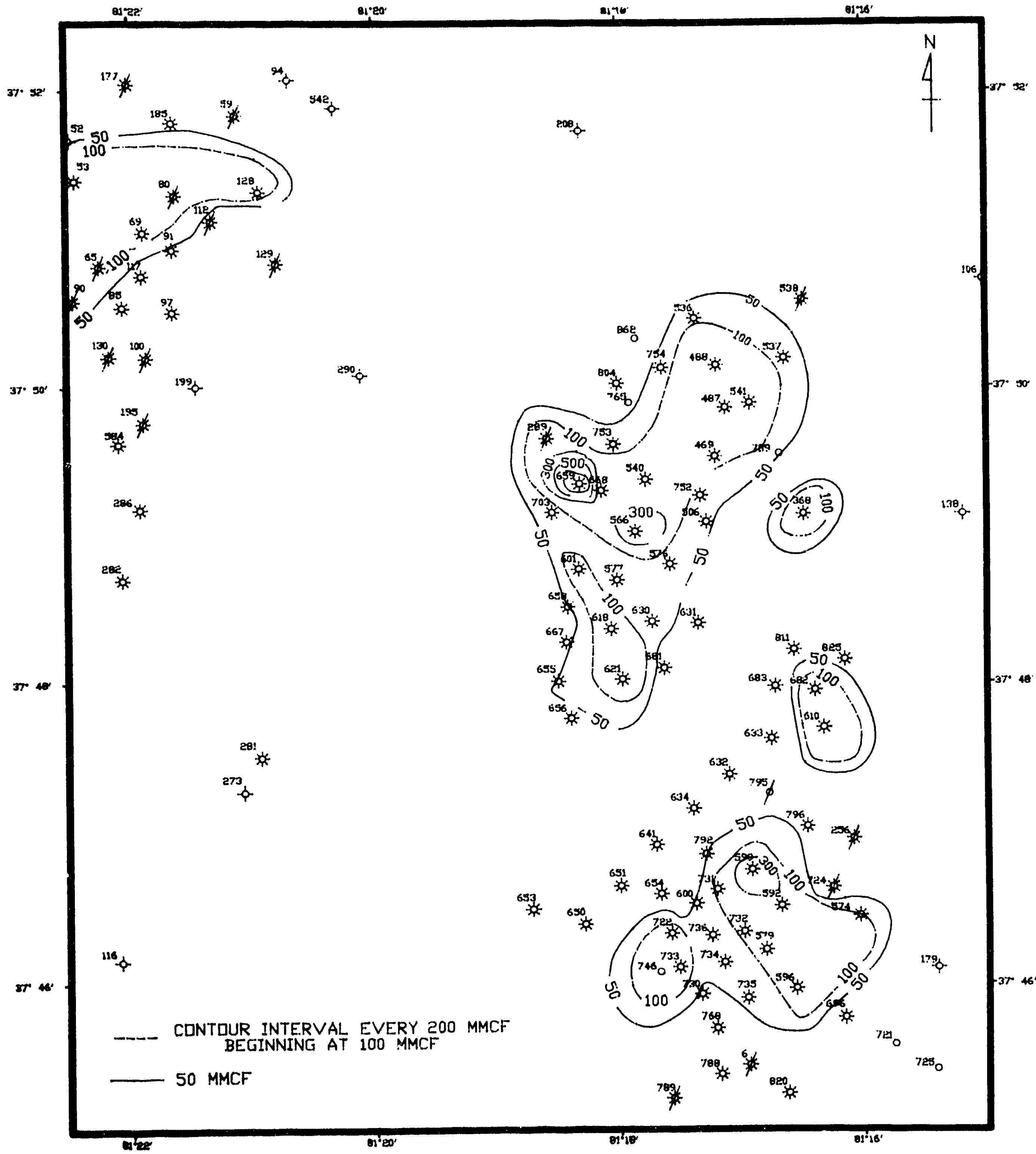


Figure 3.4.2

PROJECTED
THREE YEAR CUMULATIVE PRODUCTION (MMCF)



SCALE — FEET

ECCLES QUAD
DRAFTED BY BECKLEY COLLEGE

Figure 3.4.3

PENN. & MISS. PROJECTED CUMULATIVE PRODUCTION AT ECONOMIC LIMIT (MMCF)

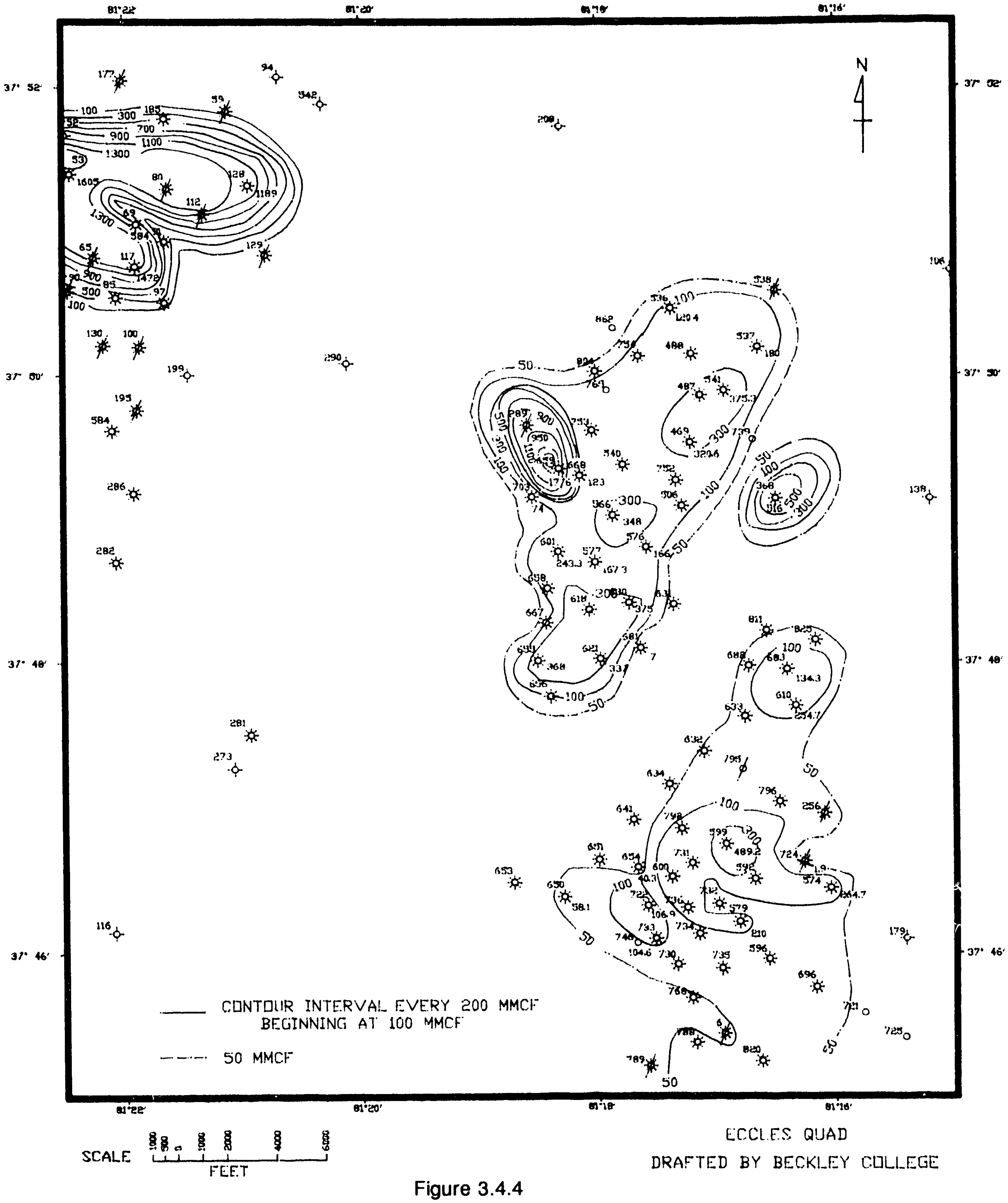


Figure 3.4.4

NATURAL GAS RESOURCE (MMCF/ACRE)

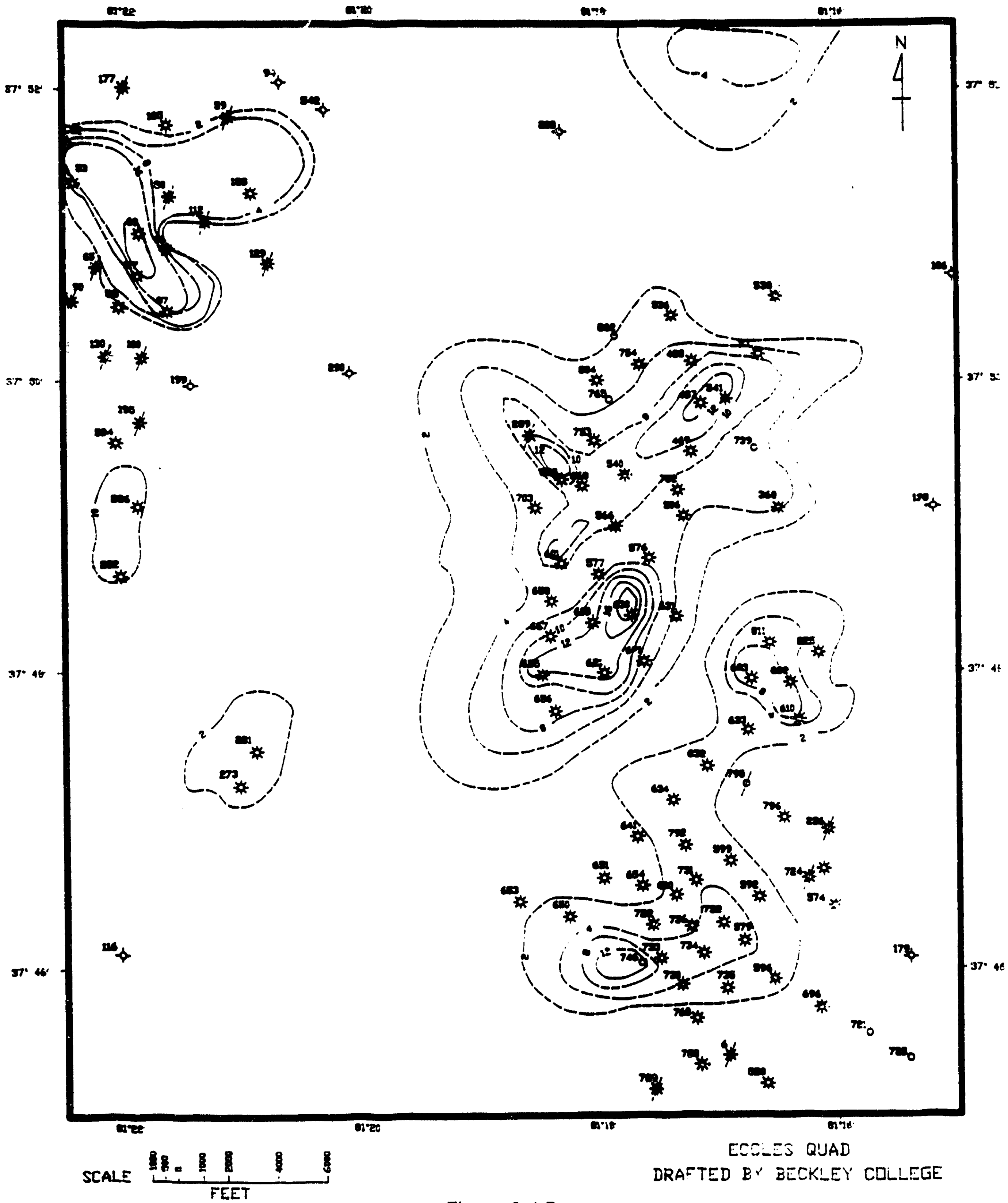


Figure 3.4.5

A three-component or ternary diagram (**Figure** 4.0.1) was used to represent the interaction of the main elements that are key to economic natural gas and coalbed methane production. The program has developed and demonstrated a methodology that can identify areas with a high probability for commercial gas production. "Commercial gas production" was defined as production at a rate sufficient to pay back the initial investment, plus a 15% rate of return, in three years, at a gas price of $2.00/mcf.

The approach utilized in this study was to examine the drilling, completion, and production databases and publicly available literature to determine the types of reservoirs that existed in the study area. Depositional environments were studied along with diagenetic and tectonic histories for the productive units. These data were then used to describe and classify or rate the reservoir units in mathematical or statistical terms to develop Reservoir Analog Probability Maps for the key conventional reservoir formations, the Big Lime and Ravencliff Sandstone.

4.1 Development Of Probability Maps For Gas Reservoirs

All hydrocarbon reserves have geologic controlling parameters which determine the location, type, and size of the reservoir. The parameters may be related to the original environment of deposition, diagenetic changes or alteration of the reservoir rock during or after lithification, or to the tectonic history of the reservoir rock unit.

4.1.1 Identification Of Controlling Parameters

In order for a hydrocarbon reservoir to be form, there must be;

a source of hydrocarbons;

a rock unit with satisfactory pore space or fractures to contain the hydrocarbon resource;

a mechanism to control or trap the accumulation of hydrocarbon in the reservoir.

In addition, to be commercial, the reservoir must have sufficient permeability or interconnection of the pores to produce the resource at an economically satisfactory rate.

Some of the key factors which determine the quality of a hydrocarbon reservoir are:

the formation thickness - helping to control the volume of the reservoir;

the formation's structural position - helping to form a trap and to separate water from oil and natural gas;

the rock density - a parameter relating to porosity within the rock helping to determine the volume of storage space within the reservoir;

the rock's electrical and sonic properties - determined, in part, by the mix of pore space and fluids within the reservoir;

the amount of water in the formation - influencing the economics of producing from a reservoir;

the formation permeability - influencing the rate of production from a reservoir.

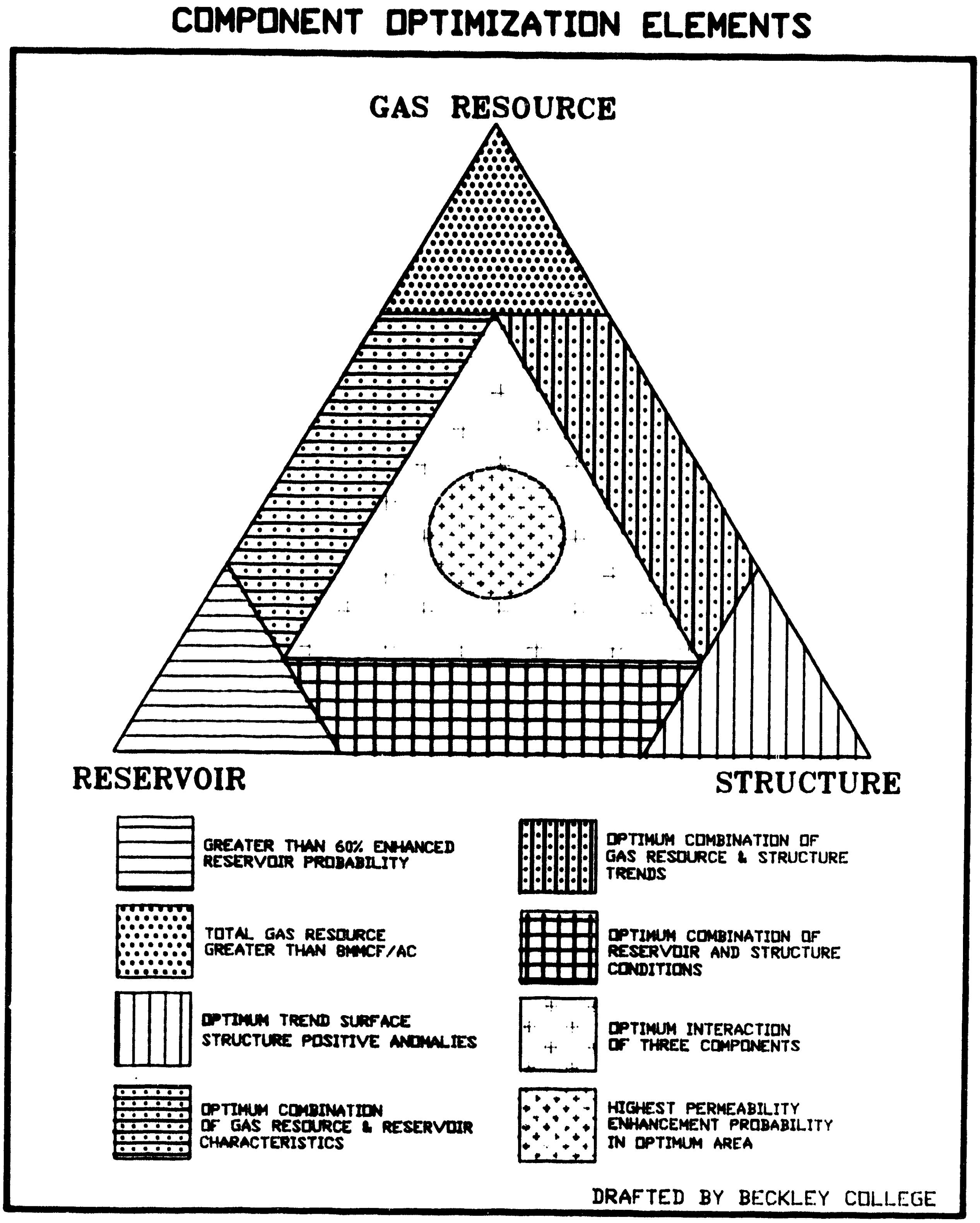


Figure 4.0.1 Resource-Permeability-Structure Ternary Diagram

Data on the first two factors are generally readily available in oil and gas development areas. The WVGES has information for most areas of the state for the mapping of both thickness and structure.

Geophysical logs or detailed production information are required to obtain data for mapping most of the other key reservoir characteristics. Core analyses will help in determining some of these features like permeability. Since such data are not always available for examination, much of this information must be estimated and/or derived indirectly when developing models or analogs for reservoirs.

4.1.2 Approach For Developing Reservoir Probability Models

BDMESC personnel prepared a series of structure and thickness maps for eight potential reservoir units in the four quadrangle study area. Color coded maps were prepared which showed how many wells produced from each unit and where the reservoirs were located. Dry holes, shows and water bearing zones were also mapped.

After examining these maps, it was clear that structure had affected the Big Lime deposition and production from that unit. Reactivated uplift of a Basement feature produced an area of shallow water on the sea floor and shoaling during Big Lime deposition. Porous oolitic units laid down on this high became an excellent reservoir. Gas accumulated in the oolite beds and adjacent oosparite and biosparite beds, with the expulsion of water from the pore space. **Figure** 2.1.13 shows a sample gamma ray/density log of the porous oolitic zone found in the Big Lime.

For this study, each reservoir, including the Big Lime, was analyzed to see not only where a reservoir would have been expected to form, but what happened to that reservoir and what its present condition should be today. This led to a series of three maps (Original Reservoir, Diagenetic Effects, Present Day Reservoir) for each formation, with lineaments and fracture zones mapped independently by remote sensing and geophysical means and combined in the Original Reservoir Map for each formation.

The following discussion examines in detail the procedures used in developing the geostatistical analysis of the Big Lime Reservoir.

4.1.2.1 Development Of Big Lime Maps

To prepare the Big Lime Reservoir Probability Maps, data on the Big Lime formation tops and thicknesses were collected, screened for obvious errors, and plotted. Structure and isopach maps were contoured which provided information on the distribution and thicknesses of the Big Lime Limestone (**Figures** 2.1.11 and 2.1.12), showed the location of modern domes at the Big Lime level, and provided clues to the various probable depositional subenvironments across the study area.

Available logs gave additional information on porosity distribution and aided in forming and confirming reservoir analogs. **Figure** 2.1.13 shows an example of an oolitic zone in a productive Big Lime well.

Production maps were prepared which showed which wells produced only from the Big Lime or from the Big Lime and another formation. Initial-open-flow and Final-open-flow-after-stimulation Maps were prepared.

The production data were used to prepare decline curves for the wells that have only produced form the Big Lime Limestone. Cumulative production maps were prepared, projecting Big Lime production to the economic limit. The "economic limit' was defined as a decline in the production rate to

120 Mcf of gas per month. Beyond this point it was assumed that well maintenance costs would exceed income from the natural gas.

The original-gas-in-place (OGIP) was calculated and an OGIP map was prepared. The economically-recoverable natural gas for the Eccles Quadrangle was calculated and mapped. It was assumed that 60% of the OGIP will be produced at the economic limit and a map of the recoverable reserves was prepared. The OGIP number was converted to MMcf (millions of cubic feet) per acre which and these data were contoured as a Mississippian-Age gas resource map.

Spacing between producing Big Lime wells was measured and the effective drainage radius for each well determined. An average drainage radius was calculated for all of the Big Lime wells on the quadrangle.

Comparison of the structure and isopach maps, along with the data from the logs, allowed the mapping of the Big Lime Original Reservoir Probability Map (**Figure** 2.1.14) showing the statistically significant chances of oolitic depositional conditions existing at various locations across the map. For this statistical evaluation process, the area was evaluated on a scale from zero to ten, with ten representing a 100% chance of encountering superb reservoir conditions and zero representing that point where no reservoir had ever formed. In this system, the higher the valuation, the greater the statistically predicted chance of encountering a high quality reservoir in a given area. Since this map is dependent on identifying or interpreting paleostructure, it is possible to make inferences and draw conclusions about undrilled areas based on statistical analysis and observed regional trends. However, confidence in the interpretation decreases as the distance from drilling control increases.

A significant problem in isopach information for the Big Lime was that the drillers learned at an early stage that most of the Big Lime production occurred in the upper portion of the formation and that there was no point in drilling through the entire Big Lime section. Therefore, little data is available listing a base of Big Lime.

The Big Lime Original Reservoir Probability Map essentially shows areas that should have had good primary porosity. To factor in secondary (fracture) porosity probabilities for the Big Lime, **Figure** 2.1.14 was overlain on a light table with a Lineament Density-Fracture Trend Map (**Figure** 2.3.2) and areas where fracturing would have been most likely to enhance the Big Lime Reservoir identified.

Figure 2.1.15 is the Big Lime Secondary Porosity Probability Map, identifying areas where fracture porosity may have enhanced the Big Lime Reservoir. **Figure** 2.1.16 combines the statistically probable primary and secondary porosity conditions and represents the maximum anticipated Big Lime Reservoir in the Eccles area if the reservoir had never been degraded in any way.

Analysis of production data, gas and water, along with well logs show that not all of the original reservoir is still productive. Good porosity still exists on some logs on the downdip, northwestern side of the map, but the Big Lime tends to be wet in the modern lows in this area. Areas that were originally high in the northwest portion of the area that retained good porosity filled with water as the region tilted to the northwest during the Alleghenian Orogeny. The areas that filled with water or where reservoir was degraded or destroyed by diagenetic activity are shown in **Figure** 2.1.17. The Modern Day Big Lime Reservoir is shown in **Figure** 2.1.18.

The Big Lime structure (**Figure** 2.1.11) and isopach (**Figure** 2.1.12) maps and well data were studied. Paleo-high areas with shoaling were identified. Such areas were given a numeric value of 10, representing a 100 percent probability of finding a commercially productive reservoir in those areas. As the indications of paleo-structure, isopachs and lithology implied deeper water, the probability value given to each area was reduced to 9, 6, 3 and to 0. The following definitions were used for the probability map:

10 - Highest probability of finding reservoir conditions and commercial production;

9 - Excellent probability;

6 - Moderate probability;

3 - Poor probability;

0 - Proven dry/wet/non-reservoir area.

4.1.2.2 Development Of Ravencliff Sandstone Probability Map

The procedure described in Section 4.1.2.1 was also used to produce the Ravencliff Sandstone Modern Day Reservoir Probability Map (**Figure** 2.1.10). Using data information on the Ravencliff tops and thicknesses, structure (**Figure** 4.1.1) and isopach (**Figure** 4.1.2) maps were prepared which provided information on the distribution of the Ravencliff sands (**Figures** 2.1.2, 2.1.3, 2.2.1 and 3.2.1) across the Eccles map.

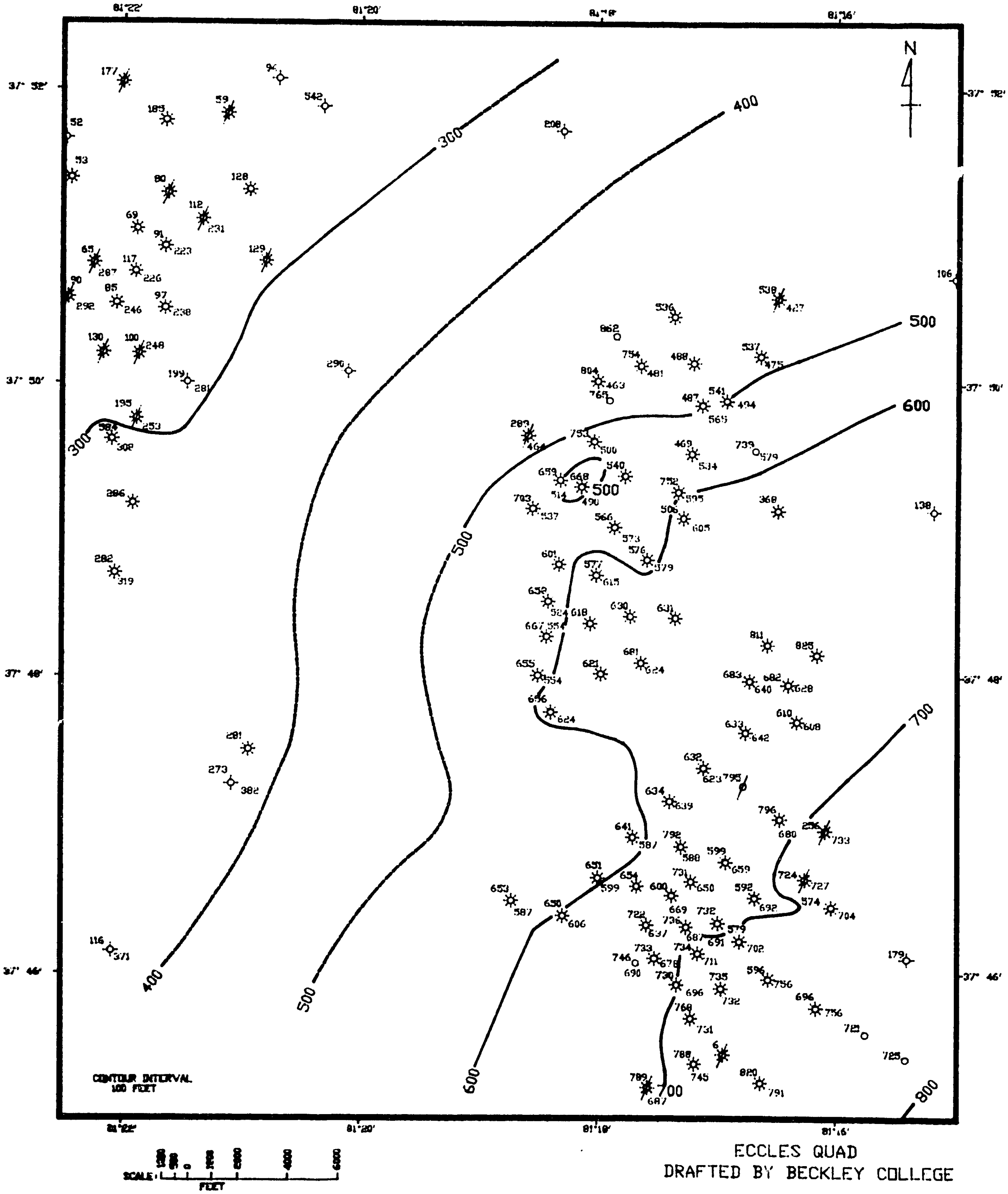
Ravencliff production was identified and isolated where possible, and open-flow maps were prepared, along with cumulative production maps. Decline curves were run for the Ravencliff Sandstone, and production was projected out to the economic limit.

The original Ravencliff gas-in-place (OGIP) was calculated. Spacing between producing Ravencliff wells was measured and the effective drainage radius for each well was determined. An average drainage radius was calculated for all of the Ravencliff wells on the quadrangle.

The Ravencliff Original Reservoir Probability Map is **Figure** 2.1.4. **Figure** 2.1.5 shows the specific fracture trends that could be expected to impact on the Ravencliff. **Figure** 2.1.6 combines the primary and secondary porosities to represent the extent of the theoretical maximum Ravencliff reservoir that could have once existed. As described above, the Ravencliff Sandstone was found to be a part of a fluvial system (**Figure** 2.1.2) that extended across several southern West Virginia counties. This sandstone was deposited at a time when the positive Basement block was inactive. Isopach and lithologic maps of the study area and surrounding quadrangles and counties seem to show little or no relationship between deeper structural features and the courses of the Ravencliff river systems.

