SECONDARY NATURAL GAS RECOVERY IN THE APPALACHIAN BASIN:
Application of Advanced Technologies in a Field Demonstration Site,
Henderson Dome, Western Pennsylvania

(Contract No. DE-FC21-97FT34182)

FINAL REPORT

Submitted to

US Department of Energy
National Energy Technology Laboratory
Morgantown, WV 26507

Submitted by

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December 2000
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ABSTRACT

Two independent high-resolution aeromagnetic surveys flown by Airmag Surveys, Inc and interpreted by Pearson, de Ridder and Johnson, Inc were merged, processed and reinterpreted by Pearson, de Ridder and Johnson, Inc for this study. Derived products included depth filtered and reduced to pole maps of total magnetic intensity, vertical and horizontal gradients, interpreted STARMAG structure, lineament analysis and an overall interpretation. The total magnetic intensity patterns of the combined survey conformed reasonably well to those of coarser grid, non-proprietary regional aeromagnetic surveys reviewed. The merged study also helped illustrate regional basement patterns adjacent to and including the northwest edge of the Rome trough. The tectonic grain interpreted is dominantly southwest-northeast with a secondary northwest-southeast component that is consistent with this portion of the Appalachian basin.

Magnetic susceptibility appears to be more important locally than basement structure in contributing to the magnetic intensity recorded, based on seismic to aeromagnetic data comparisons made to date. However, significant basement structures cannot be ruled out for this area, and in fact are strongly suspected to be present. The coincidence of the Henderson Dome with a total magnetic intensity low is an intriguing observation that suggests the possibility that structure in the overlying Lower Paleozoic section may be detached from the basement.

Rose diagrams of lineament orientations for 2.5 minute unit areas are more practical to use than the full-quadrangle summaries because they focus on smaller areas and involve less averaging. Many of these illustrate a northeast bias. Where orientations abruptly become scattered, there is an indication of intersecting fractures and possible exploration interest. However, the surface lineament study results are less applicable in a practical sense relative to the seismic, subsurface or aeromagnetic control used. Subjectivity in interpretation and uncertainty regarding the upward propagation of deeper faulting through multiple unconformities, salt-bearing zones and possible detachments are problematic. On the other hand, modern day basement-involved earthquakes like the nearby 1998 Pymatuning event have been noted which influenced near-surface, water-bearing fractures. This suggests there is merit in recognizing surface features as possible indicators of deeper fault systems in the area.

Suggested future research includes confirmation of the natural mode-conversion of P-waves to down going S-waves at the level of the Onondaga Limestone, acquisition of 3-C, 2-D seismic as an alternative to more expensive 3-D seismic, and drilling one or two test wells in which to collect a variety of reservoir information. Formation Imaging Logs, a Vertical Seismic Profile and sidewall cores would be run or collected in each well, providing direct evidence of the presence of fractures and the calibration of fractured rocks to the seismic response.

If the study of these data had indicated the presence of fractures in the well(s), and efforts to calibrate from well bores to VSPs had been successful, then a new seismic survey would have been designed over each well. This would result in a practical application of the naturally mode-converted, multi-component seismic method over a well bore in which microfractures and production-scale fractures had been demonstrated to exist, and where the well-bore stratigraphy had been correlated from well logs to the seismic response.
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EXECUTIVE SUMMARY

This project was conceived and designed to test and evaluate technologies that would result in improved characterization of Lower Silurian Medina-Whirlpool fractured natural gas reservoirs in areas where field development had encountered technical barriers to production. The Appalachian Oil and Natural Gas Research Consortium worked jointly with the Texas Bureau of Economic Geology and industry partners Atlas Resources, Inc (now Atlas America, Inc) and Vista Resources, Inc to design, execute and evaluate several field tests toward this end.

The original plan called for a two-phase research effort with a decision point after Phase 1. During Phase 1, tests conducted on acreage held by Atlas Resources south of the Henderson Dome in western Pennsylvania were of two types: (1) tests whereby small-scale microfractures observed in matrix grains of sidewall cores could be scaled up to determine reservoir properties of fractures that control production; and (2) tests that verify methods whereby robust shear (S) waves can be generated to detect and map fractured reservoir facies.

The grain-scale microfracture approach to characterizing reservoir rock was developed by the Bureau of Economic Geology and field tested in the Appalachian basin during this study. As a result of the Appalachian study, a low-cost commercial method now exists that will allow Appalachian producers to use scanning electron microscope (SEM) images of thin sections cut from sidewall cores to infer the orientation, timing and density of reservoir-scale fractures. In the area south of the Henderson Dome, large quartz-lined fractures with N20E strikes, and a subsidiary set of fractures with a N70W strike, are prevalent. The SEM study also resulted in development of a degradation index for partially filled microfractures that can predict commercial versus non-commercial wells.

Two seismic S-wave technologies were developed during Phase 1. The first was a special shaped explosive package that produces more robust S-waves than do standard explosives. This would allow operators to set straight lines through heavy timber country that cannot be done with horizontal vibrators as a source of S-waves. The second S-wave seismic technology that was investigated and confirmed was the natural mode conversion of standard P-waves to robust down going S-waves at the level of the Onondaga Limestone. This was verified by recording and analyzing a 3-component vertical seismic profile (VSP) in Atlas=Montgomery no. 4 well in Mercer County, Pennsylvania. Appalachian operators can thus use converted-mode seismic technology to create S-wave images of fractured and unfractured rocks throughout the basin where the Onondaga is present.

Following the completion of Phase 1 our industry partner, Atlas Resources, was forced to withdraw from the project. Fortunately, we were able to recruit a second industry partner, Vista Resources, Inc, that held an acreage interest in the Henderson Dome area, north of the dome. Vista Resources also had flown an aeromagnetic survey of an area that partially overlapped an area flown by DOE in a prior research effort. Therefore, a decision was made to expand the subsurface study north of the dome, merge the two aeromagnetic data sets into one, generate additional maps to interpret, conduct a lineament study of a 25-quadrangle area, and write a proposal for a Phase-2 effort in the new study area.
The aeromagnetic studies were merged and interpreted, and revealed several interesting relationships between basement structure and/or lithology and shallower reservoirs and potential reservoirs in the deeper Ordovician carbonate section. The results of the lineament study proved to be less applicable in a practical sense in this area, relative to the subsurface, seismic and aeromagnetic control used.

A Phase 2 proposal was written and submitted to NETL in August 2000. The work plan initially would have focused on the confirmation of the natural mode conversion of P-waves to S-waves at the level of the Onondaga Limestone. If confirmed in this second study area, then conventional sources that generate P-waves could be used, and converted S-waves could be received and analyzed to detect fractured reservoir rock.

A second suggestion was to record, process and interpret multi-component seismic data to demonstrate how P-wave and S-wave seismic data can be integrated to improve detection of fractured facies in the Medina-Whirlpool section. This plan was developed as an alternative to a more expensive 3-D seismic program. Assuming positive results were obtained from the interpretation of the 3-C, 2-D seismic data, one or two test wells would have been drilled on separate geological features to obtain a variety of data, including Formation Imaging Logs (FMI), a Vertical Seismic Profile (VSP) and sidewall cores, to provide direct evidence of fracturing a calibration of fractured rocks to the seismic response.

If test results indicated the presence of fractures in the well bores, and efforts to calibrate from well bores to VSPs were successful, then a new seismic survey over each well would have been designed. This could result in a practical application of the naturally mode-converted, multi-component seismic method over a well bore where microfractures and production-scale fractures had been demonstrated to exist, and where the well-bore stratigraphy had been correlated from well logs to the seismic response.
SECONDARY NATURAL GAS RECOVERY IN THE APPALACHIAN BASIN:
Application of Advanced Technologies in a Field Demonstration Site,
Henderson Dome, Western Pennsylvania

by

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INTRODUCTION

The Lower Silurian Cataract/Medina Play is one of the most significant gas plays in the Appalachian basin, in terms of proven reserves, historical production, the number of producing wells, play acreage extending across three states, and estimated undiscovered resources in those states in the 3.9 to 4.3 Tcf range. Historically, reservoir targets in this play have offered low-risk, low-cost opportunities for Appalachian producers. However, after aggressive drilling and extension of the play eastward into areas where the sandstone targets are found at depths below 5,000 feet, operators are currently facing economic limitations to continued exploration and development. One of these problem areas is the acreage held in the vicinity of the Henderson Dome, a structurally-positive, geologic feature in Mercer and Venango counties, western Pennsylvania. Unusually poor productive potential has been encountered within an expanded Medina-Whirlpool section in an arcuate trend of small grabens south and west of the dome. In contrast, unusually good production has been encountered on the structurally high sides adjacent to these grabens, suggesting that permeability enhancement by faulting and graben development offers an attractive target that operators are reluctant to ignore. Thus, the high-risk area offers high rewards if all wells are successful, but even one failure can doom a 10-well program. To many operators, the increased risk of drilling sub-economic wells within the grabens outweighs the opportunity to encounter exceptional wells on the high sides of the grabens, unless new technology can better define the high potential areas.

Because of the importance of extending this play eastward through this high-risk area, the Appalachian Oil and Natural Gas Research Consortium, in partnership with Atlas Resources, Inc and the Texas Bureau of Economic Geology, entered into an agreement with the US Department of Energy to undertake a two-pronged investigation designed to extend development of this play, not only in the vicinity of the Henderson Dome, but also in similar structural settings along the eastern edge of the entire play. Using advanced technology, researchers investigated 1) how to avoid drilling sub-economic wells by identifying fracture attributes in core samples and 2) using geophysical methods to target high-conductivity fractured reservoirs.

The initial proposal and statement of work called for a Phase 1 investigation followed by a mutual decision point, and then the writing of a Phase 2 proposal, that if funded, would complete the research. The following final report will briefly summarize technical results of Phase 1 with our industry partner, Atlas Resources; include a summary of the continuation of this
effort into the area north of the Henderson Dome with a new industry partner, Vista Resources; and make reference to the Phase 2 proposal that outlined and described the future technical effort required to complete this research effort.

A complete report of the Phase 1 effort, written by the Texas Bureau of Economic Geology (Hardage, et al, 1998), was submitted in August 1998; a Phase 2 proposal outlining the extent of future work was submitted to DOE in August 2000. The focus of this report is a new effort, similar to Phase 1, in the area north of the Henderson Dome.

SUMMARY OF RESULTS, PHASE 1

Technical Barriers to Developing the Medina Play in Western Pennsylvania

Sandstones within the Lower Silurian Medina Group represent one of the largest natural gas plays in the Appalachian basin with 9.1 Tcf of proven reserves in more than 76,000 wells in Ohio, Pennsylvania and New York. Historically, these sandstones have offered low-risk, low-cost targets for Appalachian producers, and the play has moved eastward with times, deeper into the basin where production depths now exceed 5,000 feet. However, in the vicinity of the Henderson Dome in western Pennsylvania, operators have encountered areas of graben development south and west of the dome that have presented serious economic barriers to continued development. Wells drilled in a graben typically are dry or non-economic. In contrast, wells drilled on the structurally high sides adjacent to the grabens are among the most productive in the eastward extension of the play. The possibility of encountering this fault-enhanced fracture permeability on the high sides of graben-forming faults has encouraged producers to continue to develop the area rather than move along trend northeast of the dome. For this reason, the Appalachian Oil and Natural Gas Research Consortium (AONGRC), in partnership with Atlas Resources, Inc and the Texas Bureau of Economic Geology entered into a DOE-funded research project to develop core plug and seismic techniques to enhance secondary gas recovery in the area.

