Possible continuous-type (unconventional) gas accumulation in the Lower Silurian "Clinton" sands, Medina Group, and Tuscarora Sandstone in the Appalachian basin: A progress report of 1995 project activities

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This report is preliminary and has not been reviewed for conformity with U.S. Geological Survey editorial standards and stratigraphic nomenclature. Any use of trade names is for descriptive purposes only and does not imply endorsement by the USGS.

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INTRODUCTION

In the U.S. Geological Survey's (USGS) 1995 National Assessment of United States oil and gas resources (Gautier and others, 1995), the Appalachian basin was estimated to have, at a mean value, about 61 trillion cubic feet (TCF) of recoverable gas in sandstone and shale reservoirs of Paleozoic age. Approximately one-half of this gas resource is estimated to reside in a regionally extensive, continuous-type gas accumulation whose reservoirs consist of low-permeability sandstone of the Lower Silurian "Clinton" sands and Medina Group (Gautier and others, 1995; Ryder, 1995). Recognizing the importance of this large regional gas accumulation for future energy considerations, the USGS initiated in January 1995 a multi-year study to evaluate the nature, distribution, and origin of natural gas in the "Clinton" sands, Medina Group sandstones, and equivalent Tuscarora Sandstone. The project is part of a larger natural gas project, Continuous Gas Accumulations in Sandstones and Carbonates, coordinated in FY1995 by Ben E. Law and Jennie L. Ridgley, USGS, Denver. Approximately 2.6 man years were devoted to the Clinton/Medina project in FY1995.

A continuous-type gas accumulation, referred to in the project, is a new term introduced by Schmoker (1995a) to identify those natural gas accumulations whose reservoirs are charged throughout with gas over a large area and whose entrapment does not involve a downdip gas-water contact. Gas in these accumulations is located downdip of the water column and, thus, is the reverse of conventional-type hydrocarbon accumulations. Commonly used industry terms that are more or less synonymous with continuous-type gas accumulations include basin-centered gas accumulation (Rose and others, 1984; Law and Spencer, 1993), tight (low-permeability) gas reservoir (Spencer, 1989; Law and others, 1989; Perry, 1994), and deep basin gas (Masters, 1979, 1984).

The realization that undiscovered gas in Lower Silurian sandstone reservoirs of the Appalachian basin probably occurs in a continuous accumulation rather than in conventionally trapped, discrete accumulations represents a significant departure from the 1989 National Assessment (Mast and others, 1989; deWitt, 1993). In 1989, a direct assessment (field-size distributions required for play analysis were unavailable) of the Lower Silurian sandstone play gave, at a mean value, about 1.7 TCF of gas. The 1995 estimate (~30 TCF of gas) is so much greater than the 1989 estimate (~1.7 TCF of gas) because of the interpreted continuous nature of the accumulation and the assessment methodology applied. The methodology for continuous hydrocarbon accumulations assumes that the reservoirs in the accumulation are gas-saturated and
takes into account: 1) estimated ultimate recovery (EUR) per well probability distributions, 2) optimum area that a well can drain (spacing), 3) number of untested drill sites having the appropriate spacing area, 4) success ratio of previously drilled holes, and 5) risk (Schmoker, 1995b).

Davis (1984), Zagorski (1988, 1991), and Law and Spencer (1993) were among the first petroleum geologists to suggest that gas in the "Clinton" sands and Medina Group sandstones was trapped in a basin-centered/deep basin accumulation. They recognized many of the earmarks of a basin-centered/deep basin accumulation such as low-permeability reservoirs, abnormally low formation pressure, coalesced gas fields, gas shows or production in most holes drilled, low water yields, and a general lack of structural control on entrapment. Ryder (1995) adopted this interpretation by defining four continuous-type gas plays (6728-6731) in the "Clinton" sands-Medina Group interval (fig.1).

Play 6728 (Clinton/Medina sandstone gas high potential) covers a 17,000 sq mi region of western New York, northwestern Pennsylvania, eastern Ohio, and a small part of westernmost West Virginia that is very favorable for future gas resources (fig.1). Also, this play includes a large part of eastern Lake Erie. From the late 1970's to the present, this area has produced gas from drilling depths of about 2,500 to 4,500 ft in New York, 3,500 to 6,500 ft in Pennsylvania, and 5,000 to 6,500 in Ohio. A large part of play 6728 remains undrilled along its southeastern margin and in Lake Erie. Drilling depths are as great as 7,500 ft along the southeast margin of the play and between 1,500 and 2,500 ft in Lake Erie. Very likely, the entire undrilled part of the play contains gas-saturated "Clinton" sands and Medina Group sandstones. Most of the sandstone reservoirs are tight and require stimulation by hydrofracturing. In the 1980's and early 1990's, gas production from these tight reservoirs with permeability less than 0.1 milliDarcys (mD) was encouraged with price incentives administered by the Federal Energy and Regulatory Commission (FERC). Although plays 6729 through 6731 have potential for future gas resources they are less desirable than play 6728 because of thinner and probably lower quality reservoirs.

The Clinton/Medina sandstone gas plays are flanked by two additional plays that involve the Lower Silurian sandstone depositional system. The first play (Clinton/Medina sandstone oil/gas play--6732), marks an oil and gas producing region of east-central Ohio that is updip and transitional with the continuous gas plays (Ryder,1995)(fig.1). It closely corresponds to Area 1 (oil and gas in Clinton sands of Ohio) of the Lower Silurian sandstone play of deWitt (1993). Ryder (1995) considers play 6732 to be a conventional oil and gas play because of its tendency to have discrete accumulations with well-defined oil- and gas-water contacts. Oil and gas have been produced in this play since the early 1880's and are
Figure 1. Map of the northern part of the Appalachian basin province (067) showing oil and gas plays in the Lower Silurian "Clinton" sands, Medina Group sandstones, and Tuscarora Sandstone.
now largely depleted except for the Lake Erie part. The second play, (Tuscarora Sandstone gas play--6727), marks the approximate limit of undiscovered gas in basement-controlled anticlines and combination traps in the Tuscarora Sandstone, a more proximal, sandstone-dominated facies of the Lower Silurian clastic wedge (Ryder, 1995)(fig. 1). This play extends eastward from a transitional boundary with the Clinton/Medina sandstone gas plays to near the Allegheny structural front (fig. 1). Ryder (1995) classified the Tuscarora Sandstone gas play as a conventional gas play because its scattered gas accumulations seem to be largely controlled by anticlinal structures and have well-defined gas-water contacts.

OBJECTIVES AND RESEARCH STRATEGY

The main objective of this project is to establish geologic controls and pressure/temperature conditions of the regional Clinton/Medina gas field. From these attributes, we should gain a better understanding of the field and be able to evaluate whether or not it is correctly classified as a continuous-type gas accumulation. Similar controls and conditions will be examined for the Tuscarora Sandstone reservoir and its scattered gas fields to determine the feasibility of extending the continuous-type gas accumulation eastward and deeper into the basin. Additional objectives are: 1) to define the range of gas production per well throughout the accumulation and evaluate the geologic cause(s) of the production variability, in particular, production "sweet spots" in the accumulation, 2) to develop a model for gas generation and entrapment, and 3) to review, and revise if necessary, the methodology for assessing recoverable gas in the accumulation. We anticipate that the Clinton/Medina/Tuscarora(?) example may provide an assessment analog for similar gas accumulations in the United States and the World.

Topics to be addressed in detail include:
1) stratigraphic framework of Clinton/Medina/Tuscarora sandstones across parts of New York, Ohio, Pennsylvania, and West Virginia,
2) comparison of gas-well productivity (initial production and EUR) against variations in reservoir depth, reservoir thickness, and structural setting,
3) structure contour and drilling depth maps of the reservoir interval across the Clinton/Medina/Tuscarora sandstone play area,
4) downdip limits of oil and water production,
5) thermal maturation history of the Clinton/Medina/Tuscarora reservoirs based on conodont alteration indices (CAI) and burial, thermal, and petroleum generation models, 
6) geochemistry and isotopic composition of natural gas in the Clinton/Medina/Tuscarora reservoirs and their bearing on the source, thermal maturity, and migration history of the gas, 
7) role of fractures on gas productivity and the utility of seismic profiles and(or) geophysical log suites for their detection, 
8) variation in formation pressure and temperature across the area of the Clinton/Medina/Tuscarora plays, 
9) core and well log analysis to determine the degree of continuity of small-scale lithologically and(or) diagenetically controlled zones of high porosity and permeability in the sandstone reservoirs, 
10) compilation of an oil and gas field map for the Clinton/Medina/Tuscarora reservoirs, and 
11) environmental concerns such as land use and brine composition in regions of Clinton/Medina/Tuscarora gas production.

Given the large area involved, with thousands of wells, many of these planned topics of investigation will focus along regional transects oriented normal and parallel to the paleoshoreline and the present-day basin margin. Most of the transects are designed to be long enough so as to accommodate detailed comparisons between the proposed continuous-type gas accumulation of the Clinton/Medina sandstone gas play and adjoining accumulations of the Clinton/Medina sandstone oil/gas and Tuscarora Sandstone gas plays. Substantial computer support is required for storage and manipulation of data files and the construction of digital maps.