The Ravencliff river channels had all the hallmarks of having been potentially one of the great reservoirs of West Virginia, at one time. Unfortunately, most of the original porosity has been lost to mineral overgrowths and pore clogging. In the originally thickest, best channels, little porosity remains. The few present day Ravencliff reservoirs appear to be limited to the thinner, less well developed channels, where original porosity and permeability were not as continuous. Areas with restricted permeability were isolated from the mineralizing fluids which ruined much of the reservoir when they reached the better developed, interconnected parts of the system. Even in the thicker channels, isolated areas exist where porosity was locally preserved. The geostatistical approach was aimed at distinguishing areas where diagenesis dominated from the areas where porosity was likely to remain. This involved studying the isopach data and looking for thinner channels, generally under 100 feet thick, and plotting the show and water records to see where the remaining productive areas were. The isopach data and depositional patterns indicated that there were several levee breaks in the mapped area with deposits that

RAVENCLIFF STRUCTURE



ECCLES QUAD
DRAFTED BY BECKLEY COLLEGE

Figure 4.1.1

RAVENCLIFF ISOPACH

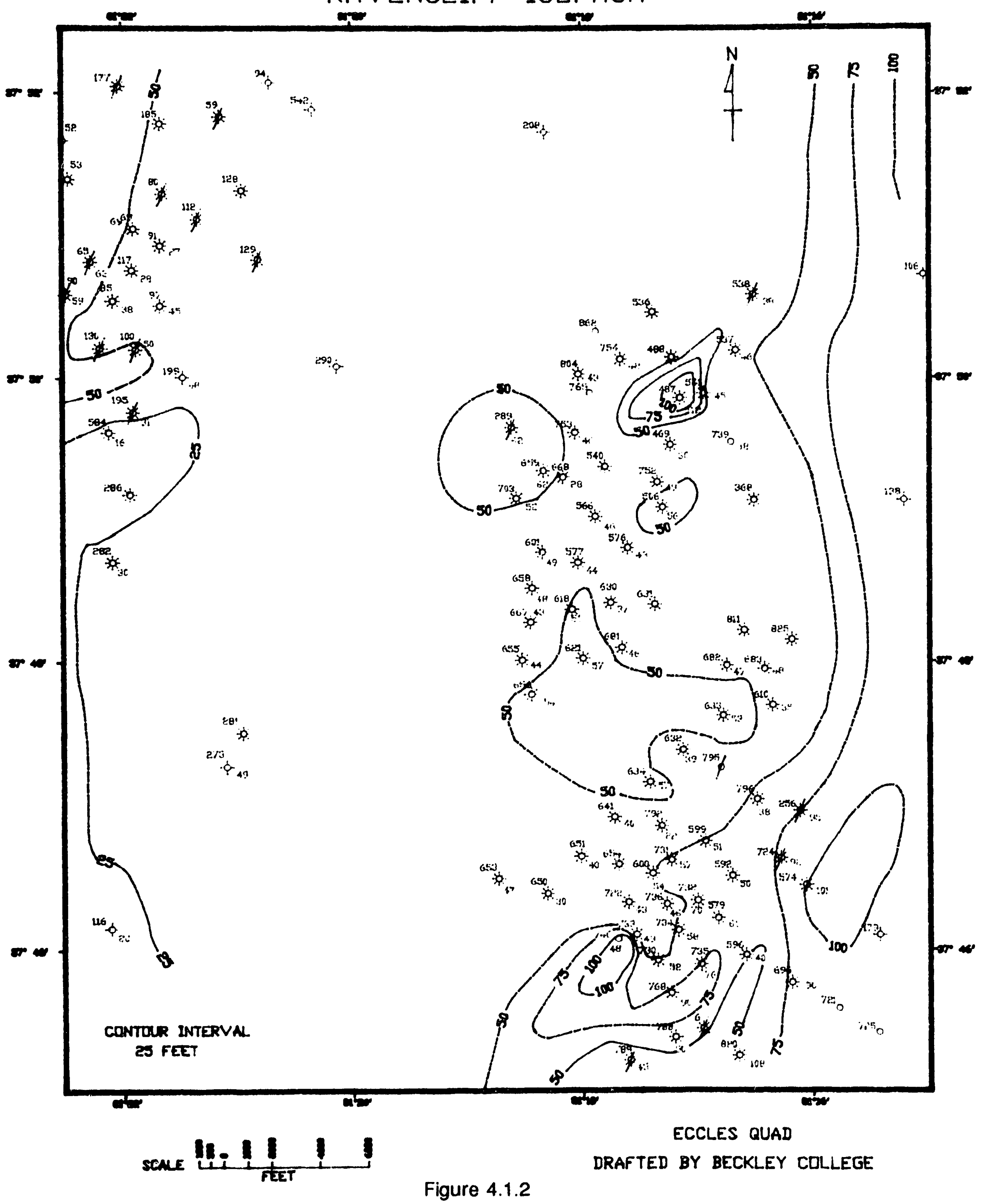


Figure 4.1.2

seemed to be gas-bearing. Most of the main-channel sands seemed to have lost their porosity, although some porosity may have been preserved right at forks in the river or where the rivers jumped from one braided course to another. **Figure** 2.1.9 shows the effects of the diagenesis and flooding on the Eccles Quadrangle. The Ravencliff Modern Day Reservoir is presented in **Figure** 2.1.10.

Only two or three wells were found which were producing from supposed Maxton Sands, and even these wells, based on log appearances, may actually be producing from deeply incised basal Ravencliff channel sands that have been misidentified as Maxton. It was concluded that the Ravencliff sand is the only unit that can be considered to be a viable producing Pennsylvanian-age target on the Eccles Quadrangle.

4.2 Development Of Coalbed Methane Resource Map

A Coalbed Methane Richness Map was produced to graphically represent the methane resource in the primary potential producing coal seams at any given site on the study area map.

The major coal seams in the study area were isopached early in the study. To quantify the methane richness, the volume of methane in the various seams was calculated on a cubic foot of methane per acre-foot of coal basis. The methane value used was 451 cubic feet per ton (see **Ref.** 4) for the Beckley Seam, based on data from mining operations. The Pocahontas #3 has not been mined in the study area, so a value of 572 cubic feet per ton was used for calculations for that seam. These numbers were converted on the basis of 2,178 tons per acre-foot of coal. These calculations produced methane volume estimates of:

982,278 cubic feet of methane/acre-foot of Beckley coal;

1,245,816 cubic feet of methane/acre-foot of Pocahontas coal.

The isopach maps were converted to Methane-richness Maps by multiplying the methane per acre-foot by the coal thickness to produce a map showing cubic feet per acre at any given location on the map. This information can be converted to volume by determining the area drained. Thus a well location on a "6" contour and draining 40 acres would be expected to produce 6 MMcf/acre X 40 acres or 240 MMcf of methane. This total resource number must then be multiplied by the anticipated recovery factor to estimate the producible portion of the resource, or reserve value for that well.

Individual Methane Richness maps were prepared for the Beckley and Pocahontas #3 Seams. A map was prepared showing the aggregate thickness for the two potential reservoir seams combined (**Figure** 2.1.24).

Adjustments were also made to account for the area mined and the methane lost. **Figure** 4.2.1 shows the Methane Originally-In-Place in the Beckley Seam. **Figure** 4.2.2 adjusts this to account for the methane that has been lost from the Beckley Seam due to mining (**Figure** 2.1.25) in the study area. It was estimated that most of the methane in place within 300 feet of the mine working has been drained. A transition zone exists for an additional 300 feet. At about 600 feet from the mine, the methane is assumed to be a near original conditions (e.g., fully saturated). This estimate will have to be confirmed by drilling core holes and gas measurements. However, the analysis shows that while a substantial amount of methane has been lost, a large resource base still remains in the Beckley coalbed for future development.

The Pocahontas #3 Methane-In-Place is shown in **Figure** 4.2.3. Since this coal has not been mined in the Eccles Quadrangle, no adjustments to this data were required for this study.

BECKLEY SEAM COALBED METHANE IN PLACE PRIOR TO MINING (MMCF/ACRE)

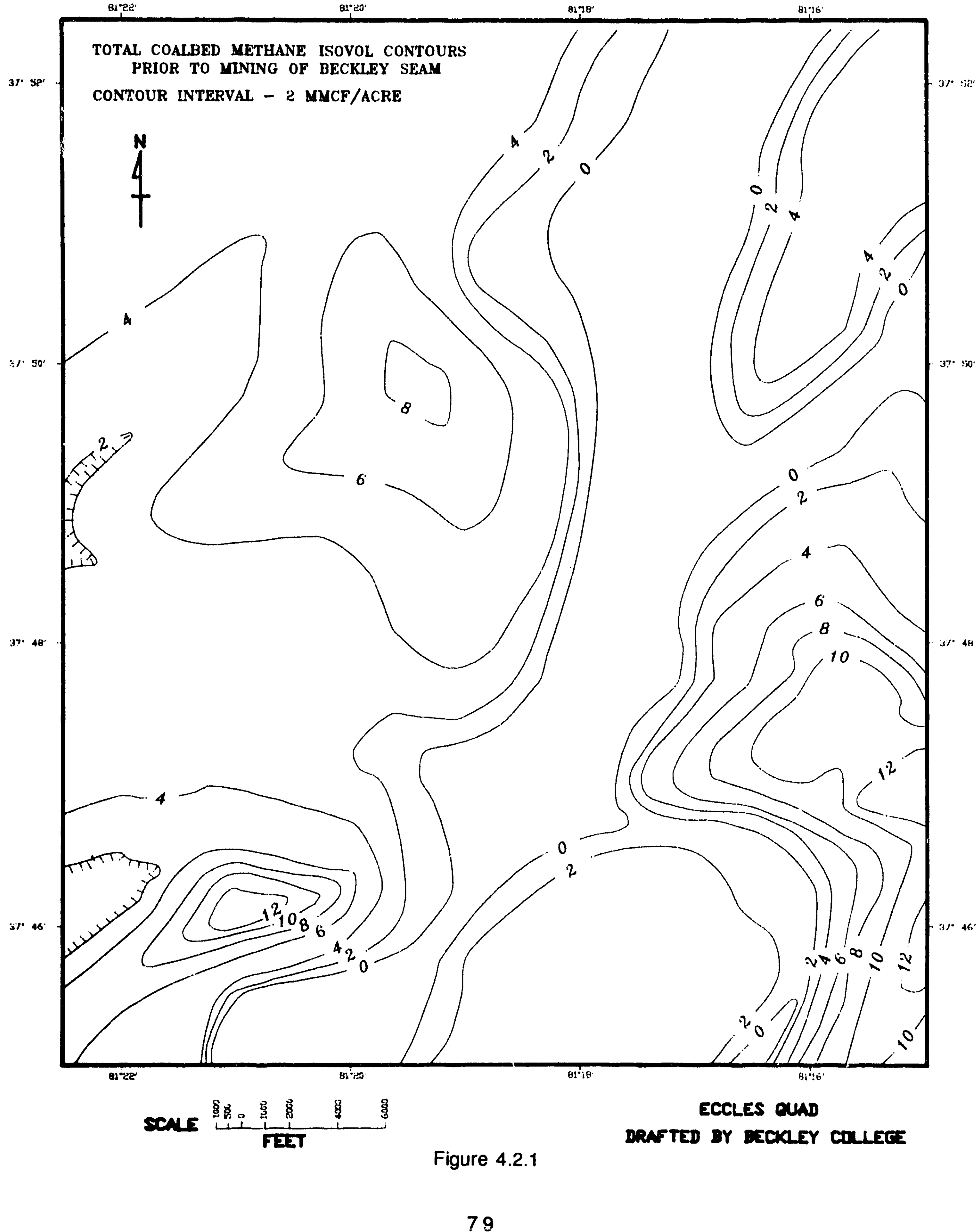


Figure 4.2.1

BECKLEY SEAM COALBED METHANE IN PLACE AFTER MINING (MMCF/ACRE)

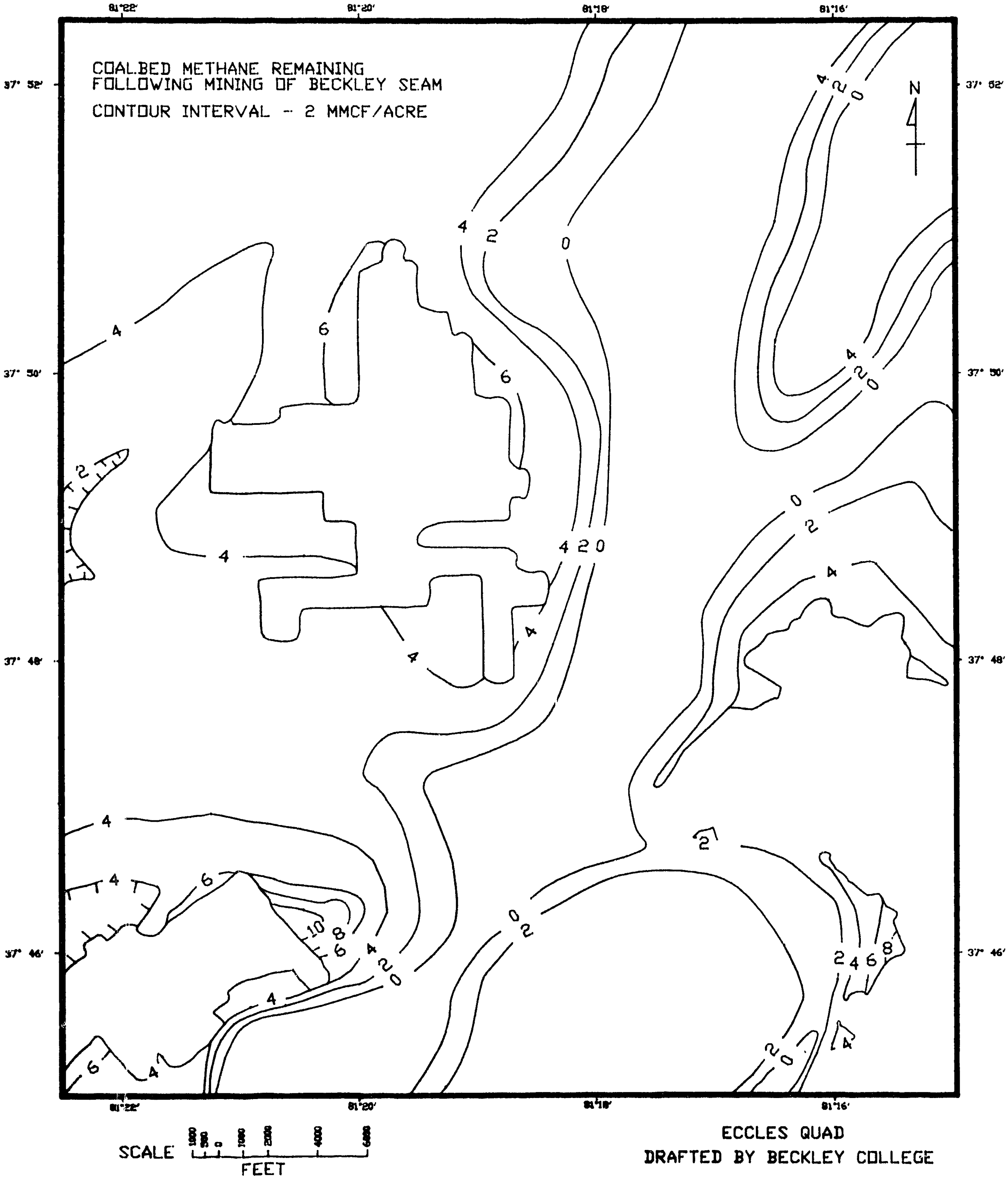


Figure 4.2.2

POCAHONTAS #3 SEAM
COALBED METHANE IN PLACE (MMCF/ACRE)

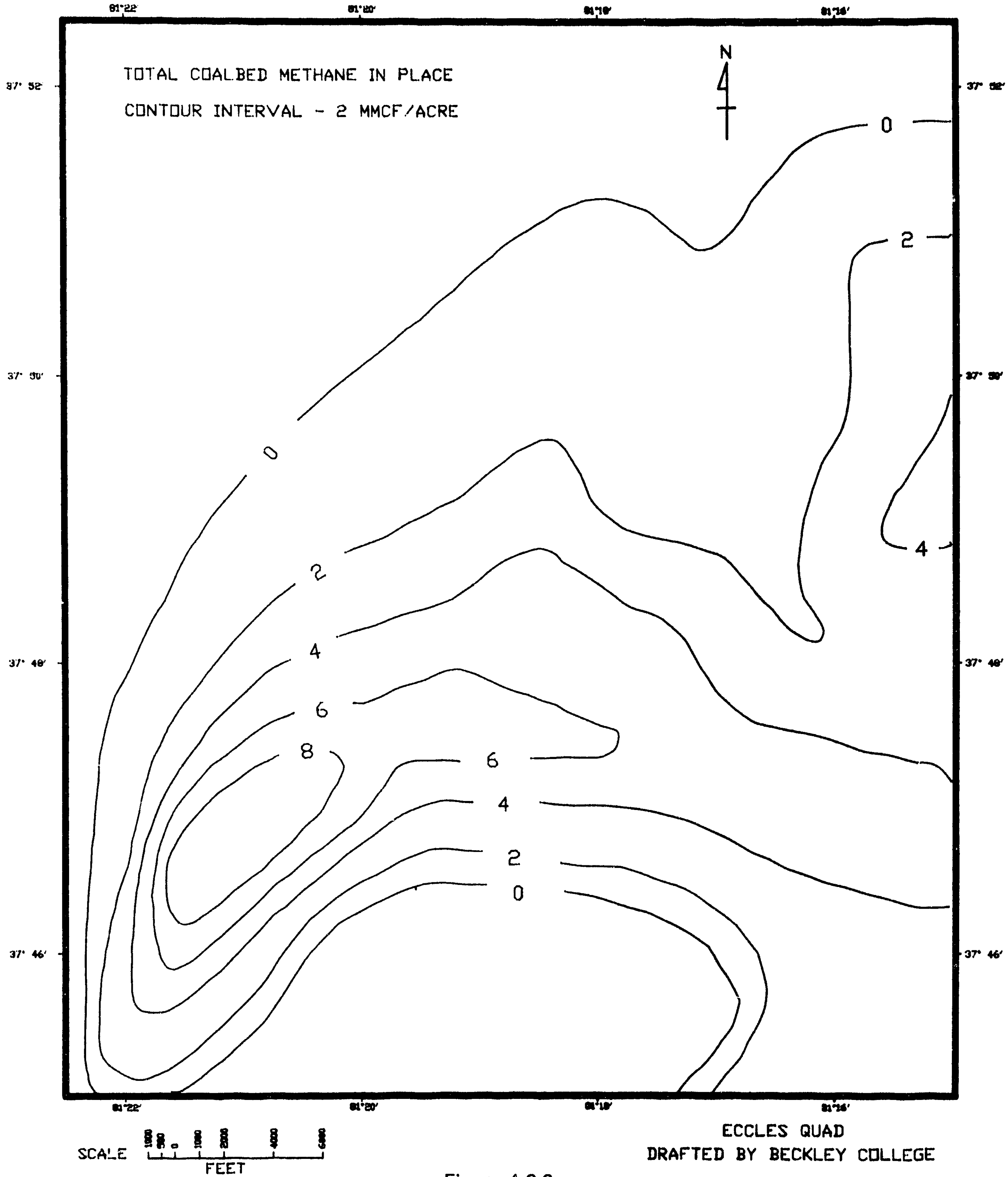


Figure 4.2.3

Figure 2.1.26 shows the Total Methane-In-Place for the Beckley and Pocahontas Seams after mining. Caution should be exercised in the use of these maps, since the estimates are based on thickness of the coals and unmapped changes in thickness would produce a corresponding increase or decrease in projected resources.

4.3 Development Of Probability Map for Reservoir Permeability Enhancement

Areas where reservoir permeability may have been enhanced either by active tectonic fracturing or by fatigue fracturing were identified by remote sensing studies and geochemical and resistivity surveys. The trends identified by Marshall Miller Associates and Mammoth Geo were used to identify areas with a probability for enhanced permeability in the shallow coalbeds (fatigue fractures) or deeper conventional reservoirs (tectonic fractures).

The studies were the bases of **Figure** 2.3.2 and of the Secondary Porosity Maps for the Big Lime (**Figure** 2.1.15) and Ravencliff (**Figure** 2.1.5).

4.4 Development of Natural Gas and Coalbed Methane Exploration Optimization Map

As discussed previously, the three most important components which determine the quality of a natural gas reservoir are:

the pore space with hydrocarbon resource in place available for extraction;

the geologic structure or trapping mechanism that allows the gas to accumulate in the internal pore space of a reservoir rock;

the permeability or pathway by which a molecule of natural gas or methane can move through a reservoir rock toward a wellbore from which it can be produced.

Finding the highest level or condition of each of these elements in an area is the goal of any exploration or development effort. For this study, all relevant, readily available data was obtained for the study area and the data evaluated as discussed below.

4.4.1 Natural Gas Resource Optimization Map

The original plan was to obtain data on each potential Pennsylvanian and Mississippian reservoir formation in the area and to calculate the reservoir volume, hydrocarbon saturation, and the total original gas in place (OGIP) for each unit. Of the historical reservoirs which had produced in the Raleigh County area, only the Mississippian Big Lime Formation and the Ravencliff Sandstone had produced in a sufficient number of wells to merit further consideration.

Well logs were examined for each formation. Porosity, gas saturation, and reservoir thickness were estimated. From this data, the OGIP was calculated on a per acre basis. Data were also obtained on the production from each well, when available. By measuring the distance between wells, the average well spacing was determined. The OGIP calculated from geophysical log data was compared with OGIP estimated from production data (assuming a 60% recovery rate). The geophysical log data gave results five to seven times lower than the estimates predicted by decline curve analyses of actual production data. The decline curve-derived OGIP, based on actual production, were divided by average well spacing (55 acres) to obtain the Mississippian-Age and Pennsylvanian-Age natural gas resource data points for mapping MMcf/acre resources. **Figures** 2.1.10 and 2.1.18 show the Mississippian (Big Lime) and Pennsylvanian (Ravencliff Sandstone) natural gas resources for the Eccles quadrangle.

4.4.2 Coalbed Methane Resource Optimization Map

As discussed in **Section** 4.2, Coalbed Methane Resource Richness Maps were prepared for the Beckley (**Figure** 4.2.1) and Pocahontas #3 (**Figure** 4.2.3) seams. The WVGES was consulted to determine if there were additional coal cores in either the Beckley or Pocahontas coalbeds which might be added to the data base. No additional data was available. Values were used to estimate the resource-in-place for the two seams as previously described. The Methane Resource Maps were then adjusted for methane vented while mining and an after-mining Total Methane Resource Map was prepared (**Figure** 2.1.26).

4.4.3 Combined Natural Gas and Coalbed Methane Resource Map

The Coalbed Methane Resource Map was combined with the Mississippian and Pennsylvanian Natural Gas-In-Place Maps to become element number one in the three-element (**Figure** 4.0.1) mapping scheme designed to identify areas with optimized gas resource, favorable structural features, and reservoir development.

To be economical, a well drilled to produce from the Big Lime, Ravencliff, Pocahontas and Beckley gas-bearing units would need to have reserves of at least 400 MMcf. To be conservative, the target area on the Combined Natural Gas and Coalbed Methane Resource Map was limited to the region within the 8 MMcf per acre contour. This area forms the target area for an Optimized Combined Resource Map (**Figure** 4.4.1).

4.4.4 Optimized Structure Map

An optimized structure map for the Eccles Quadrangle was made by conducting a first order trend surface analysis of the Big Lime and the Ravencliff structure maps. Positive residual structural anomalies correspond to structural high points where the formations stand above the regional dip surface for the quadrangle. The Big Lime structural anomaly is believed to be inherited from a large basement block (**Figure** 2.3.1) which may have been repeatedly reactivated and positive throughout much of the Paleozoic in this area. The effects of this block can be seen on the four-quadrangle structure maps for the Berea (**Figure** 3.1.1), Big Lime (**Figure** 3.1.2) and Ravencliff (**Figure** 3.1.3) levels.

The Structural Positive Residual Anomaly Map (**Figure** 3.1.4) shows all the areas that stand 100 feet or more above the norm for each formation. This map became element number two of the three component optimization map.

4.4.5 Optimized Permeable Reservoir Map

Development of the Lineament Density-Fracture Trend Probability Map (**Figure** 2.3.2) was discussed in **Section** 4.3. This map shows the areas where the reservoir has been enhanced with optimized permeability probabilities and includes all areas identified in the Marshall Miller and Mammoth Geo reports that have had a potential for enhanced fracture permeability effects in at least one of the target reservoir units.

4.4.6 Development of Three Component Exploration Optimization Map

For the final optimization map, the elements were combined as shown in the ternary diagram (**Figure** 4.0.1).

OPTIMUM COMBINED GAS RESOURCE,mmcf/ac

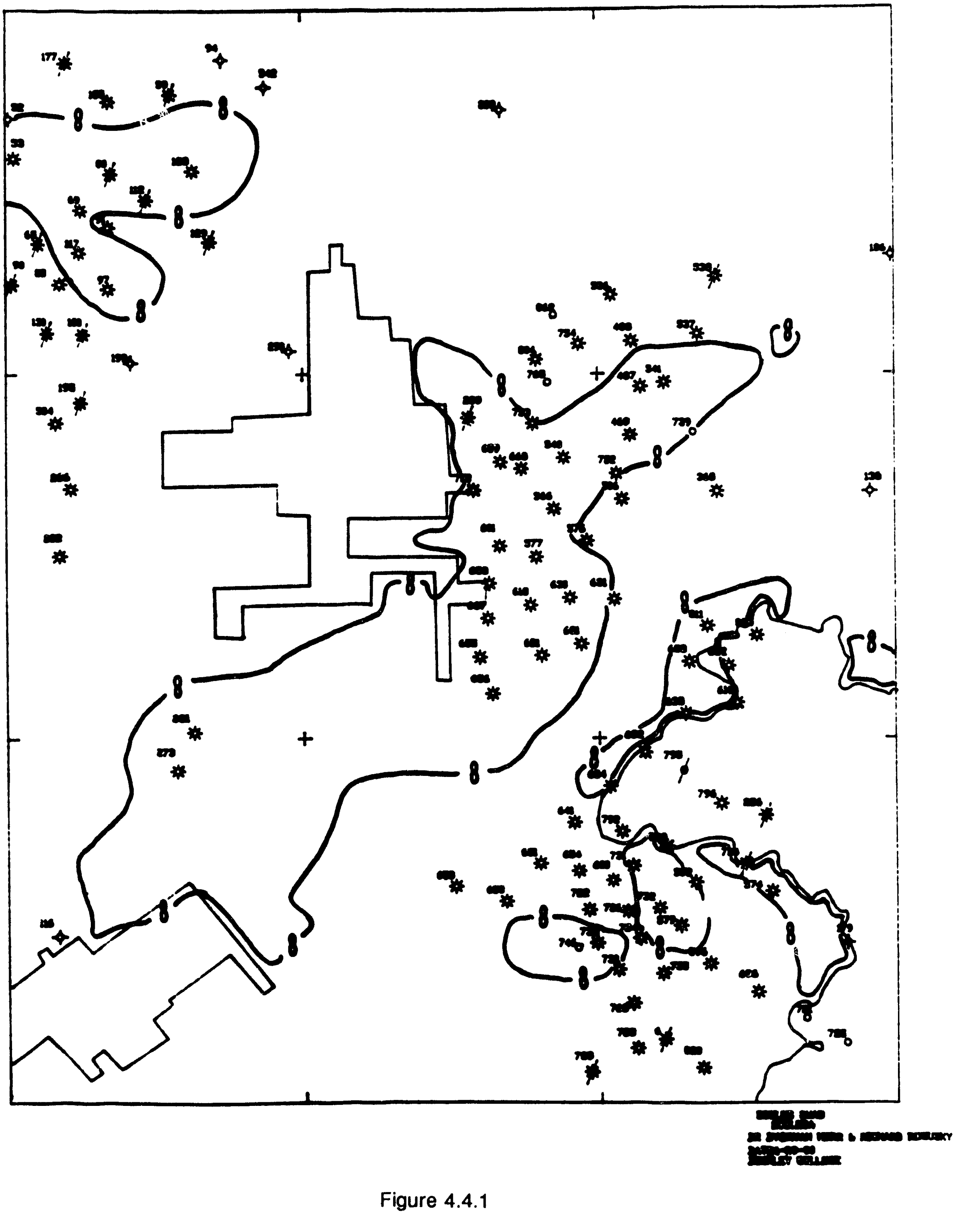


Figure 4.4.1

The possible combinations of the three components of gas resource, reservoir and favorable structural features are shown with the interaction between the various components represented by the patterns shown. A strong positive combination of all three elements represents the most favorable condition when locating areas to drill. The pattern for the optimum area with the best resource concentration, the best-developed reservoir conditions, and favorable structural elements is a set of small, closely-spaced crosses.

