**Selection of Area and Specific Site for Drilling
a Horizontal Well in Calhoun County, West Virginia**

Topical Report

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ABSTRACT

This report discusses the data collection and analysis procedures used to establish criteria for geologic and engineering studies conducted by BDM to select a general area for more detailed study and a specific site for the drilling of a cooperative well with an industry partner, the Consolidated Natural Gas Development Company (CNGD). The results of detailed geologic studies are presented for two areas in Calhoun County, West Virginia, and one area along the Logan-Boone County line in West Virginia. The effects of Appalachian Basin tectonics and the Rome Trough Rift system were identified on seismic lines made available by (CNGD). These helped to identify and define the trapping mechanisms which had been effective in each area. Engineering analyses of past production histories provided data to support selection of target areas and then to select a specific site that met the project requirements for production, reservoir pressure, and risk. A final site was selected in Lee District at the southwestern margin of the Sand Ridge gas field based on the combination of a geologic trapping mechanism and reservoir pressures which were projected as 580 psi with a stress ratio of 0.53.

**SELECTION OF A GEOGRAPHICAL AREA FOR DRILLING A HORIZONTAL WELL IN
COOPERATION WITH CONSOLIDATED NATURAL GAS DEVELOPMENT COMPANY
PHASE I - SPECIAL REPORT**

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SELECTION OF AREA AND A SPECIFIC SITE FOR DRILLING A HORIZONTAL WELL IN CALHOUN COUNTY, WEST VIRGINIA

1.0 INTRODUCTION

In accordance with the contract Statement of Work (SOW), Task 1, select data were gathered and evaluated in order to rank potential acreage as to suitability for further reservoir and geologic study to site a horizontal well. The SOW required that the data be evaluated in terms of reservoir quality and of operator willingness. Because of the existing subcontract with Consolidated Natural Gas Development Company, the "operator willingness" criterion was satisfied by the direct involvement of the operator in the evaluation process. CNGD reviewed their potential Devonian shale gas acreage, identified three areas (one along the Logan-Boone County line, and two in Calhoun County) where they would be willing to drill a horizontal well, and provided extensive geological and engineering support.

2.0 PROCEDURE

Upon finalization of the contract, CNGD was asked to supply geologic, production, reserve, and engineering data on areas with known production potential via extensive fracturing through the Devonian shale section. Each of the selected areas has been tested in the shale and has extensive shallow uppermost Devonian and Mississippian production. Exceptional shallow wells that can be tied directly to structural controls exist in each of the prospect areas. Maps and seismic information were provided by CNGD for each of the areas and additional maps were obtained from the West Virginia Geologic and Economic Survey and other sources. Gas production, reservoir pressure, and other engineering data were also provided by CNGD and Sterling Drilling, Inc. Engineering data were combined and correlated with the geologic data to evaluate each area with respect to "reservoir quality".

3.0 EVALUATION CRITERIA

Contract objectives and specifications require that the well be located in a most favorable area of established production so that exploration risks can be reduced or avoided and that areas be ranked according to reservoir quality and operator willingness to cooperate with DOE. Since each area had been recommended by the operator, willingness to participate was not considered to be a significant factor in the ranking process. Therefore, most emphasis was placed on geologic and reservoir quality factors.

3.1 Geologic Criteria

Devonian shale gas production is generally dependent upon the existence of a well-developed network of natural fractures. The picture gets somewhat more complex in the eastern portion of Calhoun County where interbedded siltstones begin to appear within the shale section, providing a series of layers with very slight primary porosity and also a more brittle silt-shale medium that may more easily support open fractures. In such an area, natural reservoir seals, even with the shale, may not be universal, and the search for the elusive, subtle shale reservoir involves a hunt not only for fracturing, but for an effective cap (less fractured area) to form a trap, as well. A number of geologic criteria can be related to shale well production. Table 3.1 shows a list of these geologic criteria.

3.2 Established Production

Because of the importance of fracturing in Devonian shale production, in each area an attempt was made to relate established production and known shallow structural trends to known or suspected natural fracture development in the shale. Since the productivity of the horizontal well is likely to be directly and proportionally related to the productivity of a vertical well in the same or similar reservoir, it is necessary to be able to extrapolate reservoir conditions derived from the established production sites to potential horizontal well sites. Model studies have indicated that horizontal wells may produce gas at rates

TABLE 3.1

GEOLOGIC CRITERIA USED IN SCREENING FOR VIABLE
HORIZONTAL WELL SITE AREAS FOR
FRACTURED DEVONIAN SHALE GAS PRODUCTION

GEOLOGIC CRITERIA

1. Thickness of Huron Shale: >250 feet.
2. Thickness of Lower Huron Shale: >150 feet.
3. Grenville Trend Faulting or Fracturing Present.
4. Rome Trough Faulting or Fracturing Present.
5. Cross-Strike Structural Discontinuity (CSD) Trend (N40-55°W) Present.
6. Stress Ratio Favorable (Generally <4.0).
7. Gas Content of Shale: 50 mcf/ac-ft.
8. Average Gas-In-Place per 160 Acres: ≥500 mmcf.
9. Devonian Shales Have Estimated Ultimate Reserves >300 mmcf.
10. One or More 160-Acre Locations Available.

between six or seven times the rate of a vertical well in the same reservoir. For these reasons, many lines of data from Table 3.1 were used in the evaluation of the prospect areas.

4.0 GENERAL GEOLOGIC SETTING

4.1 Area Evaluation for Fracturing in the Lower Huron Interval of the Devonian Shale

BDMESC is evaluating two areas of Consolidated Natural Gas acreage in West Virginia (Figure 1) for the desirability of drilling a horizontal hole through the Lower Huron section of the Devonian shale. The primary objective of the program is to encounter an enhanced number of gas-charged fractures in the long horizontal portion of this well. The areas being evaluated are:

the southeast margin of the Rome Trough along the Boone-Logan County line;

the southwest margin of the Salina evaporites through Calhoun County.

The study is aimed at identifying areas with exceptional, predictable, structurally-controlled fracture porosity. Toward this end, the main structural trends of the areas have been identified.

4.2 General Structural Setting

A very ancient North-South structural grain can be traced across Boone and Logan Counties and in deep structures under Calhoun County and along the Burning Springs Anticline northwest of Calhoun County (Figure 2). This orientation is presumably a remnant of the very ancient Grenville Orogeny ($1.1 - 0.9 \times 10^9$ years).

The Grenvillian event was a full-scale continent-continent collision, an obductive orogeny where one continental plate overrides another. Since both plates in obduction are relatively light SIAL (granitic

Figure 2 - Structural Grain of Western W. Va.

rocks), neither plunges to any great depth into the hot mantle, and there is little or no melting or destruction of the overridden plate as happens when a dense plate of SIMA (basaltic rocks) is subducted (Figure 3).

The Crust was thoroughly shattered in the Grenvillian Orogeny. A series of east-dipping faults broke through from the Moho all the way to the surface of the overriding Grenvillian Plate (Figure 4). Slivers were sheared off the upper surface of the Laurentian Plate. This picture is now being documented along the Grenville Front by ultra-deep seismic work in COCORP and GLIMPCE surveys.

As the collision proceeded, the fragments imbricated or piled up like shingles on a roof (Figure 5). The vast forces involved in this compression were driven by the mass of what may have been a Grenvillian supercontinent including both the modern eastern portion of North America, plus Africa, as well as attached smaller plates. A great, Himalaya-style mountain range would have formed at this time, probably including slivers along the contact zone of exotic materials like bits of ocean floor (ophiolites), island arcs, and possibly intrusives that worked their way up from the Mantle. Such material may be common in the Basement of western Ohio.

The Grenville Mountains were eventually eroded down to their roots before the Precambrian came to its end, leaving a surface of relatively low relief across the area of the future Appalachians. A system of great faults cut this plane (Figures 6 and 7). The period of stability would not last, however.

The eastern portion of the North American continent would be affected by a major episode of thermal instability in the mantle as the Paleozoic was about to begin. A series of long-term crustal movements began and continued well into the Paleozoic over an area stretching from Oklahoma and Texas through to New York (Figure 8). An excess of heat in the Mantle caused the Crust to blister, stretch, and eventually, to rupture.

This disturbance probably reactivated the old Grenville crustal breaks. Faults of this magnitude probably never heal completely. Their

Obduction - Plate of continental SIAL overrides a plate of continental SIAL. Slivers of ocean floor and island arcs (ophiolites) may be caught along the contact. Since there is no significant difference in density between the plates, neither plunges into the mantle.

Subduction - Plate of relatively light continental SIAL overrides a plate of relatively dense SIMA which plunges into the mantle and melts.

Figure 3 - Comparison of Obduction and Subduction

MODERN WEST

WEST
VIRGINIA

MODERN EAST

The Grenville continent overrides the east coast of Laurentia, which probably extended into the area of West Virginia.

As the overriding continues, friction builds and Grenvillia cracks with great faults extending completely through the crust to the MOHO.

Figure 4 - Grenvillia-Laurentia collision

MODERN WEST

MODERN EAST

INDIANA

OHIO

WEST VIRGINIA

Continued overriding produces massive thrusting in the Grenville plate with slices imbricating, or piling up like shingles on a roof. The collision thrust Grenville across Laurentia almost to Indiana.

Figure 5 - Formation of Himalaya-like mountains along the collision zone

EROSION SURFACE

Erosion reduced the mountains to a low relief surface at the root level of the old mountain chain by the Late Precambrian, exposing the deep, metamorphosed portions of the through-crust faults.

Figure 6 - Erosion by Late Precambrian time erases the mountains

Figure 7 - Grenville fault traces

Figure 8 - Late Precambrian, pre-Iapetus rift system of eastern US
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traces will be identifiable as zones of weakness which show up as periodically reactivated faults and/or fractures in the overlying sedimentary column. Periods of compression would reactivate the Basement thrusts and show up as thinning in the younger beds, perhaps with fracturing and shallow thrusting.

Under tension, the through-Crust fault planes would become the site of normal movements with depositional features in the overlying sediments like beachfront stillstands, straight segments of channel deposits, and thick, straight sandbars forming along the trace of the Basement downdropping. Sheet sediments thicken abruptly along these features if the Basement was active when the sheet was being laid down. These faults were not continuously active. Evidence for movement along them comes and goes during the Paleozoic.

A series of minitroughs has been tentatively identified on the Precambrian erosion surface across central Ohio and on through western West Virginia, Pennsylvania, and New York (Beardsley and Cable, 1983). These presumably formed along reactivated Grenville faults as the crust began to stretch.

The forces driving the deformation became more intense and eventually, a rift system, the Rome Trough, opened up from Kentucky through West Virginia and on to New York. In West Virginia, the trough is an asymmetrical, deep half-graben (Figure 9). The Trough developed along a new structural trend, running from southwest to northeast. In some areas within the Trough, short segments of Trough faulting follow reactivated north-south Grenville faults, but the overall Rome Trough fault trend and structural grain is southwest-northeast.

The initial drop of the rift floor was quite large and quite abrupt. This break in the Crust allowed much of the excess heat to escape from the Mantle. Following the release of this heat, there was a period of thermal contraction which led to continued downdropping of the Trough, after which there was a brief episode of stability, then renewed activity and a reversal, with the former Trough acting as a horst block during latest Devonian and Mississippian time.

A diagrammatic representation of the Rome Trough of southwestern West Virginia, showing its asymmetry and internal complexity.

Figure 9 - Rome Trough cross-section

A third significant structural orientation is demonstrated by a series of southeast-northwest cross-strike structural discontinuities (CSD's). At Basement level, this grain is often quite subtle, but the CSD systems were active periodically during the Paleozoic and did affect tectonics and fracturing within the Rome Trough. The Trough floor frequently appears to rise or fall as a CSD is crossed. Numerous units, including Silurian evaporites, Lower Devonian clastics, and coals thicken abruptly or pinch out at CSD's, indicating activity along these features at the time and up into New York, influencing the Finger Lakes area and probably even showing up as mappable faults on the Adirondack dome.

The Rome Trough orientation shows up as the location of sudden, dramatic sediment thickening into the Trough in the lower Paleozoic units at the Trough edge. Many of the Trough-edge faults also mark the site of tectonically thickened salt and a series of shallow structural axes. The Trough faults seem to exert some influence on modern drainage, but the main faults seem to have been more effective in creating ridges or monoclines than in influencing river courses. Isopach work shows that the Rome Trough faults were active for a very long time and were reactivated after many of the prime reservoir beds were laid down and lithified. This makes an understanding of these faults and the associated fracture systems very important for Appalachian hydrocarbon production.

The CSD's are the most subtle and difficult systems to identify seismically, but are locally extremely important in fracture control of hydrocarbon production. A key factor in identifying open fracture systems which may be gas or oil charged is determining the age and history of the fracture sets in a given area. It does no good to find fractures that have no effective cap, that are filled with water, or that have been plugged with secondary minerals. Many of the CSD-oriented fracture systems seem to have been active and open and to have filled with hydrocarbons at just the right time. Production trends always need to be studied for each prospect area, but many better wells lie at the intersection of a CSD and a Rome Trough and/or Grenvillian trend.

4.2.1 Boone-Logan County

A seismic section has been made available along the edge of the Rome Trough at the Boone-Logan County line. Figure 10 is a simplified representation of the geology along this line. This is probably the most dramatic area along the entire rift system. Here, the deepest portion of the Trough is bounded by a single fault. To the northeast, in Kanawha County, the bounding fault has split into first two, then four, then a multitude of faults.

The amount of basement offset at the Boone-Logan line depends on the velocity of the rocks in the deep section of the Trough. These could theoretically be very low velocity, coarse, porous fanglomerates or very dense, high velocity volcanic sills and/or lava flows. The velocity must be known to calculate an accurate drop at the Trough edge. In any case, the original throw on basement in Logan County was probably in excess of 10,000 feet, and may have been much greater if this rift contains a significant igneous section at depth, a characteristic of most other similar rifts worldwide. When an episode of Mantle thermal instability causes the crust to blister, the release of heat is often accomplished partially by igneous intrusions and volcanism. Inaccurate velocities, along with misidentified sills or dikes that have been reported as "Basement" in deep tests, may have led to some highly misleading pictures of the age and depth of the Rome Trough in the literature. The edge of the Rome Trough shows clearly on the magnetic map at the Boone County line (Figure 11).

Even if the age and depth of the Trough are uncertain, much of its history and its patterns of movement can be determined from seismic data. The intervals between the seismic reflectors document many of the details of the history of the Trough. This history supports John Sclater's work and concepts on classic rift systems and fits the Rome Trough right in with analog rifts around the world.