SANDSTONE CHARACTER AND DEPOSITIONAL SEQUENCES ALONG SELECTED TRANSECTS

Four transects were chosen to characterize the stratigraphic framework of the "Clinton" sands, Medina Group, Tuscarora Sandstone and adjoining units. Adjoining units include the Upper Ordovician Queenston Shale, Lower Silurian Clinton Group, and Lower and Upper Silurian Lockport Group. The Medina, Clinton, and Lockport Groups constitute the Niagaran Provincial Series. Three of the transects, B-B' (New York and Pennsylvania), C-C' (Pennsylvania and Ohio), and D-D' (Ohio and West Virginia), are between 120 and 185 mi long and trend northwest-southeast, approximately subparallel to the depositional dip of the Lower
Silurian sandstone system (fig. 2). A 425-mi-long, northeast-southwest trending transect, A-A' (New York, Pennsylvania, and Ohio), is oriented approximately subparallel to the depositional strike of the Lower Silurian sandstone system and connects the three northwest-southeast trending transects (fig. 2). All transects are constructed with geophysical well logs, primarily of the gamma ray/density or gamma ray/neutron type. About 35 to 40 wells are used for each of the northwest-southeast transects and about 75 to 85 wells are used for the northeast-southwest transect. Regional sections shown in Cate (1965), Knight (1969), Piotrowski (1981), and numerous M.S. theses assisted correlations between many of the control points. In addition to detailed correlations of reservoir sandstone units and the overlying Reynales/Irondequoit/Packer Shell/Dayton carbonate units, the transects contain information such as production status of wells, perforated interval(s), type and amount of gas and(or) fluids produced, formation pressure, and bottom-hole temperature.

Transect B-B'

Transect B-B' extends roughly 40 miles across Chautauqua County, New York (fig. 3). The 80- to 90-mi-long Pennsylvania part of transect B-B' has not yet been completed. The N35°W-S35°E trend of the transect is oriented nearly perpendicular to paleoshoreline trends as interpreted from Lower Silurian Medina Group sandstones and the Tuscarora Sandstone by Cotter (1983). Rocks of the Medina Group dip southeastward across the transect and occur at depths of 2,260 to 2,420 ft at the northwest end of the transect and 4,480 to 4,640 ft at the southeast end. Geophysical logs from 43 drill holes, spaced approximately 1 mi apart, are used to correlate the Medina Group and adjoining strata. The drill holes are identified and located in table 1.

Type and reference sections for the Niagaran Provincial Series are described from exposures along the Niagara Escarpment, located 55-120 mi north and northeast of transect B-B'. Brett and others (1995) give an excellent historical stratigraphic overview of these rocks and provide stratigraphic revisions based on their own research. Sequence stratigraphic interpretations for the Niagaran Series are provided by Brett and others (1990). Stratigraphic nomenclature, lithologic descriptions, and rock ages of the Niagaran Series, as used in this discussion, are based primarily on Brett and others (1990, 1995) and are summarized in table 2. Additional lithologic descriptions of the Medina Group are provided by Laughrey (1984) from drill-hole core about 40 mi west of the transect in northwestern Pennsylvania.
Figure 2. Map of the northern part of the Appalachian basin province (067) showing oil and gas plays in Lower Silurian sandstones and lines of transects.
Figure 3. Map of Chautauqua County, New York, showing locations and identification numbers of drill holes used in transect B-B'. Drill hole numbers also apply to table 1 and figures 4 and 5.
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Table 1. Name, identification number, and location of drill holes correlated along transect B-B'.

Map numbers identify the drill holes used in figures 3, 4, 5, and text. Location are shown in figure 3.
### Table 2: Stratigraphic Nomenclature of Niagaran Provincial Series in Niagaran Region

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<td>Medina</td>
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<td></td>
<td>Cambria</td>
<td>1-14</td>
<td>late Aeronian (B2-C1)</td>
<td>Interbedded fine grained ss., slst., and sh. with sparse fossils. Caliche horizons and desiccation cracks are in some western sections.</td>
<td>shallow water</td>
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<td>Thored Ss.</td>
<td>5-10</td>
<td>Aeronian (B3)</td>
<td>Mottled, cross-bedded channel sandstone that grades laterally to a massive pelletal sandstone.</td>
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<td>29-72</td>
<td>latest Rhuddanian to earliest Aeronian</td>
<td>Interbedded sandstone, siltstone, and shale. Basal 10-15 ft. is fossiliferous, bioturbated, and includes a phosphatic dolomite and pebble lag in the Artpark Phos. Bed. Oryverly beds are fine grained sandstone, conglomerate, and shale. Sandstone beds are planar laminated and hummocky cross-stratified in lower part and trough cross-stratified in upper part.</td>
<td>offshore and</td>
</tr>
<tr>
<td></td>
<td>Devils Hole Ss.</td>
<td>13-15</td>
<td>Rhuddanian</td>
<td>Fine to medium grained, horizontally to hummocky cross laminated, well sorted sandstone with shale interbeds.</td>
<td>offshore, fluvial</td>
</tr>
<tr>
<td></td>
<td>Power Glen Sh.</td>
<td>11-28</td>
<td>Rhuddanian</td>
<td>Shale containing hummocky cross-stratified and bioturbated sandstone, dolomite, siltstone, limestone, and sparse fossils.</td>
<td>lower part</td>
</tr>
<tr>
<td></td>
<td>Whirlpool Sh.</td>
<td>18-28</td>
<td>early Llandoverian</td>
<td>Lower part is fine to medium grained sandstone, trough cross-stratified sandstone and contains large channel fills. The upper part is finer grained and hummocky cross-stratified sandstone.</td>
<td>offshore marine</td>
</tr>
<tr>
<td></td>
<td>Queenston Sh.</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>II</td>
<td>Lower</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Neahga Sh.</td>
<td>2-6</td>
<td>late Aeronian (B2-C1)</td>
<td>Fossil shale with sparse fossils. Basal Densmore Creek Phos. Bed contains nodules, pebbles, and cobbles of quartzite and phosphate nodules.</td>
<td>deep water off shore</td>
</tr>
<tr>
<td></td>
<td>Kodak Ss.</td>
<td>1-11</td>
<td>Aeronian (B3)</td>
<td>Rhythmically interbedded sandstone and shale. Contains abundant trace fossils locally.</td>
<td>deep shelf</td>
</tr>
<tr>
<td></td>
<td>Cambria</td>
<td>1-14</td>
<td>Aeronian (B3)</td>
<td>Interbedded fine grained ss., slst., and sh. with sparse fossils. Caliche horizons and desiccation cracks are in some western sections.</td>
<td>deep shelf</td>
</tr>
<tr>
<td></td>
<td>Thored Ss.</td>
<td>5-10</td>
<td>Aeronian (B3)</td>
<td>Mottled, cross-bedded channel sandstone that grades laterally to a massive pelletal sandstone.</td>
<td>deep shelf</td>
</tr>
<tr>
<td></td>
<td>Grimsby Fm.</td>
<td>29-72</td>
<td>latest Rhuddanian to earliest Aeronian</td>
<td>Interbedded sandstone, siltstone, and shale. Basal 10-15 ft. is fossiliferous, bioturbated, and includes a phosphatic dolomite and pebble lag in the Artpark Phos. Bed. Oryverly beds are fine grained sandstone, conglomerate, and shale. Sandstone beds are planar laminated and hummocky cross-stratified in lower part and trough cross-stratified in upper part.</td>
<td>deep shelf</td>
</tr>
<tr>
<td></td>
<td>Devils Hole Ss.</td>
<td>13-15</td>
<td>Rhuddanian</td>
<td>Fine to medium grained, horizontally to hummocky cross laminated, well sorted sandstone with shale interbeds.</td>
<td>deep shelf</td>
</tr>
<tr>
<td></td>
<td>Power Glen Sh.</td>
<td>11-28</td>
<td>Rhuddanian</td>
<td>Shale containing hummocky cross-stratified and bioturbated sandstone, dolomite, siltstone, limestone, and sparse fossils.</td>
<td>deep shelf</td>
</tr>
<tr>
<td></td>
<td>Whirlpool Sh.</td>
<td>18-28</td>
<td>early Llandoverian</td>
<td>Lower part is fine to medium grained sandstone, trough cross-stratified sandstone and contains large channel fills. The upper part is finer grained and hummocky cross-stratified sandstone.</td>
<td>deep shelf</td>
</tr>
<tr>
<td></td>
<td>Queenston Sh.</td>
<td></td>
<td></td>
<td></td>
<td>deep shelf</td>
</tr>
</tbody>
</table>

**Legend:**
- (pt) = part
- (B2-C1) = B2-C1
- (C2) = C2
- (C6) = C6
- (sh) = shale
- (slst.) = siltstone
- (Is.) = limestone
- (dot) = dolomite
- (phos) = phosphate
- (fm) = formation
- (mbr) = member
- (f) = fine
- (med) = medium
- (c) = coarse
- (smt) = shelf margin systems tract
- (tst) = transgressive systems tract
- (hst) = highstand systems tract
- (inv) = minor unconformity
Preliminary correlations of the Medina, Clinton, and lower Lockport Groups along transect B-B' are shown in figure 4. Correlated formations are the Whirlpool Sandstone, Power Glen Shale, and Grimsby Formation of the Medina Group; the Reynales Limestone, Williamson Shale, Irondequoit Limestone, and Rochester Shale of the Clinton Group; and undivided strata of the Lockport Group. The Devils Hole Sandstone, Thorold Sandstone, Cambria Shale, Kodak Sandstone, Neahga Shale, and Rockway Dolomite are not recognized along the transect. The undivided Lockport Group contains strata that are coeval to the Gasport, Goat Island, Ermosa, and Guelph Dolomites.