Technical Results

A complete summary of the Phase 1 research effort can be found in Hardage et al, 1998. However, several results are worth noting here. First, in the area of seismic research, it was determined that shaped charges can be used to generate robust seismic shear (S) waves necessary to detect and map fractured reservoir facies adjacent to the grabens. It also was determined that a natural mode conversion of down going primary (P) seismic waves to shear waves occurs at the top of the Middle Devonian Onondaga Limestone. Thus, where the Onondaga is present in the basin, this conversion can be used to detect fractured reservoirs in deeper units.

In addition to the seismic research, tests were conducted to develop a low-cost methodology whereby small-scale microfractures observed in matrix grains of sidewall cores can be scaled up to reservoir-scale fractures that control production. As a result, a low-cost commercial procedure now exists to use scanning electron microscope (SEM) images of thin sections from oriented sidewall cores to infer the spatial orientation, relative geologic timing and
population density of reservoir-scale fractures. An innovative method also was developed to
determine the stratigraphic and geographic tops of sidewall cores, which is important in
determining the direction of fracture propagation in the Medina sandstones. Finally, it was
determined that microresistivity logs or other image logs can be used to determine accurate
sidewall core azimuths as well as the precise depths of the sidewall cores.

JUSTIFICATION FOR SHIFTING RESEARCH NORTH OF THE DOME

Following the submission of the Phase 1 final report, the AONGRC prepared a plan to
enter Phase 2, which would involve additional seismic research in the area. However, when our
company partner, Atlas Resources was forced to withdraw from the project, we set out to recruit
another industry partner who had experienced similar technical barriers to the continued
development of the Medina-Whirlpool in the study area. As a result, Vista Resources, Inc agreed
to cooperate with us in a new venture north of the Henderson Dome where similar problems to
field development had been noticed while drilling development wells.

Partnering with Vista Resources offered several advantages. First, they were an active
participant in the Media play around the Henderson Dome, and they recently had hired Robert
Heim, our main technical contact with Atlas Resources, to direct their efforts in the area. And
second, Vista had contracted an aeromagnetic study over their acreage holdings, and the area
flown slightly overlapped an area where the Morgantown DOE office had obtained similar data.
Therefore, it was determined that prior to entering Phase 2, DOE would fund the merging of the
two aeromagnetic data sets into one set and an interpretation of the data, as well as a lineament
study of the area. Following this research, AONGRC and Vista would prepare a work plan for
Phase 2 involving the application of multi-component seismic to the problem area.

The merging of the aeromagnetic data resulted in a larger, more contiguous survey that
helped illustrate basement patterns adjacent to and including the northwest edge of the Rome
trough. A distinct NE-SW tectonic grain was observed, which is consistent with this part of the
Appalachian basin, along with a secondary NW-SE trend. Magnetic susceptibility seems to
dominate basement structure in contributing to magnetic intensity based on seismic to
aeromagnetic data comparisons made to date. However, significant basement structures are not
ruled out for this area due to the currently limited seismic line control. A comparison of the
aeromagnetic data with additional seismic data is considered vital. Aeromagnetic anomalies,
along with other data, will be used to high-grade areas for future seismic acquisition. The
coincidence of the Henderson Dome with an aeromagnetic low is an intriguing observation that
warrants additional investigation. VISTA was able to import the aeromagnetic data into a GIS
format for further study.

Mammoth Geophysical performed the surface lineament study of high altitude infrared
photographs and digital elevation models obtained from the United States Geological Survey
(USGS). The study was conducted on a 25-quadrangle area at a 1:2000 scale, an area that far
exceeds the size of the 9-quadrangle study area. Interpretations were made independently from
the two separate types of medium, and gave slightly differing results due to a bias imparted by
the tonal colors due to vegetation. Lineaments were digitized and rose diagrams were generated
to illustrate frequency and orientation for every 2.5 minute area in the 25-quadrangle area.
Summary diagrams were prepared for each 7.5 minute quadrangle, and again for the entire 9 quadrangle aeromagnetic data area.

A full report on the technical results of this effort, complete with attachments and supporting documentation, follows.

AEROMAGNETIC DATA COMPILATION AND SEISMIC REPROCESSING CONDUCTED NORTH OF THE HENDERSON DOME

Introduction

In conjunction with a multi-phased exploration plan focusing on Mercer County, Pennsylvania, Vista Resources, Inc. received DOE funding to conduct tasks directed toward high-grading sites for the probability of fault related fracturing in multiple potential reservoirs. These steps were preliminary to a larger proposed project that, if funded, would have involved field testing promising multi-component (shear wave) seismic techniques for fracture identification. Such techniques were identified in an earlier pilot study conducted in 1997 under this contract. This report summarizes the more recent work conducted by Vista with DOE support. The activities discussed were reconnaissance in nature and include aeromagnetic surveying, surface lineament interpretation and the purchase and reprocessing of an existing seismic line. The project area is illustrated in Attachment 1. Following identification of leads based on this and other reconnaissance work, industry partner Vista Resources, Inc. has plans to independently acquire new seismic over high-graded sites. Drilling will be contingent on the results of initial and subsequent confirmation phases of seismic acquisition.

Geological Setting

The Lower Silurian rock units, including the Medina and Whirlpool sandstones, comprise the primary development reservoirs in the area. A general description of the Lower Silurian geology of the Mercer County, Pennsylvania area is provided in Attachment 2. The structurally anomalous Henderson Dome is located within the central portion of the study area. Gas was produced from wells drilled on this feature to Upper Devonian Venango Group sandstones prior to their conversion to storage. Deeper production has been established in the Upper Silurian Lockport Dolomite. Scattered production from Mississippian sandstones, including the Berea Sandstone, also occurs in the surrounding area. Nine penetrations of the deeper Cambrian-Ordovician section, including two basement tests, are located within or adjacent to the area of interest. Slight shows of gas and shows of water have been reported with no commercial production from these deeper intervals to date. An aeromagnetics-oriented discussion of the basement rocks through Upper Silurian strata is presented in Attachment 3.

Quaternary glaciation in northwestern Pennsylvania as portrayed in Attachment 4 is relevant to the 25-quadrangle surface lineament interpretation that was conducted. Within the eastern and southeastern portions of the study area, northeast-trending deposits of Pre-Illinoian
 (>770,000 years) till covering up to 10% of the ground are displayed. Topography reflects the underlying bedrock. Late Illinoian (132,000 - 198,000 years) till covering 10% to 25% of the ground was deposited in a northeast-oriented trend that is displaced to the northwest of the older deposits described above. Topography reflects the underlying bedrock in this area as well. Within the remainder of the study area, Wisconsin-aged till (17,000 - 22,000 years) covering 75% of the ground is present. Terrain for this region typically is gently undulating, although there is some knob-and-kettle topography. Superimposed on the laterally extensive Wisconsin till are generally northwest-oriented deposits of stratified drift composed of sand and gravel that is found principally in valleys. The recent Wisconsin-aged glaciation presumably altered and added surface features while masking some tectonically-controlled lineaments prior to the Holocene Epoch, the current interglacial period that started about 10,000 years ago. On the other hand, prominent drift-filled drainage patterns may coincide with significant cross-striking tectonic elements.

Aeromagnetic Data Compilation

General

An important product of this study was the merging of two independently-flown, high-resolution areomagnetic surveys. Airmag Surveys, Inc. of Philadelphia, Pennsylvania flew the surveys in 1997 and 1998 on 3 mi. x 2 mi. and 3 mi. x 3 mi. flight line spacing, respectively. The original data were processed by Pearson, de Ridder and Johnson, Inc. (PRJ) of Lakewood, Colorado, who then merged the two surveys in 1999. Derived products included depth filtered and reduced to pole maps showing total magnetic intensity (Attachment 5), vertical and horizontal gradients, interpreted STARMAG structure, lineament analysis and interpretation. A report also was provided for which the Table of Contents is included (Attachment 3). The two surveys totaled 2,790 flight line miles with approximately one third overlap. A summary of design parameters of each survey is provided (Attachment 3). The combined aeromagnetic data set and its derivative maps are discussed in detail (Attachment 3). Interpretation of the resulting products requires awareness that independent variables of basement rock magnetic susceptibility, structural relief and geometry cause the magnetic intensity variations observed and also presumes cultural and shallow topographic influences were successfully removed.

PRJ presents report states that previous work in the Appalachian basin has demonstrated correspondence between magnetic strike, basement lithologic contacts, and mapped faults that often crosscut the entire Lower Paleozoic column and extend into the basement. It is further noted that Paleozoic reservoirs are frequently associated with faults localized on edges of magnetic highs. Fracturing related to basement-involved faulting is known to enhance reservoir quality in many plays, including those historically productive and others with potential in the current project area. Therefore, understanding the tectonic fabric of the basement rocks and delineating potentially fault-bounded basement block contacts are desirable early steps prior to acquiring more expensive seismic surveys.

Technique Used and Technical Challenges Faced in Merging Aeromagnetic Surveys
The two surveys were flown by the same company with the same aircraft. The specifications of the survey were similar, except the DOE survey was flown on north-south and east-west sets of flight lines, whereas the Vista survey was rotated 45 degrees from the cardinal directions. The most important variable, however, was that the surveys were flown at the same elevation. This is important, as the frequency content of an aeromagnetic survey decreases if the plane operates higher off the ground. Because of the similarities in acquisition parameters, the merge was a relatively painless one. A merge was not performed on the two gridded data sets.

The integration of the two data sets was undertaken on a profile basis. A constant level shift was applied to the northern survey and both profile data sets were then combined into one large file. The area of overlapping data was large and approximated a triangular area 11 x 14 miles in size. Within this triangle, a very dense network of line intersections occurred. Locally, these intersections are very closely spaced. As even very small level differences between these tightly-spaced intersections can cause significant gridding problems, editing of the line intersections was required before a final grid was produced. The most common sources for these mis-ties were cultural anomalies. These very-high frequency anomalies typically appear only on one or two flight lines. Because of the number of flight lines that sometimes intersect in the merged area, this causes the line that the cultural anomaly is on to have a different magnetic reading than all of the other lines. When you try to grid all of the data together, the result is a data spike that smears over a larger area. Over the entire merge, the pattern appears as a series of points that reflect many of the grid nodes.

The solution to the problem is to take advantage of the very high-frequency source of the problem. Since the point cultural anomalies all have a wavelength shorter than 400 meters, the two data sets were merged and gridded as one large survey. A high-cut filter that removed all anomalies with wavelength shorter than 400 meters was then applied. An analysis of the local geology and the frequency spectrum of the survey indicated that no relevant geologic signal would be eliminated by this approach. It should be noted that because of the depth of the basin this approach was possible. This type of approach would be inappropriate if the source were closer to the surface, or if the basement cropped out close to the survey area. In any geologic problem, it is critical to have a basic understanding of the geometry of the source bodies before applying any type of filter to the area.