The Trough experienced an early extensional phase with a massive, rapid drop of the Trough floor along the southeast edge (Figure 12) and, probably, very coarse clastics. Pre-Beekmantown sedimentation

Figure 10 - The Rome Trough edge at Logan County

Figure 11 - Magnetics signature of the Rome Trough at Logan County

NW

SE

Figure 12 - The Rome Trough opens with massive faulting

rates and accumulations were an order of magnitude greater in the Trough than on the adjacent shelf (Figure 13).

A long period of thermal cooling and contraction caused continuing downward movement of the Trough at a steadily declining rate throughout much of the early Paleozoic and well into Devonian time. This is documented by reflector intervals within and along the Trough margin. The Trough dropped at a tremendous rate initially, continued to move rapidly in the Ordovician, slowed steadily into the Silurian, and then moved even more slowly during Lower Devonian time. A hypothetical Devonian section (Figure 14) shows the rift at almost its maximum development. This is the section of a classic Sclater-type rift. Figure 15 shows the amount of additional section accumulating in the Trough due to tectonic activity, and the declining rate of this activity.

It should be possible to pinpoint the time at which the Trough ceased to drop by doing extensive isopach work in this area (if a sufficient log data base exists). Such work has been done in the Calhoun County area where much of the Devonian shale section thickens noticeably across the basement faults in the deeper section, then stabilizes in the Upper Huron Shale, at approximately Speechley or Balltown time. The level at which there are no isopach changes across the faults indicates the cessation of Trough movement. This varies slightly from area to area.

This ongoing movement is pertinent to this project due to the fracture porosity that would have been generated. The movement probably continued into Devonian time in the Boone-Logan area. Long-term continued movement into post-Onondaga time would have led to the very early development of fracture porosity in the lower portion of the Devonian shales.

The Boone-Logan portion of the Rome Trough has the largest offset along the entire rift and, according to the Sclater models and mathematical predictions, should have experienced some of the latest downward fault movements. Sclater shows that large, deep sections in a rift system will experience longer, later periods of normal faulting than shallow portions of the same rift.

Figure 13 - Filling of the trough by Lower Ordovician time allows the Beekmantown to be deposited on a relatively flat sea floor

Figure 14 - An Onondaga section demonstrates approximately the maximum offset along the Rome Trough edge

Figure 15 - The shaded portion of the trough fill shows the extra section necessary to compensate for the rifting. In most similar rifts of the world, the lower sediments will include igneous intrusives and extrusives

The final stage of the Trough story is told by the presentday structural relations along the rift (Figure 16). The Onondaga reflector is now higher in many areas within the rift than on the adjacent shelf area. This is due to the effects of a late inversion of the Trough, in which the former graben area rebounded and became a horst. Similar patterns can be seen in many rift systems worldwide, including producing features in the Middle East, Europe and South America.

The rebound at Boone-Logan may have exceeded 500 feet. This Mississippian section crosses the Trough edge in a highly fractured monocline with the knee above the trough floor and the ankle at the shelf edge.

In addition to the early fracturing discussed above, this later movement would have reinforced and enhanced the shattering of the Devonian shales along the margin of the Trough. A significant trend of shallow production follows the fracture system along the Rome Trough margin in Boone and Logan Counties. The Boone-Logan area has also been affected by a zone of north-south (Grenvillian-related) fracturing which is followed by modern drainage, the Little Coal River and Spruce Fork.

Several CSD's cut through this area, a major one around Logan, and less significant ones in the vicinities of Ethel, Sharpless, Clothier, and Madison. Seismic work indicates that there are slight but noticeable changes in the time to Basement within the Rome Trough across these CSD's. There may also be slight steps across the CSD's on the shelf, but these are much less well-defined. The CSD's variously align with drainage and/or drainage divides.

Production maps and reserve maps show several exceptional shallow wells at the intersections of the Rome Trough edge and the CSD trends, and at the points where these features meet the Grenvillian fractures.

In an area as tectonically active as Logan and Boone Counties, the primary concern may not be the search for fractured shale, but the search for an intact cap rock. Although the Devonian Shale is considered to

Figure 16 - Modern Rome Trough cross-section showing the effects of rebounding, with the trough side higher at the Onondaga level, fracturing extending through the Devonian Shale section and a monocline at the Mississippian level

be relatively soft and weak, extensive data on shale production around West Virginia showed that it is possible for significant fracture systems to form and persist in the shale.

With a local history of major normal faulting both during and immediately following deposition and lithification, followed by hundreds of feet of reversal and uplift through this area, plus crossing zones of weakness that have their own tectonic histories, originally continuous layers that elsewhere act as caps are likely to be shattered and offset along the Rome Trough edge by amounts much greater than their thickness (see Figure 17).

Leakage from the shale may be indicated by production in some of the shallow fields in this area. Comparing production histories and present cumulative numbers on some of the better wells, then calculating theoretical drainage radii and looking at actual well spacing, the implication is strong that many of these wells must be experiencing some major ongoing recharge from below; i.e., they are open through the Huron section to source beds in the deep shale.

4.2.2 Calhoun County

Near the Calhoun County area, Rome Trough faulting has controlled the formation of the Warfield Anticline and a series of evaporite-cored, Chestnut Ridge-style folds. There is also a series of aligned shallow and deep structural features through this area that follow a series of closely spaced CSD's and which probably mark the feather edge or pinchout of various evaporite salts and anhydrites in the Salina section.

The shallow beds in this area seem to have moved in a "thin-skinned" manner to the northwest to form the Burning Springs Anticline. This motion occurred along several different décollements. There is great structural complexity through Calhoun County as the gliding horizons shift.

In Gilmer County and to the northeast, detachment has occurred mostly in the Silurian evaporite section. To the southwest, in

Hydrocarbons can migrate past the cap by bypassing it on one side, then spreading to fractures on the other side and continuing their climb through the section.

Figure 17 - Cross-section of a fault/fracture system, showing a caprock off set by more than its thickness.

Roane County, most of the movement has occurred by detachments and thrusts within the deeper Devonian Shales. The Roane County style of deformation has been studied and reported on by K & A for GRI. Calhoun County marks the transition zone between these two levels of detachment with the shift following CSD's (Figure 18).

This shift in the detachment level is related to differential Basement movements along the CSD's. Figure 19 shows slight offsets at the Basement level and how these have influenced breaks in the Trenton. Figure 20 extends these breaks up into the Saline section.

The Saline pinchout is poorly defined by four deep wells in Calhoun, Roane, and Wirt Counties and has been shown variously on maps of West Virginia, but indirect evidence can give a fairly accurate view of the actual edge. Analog evaporite edges from elsewhere in the world allow us to make some statements about its probable nature.

Calhoun County probably was the site of a Sabka or evaporite edge at the southwest margin of the multi-state Saline basin. The actual edge of the evaporites probably shifted back and forth from CSD to CSD as the basin sank or sea level rose or fell (Figure 21). Thin salt and anhydrite beds pinched out, one after the other, against the strong structurally controlled Sabka front.

Multiple evaporite layers which had the potential to become future decollements were all strongly controlled by the active down-to-the-northeast CSD movements that were occurring as the Saline sediments were being deposited and by the general deepening to the east of the Rome Trough. The Rome Trough was still sinking during Salina deposition and the CSD's may have been exceptionally active at that time.

Figure 22 shows cross section A-A' with the Devonian shale and Greenbrier sections having been deposited. Extensive isopach work in the Calhoun County area does not appear to show active movement on the CSD's during the Devonian, but this may be due to limited control in the deeper portion of the Shale section. The great majority of the holes in the area only go through the Greenbrier, with a fair number penetrating the

Figure 18 - CSD trends through Calhoun County and the location of cross-section A-A'

A series of small, repeated movements along the CSD's leads to fracturing at the Trenton level.

Figure 19 - Basement through Trenton section along A-A'

SW

NE

During this time interval, the CSD's appear to have been active, with the northeast side of the CSD's having dropped steadily more than the southwest sides. A series of evaporite horizons extend up to the CSD's, then abruptly pinchout. The pinchouts jump back and forth through Salina time, but repeatedly occur at CSD's, and the evaporites fail to extend into Roane County to the southwest.

Figure 20 - Trenton through Salina section along Line A-A'

This illustrates one instant in Silurian time. The sabka would jump back and forth from one CSD to the next through Salina time. Although the exact locations of the shore would change, the trend of the pinchout, southeast-northwest, would remain constant.

Figure 21 - A representative Salina sabka shoreline

SW

NE

Trough movements continue through the Lower Devonian, extending fractures up into the shale section.

Figure 22 - Salina through Mississippian section along Line A-A'

shallowest Devonian section. The limited drilling through the Huron section may simply be inadequate to demonstrate a series of abrupt thickenings or thinnings at the CSD locations in the deep Shale. Since the Rome Trough in this area was dropping until Speechley time, it is likely that better control would show the CSD's as still active up until this same point. The movement on the CSD's could logically be expected to cease at the same time that the Rome Trough stopped moving.

The deep Shale section contains a number of potential decollement or "slippery" horizons where detachment can occur. These are also shown in Figure 22.

Figure 23 shows the shallow "thin skin" layers which overlie potential decollements. These layers would be susceptible to breaking away under sufficient stress. They would eventually move to the northwest to form Burning Springs Anticline (Figure 24). This motion would produce a series of deep wrench or strike-slip faults along the CSD's where the detachment jumps from one decollement to the next.

Figure 25 shows the results of this type of motion. A series of deep parallel wrenches is shown by the T (toward) and A (away) symbols on the section. Such deep seated faulting will cause disruptions in the overlying beds, even when these beds have not been cut by the faulting. T.P. Harding (1974) has done extensive work modeling the effects of such deep wrench motion on unfaulted overlying beds. Figure 26 shows the orientation of such a buried wrench, and the deformation that will occur in the shallow beds. In the case of a deep southeast-northwest wrench (along the CSD orientation), the shallow beds will react initially in an *en echelon* series of synthetic features oriented (theoretically) at approximately 20 to 30 degrees to the wrench orientation. In Calhoun County, this means that there should be a strong shallow structural orientation varying from N60W to N10E with the features at a given spot being determined by the exact bearing of the deep wrenching at that location. There will also be a series of antithetic fracturing and faulting which will develop approximately perpendicular to the deep wrenching. In Calhoun County, this will show up as a southwest-northeast orientation.

SW

NE

The shaded area moves away from the viewer toward Burning Springs Anticline

Figure 23 - "Thin-skinned" detachment

Figure 24 - Examples of movement along CSD's toward the northwest

The thick, brittle Greenbrier section shatters above the deep wrenches and breaks in synthetic and antithetic faults.

Figure 25 - Extension of fractures through the shale section above the offsets along the CSD's.

This illustration is based on the work of T. P. Harding (1973) and shows hypothetical fracture and fault orientations in homogeneous rocks that will develop above a deep wrench (heavy line). The direction of motion is shown by the arrows.

A swarm of en echelon synthetic fractures (light lines) and antithetic fractures (dashed lines) forms.

Figure 26 - Synthetic and antithetic fault orientations above a wrench

According to Harding, the earliest and simplest features to form will be a series of small *en echelon* anticlines at the synthetic orientation. If deformation progresses, fracturing, and eventually faulting will develop at almost the same orientation in association with the anticlines.

As the intensity of the wrenching increases, the antithetic features will begin to form, first as fractures, then as faulting, generally with strike-slip movements perpendicular to the deep wrenches. Interactions between the synthetic and antithetic features may cause a general ridge or trough trend above the deep wrench zone. Such a feature will accentuate the already described synthetic anticlines. This appears to be the stage reached in Calhoun County.

Harding's theoretical studies and clay models will always be a simplified version of what will be seen in the field where lithologic inhomogeneities and preexistent structures will influence the deformation process. Still, Harding's model shows remarkable similarity to the structures seen in the study area.

In Calhoun County, the deeper shale has apparently behaved in a relatively plastic manner as would be expected. There do not appear to be any abrupt structural changes or faults along the CSD's, but this is difficult to confirm absolutely due to the limited number of deeper logs in the area.

The upper shale section with a number of more brittle silty layers and better log control still doesn't seem to show significant unusual structures above the CSD's.

The Greenbrier is another story altogether. This is a thick sequence of rigid, brittle beds, and has not warped, bent gradually or flowed as the shaley units have. Detailed structural mapping of these beds shows a complex series of faults through the Greenbrier in this area. Close variations on the synthetic and antithetic orientations are the dominant fault trends above the CSD's through most of Calhoun County. Figure 27 is a simplified stylistic presentation of these trends through

Figure 27 - A simplified, stylistic representation of synthetic and antithetic fault trends in the Greenbrier through Calhoun County

the County and shows the great concentration of faults in a band above the Saline pinchouts. The faulting is most intense over the wrenching and tapers off to the northeast and southwest. Figure 28 is taken from Figure 5 of the Oil and Gas Report and Maps of Wirt, Roane, and Calhoun Counties, WV, and shows both a ridge and trough trend developed at the Greenbrier level above the CSD's, totally independent on the local shallow structures which continue through the area. The pattern fits Harding's model amazingly well, considering the great structural complexity of the region, with Grenvillian, Rome Trough and CSD trends and numerous depositional inhomogeneities in the County. The ridge-trough complex and the synthetic-antithetic fault orientations pay much more attention to the wrenches than to the major Basin-wide trends that dominate most other sections of the state.

Figure 29 shows in a generalized way some of the synthetic and antithetic fractures and faults in the same area as Figures 26 and 27.

It can be seen in Figures 27 and 29 that the synthetic and antithetic faults frequently intersect, creating triangular trapdoor structures. These sometimes pop up and, in other cases, drop down. Vertical offset can occasionally exceed 100 feet. Such large vertical variations between adjacent wells has probably frequently been attributed to poor survey information or inaccurate surface elevations, but an extremely detailed data base shows too many of these features for them all to be mistakes. In addition, several wells in a row will often show progressive offset along a fault plane.

The exact timing on these faults is difficult to determine. Some movement may have been going on as the Greenbrier was being deposited. This would explain some evidence for thinning on the upthrown trapdoors and thickening on the downdropped blocks. However, a direct correlation is not always evident, and most of the movement obviously took place after the end of Greenbrier time.

In several cases, the Greenbrier synthetic-antithetic faults (S-AF's) must be tied to deeper fracture systems, producing areas with exceptional shallow open flows, production histories, no significant

Figure 28 - Base of Greenbrier structure in northern Calhoun County from Figure 5, WVG&E Survey Bulletin B-40

Figure 29 - Generalized representation of Greenbrier faulting through the area of Figure 28

decline in production decades after completion, oil production high on structure in the midst of a gas field, wells returning to initial flow rates after cleanout, etc. Such situations imply a steady recharging from below (i.e., from the deeper source beds in the Devonian shale) with the gas being replaced as it is drained, or with oil working its way straight up onto an anticline through exceptionally open fractures. In many cases such areas display unusual drainage features at the surface, indicating synthetic or antithetic control of modern erosional patterns. Examples of such features and wells can be seen in the southeast corner of the Annamoriah Quadrangle and along the Gilmer-Calhoun County line. These areas may have lost many of their deep reserves to the shallow reservoirs. There are still many areas out of the main S-AF zone where the fracturing may be extensive, but where there are still cap rocks intact.