Three laterally continuous depositional units are recognized in the siliciclastic strata that comprise the Medina Group along transect B-B' (fig. 5). The basal unit is 15-25 ft thick and consists of a fining-upward succession in the Whirlpool Sandstone and the lower part of the Power Glen Shale. The middle unit is 35-65 ft thick and consists of coarsening-upward successions in the upper part of the Power Glen Shale and lower part of the Grimsby Formation. The upper unit comprises the remaining 75 to 100 ft of the Medina Group and consists of laterally discontinuous units of sandstone, siltstone, and mudrock interbedded in coarsening- and fining-upward successions. In the Niagara region, these three units of the Medina Group are interpreted to contain shelf margin, transgressive, and highstand deposits within Sequence 1 (Brett and others, 1990)(table 2). However, stacking patterns observed in the Medina Group along transect B-B' suggest alternative sequence stratigraphic interpretations whereby the lower and middle units, respectively, comprise the transgressive and highstand systems tracts of Sequence I and the upper unit is within the transgressive systems tract of Sequence II (table 2). These interpretations are based on similarities of these rocks to sequence stratigraphic models described from Upper Cretaceous strata in southern Utah by Shanley and McCabe (1991) and Hettinger and others (1994).

The lower unit overlies the Cherokee unconformity (Brett and others, 1990) and fines upward from sandstone to siltstone and mudrock (fig. 5). Coeval rocks in the Niagaran Escarpment region demonstrate a significant basinward facies shift as well as a deepening upward facies succession through fluvial, shoreface, and offshore marine deposits. Fluvial deposits are placed in a shelf margin systems tract and the shoreface and offshore deposits are placed in a transgressive systems tract by Brett and others (1990). Similar interpretations are reasonable for strata within the lower unit of transect B-B'. However, all three facies may have been deposited within a transgressive systems tract during an overall retrogradational event whereby shallow incised valleys are backfilled with fluvial deposits during a rise in sea level. In both examples, overlying shoreface and
Figure 4. Preliminary stratigraphic interpretations of the Niagaran Provincial Series along transect B-B' in Chautauqua County, New York. Drill holes are located in figure 3 and identified in table 1. Sequence stratigraphic interpretations from this report are compared to those of Brett and others (1990) from the Niagara region of New York. Abbreviations are explained in table 2.
Figure 5. Shoreface stacking patterns in the Medina Group along transect B-B'. Progradational shoreface parasequences are interpreted from natural-gamma logs that show coarsening upward successions and laterally continuous sandstones that fine in a seaward direction. Retrogradational shoreface stacking patterns are interpreted in the lower part of the Medina Group from laterally continuous successions that fine upward from sandstone to siltstone and mudrock. Fluvial and tidal deposits are interpreted from serrated log signatures that show thin and fining or coarsening upwards stratal successions with limited lateral continuity. Shoreface, tidal, and fluvial interpretations are also based on sedimentological descriptions of coeval strata by Brett and others (1990, 1995) and Laughrey (1984). Lateral variations in the thickness of sandstones in the uppermost part of the progradational deposit suggest an unconformable contact with overlying fluvial and tidal rocks.
offshore marine strata were deposited during a marine transgression in response to a rise in sea level.

Coarsening-upward successions in the middle unit are 20-40 ft thick and pass upward through mudrock, siltstone, and sandstone. Sandstones are 10-20 ft thick and persist at least 10 mi in a northwest direction before they split, thin, and grade into siltstone and mudrock (fig. 5). Similar overlying successions forwardstep to the northwest and downlap onto the lower unit. These upward-coarsening and forward stepping characteristics suggest that the middle unit is a highstand deposit comprised of progradational shoreface parasequences. Interpretations of offshore and barrier bar deposits in coeval rocks in Pennsylvania (upper part of the Cabot Head Shale and lower part of the Grimsby Sandstone) by Laughrey (1984) support a shoreface interpretation. Correlations from the middle unit suggest that the upper part of the Power Glen Shale and Devils Hole Sandstone in the Niagara region are progradational rather than retrogradational as interpreted by Brett and others (1990). If this scenario is correct, the maximum flooding surface in the Niagara region may be a 2-ft-thick condensed interval at the top of the Whirlpool Sandstone (see Brett and others, 1990, fig. 4) rather than the base of the Artpark Phosphate Bed as interpreted by Brett and others, 1990).

The upper unit contains laterally discontinuous sandstone, siltstone, and mudrock interbedded in fining- and coarsening-upward successions. Siltstone and mudrock dominate the upper part of the unit. The basal contact is scoured into underlying shoreface strata and scours are as much as 35 ft deep and several miles across (see drill holes 21 through 32, fig. 4). The upper unit is interpreted to be fluvial and tidal in origin based on geophysical log signatures and core descriptions of the Grimsby Sandstone which contain braided river deposits in its middle part and tidal flat deposits in its upper part (Laughrey (1984). We interpret the basinward shift of braided river over nearshore strata to represent an unconformable facies relationship; this interpretation is further supported by the widespread erosional surface that separates the two facies along the transect. Strata in the upper unit is further interpreted to be within a transgressive systems tract based on its deposition over an erosion surface and retrogradational stacking patterns. Deepening-upward successions are characterized by braided river and superimposed tidal flat deposits in the Grimsby Sandstone (Laughrey, 1984), inner shelf muds of the Neahga Shale, and offshore carbonates of the Reynailes Limestone (Brett and others, 1990). In this interpretation, broad valleys were cut into emergent highstand deposits of Sequence I and backfilled by fluvial strata during the initial stages of sea level rise that resulted in the deposition of Sequence II of Brett and others (1990). The fluvial deposits were subsequently covered by tidal deposits as the sea advanced. Continued
rise in sea level resulted in marine transgression that cut a ravinement surface and deposited the pebble and cobble lag of the Densmore Creek Phosphate Bed followed by deposition of inner shelf muds and offshore carbonates. The top of the transgressive systems tract is interpreted to be eroded by the unconformity at the base of Sequence III following interpretations of Brett and others (1990).

Properly interpreted sequence boundaries, systems tracts, and depositional facies may be critical for understanding reservoir and production variability in the Clinton/Medina regional gas accumulation. For example, thick valleyfill sandstones of fluvial and(or) estuarine origin deposited in a transgressive systems tract may be an important control of production "sweet spots". This investigation of transect B-B' provides an alternative sequence stratigraphic interpretation for the Medina Group and lower part of the Clinton Group in New York State; however, core studies and additional detailed correlations are needed to substantiate the interpreted unconformity near the base of the Grimsby Formation and the tidal and fluvial origin of Grimsby Formation strata above the unconformity. Moreover, perforated gas-bearing zones and their initial and ultimate gas yield must be identified for each well of transect B-B' to determine which sequences, systems tracts, and depositional facies have the most favorable gas reservoirs.

Transect C-C'

A preliminary east-west cross section, several miles north of transect C-C', was prepared from seven drill holes used in deWitt and others (1975)(figs. 6, 7). This section shows the general stratigraphic relationships of the Lower Silurian Medina and Clinton Groups prior to studies by Piotrowski (1981), Laughrey (1984), and Zagorski (1991). For example, except for cross sections by Cate (1961) where a combined Irondequoit-Reynales lime was identified, the Irondequoit (Limestone) has only recently been recognized as a separate unit in northwestern Pennsylvania (Laughrey, 1984).