Comparison of Aeromagnetic Survey and Seismic Survey Results

A 9.5 mile long, east-west oriented Vibroseis line (P-6N Extension) recorded for PeopleNatural Gas Company by Western Geophysical in 1974 was purchased from GeoData Corporation of Tulsa, Oklahoma and reprocessed by Custom Geophysical Services, Inc. of Denver, Colorado. Attachments 6a and 6b indicate the recording parameters and reprocessing sequence. Vista created a synthetic seismogram from the velocity log of an older basement well drilled 200 feet off this line.

Correlation of the synthetic seismogram to P-6N Extension allowed one to identify the basement surface on the seismic. Discontinuous events (ranging from 1.24 seconds to 1.32 seconds) appear across the line, suggesting stratigraphic truncations at the basement surface.
Otherwise, there is minimal current-day structure suggested at the top of the basement, except for a gentle regional dip. A deeper basement feature, however, visible between 1.4 and 2.1 seconds, suggests a Grenvillian limb dipping more abruptly in an apparent eastward direction.

Coincident with the abrupt change in attitude of this deeper basement feature is a northeast-trending aeromagnetic anomaly that is particularly evident on three derivative maps created from the aeromagnetic data set. These anomalies appear on the horizontal gradient, STARMAG structure and vertical gradient maps. While parallel, these map trends are progressively offset to the southeast and correspond to different positions on the Grenvillian structure identified on the seismic line.

A tentative interpretation is that this Grenvillian basement feature was a northwest-projecting thrust limb. Subsequent movement along the foot wall in response to tension and compression of later tectonic events may have projected stresses through the overlying stratigraphic section. Another seismic line in the area suggests a vertically uplifted basement surface and an overlying flexure in the strata that appear to be on trend with this Grenvillian feature.

Across the feature described above, magnetic intensity increases over the adjacent lower block, apparently due to its higher magnetic susceptibility. The anomalies on the derivative maps mentioned above are, therefore, caused chiefly by juxtaposition of rocks of different magnetic susceptibilities, rather than as a result of basement relief in this example. While the STARMAG neural network is purported to recognize residual basement structures given proper assumptions and input, in this case this product interpreted a basement structural high that was actually low according to the seismic interpretation.

Consequently, the authors feel that structural interpretations from this product should be avoided until calibrated locally to seismic or subsurface control. After such calibration and assessment, the various aeromagnetic derivative maps provided appear to be effective tools for projecting the strike of corresponding basement-involved seismic features.

Jump correlating from the P-6N Extension seismic line previously mentioned southeastward to other seismic control indicates that the basement dips regionally to the southeast in eastern Mercer County and western Venango County. Although it is complicated by various superimposed anomalies, there is a coincident gradient of increasing aeromagnetic intensities displayed in the southeast direction as well. Again, the implication is that magnetic susceptibility rather than structural position dominates the magnetic response in the merged survey. If the basement rock type was a constant, magnetic intensity would diminish rather than increase as the depth to basement becomes greater to the southeast.

One very unexpected result of the aeromagnetic survey was the observation of a pronounced eastward projecting nose of low magnetic intensity that directly coincides with the Henderson Dome. Possible explanations for this occurrence include (1) an underlying high basement block with very low magnetic susceptibility relative to the surrounding basement, (2) an underlying basement block flat to surrounding basement and having relatively low magnetic susceptibility, or (3) an underlying basement block that is structurally low, yet has magnetic susceptibility similar to surrounding basement. Explanations (2) and (3) would require a deep detachment to allow for a dome-like anticline in the Paleozoic strata over a basement that was
not uplifted.

Conclusions

The merging of the two high-resolution aeromagnetic sets resulted in a survey of greater size and provided continuous data throughout the area of interest, serving as a foundation for subsequent work. The total magnetic intensity patterns of the combined survey conformed reasonably well to those of coarser grid, non-proprietary, regional aeromagnetic surveys reviewed. The merged survey helped illustrate regional basement patterns adjacent to and including the northwest edge of the Rome Trough. The tectonic grain interpreted is dominantly southwest-northeast and secondarily northwest-southeast in keeping with what would be expected in this part of the Appalachian basin.

Magnetic susceptibility appears to be more important locally than basement structure in contributing to the magnetic intensity recorded. This statement is based on seismic to aeromagnetic data comparisons made to date that are admittedly limited due to the gaps in seismic coverage. Significant basement structures are not ruled out for this area and are in fact strongly suspected. The coincidence of the Henderson Dome with a total magnetic intensity low is an intriguing observation that suggests the possibility that structure in the overlying stratigraphic section may be detached from the basement.

Our evaluation has reinforced the awareness of limitations in the interpretation of basement structural relief from aeromagnetic data alone. On the other hand, coincidence observed between features identified in subsurface data, seismic control and aeromagnetic derivative maps suggest that certain aeromagnetic anomalies in this study are responses to real geological changes in the basement. Where so calibrated, this magnetic survey has been utilized with greater confidence and has significantly biased the design of new seismic acquisition plans. The orientation of the aeromagnetic anomaly in one lead area, for example, helps project the strike of a flexure observed on existing 2-D seismic that is associated with offset along a basement block boundary. Associated faulting and fracturing of potential reservoirs may exist along such trends.

SURFACE LINEAMENT ANALYSIS NORTH OF THE HENDERSON DOME

General

In contrast to the previously discussed aeromagnetic study where delineating fault-bounded basement blocks was the goal, the goal of the lineament analysis task was to identify possible surface expression of stresses related to deeper faulting. In concept, the aeromagnetic survey and surface lineament analysis provide bracketing control on fracture systems that are being viewed (depth wise) in a more intermediate sense by both seismic interpretation and well control-based subsurface investigation.

Technique
Mammoth Geophysical of Barrackville, West Virginia conducted the surface lineament study by analyzing digital elevation models (DEMs) and by stereoscopic interpretation of infrared National High Altitude Photographs (NHAPs). This study was conducted over a 25-quadrangle area intentionally extended beyond the limits of the aeromagnetic survey for regional context. Working from these two sources, interpretations were performed independently and transferred to standard topographical quadrangle base maps. A two-color scheme was used for these lines to indicate the source from which the interpretations were made.

For a centrally-located, nine-quadrangle area that included the extent of the aeromagnetic survey, lineaments were digitized and rose diagrams were created from the digitized data to illustrate lineament frequency and orientation. Rose diagrams summarizing interpreted lineaments were provided as a composite for the full nine-quadrangle area and individually for each 7.5-minute quadrangle and each 2.5-minute area. This was accomplished for both the DEM- and NHAP-sourced interpretations.

Based on conversations with Eb Werner of Mammoth Geophysical, identification of visibly continuous features and strings of aligned points were interpreted at a scale of 1:80,000 on both the DEM and NHAP media. As a result of the scale used, features less than 1 mile in length were rarely interpreted. Interpreted features were not field checked.

Discussion

A commonly quoted rule of thumb is that lineaments are considered significant only if they are as long as the drilling target is deep. In the central portion of the project area, Lower Silurian through Cambrian intervals of interest range in depth from 5,000 to 10,000 feet. Upon initial observation of the interpreted quadrangles, it was obvious that prominent northwest-trending stream valleys, apparent cross-strike discontinuities with speculated strike-slip character, were not interpreted as lineaments. These wider, drift-filled stream valleys did not fit the interpreter’s criteria for being a lineament. Satellite images or SLAR may have resulted in a different result due to their perspective and scale. Such media were not selected due to their higher cost. In hindsight, however, these images may have been more appropriate for use in this project.

In general, numerous lineaments were interpreted on all quadrangles. DEM and NHAP lineaments frequently did not coincide. DEM interpretations are linked to the geomorphology since the images are the topography stripped of cultural features. Artificial sun angles were applied to the DEMs to throw shadows that increased visual contrast and facilitated interpretation. NHAPs, on the other hand, being photographs, are subject to variations in reflected light caused by moisture and vegetation patterns.

The rose diagrams constructed to characterize the interpretive work resemble radial histograms with all lineaments of the same azimuth summing to create longer petals. For example, three one-mile lineaments oriented north-south would appear the same as one three-mile lineament with the same orientation. Rose diagrams based on the DEMs and the NHAPs summarizing the central nine-quadrangle area are provided as Attachments 7a and 7b respectively. The DEM summary illustrates dominant strike trends clustered between N23E and N73E. Secondary dip trends cluster between N18W and N62W. Compiled DEM lineament
interpretations along the dip azimuths are approximately 1/3 to 2 the length of those compiled along strike orientations. The NHAP summary for the nine quadrangle area shows strike trends clustered between N23E and N68E. Dip trends for the NHAP lineament interpretations cluster between N17W and N57W and, in contrast to the DEM summary, are similar to the strike trends in abundance and magnitude.

Within the strike and dip clusters, orientations for the NHAP-based interpretations had 4-5 degrees less divergence than those based on DEMs. Perhaps more noteworthy was the more frequent interpretation of dip-oriented lineaments using the NHAP source rather than the DEM source. The variation may be related to the fact that the photographic (NHAP) approach potentially detects moisture differences in the soil overlying fractures in contrast to areas that do not overly fracture traces. The DEM interpretation, on the other hand, is more geomorphically biased. Rose diagrams summarizing each of the nine individual quadrangles also are presented as Attachment 8a (DEM interpretations) and Attachment 8b (NHAP interpretations).

Hydrological effects described (Attachment 9) following the Pymatuning Earthquake of September of 1998 seem to support the relationship between tectonic movement and very shallow fractures. The epicenter of this 5.2 magnitude earthquake, the largest ever recorded in Pennsylvania, was placed northeast of Jamestown in southwestern Crawford County, immediately northwest of the 25-quadrangle study area. The quake was felt over a 125,000 square mile area and had an epicenter depth of approximately 3 miles, or 1.5 miles below the estimated top of basement. North of Greenville, in Mercer County, water wells located along a narrow ridge bordered by the Shenango River on the west, Crooked Creek on the east, and the Little Shenango River on the south went dry immediately after the earthquake. This was accompanied by increased discharge in wells and springs along the flanks of this ridge which had approximately 250 feet of relief. One hypothesis is that the earthquake created new or opened old fractures increasing the downward permeability of the bedrock to water.

The northwestward course of a prominent drainage pattern more centrally located within the study area aligns with a similarly oriented aeromagnetic lineament. Alignment of this stream segment and the aeromagnetic lineament suggest truncation of the northeast strike of a subtly uplifted structural block. This block exhibited displacement of the basement on seismic and timing at least as recent as Upper Mississippian based on bedrock mapping.

The possibility of salt tectonism is a concern in considering the relatedness of surface features to faults cutting deeper strata and/or the basement. Upper Silurian-aged Salina Group units A through G are present and span a 800-foot interval in a typical well in the center of the study area. In this well, 30% of the Salina beds are salt, with individual salt units up to 60 feet in thickness, based on log interpretation. Rapidly varying thicknesses of individually correlated Salina units has been observed in the detailed subsurface study conducted by Vista in the project area. Closely related to the variable of salt tectonism is the possibility of detachment zones and the potentially complex and non-vertical interplay between movements of basement and/or deeper Paleozoic section and faults expressed at the surface.

Conclusions

A tangible benefit from the surface lineament study was simply obtaining the individual
Digital Elevation Model (DEM) for each of the 25 quadrangles involved. Compiled into a mosaic, the DEMs provided a regional image of the ground surface. Their digital format allowed for scale adjustments and integration with other project maps manipulated in GeoGraphix. The digitized lineaments from DEMs and NHAPs can likewise be transferred to Vista=.digital data base.