One particular synthetic fracture system between the areas of Stumptown and Sand Ridge along the Gilmer-Calhoun county line has been documented by a string of unusual wells. Seven wells lie along the trend. Each produces from an interval different from the adjacent wells, lending support to the concept of an open fracture network and extensive migration from one horizon to another.

Initial interest in the area was spurred when Pennzoil drilled two oil wells in the early 1930's. Initial flows were modest; however, one of the wells had a very unusual decline curve.

Figure 30 shows the production rate for the first fifteen years for this well. There was almost no decline through this time period, and as late as year eight, production was better than it had been in year one. The well seemingly was being recharged as it was produced.

Numerous close offsets were rapidly drilled without encountering any additional exceptional wells. In addition, most of the offsets made only gas, not oil.

In 1974, Consolidated Gas Supply Corporation drilled a well that seems to have hit the trend. The Devonian shale section looked very promising and was perfed and shot. Before the well could be finished and

PENN 2/GILMER COUNTY PRODUCTION ANALYSIS

Figure 30 - 15 year production curve on a synthetically fractured oil well

produced, it was lost and had to be abandoned due to problems caused by uphold water.

The trend was again encountered in 1985. CNGD drilled a hole in October of that year that was very promising. It had very good shows in the shale, probably in a silty equivalent of the Speechley, and in the shallow section, in the Weir and Gordon Stray. These zones covered too great a vertical range to co-produce, so the best zone in the well, the Speechley equivalent, was treated and immediately plugged off. It remains behind pipe. the Weir and Gordon Stray were fract and are still producing. The results of this well were 1000 mcf/day and 250 bbl/day of oil.

In December, 1985, the next well along the trend came in for 1000 bbl/day of oil and 750 mcf/day of gas. This well produced from a silty equivalent of the Balltown.

The next hole on the trend came in at well over 300 bbl/ day of oil, producing from a shallow zone.

The last well drilled on the trend was a gas, not an oil, well and produced at 15 mmcf/day, natural. It was never fract. The gas was encountered in an intermediate silt layer.

An additional hole was drilled slightly off the main trend near the gas well and came in for 1000 mcf/day, natural.

The alignment of these wells, each very productive, but each producing from a different interval, supports the idea of synthetic fracture systems which have been open and fed to different horizontal reservoirs through time. It also verifies the "synthetic" angle and its relationship to the evaporite pinchouts along the CSD orientation.

Hydrocarbons have entered this synthetic network of fractures and risen through the system until they encountered a relatively porous reservoir or an intact caprock that prevented a further rise.

There are exceptional wells and distinctive drainage patterns in the Mount Zion area that indicate that that area is also cut by both synthetic and antithetic fracture systems. Several wells in that area have had very large cumulative production numbers and/or unusual well pressure histories or decline curves. These wells may also be recharging through the fracture network. The best Mt. Zion wells seem to follow antithetic instead of synthetic trends.

In addition to the CSD-related S-AF features, there are a series of Rome Trough Basement faults under Calhoun County (Figure 31). The actual trough edge is just southeast of the county. Within the map area, the main faults seem to be mostly a series of short north-south breaks, some with quite large offsets, considering the shortness of the faults themselves. These faults occur in groups, arranged *en echelon* along southwest-northeast trends. It appears that the Basement was attempting to break along the Rome Trough trend, but repeatedly found it easier to reactivate a short stretch of a preexisting Grenvillian zone of weakness. The north-south Basement trends are generally smoothed over by deformation within the Ordovician Shales, Silurian evaporites, and Devonian shales, and the dominant shallow fold axes again appear to be dominantly southwest-northeast features (Figure 32), although they frequently twist and turn, probably reflecting a long Basement break or the crease as deformation jumps from one *en echelon* leg to another. The smoothing effects of the shale and evaporites is evident in Figure 32.

The longest Grenvillian-related feature in this area is a major north-south fault that lies below the Burning Spring Anticline, just northwest of Calhoun County. There may be a parallel feature to the east, which may extend into Calhoun County, but additional seismic lines need to be checked to confirm this.

There are several of the aforementioned exceptional wells that probably occur right at the intersection of a CSD or S-AF feature with either a Rome Trough or Grenvillian Basement break. This makes sense as reactivation of any of the systems would open or reopen the fractures in such a situation.

Figure 31 - Diagrammatic representation of Basement faulting in Calhoun County

Figure 32 - Diagrammatic representation of shallow structures in Calhoun County

The Calhoun County area was the site of a combination study using seismic sections for deep mapping and a very large gamma ray/density log data base for shallow isopach work. A nine quad area was covered, extending from the south end of the Burning Springs Anticline to the north end of the Warfield Anticline and including the end of the chestnut Ridge feature, as well as many Rome Trough faults and shallow structures like the Rosedale Basin. This work allowed seismic location of the Rome Trough faults, and then permitted careful isopaching along the shallow traces of the faults. It showed that the Rome Trough continued to drop in this region until approximately Speechley time. It was also possible to see a reversal of this motion with the early beginnings of an inversion or uplift of the former trough in latest Devonian time.

Calhoun County is an area with extreme fracture porosity due to its tectonic history. Any test in Calhoun County should take into consideration the shallow production history of the area. Areas with shallow wells, closely spaced, which have produced in the multiple bcf range or that have retained original production rates or well pressures after decades of production may be directly connected to the deep shales by open fractures. There are also several small oil pools high on anticlinal structures at points where the Rome Trough faults and CSD's intersect. These may also mark zones of exceptional fracturing. There are still many promising areas for a shale test in Calhoun County.

5.0 EVALUATION AND RANKING OF AREAS

5.1 Areas Proposed by CNG Development Company

CNG Development Company proposed three areas for evaluation on large acreage blocks or in areas where they hold an extensive lease position. The first (Figure 33) is an extensive cluster of leases around Mt. Zion in Calhoun County, and the second (Figure 33) is in Calhoun and Gilmer County, on a very large tract near Sand Ridge. The third area (Figure 34) is a large block at the Boone-Logan County line.

All three areas are in the midst of shallower Mississippian production and are served by extensive pipeline networks.

Figure 33 - CNG Prospect Areas 1 and 2

Figure 34 - Prospect Area 3

5.1.1 General Description of the Three Areas

The area nominated by CNGD in Logan County at the Boone County line is right at the edge of the Rome Trough with faulting continuing up through the Onondaga section.

The two areas in Calhoun County are just to the northeast of the Saline evaporite pinchout zone. The structural framework in this area is controlled by a complex interaction of Rome Trough-age faulting, much of which follows an older Grenvillian structural grain, and Crossstrike Structural Discontinuities (CSD's). Normal faults and thrusts are present at the Onondaga level. The Greenbrier is faulted above the Saline pinchout.

Each of the three areas will be discussed in detail to evaluate them for possible horizontal well locations.

5.2 Logan County Area at the Boone County Line

CNGD's acreage at this prospect area is partially along the very edge of the Rome Trough, with the bulk of the block to the southeast of the disturbed zone that overlies the trough edge. A major Grenville trend feature, a significant fracture zone, runs down Spruce Fork, cutting through CNGD's acreage (determined by correlation with seismic data and surface drainage features).

5.2.1 Geology of the Logan-Boone Area

5.2.1.1 Stratigraphy

The Lower Huron shale is approximately 180 feet thick in this area, based on log control. The section here is a relatively featureless succession of very fine material with very few marker beds. Most of the shale production here is from the Middle and Lower Huron sections and probably had its source in the deepest, organic-rich, black shale section. A correlated log section of the Upper Devonian section is shown in Figure 35. This is a GRI Comprehensive Study Well (CSW) that

Figure 35 - Boone County log section

was recently successfully stimulated and is currently undergoing pressure build-up and drawdown tests after stimulation clean-up.

5.2.1.2 Structure

The major structural feature in this area is the Rome Trough edge. The rocks draped over this edge have been repeatedly fractured, first by normal faulting that cracked the rocks almost as soon as they were lithified. This downdropping movement persisted into the time of deposition of the Devonian shale section. The rocks were later (probably from Upper Devonian and Mississippian time onward) broken once again as the trough section began to rebound or rise.

At present, the Trenton forms an almost level surface across the trough edge, even though the Trenton had dropped a considerable amount in the trough during the Silurian and early Devonian periods. This is verified by the thick Trenton-Onondaga interval on the trough side of the boundary fault.

The Onondaga now is high on the trough side of the boundary due to the rebound (Figure 36). There is greater throw on the Logan County side as compared to the Boone County side.

The seismic evidence implies that there is splaying or rooster-tailing within the fault zone as it climbs through the section. There seem to be major breaks climbing toward the vertical northwest of the main fault plane. Several discontinuities in the seismic reflector at the Onondaga level indicate probable splays off the main fault. These faults are shown in Figure 37. These mostly cut the Onondaga northwest of the main fault, but some wedges appear to have broken off on the shelf side as well, causing significant faulting and fracturing southeast of the trough, cutting into the CNGD acreage.

Above the deeper Devonian shales, syndepositional movement allowed many of the formations to compensate for the tectonic activity, and the shallowest formations appear to cross the boundary zone

Figure 36 - Onondaga structure at the Logan-Boone County Line

in a monocline instead of abrupt fault breaks. The amount of movement has probably induced extensive fracturing across the monoclines, however.

5.2.2 Production Information

Open flow and shallow production trends show a very strong association with the Rome Trough edge fracture/fault orientation, although there is also a clustering of the best wells at the intersection of the trough edge and CSD and Grenville structural trends (compare Figures 37, 38, and 39). The calculated or produced reserves and wellhead pressures of the best of the shallow (Mississippian) wells indicate that some very unusual conditions exist along the margin of the Rome Trough. The best of these wells have produced amounts of gas that should have come from very large drainage radii, even though the wells are relatively closely spaced. Pressures vary greatly, and don't obviously correspond to expected production histories of the wells.

The most likely explanation for these seeming inconsistencies is production from a series of vertically fractured reservoirs, instead of the traditional horizontal, bedded reservoirs. The pressure situation is not related to the depth of a given bed and the expected hydrostatic load at that depth, but to an open vertical system, and the expected pressure at the shallow end of this unconventional reservoir. Other possible explanations for the low pressures include casing or completion problems.

Along adjacent fractures, very different pressures can exist in closely-spaced wells, dependent on the vertical extent of the fracture sets encountered in any specific hole. A better well, tapping into a more extensive, vertical system can have a lower pressure than an adjacent well that doesn't drain from as great a vertical range of fractures and interconnected silt or sandstone reservoirs. In this area, a well displaying "normal" initial rock pressure may only be draining from a single deep bed. The nearby wells that are vastly "underpressured" may be pulling gas not only from treated deep formations but from vertical openings and from much shallower beds that are connected to the fractures. This complexity can make it very difficult to evaluate wells by conventional methods of

Figure 37 - Main Rome Trough fault and splay faults the the level of the Lower Huron level from seismic control

Figure 38 - Open flows and original rock pressure data for Area 1

Figure 39 - Cumulative production and current rock pressures for Area 1

initial open flows or wellhead pressures. Comparing adjacent wells with similar high initial open flows but very different wellhead pressures or production histories, it quickly becomes obvious that the only thing that truly counts is the final history of a given well. This, of course, is true in any area, but seems to be even "more true" along the complex structures of the Rome Trough edge.

5.2.3 Relationship of Production to Geologic Conditions

There is an obvious, strong association between shallow and Devonian shale production trends and the Rome Trough orientation (N40 to 55E) along the shallow monocline (Figure 40) over the Basement break. There are also clusters of excellent wells at the intersection of the Rome Trough edge and the generally North-South Grenvillian controlled fracture system that runs down Spruce Fork and at the intersection with CSD (N45W) trends that cross the Trough edge near the towns of Ethel and Clothier (Figure 41). There are also some exceptional wells to the northwest, within the Rome Trough, that seem to fall along the CSD trends. The CSD-oriented features seem to have had minimal effect on shallow production on the shelf southeast of the trough and doesn't seem to show up as major production trends on this shelf. Within the trough, however, the basement seems to have dropped by slightly different amounts across the CSD trends, and the slight variations in vertical displacement seem to have led to fracturing along the CSD's. The timing of the movements within the trough has been critical in determining which areas along the CSD's have become good shale reservoirs.

Siting a well in this area involves the consideration of all three natural fracture orientations. Given the size and continuity of CNGD's acreage, a large area is open for development. Three potential horizontal well locations are presented in Figure 42 to provide an example of how wells can be drilled to intercept faults in this area.

5.3 Mt. Zion Area, Calhoun County

CNGD has a very large cluster of small and medium size leases in the Mt. Zion area that it is willing to make available for this project.

Figure 40 - Shallow monoclinal structure at the Logan-Boone County Line

Figure 41 - Relationship of production to structural trends at Logan-Boone

Figure 42 - Sample desirable horizontal shale well locations at Logan-Boone

Figure 43 shows the area under discussion, and Figure 44 shows CNGD's acreage position. It is an area where production is controlled by deep seated basement faulting.

5.3.1 Geology of the Mt. Zion Area

5.3.1.1 Stratigraphy

The Lower Huron Shale section exceeds 1000 feet in thickness at Mt. Zion. A few of the major lithologic markers like the Speechley can be identified in the wells at this area, but they are just slightly coarser shale units, hardly true silts or sandstones. CNGD's results from a shale drilling program in southern Calhoun County in the early mid-80's led them to conclude that the largest reserves were in the Lower Huron or above. Deeper testing was deemed not worthwhile economically.

5.3.1.2 Structure

Figure 45 shows the Basement structure in the Mt. Zion area. Faults with an apparent throw in excess of the range of 1000 feet are shown as double lines, those with throws that are probably in the hundreds of feet are shown as heavy single lines, and minor faults are shown as thin lines. The major faulting appears to have developed as part of the Rome Trough formation activity, but occurs as a series of *en echelon* breaks along much older Grenville trends (zones of weakness).

The trough is deepest near the Gilmer County line, climbs toward the Mt. Zion area, then drops again across a major intra-trough fault system.

A large number of CSD's can be identified through the area. These are shown as dashed lines and may be more extensive and continuous than shown. Generally, the basement drops toward the northeast across these CSD's.