The map was constructed by overlaying the Optimized Combined Natural Gas and Coalbed Methane Resource Map (**Figure** 2.1.27) with the optimized structure from the Positive Residual Anomaly Map (**Figure** 3.1.4) and the optimized areas where the reservoir quality has high permeability as identified on the Lineament Density-Fracture Trend Map (**Figure** 2.3.2). The resulting map, **Figure** 2.4.1, shows extensive areas where two components are active, but only one area of considerable size where all three components are active.

5.0 LOCATION OF OPTIMIZED EXPLORATORY WELL SITES

With the geostatistically derived structure and isopach maps prepared, additional information, including production and reserve estimates, was analyzed. Analog models were derived for the reservoirs, using available well logs and published information. Finally, specific well sites were selected and a validation check was run on the geostatistical approach.

5.1 Identification Process For Recommended Areas

The study and mapping of the coals and conventional reservoirs on the Eccles Quadrangle indicated that one general area on the western flank of the Basement high had the best potential for both methane and deeper gas production. The coal here begins to thicken rapidly to the west.

The Big Lime in the same area appears to be oolitic with good porosity development along this margin of the structural high. It was not possible to completely delineate the margins of the Big Lime features, but oolites seem to have extended across this area. Regional tilting has depressed the western margin of the paleohigh, and the shoal area in the Big Lime sea may originally have extended farther to the west than is now evident. Isopach work and electric logs imply that shallow water may have extended well beyond the present drilling limit. Several of the best wells on the map lie along the northwestern margin of the drilled area. One Big Lime well, out in the supposed deep to the west, shows excellent porosity on the logs, but apparently had significant water problems, probably due to its low structural position. That well was plugged.

Additional shoal areas may lie to the north of the present drilled area. The northern area has to be considered exploratory at this time. However, there may be a number of good drilling locations in the northeastern corner of the Eccles Quadrangle.

The Ravencliff reservoir is of less importance than the coals and Big Lime on the Eccles map. The Ravencliff "D" Channel crosses the center of the Lester Quadrangle and the eastern edge of the Eccles Quadrangle. This channel is not as productive as the "F" Channel which crosses the Beckley and Crab Orchard Quadrangles. Numerous wells on the Lester and Eccles Quadrangles penetrated the heart of the "D" Channel without evidence of significant natural gas production. Several of these wells were wet in the Ravencliff. The main body of the "D" Channel generally has in excess of 100 feet of channel sands, with one well reporting a supposed 190 feet of sand.

Wrightstone (**Refs.** 5, 6) describes the "D" channel as thick but nonproductive. He notes that the exceptionally thick channels, like the "D", have typically lost most of their porosity to secondary mineralization and clogging with clays. Depositional conditions here presumably produced excellent primary porosity which allowed mineral-bearing waters to move through the sands at a very early stage. Precipitation of clays from these fluids clogged much of the original pore space. The Ravencliff "D" channel probably once rated very high in depositional reservoir quality, but was severely degraded by diagenetic activity.

Occasional pods of Ravencliff sand along the margins of the "D" channel appear to have been isolated and cut off from the main channel during deposition as the river migrated back and forth. These cut off bodies apparently remained dry and clays do not seem to have clogged the pore spaces in these pods. Small Ravencliff reservoirs occur in these isolated bodies.

There is evidence of thick Ravencliff sandstone in the northwest corner of the Eccles Quadrangle. Since the sand barely touches the study area, it is not clear if this is the main body of the "C" Channel or if it might be an overbank deposit just outside that channel. Porosities in this area seem to be high. This again fits Wrightstone's model (**Refs.** 5, 6). The thinner "C" Channel had poorer primary porosity, limiting the circulation of the type of mineralizing fluids which presumably ruined the "D" Channel.

Wrightstone (**Refs.** 5, 6) observed on thin sections that there was a thin protective clay coating on the walls of the pores of the thinner channel sands. The coating protected the sands from further mineral growth or alteration that might have closed the pores. As a result, the thinner "C" Channel with poorer depositional qualities had a more favorable diagenetic history.

The central area of the map has only relatively thin, overbank Ravencliff sands and little Big Lime potential.

The southeast corner of the Eccles Quadrangle had the thickest Ravencliff sands but poor Ravencliff porosity, a significant potential for water problems and the lack of any indications of good, predictable Ravencliff production or extensive "D" Channel reservoirs. Extensive mining of the Beckley Coal in the southeast corner of the map also mitigated against the possibility of siting the Multi-Strata test in this area.

The Maxton Sands are not widespread on this map and don't show much porosity on the logs. Gas possibilities from the Ravencliff and Maxton Sandstones are like the methane potential from a minor coal; they are not a major consideration in siting the hole, but should be watched for and exploited if an opportunity presents itself.

5.2 Final Screening Process

The final site selection process narrowed the search to looking for an area with the thickest unmined coal, in close proximity to an identified Big Lime shoal area with good natural gas production and reserve numbers.

These criteria, as explained above, pointed to the west side of the main Big Lime pool near the center of the Eccles map. This pool has the best individual Big Lime wells on the map. The superior wells are located near the western edge of the pool, in an area where the coal begins to thicken markedly.

The Big Lime in the southeast corner of the quadrangle map has poorer wells and lower gas reserves. Coal mining has been extensive in the Beckley Seam in this area. The southern Big Lime pool was not as satisfactory as the northern field with respect to natural gas or methane potential.

The low areas east and west of the paleohigh were eliminated from consideration for this project due to their low porosities, poor production numbers, dry hole ratios, histories of extensive water production and the presence of extensive micritic limes in the Big Lime Limestone. These areas originally had large coal accumulations, but the thickest areas of Beckley Coal have been mined out. The deepest portions of the basins had problems with water and porosity in the conventional reservoir formations and could not to meet the coalbed methane requirements of this project, considering the effects of mining.

Drilling in the Irish Lick Knob area began many years ago. Much of this corner of the map was drilled in the 1940's. Some of the early wells were apparently very good, but the WVGES data base had too little production information in this corner of the map to perform a satisfactory economic or production analysis and evaluation. If the data had been available, this area would have been ideal for geostatistical analysis since many of the wells were drilled in a sequence with the early wells producing from shallow formations exclusively. Later drilling occurred in waves, testing deeper units, then targeting still deeper formations. If the data had been available, this pattern would have allowed valid reserve figures to be identified for individual units. In our data base, with no early production values for the older wells, no detailed analysis was possible. Much of the key production in this corner of the quadrangle occurred decades prior to the accumulation of information by the Survey.

Well PN 584 is a newer hole, with production data, in this corner of the map, but low reserve figures imply that it was drilled into significantly depleted reservoirs.

The Irish Lick Knob area was developed over a long period of time by a number of competing companies, drilling interlocking acreage blocks, so that there was no one central operator who could be contacted to gather the missing production and engineering numbers for analysis and evaluation.

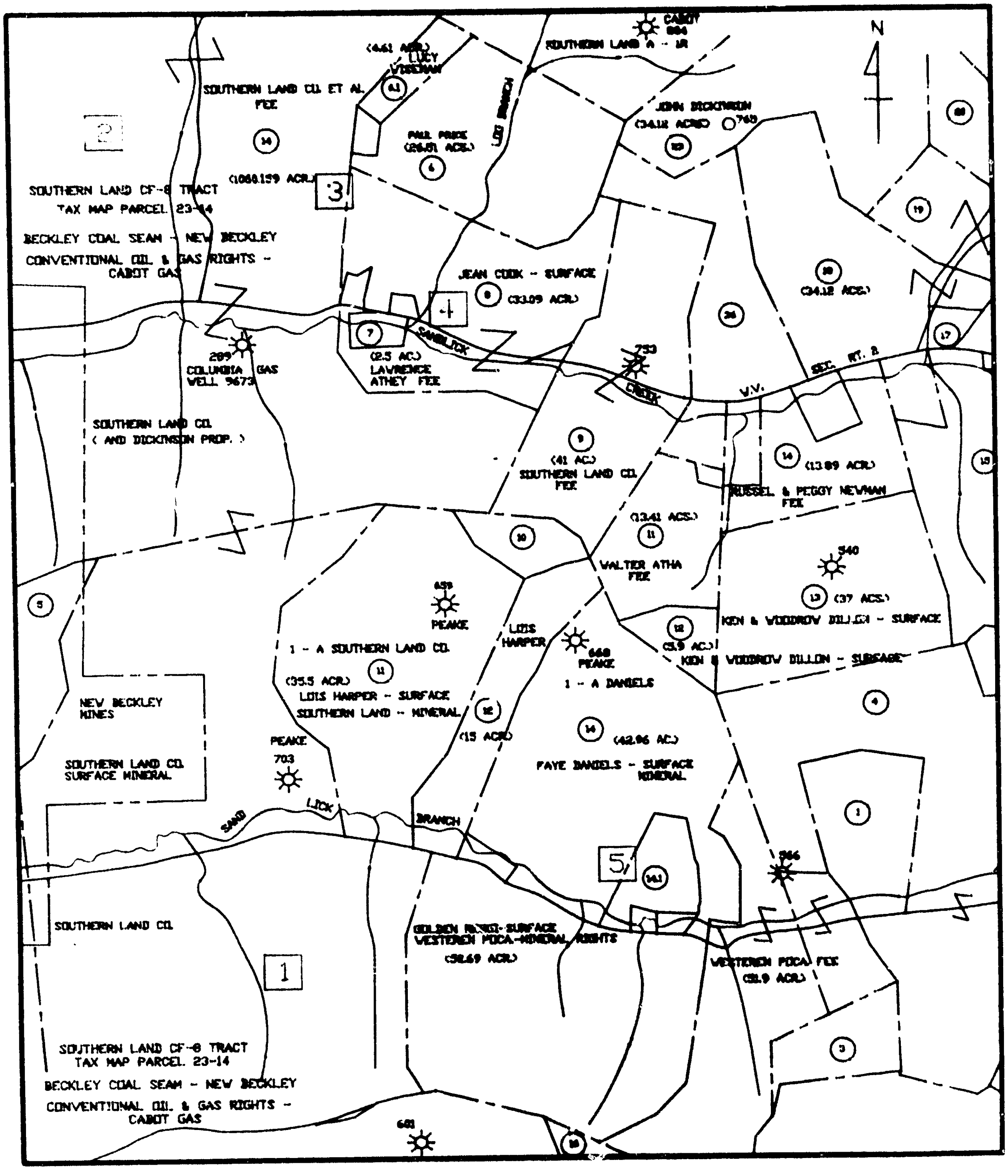
In addition to the shortage of data on the gas sands, the Irish Lick Knob area has a very skimpy coal data base. The major and minor coal seams are too deep here to be considered as viable targets for mining under current economic conditions, sc few core holes have been drilled in this corner of the map. This makes it impossible to accurately evaluate and isopach the coals in that area. While the greater depth and additional overburden theoretically should improve methane producibility in the area, resource quantification cannot be performed without thickness information.

Having defined satisfactory production analogs for both the Big Lime and the Ravencliff reservoirs, and having established a good understanding of the depositional environments and diagenetic histories associated with these formations and the tectonic history of the area, the conventional natural gas resource data were combined with the coalbed methane richness data to identify prime target areas for the Multi-Strata program.

Using the composite Component Optimization Map (**Figure** 2.4.1) constructed from the three element, resource-permeable reservoir-structural features study, the surface map was reviewed for potential well sites, considering spacing requirements and surface, coal, and oil and gas ownership information (**Figure** 5.2.1), and topography. Several undrilled, high-ranking areas were identified. These spots have good possibilities for commercial production from multiple strata, including the Big Lime, Ravencliff and the major coals. Five specific areas were selected as possible drilling targets (**Figure** 2.4.2). These had a high overall ranking, meaning that they excelled in resource accumulation, reservoir properties, and/or favorable structural position and features and were sufficiently far from existing wells or mining to offer good drilling opportunities. The target sites are shown relative to surface features in **Figure** 2.4.3.

The target areas were examined in greater detail to further refine the drill site locations. In addition to the geological and reservoir parameters, other factors were considered, including lease availability,

TRACT OWNERSHIP AND WELL LOCATIONS IN THE TARGET AREA



NUMBERED SQUARES REPRESENT PROPOSED TARGET SITES FOR DRILLING

ECCLES QUADRANGLE
RALEIGH COUNTY, WV

DRAFTED BY BECKLEY COLLEGE

Figure 5.2.1

operator cooperation, topography, uncharted wells or mining operations, and similar geographic, physiographic and business considerations.

5.3 Validation Check Of High Probability Areas

As a check of the numerically driven geostatistical approach, the area was also assessed and mapped using a series of geologic criteria that were subjectively derived. This evaluation was conducted at the end of the project so that the geology of the area was as well understood as possible.

Three geologic criteria were evaluated for each of the conventional reservoirs:

depositional features - features that favored the creation of reservoir conditions;

diagenetic features - features that may have helped to create or preserve porosity;
tectonic features - features that may have created enhanced secondary fracture porosity.

The Eccles Quadrangle map was divided into a grid of 180 squares and each grid square was considered and assigned a value for each of the three factors described above. The three values were totaled for each square for each of the formations evaluated.

In this evaluation, the Big Lime and Ravencliff were analyzed separately. For the purposes of this mapping, only these two units were considered to be significant reservoir formations. The Maxton Sandstone may be contributing gas in occasional, isolated wells, but this family of sands is not widespread or thick enough and sufficiently gas-charged to have been identified as a significant gas producer over any large area.

The three criteria were rated on a scale ranging from zero through ten, with zero indicating no contribution by that element to porosity or reservoir formation, and ten indicating a very significant contribution. The 0 - 10 values were assigned for all three elements, so that a location with excellent depositional qualities and good primary porosity, where the reservoir conditions had been well preserved and extensively enhanced by diagenesis, and then added to substantially by tectonic activity with fracturing and the formation of extreme secondary porosity, would have a score of thirty. There were no such points on these maps.

To arrive at the "tectonics" value, the Marshall Miller Associates report and maps were used. Studying the lineaments identified by Marshall Miller Associates, there seemed to be either a very low, or even a negative correlation between lineaments and production. Many of the best wells on the map lie in areas that the Marshall Miller Associates report describes as "undisturbed." Wells closest to the lineaments must be classified as "average" or "poor."

Since the correlation between the "tectonic" features and production patterns was low, the lineaments were all assigned low values, with "primary" features receiving the highest rating and "secondary" features being assigned a lower number. The "tertiary" lineaments received a zero value.

Due to the gridding system used, the resultant map showed a strong checkerboard effect. To eliminate this pattern and to show an accurate orientation and location for this Marshall Miller Associates lineaments, the final map was smoothed and corners were rounded off or eliminated.

Comparing the resultant subjective map to the geostatistical maps, a close match was evident. The biggest difference is a slightly more favorable outlook for the Irish Lick Knob area on the subjective map. This was an area with extensive older production, lacking in information in the computerized data base, that was discriminated against in the geostatistical study as "unknown." The overall close match between the maps appeared to validate the geostatistical approach.

Comparing the two methods, the geostatistical approach gave a greater degree of resolution and was better at pinpointing small target areas than the subjective study.

6.0 ECONOMIC EVALUATION OF PRODUCTION

The WVGES data base was used to conduct an economic assessment of the various gas producing formations on the Eccles Quadrangle. As a result of the geologic and engineering analyses, it was determined that four formations, the Ravencliff, Big Lime, Maxton and Berea have been the major natural gas producing units in this region.

Since production data were limited and few well logs were available, there were severe constraints on the economic assessment. The biggest problems were:

> the number of wells completed prior to 1980. There were minimal pre-1980 production data available;
>
> discontinuous data. Many wells had production data for several years, then unexplained gaps. There were no data to explain whether the wells had been shut in or were producing, but not reported for these intervals;
>
> multiple wells per meter. In one area, several adjacent wells had identical production histories throughout their reported lives, except for the initial month. This was probably an indication that all of these wells were being run through a single meter.

Despite these problems, it was determined that fifteen of the study wells were producing primarily from the Big Lime and three wells were producing primarily from the Ravencliff. In addition, three wells included production from the "Maxton," and three from the Berea. The wells which were producing from the "Maxton" and Berea were actually multi-strata, commingled wells. Ultimately, the economic analysis identified two formations, the Big Lime and Ravencliff, as the primary drilling targets for the Eccles Quadrangle. Ninety percent of the producing wells on this map have been completed in one or both of these units.

Two methods were used to evaluate reserves and the initial-gas-in-place (OGIP). First, thirty-year reserves were estimated using a decline curve analysis approach, based on available production data. Then, values were calculated based on porosity footage and saturation values from well logs.

6.1 Economic Evaluation of Each Reservoir Type

The two reserve assessment approaches are described in greater detail below.

6.1.1 Decline Curve Analysis

A computer model was used to analyze decline curves of the production data for individual wells. The curves were projected out to a theoretical "economic limit." This limit was set at 120 mcf/month. Beyond this point, it was assumed that well maintenance costs would exceed well income.

The production analyses indicated that average initial production values were 72 mmcf/yr, with a decline ratio of -0.243 for Big Lime wells on the Eccles Quadrangle, and 34.5 mmcf/yr, with a decline ratio of -0.173 for wells producing from the Ravencliff. General decline curves for both formations are illustrated in **Figures** 6.1.1 and 6.1.2.

Table 6.1.1 presents a summary of the production analyses produced by the decline curve computer model. It is important to note that the assumptions and estimates used to calculate the initial gas production and decline ratio were quite conservative. They were based on an exponential fit technique for the data rather than a more optimistic hyperbolic fit approach.

Average thirty-year reserve figures were estimated at 367 MMcf for the Big Lime and 240 mmcf for the Ravencliff. The average Big Lime well should produce for 25 years before it reaches its economic limit, whereas the average Ravencliff should reach its economic limit in twelve years.

6.1.2 Geophysical Well Log Analysis

As a check on the values determined above, geophysical well logs were used to estimate the OGIP for selected wells on the Eccles Quadrangle. Four geophysical well logs were available for the Big Lime calculations, while eight well logs were collected showing the Ravencliff. The results of these analyses are summarized in **Table** 6.1.2.

For calculation purposes, gas saturation was assumed to be 70 percent, with average formation pressures of 500 psi for the Big Lime and 250 psi for the Ravencliff. The average pressure values were calculated based on data from the WVGES. Assumed well spacings were forty and eighty acres, respectively. The amount of recoverable gas was estimated to be sixty percent of the OGIP.

The log analysis method, based on eighty acre well spacing, predicts 72 MMcf of recoverable gas from the Big Lime and 96 MMcf from the Ravencliff. **Figure** 6.1.3 compares the results of the decline curve analysis and the geophysical well log calculations. The poor correlation between the estimates may be due to the fact that the geophysical logs are only able to measure and account for rock conditions in a limited area immediately adjacent to the borehole, while the decline curve analysis includes production effects from a larger area within the reservoir. It seems that porosity pods are coming and going very rapidly in this area, and that significant zones at some distance from the wellbore are contributing natural gas, but are not "seen" by logging tools.

6.2 Economic Evaluation of Production Methods

A commercial spreadsheet was used to analyze the economics of each producing formation. The cumulative cash-flow before federal income tax was computed based on an assumed 100% equity and a 77% success ratio. Initial cost estimates for drilling and single-stage completions in the Big Lime and Ravencliff were obtained from local operating companies. **Table** 6.2.1 summarizes these estimates. The economic analyses assumed well maintenance costs of $3,600.00 per year, a dry hole cost equal to 60% of the producing well cost, and a 77% success ratio. 12.5 % royalty payments and 8% state taxes were also incorporated in the model.

Figures 6.2.1 and 6.2.2 show the cumulative cash flow, before income tax, for a ten year period at various gas prices for wells producing from the Big Lime and Ravencliff sands. **Table** 6.2.2 summarizes the results of the economic analysis in terms of the payout period, based on gas prices ranging from $2.00/mcf to $3.00/mcf.

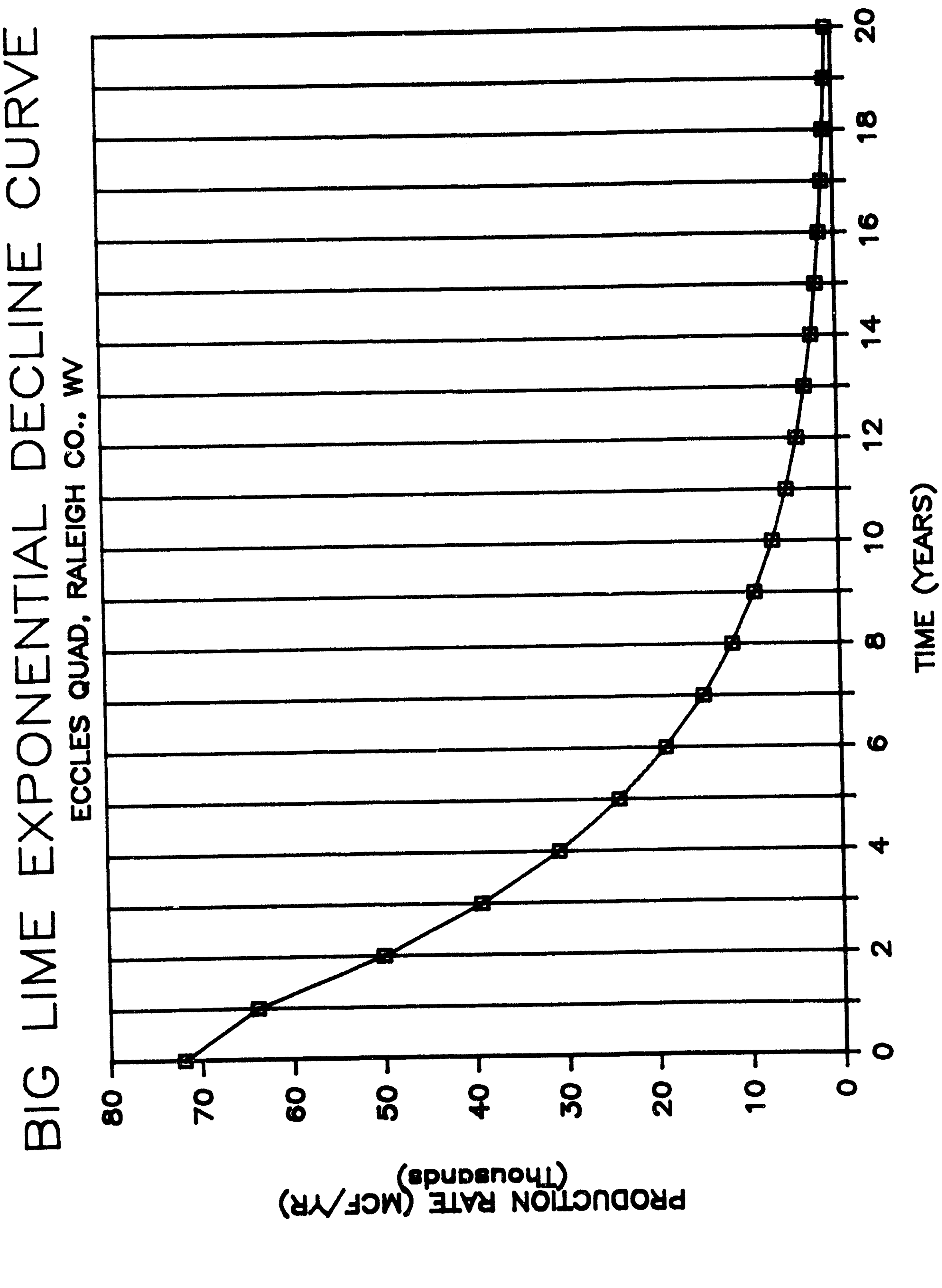


Figure 6.1.1 Big Lime Target Areas Production Decline Curve

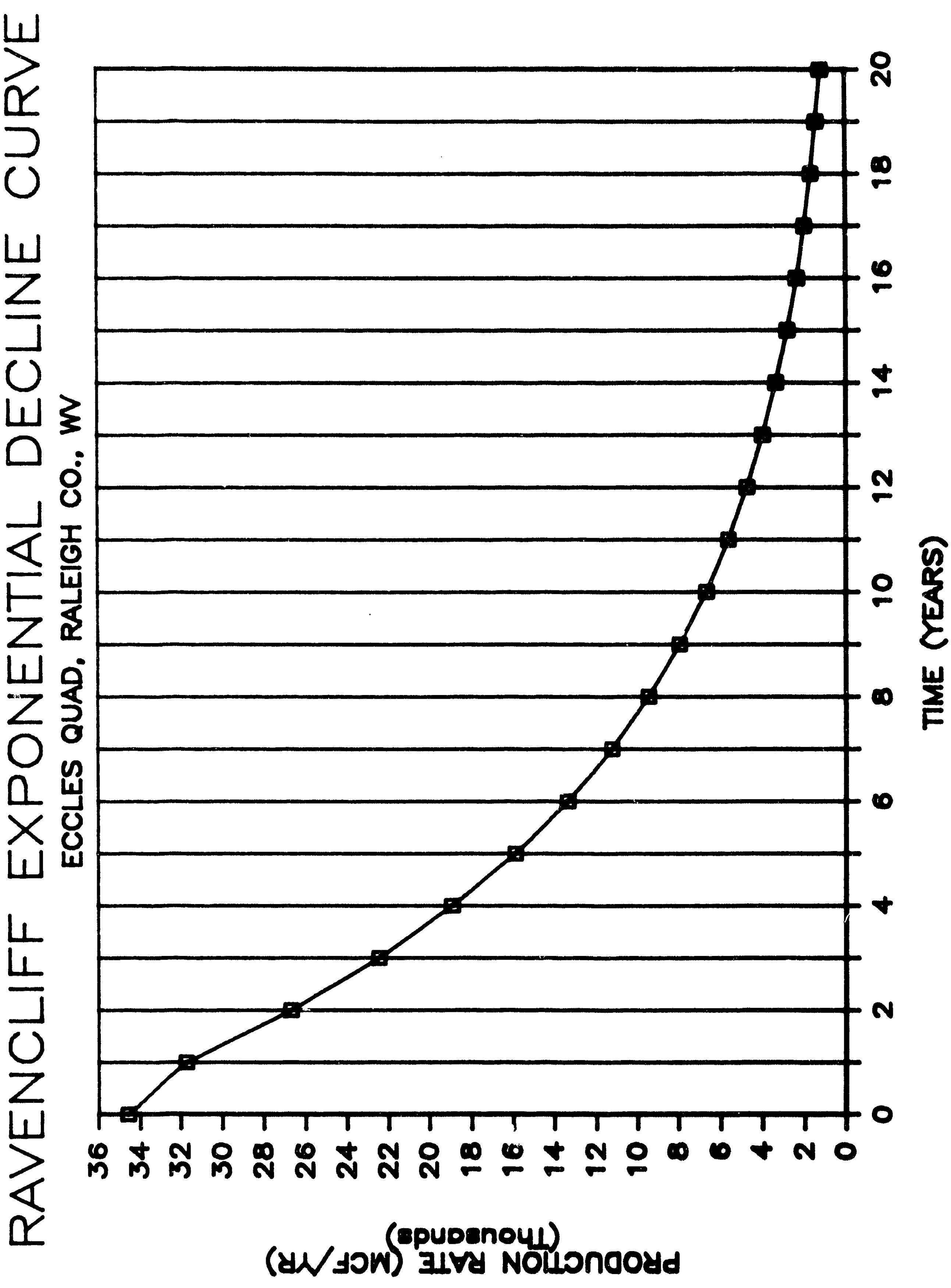


Figure 6.1.2 Ravencliff Production Decline Curve

Table 6.1.1 - PRODUCTION DECLINE ANALYSIS
ECCLES QUADRANGLE, RALEIGH COUNTY, WV

API Well No.	Initial Production Mcf/year	Decline Ratio Reciprocal Loss Ratio (1/E)	Thirty Year Reserve Mcf	Production To Economic Limit* Mcf	Time To Economic Limit* Years
BIG LIME FORMATION					
97	103,801	-0.10051	982,085	1,018,788	43
601	69,749	-0.23669	294,447	288,755	17
610	67,782	-0.28694	236,177	231,341	14
621	80,736	-0.21240	379,456	373,514	19
630	26,830	-0.01918	612,005	1,325,690	50
632	34,538	-0.37175	92,905	89,140	9
634	38,775	-0.38760	100,039	96,428	9
641	48,711	-0.41271	118,025	114,634	9
653	25,921	-0.32520	79,703	75,402	9
654	7,864	-0.20614	38,072	31,359	8
655	46,438	-0.14950	307,121	301,259	23
659	477,142	-0.25157	1,895,639	1,891,074	23
668	8,279	-0.23781	34,785	28,925	7
681	3,845	-0.32531	11,818	7,515	3
683	39,464	-0.11616	329,325	327,690	29
Average	71,992	-0.24300	367,440	413,434	18
RAVENCLIFF FORMATION					
85	22,971	-0.07960	262,088	270,996	15
91	26,416	-0.07707	308,799	324,583	17
703	54,382	-0.36232	150,090	146,229	4
Average	34,590	-0.17300	240,326	247,269	12