The rose diagrams described previously were created to summarize the interpretive results and for reporting purposes. The rose diagrams for the 2.5-minute unit areas (81 in total) are more practical to use than the full-quadrangle summaries since they focus on smaller areas and include less averaging. Many of these 2.5-minute summaries illustrate a northeast bias. Where the orientations abruptly become scattered, there is a suggestion of intersecting fractures and possible exploration interest. Mammoth Geophysical has the ability to generate rose diagrams for any arbitrary lead area within the nine quadrangles digitized.

Overall, the surface lineament study results have been less applicable in a practical sense in this project than the seismic, subsurface, or aeromagnetic control utilized. Subjectivity in interpretation and uncertainty regarding the upward propagation of deeper faulting through multiple unconformities, salt zones, and possible detachments are problematic. On the other hand, modern day basement-involved earthquakes such as the nearby 1998 Pymatuning occurrence have been noted which influenced near-surface water-bearing fractures. This suggests merit in recognizing surface features as possible indicators of deeper fault systems within the project area, in spite of the significant percentage of the ground that is covered by recent glacial deposits.

CONCLUSION: SUGGESTED FUTURE RESEARCH

Vista Resources continues to analyze and interpret data generated in this project, even though it was of relatively short duration and did not lead to a Phase 2 award. Now that they have succeeded in importing the aeromagnetic data into a GIS format, additional interpretations can be made by integrating magnetic data with other data. Vista stills believes that the plan proposed for Phase 2 was technically solid, and has much to offer independent operators. Thus, our suggestions for continued research in this area are those expressed in our Phase 2 proposal submitted in August 2000. Details can be found in the proposal, so only a brief summary will be included here.

The Phase 2 work plan initially would have focused on confirmation of one important observation made during Phase 1: that down going P-waves are naturally converted to S-waves at the top of the Onondaga Limestone. If this could be confirmed, then sources that generate shear waves are not essential; conventional sources that generate P-waves could be used, and converted shear waves could be received and analyzed to detect fractured reservoirs.

A further suggestion was to record, process and interpret multi-component seismic data to demonstrate how P-wave and S-wave seismic data can be integrated to improve detection of fractured facies in the Medina-Whirlpool section. This plan was developed as an alternative to a more expensive 3-D seismic approach. If successful, 3-D seismic would not be necessary to obtain similar results. Our suggested approach would be to acquire, process and interpret 3-C, 2-D seismic data to determine if naturally converted S-wave data can be recorded in useable form,
as was suggested in Phase 1.

Assuming positive results were obtained from the 3-C, 2-D data and prospects were identified, one or two test wells would have been drilled on separate geological features to obtain a variety of data, including Formation Imaging Logs (FMI), sonic logs, a Vertical Seismic Profile (VSP) and sidewall cores. FMI logs and core data would provide direct evidence of fracturing, whereas sonic logs and VSP data would allow calibration of fractured rocks to the seismic response.

If the results of the study of well data indicated the presence of fractures in the well bores, and efforts to calibrate from well bores to VSPs were successful, then a new seismic survey would have been designed to include each well drilled and tested. This could result in a practical application of the naturally mode converted, multi-component seismic method over a well bore where microfractures and production-scale fractures had been demonstrated to exist, and where the well-bore stratigraphy had been correlated to the seismic response.

REFERENCES CITED

ATTACHMENTS

Attachment 1: Project Index Map
Attachment 2: Excerpts from the Final Report for Phase 1
Attachment 3: An Aeromagnetic Basement Interpretation of the Area
Attachment 4: Map of Glacial Deposits in Pennsylvania with Lineament Study Area
Attachment 5: Aeromagnetic Survey (Total Magnetic Intensity) with County Outlines
Attachment 6: Recording Information and Processing Sequence, Line P6N
Attachment 7: Rose Diagrams for Lineaments Derived from DEGs and NHAPs
Attachment 8: Rose Diagrams for Lineaments for each of Nine Quadrangles
ATTACHMENT 1:

PROJECT INDEX MAP
ATTACHMENT 2:

EXCERPTS FROM THE FINAL REPORT FOR PHASE 1
"Secondary Natural Gas Recovery in the Appalachian Basin: Application of Advanced Technologies in a Field Demonstration Site, Henderson Dome, Western Pennsylvania"

Hosted by:

Appalachian Region PTTC Resource Center
Texas Region PTTC Resource Center
Pittsburgh Association of Petroleum Geologist
Appalachian Oil and Natural Gas Research Consortium

November 19, 1998

Pittsburgh Marriott Green Tree
Pittsburgh, Pennsylvania

PTTC is primarily funded by the U.S. Department of Energy, Office of Fossil Energy through the National Petroleum Technology Office and Federal Energy Technology Center.
sandstones. In addition, it may be possible for seismic-attribute analysis to identify Cataract/Medina fracture trends in the Henderson Dome region. Natural-gas plays throughout the Appalachian Basin where surface seismic technologies will be applied will also benefit from improved techniques for near-surface velocity corrections that are necessary due to variations in glacial-till thickness.

Geologic Setting

The Lower Silurian strata in the Appalachian Basin are known by several stratigraphic names: the Clinton Group (Kentucky), the Clinton and Cataract Group (Ohio), and the Cataract Group (Ontario). In Pennsylvania and New York, equivalent rocks are included within the Medina Group (Piotrowski, 1981). Unfortunately, Cataract/Medina Group sandstones are widely known as “Clinton” by Appalachian operators as a result of miscorrelations that occurred during the early development of the gas play (McCormac and others, 1996). The Medina and Cataract Groups are subdivided as follows (in ascending order): Whirlpool Sandstone, Cabot Head Shale, Grimsby Sandstone, and Thorold Sandstone (figs. 3 and 4). In the Henderson Dome region, the gas-producing units are the Whirlpool, Grimsby, and Thorold. Drillers in the producing area commonly refer to the Grimsby and Thorold Sandstones as the White Clinton and Red Clinton sandstones, and the Stray Clinton sandstones, respectively (fig. 3). The Whirlpool unconformably overlies the Upper Ordovician Queenston Shale, and the top of the Medina Group (Thorold Sandstone) is also marked by a hialtal depositional surface (fig. 3).

Although regionally within the Appalachian Basin the Whirlpool Sandstone is divided into three major lithofacies (sandstone, calcareous shale, and dolostone), the sandstones facies dominates in Pennsylvania, New York, and Ontario (Coogan, 1991). In these areas, the sandstone is inferred to have originated as a transgressive marine sheet sand (Martini, 1971; Kearney, 1983). The lower part of the Whirlpool in Pennsylvania records a braided-river environment of deposition, whereas the upper part is interpreted as marine wave-dominated nearshore deposits.
<table>
<thead>
<tr>
<th>SYSTEM</th>
<th>UNIT</th>
<th>DRILLERS' TERMINOLOGY</th>
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</thead>
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<td>Queenston</td>
</tr>
<tr>
<td>Silurian</td>
<td>Whirlpool Sandstone</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Cabot Head Shale</td>
<td>&quot;Medina&quot;</td>
</tr>
<tr>
<td></td>
<td>Medina Group</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Shinarick Formation</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Stray &quot;Clinton&quot;</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Red &quot;Clinton&quot;</td>
<td></td>
</tr>
<tr>
<td></td>
<td>White &quot;Clinton&quot;</td>
<td></td>
</tr>
</tbody>
</table>

**Figure 3.** Generalized stratigraphic column of Silurian strata in west-central Pennsylvania.

**Figure 4.** Representative well log of the study area (Atlas Lucas No. 1 well).
(Zagorski, 1991; Cheel and Middleton, 1993). Overlying Grimsby and Thorold reservoir sandstones (Stray, Red, and White Clinton) were deposited in a complex deltaic to shallow-marine environment during an overall regressive depositional stage (Overbey and Henniger, 1971).

The Cataract/ Medina Group play occurs on the northwest flank of the Appalachian Basin in northeast Kentucky, east Ohio, northwest Pennsylvania, west New York, and southeast Ontario. Throughout the play, the trapping mechanism is primarily stratigraphic, although subtle structure also has considerable influence on gas production in some fields (McCormac and others, 1996). Structures identified in the Henderson Dome area record basement-involved faulting along SW-NE structures such as the Rome Trough that roughly parallel the basin trend as well as cross-strike discontinuities related to the Taconian Orogeny. Wrench faulting is probably the source of the subtle local structural patterns. The basement faults were probably reactivated during the Appalachian Orogeny, and again during the opening of the Atlantic Ocean basin in the Late Triassic/Early Jurassic. A mantle hot spot may have existed near the study area during the Late Triassic/Early Jurassic (Crough and others, 1980; Parrish and Lavin, 1982) that could be related to the emplacement of two kimberlite pipes near the study area. An arcuate graben trend has been detected in the subsurface near Henderson Dome (Atlas Resources, 1997). Major vertical displacements are not observed on faults here, but compartmentalization of the reservoir is likely, as deduced from production data. Fracturing associated with the faulting is probably a control on local reservoir quality in the Henderson Dome area, both in terms of the fracture density and fracture porosity and permeability.
ATTACHMENT 3:

AEROMAGNETIC BASEMENT INTERPRETATION

OF THE AREA
AN AEROMAGNETIC BASEMENT INTERPRETATION OF AN AREA OF NORTHWESTERN PENNSYLVANIA (INTEGRATED DATA SETS)

for:

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September, 1999
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I. INTRODUCTION

In July of 1999, Pearson, deRidder and Johnson, Inc. (PRI) of Lakewood, Colorado, was engaged by Vista Resources, Inc. of Pittsburgh, Pennsylvania, to merge and interpret two aeromagnetic data sets over a portion of western Pennsylvania. The aeromagnetic data were acquired by Airmag Surveys, Inc. of Philadelphia, Pennsylvania. Figure 1 shows the area covered in this interpretation. The study area extends from about 41°07'30" North to 41°30' North, and 80°20' West to 79°52'30" West.

The scope of the study included a comprehensive interpretation of aeromagnetic data in both 2-D profile and 3-D map forms. In particular, the neural network magnetic basement mapping technique, STARMAGSM, was applied to the aeromagnetic profile data to enhance and identify basement structures that produce subtle, but identifiable, anomalies.

The aeromagnetic profiles for the northernmost survey were flown on an northeast-southwest/northwest-southeast orthogonal grid; flight lines at ¼-mile spacing were oriented NE-SW and tie lines at ½-mile spacing were oriented NW-SE. The data set was flown at an altitude of 500 feet above ground level. The second survey was flown at ¼-mile x ¼-mile on a north-south and east-west grid.

The merging of the two existing interpretations was undertaken to identify basement related structures which may have influenced patterns of deposition in the overlying stratigraphic column, with the goal of identifying basement responses in an area of known production; and to find analogous responses elsewhere in the study area.
II. SURVEY SPECIFICATIONS AND DATA INTEGRATION

*Vista survey*

Contractor: Airmag Surveys, Inc.
Philadelphia, PA

Date of survey: 1997
Line spacing: ¼-mile x ¼-mile
Flight line course: NE-SW
Tie line course: NW-SE
Flight altitude: 500 feet above ground level
Sample Rate: 0.25 second
Line mileage: 1,350 line miles
Navigation: Differential GPS
Instrumentation: High-sensitivity optically-pumped magnetometer

*DOE survey*

Contractor: Airmag Surveys, Inc.
Philadelphia, PA.