Figure 43 - Map of Calhoun County prospects

Figure 44 - Map of CNGD's acreage position in the prospect areas

Figure 45 - Generalized Basement map of the prospect area

Figure 46 shows a simplified map of the Greenbrier structure in the Calhoun County area. The extensive faulting at this level is due to the response of a thick, brittle unit to underlying wrench or strike-slip motion at the pinchout of the Salina salt and anhydrite beds. Certain selective ("synthetic" and "antithetic") orientations keep recurring in the fault patterns.

The structural history of this area was intensively studied, with detailed correlation of a large number of gamma ray and density logs and drillers tops over a nine quadrangle area. Thrust faults were identified and repeat sections removed and isopachs made for all significant intervals.

The study showed that the Rome Trough faulting continued upward through the nine quad area into Lower Huron time. Finally, from approximately Balltown or Speechley time until approximately Gordon or Gantz time, the area was tectonically quiet. By Greenbrier time, mild tectonic reactivation had occurred, with the trough section beginning to rise as Basement faults reversed their earlier directions of movement, and new deep breaks possibly formed. Syndepositional activity like this affected the Greenbrier, and may have made it more susceptible to faulting during the Appalachian Orogeny.

The Mt. Zion area shows evidence of Basement fault activity, Greenbrier faulting, and also productive fracture trends.

5.3.2 Production Information

Shallow production at Mt. Zion seems to relate very closely to Basement structure, with less obvious ties to the synthetic-antithetic fault/fracture orientation. Both Rome Trough and CSD structures seem to be very important in this area.

In this area, as at Logan County, there are anomalous wells overlying the intersection of basement features that seem to have produced more gas than is credible, considering well spacings and normal drainage radii. Here too, a possible explanation is gas being fed

Figure 46 - Generalized Greenbrier fault map of the prospect area

continuously into the shallower beds from deep sources through an open fracture network.

Consolidated Gas Supply Corporation has heavily developed this area with Greenbrier wells generally spaced between 1200' and 1800' apart. Although the locations are relatively tight, there are several wells in the interior of their field that have produced over 1 bcf, even 2 bcf, of gas from an apparently limited drainage area. It is difficult to explain the production numbers on the best wells by conventional drainage considerations, given the spacing on the wells.

In addition to unusual production statistics, there are some unusual pressure data in this area. Several of the old prefrac wells around the area were cleaned out after many years of production and retested. Some of these wells went back to seemingly abnormally high pressures and then produced at higher rates than would have been considered normal, given the age and history of the wells.

This type of information lends credence to the idea of open fractures still feeding gas into the Greenbrier, even as the gas is being produced. Although the Greenbrier has been extensively tested, the Devonian shale is still largely undeveloped around Mt. Zion. Figure 47 shows the control in the Devonian shale and reports shale well open flows. Figure 48 gives wellhead pressure data, and Figure 49 is a map of available projected ultimate recoverable reserves in the shale.

5.3.3 Relationship to Production to Geologic Conditions

Mt. Zion shows a very close correlation between Big Lime/ Big Injun production and Basement structure. At this time, shale data is too skimpy to draw production or reserve patterns or associations.

Figure 50 shows the Greenbrier production trends at Mt. Zion. The main trends are two elongate pods which follow two major Basement CSD's through the Mt. Zion area. The northerly of the two features continues further to the northwest into another highly productive gas

Figure 47 - Basement Structure and Location of Shallow Wells and Devonian Shale Initial Open Flow Rates

Figure 48 = Initial Rock Pressure in the Devonian Shale

Figure 49 - Projected Ultimate Recovery of Vertical Shale Wells in the Area

Figure 50 - Relationship of Greenbrier Production Trends to Basement Faulting, Greenbrier Faulting, and CSDs.

pool. There is no data in the area of the two CSD's in the northeast corner of the map. These may also be productive areas.

The northeastern productive trend has a pair of north-south projections that extend to the south. These seem to relate to a large Basement fault with a throw that may range in the thousand foot plus order of magnitude. This fault is one of the major intratrough breaks already discussed that may have reactivated an older Grenville zone of weakness.

The fault plane here would be expected to be inclined and to dip to the west. This fits in with the major north-south producing band which lies east of the Basement location of the fault. The pattern of two parallel productive zones with a poorer strip of wells in between fits the idea shown in Figure 51. This is a cross section showing an inclined fault plane that allows migration of gas up and through the reservoir and out at the surface. Wells too close to the fault lack a cap or trapping mechanism and have poor results. The faulting is accompanied by extensive fracturing in the rocks near the fault plane. This will lead to better productive areas near the fault on both sides of the main break. This is exactly the pattern shown here.

There is also a wing projecting out to the east-northeast of the main trend. This appears to be following one of the local synthetic fracture zones. The zone is delineated by a string of three Consolidated wells (and may include other, non-Consolidated wells for which there is no data) and also shows up in very strong distinctive structural control of drainage in this immediate area.

Where production and reserve data are available, they can be seen to follow CSD and Rome Trough trends. Synthetic (and in the area northwest of the map, antithetic) faults in the Devonian and Greenbrier sections also affect these numbers.

The degree of deformation can also be seen to be important, with too much faulting destroying the traps, but flanking fractures creating good associated reservoirs.

Cross-section shows how Basement fault is offset to the east at the Greenbrier level.

Open faults allow gas migration to the surface at the fault plane.

Fractures flanking the fault concentrate gas on both sides of fault plane.

Figure 51 - Cross-section of Fault Plane

5.4 Sand Ridge, Calhoun County

CNGD has a large lease position at Sand Ridge where they have had some very interesting results in the shale section. Figures 43 and 44 show the area of Calhoun County and CNGD's acreage position.

5.4.1 Geology of the Area

5.4.1.1 Stratigraphy

The Lower Huron Shale section exceeds 1100 feet in thickness at Sand Ridge. The shale has begun to pick up identifiable silty markers extending into the area from the major delta complex to the east. Shale beds which display the typical 200 plus API count gamma ray signature have thinned to 40 to 50 feet in this area.

5.4.1.2 Structure

Figure 45 shows the Basement structure (as determined from seismic data) in the Sand Ridge area. A major Rome Trough fault cuts through the heart of the CNGD acreage block and intersects one of several CSD's in the area right at the point where Chestnut Ridge (or Wolf Summit) anticline crosses the lease.

This is at one of the deepest portions of the Rome Trough in Calhoun County, where there should theoretically be maximum thicknesses of source beds, potential reservoir rocks and thicker, more effective cap rocks to maintain a seal.

Figure 52 shows Onondaga structures in the area of Sand Ridge. The Rosedale basin appears to be underlain by grabens at the Onondaga level, probably related to some structural event in the Salina section related to the evaporite pinchout. Nearby, on Chestnut Ridge-Wolf Summit anticline, there is apparent Onondaga thrusting.

Figure 46 shows Greenbrier limestone structure in the Calhoun County area. There is extensive synthetic and antithetic faulting to the

Figure 52 - Generalized Onondaga fault map of the Sand Ridge area

southwest of Sand Ridge. Shale tests in that very disturbed zone showed the shale to have very low pressure and be uneconomical as a reservoir. Cap rock integrity has apparently been breached in that area. This does not seem to be a problem at Sand Ridge, away from the extensive faults.

5.4.2 Production Information

The drilling at Sand Ridge has found production along the previously discussed synthetic fracture pattern trends (Figure 53) and in areas away from the major Basement faults. Drilling patterns have not followed the Basement features.

Again there appears to be a complex history at work in this area, controlling a complicated set of production factors. Adjacent wells along apparently the same synthetic fracture feature will produce from quite different stratigraphic levels within or above the Huron Shale section. Once again, the reservoirs do not appear to follow the norms of horizontal bedded units, but a more complicated set of vertical features charging various silty zones along the fracture network. Projected reserves shown in Figure 53 characterize a reservoir controlled by a limited number of fracture orientations.

5.4.3 Relationship of Production to Geologic Conditions

Drilling in this area was originally conducted down to the Berea Horizon in the 1930's and 1940's. Salt, sand, Big Injun and the Berea were the primary targets. Later drilling found production in upper Devonian-age sands and siltstones. Since 1980, the area has undergone another round of drilling to the deeper Devonian shales and silty shales. Some wells have been quite successful, while others have not. In general, drilling has not been conducted with knowledge of the basement structures and the implications of tectonic history on the various reservoir units in the Calhoun-Gilmer County area.

The periodic reactivation of basement faulting has produced fractures in both shallow and deeper formations. These faults and fractures do not control production everywhere in all cases, but do exhibit

Figure 53 - Projected Reserves of Sand Ridge Area

structures and the best deeper wells are detected in the area. Better Devonian shale production occurs where there is less intense Greenbrier faulting and fracturing. In Figure 45 the major basement structures are located southeast of the current Sand Ridge development. In this area, two major CSD's interrupt the trace northward of the basement fault. There appears to be a downward displacement of the fault block on the north side of the CSD's. Reverse faulting has not been as effective in this area as in many areas. The normal shelf side up - trough side down relationship still exists here which we interpret to mean that reverse faulting in this area was not active long enough to make a reversal of Upper Devonian reflectors like the Onondaga Limestone. Antithetic faults and fractures are likely to be developed on the down-thrown sides of the basement fault.

The development of such faults is somewhat supported by the shallow well cumulative production as shown in Figure 54. On this figure shallow production shows a relationship to both basement faulting and the CSD's. A relationship to late tectonic activity which produced thrusting from the northwest in the Onondaga Limestone is also indicated. In view of horizontal wells to intercept fractures is highly probable. Figure 55 shows examples of possible horizontal shale locations.

5.5 Analysis and Ranking Summary

Table 5.1 presents a summary of the geologic criteria and data used to screen the three CNGD prospect areas. Using these criteria, Boone-Logan and Sand Ridge prospects meet the requirements of the test program.

Mt. Zion has few shale tests, but the wells that have been drilled do not appear to meet the well reserve requirements for a horizontal test under the guidelines required by DOE.

Analysis of both shallow production and Devonian shale production was made of each area to determine the area with the best production potential in the Devonian shale. The history of oil and gas

TABLE 5.1
GEOLOGIC CRITERIA USED IN SCREENING FOR VIABLE
HORIZONTAL WELL SITE AREAS FOR
FRACTURED DEVONIAN SHALE GAS PRODUCTION

<u>GEOLOGIC CRITERIA</u>	<u>MT. ZION- CALHOUN</u>	<u>SAND RIDGE- CALHOUN</u>	<u>BOONE- LOGAN</u>
1. Thickness of Huron Shale >250 feet.	Yes (1000')	Yes (1500')	Yes (480')
2. Thickness of Lower Huron Shale >150 feet.	No (60')	No (40')	Yes (180')
3. Grenville Trend Faulting or Fracturing Present.	Yes	Yes	Yes
4. Rome Trough Faulting or Fracturing Present.	Yes	Yes	Yes
5. Cross-strike Structural Discontinuity (CSD) Trend Present (N40-55°W)	Yes	Yes	Yes
6. Stress Ratio Favorable (generally <4.0)	Yes (0.34)	Marginal (0.53)	Yes (0.32)
7. Gas Content of Shales Should Be 50 mcf/ac-ft or greater/	No (32 for L Huron)	No (21 for L Huron)	Yes (195 for M & L Huron)
8. Average Gas-in-Place per 160 acres >500 mmcf.	Yes	Yes	Yes
9. Devonian Shales have Estimated Ultimate Reserves of More than 300 mmcf.	No	No	No
10. One or More 160-acre Locations Available.	Yes	Yes	Yes

development in the Appalachian Basin has been to find deeper production below shallow production. All three areas studied are characterized by shallow Big Lime, Big Injun, and Berea production. All three areas produced in large part because of the geologic control of the area by deep-seated basement faulting. Fracturing of Devonian age shales provides the reservoir space either within the shales or in other reservoirs above.

CNGD and BDMESC believe all three areas examined have considerable promise for future development of Devonian shale gas, however, our task is to select the best of the three areas.

Logan County seems to have the greatest amount of fracturing of the three areas under study due to the massive Rome Trough edge faulting there. Although shale drilling in that area has been very limited up to this time, the wells that have been drilled show high enough gas content, cumulative production numbers and projected reserves to make the area attractive. Logan County ranks first among the three areas.

There is underground coal mining in the area of the town of Logan, southwest of the prospect area, and stripping extending up toward the county line. A well location at this prospect would need to be designed considering coal data, mine plans, and current operations.

The Sand Ridge area shows well reserves that cluster around either high or low numbers. The low numbers probably represent the "background" range of a "normal" well. The high reserves seem to fall along synthetic fracture trends. Keeping the synthetic concept in mind in siting a test well can hopefully bias the results here toward the high end of the range of results.

Shale drilling at Sand Ridge has resulted in a number of producing oil wells as well as gas wells. The test program has been designed to drill at an angle sufficient to cope with possible oil production.

Table 5.2 incorporates all the pertinent engineering parameters and data that could be assembled to screen, evaluate, and rank

the three prospect areas. Each area has been compared and scored and a composite ranking and final ranking been made for the areas under evaluation.

6.0 SPECIFIC SITE SELECTION

6.1 Approved Candidate Areas

Of the original three areas under consideration, Area One, near Mt. Zion, was eliminated due to the small number of shale wells in the area. The area has been intensively drilled and mapped at the Big Injun/Big Lime level and has produced prodigious amounts of shallow gas, but it was impossible to collect sufficient data at the shale level to meet the task definition and requirements for a shale development location. The structural concepts for Area One suggested several possible desirable test well locations, but these fell, without exception, outside the well-spacing limits as defined in the SOW for this project.

The study proceeded in Areas Two and Three with additional data collection, evaluation and mapping. Finally, sites were selected in each area for a CNGD horizontal test well and a final recommendation was prepared.

6.2 Geology of Candidate Area Two

Candidate Area Two lies along the Calhoun-Gilmer County Line near Sand Ridge. An anticline, variously referred to as Wolf Summit or Chestnut Ridge on West Virginia Geological and Economic Survey maps, cuts through the heart of the 19,000+ acre lease. The prospect area is high on the northwest flank of the structure (Figure 56).