Twenty wells (table 3) along transect C-C' have been correlated with the Mark Resources Shaffer #1 well in the Cooperstown gas field (Zagorski, 1991)(fig. 7). Three of these wells are shown on figure 8: the Transamerica Acker #1 (API 37-039-20077), the Mark Resources Shaffer #1 (API 37-121-42719) and, to the east, the Quaker State Fee #1-H (API 37-053-21250). Only the Benedum Trees J. Kardosh #1 drill hole (P67; API 37-039-20007) is common to the two cross sections (fig. 6). The Reynales Limestone of the earlier preliminary cross section has been
Figure 6. Map of six counties in northwestern Pennsylvania showing location and identification numbers of drill holes used in transect C-C' and in the east-west cross section in deWitt and others (1975). Identification numbers for the drill holes used in the northern cross section have been assigned by the Geological Sample Log Company, Pittsburgh, PA.
Figure 7. Preliminary east-west cross section through northwestern Pennsylvania based on drill holes used in deWitt and others (1975). Datum is the base of the Silurian Lockport Dolomite.
<table>
<thead>
<tr>
<th>API UNIQUE #</th>
<th>County</th>
<th>Operator - Farm</th>
<th>Quadrangle (71/2')</th>
</tr>
</thead>
<tbody>
<tr>
<td>37039-20607</td>
<td>Crawford</td>
<td>James I. Shearer - Bish #2</td>
<td>Beaver Center</td>
</tr>
<tr>
<td>37039-22112</td>
<td>Crawford</td>
<td>Mitchell Energy - Jacob #1</td>
<td>Linesville</td>
</tr>
<tr>
<td>37039-20007*</td>
<td>Crawford</td>
<td>Benedum Trees - Kardosh #1</td>
<td>Harmonsburg</td>
</tr>
<tr>
<td>37039-20077</td>
<td>Crawford</td>
<td>Transamerica - Acker #1</td>
<td>Meadville</td>
</tr>
<tr>
<td>37039-21523</td>
<td>Crawford</td>
<td>Ingram - Zinchiak #1</td>
<td>Meadville</td>
</tr>
<tr>
<td>37039-20455</td>
<td>Crawford</td>
<td>Meadville Forging Co - Fee #1</td>
<td>Meadville</td>
</tr>
<tr>
<td>37039-21922</td>
<td>Crawford</td>
<td>Ingram - North #1</td>
<td>Blooming Valley</td>
</tr>
<tr>
<td>37039-20728</td>
<td>Crawford</td>
<td>Cabot - Noah Wengard #1</td>
<td>Sugar Lake</td>
</tr>
<tr>
<td>37039-20830</td>
<td>Crawford</td>
<td>Cabot - ILA Smith #1</td>
<td>Sugar Lake</td>
</tr>
<tr>
<td>37039-22686</td>
<td>Crawford</td>
<td>Mark Resources - Motter #1</td>
<td>Sugar Lake</td>
</tr>
<tr>
<td>37121-42243</td>
<td>Venango</td>
<td>Cabot - Sauerland #2</td>
<td>Demseytown</td>
</tr>
<tr>
<td>37121-25522</td>
<td>Venango</td>
<td>Quaker State - McCaslin #1</td>
<td>Pleasantville</td>
</tr>
<tr>
<td>37121-40513</td>
<td>Venango</td>
<td>Quaker State - Allis #1</td>
<td>Pleasantville</td>
</tr>
<tr>
<td>37053-26222</td>
<td>Forest</td>
<td>Quaker State - Watson #1</td>
<td>West Hickory</td>
</tr>
<tr>
<td>37053-22185-D</td>
<td>Forest</td>
<td>Vertullo - #DJV-0001</td>
<td>Kelletsville</td>
</tr>
<tr>
<td>37053-21250</td>
<td>Forest</td>
<td>Quaker Stata - Fee #1-H (Levoren [324] field)</td>
<td>Kelletsville</td>
</tr>
<tr>
<td>37053-20903</td>
<td>Forest</td>
<td>E.H. Linn - E.S. Collins - ClingerTract #1-293</td>
<td>Tylersburg</td>
</tr>
<tr>
<td>37031-20751</td>
<td>Clarion</td>
<td>Peoples Nat. Gas - N. Penn Gas #75356</td>
<td>Tylersburg</td>
</tr>
<tr>
<td>37065-04071</td>
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<td>E.H. Linn - Kittanning State Forest- UNG #1-289</td>
<td>Sigel</td>
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<tr>
<td>37047-20287</td>
<td>Elk</td>
<td>Amoco - United Natuaral Gas #1-R</td>
<td>Ridgway</td>
</tr>
</tbody>
</table>

*P67 on figure 6

Table 3. Drill holes used in the preparation of transect C-C'.
reclassified into three carbonate units in transect C-C'. In ascending order, these carbonates are named, respectively, 1) the Irondequoit Limestone, 2) an unnamed limestone unit, and 3) the Reynales Limestone as restricted by Zagorski (1991). These latter correlations are shown in figure 8 and are used throughout the correlation of logs along transect C-C'. Care must be taken in the correlation of the carbonate intervals above the Medina Group sandstones. It would appear that the Dayton Limestone (Packer Shell) has been confused with the Reynales Limestone in western Pennsylvania.

Commonly, the bulk density of the basal part of the Reynales Limestone in the western part of transect C-C' is high with respect to the bulk densities of the younger carbonates. The most likely explanation is that the basal unit of the Reynales Limestone is dolomite rather than limestone.

A preliminary examination of bulk density values within the sandstone intervals of the Whirlpool Sandstone, Cabot Head Shale, and the Grimsby Formation along transect C-C' indicates that the Whirlpool Sandstone commonly has very low porosity. Porosity values calculated for sandstones in the Cabot Head Shale and the Grimsby Formation commonly range from 3-4%. These porosity values calculated from well logs, however, are considerably lower than the 5-8% porosity values measured from core in nearby wells (Laughrey, 1984).

Transect D-D'

Lack of funds for geophysical logs in Ohio prevented the completion of transect D-D' in FY1995. This transect should be completed in FY1996.

Transect A-A'

During FY95 geophysical logs from about 100 drill holes were correlated across transect A-A', thus, providing us with a reasonably good understanding of the distribution of Lower and lower Upper Silurian strata across the length of Clinton/Medina gas play 6728. The transect is incomplete across several 10- to 20-mi-wide gaps where well logs have not been purchased. For this report, seven drill holes were selected to characterize the preliminary stratigraphic correlations and framework along transect A-A' (figs. 9, 10). Stratigraphic nomenclature for the Medina and Clinton Groups in New York follows Brett and others (1995). In most cases, the New York terminology for the Medina and Clinton
Figure 8. Correlation of Medina Group sandstones and overlying Clinton Group carbonates and shale between three drill holes along transect C-C'. See figure 6 for location of the drill holes.
Figure 9. Map of the northern part of the Appalachian basin province (067) showing oil and gas plays in Lower Silurian sandstones and location of drill holes (in figure 10) along transect A-A'.

LOWER SILURIAN SANDSTONE OIL & GAS PLAYS
6727 Tuscarora Sandstone gas
6728 Clinton/Medina sandstone gas high potential
6729 Clinton/Medina sandstone gas medium potential
6730 Clinton/Medina sandstone gas medium-low potential
6731 Clinton/Medina sandstone gas low potential
6732 Clinton/Medina sandstone oil/gas
Figure 10. Correlation of "Clinton" sands, Medina Group sandstones, Clinton Group, and Lockport Group between selected drill holes along transect A-A'. See figure 9 for location of drill holes.
Groups can be extended into Pennsylvania (Piotrowski, 1981; Pees, 1983; Laughrey, 1984). In Ohio, a combination of commonly used driller's terms and formal nomenclature are applied to strata equivalent to the Medina and Clinton Groups (Pepper and others, 1953; DeBrosse and Vohwinkle, 1974; Gray and others, 1985).

One important aspect of the transect is that it shows regional thickness variations of the Medina Group in New York and Pennsylvania and of equivalent strata (Medina sand, Cabot Head Shale, "Clinton" sands, upper tongue of the Cabot Head Shale) in Ohio (fig. 10). The maximum thickness of the Medina Group and equivalent strata along transect A-A' is located in the vicinity of Mercer County, PA (drill hole 4) and Columbiana County, OH (drill hole 5)(figs. 9, 10). The 210- to 220-ft-thick Medina Group and equivalent strata there constitute part of the Canton embayment, a depocenter recognized by Knight (1969) consisting of Medina Group siliciclastic units, lowermost Clinton Group carbonate units, and equivalent strata. From this depocenter, the Medina Group thins northward to about 96 ft in Erie County, NY (drill hole 1) and southward to about 156 ft in Washington County, OH (drill hole 7) (figs. 9, 10).

A second important aspect of the transect is that it shows the net thickness and geometry of sandstone in the Medina Group, "Clinton" sands, and Medina sand. Net sandstone thicknesses in the Medina Group and equivalent strata in the seven selected drill holes are greatest in Mercer County, PA (drill hole 4, 96 ft), Chautauqua County, NY (drill hole 2, 90 ft), and Columbiana County, OH (drill hole 5, 85 ft)(figs. 9, 10). The Chautauqua County, NY site, located nearly 100 mi north of the Canton embayment, represents a subsidiary sandstone depocenter in the "Clinton" sand and Medina Group sequence. The net sandstone thickness of the Medina Group interval thins to 64 ft in Erie County, NY (drill hole 1) at the north end of the transect and to 29 ft in Washington County, OH (drill hole 7) at the south end (figs. 9, 10).

Basal sandstone units in the Medina Group and equivalent units (Whirlpool Sandstone and Medina sand) are characterized by an 8- to 20-ft-thick, well-defined low ("clean") gamma ray log response that gradually changes upward to a higher response (higher clay content)(fig. 10). This log shape has been interpreted by Metzger (1981) and Laughrey (1984) to represent sublittoral sheet sandstones. Based on outcrop studies, Middleton and others (1987) suggest that the lower part of the Whirlpool Sandstone has been deposited in a braided fluvial environment. Sandstone units in the Devils Hole Sandstone, upper part of the Cabot Head (Power Glen) Shale, lower part of the Grimsby Formation, and lower part of the "Clinton" sands are 10 to 30 ft thick and commonly have blocky to upward-decreasing ("cleaner") gamma ray log responses (fig. 10). These log shapes have been interpreted in previous investigations to represent
littoral (barrier bars and tidal deltas), distributary mouth bar, distributary channel, tidal-dominated delta, tidal ridge, and offshore marine bar sandstones (Metzger, 1981; Laughrey, 1984; Keltch, 1985). Directly overlying these shallow-marine sandstones are 2- to 14-ft- thick sandstone units in the upper part of the Grimsby Formation and "Clinton" sands that have spike-shaped to upward-increasing (higher clay content) gamma ray log responses (fig. 10). These log shapes have been interpreted in earlier investigations to represent braided fluvial channel, meander point bar, and tidal channel sandstones (Metzger, 1981; Laughrey, 1984; Keltch, 1985).