Date of Survey: 1998
Line spacing: ¼ X ¼ mile
Flightline Course: N-S
Tie line course: E-W
Flight altitude: 500 feet above ground level
Sample Rate: 0.25 second
Line mileage: 1,440 line miles
Navigation: Differential GPS
Instrumentation: High - Sensitivity optically - pumped magnetometer

The integration of the two data sets was undertaken on a profile basis. A constant level shift was applied to the northern survey, and both profile data sets merged to form a single data base.

The area of overlapping data is quite large, and form a rough triangle some 11 x 14 miles in size. Within this area, a very dense network of line - intersections is located, which locally are very closely spaced. An example is the group of six intersections common to lines 170 and 1290 of the southern survey with lines 1490 and 10900 of the northern survey, which are all located within 50 feet of each other. As even very small level differences between these closely-spaced intersections can cause significant gridding problems, major editing of line intersections was undertaken before a final grid was produced.
III. AEROMAGNETIC DATA SET AND DERIVATIVES

In oil and gas exploration, magnetic methods have been used both to determine the depth to basement in new or unexplored basins and to map positive basement features that affect the depositional patterns of overlying strata (Dobrin and Savit, 1988). Magnetic data are very useful for determining basement structure because the Precambrian has, in most cases, a measurable magnetic response, while the overlying stratigraphic section is mostly non-magnetic. This is due to the presence, or absence, of magnetic minerals in the composition of these rocks. As a result, magnetic surveys can, in many cases, effectively see through the stratigraphic column.

Magnetic responses are created as a result of the magnetic susceptibility of minerals in a body of rock. The susceptibility of a body is a measurement of the degree to which it is magnetized by the earth's field (Nettleton, 1976). Magnetic susceptibility is the critical parameter in magnetic prospecting, just as density is the critical parameter in gravity prospecting. While many minerals possess a measurable magnetic susceptibility, only a few possess significant ones. Of these minerals, the most important is magnetite, while to a lesser extent, pyrrhotite and ilmenite can also be significant. The magnitude of an anomaly is determined by the composition of the causative geologic body. Since different rock types have varying amounts of these magnetic minerals, it follows that certain rock types will display observable magnetic responses while others will not. Table 1 lists the calculated susceptibilities of many common rocks. As can be seen, there is both a great amount of variation for a given type of rock, as well as a significant amount of overlap between different types. However, Figure 2 shows that four different types of rocks, there exist recognizable distinctions. For example, basic and ultrabasic igneous rocks usually possess susceptibilities two or three orders of magnitude greater than sedimentary rocks.

The susceptibility variations within basement, however, are not the only factors in quantifying magnetic anomalies. In a geologic body, increasing the susceptibility only increases the amplitude of an anomaly. Magnetic anomalies are also dependent upon the strike, dip, depth, and shape of a body. Additionally, the inclination and declination of the earth's field will affect the response (Vacquier et al., 1963). Consequently, by combining these different attributes with available geologic control, it is possible to interpret magnetic fields.

Several derivative maps of the total magnetic intensity were created and used in the analysis of the data and are discussed hereunder. A summary of these maps is given in Table 2.
Figure 2. Average magnetic susceptibilities for surface samples and cores
<table>
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<th>Material</th>
<th>Minimum</th>
<th>Maximum</th>
<th>Average</th>
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<td>Quartz porphyries</td>
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<td>7.4</td>
<td>22.000</td>
<td>3.45</td>
<td>10.400</td>
<td>2.44</td>
<td>4200</td>
<td>1.2</td>
<td>7.4</td>
</tr>
<tr>
<td>Peridotites</td>
<td>1.6</td>
<td>7.2</td>
<td>22.000</td>
<td>4.60</td>
<td>13.800</td>
<td>1.31</td>
<td>1800</td>
<td>1.6</td>
<td>7.2</td>
</tr>
<tr>
<td>Basalts</td>
<td>2.3</td>
<td>8.6</td>
<td>26.000</td>
<td>4.76</td>
<td>14.300</td>
<td>1.91</td>
<td>2600</td>
<td>2.3</td>
<td>8.6</td>
</tr>
<tr>
<td>Diabases</td>
<td>2.3</td>
<td>6.3</td>
<td>19.000</td>
<td>4.35</td>
<td>13.100</td>
<td>2.70</td>
<td>3600</td>
<td>2.3</td>
<td>6.3</td>
</tr>
</tbody>
</table>

Table 1. Calculated susceptibilities (Slichter's method) of rock materials
TABLE 2. Summary of maps derived from the total magnetic intensity

<table>
<thead>
<tr>
<th>MAP</th>
<th>PURPOSE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reduction to pole (RTP)</td>
<td>Removes effects of inclined magnetic field;</td>
</tr>
<tr>
<td></td>
<td>positions anomalies more correctly over causeative bodies</td>
</tr>
<tr>
<td>Horizontal gradient (HG)</td>
<td>More accurately defines basement lineations,</td>
</tr>
<tr>
<td></td>
<td>faults, and different provinces</td>
</tr>
<tr>
<td>High pass of magnetics</td>
<td>Identifies basement structures and/or intrasedimentary sources</td>
</tr>
<tr>
<td>Low pass of magnetics</td>
<td>Identifies lithology contacts of magnetic bodies</td>
</tr>
<tr>
<td>Vertical Gradient (VG)</td>
<td>Attenuates regional anomalies</td>
</tr>
<tr>
<td><strong>STAR MAG</strong>™ neural network analysis</td>
<td>Recognizes magnetic anomalies of structural origin</td>
</tr>
</tbody>
</table>

A brief discussion of each of the maps presented with this report is presented hereunder:

A. Flightline location maps

This map shows line identifiers and fiducials (time marks) along profile. Line spacing and location was generally well maintained for both surveys, and no crossing lines are present. Local irregularities and minor deviations in the plotted flight path are due to short term loss of GPS satellite configuration. These could quite easily have been removed by interpolation techniques, but as most are smaller than the grid spacing and did not degrade data quality, they were left in the line locations.

B. Total Magnetic Intensity (TMI) Map

This map is presented as a color shadow graph with a contour interval of 2nT, and shows a magnetic relief of some 650 nT across the map. A strongly positive response, generally north to northeasterly - trending, characterizes the eastern half of the survey area, while more negative responses are present in the western half. Areas of strong positive anomalies are areas likely containing locally higher susceptibility Precambrian rocks. Similarly, the large, broad magnetic lows are likely areas of lower susceptibility Precambrian rocks. While these broad magnetic highs and lows probably result mostly from lithologic variations in basement, a degree of structural variation may also be present in these anomalies, primarily near the lithologic contacts. It is certain, however, that the biggest anomalies are not caused exclusively by suprabaseinent features, as the lateral and vertical constraints of such a structure are not supported by other data.
C. Reduction-to-Pole (RTP) Map

Unlike gravity anomalies that are primarily located over their causative bodies, magnetic anomalies are dependent upon their directions of magnetization and on the direction of the earth's regional field. Reduction to the pole filtering removes the directional dependency of the earth's field and transforms an anomaly into the one that would be observed with vertical magnetization. As a result, reduction to the pole filtering removes asymmetries caused by the non-vertical inducing field and moves the anomalies to a position more directly over their causative bodies, thus facilitating the integration of seismic and gravity data with the magnetic data set. The reduction to the pole operator has shifted the larger magnetic responses northwards as much as several hundred feet. Additionally, linear features and contacts are better defined. For this study, the earth's principal magnetic elements that are accounted for in the reduction to pole filter are:

Total Intensity: 55,450 nT
Declination: 9.2° east of north
Inclination: 69.8° down to the north

D. Horizontal gradient (HG) maps

1. Color map of Horizontal gradient

After the reduction to pole correction, a magnetic body is spatially more directly associated with the related magnetic response. The maximum gradient of the anomaly slope is located near, or over the body edge. Figure 3 shows a west to east profile over a theoretical magnetic body edge. The magnetic anomaly trace shows a magnetic high on the positive side of the block and a low on the negative downthrown side. The horizontal gradient operator computes the absolute value of the slope of the magnetic curve. The maximum of the horizontal gradient curve appears over the contact. That is, the horizontal gradient operator produces maximum ridges on a map over edges of magnetic basement blocks and faults. In addition, the horizontal gradient highlights linear features, related to linear contacts, in the data set.

Analysis of the HG color map shows very strong contact anomalies to be associated with the strongly positive magnetic source body in the eastern part of the survey. The eastern edge of this body, in the extreme southeastern corner of the map, is a linear feature, while the western flank displays a distinct sinuous character, probably related to adjacent circular, or semi-circular, source-bodies.

In the northern part of the map a pronounced alignment of NW to NNW, NE and minor N - trending contacts is indicated.
Figure 3. Horizontal gradient operator
2. Lineament analysis map

This map is a derivative of the data set discussed under 1) above, and indicates individual points of horizontal gradient maxima. Alignment of these points as linear features is observed, and the maxima "picks" can be used as an overlay to the shadowgraphs of the horizontal gradient maps to additionally define linear elements in the magnetic data set. As the horizontal gradient operator enhances high-frequency features, subtle line-oriented anomalies (due to minor "herring-boning") and small, high-frequency magnetic responses are also enhanced. They are present in both the gradient map and in the mapped, maximum gradient picks. Because of significant shallow sources, the horizontal gradient tools do not effectively reflect deeper-seated contacts.

E. Vertical Gradient of RTP magnetics

The vertical gradient operator attenuates broad, more regional anomalies, and enhances local, more subtle magnetic anomalies. In the map presented with this report, the NNW-trending, major feature along the eastern flank of the survey is significantly enhanced, and individual source bodies, linear contacts, and zones of cross-trending structures can be seen.

The combined analysis of both the HG and VG maps of the data set was used to outline individual source bodies and structures.

F. Filtered Maps of Reduced-to-Pole Magnetics

In an effort to discriminate between components of the reduced-to-pole map due to shallower and deeper features, filters were applied to the reduced-to-pole data. The filter designs used are least-squares (Wiener) designs which rely on statistical models of the sources that assume a small number of depth horizons are effectively present in the data. If this is the case, the power spectrum of the data is a superposition of exponential terms whose exponents are, up to numerical factors, the depths of the horizons. Once these exponents are identified, linear filters which optimally extract the contribution of any horizon from the data can be designed and applied.

Figure 4 shows the power spectrum of the reduced-to-pole magnetics, averaged over directions and plotted on a semi-logarithmic scale. From this data, three depth horizons were identified. The first is approximately 0.3 kilometers below the sensor, i.e., essentially at ground level, and clearly represents the effects of culture. This component was discarded. The second component has an apparent depth of 1.87 kilometer, and is plotted as the intermediate component of the reduced-to-pole magnetics. The third component has an apparent depth of 7.5 kilometers below the sensor and is plotted as the deep component of the reduced-to-pole magnetics.
F1 Intermediate component of Reduced-to-Pole Magnetics

This map is presented with the report as a color map with a contour interval of 0.2nt to enhance very subtle responses. Although the apparent depth range of these sources is of the order of 6000 feet below surface, it must be realized that many cultural sources, such as pipelines and/or electrical installations, have a significant low frequency component as part of their magnetic responses. Additionally, lenticular, shallow sources, or rounded topographic relief, can give rise to magnetic responses with a well-defined, low frequency component which can be interpreted as a deeper-seated source.