6.2.1 Basement Structure

The basement near the junction of Calhoun, Gilmer and Braxton Counties is broken in a major set of southwest-northeast trending faults which mark the edge of the Rome Trough, and by associated faults within

TABLE 5.2 - SCORING OF SITE SELECTION CRITERIA AND RANKING OF AREAS

ENGINEERING PROPERTIES	BOONE/LOGAN #3	RANK	MT. ZION/CALHOUN #2	RANK	SAND RIDGE/GIL #3	RANK
Thickness of Lower Huron	180	1	40	2	40	2
Average Initial Rock Pressure (psig)	373(5)	3	732(7)	1	416(43)	2
Average Current Rock Pressure (psig)	170(5)	1	290(5)	1	240**	2
Average Init. Open Flow After Stim. (mcf)	369(5)	3	1046(7)	1	737 (gas) 110 bbl (oil)	2
Average 3 Yr. Cumulative Production (mcf)	37,000(4)		20,100*(4)	3	37,200*	1
Average Projected Ultimate PRD (mmcf)	257(4)	2	55(4)	3	263(43)	1
Average Stress Ratio	0.32(1)	1	0.34(4)	2	0.53(4)	3
Normalized Pressure	0.43	3	1.75	1	1.0	2
Normalized Thickness	4.5	1	1.0	2	1.0	2
Normalized Pres. x Thickness	4.03	1	1.7	2	1.0	3
Gas Content (mcf/Acre-Ft)	195.0	1	32.0	2	21.0	3
Average Gas-In-Place (160 acres)	15.040 bcf	1	5.12 bcf	3	5.42 bcf	2
Coal Mines	Yes	2	No	1	No	1
Water Production	No	1	No	2	No	3
Composite Ranking		1.78		1.85		2.00
Individual Ranking		1		2		3

* Mcf equivalent (includes oil production).

** Estimated current values.

Figure 56 - Structure on Big Injun at Area Two

the trough (Figures 45 and 47). Some of the intra-trough faults parallel the trough edge. Others, to the north and northwest, seem to be turning to a Grenvillian, north-south trend.

There is extensive sedimentary and surface evidence that a series of very significant and some relatively minor CSD's cut across Area Two (Figure 45), although these have been almost impossible to identify seismically. Several minor basement breaks show up seismically which could be expressions of either Rome Trough- or CSD-related faulting. The seismic control in the area was generally laid out to define relatively shallow structures, often to look for Oriskany prospects, not to answer theoretical questions about the nature of the basement and CSD's. Most of the line locations through Calhoun County are very much dependent on the topography and are quite crooked. Several apparent 100-foot+ faults at the basement level could be north-south, southwest-northeast, southeast-northwest, or could be artifacts of processing.

The CSD's in the study area generally seem to mark boundary zones along the northeast flank of a southeast-northwest-trending basement high. This high runs through the area of the Calhoun-Roane County Line from Braxton County on the southeast to the south end of the Burning Springs Anticline. The depth of the Rome Trough increases steadily from Calhoun to the southwest through Roane into Kanawha County and to the northeast into Gilmer, Lewis and Harrison Counties.

Seismic times to basement increase steadily to the southwest and northeast.

The CSD's and the Calhoun County basement high seem to have affected sedimentation throughout much of the Paleozoic. The Cambrian and Ordovician sections thicken to the southwest and northeast. The Silurian environment changed dramatically in Calhoun County. The evaporite basin that had extended from New York, through Pennsylvania and West Virginia, down to Calhoun County, finally ended, presumably at a sabka or evaporite coastal flat through Calhoun County. The position of the basin edge seems to have fluctuated within a very narrow band along the CSD trend throughout much of Silurian evaporite time. During Upper

Devonian time, various sands and silts were deposited across much of northern West Virginia. These extend into Gilmer County, but generally shale out in Calhoun County. By Roane County, the Upper Devonian section consists almost entirely of shale. Several of the Upper Devonian units appear to change from silt to shale right at a CSD. Coal mapping shows the Pittsburgh Coal pinching out in Area Two along a CSD trend.

6.2.2 Trenton Structure

The Trenton lies below the thin-skinned detachment layers, and its structure in Calhoun County primarily reflects major Rome Trough tectonics. Following deposition, the Trenton dropped as rifting continued during the Silurian, but later inversion of the trough area lifted the Trenton back almost to its original position. On some seismic lines, the Rome Trough edge shows up at the Trenton level as only a short, non-reflecting skip on a seemingly undisturbed, gently dipping reflector. The evidence for the drop and rebound of the Trenton within the trough is a thick isochron between the Trenton and the Onondaga on the trough side of the boundary fault. Restoring the Onondaga to a flat reflector shows the approximate, lower position of the Trenton in the trough at the time of Onondaga deposition.

6.2.3 Onondaga Structure

At the Devonian level, there is significant structure along the Calhoun-Gilmer County line. The Onondaga is quite broken up in the syncline northwest of Chestnut Ridge and in the Rosedale Basin to the southeast (Figure 57). In the Rosedale Basin, the Onondaga has formed two southwest-northeast-oriented grabens and a central horst.

These features occur along the margin of the Salina evaporites, with the grabens having formed where the evaporites have been mobilized and withdrawn from below the Onondaga. The anticline and the lows end on the southwest at the limits of the Salina evaporites.

The anticline is formed by a gentle fold at the Onondaga level. The structure apparently has grown over a buildup of detached Silurian

Figure 57 - Onondaga Structure at Area Two

Salina material. There is seismic evidence for a pair of minor thrust faults, directed to the southeast, cutting through Area Two at an angle to the anticlinal axis, but these thrusts are minor and are clearly incidental features with little effect on the much larger anticlinal form.

6.2.4 Big Injun Structure

The Big Injun structure (Figure 56) has also been greatly influenced by the edge of the evaporites. Over the evaporite-cored anticline, the Big Injun is essentially unbroken, simply forming a broad, gentle fold with smooth, widely-spaced contours. Occasional slight ripples or noses at the Big Injun level may mark the effects of synthetic features on the northwest flank of the anticline.

Most of the CNGD prospect falls within the area of the lightly deformed Big Injun.

The Rosedale Basin, southeast of the anticline, formed at the intersection of the Salina evaporite pinchout and the edge of the Rome Trough. The prospective productivity of the shale has been affected by the evaporite limit. The Basin is part of a zone of intense deformation in the shallow sediments overlying the Salina margin. There is a large risk of caprock being shattered and loss of deeper shale traps in areas like this. Such caprock problems should not be a problem in most of the lightly deformed CNGD prospect area.

The faulting and structural orientations at the Big Injun level in the Rosedale Basin are quite different from those at the Onondaga level. The Onondaga grabens previously described follow the southwest-northeast Rome Trough structural grain, while the Big Injun structures appear to follow more of an easterly, synthetic fracture orientation.

Faulting has been integral to the formation of the Greenbrier and Coal lows at Rosedale. Long faults oriented between N70E and N80E extend across the north side of the Basin, dropping the Big Injun and Big Lime toward the Basin center. Smaller faults, down to the north, cut the south edge of the Basin. The change in structural orientation from the

Onondaga to the Big Injun indicates that there was active tectonism at Rosedale and across the region during the Devonian. The Onondaga may have been fractured, if not actually faulted, along the Rome Trough trend, soon after lithification. The Rome Trough was still dropping, although very slowly, at that time and would later rebound. By the time that the Big Injun was being deposited, lithified, and deformed, the local stress regime had changed. The Greenbrier thus broke in the same geographic area as the Onondaga, but at a different set of angles.

The Rosedale style of faulting continues to the west, forming a similar set of smaller, unnamed, faulted Greenbrier basins around the south and west ends of the anticline. One of these, located along the Washington-Lee District Line in Calhoun County, is misidentified on the Oil and Gas Report and Maps of Wirt, Roane and Calhoun Counties, W. Va., WV GES Bulletin B-40, as the "Rosedale Basin". The true Rosedale Basin is in Gilmer County.

The Greenbrier structure map enclosed with Bulletin B-40 includes many small lows and highs, but does not depict any faults. Fault identification and location are difficult without very tight well control and reliability in the surface elevations being used. Confidence can be gained when several wells all verify an abrupt structural change from a cluster of high wells to a cluster of low wells across a narrow zone and that zone parallels several other nearby similar tentative faults. The individual faults here are part of a large regional system. Extensive Greenbrier faulting continues through the area from the Washington-Lee District line to the Burning Springs Anticline.

The fault pattern consists of synthetic and antithetic breaks following the Salina evaporite pinchout. The trend can be identified by extensive Big Injun oil production, some of it well up on anticlines, and several closely-spaced multi-bcf gas wells. Some of the outstanding wells have held relatively high pressures or managed to sustain steady production rates over multi-year periods. Shallow well histories through this zone provide evidence for the deep wrenching along the Salina pinchout.

The evaporite edge and Devonian wrenching have caused extensive disruption and destruction of normal cap rocks and seals in the Upper Devonian section through Calhoun County along the synthetic and antithetic fault and fracture trends. Some fractures have remained open, allowing migration vertically through the fine grained shales and silts until a truly porous unit, like the Big Injun, has been encountered. At that point, the gas or oil have charged the shallow units. The most outstanding wells still have the Big Injun in direct communication with the shale. This has allowed the Injun to recharge from deeper reservoirs as the wells were produced.

There is some evidence that gas has moved through moderately broken migration pathways and that oil has only been able to work its way through the most intensively faulted zones. Large oil fields like the Sycamore-Millstone Field occur, as would be expected, in a syncline, but this syncline was formed by extensive faulting. The floor of the syncline consists of three down-faulted blocks with two intervening horsts. All this faulting provided adequate migration pathways for oil in this area. Oil production continues upstructure to the southwest as the faults bounding the horsts and grabens die out and intersect the main band of synthetic and antithetic fractures and faulting at the evaporite edge. The zone of shallow oil production continues intermittently along the synthetic/antithetic trend through northwestern Calhoun County to Burning Springs Anticline, often irrespective of highs and lows at the Greenbrier level.

There are also small pools with isolated oil production well up on the flanks of the anticline in the study area. This oil production comes from localized areas with faulting or areas with very tight contours on the Big Injun, indicating high deformation. The correspondence between the most intense deformation and oil production seems quite good.

One of these local oil pools occurs northeast of Sand Ridge. The flank of the anticline above and below this pool are smooth, with widely-spaced contours, but right at the pool there is an anomalous low with short synthetic and antithetic faulting at the Big Injun level.

Deeper gas wells also exhibit unusual characteristics over the pinchout at Calhoun County. Wells in the zone of intense deformation that have tested the shale have often encountered unusually low pressures, even in supposedly virgin areas. The pressures along open vertical fracture systems will reflect the depth of the shallow end of the system, rather than the expected shale pressures.

In locating the CNGD well, it was considered important to be in an area on the anticline that shows some evidence of enhanced fracturing, but not too much. Proximity to a multi-bcf Big Injun well was considered to be a negative indicator under the assumption that these extremely productive shallow wells had drawn at least some of their reserves from the deeper shale, partially depleting the test reservoir.

The CNGD lease seems to be in a generally good area, high on structure, with smooth, open Big Injun contours. The contours wrap smoothly around the nose of the anticline, then wrap gradually into a north-south, Grenvillian orientation on the north flank of the anticline in the study area. A prominent structural nose juts out at the synthetic orientation right at the line of the best production along Fern Run on the CNGD lease. The additional deformation which formed this nose and created the synthetic fractures which Fern Run has followed may be key to the exceptional production along that synthetic trend.

A structure map of the prospect was prepared at a twentyfoot contour interval, but no additional similar noses were found. There are several stream segments crossing the lease that follow the Fern Run orientation, indicating probable synthetic fractures, but none other than the Fern Run trend display structural effects at the Big Injun level.

6.3 Geology of Candidate Area Three

Candidate Area Three is located at the Logan-Boone County Line along Spruce Fork of the Coal River near the town of Clothier. Structurally, the area is located along the area of maximum offset on the Rome Trough. Spruce Fork is following a major Grenvillian zone of weakness that extends north-south from Ohio to southern West Virginia

(Figure 58). A significant CSD trend cuts through the area at Clothier, and another runs by Sharpless, to the southwest.

6.3.1 Basement Structure

The Logan-Boone area exhibits intense deformation at the basement level. All three major structural trends run through the prospect.

The Rome Trough trend dominates here, as would be expected along a fault that displays a minimum of 10,000 feet of basement offset. Structural contours at all stratigraphic levels parallel the trough edge.

The long-term history of Rome Trough faulting should have produced intense fracturing through the shale section along the edge of the rift.

The Rome Trough basement fault in this area is a single break with all the offset concentrated in a very narrow zone.

The CSD trend may show up structurally on the basement surface, but limited seismic control makes it difficult to be certain about this. CSD effects are complex. The shelf edge southeast of the trough drops to the northeast across the CSD's. In the Rome Trough the floor rises to the northeast across the same CSD's from Logan County into Boone, then deepens into Kanawha County. The relative direction of movement across given CSD's seems to have varied along the CSD, sometimes coinciding on the shelf and within the trough, in other cases moving in opposite directions as a CSD crosses the Rome Trough edge. This might be expected if the CSD's were ancient features, already present before the trough opened, and if they had long been acting as local zones of weakness, readily adjusting to local stress fields. The CSD's show no indications of major, consistent, late motion, rising or falling in a uniform direction along the length of the Rome Trough.

There is also no evidence for significant strike-slip motion along the CSD's at the Rome Trough edge. If strike-slip has taken place

Coal River has cut a very wiggly course within very narrow limits following a Grenville trend.

Figure 58 - Grenville Control of a Minor Drainage Course

along these trends, it apparently predated formation of the trough in the Late Precambrian.

The seismic control in southwestern West Virginia has not been laid out with the study of CSD's in mind. Some lines in this area may show relief across the CSD's, but these points tend to occur in areas where the lines are making U-turns or where the relief could be attributed to Rome Trough-related structures.

6.3.2 Trenton Structure

The seismic control for this project shows only a slightly higher Trenton reflector within the Rome Trough. If any Grenvillian or CSD-related structure exists at the Trenton level, it could not be recognized on the data seen.

6.3.3 Onondaga Structure

Several breaks occur on the Onondaga reflector along the edge of the Rome Trough. These have been assumed to be Rome Trough-parallel faults, but since the seismic line runs right down Spruce Fork and crosses the CSD at Clothier, it is possible that some of the breaks could have been caused by the other structural features described.

The Onondaga is now much higher on the trough side than on the shelf. This is strong evidence for reactivation and inversion of the trough in post-Onondaga time. The intervals between the reflectors document the original depositional history along the trough margin.

Assuming that the Onondaga breaks seen on the seismic line are Rome Trough-related, it is evident that the single break at the basement level has splayed into multiple fault traces as it climbed through the section. The length of the individual fault segments is unknown, but the zone of faulting has spread approximately 1-1/2 miles to the northwest, splaying more vertically into the trough-side sediments. Lower angle faults cut 1/2 mile or so to the southeast onto the shelf side of the main fault.

6.3.4 Shallow (Berea and Greenbrier) Structures

Shallow reflectors, possibly units in the Berea and Greenbrier sections, show a simple monocline over the trough edge. There are no obvious seismic breaks at these levels. This is confirmed by structure maps on the Berea and Big Lime (Figures 59 and 60).