*Economic Limit = 1,400 Mcf/year

Table 6.1.2 - INITIAL GAS IN PLACE (IGIP)
USING GEOPHYSICAL WELL LOG DATA
ECCLES QUADRANGLE, RALEIGH COUNTY, WV

API Well No.	Thickness, feet	Porosity, percent	IGIP, Mcf/acre	IGIP, Mcf/40 acres	IGIP, Mcf/80 acres	Recoverable Gas @ 60%, Mcf/acre	Recoverable Gas @ 60%, Mcf/40 acres	Recoverable Gas @ 60%, Mcf/80 acres
BIG LIME FORMATION								
599	15	11.7	1,877	75,080	150,160	1,126	45,048	90,096
538	18	7.7	1,483	59,320	118,640	890	35,592	71,184
621	17	6.4	1,164	46,560	93,120	698	27,936	55,872
Average	17	8.6	1,508	60,320	120,640	905	36,192	72,384
RAVENCLIFF FORMATION								
540	30	8.3	1,189	47,560	95,120	713	28,536	57,072
538	38	8.2	1,497	59,880	119,760	898	35,92[illegible]	71,856
599	50	9.0	2,162	86,480	172,960	1,297	51,888	103,776
555	110	8.9	4,703	188,120	376,240	2,822	112,872	225,744
621	56	8.1	2,166	86,640	173,280	1,300	51,984	103,968
590	40	9.9	1,908	76,320	152,640	1,145	45,792	91,584
431	26	7.8	968	38,720	77,440	581	23,232	46,464
297	60	4.8	1,369	54,760	109,520	821	32,856	65,712
Average	51	8.1	1,995	79,810	159,620	1,197	47,886	95,772

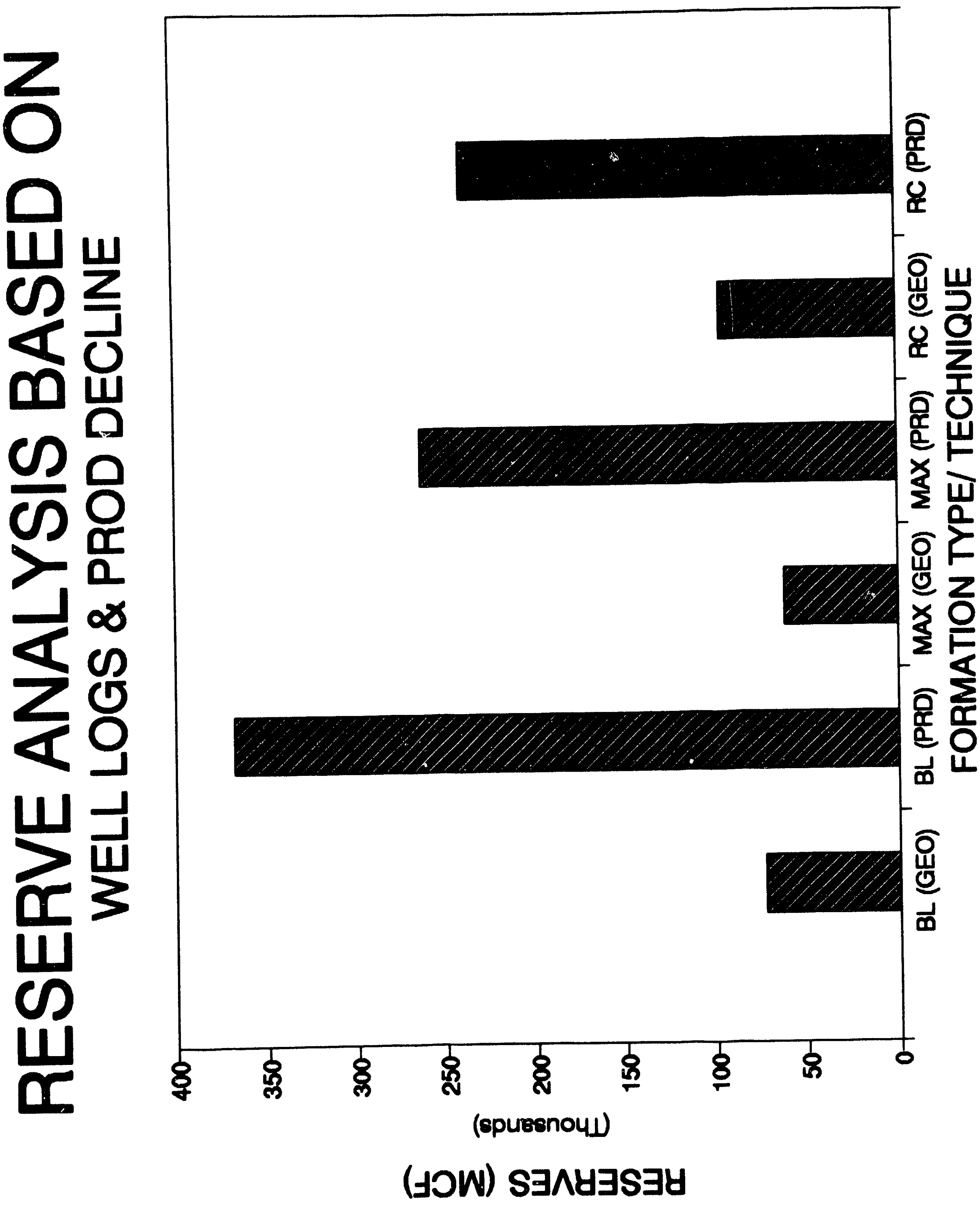

RESERVE ANALYSIS BASED ON
WELL LOGS & PROD DECLINE
RESERVES (MCF)
(Thousands)
400
350
300
250
200
150
100
50
0
BL (GEO)
BL (PRD)
MAX (GEO)
MAX (PRD)
RC (GEO)
RC (PRD)
FORMATION TYPE/ TECHNIQUE

Figure 6.1.3

Table 6.2.1 - WELL COSTS
ECCLES QUADRANGLE, RALEIGH COUNTY, WV

Target Formation	Cost Estimate *
Ravencliff	$110,000
Maxton/Big Lime	$155,000
Weir/Berea	$165,000

* Cost estimate includes drilling, completion and pipeline
Dry hole cost = 60% of producing well cost

Table 6.2.2 - PAY-OUT ANALYSES
BIG LIME AND RAVENCLIFF WELLS
ECCLES QUADRANGLE, RALEIGH COUNTY, WV

Gas Price, $/Mcf	Pay-Out Period, years
	BIG LIME WELLS
$2.00	2.1
$2.50	1.5
$3.00	1.3
	RAVENCLIFF WELLS
$2.00	3.5
$2.50	2.5
$3.00	2.1

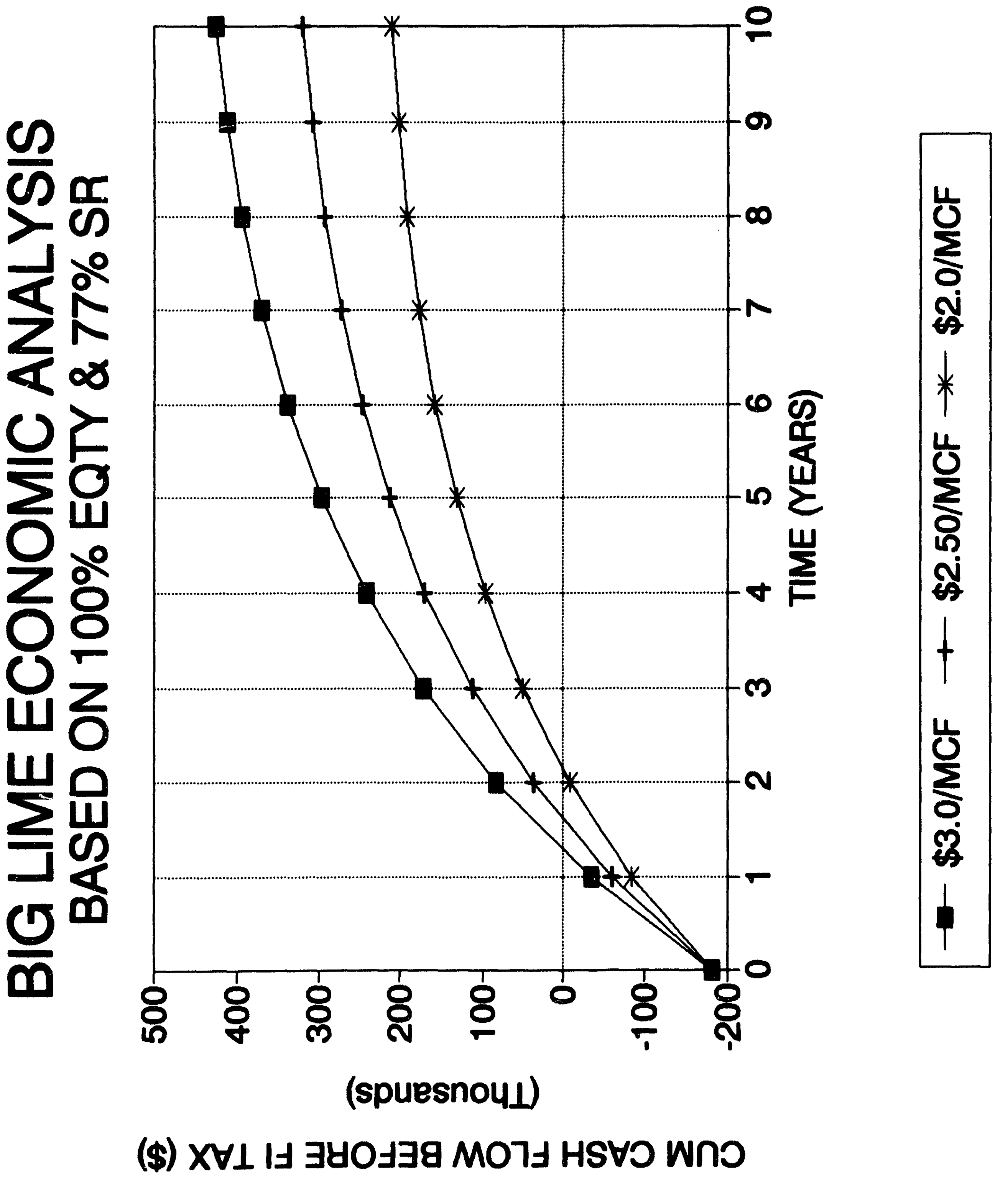
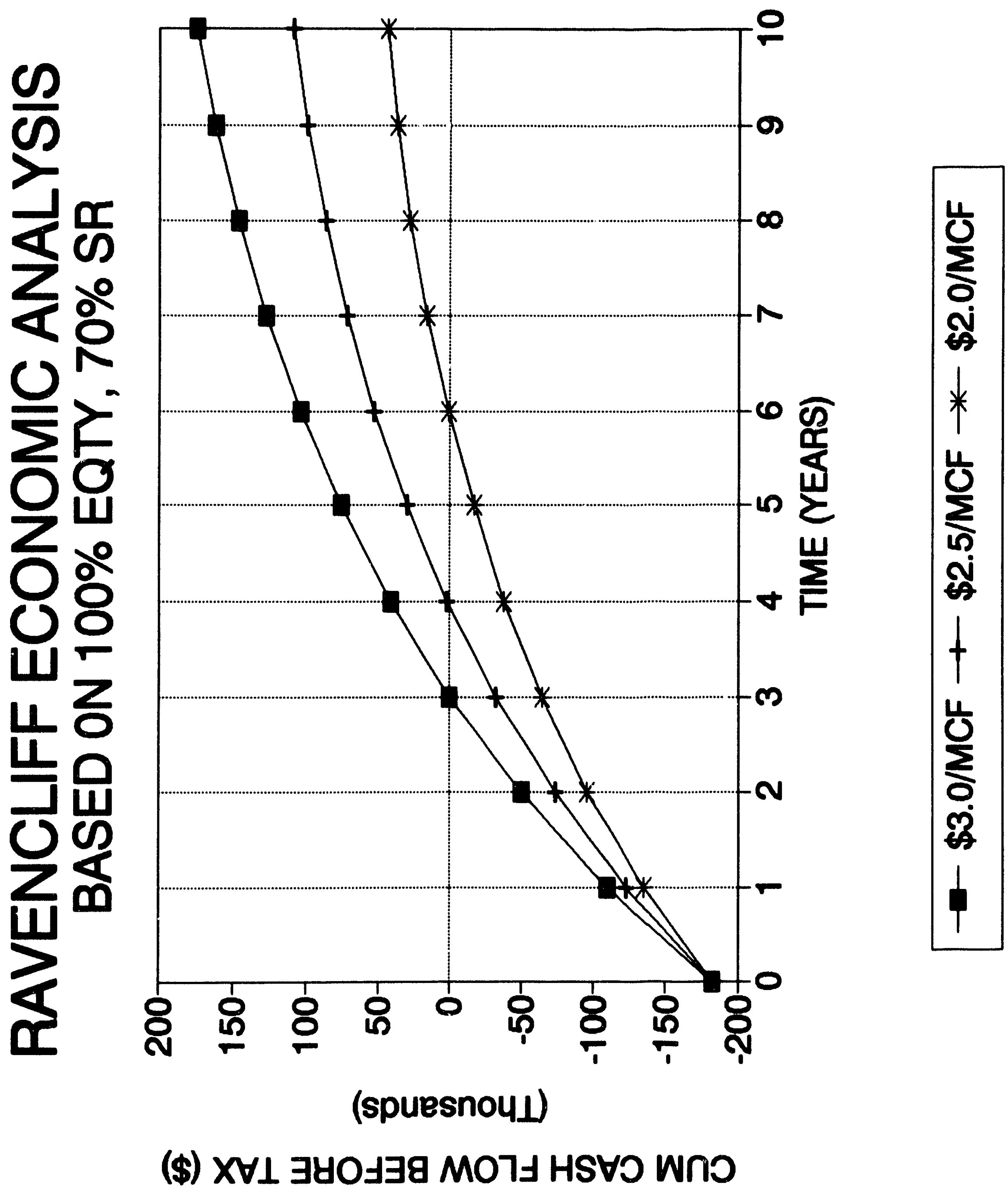

BIG LIME ECONOMIC ANALYSIS
BASED ON 100% EQTY & 77% SR
CUM CASH FLOW BEFORE FI TAX ($)
(Thousands)
500
400
300
200
100
0
-100
-200
0
1
2
3
4
5
6
7
8
9
10
TIME (YEARS)
$3.0/MCF
$2.50/MCF
$2.0/MCF

Figure 6.2.1



RAVENCLIFF ECONOMIC ANALYSIS
BASED 0N 100% EQTY, 70% SR
CUM CASH FLOW BEFORE TAX ($)
(Thousands)
200
150
100
50
0
-50
-100
-150
-200
0
1
2
3
4
5
6
7
8
9
10
TIME (YEARS)
$3.0/MCF
$2.5/MCF
$2.0/MCF

Figure 6.2.2

7.0 ECONOMIC ASSESSMENT OF MULTI-STRATA CONCEPTS

The overall economics of the project were evaluated in several ways to identify possible problems.

7.1 Exploration and Development Costs

Engineering models were used to predict the reserves and to estimate the cumulative production-to-economic-limit for the existing wells in the study areas.

A resource map, showing the OGIP for the Big Lime, Ravencliff and Coals, combined, was generated. Based on this map, this amount of producible gas at each of the proposed sites was determined, and the economics of the selected sites projected.

The resource analysis indicated that the methane from the coalbeds should contribute significantly to the productivity of these wells. In many cases, the methane reserves could approximately double the overall productivity of a well.

The average thirty-year reserve figure for a Big Lime well is 374 mmcf, while the average increase in reserves assignable to methane production should be 200 mmcf. At a wellhead price of $1.70/mcf, the additional revenue generated by methane production would be $340,000.00. The multi-strata exploration and development technique will significantly improve the overall revenues for wells in the Raleigh County study area.

7.2 Comparison of Current Completion Techniques and The Proposed Multi-Strata Approach

Almost all of the modern wells on the Beckley and Crab Orchard Quadrangles have been drilled through the Ravencliff Sand, and been tested in more than one formation. Significant economic production on these quadrangles, nevertheless, has been limited almost exclusively to the Ravencliff "F" Channel. There is little production deeper than Ravencliff on either of these maps. There are few true multi-strata wells on these quadrangles, due to a lack of economic quantities of gas so far discovered below the Ravencliff.

On the Eccles and Lester Quadrangles, the "D" Channel Ravencliff sand is much less productive than the "F" Channel, while the Big Lime frequently has good reserves on top of the Basement high block. No other units are consistently productive over large areas on these maps.

To be an economic producer, a well on the Eccles or Lester Quadrangle needs to encounter an exceptional Big Lime reservoir or to be completed in multiple zones, including all formations showing potential signs of natural gas. The multiple stage completion techniques currently being used in this area have not included any production from coal seams.

Even with the multiple completions that are common on the Eccles Quadrangle, several wells there have had total combined projected reserves of less than 10 mmcf and many more have under 100 mmcf of projected reserves. Such wells will never pay back their drilling costs.

To increase the potential economic return, this project is designed to formulate a drilling plan and well completion design that will add significant quantities of economically attractive methane to the total resource base at marginal increases in cost.

The Multi-Strata concept envisions a standard well completion along with a shallow dewatering mechanism for methane extraction from the coal. The methane would be commingled with conventional natural gas production from the deeper reservoir beds. The natural gas and methane will be metered separately, prior to blending into a pipeline quality mix. The local methane is of high quality and should not present BTU problems in a blend. The extra well costs involved in a Multi-Strata completion should be minimal when evaluated in light of the increase in the resource base.

7.3 Completion Equipment and Procedures

The coalbed methane and conventional natural gas will be produced separately via independent casing and/or tubing strings. The coalbed methane will be produced through the annulus of the 8-5/8" casing and will be metered using an orifice meter prior to its entering the common pipeline system. Deeper natural gas will be produced via 4 1/2" casing and a 1.9" OD tubing system. It also will be metered prior to entering the common pipeline using a second orifice meter. The orifice meters will be sized on the basis of openflow tests and/or pressure build-up tests.

It is anticipated that coalbed pressures will be too low to produce directly into a pipeline. Therefore, a small compressor will probably have to be installed near the well. The compressor will be sized to match the expected production rate from the coalbeds. A common pipeline will be used to transport the natural gas from the coalbeds and the and the deeper formations. This pipeline will consist of approximately 2500' of 1 1/4" to 2" plastic pipe conforming to ASTM standards for natural gas. The actual size of the pipe will depend on the rate at which the gas must be transported.

Although, based on available information, it is believed that continuing water production from the coals and from the deeper natural gas formations will not be excessive, a string of tubing will be installed for swabbing or pumping. A 100 barrel water tank will be installed to handle water production. Downhole completion techniques using external casing packers, port collars and/or slotted pup joints will be used to gain access to the behind-the-pipe formations for cementing, stimulation, and/or production purposes. In all cases, available standard completion and production equipment will be used which will not require the design of any special field equipment.

7.4 Projected Economics of the Selected Test Areas

Five potential well locations were selected during the project. These sites have projected production from the Big Lime, Ravencliff, and the major coal seams. OGIP reserve estimates for the proposed sites were computed using **Figure** 4.4.1. The recoverable gas was estimated to be 60 percent of the OGIP.

Table 7.4.1 shows the results of the economic analyses in dollars/Mcf for the various proposed sites and for typical Big Lime and Ravencliff wells. Two scenarios were run. The first exhibits dollars/Mcf with development costs included. The second scenario excludes any development costs. Proposed sites 1 and 2 are economically attractive when the development costs are eliminated.

Figure 7.4.1 shows a projected cumulative methane production curve for a hypothetical well producing from the Pocahontas and Beckley Seams in southern West Virginia. The average 20-year cumulative production value has been estimated at 260 MMcf. The producible methane reserve at the proposed five sites are included in **Figure** 7.4.2.

A cash flow model was used to evaluate the economics of the methane wells. For the purpose of the model, an average decline ratio of -0.1464 was assumed, with an estimated initial production of 41,235 mcf/year. The payout period was projected at 1.5 years. **Figure** 7.4.3 illustrates the results of the economic analysis for a typical hypothetical methane well.

Table 7.4.1 - RESOURCE AND DEVELOPMENT COST ESTIMATES
FIVE PROPOSED DRILLING LOCATIONS
ECCLES QUADRANGLE, RALEIGH COUNTY, WV

Cost Estimates:

Big Lime Well	=	$155,000
Ravencliff Well	=	$110,000
Dual Completion	=	$200,000*

Proposed Site	GAS RESOURCE ESTIMATES: Coal-Bed Methane, MMcf/acre	Conventional Gas Resource, MMcf/acre	Combined Resource, MMcf/acre	Combined Resource, MMcf/55 acres	Estimated Production, MMcf	Development Costs, $/Mcf
Dual-Completion Wells*						
1	8	9	17	935	701	$0.29
2	8	8	16	880	660	$0.30
3	6	6	12	660	495	$0.40
4	7	3	10	550	413	$0.48
5	4	8	12	660	495	$0.40
Average Dual-Completion Well					553	$0.38
Average Big Lime Well					367	$0.42
Average Ravencliff Well					240	$0.46

*Assumes that the well is completed in the coal-bed plus one conventional formation, either Big Lime or Ravencliff.

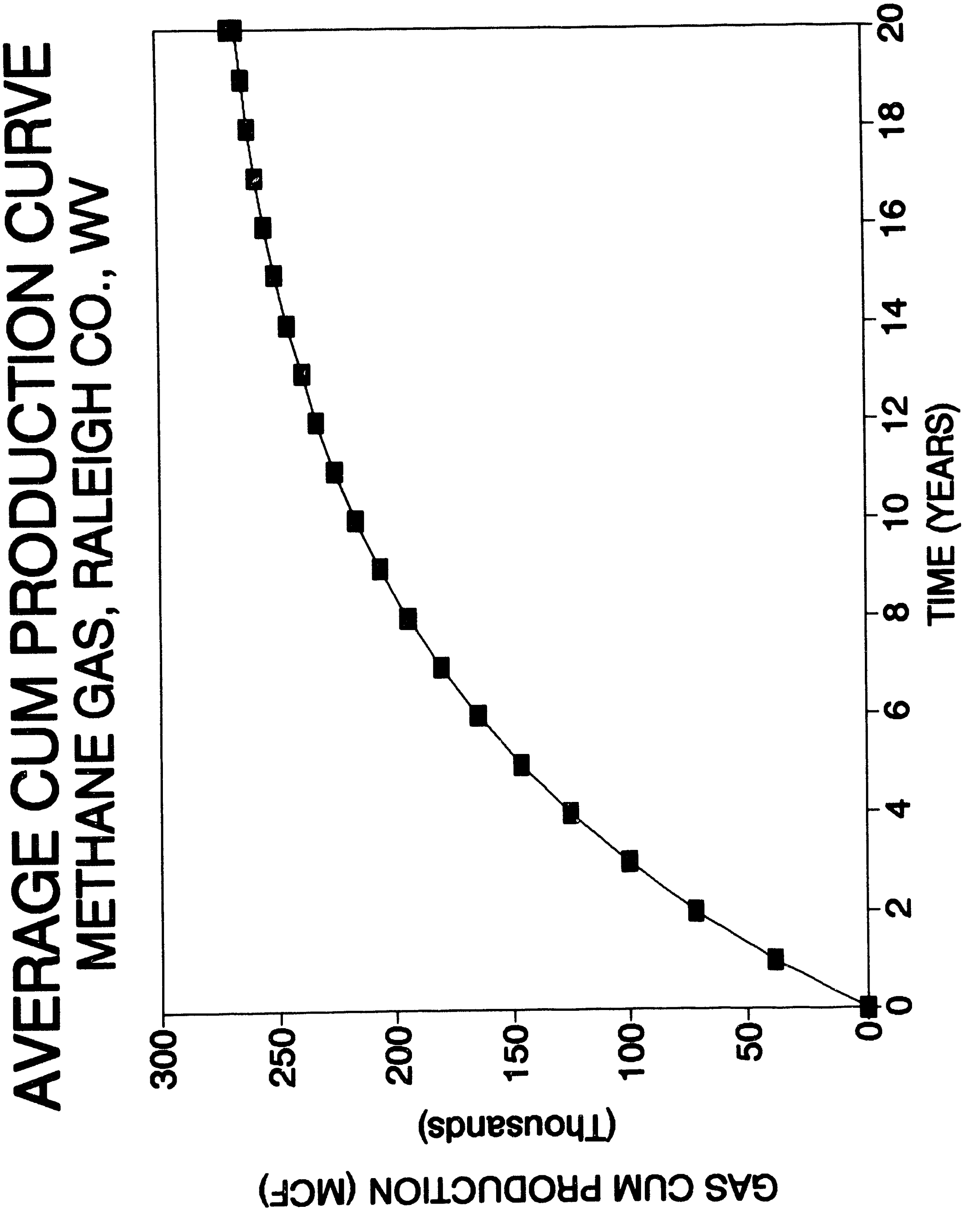

AVERAGE CUM PRODUCTION CURVE
METHANE GAS, RALEIGH CO., WV
GAS CUM PRODUCTION (MCF)
(Thousands)
300
250
200
150
100
50
0
0
2
4
6
8
10
12
14
16
18
20
TIME (YEARS)

Figure 7.4.1

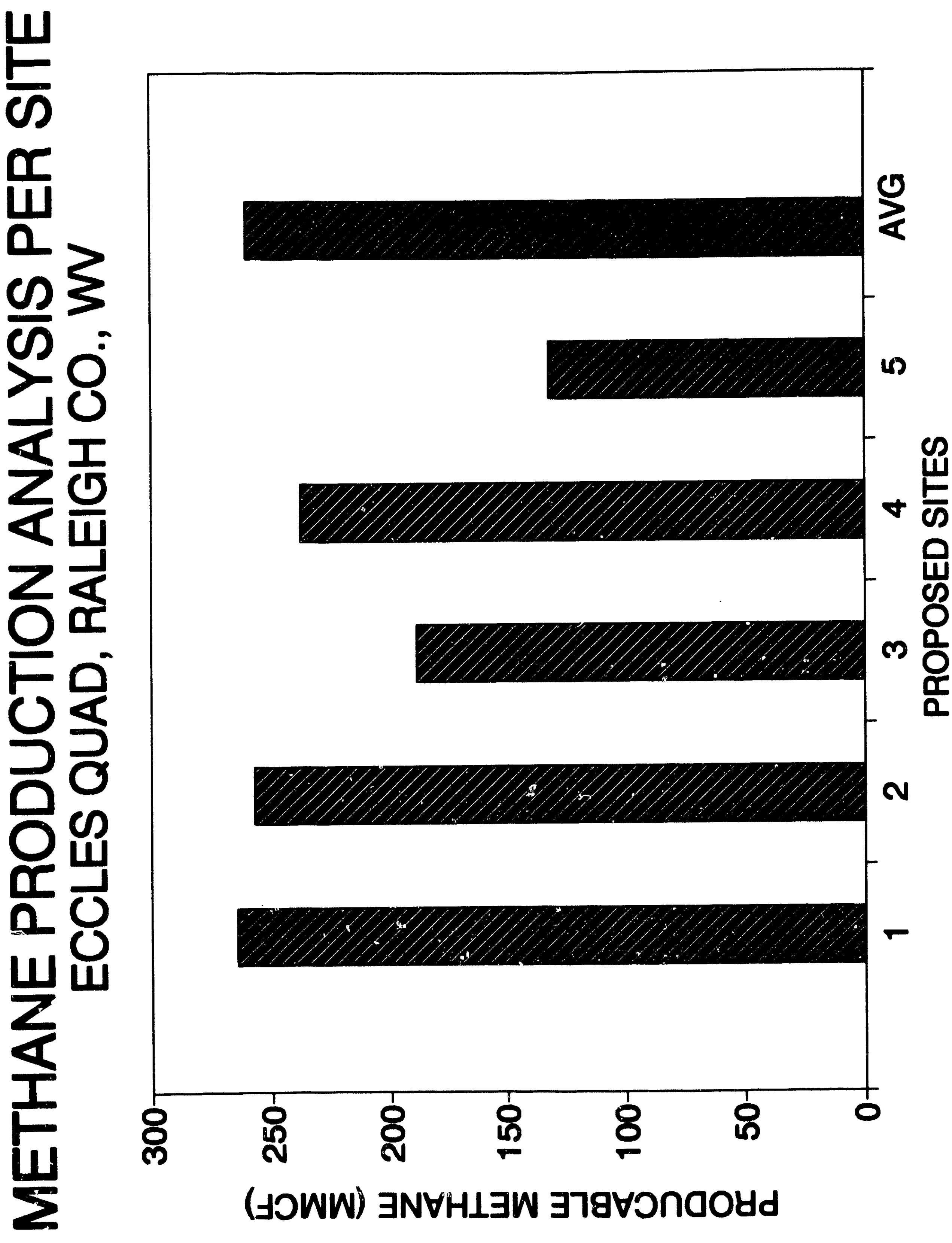

METHANE PRODUCTION ANALYSIS PER SITE
ECCLES QUAD, RALEIGH CO., WV
PRODUCABLE METHANE (MMCF)
0
50
100
150
200
250
300
PROPOSED SITES
1
2
3
4
5
AVG