A comparison of the magnetic responses with the topographic data base was undertaken, and the following correlations noted:

- **Topographic relief**

  A good correlation between magnetic anomalies and topographic relief is locally present, for example for a small, circular hill west of Hendersonville, the topography centered around the town of Fairview and a partial correlation for the hills east of Stoneboro. Glacial material may possibly be related to these anomalies.

- **Cultural anomalies**

  Well-defined low frequency anomalies are for example associated with the towns of Grove City and Memorial Park to the west, as well as near London and the town of Folk.

- **Pipeline anomalies**

  Pipeline locations, supplied by Vista, were identified on the base map. Observed magnetic responses were highly variable, and are considered related to the amount (if any) of cathodic protection applied to the line. Possible low frequency pipeline anomalies may be indicated along the line from Fairview to Clark Mills, as well as being shown by responses trending east-west, along a series of parallel pipelines from Henderson Station to Jackson Center.

- **Drainage-related anomalies**

  A number of observed magnetic anomalies are bounded by drainage patterns, such as the NW-trending anomaly just north of Nectarine, bounded by Gilmore Run and Grass Creek, as well as the NW-aligned anomaly north of New Vernon, bounded on the south by Lake Wilhelm.

  The geologic origin of these responses is unknown. They may reflect real structural features with associated susceptibility contrasts, of possibly shallow, glacial material bounded by surface structural elements.
Interpretation results obtained from the data analysis that indicated a direct correlation with the above were not included in the interpretation overlay.

F2 Deep Component of reduced-to Pole magnetics.

The deep component of the RTP magnetic data set is included with this report as a black line contour map with a contour interval of 2nT. This map is considered to represent the deep seated magnetic sources within the study area.

To further assist in the discrimination between possibly shallower seated sources, and basement-related responses, the following operator maps were also completed on the deep component.

- Horizontal Gradient of RTP (deep)
- Vertical Gradient of RTP (deep)

These maps were primarily used to outline interpreted, basement-related susceptibility contrasts and deep, linear features.

G. Previous work completed

During the analysis of the individual data sets, previously completed, the following methods were additionally applied to the data sets.

G1 Susceptibility Map

A 3-dimensional susceptibility inversion was completed using the structure map of the top of Precambrian and the reduced-to-pole map as input data sets. A constant thickness of 20,000 meters below the top of Precambrian was used to represent the upper part of the Precambrian section.

The resulting susceptibility map indicates the broad susceptibility variations required within the upper Precambrian section to satisfy the regional features of the magnetic field, corrected for the variable depth of basement.

As the susceptibility determined is a contrast, rather than an absolute value, calculated values range between 150 and 1,000 μcgs units. It must be realized that the relative values of the determined susceptibilities can be changed by changing the thickness of the plate used in the inversion, but it is considered that the upper 20,000 meters of the Precambrian section probably represents the main part of the magnetic field associated with basement.

A zone of higher susceptibility is located in the eastern portion of the survey. Lower susceptibility areas of the area are typical of a gneissic-metasedimentary basement. It is
clear that significant lithology differences are present within the assumed Precambrian basement section. It is critical to remember that the susceptibility of a magnetic body will determine its amplitude. As an example, Figures 4 and 5 are forward models of the same body at the same depth with different susceptibilities. The response from Figure 4 ($k=250 \, \mu\text{cgs-units}$) is in the noise range. Conversely, the response from Figure 5 ($k=2,250 \, \mu\text{cgs-units}$) is very easily identified.

G2  \textit{STARMAG}^{3D}  Residual Basement Structure Map

This procedure is applied line-by-line to the profile magnetic data, and the results are then gridded and mapped. The basic premise is to use a neural network to recognize the magnetic signature of a user-defined basement uplift, which is then located in the real profile data. This neural network can be thought of as a pattern recognition tool. Numerous examples of the particular pattern sought in the data were presented to the network along with the desired output associated with the input pattern. For this project, \textit{STARMAG}^{3D} was trained to identify features that ranged in width from 200 meters to 1,200 meters and in height from 50 to 800 meters.
V. GEOLOGIC SETTING

The study area is situated along the northwestern edge of the Appalachian Basin, an elongate downwarp that trends northeast-southwest. The basin is a highly asymmetrical syncline that is over 1,000 miles in length and over 300 miles in width at its broadest point. The basin is bounded to the north by the Adirondack Uplift and to the west by the Algonquin Axis, Findlay Arch, and Cincinnati Arch. The eastern margin of the basin is significantly more difficult to delineate, although some locate it beneath the thrust sheets of the Piedmont. A subtle feature, the Sequatchie Anticline, separates the Appalachian Basin from the Black Warrior Basin.

The overall shape of the Appalachian Basin first began to form during the Precambrian. Within the survey area, the Precambrian does not outcrop. In all of western Pennsylvania, only a few wells have been drilled down to crystalline basement. Hence, most information about the basement is indirect. Regional studies indicate that the Grenville Province extends south and southeast of the Adirondacks and the Canadian Shield. This material is presumed to underlie the Appalachian Plateau physiographic province, in which the study area is located.

Canadian geologists relate that the entire basement within the northern Appalachian Basin has been affected by the Grenville Orogeny, a major compressional and thermal metamorphic event involving northwesterly directed thrusting. The study area is located near the boundary of the Central Metasedimentary and Central Granulite Belts. The Central Metasedimentary Belt is subdivided into several distinct blocks, primarily by aeromagnetic anomaly patterns. These supracrustal rocks have been intruded by a compositionally diverse variety of syntectonic, late-tectonic, and post-tectonic plutonic rocks that subsequently were metamorphosed to varying degrees. The study area is in the Frontenac block, which is characterized by a series of high-amplitude, northeast-trending aeromagnetic highs and lows. The Frontenac block is separated from the Central Granulite Belt to the east by the Carthage-Colton mylonite zone. Along this margin, tectonic breccias comprised of metasedimentary, plutonic, and amphibolite rocks are common. The Central Granulite Belt differs from the metasediments to the west in that there is a higher level background magnetic field and more northwest and east-west trending aeromagnetic anomalies. Basement wells indicate that the Central Metasedimentary Belt is composed of a variety of rock types consistent with Grenvillian protoliths and that the Central Granulite Zone is comprised of rocks similar to those seen in outcrop of the Adirondack Massif. It should be noted that the regional trend of aeromagnetic features is normal to the interpreted direction of maximum compressional stress throughout the lower Paleozoic.

Stratigraphic units within the basin thin northward to where basement (Laurentian shield) is exposed. Lower Paleozoic sedimentary rocks in New York are separated from similar stratigraphic units in the East Ontario basin of the St. Lawrence lowlands by Precambrian exposures of the Frontenac axis and Adirondack massif. In Pennsylvania, sedimentary rocks from Cambrian to Permian in age attain a thickness in excess of 10 km (33,000 ft). Across New York, Paleozoic sediments thicken southward from Precambrian exposures in the north.
to 3 km (9,800 ft) at the Pennsylvania border. The sequence of sediments in the basin consists of sandstone, shale, coal, graywacke, limestone, and evaporites.

Several discrete structural domains impinge upon the basin. A series of northeast-striking basement-involved faults that parallel the St. Lawrence River occur in a well-defined zone along the northwest flank of the basin. These faults, have experienced recurring Precambrian movement, but they deform only the lower Paleozoic section. In this area, fractures of the same northeast strike are well developed.

The most pervasive fracture system in the northern Appalachian basin consists of intraformational fractures that occur throughout the more brittle units of the Paleozoic section and across the entire basin. They do not diminish in frequency either up-section, as do those associated with the basement faults, or away from the structural fronts as do the Alleghanian fractures. Trends of the three sets within this system are west-northwest, east-northeast, and northwest. These orientations do not change substantially throughout the domain.

It is not believed that any sediments ranging in age from late Precambrian to middle Cambrian are present within the study area. The early Cambrian sea lay to the southwest. As such, lower Cambrian sediments are absent in most places in New York. (A time-transgressive basal sandstone composed of non-marine quartz arenite and overlain by marine bar/channel sands of middle to late Cambrian age, unconformably overlies the Precambrian.) Swartz (1948) concluded that irregular deposition of the Potsdam "reflects deposition on a surface marked by 30 to 60 meters of local relief and in valleys up to several miles wide." Conversely, several authors have determined that in places, up to several hundred meters of paleotopographic relief on the surface of the Precambrian are present (Reed, 1955; Gathright, 1976; Allen, 1967). For this reason, the STARMAG® neural network was trained to recognize residual basement structures with varying amplitudes.

The basal sandstone (Potsdam) is overlain by a transgressive sequence that thins to the northwest. Because of the lack of fossils, it is difficult to draw the distinction between the Cambrian and Ordovician within western New York. Hence, the overlying transgressive sequence has been designated as middle Cambrian to middle Ordovician. Inundation of the study area by the early Paleozoic sea resulted in the formation of a carbonate wedge all along the gently southeast dipping continental shelf. The lower portion of this Cambro-Ordovician carbonate assemblage consists of interbedded dolomite, sandy dolomite, dolomitic quartz sandstone, and very pure quartz sandstone, while the upper portion is chiefly limestone and argillaceous limestone (Colton, 1970). This sequence includes the Mount Simon Sandstone, and the Trempealeau Formation, Rose Run Sandstone, Theresa Dolomite, and the Beekmantown Formation. In the study area, the total thickness of this shelf assemblage is about 300 meters.

Development of a regional unconformity on the top of the Knox was followed by a period of shelf subsidence. Middle Ordovician carbonates (Black River and Trenton Groups) were emplaced in an entirely different tectonic setting and reached thicknesses of about 200 meters.
in the study area. Severe deformation and uplift associated with the Taconic Orogeny created an elongate landmass which served as a new source for terrigenous sediment (Rickard, 1973). A westward thinning elastic wedge (Queenston Delta) of unknown thickness of shales and sandstones exists in the area of the study.

In the study area, it is believed that Silurian strata disconformably overlie the Queenston. The Silurian section reaches about 200 meters in thickness in western Pennsylvania. The lower Silurian reaches thicknesses of about 70 meters consisting of terrigenous sandstones deposited on a stable cratonic platform. In central Pennsylvania, this is represented by the gas-productive Tuscarora which grades laterally into the Medina Group. These sandstones have been interpreted to have been deposited in alluvial-fan, coastal-plain and estuarine environments and in shoreline and offshore shelf sand wave complexes. The sandstones are overlain by interbedded sandstones and shales of the Clinton Group that were deposited in a variety of environments. Erosion of the Taconic highlands along the eastern margin of the craton resulted in a change from clastic to carbonate depositional patterns. This is reflected in the Lockport Dolomite and Salina Group. Closings of shallow epicontinental basins also resulted in salt deposition. Surface mapping of Devonian strata in New York shows a series of northeast-southwest open folds.

Sandstones in the Lower Silurian Medina Group have produced a number of significant hydrocarbon reservoirs in northwestern Pennsylvania. During the past few years, the Medina Group has replace the Lower Devonian Oriskany Sandstone as the principal objective of deep (Middle Devonian or older) drilling in the state. Consequently, the Medina Group now contributes a significant and increasing amount to the production of natural gas in Pennsylvania.