In this report, the Whirlpool Sandstone and Medina sand are interpreted as shoreface or sublittoral sheet sandstones, possibly with a lowermost braided fluvial component, deposited in a transgressive systems tract that unconformably overlies the Upper Ordovician Queenston Shale. This unconformity is recognized as the Cherokee unconformity by Brett and others (1990). Following the preliminary interpretation of the middle unit in transect B-B' (fig. 5), sandstones in the lower part of the Grimsby Formation and "Clinton" sands with blocky and upward-decreasing gamma ray responses are identified here as shoreface sandstones deposited in a highstand systems tract (fig. 10). These shoreface sandstones constitute parts of progradational parasequences that successively overlap one another toward the northwest, pinch out seaward into offshore marine shale of the Cabot Head and Power Glen Shales, and appear to downlap across the underlying transgressive systems tract. Although transect A-A' is largely oriented normal to depositional strike, it has a slight dip-oriented component that cuts obliquely across the paleoshoreline from north to south in a seaward direction and exhibits locally the stacking and westward progradational character of the parasequences (Figs. 9, 10). The Devils Hole Sandstone of Brett and others (1990, 1995) and informally named sandstones in the Cabot Head Shale (Pees, 1983; Laughrey, 1984; Zagorski, 1991) are interpreted here to be part of the same progradationally stacked parasequences. Following the interpretation of the upper unit in transect B-B' (fig. 5), sandstones with spike-shaped and upward-increasing gamma ray responses that overlie the shoreface sandstones are identified here as estuarine (tidal) and fluvial sandstones in a transgressive systems tract deposited unconformably across a highstand systems tract (fig. 10). The unconformable contact between the proposed highstand and transgressive systems tracts is subjective because of the variety of gamma ray log signatures involved. This boundary may mark a previously unrecognized sequence boundary (unconformity) caused by a eustatic fall in sea-level (see discussion of transect B-B').

A third important aspect of transect A-A' is that it shows the regional distribution of carbonate units in the Clinton Group (Reynales
Limestone, Irondequoit Limestone, Dayton Limestone, Packer Shell of drillers). These units are commonly used as a datum horizon for stratigraphic cross sections (transects) through the "Clinton" sands and Medina Group sandstones or the contoured horizon on structural contour maps. Figure 10 shows that, although these carbonate units are regionally extensive, long-distance correlations between them can be erroneous because of pinch outs and thickness changes in the intervening shale beds. The Irondequoit and Reynales Limestones extend across most of transect A-A' and the latter unit is used as the datum horizon (fig. 10). However, at the north end of the transect in New York State they are separated from one another by 2 to 5 ft of shale whereas at the south end in Ohio they are separated by a 70-ft-thick shale and a 10-ft-thick unnamed limestone unit. This unnamed limestone extends as far north as Crawford County, PA. The Dayton Limestone (Packer Shell of drillers) is located stratigraphically about 45 ft beneath the Reynales Limestone in southern Ohio (drill hole 7, Washington County, OH) and extends as far north as northwestern Pennsylvania (drill hole 4, Mercer County, PA) where it underlies the Reynales Limestone by less than 10 ft (figs. 9, 10).

GAS PRODUCTION AND DECLINE OF SELECTED WELLS

Estimated ultimate recoverable (EUR) gas from individual wells is an essential parameter for assessing recoverable gas in continuous-type (unconventional) accumulations in reservoirs such as the "Clinton" sands and Medina Group sandstones (Schmoker, 1995b). Basically, the EUR probability distribution for a set of producing wells in a given play can be used to approximate an expected EUR distribution for wells in undrilled parts of the play. EUR's either may be calculated directly from production-history records of abandoned wells or calculated from production decline curves of active or shut-in wells. As a rule, wells must have produced gas from the same reservoir for at least 5 years to provide a reliable decline curve. In the Appalachian basin, oil and gas production data for fields and wells have been compiled by most State Oil and Gas Agencies and State Geological Surveys since the early 1960's and many of them are available in digital form. Proprietary production files and data bases have been compiled by several oil and gas companies and consulting geologists in the basin. Several of these proprietary files may be purchased in digital form. Large commercial organizations such as Petroleum Information Corporation (PI) and Dwights Data Corporation have compiled very few oil and gas production records for the Appalachian basin.
In May 1994, the Ohio Division of Geological Survey provided the USGS with an 11,000 well digital production file to assess Clinton/Medina sandstone gas plays for the 1995 National Assessment of oil and gas. Production data from 1972 through 1986, organized by county, township, formation, well, and field, are recorded in this data file. Since then, the Ohio Survey has increased their oil and gas production file to about 37,000 wells. A major activity for FY95 was to identify and acquire well production data in the States of New York and Pennsylvania and to acquire the update of the production data base in Ohio.

Approximately 37,000 annual production records from 10,000 wells in 6 counties in western New York State were acquired from the New York State Department of Environmental Conservation (Bureau of Oil and Gas Regulation, Division of Mineral Resources) in early 1995. The records extend from 1985 through 1994 and are organized by county, township, formation, field, and well. Production data as far back as the early 1960's are stored on paper records but have not yet been converted to digital form. An additional 6,000 well records were acquired in the 6 counties of western New York for which no production records are available. Also in early 1995, deep reservoir production data consisting of 32,000 wells in 5 counties in northwestern Pennsylvania was acquired from the Pennsylvania Topographic and Geologic Survey. These data record oil and(or) gas production from units below the Middle Devonian Tully Limestone and are organized by County, 7.5 minute quadrangle, formation, field, and well. Because of a five-year confidentiality clause, the data file is restricted to annual gas production from 1980 through 1989. Annual updates will be made available for New York and Pennsylvania production records through the respective State agencies. The 26,000 well, production-records update in Ohio is still being compiled and edited by the Ohio Division of the Geological Survey and should be available to interested users in early 1997.

The New York, Ohio, and Pennsylvania production files are presently stored in the USGS Wells database. To date, an evaluation of these production records has been limited to selected wells in eastern Ohio where EUR's were calculated for the 1995 National Assessment. Decline curve analysis is planned for wells along or nearby the transects so that their gas yields can be compared with stratigraphic and structural characteristics of the "Clinton" sands and Medina Group sandstones.
Land use-land cover and political-boundary data from the EROS Data Center in Sioux Falls, South Dakota were converted into ARC/INFO coverage for this project. When combined with existing play boundary maps and oil and gas cell maps from the 1995 National Assessment (Ryder, 1995; Beeman, 1995), also in ARC/INFO format, they illustrate the types of environments that are impacted by Clinton/Medina sandstone gas plays. PI's Well History Control System (WHCS) file, consisting of over 100,000 wells for the Appalachian basin, was used by Beeman (1995) to create the oil and gas cell maps. Figure 11 shows a representative piece of the resulting map for northeastern Ohio and adjoining Pennsylvania.

Land use and land cover on figure 11 is differentiated with colors coded by general type (see explanation for fig. 11). Each 1/4-mile-square area (cell) of figure 11 that was drilled into or through the Clinton/Medina interval is shown by an X. The X's are color-coded according to the production status of the drill holes (see explanation for fig. 11). For example, a red X indicates that at least one gas well produces from the Clinton/Medina play in the cell.

Also for this project, an oil and gas field map was compiled for "Clinton" sands, the Medina sand, Medina Group sandstones, and the Tuscarora Sandstone at a scale of 1:500,000. States that are shown on the map and have production from the Clinton/Medina/Tuscarora interval are Kentucky, New York, Ohio, Pennsylvania, and West Virginia. An example of this oil and gas map from a three-county area of southeastern Ohio is shown in figure 12. This map probably will be digitized into ARC/INFO format in FY1996.

Analyses of formation water produced from the "Clinton" sands, Medina sand, Medina Group sandstones, and the Tuscarora Sandstone are available in a brines data file compiled for a joint USGS/Department of Energy/University of Oklahoma project in the 1970's. The file contains approximately 6,000 analyses for the Appalachian basin. An additional 100 brine analyses, with interpretations, were acquired from the New York State Department of Environmental Conservation (Bureau of Oil and Gas Regulation, Division of Mineral Resources). These formation water analyses are stored in a USGS database for future studies of water quality and water volume in gas-bearing Clinton/Medina/Tuscarora sandstone reservoirs.
Explanation for Figure 11

**Land Use/Land Cover**

- **Pink**
  - Land used for urban, commercial, industrial, and transportation activities
- **White**
  - Agricultural land
- **Green**
  - Forest land
- **Dark blue**
  - Wetlands
- **Light blue**
  - Lakes, rivers, and reservoirs
- **Gray**
  - Barren lands that include quarries and strip mines

**Hydrocarbon Production Status**
Each X represents a 1/4-mi-square area (cell) that was drilled into or through the Clinton/Medina interval

- **X green**
  - Oil
- **X red**
  - Gas
- **X purple**
  - Oil and Gas
- **X black**
  - Nonproductive
Figure 11. Map of Northeast Ohio and Northwest Pennsylvania showing land use/land cover and hydrocarbon production status by 1/4 sq mi cells for wells penetrating the "Clinton" sand and Medina Group sandstones.
Figure 12. Map(part) of oil and gas fields that produce from the "Clinton" sands, Medina Group sandstones, and Tuscarora Sandstone. Sample from Morgan, Noble, and Washington Counties, Ohio.
Because of the large number of wells in the Clinton/Medina/Tuscarora play, the initial problem to be addressed is to determine the feasibility of constructing structure-contour and drilling-depth maps by machine from existing databases. Approximately 78,000 of the 211,000 wells in PI WHCS data files for the Appalachian basin penetrate the Clinton/Medina/Tuscarora interval. Although the regional structure of the producing interval is characterized by gentle, eastward homoclinal dip, with low and fairly uniform structural relief, enhanced gas production has been attributed to local structures by some workers (for example, Osten, 1982; Zagorski, 1991). These structures may include anticlines, anticlinal noses, terraces, and fault zones, all of which may influence hydrocarbon entrapment and/or fracturing in Clinton/Medina/Tuscarora sandstone reservoirs. In order to identify such features it will be necessary to utilize as many data points as possible, preferably with various contouring packages and the WHCS database. Use of the WHCS database is, however, complicated by the use of inconsistent operator terminology to identify stratigraphic units.