Figure 7.4.2

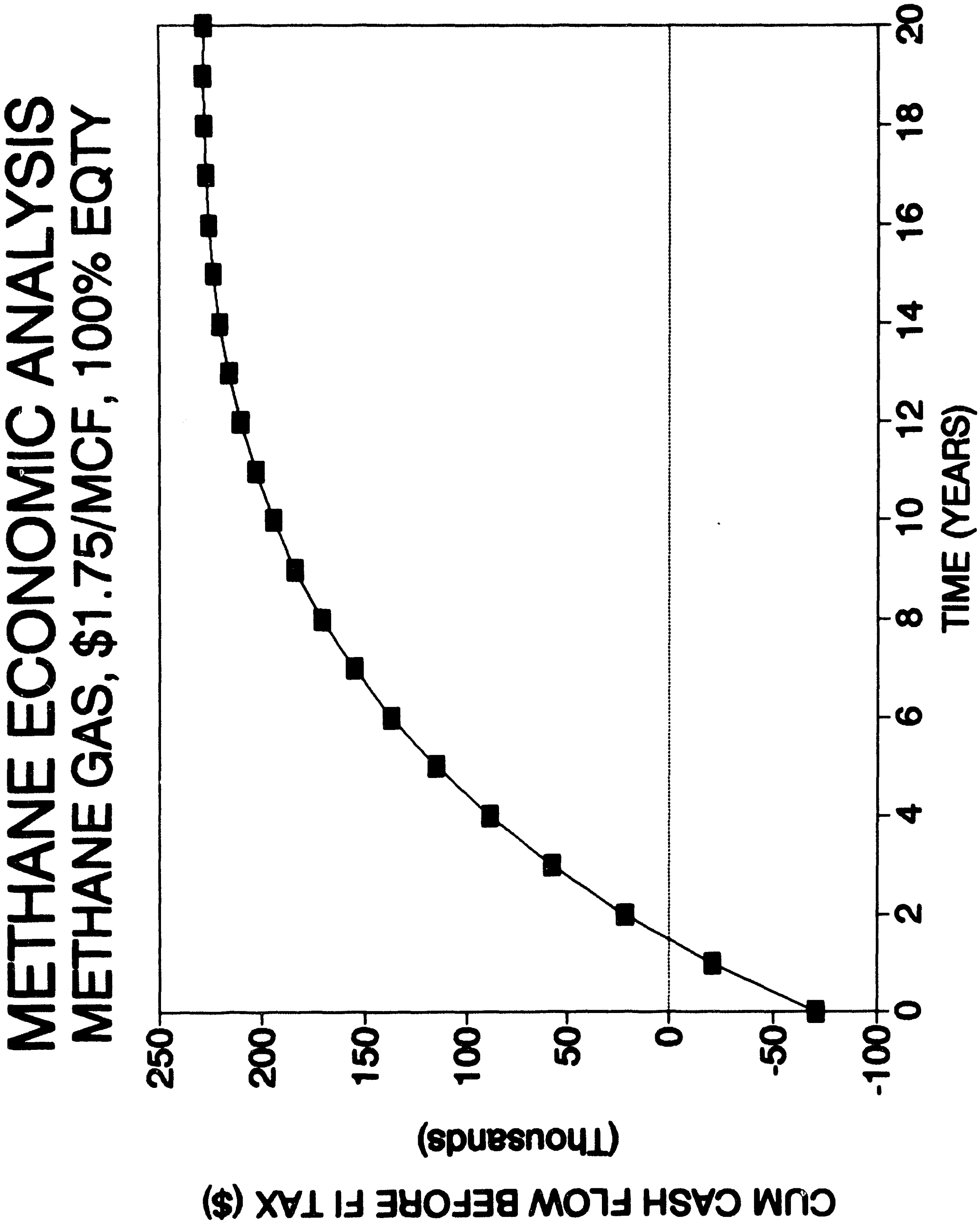

METHANE ECONOMIC ANALYSIS
METHANE GAS, $1.75/MCF, 100% EQTY
CUM CASH FLOW BEFORE FI TAX ($)
(Thousands)
250
200
150
100
50
0
-50
-100
0
2
4
6
8
10
12
14
16
18
20
TIME (YEARS)

Figure 7.4.3

Finally, the cash flow model for a projected methane well was utilized in an analysis of the economic feasibility of co-producing methane and natural gas from multiple formations at the different proposed sites. An average decline ratio of -0.1875 was computed and used to predict the production performance over a twenty year period. **Table** 7.4.2 summarizes the economic estimates for the proposed sites.

The producible gas reserve values from **Table** 7.4.1 were used as a constraint for the cash flow model. **Figure** 7.4.4 and **Table** 7.4.3 summarize the results of the economic analyses, including payout periods.

7.5 Identification Of Potential Problems For The Multi-Strata Concept

In addition to the geologic, engineering, and economic considerations discussed above, it was recognized that certain legal and environmental factors could affect the Multi-Strata project. Several of the most important non-geologic, non-engineering aspects of the program are discussed below.

7.5.1 Mineral Rights Ownership

A major aspect of the development of any mineral or energy resource has always been the establishment of clear and uncontested ownership of mineral rights or access to those mineral rights by lease. In West Virginia, mineral rights have frequently been severed from the surface land ownership for many decades. The owners of large land tracts, some dating back to colonial times, others of which were put together in the 1800's, often transferred mineral rights, including oil and gas, coal, limestone, salt and other ore mineral rights to various large holding interests. Rights were commonly severed from the surface ownership, even as the surface tracts were fragmented and changed hands many times.

In Raleigh County, coal mineral rights have generally been assembled into large blocks for mining purposes. Quite often a holding company will own all coal, but will lease the rights to mine and sell an individual seam to another corporation for a flat fee plus a royalty charge on each ton of coal mined.

As long as the methane associated with a coalseam was being vented before or during the mining process and was deemed to have little or no commercial value, ownership of that methane was of little interest. However, if an operator other than the coal owner should wish to recover and sell the methane from a seam, without associated income-generating mining, they would likely have to determine ownership rights, unless the methane rights were specially discussed in the original lease to operate and sell coal. This determination would probably involve the oil and natural gas owner.

Because of the separation of ownership, major efforts will have to be mounted in programs involving methane production to develop joint venture agreements between coal owners and oil and gas mineral rights owners. In addition, fair and equitable arrangements need to be made with surface owners regarding disruptions of the surface by drilling operations.

A significant effort has been required to negotiate the numerous agreements needed for this project. With these agreements now in place, field activities are scheduled to begin in April 1991. The resultant agreements can serve as a model for others for similar multi-strata joint venture recovery operations.

7.5.2 Coalbed Water Disposal

To recover methane from the coalbeds, water must be removed from the seams. This water normally fills the fractures in the cleat systems and prevents or retards the flow of methane gas into the well

Table 7.4.2 - ASSUMPTIONS USED IN CASH FLOW ANALYSES
FIVE PROPOSED DRILLING LOCATIONS
ECCLES QUADRANGLE, RALEIGH COUNTY, WV

Decline Ratios:	Big Lime	=	-0.2430
	Ravencliff	=	-0.1730
	Methane	=	-0.1464
	Average Decline	=	-0.1875
Gas Price	=	$1.90/Mcf	
Success Ratio	=	77% & 100%	
Equity	=	100%	
Cost of Development, Drilling and Completion		=	$200,000
Maintenance Cost (per year)		=	$3,600
State Taxes		=	8.00%
Royalty		=	12.50%

Table 7.4.3 - CASH FLOW ANALYSIS
FIVE PROPOSED DRILLING LOCATIONS
ECCLES QUADRANGLE, RALEIGH COUNTY, WV

Proposed Site Number	Success Ratio = 100%		Success Ratio = 77%	
	Pay-Out Period, yrs.	Internal Return, %	Pay-Out Period, yrs.	Internal Return, %
1	1.5	44	2.1	34
2	1.7	40	2.2	31
3	2.1	26	3.3	19
4	3.0	17	4.7	12
5	2.3	25	3.5	18

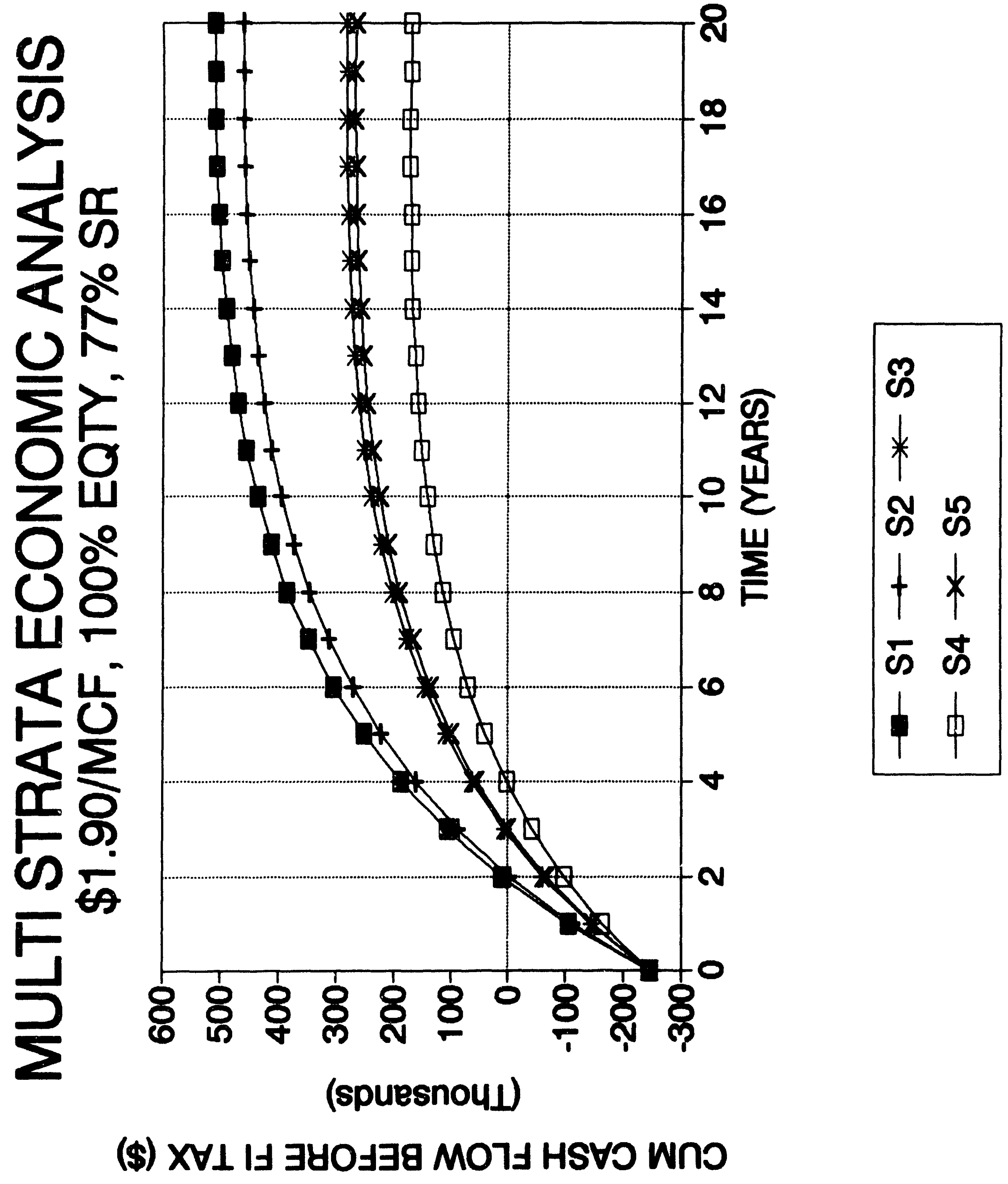

MULTI STRATA ECONOMIC ANALYSIS
$1.90/MCF, 100% EQTY, 77% SR
CUM CASH FLOW BEFORE FI TAX ($)
(Thousands)
600
500
400
300
200
100
0
-100
-200
-300
0
2
4
6
8
10
12
14
16
18
20
TIME (YEARS)
S1
S2
S3
S4
S5

Figure 7.4.4

bore. Quite often, water must be pumped for six months or longer from a coalbed methane well before significant quantities of methane gas will be produced.

Dewatering requires environmentally acceptable means of handling and disposal of the produced water. Depending upon the chemistry of the materials contained in the water (chlorides, sulfur, iron, dissolved solids, etc.) discharge into surface streams may be possible after minor treatment. If the water quality is lower, it may be possible to pump the water into abandoned coal mines after treatment in effluent treatment plants, or into disposal wells drilled specifically for this purpose.

In some areas, considerable volumes of water may have to be handled which could significantly impact the economics of the overall plan. The range of costs associated with these activities were too speculative and variable to accurately assess until actual field data has been collected. Therefore, these costs, if any, have not yet been included in the estimates for this project.

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2. Kamm, M.W. and Heald, M.T., 1983. Petrology and Diagenesis of the Ravencliff Sandstone in West Virginia; Southeastern Geology, V. ?4, No. 1.

3. Kelleher, G.T., 1990. Stratigraphy and Diagenesis of the Greenbrier Group in the Rhodell Field Area of Southern West Virginia; Unpublished Master's Thesis, West Virginia University, Morgantown, West Virginia.

4. ?opp, J.T. and McCulloch, C.M., 1976. Geological Factors Affecting Methane in the Beckley Coalbed; U.S. Department of Interior, Bureau of Mines Report of Investigations, No. 8137, 35 p.

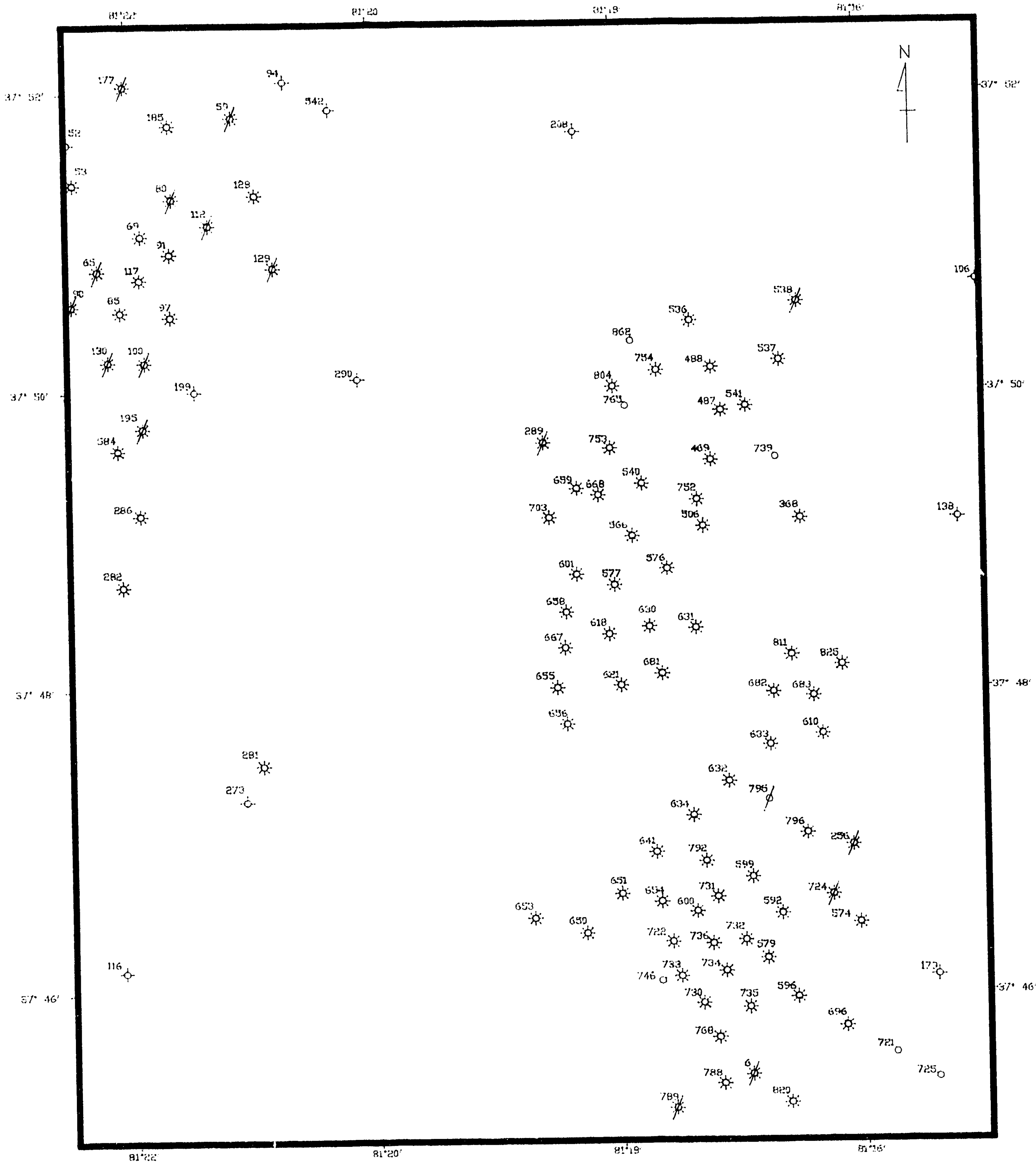
5. Wrightstone, G.R., 1984. Ravencliff Becomes Exploration Target; Northeast Oil Reporter, V. 4, No. 9, pp 33-41.

6. Wrightstone, G.R., 1985. The Stratigraphy and Depositional Environment of the Ravencliff Formation in McDowell and Wyoming Counties; Unpublished Master's Thesis, West Virginia University, Morgantown, West Virginia.

APPENDIX A

GEOLOGY DATA BASE

A-1 ECCLES QUAD DATABASE



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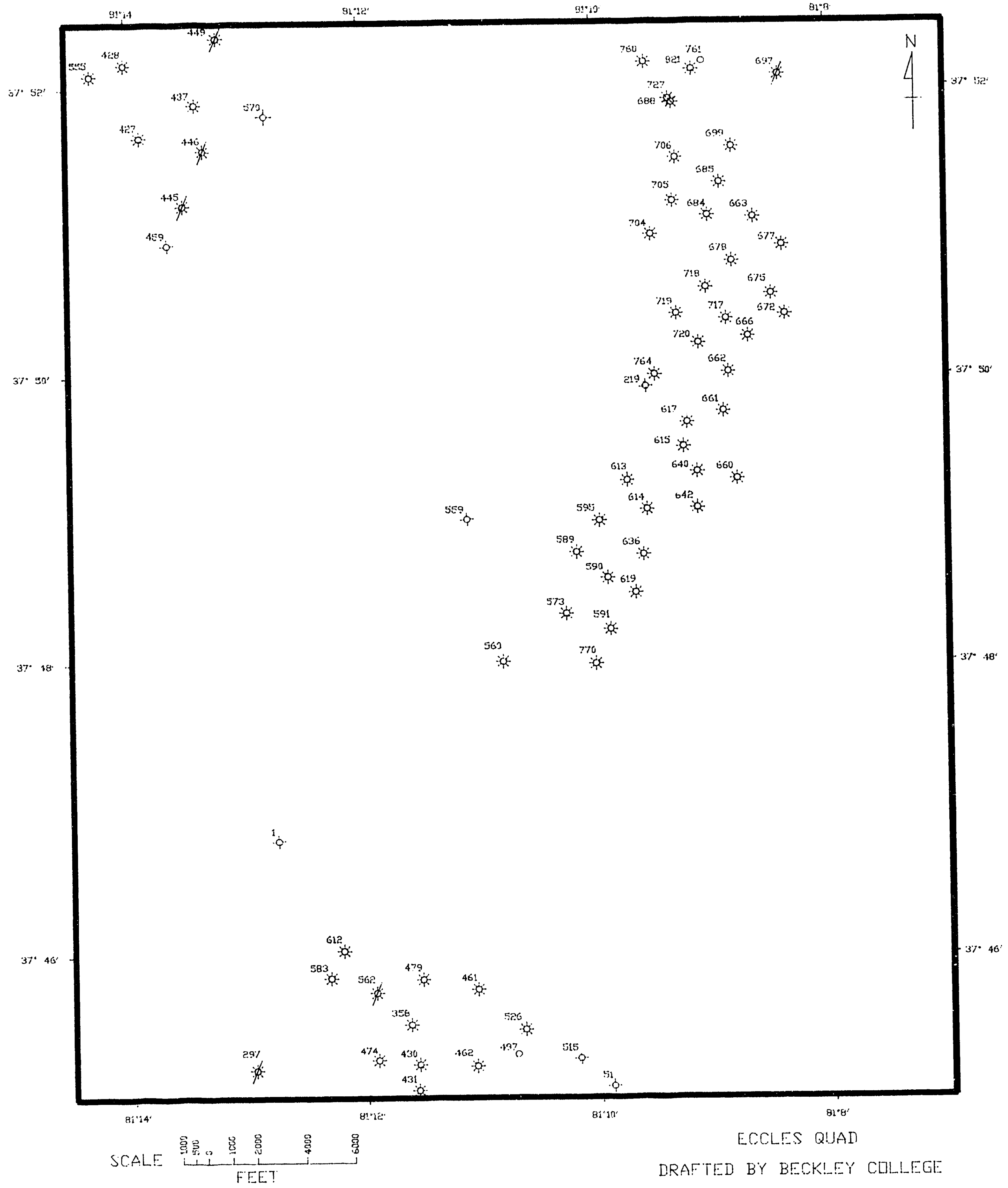
ECCLES QUAD

DRAFTED BY BECKLEY COLLEGE

A-2 BECKLEY QUAD DATABASE



ECCLES QUAD

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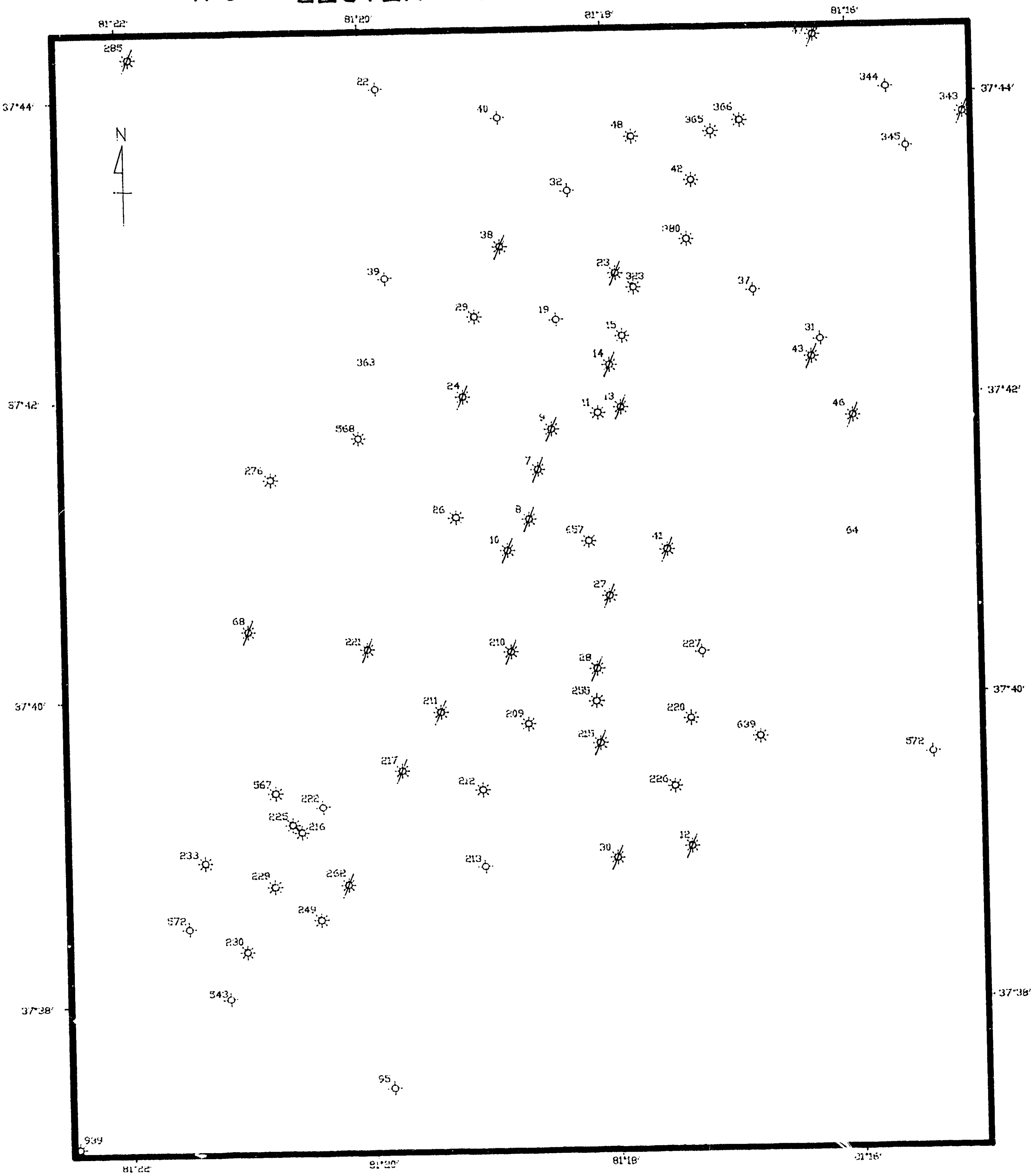
A-3 LESTER QUAD DATABASE