Both the Berea and Big Lime in this trough are high, dipping toward the southeast. They both abruptly increase their plunge at the "knee" area of a monocline as they reach the edge of the basement fault zone. At the southeast edge of the fault zone, the monocline passes through an "ankle" and resumes a low dip to the southeast. Through the monocline, the contours are quite close together and the dip is very steep. Fracturing should be intense through the monoclinal area where the dips are steepest.

The CSD's can often be recognized at depth as slight bends in structure contours. These bends may reflect either small fault steps or monoclines at the basement level. These bends often coincide with sets of stream alignments or surface lineaments.

When mapped in detail, CSD's are usually expressed as swarms of closely-spaced, parallel features, rather than single lines, implying that they are zones with some discrete width, rather than one single, planar break. CSD-oriented drainage trends through Clothier and Sharpless include several sets of fractures which are being followed by streams. The Clothier feature seems to consist of a zone of fractures about 0.6 miles in width. The Sharpless feature is less well defined, and is about 1/2 mile in width. The diffuse nature of the CSD's makes it difficult and inaccurate to pin a CSD down to a single line on a local-scale map.

A major Grenvillian structure runs from Ohio, down the Coal River and Spruce Fork, through the study area. This trend, like the CSD's, consists of several closely-spaced fracture sets. This trend is approximately 1-1/2 miles wide at Clothier with a subsidiary structure about one mile to the east.

Figure 59 - Berea Structure at Boone-Logan

Figure 60 - Big Lime Structure at Boone-Logan

The through-crust Grenvillian thrusts broke catastrophically, producing zones of intense mylonitization. Wide bands of rock were pulverized along the imbricate fault planes during the collision of Grenvillia and North America. The zones of weakness have propagated through the sedimentary cover and show up as bands of parallel fracture traces at the surface today.

As with the CSD fractures, Grenvillian breaks occur in zones. General limits can be defined for the Grenvillian features, but predicting the presence of specific fault traces at a given location is difficult.

6.4 Specific Candidate Sites

Candidate sites were selected in each area based on apparent favorable geologic conditions. The candidate sites were evaluated under the engineering guidelines and checked to determine if a well could be drilled at proper spacing to maintain a 160-acre drainage area between the horizontal test well and adjacent existing shale wells.

In addition, the well was required to be in a "development" location that would reduce "exploration" risks and the projected five-year recovery was to be at least 100 million standard cubic feet of gas.

BDMESG systematically collected, compiled, collated and annotated a geologic and engineering database to evaluate the reservoir properties and conditions for each of the areas studied. The database was used to rank the areas against each other, then to rank potential locations.

6.4.1 Area Two Candidate Site Attributes

Three test well sites, Figure 55, were originally recommended for Area Two, but one of these was too far southeast of the group of shale wells near Sand Hill and thus was eliminated due to its distance from established shale production.

Additional production data have become available for several recent CNGD wells. Evaluation of these has helped in the study of Area Two and strengthened the evidence for several of the previous concepts.

Of the two remaining sites, one was eliminated by CNGD Well 2609 (PN 4657). This well has only produced 1.9 mmcf in two months with no oil production, and is not considered by CNGD to be a good well. Projected ultimate reserves are 11 mmcf. This well is approximately 2000 feet from CNGD Shale Wells 2520 (PN 4281) and 2605 (PN 2605). Both those shale wells started out nicely, with CNGD 2520 (PN 4281) making 44 mmcf in its first 12 months and CNGD 2605 (PN 4057) making 48 mmcf over its initial year.

Well CNGD 2605 (PN 4057) is on a known synthetic trend which includes Well 2521 (PN 3811). When 2605 (PN 4057) was treated, there was communication between it and CNGD 2521 (PN 3811). The projected reserves for Well 2521 (PN 3811) are 586 mmcf and for Well 2605 (PN 4057) are 244 mmcf (Figure 53). These two wells are on a trend slightly more East-West than the Fern Run trend orientation, but similar enough for both to be accounted for by the synthetic orientation. In the inhomogeneous world of real life geology, as opposed to clay models, slight variations in orientation are to be expected as irregular sedimentary units break at varied angles under similar stresses.

Well CNGD 2520 (PN 4281) is on a synthetic trend with CNGD 2557 (PN 3965). These wells have projected reserves of 170 mmcf and 226 mmcf, respectively (Figure 53). These two sets of wells show that the synthetic fracture system does extend through this portion of the study area.

Well 2609 is not on a synthetic trend with any other known good producer and is not performing well. In addition, the well has several other strikes against it. The well site is right on a Grenvillian trend, on a CSD trend, and along a Rome Trough-parallel trend. The intersection of these three trends right at Well 2609 may have been too much of a good thing. While fractures are necessary in the shale to provide a reservoir that will produce gas at an economical rate, too many fractures or actual

faults may provide an open conduit right through the shale and through normal caps or seals into shallower beds. This may well have happened at Well 2609 (PN 4657). The Big Injun in this area is a relatively porous unit that forms a good reservoir when charged with hydrocarbons. Here, however, it has become an outstanding reservoir at the intersection of the three trends.

Shale well 2609 (PN 4657) is only 600 feet from a Big Injun well, PN 914, which has produced almost two bcf of gas from the shallow reservoir. The Big Injun well spacing through this area has been reasonable, generally over 2000 feet, and the wells near Well PN 914 have themselves been good, averaging over 500 mmcf cumulative production, indicating that Well PN 914 has not drained its reserves from an exceptionally large horizontal area. The adjacent wells show no signs of unusual depletion by PN 914.

If the production has been exceptional but there is no evidence for unusual horizontal drainage, it leads to the conclusion that much of the two bcf has been produced from deeper (shale) reservoirs that are in vertical communication through fractures with the Big Injun.

Putting this evidence together reinforces the concept that a test shale location at Area Two should not be in the immediate vicinity of a superior Big Injun well when there is good evidence of communication between the shale and the Big Injun. Multiple trend intersections and exceptional shallow wells in the midst of better-than-average shallow pools are warning signs of deeper shale caprock and trap destruction. Both these red flags are present near Well 2609 (PN 4657).

A test well location, Figures 61 and 62, had been under consideration to the southeast of Well 2609 (PN 4657). There are seismic and structural clues that the southwestern portion of the CNGD lease is on a thrust sheet that has broken through the Oriskany and Onondaga and presumably penetrated into the shale. The 2 bcf Big Injun well (PN 914) and another 1+ bcf Big Injun well (PN 663) both lie on that thrust sheet. The pair of wells also fall along a CSD.

Figure 61 - Thrust Sheet, CSD, and Synthetic Trends at Area Two

The identification of the thrust sheet is based on some widely spaced seismic lines. A thrust has been identified seismically to the southwest, off the edge of the lease. A thrust also cuts a seismic line running down Trace Fork in the middle of the lease. Connecting the two points as part of a single thrust sheet makes good geologic sense. The orientation matches other Onondaga faults in the area and surface features also indicate fracture and drainage trends that may outline the sheet.

The displacement on the Onondaga thrust is minor and while it probably enters the shale section, the fault doesn't break through to the Greenbrier level, Figure 63. The direction of movement is at an angle to the anticline, which may be one reason that the fold is so broad and gentle. At this angle, the faulting causes the contours to spread out and open up instead of tightening the fold.

The CSD zone-of-weakness defined by the two good shallow wells may have affected the Greenbrier at a very early stage. Then, when the thrust fault broke loose, fracturing through the mobile sheet was enhanced at all levels, allowing vertical migration and charging the superior shallow reservoir along the CSD trend. This concept fits the well production pattern and the projected reserves for the area quite well.

Looking at the CSD trend off the thrust sheet to the southeast, nothing unusual shows up. Big Injun production drops off dramatically in the in-place rocks, Figure 64, and may actually be worse along the CSD trend. This could be explained by early fracturing of the CSD trend, with mineralization of the fractures. When the thrust sheet broke loose, the mineral-filled veins would have behaved quite differently from the country rock. They would have been much more brittle than the surrounding shale and silt. As the sheet moved, the veins would have fractured again, this time filling with gas on the disturbed thrust sheet.

It is possible to site a location southeast of the thrust sheet to take advantage of most of the previously described trends (Figure 55). A location was studied that would start southeast of the projection of the Onondaga thrust, penetrate the shallow section vertically, then curve to

Figure 63 - Big Injun Structure - Recommended Area Two Well Location

the northwest to intersect the faults and fractures associated with the thrust as it rises through the shale section. The orientation of the directional hole would have cut the thrust, the CSD trend, and crossed one, or possibly two, synthetic orientations that may run down the Trace Fork of Bear Fork.

This location would have passed very near Well 8906 (Pn 663) which has made 1189 mmcf of gas from the Big Injun. This would be a negative indicator for this proposed location. Big Injun production like this in an area where all the adjacent wells have also been good to exceptional producers probably indicates that there has been some communication with and drainage of the shale section.

In light of the shale results at Well 2609 (PN 4657), near a multi-bcf Big Injun well, it is best to avoid putting a shale test well too near Big Injun Well 8906 (PN 663). This eliminated the potential location on the thrust sheet at the CSD trend.

With the elimination of this location, two other sites were reviewed. One of these would be located along Trace Fork of Bear Run right at a line of seismic control (Figure 55). A location here would meet the "development" requirements of the SOW, yet would not crowd existing shale locations. It would be in an area of gentle Big Injun contours (Figure 63) with no exceptional shallow wells, indicating that the shale should not be in communication with the shallow reservoirs and drained (Figure 64).

The seismic line shows a slight basement disturbance crossing Trace Fork (Figures 45 and 55). It has been assumed that this relates to a Grenvillian trend that can be seen through the area. There has not been any significant offset at depth, but the feature has been strong enough to create shallow fractures that are being followed by short drainage courses. A test well here should be able to take advantage of this fracturing.

The shallow Onondaga thrust discussed above continues through this area. There is also a segment of Trace Fork that follows the

synthetic trend (Figure 65). The Trace Fork location would have the advantage of displaying subtle evidence for these three orientations, but not all overlapping at exactly the same point. This would give the test well a good chance of encountering an open fracture system in an area where there are still intact seals and traps in the Upper Devonian section.

Another possible shale test location would be on Hooppole Run, just west of Bear Run (Figure 66). This area would also be well up on the anticline, in an area of smooth Big Injun contours (indicating less chance of cap rock destruction), along a Fern Run-parallel feature (giving the maximum opportunity for fracturing along the most beneficial orientation). The potential location would be near a major Grenvillian trend that seems to have controlled much of the *en echelon* north-south course of Bear Fork over a distance of several miles. Several small CSD features also run by this area.

The Hooppole location is worryingly close to a line of very good Big Injun wells (Well 9830, PN 961 @ 1.14 bcf; Well 9706, PN 905 @ 1.1 bcf; and Well 9812, PN 960 @ 0.9 bcf). These outline an area of exceptional shallow production, which, as has been shown, can be an indicator of loss of shale caprock, communication with the Big Injun and depletion of the shale section. The exceptionally productive Big Injun trend with its area of potential depletion in the shale is very close to the straight segments of Hooppole Run. The features are generally parallel and are all probably controlled by the same set of synthetic fractures. These fractures appear to be so well developed that they are open through the shale cap into the Big Injun.

The Hooppole trend at first appeared to be a prime candidate for the recommended location at Sand Ridge. It was close to Fern Run and paralleled this line of excellent shale wells. Hooppole Run seems to be the longest Fern Run-parallel feature in the prospect area. The Big Injun contours were smooth with no indication of cap-destroying faults or excessive fractures. Nonetheless, the excessive quantities of gas produced nearby from the Big Injun had to come from somewhere and the concern is that the Hooppole Run area may be depleted at the shale level.

Figure 65 - Trace Fork Trends

Figure 66 - Hooppole Run Location

Due to the concerns about the Big Injun production near Hooppole Run, the recommended location for Area Two is at Trace Fork.

6.4.2 Area Three Candidate Site Attributes

Three potential well locations were initially proposed at the Logan-Boone County Line Area.

Detailed geologic mapping and comparison of engineering and reserve data showed that there is only a narrow band of reliably productive acreage through the CNGD acreage. This all falls along the knee area of the monocline. Wells located on the steep slope or at the ankle have been poor, with only one or two exceptions. This led to a rethinking of concepts and to rejection of proposed locations in mid- or low-slope regions.

While fractures are critical for shale gas production, the environment of the fractures is also important. The zone of maximum fracturing should coincide with the area of maximum deformation in this case, the band with the maximum dip. While this is true, it is also important that along a steep monocline, the fractures at the knee area will fall in a tensional environment. Fractures in the slope area may be more numerous, but will be in a neutral stress area, with no tendency to open and a great danger of caprock destruction and loss of trap. Fracturing will also be intense at the ankle area, but here the stress regime will be compressional, and the fractures will tend to close under any but the highest pressures. Any gas or oil filling fractures in the ankle would probably be driven up-structure to the tensional area.

Using these standards and applying them to the CNGD acreage, it was obvious that most of the CNGD lease position would not meet the guidelines. The recommended well location had to fall within a narrow band at the extreme northwest border of CNGD's lease position.

The first well location that was studied in detail was near Ottawa, east of Spruce Fork of the Coal River. There was an area here at the knee that seemed attractive. Directional test well Consolidated 12458

(PN 1403) was drilled here in 1983. The hole went down vertically into the shale, then tight radius turns were made and directional holes were drilled both to the northwest and southeast. At that time, it is certain that mud was used in drilling the tight turns and short horizontal hole segments. This almost certainly ruined the shale, which should never be drilled on mud in a low rock pressure area like this. With the fractures plugged, the hole did nothing and the well gauged at zero IOF prior to being plugged and abandoned.

Well 12460 (PN 1069) was also drilled along the knee, but the shale was fract with water. These two wells should not condemn this whole area. There is an elongate trend of good wells all along the knee which abruptly stops at PN 1069 and PN 1403 and then resumes. There is no geologic reason, other than the water and mud in the hole, that would explain the poor results. The Ottawa area was studied, but CNGD's acreage position here would not allow a well to be located at the required well spacing while keeping the entire borehole under a Consolidated lease (Figure 67). There may be possibilities for a joint venture well here, but this did not fit the current SOW.

An area downriver, northeast of Secoal, was studied and also seemed to hold great promise, but there were no existing shale wells here to meet the SOW requirements for a development well location. BDMESC liked this area, but any recommended locations could only be described as "exploratory".