A test map showing structural contours has been constructed for the study area at a scale of 1:500,000 using the Dynamic Graphics Inc. Interactive Surface Modeling (ISM) system and WHCS data files. The top of the Packer Shell or the Reynales Limestone (fig. 10) was chosen as the datum because they are well represented in the database and assumed to be approximately equivalent. The north-central Ohio portion of the map is shown at a reduced scale in figure 13. The entire map utilizes approximately 58,000 data points and covers most of the play areas. Regional structure is adequately shown on the map, but there are a number of artifacts that may be a function of data distribution or miscorrelation. The Packer Shell and Reynales Limestone are convenient datum horizons from a geological standpoint, in that they are widespread, easily picked on geophysical logs, and probably reasonably approximate time lines. Subsequent correlations (fig. 10) show that, in fact, the Packer Shell and Reynales Limestone are not equivalent. In southern Ohio, for example, the Dayton Limestone (Packer Shell) (fig. 10) is typically more than 30 ft below the Reynales Limestone. Furthermore, there are a number of differences as to the usage of the terms Packer Shell and Reynales within the WHCS database and these differences affect the structure contours to some degree. In New York and Pennsylvania, for example, the Irondequoit Limestone (fig. 10) is commonly identified as Packer Shell in the WHCS database and, where identified as such, ranges
Figure 13. Structure-contour map drawn on the top of the Packer Shell/Reynales limestone interval in north-central Ohio. Contours were drawn using the Interactive Surface Modeling (ISM) System and Petroleum Information Corporation WHCS data files. The contour interval is 250 ft.
from about 15 ft higher than the Reynales Limestone datum in New York to over 30 ft higher in Pennsylvania.

Such discrepancies may be tolerable on a regional level, particularly, at the original map scale of 1:500,000 and at the contour interval of 250 ft shown in figure 13. However, because the Packer Shell has been inconsistently picked in the WHCS database, it is possible that use of this datum, without editing, would be unsatisfactory at larger scales. Also, "Clinton" sands and sandstones of the Medina Group are inconsistently picked in the WHCS database. The database is now being examined for other possible datums. This work is still in progress, but initial indications are that other structural datums may be more suitable for searching the WHCS database, such as, the top of the Medina Group in New York and Pennsylvania and the top of the "Clinton" sands in Ohio.

In addition to preliminary work with the WHCS database, a fairly comprehensive search of the literature on structure below the Upper Silurian Salina Group salt in the play area has been made. Most of the literature is in the form of graduate-school theses. Twenty six such theses were obtained through inter-library loans and were searched for structural information, as well as other information pertinent to the project. Other sources of existing sub-salt structural information are mostly limited to State geological survey reports that are typically generalized or cover only small areas. The literature search has identified several articles where cross-strike discontinuites (CSD's) of Wheeler, (1980) may have influenced hydrocarbon production (Rodgers and Anderson, 1984; Coogan, 1991). These CSD's will be incorporated into the structure and depth maps subject to time limitations and software capabilities.

RESERVOIR PRESSURE AND TEMPERATURE

One of the more important defining characteristics of continuous-type (basin-centered) gas accumulations is their pressure history. Continuous-type (basin-centered) gas accumulations are always abnormally pressured. They are either overpressured or underpressured with respect to normal hydrostatic pressure gradients which range from 0.43 to 0.46 pounds per square inch per ft (psi/ft), depending on the salinity of the formation water. In the Appalachian basin, Russell (1972) first recognized abnormally low reservoir pressures in the "Clinton" sands. Later, Davis (1984), Zagorski (1988; 1991), and Law and Spencer (1993) suggested that the abnormally low pressures in "Clinton" sands and Medina Group sandstone reservoirs were indicative of a regional, continuous-type (basin-centered) accumulation. Law and Dickinson (1985) suggested that
the abnormally low pressures in low-permeability reservoirs, like those in "Clinton" sands and Medina Group sandstone reservoirs, had evolved from an earlier abnormally high pressure history caused by hydrocarbon generation.

Based on analogs of continuous-type (basin-centered) gas accumulations in the Rocky Mountain region, we have developed a working hypothesis that the Clinton/Medina sandstones and the equivalent Tuscarora Sandstone in the Appalachian basin should have three pressure domains; a normally pressured domain, a low-pressured domain, and a high-pressured domain. The normal and underpressured domains have been fairly well defined by industry operators in the region. The normally pressured domain is located in east-central Ohio (Davis, 1984, Thomas, 1993) where "Clinton" sands produce oil and gas with water. This normally pressured domain coincides approximately with Clinton/Medina sandstone oil/gas play 6732. In eastern Ohio and western Pennsylvania and New York, downdip from the normally pressured "Clinton" sands, is the underpressured domain. Since the inception of this project, abnormally low pressures have been verified throughout most of northwestern Pennsylvania and adjoining western New York (play 6728). Pressure gradients measured here commonly range from 0.30 to 0.40 psi/ft. The location of the transition into updip, normally pressured reservoirs is uncertain, however, and remains an objective of this project.

The postulated overpressured domain, may be located east of the underpressured domain, where the "Clinton" sands, Medina Group sandstones, and the equivalent Tuscarora Sandstone are more deeply buried and present-day subsurface temperatures are higher than at shallower depths. Empirical evidence in the Rocky Mountain region has shown that in rock sequences that have adequate amounts of organic carbon to generate hydrocarbons (a condition not yet confirmed for Lower Silurian strata in the Appalachian basin), the top of the zone of active generation of hydrocarbons and overpressuring occurs at temperatures of about 200°F (90°C). In areas where the rocks have experienced a cooling event, a common situation in most basins, the top of overpressuring may be significantly less than 200°F(90°C). Our search for this overpressured component has just begun; however, there are some encouraging beginnings.

A report by Avary (in press) indicates that some of the Lower Silurian Tuscarora Sandstone reservoirs in the Runville, Black Moshannon, and Devils Elbow gas fields near the Allegheny structural front in Pennsylvania are overpressured (0.5 - 0.6 psi/ft). The depth to the Tuscarora Sandstone in these fields ranges from 8,100 - 11,100 ft and reservoir temperatures range from 138 - 167°F. However, because these gas fields produce from anticlinal traps there is some uncertainty about
the pressure relationships. For example, high reservoir pressures (greater than hydrostatic pressures) are common in hydrocarbon accumulations that have long columns. Thus, the reservoir pressure in these fields may, in fact, be normal when considering their mode of accumulation. Through the next year, one of our objectives will be to determine the pressure conditions of the Tuscarora Sandstone. The recognition of a regionally overpressured domain in the Tuscarora Sandstone would have the effect of enlarging the geographic and stratigraphic distribution of the Clinton/Medina continuous-type (basin-centered) gas accumulation in the Appalachian basin.

DOWNDIP LIMIT OF WATER PRODUCTION

Another diagnostic characteristic of continuous-type (basin-centered, deep basin) gas accumulations is the absence or near absence of producible formation water (Masters, 1979; 1984). Masters (1979; 1984) further reports that water-deficient, gas-saturated sandstone reservoirs in continuous-type gas accumulations are replaced updip by water-saturated sandstones that control entrapment. These zones of predominantly gas-saturated/little producible water and gas-bearing/water-saturated sandstones, as well as an intervening transition zone, can be interpreted from resistivity logs (Masters, 1979; 1984). Analogous zones of low-water, gas-saturated zones flanked by updip high-water saturated oil-and gas-bearing zones are noted by Davis (1984) and Zagorski (1991) in the Appalachian basin. Based on 33 control points, Davis (1984) suggests that the change from gas-saturated "Clinton" sands with little producible water to gas-bearing "Clinton" sands with high water saturation occurs abruptly westward (updip) across a north-northeast trending line through eastern Ohio. In contrast, Zagorski (1991) -- using resistivity logs across two short dip-oriented sections in northwestern Pennsylvania and adjoining Ohio--suggests that the updip change from gas-saturated Medina Group sandstones to water-saturated sandstones is very transitional.

A map showing wells that produce or have produced water from the "Clinton" sands, the Medina sand, Medina Group sandstones, and the Tuscarora Sandstone was started for this project. In addition to showing the distribution of Lower Silurian sandstones that have high water saturations, this map may help to locate the probable updip limit of the adjoining continuous-type gas accumulation. The compilation of such a map is hindered by several factors. First, not all States require operators to document the character and quantity of water produced from oil and gas wells. Second, produced water that is reported is not always identified
by stratigraphic interval. Thirdly, water-bearing parts of the Clinton/Medina interval may be intentionally cased and cemented and, thus, are not reported. Compilation of water data to date consists of recording relevant data from PI's weekly Appalachian Basin Report and plotting it by hand on a 1:500,000 scale map. Other data sources for this compilation are State Agency production files and published articles. The map is still too preliminary to indicate any definite patterns and resistivity logs have not been evaluated for evidence of high-water saturation.

BURIAL, THERMAL, AND PETROLEUM GENERATION HISTORY MODELS

Except for local CAI values for conodonts recovered from the Packer Shell and "Clinton" sands (Nancy R. Stamm, written commun. 11/18/94), thermal maturation indices are unavailable for most of the Lower Silurian sequence in the study area. In the absence of thermal maturation indices, paleotemperatures for the Clinton/Medina sandstones were estimated from burial and thermal history models calibrated with data from other stratigraphic units.