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LESTER QUAD

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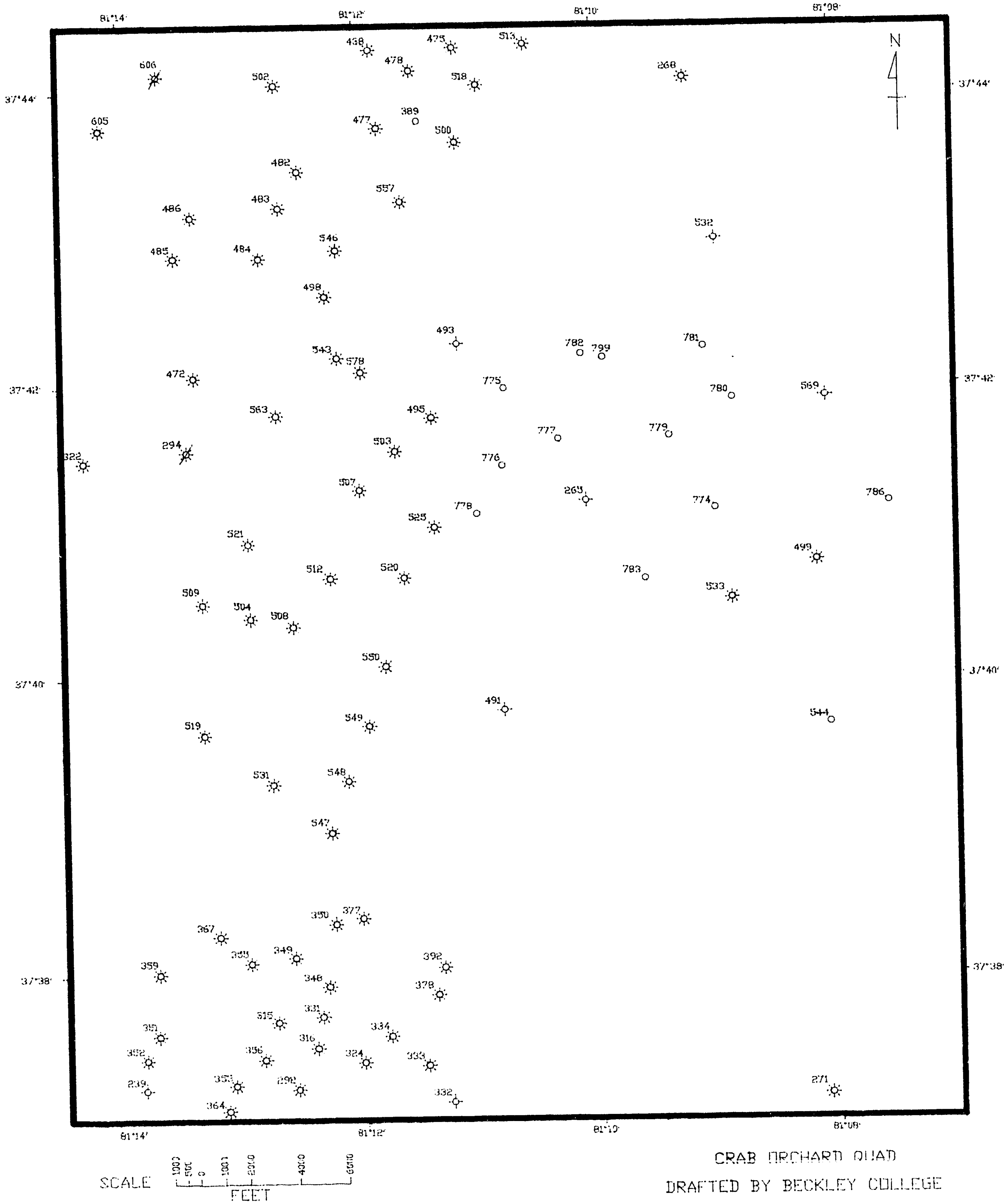
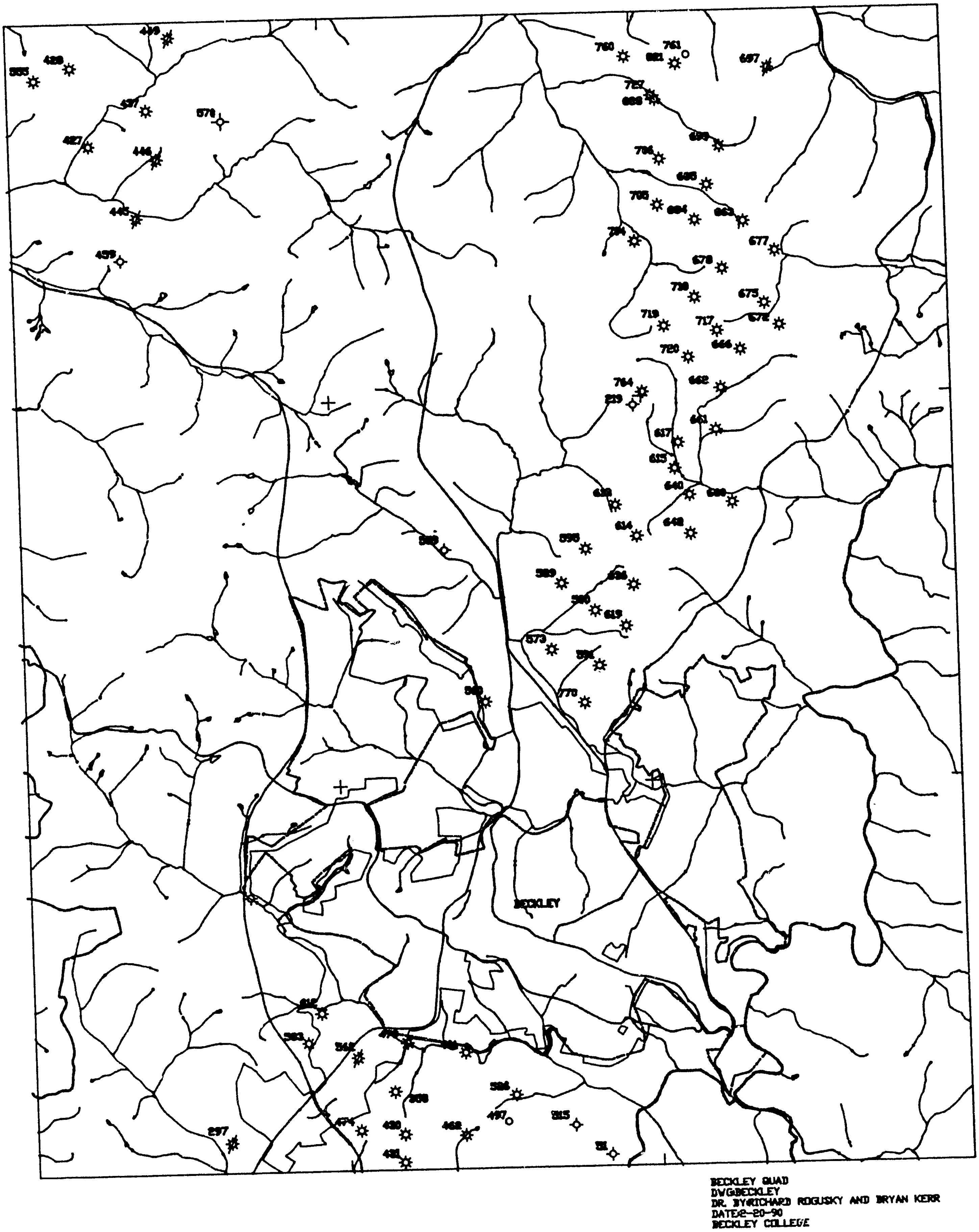
A-4 CRAB ORCHARD QUAD DATABASE



CRAB ORCHARD QUAD

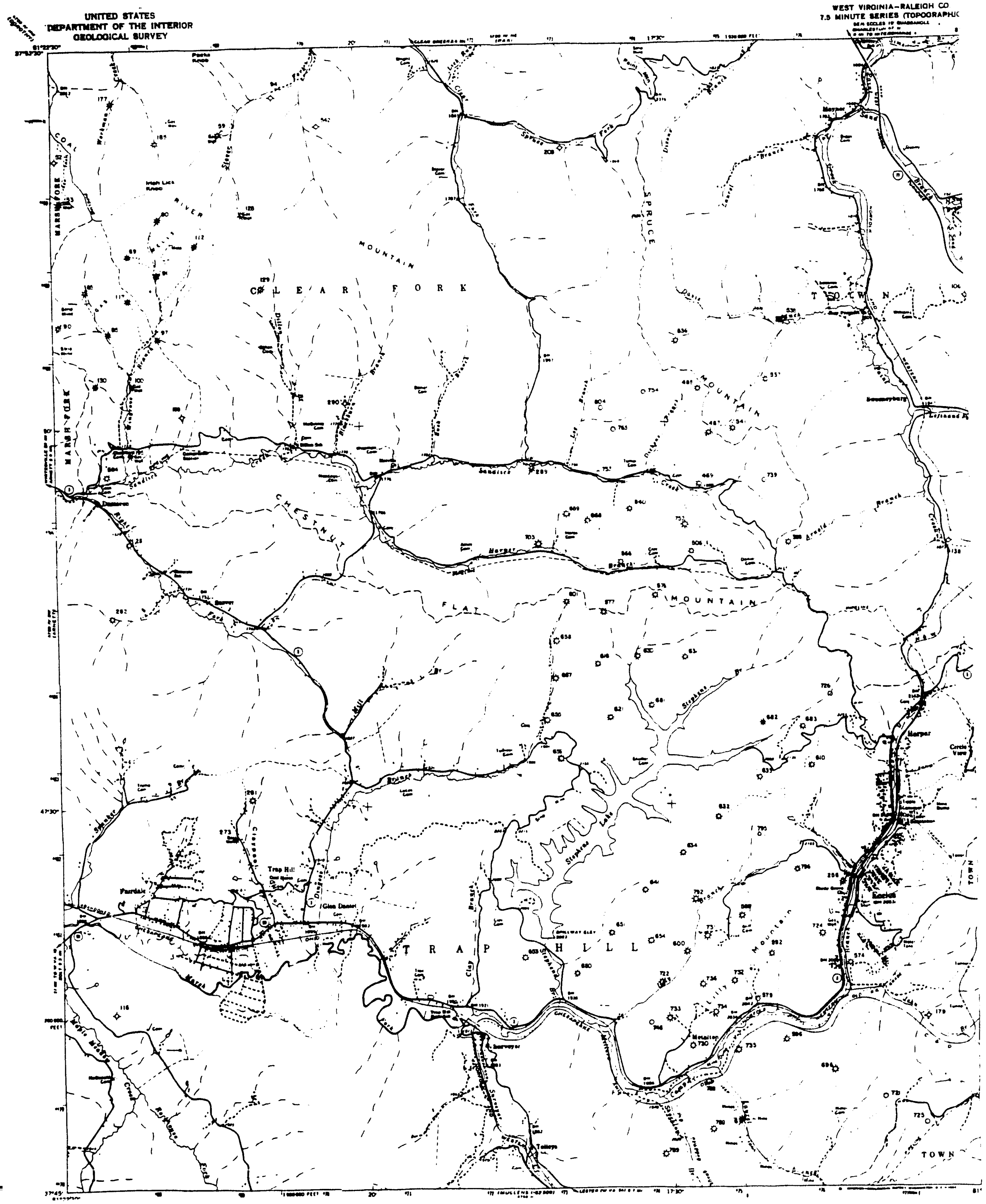
DRAFTED BY BECKLEY COLLEGE

A-5 BECKLEY QUADRANGLE BASE

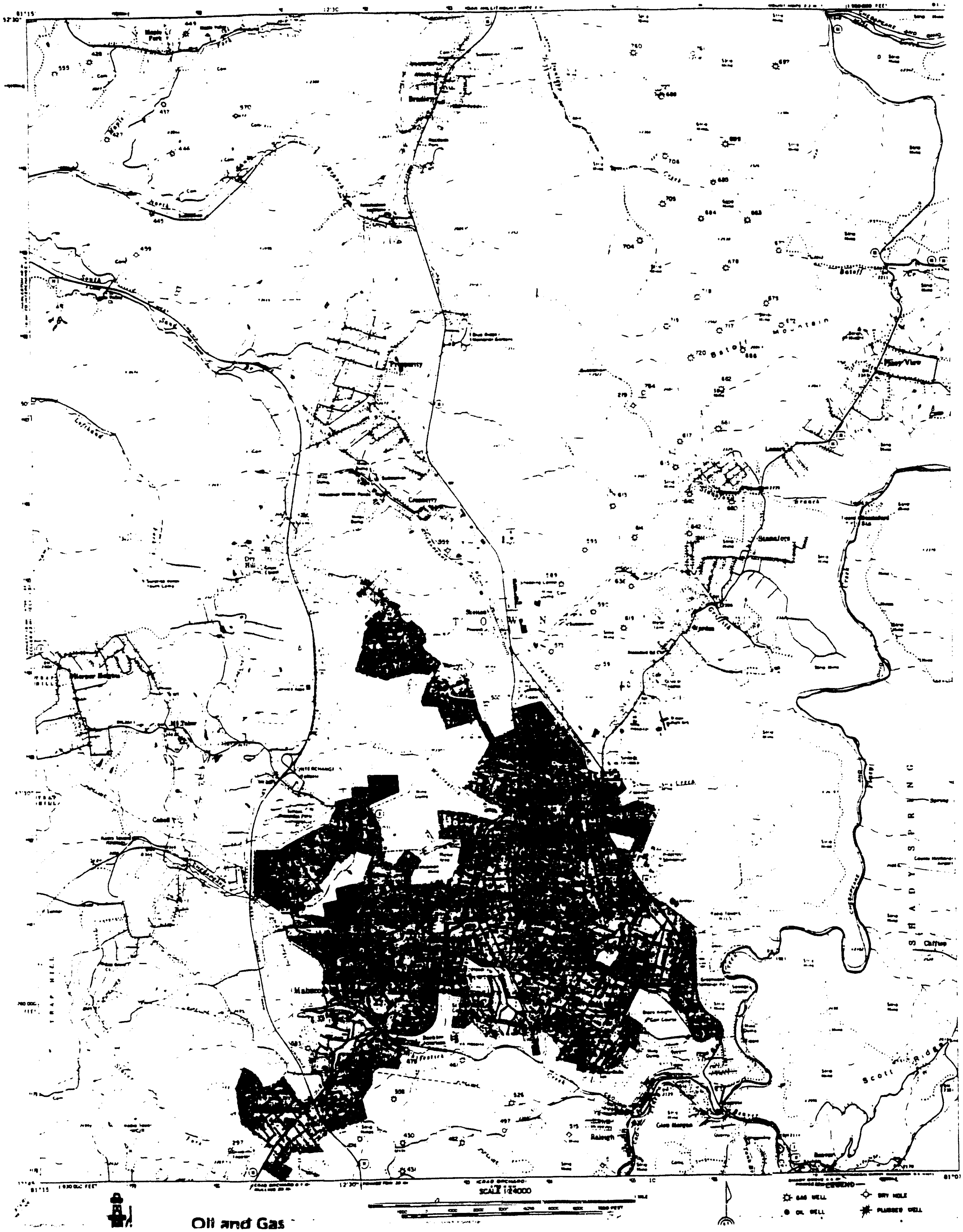


BECKLEY QUAD
DWG:BECKLEY
DR. BY:RICHARD ROGUSKY AND BRYAN KERR
DATE:2-20-90
BECKLEY COLLEGE

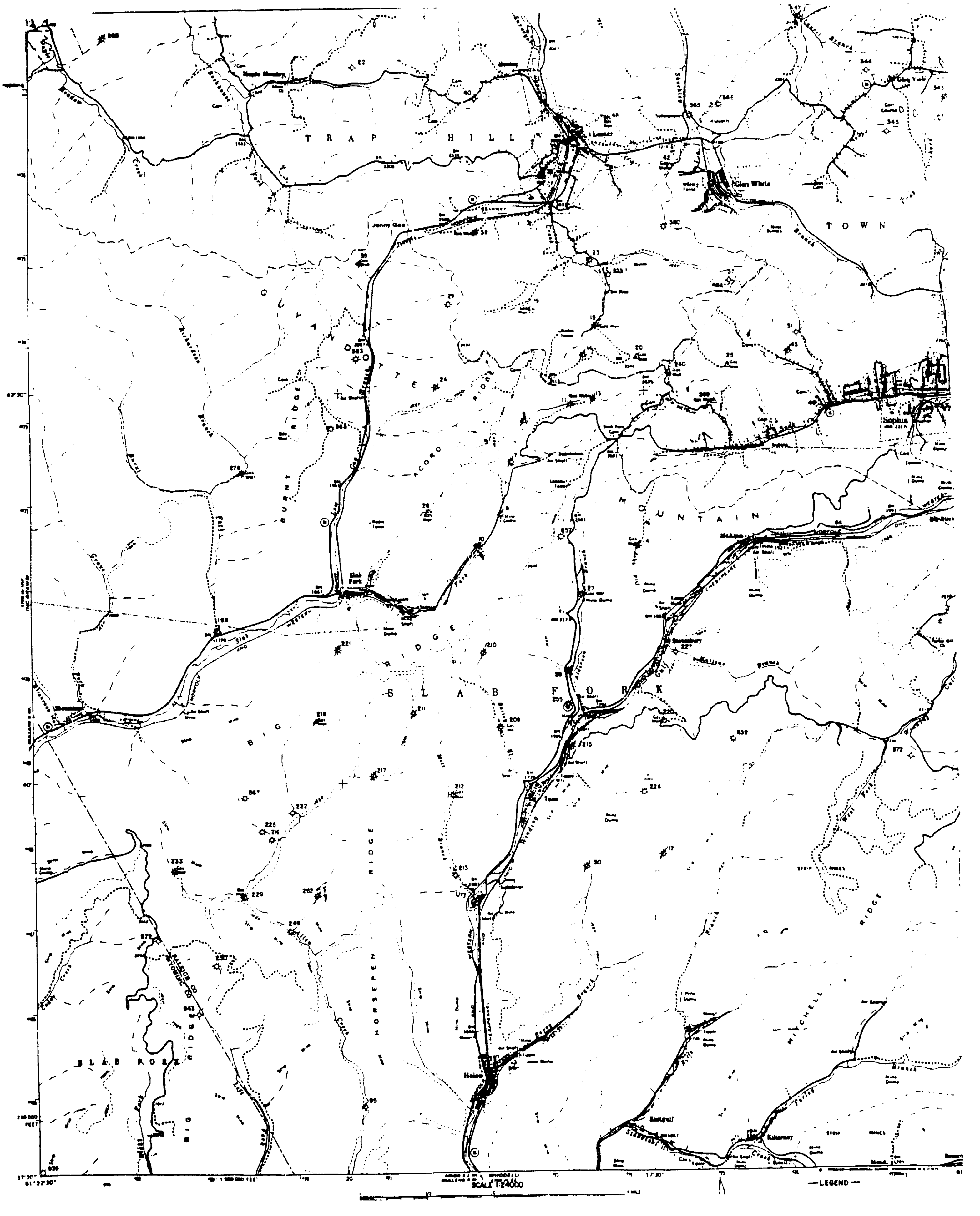
A-6 OGIS BASE, ECCLES QUADRANGLE



A-7 OGIS BASE, BECKLEY QUADRANGLE

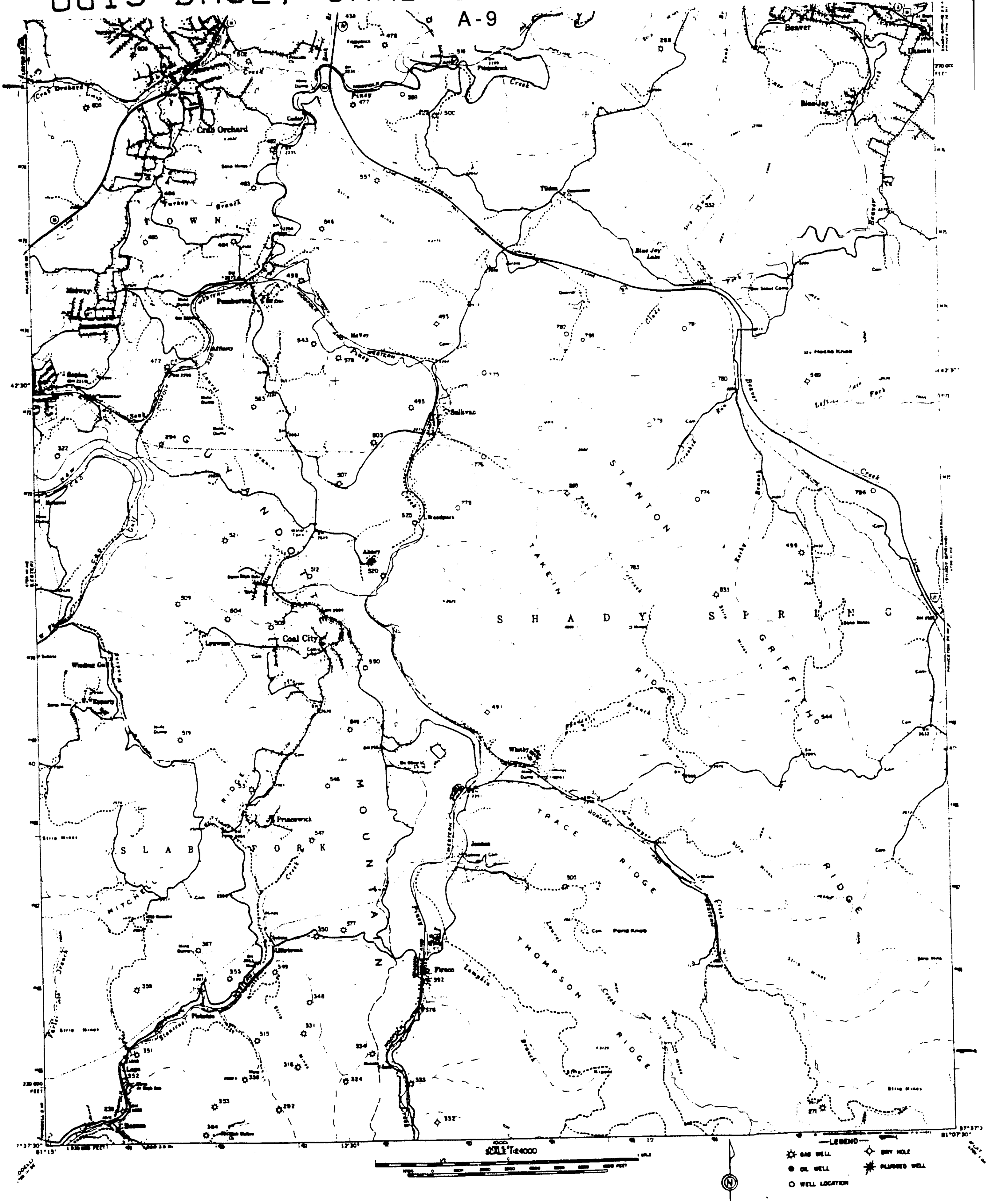


A-8 OGIS BASE, LESTER QUADRANGLE



OGIS BASE, CRAB ORCHARD QUADRANGLE

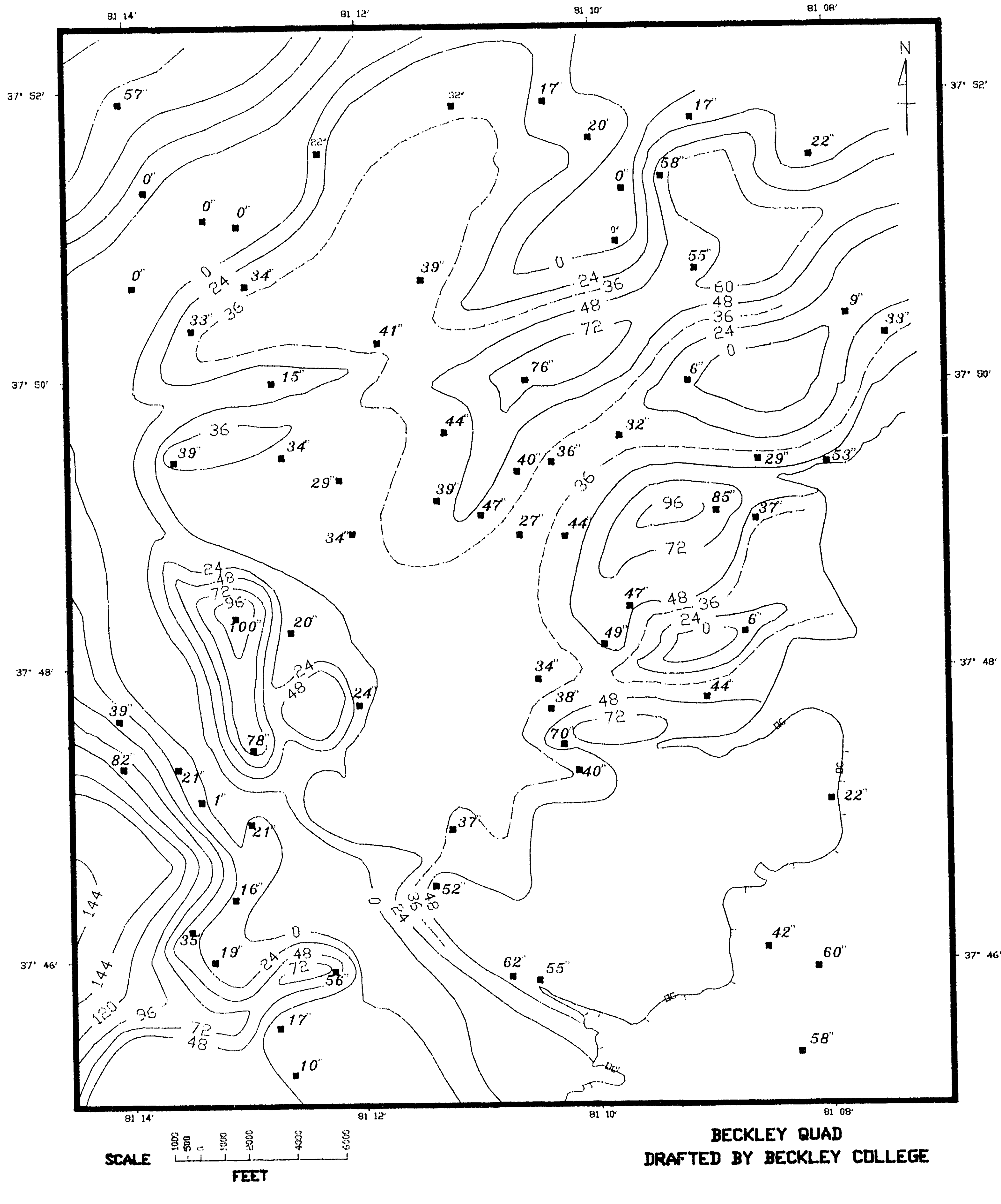
A-9



APPENDIX B

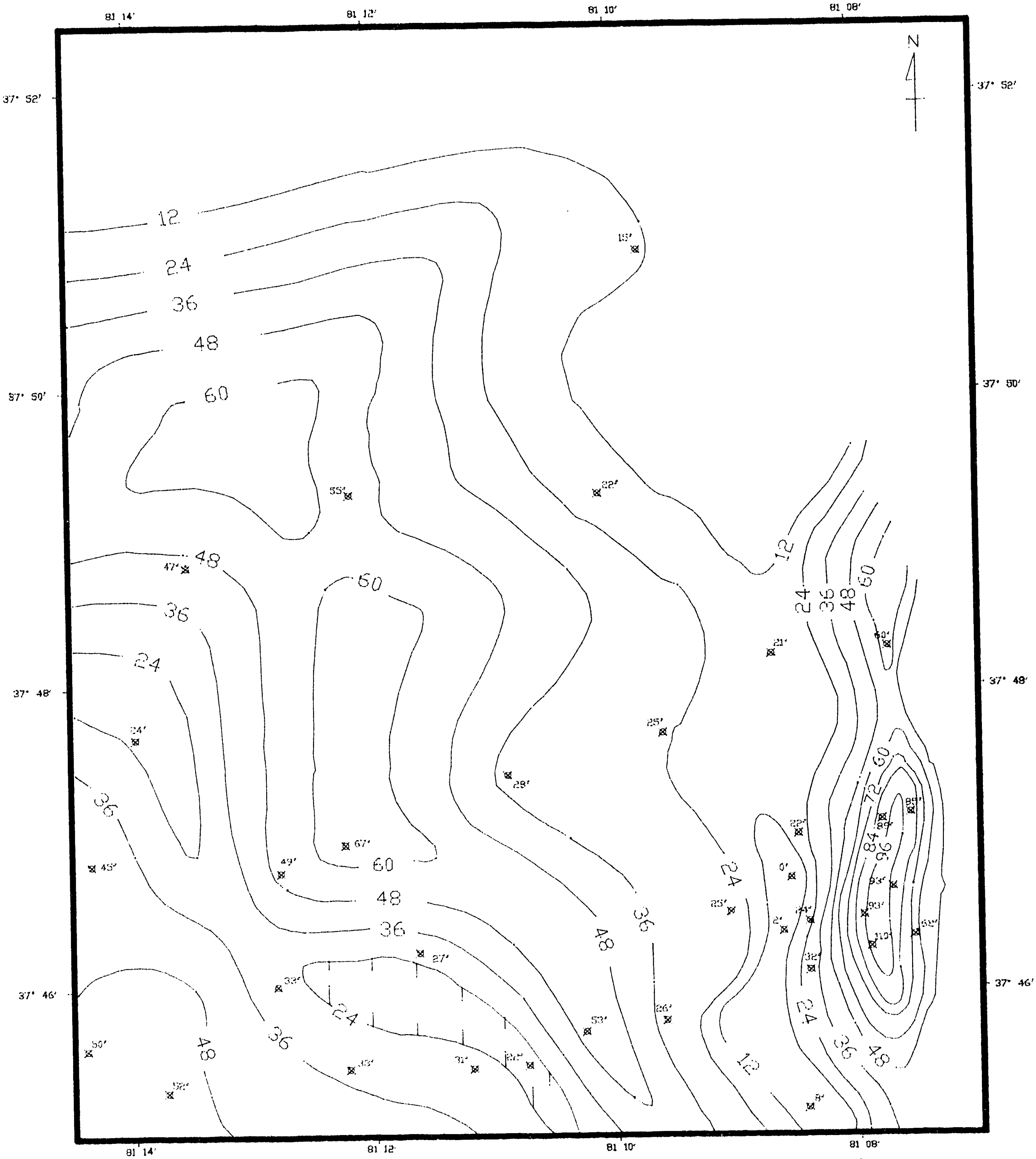
GEOLOGY AND PRODUCTION ANALYSIS

B-1 BECKLEY SEAM ISOPACH



BECKLEY QUAD
DRAFTED BY BECKLEY COLLEGE

B-2 ISOPACH OF THE POCAHONTAS #3 COAL (BECKLEY QUAD)