From an exploration point of view, the Medina Group largely has been a statistical play (completion based upon anticipated success). The reported success rate for Medina drilling activity in Pennsylvania has exceeded 95 percent during the past three years (Harper, 1982, 1983). Copley (1980, p. 97) points out, however, that the reported high success ratios for Medina wells drilled in the central Appalachian basin more accurately reflect the number of wells completed and that these "run the gamut from totally non-economic to prolific producers strictly as a function of reservoir characteristics." Previous work in New York and the western Appalachian Basin has revealed the Paleozoic reservoir fracturing patterns is related to reactivation of existing deformation planes in the basement underlying the sediments.

In summary, previous work in the Appalachian Basin has demonstrated that magnetic strike correlates with the strike of lithologic contacts in the Precambrian basement. These lithologic contacts also correspond with many mapped faults. These faults often crosscut the entire lower Paleozoic column and extend down into the basement. Finally, many Paleozoic reservoirs are frequently associated with faults conformable with magnetic trends localized on the edges of magnetic highs. Hence, any interpretation of aeromagnetic data in Pennsylvania should take these observations into consideration and should start from a similar perspective.
ATTACHMENT 4:

MAP OF GLACIAL DEPOSITS IN PENNSYLVANIA

WITH LINEAMENT STUDY AREA
ATTACHMENT 5:

AEROMAGNETIC SURVEY (TOTAL MAGNETIC INTENSITY)

WITH COUNTY OUTLINES
ATTACHMENT 6:

RECORDING INFORMATION AND PROCESSING SEQUENCE, LINE P6N
VISTA RESOURCES, INC.

LINE: P-6N EXT 1
UP 254 - UP 101
MERCER COUNTY,
Pennsylvania

254 STATIONS 101
W E

MIGRATION
NORMAL POLARITY

RECORDING INFORMATION

RECORDED FOR: PEOPLE'S NATURAL GAS COMPANY
RECORDED BY: WESTERN PARTY V-9    DATE: JULY 1974
INSTRUMENT: SDS 1018-55-210    ACG: BINARY GAIN
FILTERS: OUT-50 HZ    NOTCH: IN
RECORD LENGTH: 10 SEC    SAMPLE RATE: 2 MSEC
GROUP INTERVAL: 330 FT    SHOT INTERVAL: 330 FT
NUMBER OF CHANNELS: 24    COVERAGE: 1200X
ENERGY SOURCE: VIBROSEIS
ARRAY: 3-4 VIBS INLINE
SWEEP FREQUENCY: 56-14 HZ    PATTERN LENGTH: 650 FT
GEOPHONES/GROUP: 24    ARRAY: INLINE / 500 FT

SPREAD DIAGRAM

E

13 12

CHANNELS

4620 FT DISTANCE 990 FT 5 990 FT DISTANCE 4620 FT

PROCESSING SEQUENCE
PROCESSING SEQUENCE

RECORD LENGTH: 3 SECONDS  SAMPLE RATE: 2 MSEC

1. REFORMAT
2. VIBROSEIS CORRELATION
   RECORDED SWEEPS
3. GEOMETRY APPLICATION
4. TRACE EDITS
5. REFRACTION STATICS COMPUTATION
   GMG DELAY TIME METHOD
6. SPHERICAL DIVERGENCE COMPENSATION
7. SPIKING DECONVOLUTION
   SURFACE CONSISTENT
   160 MSEC OPERATOR
8. CDP GATHER
9. WEATHERING/ELEVATION STATICS
   APPLICATION TO FLOATING DATUM
10. PRELIMINARY VELOCITY ANALYSIS
11. SURFACE CONSISTENT RESIDUAL STATICS
12. SPECTRAL ENHANCEMENT
    7/14-56/66 HZ
13. FINAL VELOCITY ANALYSIS
14. NORMAL MOVEOUT CORRECTIONS
15. MUTE
16. SURFACE CONSISTENT RESIDUAL STATICS
17. WEATHERING/ELEVATION STATICS
    APPLICATION TO FLAT DATUM
    DATUM=1200 FT  VE=12000 FT/SEC
18. SHOT/RECEIVER CONSISTENT GAIN
19. CDP CORRELATION RESIDUAL STATICS
    MAXIMUM SHIFT: 4 MSEC
20. STACK
21. VIB DECON PHASE CORRECTION FILTER
22. FX DECONVOLUTION
23. FK MIGRATION
    98% SMOOTHED RMS VELOCITIES
24. BANDPASS FILTER
    8/16-50/68 HZ  0.8 - 1.4 SEC
    7/14-48/58 HZ  2.0 - 3.0 SEC
25. TRACE EQUALIZATION
26. FILM DISPLAY

DISPLAY PARAMETERS
ATTACHMENT 7:

ROSE DIAGRAMS FOR LINEAMENTS DERIVED FROM DEGs AND NHAP
Rose diagrams for lineaments derived from images created from digital elevation models for USGS 7½-minute topographic quadrangles: Hadley, New Lebanon, Utica, Jackson Center, Sandy Lake, Polk, Mercer, Grove City, and Barkeyville, located in northwestern Pennsylvania.
Strike trends cluster between N23°E and N73°E. Dip trends cluster between N62°W and N18°W. Compiled DEM lineament interpretations along the dip azimuths are 1/3 to 1/2 the length of those compiled along strike orientations.
Rose diagrams for lineaments derived from National High Altitude Photography Program images for USGS 7½-minute topographic quadrangles: Hadley, New Lebanon, Utica, Jackson Center, Sandy Lake, Polk, Mercer, Grove City, and Barkeyville, located in northwestern Pennsylvania
Combined NHAP Lineaments

Strike trends cluster between N23°E and N68°E.
Dip trends cluster between N57°W and N17°W.
The lengths of compiled NHAP lineaments are equal for the strike and dip directions.
ATTACHMENT 8:

ROSE DIAGRAMS FOR LINEAMENTS FOR EACH OF NINE QUADRANGLES
Rose diagrams for lineaments derived from images created from digital elevation models for USGS 7½-minute topographic quadrangles: Hadley, New Lebanon, Utica, Jackson Center, Sandy Lake, Polk, Mercer, Grove City, and Barkeyville, located in northwestern Pennsylvania.
Rose Diagrams of DEM Lineaments
Rose diagrams for lineaments derived from National High Altitude Photography Program images for USGS 7½-minute topographic quadrangles: Hadley, New Lebanon, Utica, Jackson Center, Sandy Lake, Polk, Mercer, Grove City, and Barkeyville, located in northwestern Pennsylvania.
Rose Diagrams of NHAP Lineaments
ATTACHMENT 9:

HYDROLOGIC EFFECTS OF THE PYMATUNING EARTHQUAKE OF SEPTEMBER 25, 1998 IN NORTHWESTERN PENNSYLVANIA
Hydrologic Effects of the Pymatuning Earthquake of September 25, 1998, in Northwestern Pennsylvania


Within hours after the Pymatuning earthquake of September 25, 1998, in northwestern Pennsylvania, local residents reported wells becoming dry, wells beginning to flow, and the formation of new springs. About 120 household-supply wells reportedly went dry within 3 months after the earthquake. About 80 of these wells were on a ridge between Jamestown and Greenville, where water-level declines of as much as 100 feet were documented. Accompanying the decline in water levels beneath the ridge was an increase in water levels in valley wells of as much as 62 feet. One possible explanation of the observed hydrologic effects is that the earthquake increased the vertical hydraulic conductivity of shales beneath the ridge, which allowed ground water to drain from the hilltops. Computer simulations of ground-water flow beneath the ridge between Jamestown and Greenville indicate that increasing the vertical hydraulic conductivity of shale confining beds about 10 to 60 times from their pre-quake values could cause the general pattern of decreased water levels on hilltops and increased levels in valleys.

An earthquake occurred on the afternoon of September 25, 1998, near the southern end of Pymatuning Reservoir in northwestern Pennsylvania (Fig. 1). Seismologists determined the earthquake had a magnitude of 5.2, which is the largest ever recorded in Pennsylvania (Armbruster and others, 1999). Although the Pymatuning earthquake was felt over approximately 125,000 mi² (square miles) of the northern United States and southern Canada, structural damage was minor in the communities of Jamestown and Greenville near the epicenter. The most serious consequence of the earthquake was to the ground-water supply tapped by rural domestic wells.

As early as the morning after the earthquake, residents in the vicinity of Greenville and Jamestown observed its effects on their water wells. The Mercer County Department of Public Safety received reports that some wells had lost all water and the yields of others had significantly decreased. Conversely, at the same time that some wells were going dry, others started to flow, some spring discharges increased, and pond levels rose. Complaints of changes in water quality, typically that well water had turned black or smelled of sulfur, also were reported after the earthquake.

This report summarizes findings from a study of the hydrologic effects of the Pymatuning earthquake conducted by the U.S. Geological Survey and the Pennsylvania Bureau of Topographic and Geologic Survey, with assistance from Thiel College and the Mercer County Department of Public Safety. The report documents the location and magnitude of changes in ground-water levels, particularly where wells went dry. The report also presents a hypothesis to explain the documented water-level changes and tests that hypothesis with simulations from a ground-water flow model.

Figure 1. Study area of the ridge between Jamestown and Greenville, earthquake epicenter, and location of wells that are known to have gone dry after the Pymatuning earthquake.
STUDY AREA

The study area is a northwest-southeast trending ridge about 5 mi (miles) long and 2 mi wide between Greenville and Jamestown in northern Mercer County, Pa. (fig. 1). The ridge is centered about 5 mi south-southwest of the epicenter of the Pymatuning earthquake. The elevation at the ridge top is 1,204 ft (feet) above sea level. The valleys of the Shenango River, Little Shenango River, and their tributaries completely encircle the ridge. The maximum relief from the ridge top to the adjacent valley is about 250 ft.

HYDROGEOLOGIC SETTING

The bedrock comprising the ridge (fig. 2) consists of interbedded sandstone, siltstone, and shale of Mississippian age (about 350 million years old). From oldest to youngest, the bedrock units in the ridge are the Cussewago Sandstone, Bedford Shale, Berea Sandstone, Orangeville Shale, Sharpsville Sandstone, Meadville Shale, and the Shenango Formation. Each unit contains all the rock types present in the area but in different proportions. The area has been glaciated, but the glacial sediment on the ridge is generally less than 15 ft thick. The adjacent Shenango and Little Shenango River valleys are partially buried with glacial sediments up to a maximum depth of 200 ft.

The ability of a geologic material to transmit water is described by its hydraulic conductivity (or permeability). The hydraulic conductivity of solid bedrock is usually not great unless the rock contains open fractures. Near the surface, where weathering agents have been able to penetrate the rock, fractures are usually open. In addition, as valleys are eroded, the lateral support for the adjacent hills is removed, and stress-relief fractures tend to form on the hillside parallel to the valley. Deeper into the ridge, hydraulic conductivity is low because fewer fractures exist, and they are more tightly closed.

The origin of all ground water beneath the ridge is precipitation, which infiltrates to the water table mostly during the fall and spring when evapotranspiration is low and the ground is not frozen. The ridge is the ground-water recharge area. Precipitation that falls on the ridge filters through the glacial sediments and upper part of the bedrock until it reaches the water table, below which water is stored in all openings in the rock. The water table is deeper beneath the ridge top than beneath the slopes or valleys.