Burial, thermal, and petroleum generation history models were generated from data in six deep drill holes in Ohio and West Virginia (fig. 14). From northwest to southeast these drill holes are: 1. Pan American No. 1 Windbigler, Morrow County, Ohio; 2. Redstone No. 3 Barth, Coshocton County, Ohio; 3. Lakeshore No. 1 Marshall, Guernsey County, Ohio; 4. Amerada No. 1 Ullman, Noble County, Ohio; 5. Exxon No. 1 Deem, Wood County, West Virginia; and 6. Exxon No. 1 Gainer-Lee, Jackson County, West Virginia (fig. 14). These models provide an estimate of the thermal history in three Clinton/Medina plays (6728, 6730, 6732) and the adjoining Tuscarora Sandstone play (6727). All models assume that 5,000 ft (1.5 km) of overburden have been removed from the drill site during post-Alleghanian uplift and erosion. Thermal gradients used in the models were constrained by Rock-Eval data from the Middle Ordovician Utica Shale (Ryder and others, 1991), vitrinite analyses from Pennsylvanian strata (Chyi and others, 1987) and CAI data from selected strata (Harris and others, 1978). Because overburden removal estimates remained constant, geothermal gradients were adjusted until the calculated thermal maturity based on vitrinite kinetic reactions (BasinMod Program, Platte River Assoc., Inc.) matched the measured maturity.

The burial, thermal, and petroleum generation history model of the Amerada No. 1 Ullman drill hole is shown in figure 15. Table 4 lists the stratigraphic sequence, geochemical data, and measured thermal maturation indices used to constrain the model. Geothermal gradients
Figure 14. Map of the northern part of the Appalachian basin province (067) showing drill holes used for burial, thermal, and petroleum generation history models.
Figure 15. Burial, thermal, and petroleum generation history model for the Amerada No. 1 Ullman drill hole, Noble County, Ohio. The model was generated from the BASINMOD program. See figure 14 for location.
Amerada No. 1 Ullman  
Elk Township  
Noble County, Ohio  
API 34-121-21278

<table>
<thead>
<tr>
<th>Tops(ft)</th>
<th>Formation (Group)</th>
<th>Geochem.&amp; Thermal Ind.</th>
<th>Period(Epoch)</th>
<th>Age(Ma)</th>
</tr>
</thead>
</table>
| Surface-1530 | Mononghelia Group  
Conemaugh Group  
Allegheny Formation  
Pottsville Group  
---unconformity---  
~ 400 ft removed | Ro~0.6,  
100% type III kerogen | Pennsylvanian | 320-288 |
| 1530-1912 | Pocono Group  
Sunbury Shale  
Berea Sandstone | | Mississippian | 360-335 |
| 1912-4795 | Upper Devonian shale  
and siltstone undiff. | | Late Devonian | 374-360 |
| 4795-5224 | Marcellus Shale  
Columbus Limestone  
Oriskany Sandstone  
Helderberg Limestone | | Early and Middle Devonian | 408-374 |
| 5224-6060 | Bass Islands Dolomite  
Salina Group | | Late Silurian | 421-408 |
| 6060-6835 | Lockport Dolomite  
Rochester Shale  
"Clinton" sands | | Early Silurian | 438-421 |
| 6835-8220 | Queenston Shale  
Reedsdale Shale | | Late Ordovician | 458-438 |
| 8220-9382 | Utica Shale-190 ft thick  
Trenton Limestone  
Black River Limestone  
Wells Creek Formation  
---Knox unconformity---  
~ 350 ft removed | PI~0.03,  
TOC=3-4,  
50% type II &  
50% type III | Middle Ordovician | 473-458 |
| 9382-10545 | Knox Dolomite | | Late Cambrian and Early Ordovician | 510-478 |
| 10545-11420 | Conasauga Formation  
Rome Formation  
Mt. Simon Sandstone  
---unconformity---  
11420 | | Late Cambrian | 523-510 |

| | | | Middle Proterozoic | 1,000 |

Table 4. Stratigraphic, geochemical, and thermal maturation indices used to constrain the subsidence and maturation kinetic model for the Amerada No. 1 Ullman, Noble County, Ohio.
required to match the modeled (calculated) maturity with the selected measured thermal maturation indices are: 1.60°F/100 ft (2.90°C/100 m) for the beginning (523 Ma) and end (0 Ma) of the model and 1.80°F/100 ft (3.27°C/100 m) for an Alleghanian-age heat pulse at 230 Ma. This model suggests that at maximum burial, in Early Triassic time, the "Clinton" sands in the No. 1 Ullman drill hole had reached a maximum temperature of about 250°F (120°C). The model further suggests that the main phase of oil generation in the Middle Ordovician Utica Shale, a probable source of hydrocarbons in the "Clinton" sands and Medina Group sandstones, occurred in Permian time (fig. 15). Abundant natural gas was probably generated from the Utica Shale in the vicinity of the No. 1 Ullman drill hole in early Mesozoic time as a result of the thermal cracking of oil and availability of types II and III kerogen. Fracturing by several mechanisms--basement tectonics, gas generation in the Utica Shale during maximum burial ~230 Ma, and thermoelastic expansion during post-Alleghanian uplift--may have permitted much of this natural gas to migrate vertically between 1,000 and 1,400 ft into "Clinton" sands and Medina Group sandstone reservoirs. Stable isotopic compositions of Medina Group gas in New York and Pennsylvania support the vertical migration theory (Jenden and others, 1993; Laughrey and Baldassare, 1995). Thus, the proximity of source and reservoir rocks that characterize Rocky Mountain continuous-type (basin-centered) gas accumulations may not apply to the proposed "Clinton"/Medina/Tuscarora continuous-type gas accumulation.

The required 1,000 to 1,400 ft of vertical migration, through fractured Upper Ordovician shale and siltstone, may be a deterrent to gas moving into the "Clinton"/Medina sandstones from the underlying Utica Shale. Particularly troublesome are the high formation pressures needed to displace water from the "Clinton"/Medina continuous-type accumulation. These high formation pressures may be difficult to achieve with the proposed source-to-reservoir distance.

FRAC'TURES AND THEIR DETECTION WITH LOG SUITES

Fractures undoubtedly play a major role in the creation of "sweet spots" in continuous-type (basin-centered) gas accumulations. Thus, data regarding the character and distribution of reservoir fractures and well-site evaluations of fracture-detection techniques would assist in the exploration, development, and assessment of the "Clinton"/Medina gas resource. Progress on these topics in FY95 was limited largely to a literature compilation on the subjects of fracture detection and evaluation,
wellbore breakouts, and analysis of in situ stress (Appendix I, this report; Prensky, 1995). Publications by Alexander and others (1985) and Hill and others (1992) were valuable introductions to the role of fractures on gas production from the "Clinton" sands in Ohio.

SEISMIC PROFILES

Seismic profiles are of interest to this project because they may help to identify local and regional controls of tectonic fractures in the "Clinton" sands, Medina Group sandstones, and Tuscarora Sandstone. Several seismic profiles at the northeast edge of the study area are available in USGS files in Denver and numerous profiles that cross the study area are available through seismic-data brokers.

The profiles at the USGS are stored in the GEOFILE data set. They constitute 1,507 miles of single-channel (1-fold) seismic records from New York and Pennsylvania that were purchased by the USGS with limited publication rights (that is, page-size illustrations without shotpoint numbers). Although most of the lines are located too far east of the study area, some are close enough to be useful to the project. These data are old (1940's and 1950's vintage) but are of good to excellent quality. They are in digital form (8mm exabyte magnetic tape; SEG-Y format) and thus may be reprocessed. Figure 16 is an example of the typically good quality of the profiles. Profiles are available in Broome, Chemung, Schuyler, Tioga, and Tompkins Counties in New York and Bradford, Cameron, Clinton, Lycoming, Potter, and Tioga Counties in Pennsylvania.

Western Atlas and Geodata Corporations offer for purchase (with limited publication rights) other seismic profiles which cross the study area. Figure 17 is a sketch map showing the general location of lines 1-5 that were reviewed by USGS scientists. These data are 12-fold, 48-channel Vibroseis, recorded and processed in 1974. The data quality is good, especially in the northern part of the study area. Most promising is line 5 which extends from central Ashtabula County, Ohio, to the southeast corner of Mercer County, Pennsylvania. This profile crosses Henderson Dome in southeastern Mercer County (Fettke, 1950; Kuminecz and Gorham, 1993) and appears to image a highly faulted anticlinal structure. Lines 3 and 4 also show evidence of small faults and anticlines, but not to the same extent as in line 5. Geodata Corporation has access to a seismic line (P-7) that runs across Crawford and Venango Counties, Pennsylvania, northeast of, and parallel to line 5 (fig. 17). We have not yet reviewed this line. Future inquiries regarding seismic profiles in the study area will include profiles recorded in western New York State and in Lake Erie.
Figure 16.
Single fold seismic line in Tioga County, Pennsylvania, showing typical quality of the GEOFILE data set in this area.
Figure 17. Sketch map showing the general location of seismic lines available for purchase from Western Atlas (Lines 1-5) and Geodata (Line P-7) Corporations.
ENVIRONMENTAL IMPACT ASSOCIATED WITH DEVELOPMENT OF CONTINUOUS GAS ACCUMULATIONS

The high drilling density required to develop continuous gas accumulations can have a great impact on the environment. Visual impacts related to dense well spacing include those created by access roads, pipelines, and well locations. In many cases, the amount of land disturbed can be minimized through the early identification of the accumulation type and size. First, a well-designed access and transportation network should be planned in advance. Where several operators are developing the accumulation, a cooperative planning and construction effort is desirable to reduce visual impact and costs. Secondly, surface impact can be reduced by having several wells share a single-well location. Having multiple wells at a single location is accomplished by directional drilling techniques. Also, visual impact can be reduced by locating well sites, roads, and pipelines in areas that are visible only over short distances such as in ravines and behind small hills.