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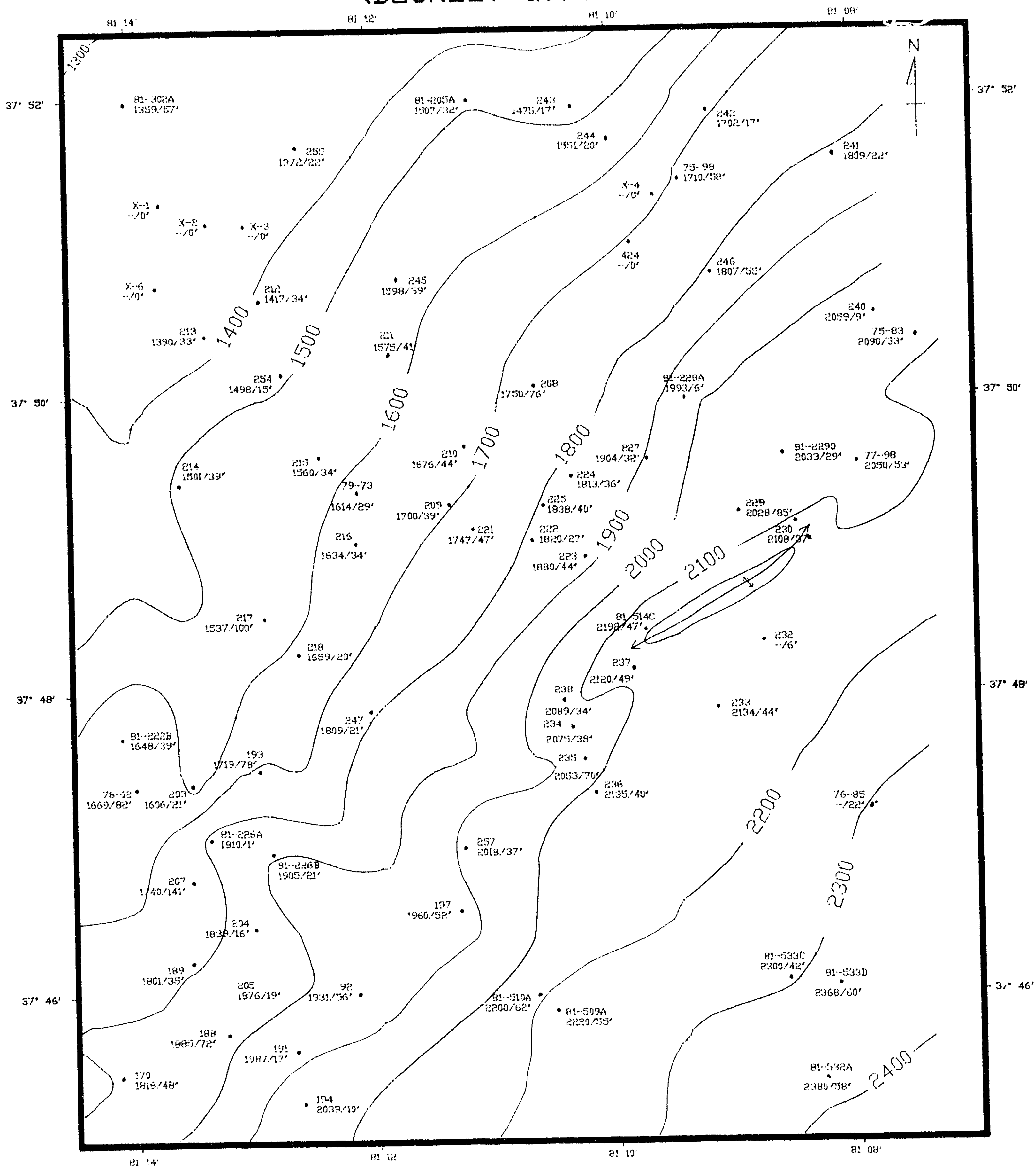
BECKLEY QUAD
DRAFTED BY BECKLEY COLLEGE

B-3 STRUCTURE ON TOP OF THE BECKLEY COAL (BECKLEY QUAD)



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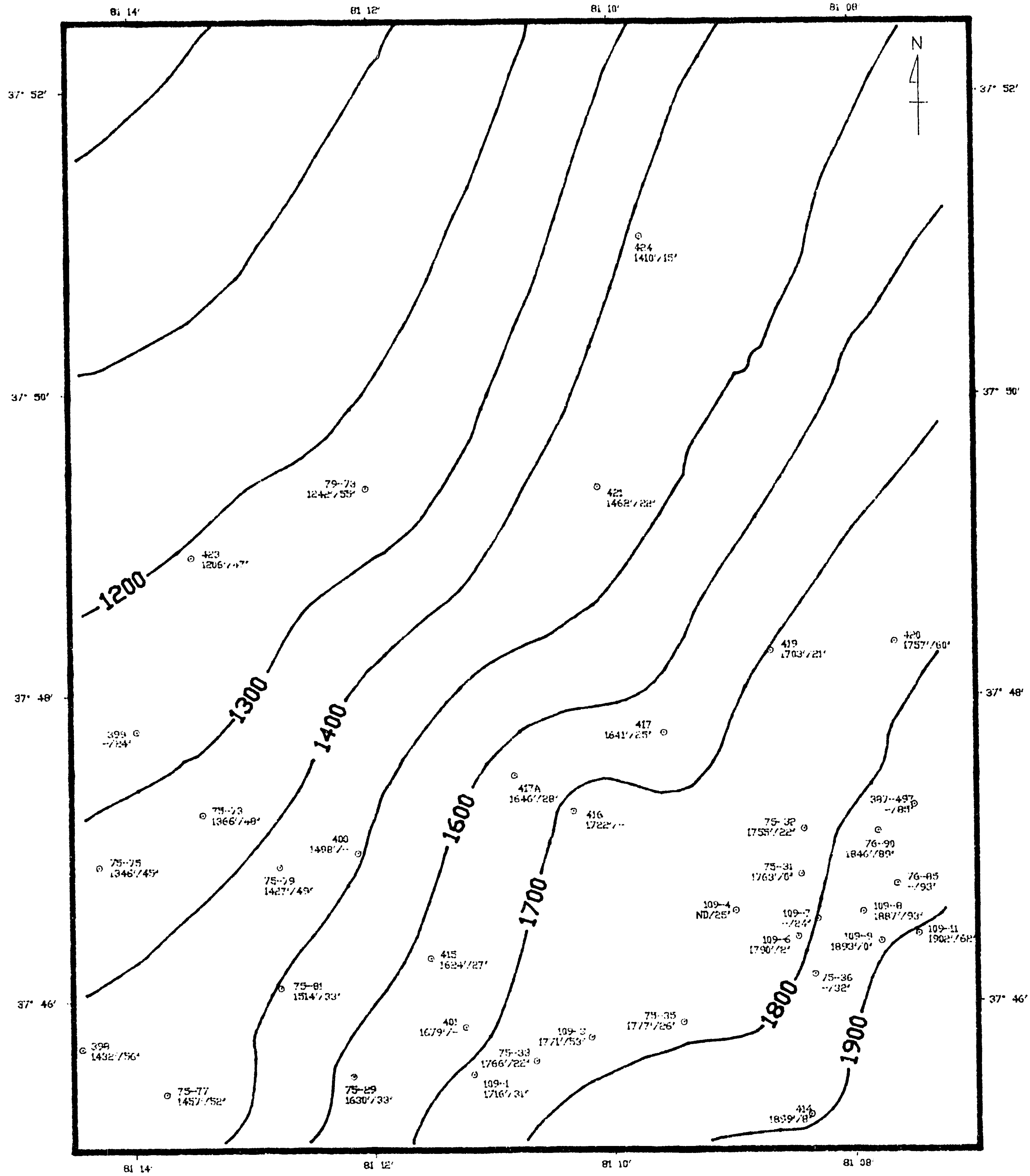
BECKLEY QUAD

DRAFTED BY BECKLEY COLLEGE

B-4 STRUCTURE ON TOP OF THE POCAHONTAS #3 COAL



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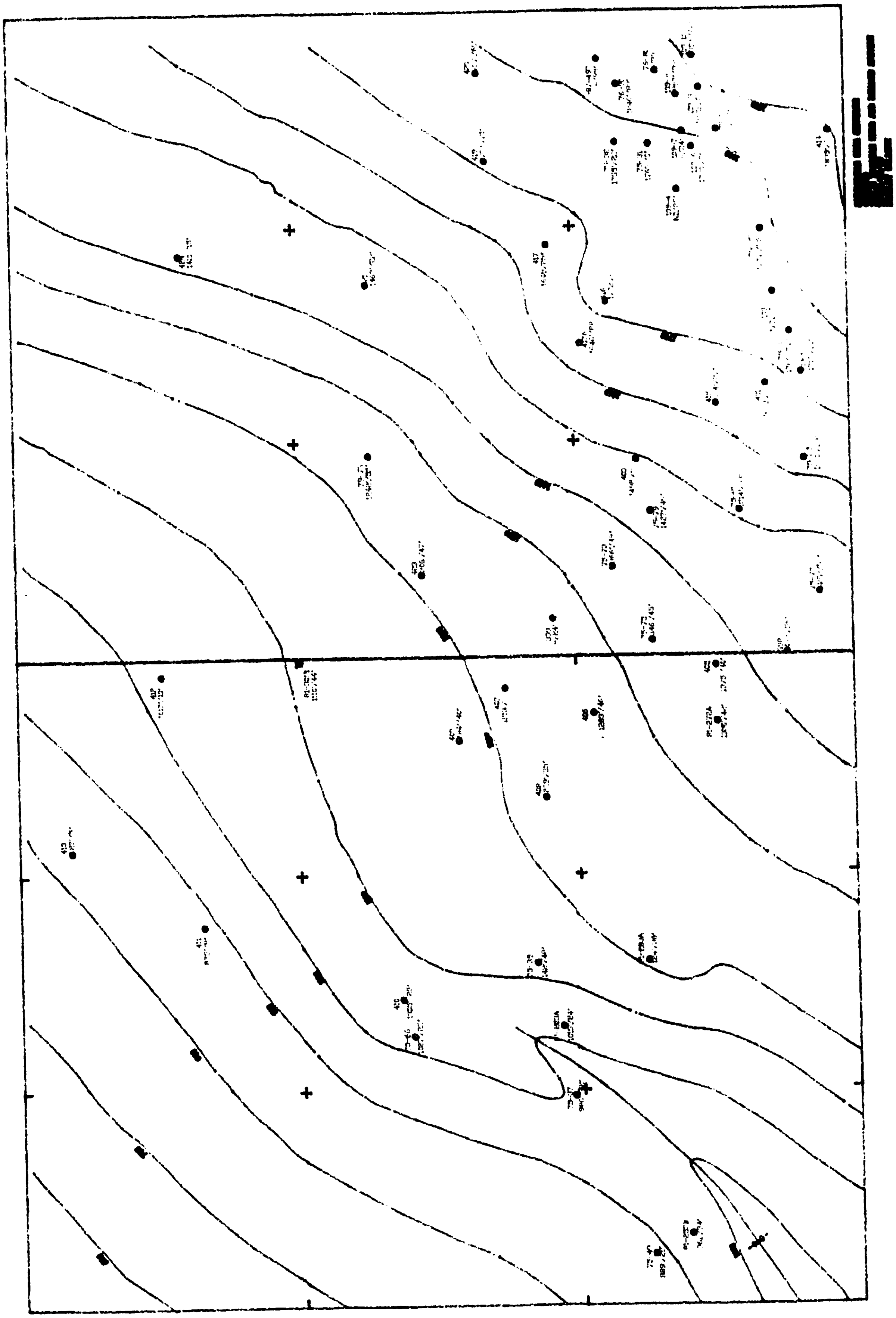
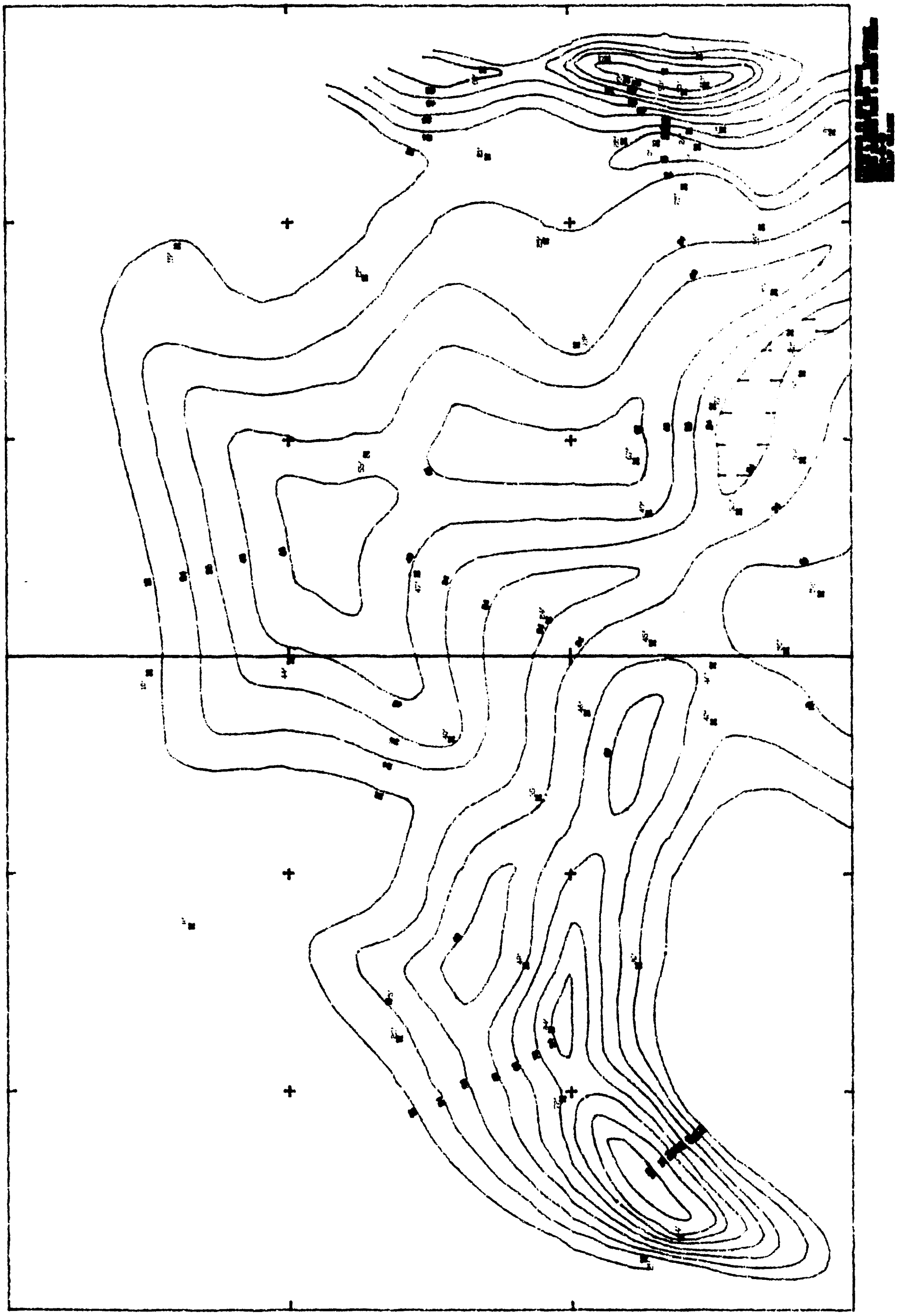
DRAFTED BY BECKLEY COLLEGE

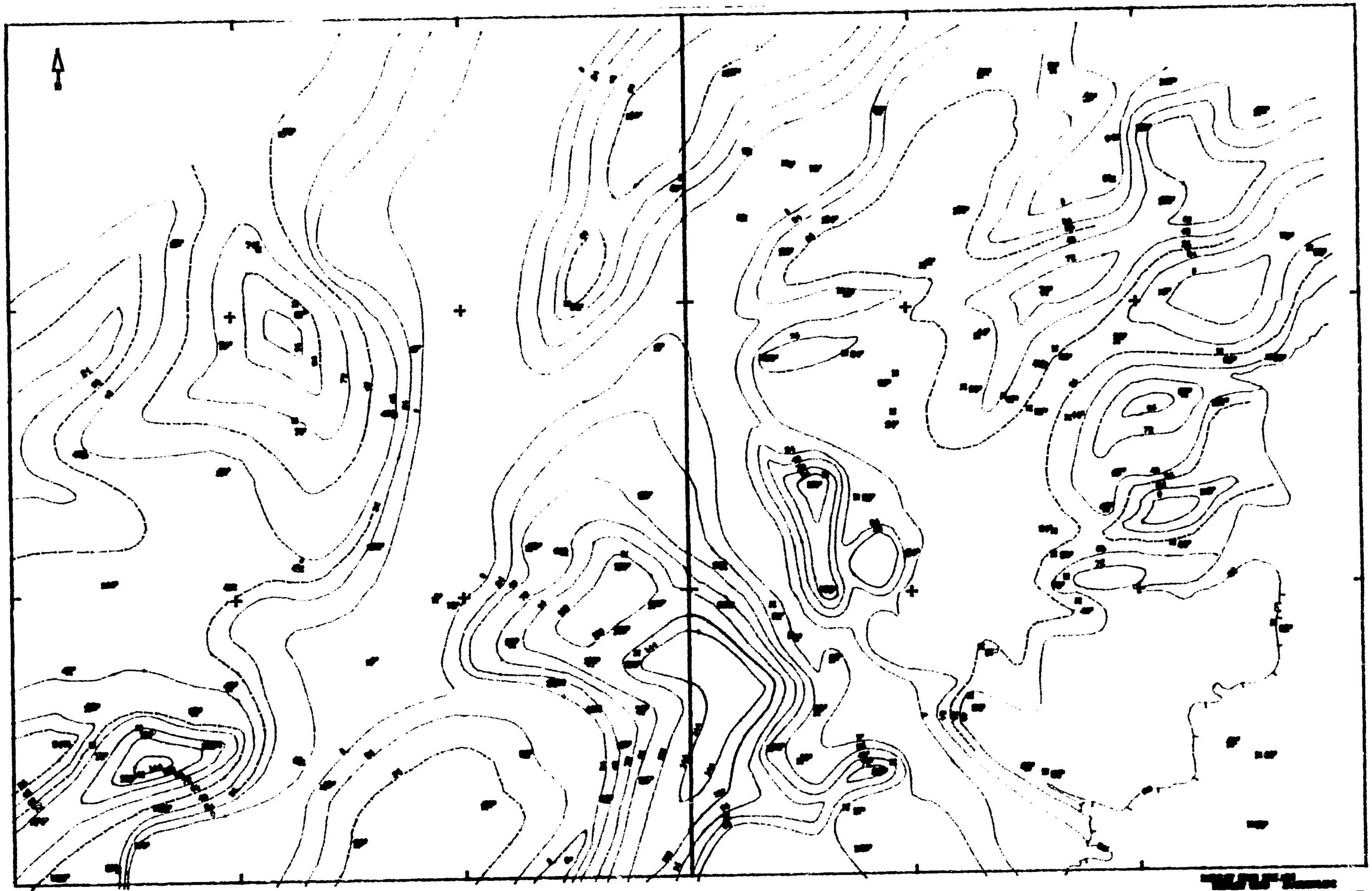
COAL STRUCTURE, POCAHONTAS #3
BECKLEY AND ECCLES QUADRANGLE



POCAHONTAS #3 ISOPACH
BECKLEY AND ECCLES QUADRANGLE



BECKLEY COAL ISOPACH
BECKLEY AND ECCLES QUADRANGLE

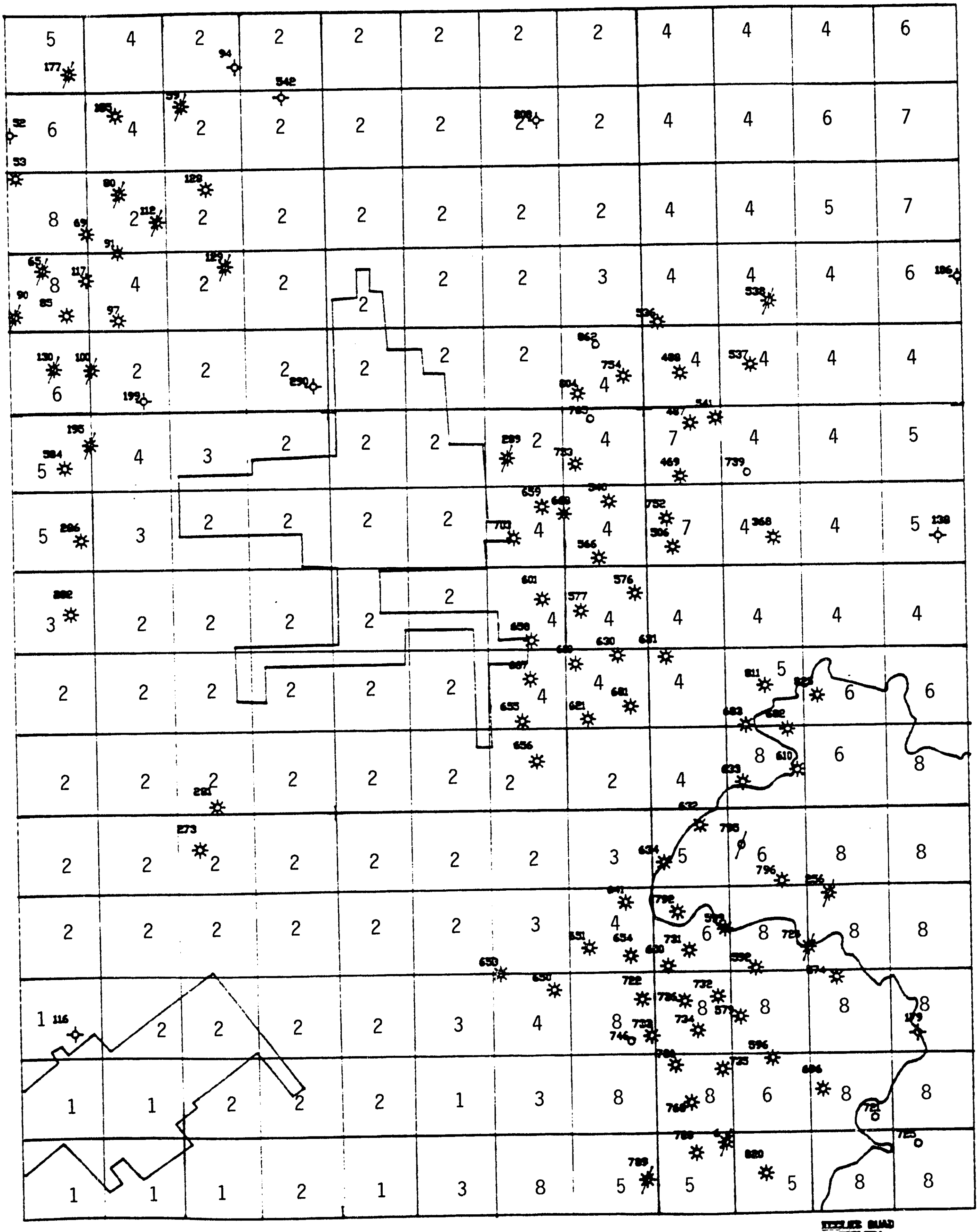


APPENDIX C

DEVELOPMENT OF SCREENING AND RANKING CRITERIA FOR AREA SELECTION

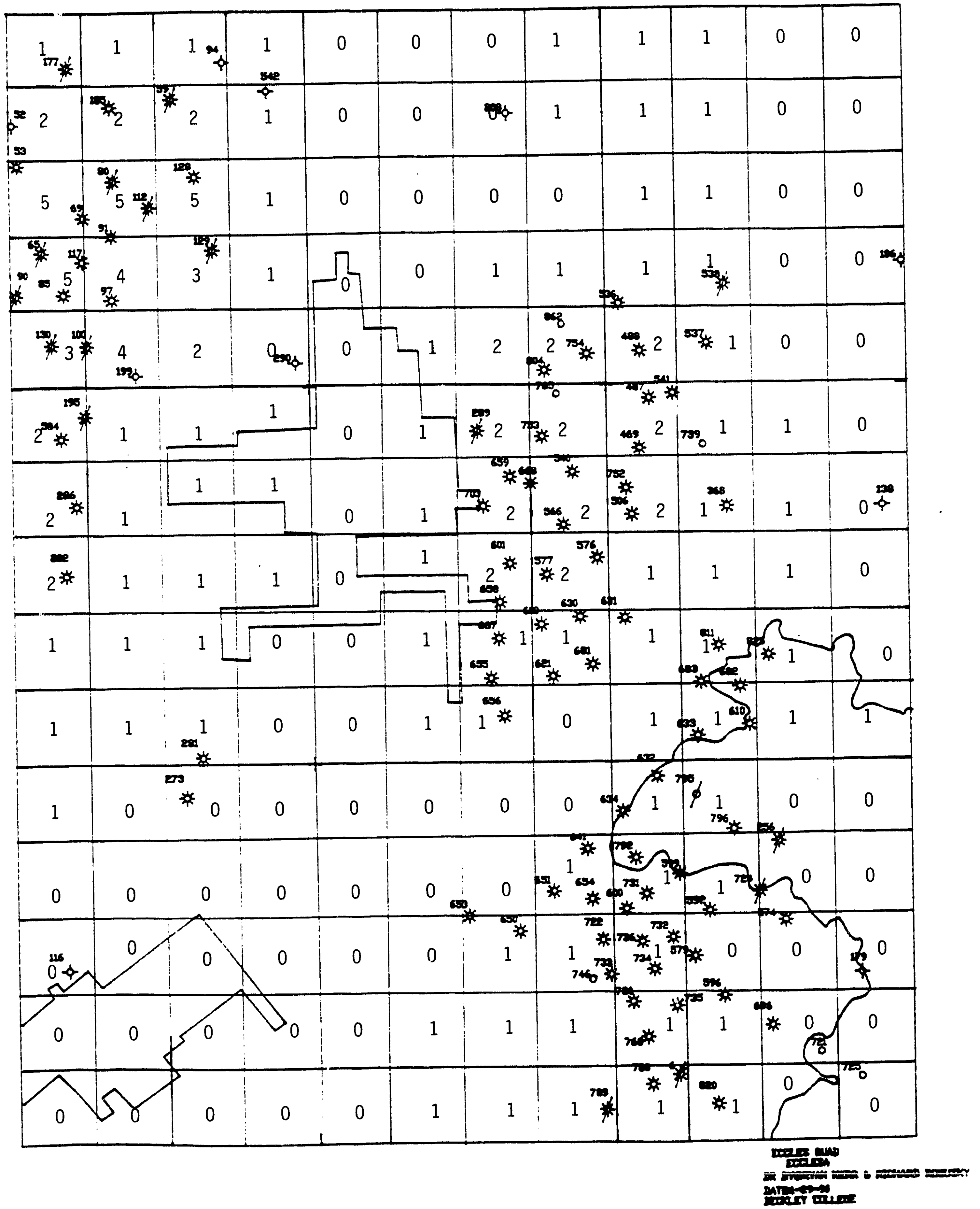
C-1	RAVENCLIFF RESERVOIR QUALITY
C-2	RAVENCLIFF DIAGENETIC ENHANCEMENT
C-3	BIG LIME RESERVOIR QUALITY
C-4	BIG LIME DIAGENETIC ENHANCEMENT
C-5	TECTONIC ENHANCEMENT
C-6	MISSISSIPPI AND PENNSYLVANIA RESERVOIR QUALITY

C-1 RAVENCLIFF RESERVOIR QUALITY

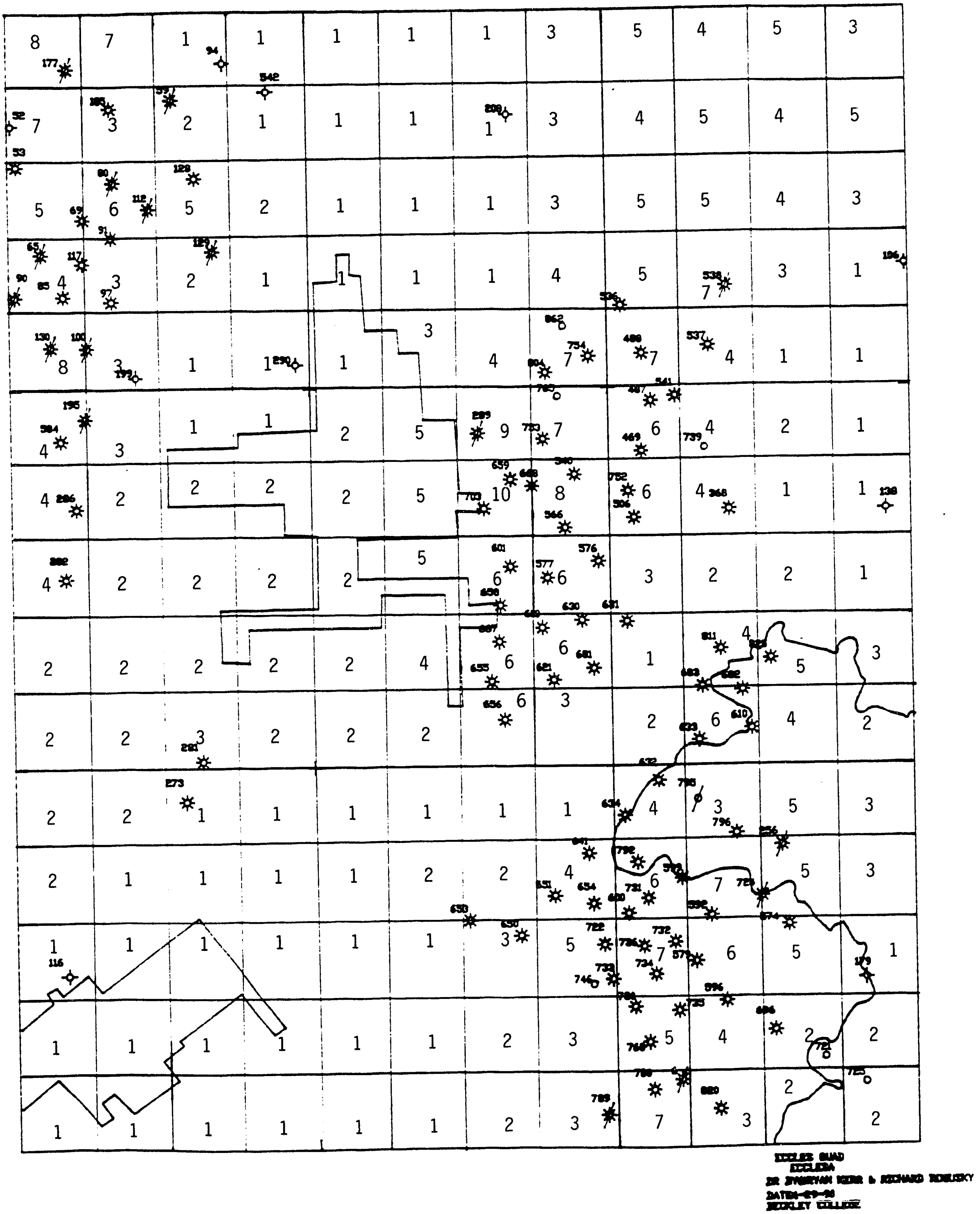


[illegible] QUAD
[illegible]
DR [illegible] & RICHARD [illegible]
DATE[illegible]
[illegible] COLLEGE