Finally, a location was made on the ridge between Hewett Creek and Rockhouse Creek, right at the Logan-Boone County line (Figure 68). This area is close enough to existing shale production to qualify as a development well; it offsets the best shale well in the area with a current cumulative production of almost 300 mmcf. It is under an area with good, but not exceptional, production from the shallow Big Injun or Berea reservoirs (Figures 69 and 70), indicating that there should still be gas left at the shale level.

Shale Well Locations

Figure 67 - Potential Well Location at Boone-Logan
117

Figure 68 - CNG Acreage (Shaded) at Area Three

Figure 69 - Initial Production Potential at Boone-Logan

Figure 70 - Cumulative Reserves at Boone-Logan
120

Structurally, this location is at an ideal location. It falls right across the knee area for both the shale, the Berea (Figure 71) and the Big Injun (Figure 72).

Looking at the best wells in relation to known and projected faults in the Logan-Boone region, it seems that the best wells lie within Rome Trough-parallel slabs. The major faults along the edges of the slabs may mark zones where caprocks and traps have been destroyed and gas has vented right through the section, including the Berea and Big Injun/Big Lime formations. This is evidence that even at the "unfaulted monocline" the shallow section is actually cut by numerous small faults and fractures (Figure 73). The broken areas of greatest deformation have provided routes for the escape of gas. While at Calhoun County, the gas would rise until it reached the relatively very porous Big Injun; here at the Logan-Boone County line area, it has been easier for the gas to continue leaking vertically along the open tectonic features. When the gas reached a formation like the Berea or Big Injun, it followed the route of lowest pressure. At Calhoun County, this was generally horizontally, into the porous unit. At the Logan-Boone Trough edge, the direction of lowest pressure was vertically, conducting the gas up open fault or fracture planes.

The Rome Trough edge includes numerous, excellent reservoirs in swarms of fractures, but here, as elsewhere, there is a need for intact caprocks.

The recommended test well site would concentrate on cutting through the heart of one of the best gas producing slabs along the Trough edge (Figure 74). The recommended well location takes the slab patterns into account, and is located to optimize the effects of the Trough-parallel faulting.

The recommended location falls to the west of the main Grenvillian feature that extends down the Coal River and Spruce Fork. The large-scale trend of this Grenvillian zone includes Spruce Fork on the west and the southern headwaters of the Coal River on the east. While the

Figure 71 - Berea Structure at Boone-Logan
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Figure 72 - Big Lime Structure at Boone-Logan

Figure 73 - Major Fracture Traces at Boone-Logan
124

Figure 74 - Fault Block Outlines at Boone-Logan

band is quite wide, overall, it is well defined on its east and west limits and doesn't have much evidence of tributaries on either side. The Grenvillian trends seem to be tightly defined within very specific limits.

In an area where preservation of caprock and traps is a concern, being slightly to the west of the main Grenvillian trend should be a benefit.

Relating structural trends versus initial open flow results, production and reserve data, the Rome Trough trend and the knee area clearly dominate the production trends. There does not seem to be any simple, obvious relationship to the CSD's that cut through the area. Structure contours on the Berea and Big Lime seem to shift slightly at certain CSD's. This could be due to very slight strike-slip movement along the CSD's, but the offset is so slight that there has obviously not been any significant horizontal component of motion at this area. The same effect could be produced by slight vertical movements on a sloping surface. The CSD's do seem to allow some adjustments along the Rome Trough-parallel slabs and may coincide with areas of somewhat lower shallow production, but this is not entirely certain. In any case, there is no evidence that the presence of a CSD significantly adds to the productivity of a given area.

The proposed location falls close to a possible CSD, but this shouldn't have any significant effect on the productivity of the site.

The proposed location was chosen to be high on the Rome Trough-oriented monocline, at the knee. It should avoid the main fault and cut through the heart of an exceptionally productive slab. Grenville trends and CSD's should not present any problems at this site. The well would be oriented to take advantage of the predicted main fracture trends and to fit the SOW requirements relative to the local primary stress direction.

6.5 Recommended Site

The site recommended by BDMESC to CNGD and DOE is at Area Three. CNGD favors this location very strongly, and the geology supports this conclusion.

Area Three has intense fracturing at the edge of the Rome Trough. The rocks here have been fractured initially as the rift was dropping, then refractured as the Trough rebounded and rose along the same faults.

The recommended site has been chosen to cut across a large slab to minimize the danger of lost caprock in such a massively deformed area.

Grenvillian and CSD trends have been taken into account.

The well has been oriented to fit the local and regional stress regimes.

There is sufficient well spacing to fit the SOW, yet to stay within the development requirements.

7.0 RETURN TO CALHOUN COUNTY

7.1 Review of the Boone-Logan Recommendation

Following an extensive review of the engineering data by METC contract personnel, it was determined that the Boone-Logan County area was attractive in many ways and had some exceptionally good shale wells, but that the completion pressures in the Huron Shale were not high enough to meet the specifications for this project.

At this point, the focus of the study shifted back to the Sand Ridge area, along the Calhoun-Gilmer County line (Figure 53).

Since the portion of the 19,500 acre Bennett lease originally considered southeast of Sand Ridge had been judged to be too exploratory, the area was expanded to the northwest and into an area with smaller parcels and mixed CNGD/Sterling Drilling and Producing Company (Sterling) acreage, although the main focus was still on CNGD leases as spelled out in the original contract.

7.2 Production and Reserve Trends at Sand Ridge

For the new phase of the review, the data base was expanded to include additional areas to the west of the original study.

7.2.1 Identification of Production Fairways

CNGD and Sterling have independently and in collaboration drilled several lines of oil and natural gas wells with very good to exceptional production histories in the Sand Ridge area. Fourteen of these shale wells have been assigned total reserves of more than 200 mmcf.

The better wells fall along fairways that are quite narrow. These fairways are parallel or subparallel and in at least two cases have an identified length of two miles or more. The shorter trends generally have not been fully explored and may be longer than they appear at present. Additional drilling will be necessary along the projections of the shorter fairways to determine their full length.

The northeasternmost of the trends is the Fern Run feature that has been previously described in this report. The two best wells PN's 4426 and 4278, on this fairway have been assigned total reserves equivalent to 847 and 526 mmcf of gas. Both wells have made substantial oil, with the better of these two holes having 84% of its total reserves as oil. Total reserve figures are not available for the two Pennzoil wells at the east end of the trend, Gilmer County, PN's 77 and 108, both of these were oil wells and as of several years ago, the wells had produced 177,224 bbl and 142,285, respectively. PN 4428 has its major reserves, largely oil, still untreated, behind pipe. PN 2486 was lost to water from the shallow section and was never treated, so no reserve figure or proportional division between gas and oil is available for that hole.

The Fern Run feature has been well defined and documented. It follows a shallow structural nose that shows up at the Big Lime which may relate to Big Lime/Big Injun faulting and to a structural trend at the Warren equivalent level within the Devonian Shale section. The orientation of the Fern Run feature established the orientation for

prospecting in this area. The fairway at Fern Run is approximately two miles long.

West of the Fern Run trend is another two mile long fairway of six wells, all with reserves equivalent to 190 mmcf of natural gas or better. Four of these six wells have reserves equal to or better than 395 mmcf, gas equivalent (GE). The best well on that feature PN 3796 has 632 mmcf GE reserves. All six of these holes are producing predominantly oil, ranging from 94% oil at the east end (PN 3953) through 60% in the central area, PN's 3796, 3920 then back up as high as 80% oil near the west end of the feature at PN 3828.

The west end of this trend has not been definitely established. The fairway follows a shallow Big Lime structural break that may be related to faulting in the Shale. Shallow faulting continues to the west beyond the drilled limits of the shale field at PN 4043. This suggests that the deep structure and production potential may continue further to the west along this fairway.

A third trend lies just north of Sand Ridge. This feature is much more poorly defined than the previously described fairways. PN 3952, a good oil well (87% oil) anchors the east end of this feature with GE of 460 mmcf. At the west end, PN 3810 is a 312 mmcf GE well that is producing 63% oil. These good oil wells imply the presence of another fairway through this area.

A Big Lime fault trend and Warren feature extend through these wells, implying the presence of another probable fairway.

The two good wells on this trend have both been oil wells, as have all the best wells on the previously described fairway. A third well, PN 3804, midway on this trend, located dead center on the fault and midway between the oil wells, is not a good producer. This well has GE reserves of only 51 mmcf. PN 3804 is a predominantly (63%) gas well instead of an oil well. On all three of these trends, all the wells with economical reserve quantities have produced primarily oil.

The poor results on PN 3804 may indicate that this well was too highly fractured to retain its reserves since it lay exactly on, the fault trace identified at the Big Lime level. The better wells have all been located close to faults, but have not been centered precisely on a break.

An isolated good oil well, PN 4036, with 348 mmcf GE reserves lies between the two western fairways. This is the only better Shale well on the map that doesn't lie along one of the main production trends. All the other better wells can be related to west southwest - east northeast faults or nosing at the Big Lime level and probable structure at the Warren level.

PN 4036 lies along a CSD that appears to cut through the countyline area. These CSD's have been the sites of subtle features and structural adjustment over long periods of time, with recurrent motion shattering the beds above the traces of CSD's. The Basement here steps down to the northeast across the CSD's. In the immediate prospect area, there has been a long term trend for the CSD's to drop on the northeast side. The Basement here steps down to the northeast across the CSD's. Since the Basement offset is small at the CSD's, individual motions probably alternated between up and down at various times, with the long-term trend being down slightly on the northeast side.

The increased fracturing along CSD's may account for wells with decent reserves that do not lie along the fairways, as well as PN 4036.

A fourth fairway passes southwest of Sand Ridge. This feature has only two wells drilled along it so far (PN's 3811 and 4057), but the structural evidence suggests that it projects well to the east into the Bennett Lease. There could also be an extension of the feature to the west by several wells were located too far to the north or south to intersect the main trend.

This feature has a different character from the three long trends discussed above. Both PN's 3811 and 4057 are 100% gas wells, in

contrast to the oil production that supported all of the better wells so far described.

The discovery well on this trend, PN 3811, was drilled by Sterling in 1986. It came in at 15 mmcf natural. This well appears to be on the same CSD trend that has influenced PN's 3810 and 4036. The exceptionally high natural open flow from PN 3811 may be attributed to the combined influence of fracturing from a fairway trend and CSD-oriented fracturing. This is the only exceptional well on the map that relies solely on gas. All the other producing holes in the Sand Ridge area are oil wells.

CNGD eventually offset the Sterling hole at approximately 2000 foot (92 acre) spacing, with PN 4057 in 1987. This well was exactly on the fracture/fault/fairway trend. When PN 4057 was fractured, communication was immediately established with PN 3811. This provides confirming evidence for the orientation of the main faults and fracture trends and supports the orientation described for the fairways. PN 4057 has reserves of 245 mmcf, all from gas.

The trend through PN's 3811 and 4057 could possibly extend further to the west, but this is unlikely to be tested due to closely spaced offset wells which were drilled in the blocks between the productive fairways. The closest remaining test location west of wells 3811 and 4057 is on acreage not held by CNGD or Sterling.

Structural nosing at the Big Lime level on the Bennett Lease suggests that the faults/fractures may extend well into this area along the trend, extending almost as far onto the anticline as the Fern Run zone. The structural patterns on this feature very closely match the style at Fern Run; however, proper development is again hampered to the east by close offsets that were drilled between the fairways. These offsets are close enough to the feature to create spacing problems for potential locations along the productive trend.

Many of the offset wells that missed the trend were drilled before the geology had been mapped in detail. Other wells did not follow

the structural indicators for the area. In addition to faulting or nosing at the Big Lime/Big Injun level, a set of stream valleys, paralleling the Fern Run stream, connects well 3811 and 4057.

The Big Lime structural trend continues to the east from well 4057, and a long segment of Hooppole Run, off Bear Fork, follows this same trend. Shale well development between CNGD well 4057 and Hooppole Run will be difficult, considering current well spacing, although there are strong indicators that reserves and producibility should be high east of PN 4057.

Recent drilling results by Sterling and shallow structural control imply the existence of two more fairways at the southwestern end of the study area. Well 3965, with GE reserves of 227 mmcf and Big Lime structural control suggest one of these trends. PN 4281 may define the east end of the trend. The GER for well 4281 are 171 mmcf.

Well 3967 is located on a nearby but separate Big Lime fault trend and has projected GE reserves of 221 mmcf. Well, PN 2515 was drilled near this second trend in 1974 by a small operator with limited experience in Devonian Shale drilling. This operator, Rodgers and Son, Judymited the Shale and plugged the hole back with little or no testing. Technology for working in the Devonian Shale has improved considerably since 1974 and a more experienced operator today might be able to successfully complete a hole like that at the site of 2515. No flow was reported for PN 2515 and no reserve estimate can be made for that area.

7.2.2 Relationships of Oil and Gas Reserves Along the Fairways

The wells drilled so far on the newer, less well defined southern trends have all had much lower assigned reserves than the better wells on the more northerly fairways. This may in part be due to lower oil production in the southern wells. Seven of the nine wells with projections of over 300 mmcf GE reserves are predominantly oil wells. Only PN 3811 on the intersection of a fairway and a CSD, and one of the Fern Run wells have relied mostly on gas and still been good wells.

Except for PN 3811, all of the best wells south of Sand Ridge are poorer than the mediocre wells on the fairways north of Sand Ridge. There is a strong correlation between the overall decline in reserves and the shift from dominantly oil to dominantly gas production. For wells within the fairways, average assigned GE reserves north of Sand Ridge and along Fern Run are 406 mmcf, including the poor well with 51 mmcf. South of Sand Ridge, average GE reserves are 216 mmcf, excluding the special case of PN 3811, which has benefitted from the influence of the CSD.

The two best wells in the northern area include wells that were completed for 1,000 bbl of oil per day from the first hole and 250 bbl of oil plus 1 mmcf per day at Fern Run. The only outstanding well south of Sand Ridge is the hole with 15 mmcf, natural, all natural gas production, at the intersection of a CSD with a fairway.

7.2.3 Stratigraphy of the Producing Intervals

At Fern Run, the wells have produced, in geographic order from southwest to northeast: PN 4426, from the Balltown; PN 4278 from the Speechley; PN 4428, from both the Balltown and Gantz; PN 2486, over multiple long intervals in the Shale; and in PN's 77 and 108, at the northeast end of the trend, from the Speechley in one well, and from the Gordon in the other just a few hundred feet away.

In each of these wells, the hydrocarbon has been trapped in vertical fractures at a different level where an effective caprock has been preserved. With the reserves in vertical cracks, there is no consistency of reservoir formations along the trend.