Water production may be associated with continuous gas accumulations but it is low in comparison to that in conventional and coalbed gas accumulations. This water production, which generally is less than 10 barrels of water a day for the Clinton/Medina sandstone reservoirs, must be disposed of in a safe and economical manner. The free water is separated from the gas stream by a separator whereas molecular water is commonly separated from the gas stream by glycol dehydration. Current disposal methods include reinjecting the water, evaporation, creating wetlands, or hauling it to a treatment plant. The amount and quality of the water dictate the method used. Reinjecting the water is accomplished either by using a nonproducing well, or drilling a new well. The water may be reinjected into the same formation from which it was produced or into a different formation that is isolated from water aquifers used for domestic, agricultural, or industrial purposes. In some areas, the water is discharged into the local drainage system and, in at least one case, in the Green River Basin of Wyoming, it is used to create a wetland. Also, the water can be stored in tanks at the well site and hauled to a common treatment and disposal site.

A study by Callaway (1987) indicates that in New York State there is little between-well variation in the quality of formation water produced from a given reservoir. Forty-six of the eighty-six water samples used in the study were collected from Medina Group sandstones. Previous studies indicating significant between-well variation in the quality of formation water were based on a large number of samples, many of which were
inconsistently sampled and analyzed. For example, analyses from numerous labs failed to meet basic ionic and mass balance checks. Water samples utilized by Callaway (1987) indicate that 98% of their dissolved solids, ranging from 10,000 to 25,000 ml/l, are accounted for by sodium, calcium, magnesium, potassium, and chloride. The addition of barium and strontium to this list of elements accounts for over 99% of the dissolved solids. Similar high dissolved solids and chemical constituents are recorded in formation waters in Medina Group sandstones in Pennsylvania (Young and others, 1991; Siegel and others, 1990) and "Clinton" sands in Ohio (Breen and others, 1985).

SUMMARY OF FY95 ACCOMPLISHMENTS

1. Three regional transects have been drawn through selected parts of New York, Ohio, and Pennsylvania to show the stratigraphic, facies, and sequence stratigraphic framework of the Niagaran Series (Medina, Clinton, and Lockport Groups and equivalent strata).
2. New facies and sequence stratigraphic interpretations are suggested for sandstones of the Medina Group in western New York State. One new interpretation is the sequence boundary within the Grimsby Formation. This proposed sequence boundary resulted from broad valleys cut into emergent, progradational shoreface sandstone (highstand tract deposits) and backfilled by fluvial and tidal sandstone (transgressive tract deposits) during a rise in sea level.
3. Several thousands of gas production records for individual wells have been acquired in digital form for six counties in New York and five counties in Pennsylvania. These production records are stored on the USGS Wells database.
4. A land-use and land-cover map with political boundaries was compiled at a scale of 1:500,000. Also included on the map are boundaries of Clinton/Medina/Tuscarora oil and(or) gas plays and 1/4 sq mi cells showing the distribution of wells that penetrate the Clinton/Medina/Tuscarora interval and their hydrocarbon status.
5. An oil and gas field map was compiled for the "Clinton" sands, Medina Group sandstones, and Tuscarora Sandstone at a scale of 1:500,000.
6. A preliminary map showing structural contours has been constructed for the study area at a scale of 1:500,000 using the Dynamic Graphics Inc. Interactive Surface Modeling (ISM) system and WHCS data files.
7. A comprehensive literature search was made for structure below the Upper Silurian Salina Group salt in the play area to identify potential
structural elements that may control fracture patterns in Clinton/Medina sandstone reservoirs.

8. A working hypothesis suggests that the Clinton/Medina sandstones and the equivalent Tuscarora Sandstone in the Appalachian basin should have three pressure domains; a normally pressured domain, a low-pressured domain, and a high-pressured domain. The normal and underpressured domains have been verified by project investigations in FY95. The postulated overpressured domain has yet to be verified but there are some indications that the Tuscarora Sandstone reservoirs in central Pennsylvania may be overpressured.

9. Wells that produce or have produced water from the "Clinton" sands, Medina sand, Medina Group sandstones, and Tuscarora Sandstone were compiled on a preliminary map. These maps will be used to better define the boundary between continuous-type and discrete hydrocarbons accumulations in the Clinton/Medina sandstone reservoirs.

10. Several hundred published and unpublished analyses for brines and formation waters in the Clinton/Medina sandstone reservoirs were compiled and loaded into a USGS database.

11. Burial, thermal, and petroleum generation history models were generated from data in six deep drill holes in Ohio and West Virginia to estimate paleotemperatures of the "Clinton" sands and Tuscarora Sandstone and to test the feasibility of the Middle Ordovician Utica Shale as the source of the gas in the "Clinton"/Medina/Tuscarora interval. These models suggest that the Utica Shale, located 1,000 to 1,400 ft beneath the Clinton/Medina/Tuscarora sandstones, is a plausible source of the gas.

12. Seismic profiles were located in New York, Ohio, and Pennsylvania that may help to identify local and regional structures capable of generating tectonic fractures in the "Clinton" sands, Medina Group, and Tuscarora Sandstone.

13. Environmental issues were investigated to evaluate the impact of high drilling density and local brine disposal associated with extracting gas from a continuous-type accumulation.

14. An extensive selected bibliography was compiled for literature regarding the geology and oil and gas resources of the "Clinton" sands, Medina Group, and Tuscarora Sandstone in the Appalachian basin.

15. The preliminary results of this project generally support the Lower Silurian Clinton/Medina/Tuscarora sandstone plays as defined for the 1995 National Assessment and the assessment methodology applied to them.

a. The characterization of the Clinton/Medina sandstone gas plays (6728-6731) in the 1995 National Assessment as a part of a continuous-type gas accumulation is justified. Moreover, the
assessment methodology applied to these plays—which accounts for regionally extensive, gas-saturated reservoirs—is appropriate.
b. The Clinton/Medina sandstone oil/gas play (6732) in the 1995 National Assessment, that adjoins the continuous-type gas accumulation plays on the west, seems to be appropriately defined as a conventional oil and gas play having discrete accumulations. However, the trapping mechanism(s) of the oil and gas in the conventional play and the limits of the transitional boundary between the conventional and continuous-type (unconventional) plays remain poorly known.
c. The Tuscarora Sandstone gas play (6727) in the 1995 National Assessment, that adjoins the continuous-type gas plays on the east, may need to be revised. Sparse pressure and temperature data suggest that this play may be a continuous-type gas play rather than a conventional gas play as originally suggested in the 1995 National Assessment. More data are needed to support the new interpretation.
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APPENDIX I

Selected bibliography of the geology and oil and gas resources of the Lower Silurian "Clinton" sands, Medina Group sandstones, and Tuscarora Sandstone, Appalachian basin of New York, Ohio, Pennsylvania, and West Virginia
(as of October 1, 1995)


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APPENDIX II

Contacts with State Geological Surveys and Agencies

NEW YORK

New York State Department of Environmental Conservation, Division of Mineral Resources

1. Gregory H. Sovas, Director
2. Sandra F. Brennan, Director, Bureau of Oil and Gas Regulation
3. Donald J. Drazan, Chief, Technical Assistance Section
4. Eric B. Shyer, Mineral Resources Specialist

New York State Geological Survey

1. Robert H. Fakundiny, State Geologist and Chief
2. Richard Nyahay, Geologist

Northeastern Science Foundation Inc.

1. Jon Bass, Geologist

OHIO

Ohio Division of Geological Survey

1. Thomas M. Berg, State Geologist and Chief
2. Lawrence H. Wickstrom, Geologist
3. Garry E. Yates, Environmental Technology Supervisor

Ohio Division of Oil and Gas

1. Michael P. McCormac, Geologist
PENNSYLVANIA

Pennsylvania Topographic and Geologic Survey

1. Donald M. Hoskins, Director and State Geologist
2. Cheryl Cozart, Data Management Specialist
3. John A. Harper, Chief, Oil and Gas Section
4. Christopher D. Laughrey, Oil and Gas Geologist

WEST VIRGINIA

West Virginia Geological and Economic Survey

1. Larry D. Woodfork, Director and State Geologist
2. Douglas G. Patchen, Program Manager, Appalachian Oil and Natural Gas Research Consortium
3. K. Lee Avary, Geologist
APPENDIX III

Project members and their contribution(s)

Kerry L. Aggen - GIS support for land use/land cover map.

Robert D. Hettinger - Cross section B-B'; Lower Silurian stratigraphy and facies; sequence stratigraphic interpretations.

Ben E. Law - Interpretation of reservoir pressure and temperature data.

John J. Miller - Location and availability of seismic profiles.

Vito F. Nuccio - Burial, thermal, and petroleum generation history models.

William J. Perry, Jr. - Cross section C-C'; Lower Silurian stratigraphy and facies.

Stephen E. Prensky - Application of log suites to fracture detection.

Robert T. Ryder - Chief, Appalachian basin project; cross section A-A'; Lower Silurian stratigraphy and facies; Clinton/Medina/Tuscarora oil and gas map; bibliography.

John R. SanFilipo - Structure contour map; application of digital contouring programs.

Craig J. Wandrey - Storage and manipulation of digital data; GIS technology; land use/land cover cell map; gas production data base; formation water quality data; environmental impact of continuous-type gas accumulations