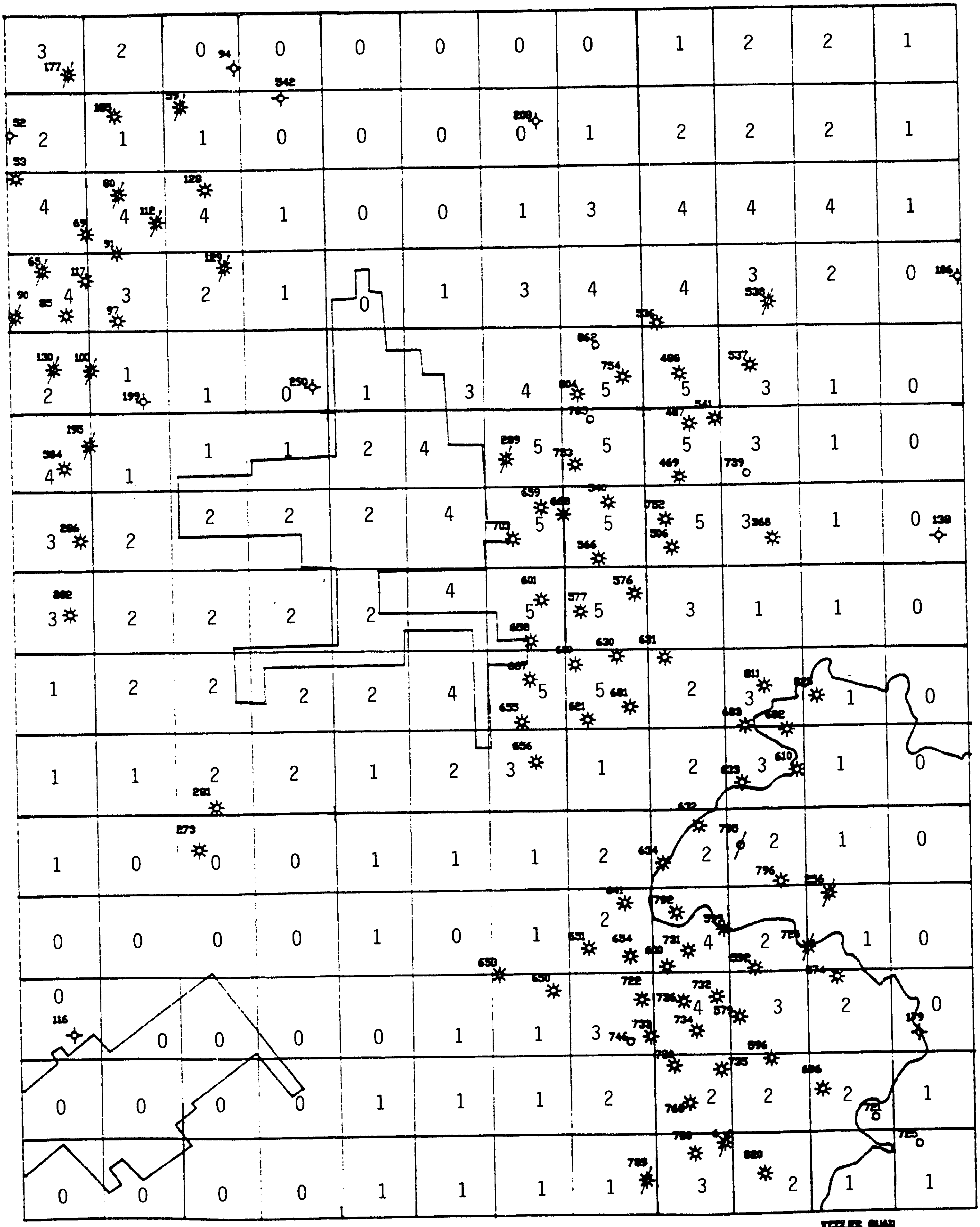
C-2 RAVENCLIFF DIAGENETIC ENHANCEMENT



C-3 BIG LIME RESRVOIR QUALITY



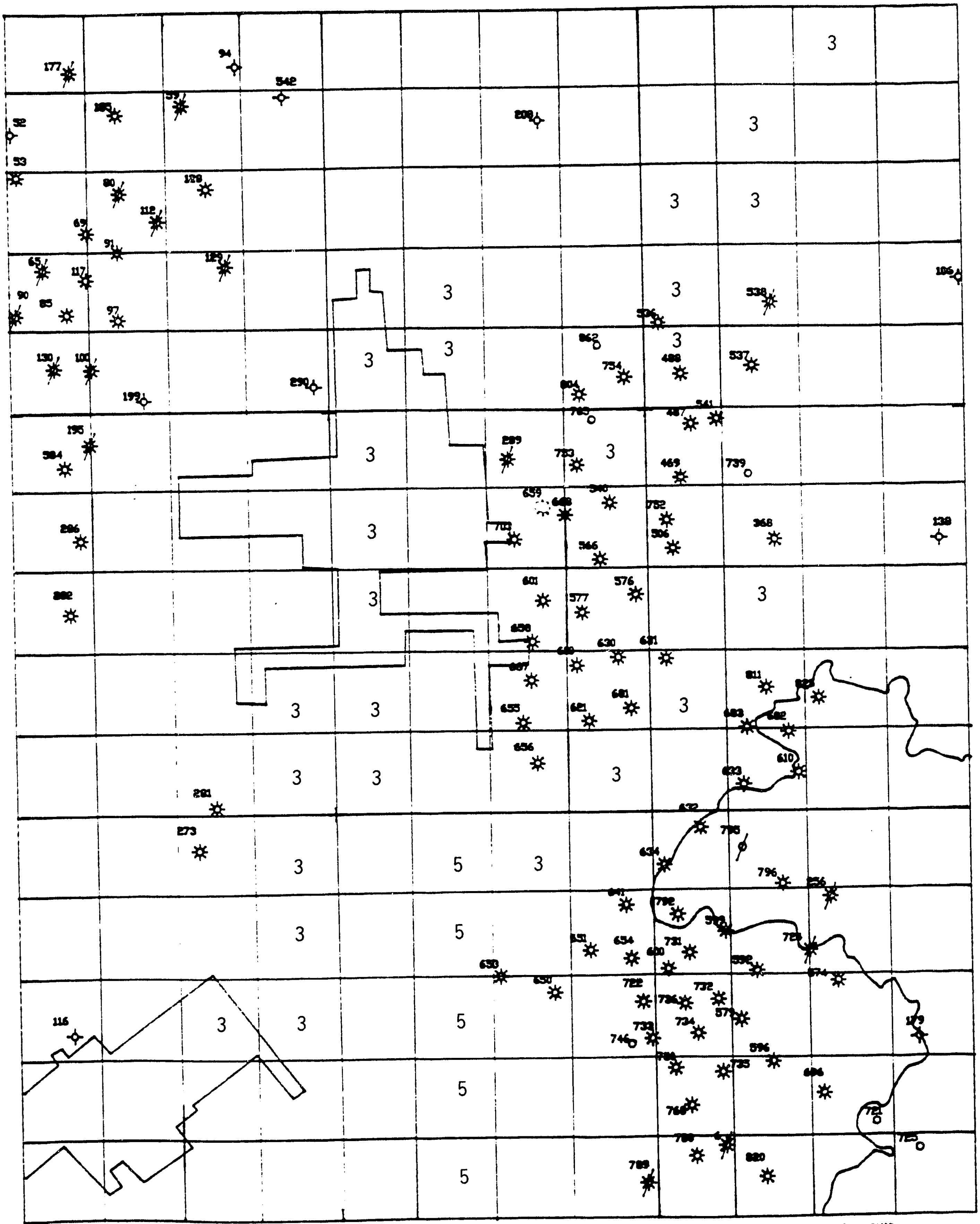
C-4 BIG LIME DIAGENETIC ENHANCEMENT



ECCLES QUAD

BECKLEY COLLEGE

C-5 TECTONIC ENHANCEMENT

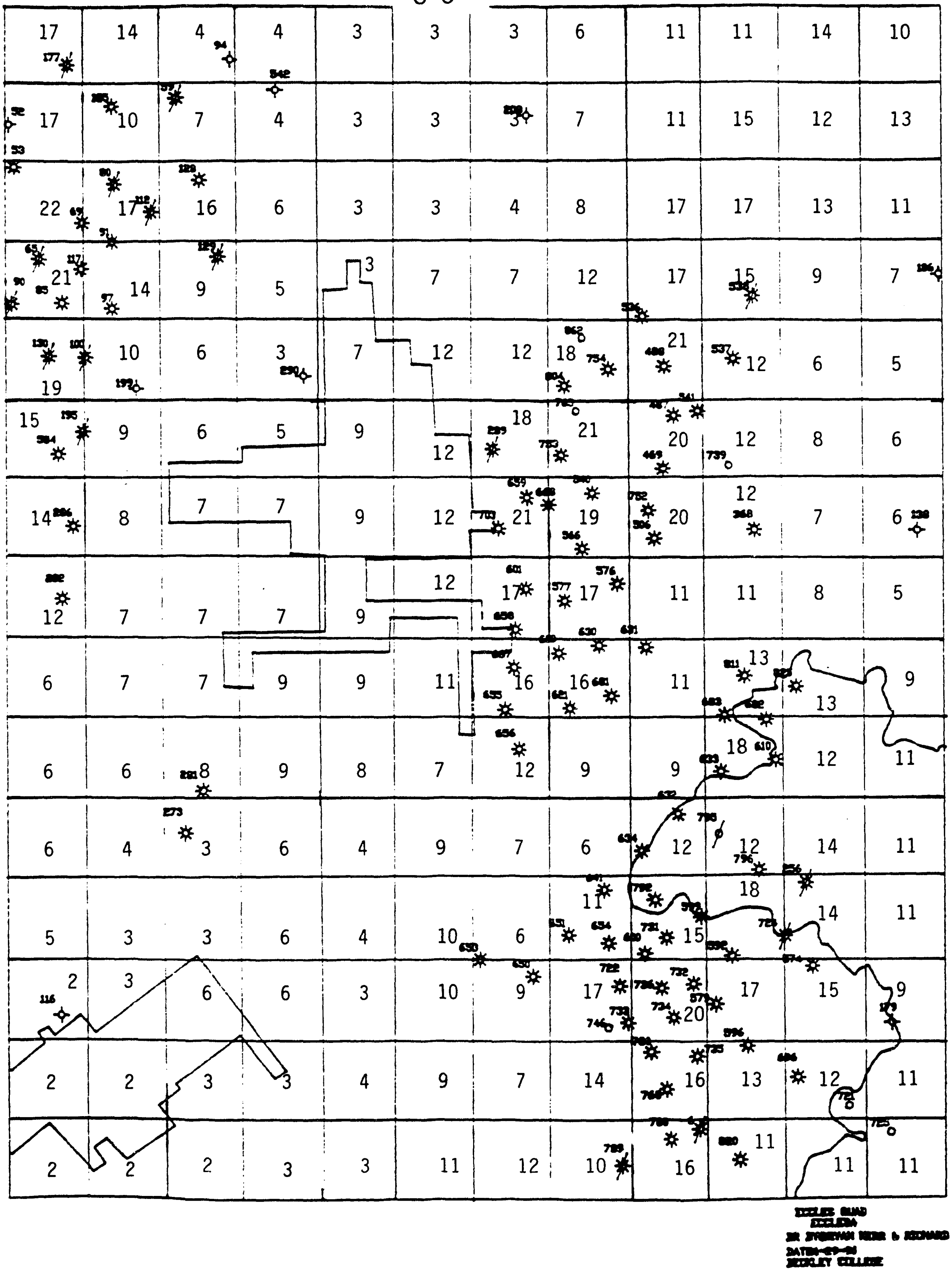


ECCLES QUAD

BECKLEY COLLEGE

MISS. AND PENN. RESERVOIR QUALITY

C-6

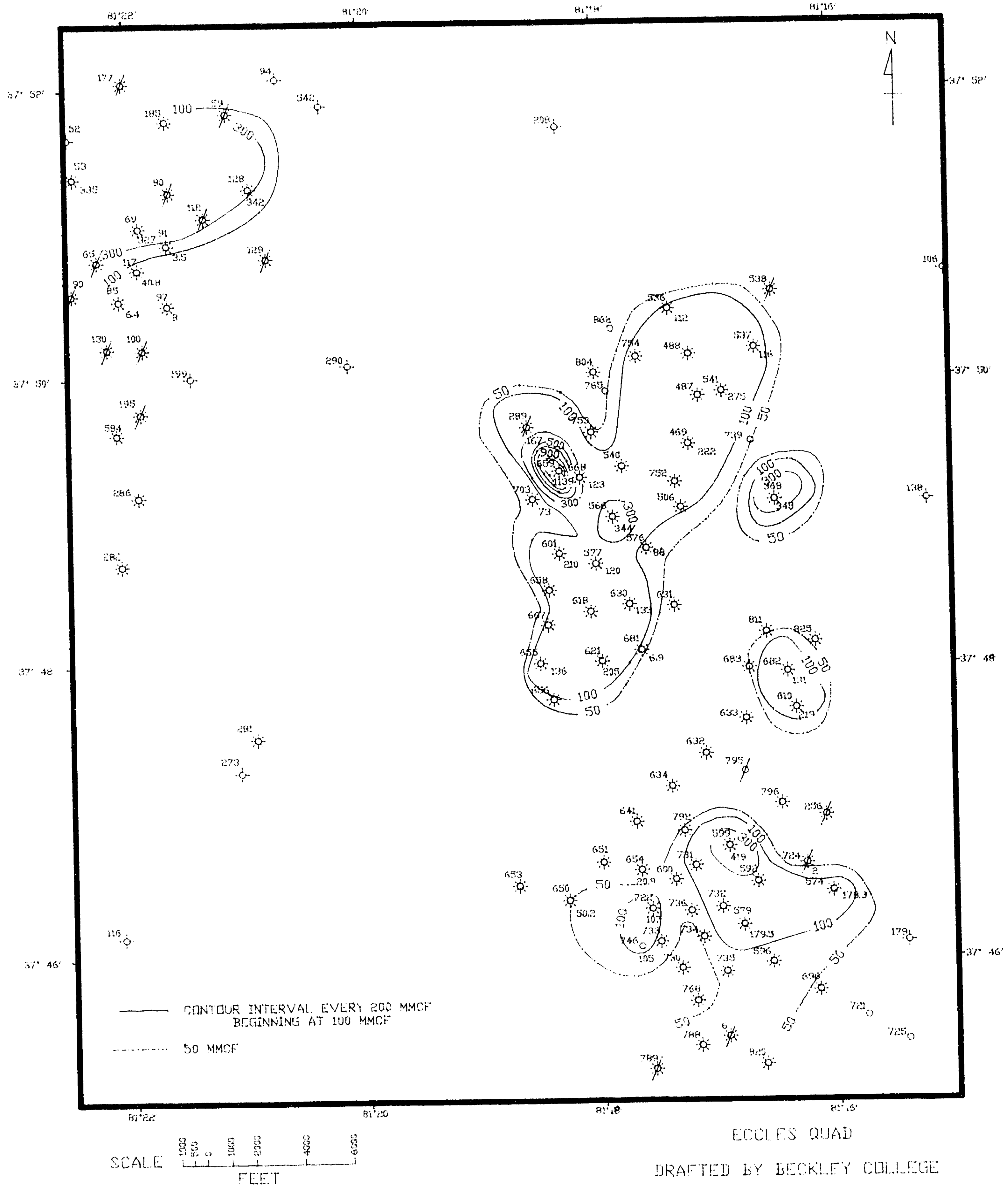


APPENDIX D

ECONOMIC EVALUATION OF PRODUCTION

D-1	PROJECTED FIVE YEAR CUMULATIVE PRODUCTION (MMCF)
D-2	30 YEAR RESERVES (MMCF)
D-3	MONTHS OF PRODUCTION TO ECONOMIC LIMIT
D-4	RECOVERABLE NATURAL GAS RESERVES MMCF/ACRE

D-1 PROJECTED FIVE YEAR CUMULATIVE PRODUCTION (MMCF)



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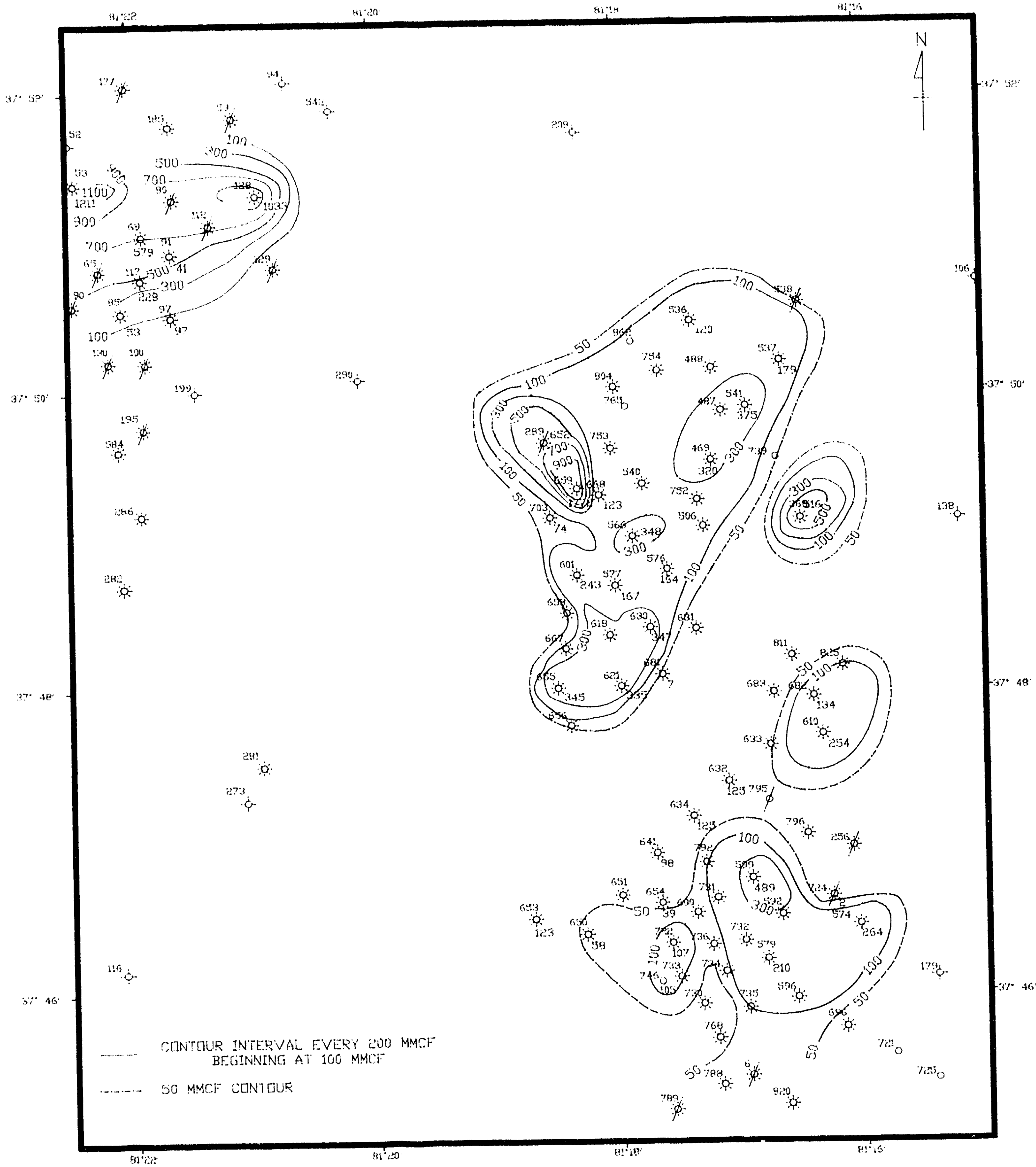
DRAFTED BY BECKLEY COLLEGE

D-2 30 YEAR RESERVES (MMCF)



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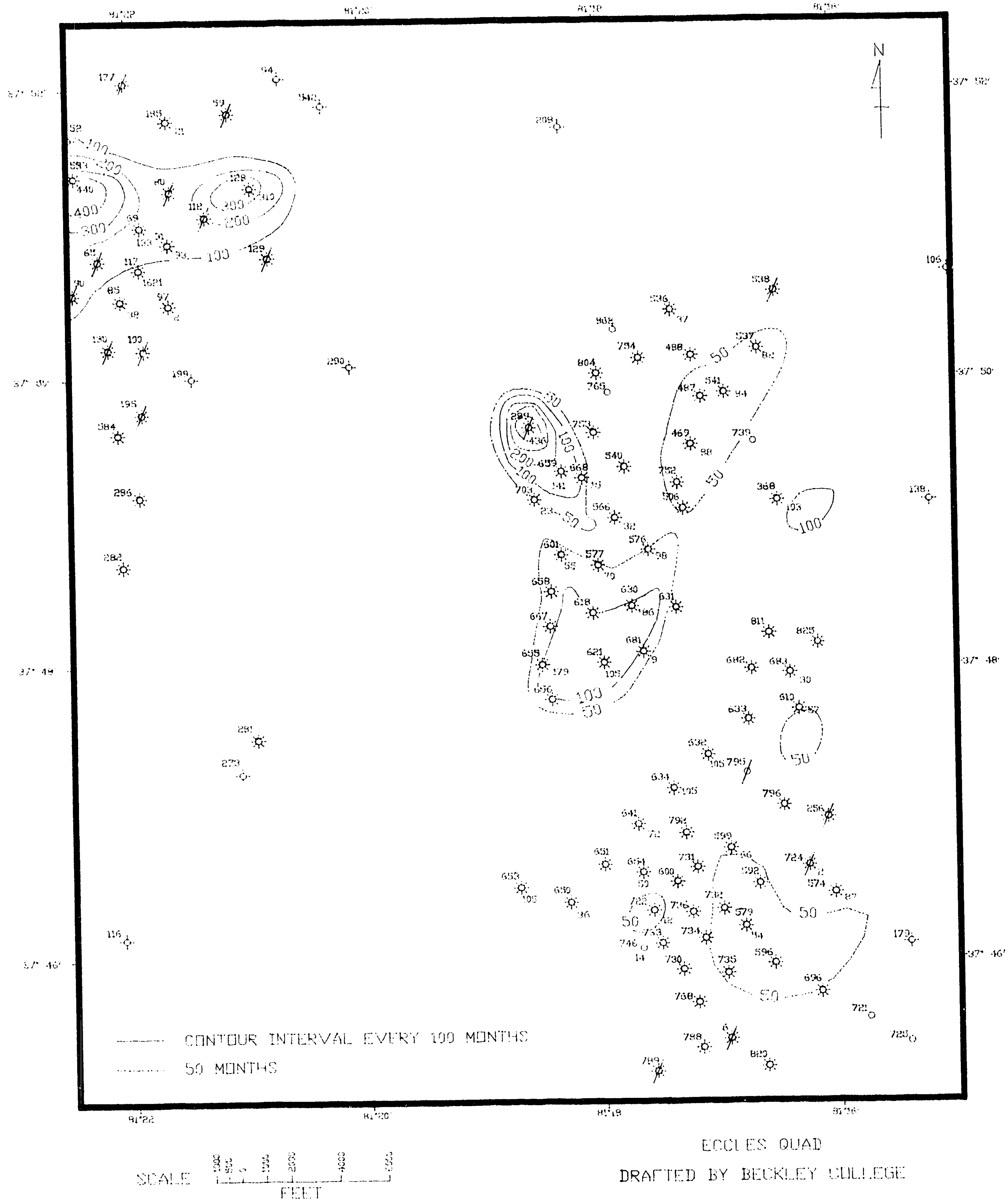
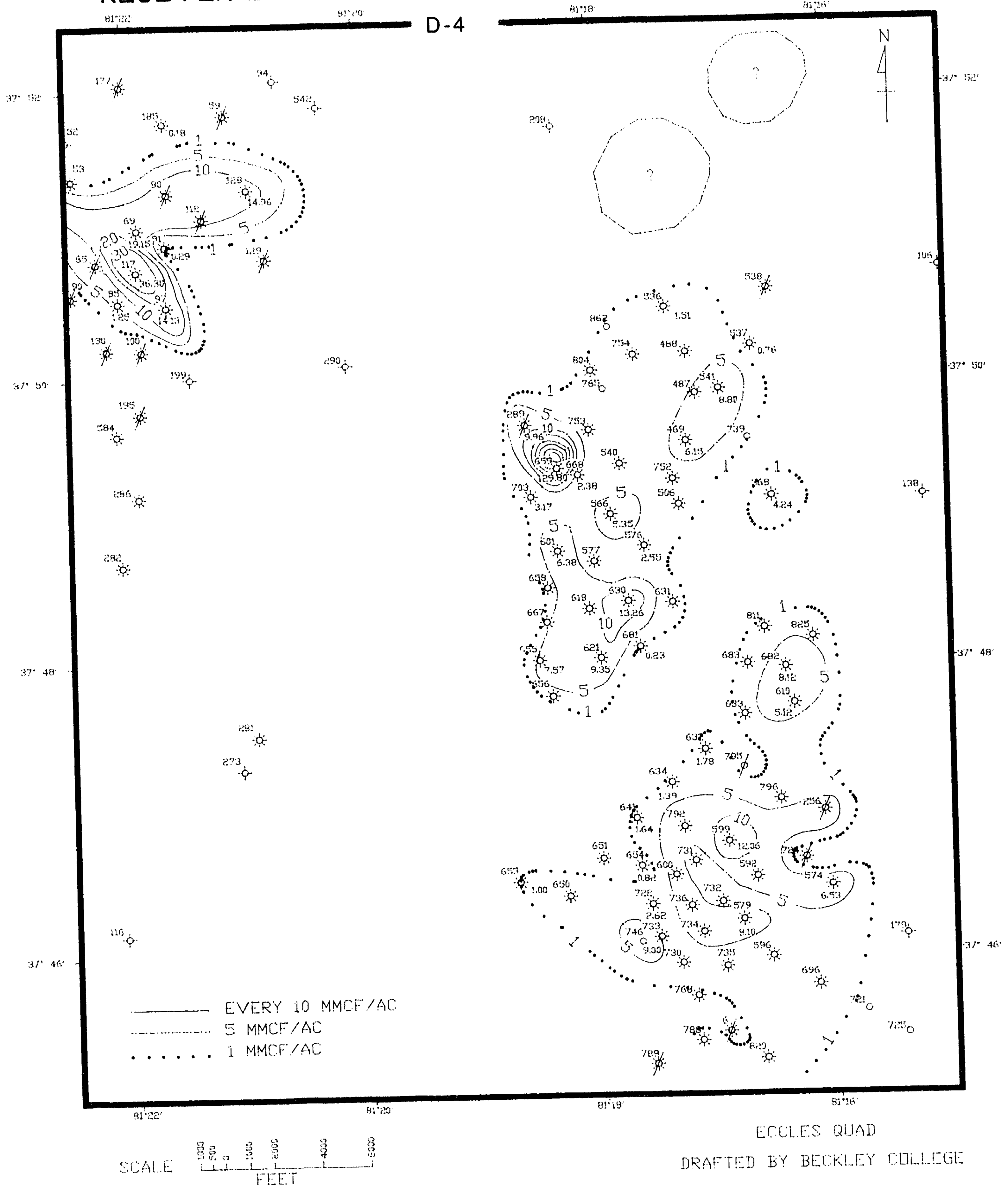
D-3 MONTHS TO ECONOMIC LIMIT



ECCLES QUAD

DRAFTED BY BECKLEY COLLEGE

RECOVERABLE NATURAL GAS RESERVES (MMCF/ACRE)



ECCLES QUAD

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DATE
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8 / 6 / 92