Most of the Sterling wells north of Sand Ridge have had their main reserves concentrated around the Speechley and Warren intervals, but there has been significant variability in these holes as well. Looking at electric log data, at mud and sibilation logs and at videos of the wells, it seems that the well operator should anticipate and to be prepared for potential production starting shortly below the Berea, increasing in likelihood through the shallow silty stringers, with the maximum

production potential coming from the Warren, Speechley and Balltown silt equivalents.

7.3 Geology of the Expanded Study Area

The production fairways around Sand Ridge can be explained as synthetic fracture systems which have formed in the shallow Upper Devonian beds. Such synthetic features develop in sediments which overly deeper wrench faults (Figure 26). In this area the wrench zone has formed between decollement levels in the upper Silurian and deepest Devonian strata. The wrench and synthetic disturbed zone runs through southern and western Calhoun County, separating an allochthonous thrust sheet comprising much of Gilmer and northeastern Calhoun Counties which has detached on the Silurian Salina evaporites, from a sheet to the southwest, including Roane County, that has not moved the same amount.

During the Appalachian Orogeny and uplift to the east, the allochthonous Gilmer County sheet slid on the Salina evaporites to the northwest, ultimately crumpling at its western limit to form the Burning Springs Anticline; while the Roane County area was dragged along much less freely on a number of minor detachments in the Devonian shale section (Figure 24).

7.3.1 Regional Geology

The Silurian evaporite basin reached its southwestern margin in Calhoun County (Figure 21) pinching out against a CSD-oriented basement high that runs southeast-northwest from the Calhoun-Braxton-Clay County junction to the southern end of the Burning Springs Anticline. Northeast of the pinchout, a number of salt and anhydride horizons provided a ready means for the overlying sheet to slide. This sheet moved relatively far, relatively easily on a few major detachments.

Southwest of the Salina pinchout, horizons in the Shale formed far less efficient surfaces for detachment and gliding than the salts and anhydrides. In Roane County, a number of low angle thrusts broke free in the deep Shale, transporting material from the southeast to the northwest

(Figures 22, 23, and 25). These decollements were poorly developed and inefficient. Faults were numerous, but displacements were minor. These detachments and movements have been documented as thrust faults with repeated sections in a number of CNGD and Sterling wells in Roane and southern and southwestern Calhoun Counties.

The Roane County Shale is much more broken up than the equivalent section to the northeast (Figure 46). The multiple thrusts are numerous, small and inefficient in contrast to the deeper, more concentrated detachment zone within the Salina beds to the northeast in the Gilmer-northeastern Calhoun county region.

Southwestern Calhoun County is the transition zone where the detachment level jumps from the Silurian to the Devonian. At depth, in a situation like this, there will be a series of left-lateral strike-slip faults formed in the uppermost Silurian and lowermost Devonian beds. At those levels, the beds will still be rooted and in place on the southwest side of the wrench but, on the northeast side, will have moved to the northwest above the Saline evaporites. Deeper than the Silurian, the section is still in place. Above the Shale, all the Upper Devonian and shallower units have moved an approximately equal amount to the northwest.

The buried wrench zone has had effects on the shallow section as outlined by Harding (Figure 26). The thin-skinned overburden, even though it has moved relatively uniformly to the northwest, will still display a disturbed zone above the wrench and projecting some distance laterally, flanking the wrench zone. The style of deformation a hypothetical zone like this initially involves the formation of synthetic fractures immediately above the wrench. As deformation proceeds, these fractures will lengthen, extending beyond the area of the deep faulting. They continue to evolve as the deep movement proceeds until the rock actually breaks and form faults in the competent, brittle units in the transported sheet. Such synthetic faulting can be seen in southern and western Calhoun county in the first massive, brittle competent units above the Shale, the Big Lime/Big Injun interval. An extensive series of faults, generally trending somewhat north of due east-west, can be seen throughout this area. This style of faulting generally decreases to the

northeast and southwest, beyond the limit of the wrenching, although some faults do extend well into the Rosedale Basin and the Millstone-Sycamore Syncline. Generally, there is less evidence of faulting on top of Chestnut Ridge Anticline than in the Syncline or Basin Area.

As the intensity of deep deformation increases, the complexity of the associated shallow structures will continue to increase with a series of antithetic faults eventually forming. In the Calhoun County situation, antithetic faults should hypothetically have an orientation around N20E to N40E (Figure 27 and 28), although there will be a considerable range of variability in orientations in homogeneous rock material with a prior deformation history and pre-existent structures, as opposed to uniform laboratory clay beds. Antithetic faults will be less well developed than synthetic faults.

The rocks of southwestern Calhoun County do show an extensive series of breaks with the hypothetical orientation in the Big Lime/Big Injun rocks (Figure 29). These faults are generally subordinate to longer and more numerous faults at the synthetic orientation. The antithetic faults are generally short, dying out more quickly than the synthetic faults.

The zone of most intense faulting immediately above the wrenching in southwestern Calhoun County is an area where cap rocks and the traps within the Shale interval have frequently been destroyed. Many of the wells drilled into the shale in this area have had abnormally low pressures, considering their depths, and had no significant deep Shale gas reserves. The gas and oil that were originally in the Shale have apparently migrated upward and charged a series of exceptional Big Injun wells in this area. A series of outstanding shallow wells follows the trend of the deep wrenching. This indicates that there are significant dangers of too much fracturing at the shale level for the preservation of good deeper reservoirs in the heart of the wrench zone. Relatively high porosities in the Big Lime and Big Injun provide a ready reservoir which is filled more easily than further vertical migration.

This extreme fracturing appears to continue into the Millstone-Sycamore Syncline. Several recent poor shale wells have been drilled in that area. Reserves appear to have migrated vertically through faults into the shallow section above the most intense zones of wrenching to charge the Big Injun reservoirs in the superior shallow wells.

Along the edges of the wrench zone, the degree of deformation decreases with only fracture zones having formed in the Shale (Figure 56). For oil and gas production, a fracture zone is often preferable to a fault. A fault may allow the hydrocarbon to bypass the trapping mechanism, or may allow the entry of mineral-bearing fluids, flooding the reservoir or allowing deposition of secondary minerals, plugging the porosity and destroying the reservoir.

The Sand Ridge area apparently falls along the margin of the wrench zone with caprocks generally still intact and the development of good reservoir conditions. The vertical nature of the fracture and reservoir system here is indicated by the way the pay horizons jump up and down from one well to the next along the fairways.

7.4 Geologic Technique

When the original CNGD development was done on the Fern Run Trend, there were few shale wells in the area and very little deep structural control. Lacking deep information, most of the initial well-location geology was done using only shallow data. It was established at the time that there were close relationships between the shallow structure and the deeper Shale production. In 1985, the best deep holes seemed to be near, but off the shallow fault trends.

The original mapping concentrated on the best data groups available, the Big Lime and Big Injun tops and the base of the Big Injun. All three maps were prepared and compared to develop the most complete fault information possible.

The Millstone and Normantown Quadrangles are areas with extensive, closely-spaced well control across many sections of the maps.

However, well spacing is generally much further apart on the Bennett Lease, so some faults may have been missed on the CNGD acreage. With the information available in 1985, a structural nose was identified at the Big Lime/Big Injun level along Fern Run, although this could easily have represented a fault instead of a bending on the contours.

In 1985 and 1986, there were fewer Sterling wells and no drilling out to the northwest or southwest of the prospect area, so the extent of faulting was unknown in those directions as well.

For this expanded second look at Sand Ridge, all the available data on the deeper formations and on the Big Lime top were collected, including the WV GES computerized data base. This was added to data that had been supplied by CNGD.

Structure maps were prepared for the tops of the Sunbury Shale and for the silty zone that represents an equivalent to the Warren unit. The initial version of these maps with limited data showed a straight, steep area on the northwest of the prospect, with a peculiar-appearing shelf to the southeast. An apparent dome on the shelf marked the location of the 15 mmcf natural well, PN 3811. To the east, the slope seemed to resume, but on a different trend than that seen to the west. The contortions around the apparent shelf were extreme, and did not make geologic sense.

Such complex variations in structure at the Warren and Sunbury levels did not appear realistic. It implied an episode of extreme vertical tectonism coincident with the deposition of those units. This did not fit the geologic model for the area at all.

To explain this structural pattern, the Big Lime top was remapped using all available data points from CNGD and WV GES. The data control was tight enough to reinterpret the pattern of synthetic faults that passes through the Sand Ridge area. The new map closely resembled the maps made from an even more complete data base used at CNGD in 1985 and 1986. The faulting evident at the Big Lime level is very regular in orientation. Most of the faults are between 1-1/2 and 2-1/2 miles in

length, with the sense of movement generally up on the northside, and a throw of about 80 to 120 feet at the point of maximum offset.

The faulting increases in intensity and frequency to the southwest, into the main wrench zone. Numerous antithetic faults also appear in the area in the southwest, as would be expected upon entering an area above wrench zone. The data base for this mapping, did not reach into the areas of extreme faulting at the southern edge of the Millstone map onto the Chloe Quadrangle to the south. The western portion of the Millstone Quadrangle also has faulting which becomes very intense, but the data did not cover that area either. Some older CNGD maps were relied upon to determine structure in those regions.

The relationship between the synthetic and antithetic faults on the quadrangles could be used as a textbook-quality example. The angle of intersection between the breaks almost perfectly mirrors the clay table models.

Using the Big Lime data, the faults were projected vertically down to the Sunbury and Warren levels. This mimics what happens with the synthetic and antithetic models on the clay table. These breaks tend to be vertical and die out with depth as the lateral constraints and overburden pressure limit the ability of the rock to react to the underlying motion.

With clay models, the throw on the synthetic or antithetic cracks is greatest at the surface where there is a free face, restrained only by atmospheric pressure. The offset decrease with depth as lateral constraints and overburden pressure increase, until, at the decollement, the level of the wrenching, the clay simply moves horizontally under a solid overburden. The motion in the overburden above the wrench theoretically has no vertical component at the detachment level.

Applying this theoretical model to the Sand Ridge data suggested a much more logical analog for the Sunbury structure map. The Sunbury structure map suggests the same faults in the same locations as the Big Lime map. The locations and orientations are identical. The throw

has the same sense of motion, but seems to have decreased in intensity, as theory would predict. Knowing the location of faults at the Big Lime level, the Sunbury could be mapped in a logical way.

The faults were then projected further down and the Warren was mapped with the same results. The faults again seem to be present, to project vertically, and to be decreasing in offset with depth.

The additional drilling since the 1985-1986 also reinforces the analog. the Big Lime level. The original data had raised concerns that the cap rock was easily destroyed and that the better wells might be away from the Big Lime/Big Injun faults. The addition of several newer superior wells changes the picture, showing that the better wells are closely associated with faults. The additional data also change the economics of the area, indicating some better opportunities to drill an economical well as long as one concentrates on a fault trend in the northwestern end of the prospect, near one of the better predominantly oil producing wells.

Several fault trends were identified on CNGD or Sterling acreage in this northwestern area. All the features except for the northwesternmost line have had good production and reserve information associated with the faulting. This northwesternmost feature may have simply been too near the Millstone-Sycamore Syncline where deformation becomes more intense. There is one well at the southwest end of this feature that had GE reserves greater than 100 mmcf. It will be possible to offset that well, but it is not too promising an area, since the other holes on that specific trend have been mediocre.

In addition to looking at structure, a number of analyses were performed and tables and graphs prepared in the reevaluation phase. These studied the wells in terms of pressure, time and oil vs. gas production.

No relationship was found in this area between well quality and initial well pressure. In the best areas, along Fern Run and in the northwest corner of the study area, several of the best wells had pressure

in excess of 700 pounds, but many excellent wells dropped the 200 pound range, as well.

On the other hand, almost all the wells north of Sand Ridge had pressures well over 700 pounds, including a string of very poor, uneconomical wells. Pressure seems to be somewhat predictable geographically, but doesn't seem to have relevance to the economics of the wells in this play.

To check for vagaries of measurement, pressure buildup and reserves were plotted vs. time. It was found that the high pressure wells built their pressures quickly, whether the wells were economical or not. Allowing long delays for pressure buildup did not seem to produce significantly higher pressure readings on most wells. The northwest area had high pressures on wells even if the reading time was short, whereas longer times to the south did not allow higher pressures to build.

Strong positive correlations were found between well pressures and proximity to a productive fault trend (some trends like the northwesternmost fault, may be too highly fractured or faulted for their own good) and to the proportion of oil that a well was producing. All but two of the best wells were predominantly oil wells. Most of the predominantly gas wells were subeconomic or, at best, marginally economic.

7.5 Recommendations

Reviewing all the data, a set of five options were identified. These included potential locations around Fern Run, north and northwest of Sand Ridge and to the southwest of the Bennett acreage. The possible well locations with the highest projected reserves fell on the Bennett lease southwest of Fern Run and near Sand Ridge. Both of these areas had potential well sites on fairways with good reserve projections, but both areas had a high probability of oil production.

Fluid control and/or production in a horizontal/high angle slant hole can create engineering difficulties and complicate well completion procedures.

For these reasons, DOE preferred a location in an area where there was minimal possibility of oil production (Figure 75). The final well site was chosen on a small Hunter Bennett tract west of the main Bennett lease. This lease involved Sterling in the project, somewhat complicating the title situation.

The structure map (Figure 76) at the Fifth Sand equivalent level clearly shows two significant faults at the synthetic orientation with an intersecting fault creating a down-dropped trapdoor structure. The well location was selected at the hinge area where extensional fractures could be anticipated. The major faults are at the normal synthetic orientation for the Sand Ridge area. In addition to these features, a CSD runs through the area.

The Hunter Bennett well, #3997, spudded on November 9, 1990.

Figure 75 - Potential Horizontal Well Locations at Sand Ridge Prospect

Figure 76 - Drilling Unit and Structural Position

8.0 BIBLIOGRAPHY

Beardsley, R.W. and Cable, M.S., 1983. Overview of the Evolution of the Appalachian Basin; *Northeastern Geology*, V. 5, No. 3/4, pp. 137-145.

Harding, T.P., 1974. Petroleum Traps Associated with Wrench Faults; *AAPG Bulletin*, V. 58, No. 7, pp. 1290-1305.

K&A Energy Consultants, Inc., 1989. Well Report, CNG Development Co., United Affiliates Corp. No. 2814, GRI Comprehensive Study Well No. 3, Logan County, WV, Topical Report.

Sclater, J.G. and Francheteau, J., 1970. The Implications of Terrestrial Heat Flow Observations on Current Tectonic and Geochemical Models of the Crust and Upper Mantle of the Earth; *R. Astron. Soc., Geophys. J.*, Vol. 20, No. 5, pp. 509-542.

Sweeney, J., 1986. WV Geological and Economic Survey, Bulletin B-40, Oil and Gas Report and maps of Wirt, Roane, and Calhoun Counties, W.V.

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