Figure 2. Geology of the study area and location of selected wells where water levels were measured.

After reaching the water table, ground water flows through the ridge mainly in fractures through the rock and between layers of rock (fig. 3). In the ridge, ground water moves under the influence of gravity, downward and laterally toward the valleys. Ground-water flow has its greatest downward component beneath hilltops and more of a lateral component along the ridge slopes. Beneath the valleys, water moves upward, under pressure, toward the surface to form the hillsides parallel to the valley. Deeper into the ridge, hydraulic conductivity is low because fewer fractures exist, and they are more tightly closed.

Figure 3. Schematic cross section showing conceptualized flow of ground water (blue arrows) from ridge top to valleys. Geologic unit abbreviations are defined in figure 2. (As a result of the earthquake, fractures through which ground water moves were enhanced, allowing rapid movement of water out of the hill into discharge areas. The drainage of ground water stored in the hill lowered the water table, causing many shallow wells, such as the one illustrated in this sketch, to become dry.)
discharge through springs and seeps. Almost all water entering the ground-water system on the ridge will eventually (in months or years) discharge into the adjacent stream valleys. The ridge forms a "hydrologic island" as described by Poth (1963) in that its ground-water flow is almost totally isolated from the ground-water flow in adjacent hills and ridges.

**HYDROLOGIC EFFECTS OF THE EARTHQUAKE**

Within hours of the earthquake, residents began to notice changes in the quantity of their well water. The most significant effect was the decline of ground-water levels (fig. 4). As early as the morning after the earthquake, some residents had lost water in their wells. Additional residents lost water over the next 3 months. The timing of the water loss depended on the elevation and well depth. In general, shallow wells (primarily those completed in the Meadville Shale) near the ridge top went dry first. Deeper wells (drilled to the upper Sharpsville Sandstone) and wells toward the margins of the hill went dry over the next several months. The declining water levels were exacerbated by drought conditions through the summer and fall of 1988. A few wells above elevation 1,100 ft on the ridge did not go dry because they were drilled deeper (to the lower Sharpsville Sandstone or Orangeville Shale) than the wells that went dry.

At the same time that wells on the ridge top were going dry, some residents in the valley and along the base of the ridge noticed an increase in the flow of springs and streams, and several wells began to flow. The streamflow-gaging station on the Little Shenango River at Greenville recorded a small increase in streamflow beginning about 4:00 a.m. on September 26, 1988, the morning after the earthquake.

**CHANGES IN GROUND-WATER LEVELS AND DISCHARGE**

Water-level declines causing water loss in household-supply wells were documented in 121 wells. Eighty of those wells were on the ridge between Greenville and Jamestown (fig. 1). Water-level increases were documented along the base of the ridge.

**Declines**

Water-level declines were recorded in all wells measured on the top and upper slopes of the ridge between Greenville and Jamestown. One of the most dramatic changes in water level occurred in well MR-844 (fig. 5).

**Figure 4.** Cross section through the "hydrologic island" showing the interpreted change in ground-water level from before the earthquake through mid-January 1989. The section is based on the reported date that each well went dry, and the depth of the well. Note that the water level increased along the sides of the ridge, reflected in newly flowing wells after the earthquake. Also note the zones of depression in the water table near the center of the ridge, especially at the October 7 level. These zones presumably developed along the earthquake-enhanced fractures, and extended deeper and spread laterally over several months. Well MR-3277 went dry by October 7. Well MR-3270 did not go dry until late in October. Well MR-3205 began to flow immediately after the earthquake and stopped in late November. It began flowing again in March after the precipitation and snowmelt had recharged the ground-water system. Location of the cross-section is shown on figure 2.

**Figure 5.** Water-level fluctuations in selected wells. (Pre-quake levels are estimated on the basis of historical measurements and reports from well owners.) Location of wells are shown on figure 2.
located near the highest point on the ridge. The water level in that 65-ft deep well was 18 ft below land surface in June 1967 (Schiner and Kimmel, 1976). The well was dry by the morning after the earthquake. Assuming that the water level was within 25 ft of the surface immediately prior to the Pymatuning earthquake, the water level decreased about 40 ft overnight. Well MR-844 was deepened to 120 ft in October. By early November, however, the water level had dropped below 120 ft and the well went dry again. It was subsequently deepened to 155 ft.

Most wells on the ridge were less than 100 ft deep, and almost all went dry over a 3-month period. Several wells were more than 150 ft deep. These deeper wells experienced significant water-level declines but did not go dry. The water levels in wells stopped dropping temporarily after precipitation and snowmelt in January, then resumed their decline. The water levels in the hilltop wells continue to be substantially below pre-quake levels (as of June 1999).

**Increases**

An increase in water levels in wells and spring flow near the base of the ridge accompanied the decline in water levels in wells on the ridge. Although the declines caused more problems, the increases were much more dramatic. Most increases are never reported, however, because the owner is not aware of the increase unless the well or spring begins to flow. Examples of documented increases in water level or flow include:

1. The water levels in some wells rose.
   + In USGS observation well MR-1364, the sudden rise was documented with a graphical recorder. Within hours of the earthquake, the water level in the well rose about 2 ft and did not immediately decline (fig. 6).
   + The greatest documented increase of water level was at least 62 ft, in well MR-615.
   + Five wells started to flow (fig. 7), including one in the basement of a house. The discharge of a previously flowing well also reportedly increased.
2. The flow of existing springs reportedly increased and new springs developed.
3. The water level in a 1/2-acre, spring-fed pond reportedly rose 6 inches within several hours after the earthquake.
4. Wet areas developed in fields after the earthquake, and one resident reported "mini-geysers."
5. The streamflow of the Little Shenango River increased slightly [about 0.4 ft³/s (cubic feet per second)] during the first 24 hours after the earthquake.

**Explanation for Observed Water-Level Changes**

The observed water-level changes indicate that ground water stored in the ridge between Jamestown and Greenville moved more rapidly from the recharge area (hilltop) to the discharge area (surrounding valleys)
after the earthquake than it did prior to the earthquake. Because almost all ground water in the ridge flows through fractures, either between layers of rock or through the layers, one hypothesis is that the earthquake either created new fractures or widened existing fractures in the rock. Increasing the size and/or number of fractures increased the rock’s hydraulic conductivity, which allowed the ground water to flow more rapidly to the discharge areas.

Shallow wells on top of the ridge went dry first because (1) the water table is deepest beneath the hilltop, and those wells probably had less water in them at the time of the earthquake than those on the ridge slopes, and (2) the greatest downward component of ground-water flow is beneath the hilltops, allowing for the most efficient drainage. Deeper wells on top of the ridge went dry later as the water table continued to decline. Wells further down the ridge slope did not go dry until later, probably because the ground-water flow has less downslope component and more lateral component away from the ridge top. Also, the water table decline was not smooth over the ridge; zones of depression probably developed in the water table near the earthquake-enhanced fractures. For several months, these depression zones probably deepened and spread laterally (fig. 4). As the depression zones spread from the fractures toward the margins of the ridge, wells along the upper slopes were intercepted, causing them to go dry. Multiple enhanced fractures in various locations created complicated patterns of water-table decline.

The greatest concentration of water losses (80 wells in 10 mi²) was on the ridge extending northwest from Greenville to Jamestown. Water-level declines were documented in almost every well above elevation 1,100 ft. Within a radius of about 15 mi from the ridge, water losses were reported for only 41 additional wells. An explanation for the concentration of water losses on this ridge may lie in the size of the ridge because:

1. The ridge contains less ground-water storage than other ridges, and ground water has a shorter distance to travel to its discharge area along stream valleys and at springs. The amount of ground water drained from storage is a much larger percentage of the total storage in this ridge than in adjacent larger ridges, allowing the water table to drop more quickly than in larger ridges.

2. Stress-relief fractures concentrated along the margins of a ridge comprise a larger percentage of the volume of this small ridge than larger ridges. Ground water, which flows more easily through these fractures, thus drains more quickly from this small ridge than from larger ridges.

**Simulating the Observed Hydrologic Effects**

A 3-dimensional, ground-water flow model was constructed of the ridge between Greenville and Jamestown where most hydrologic effects were reported. The model tests the hypothesis that the earthquake increased the hydraulic conductivity of geologic units, which caused the observed hydrologic effects (water-level declines beneath the ridge top and water-level and spring-flow increases on the lower hillsides and in the adjacent valleys). The model was constructed and adjusted to simulate hydrologic conditions that existed prior to the earthquake and then used to simulate the effect of the earthquake on water levels and streamflow.

**Model Construction and Adjustments**

The modeled area (same as the study area) was bounded by the Shenango River, Little Shenango River, and their tributaries (fig. 1). The area was divided for modeling purposes (Harbaugh and McDonald, 1996) using a grid with 77 rows, 36 columns, and 8 layers. Hydraulic properties were assigned to represent each geologic unit in the grid (fig. 8 and table 1). Except for the overburden and shale units, initial horizontal hydraulic conductivities were estimated by use of pumping-test data for wells in Crawford and Mercer Counties. The vertical hydraulic conductivity of alluvium and sandstone were assumed to be one-tenth of the horizontal value; for the overburden/weathered zone and shale, the horizontal and vertical hydraulic conductivities are assumed to be equal. Ground-water recharge of 10 inches per year was estimated from the average annual base flow of Little Shenango Creek from 1927 to 1997.

**Figure 8.** Cross section showing layers in the ground-water flow model that represent the geologic units of the ridge between Greenville and Jamestown. (Approximate location of the section is the western half of the trace shown in figure 2).
Hydraulic properties in the model were adjusted (calibrated) until the model could closely simulate pre-quake water levels (fig. 9). The final hydraulic conductivities used in the pre-quake model are listed in Table 1. During the model-adjustment process, increasing the vertical hydraulic conductivity of sandstone layers 4, 6, and 8 caused a decrease in the simulated water levels in all model layers. Increasing the hydraulic conductivity of shale layers 3, 5, and 7, however, resulted in a decrease in the simulated water levels in overlying units and an increase in the simulated water levels in underlying units. The adjustment procedure also showed that an increase in hydraulic conductivity of the shale (layers 3, 5, and 7) will result in a larger change in water level beneath the ridge top than beneath the hillside, which is consistent with observations that most wells that went dry were located on the ridge.

### Ability to Simulate Post-Quake Conditions

The general pattern of water-level change observed after the earthquake was approximately simulated in the ground-water model by increasing the vertical hydraulic conductivity of the near-surface fractured zone and shale (model layers 2, 3, 5, and 7) by 10 to 60 times their pre-quake values (Table 1). The general features of observed water-level changes (estimated on the basis of historical measurements and reports from homeowners and drillers) are large decreases in water levels in shallow units on the ridge and increases in water levels beneath valleys. Simulated water-level changes in the near-surface fractured zone (model layer 2) are compared to observed changes in Figure 10. The model closely simulates where 25 ft of water-level decline was estimated but fails to simulate the estimated declines of more than 100 ft at the ridge top. Water-level increases were simulated by the model but not in the near-surface fractured zone (model layer 2) shown in Figure 10.

Increasing the vertical hydraulic conductivity of shale also caused simulated water levels to rise in model layers 3 through 8 beneath the near-surface fractured zone (fig. 11). Because most deep wells in the area are open to the near-surface fracture zone, few measurements of water level are available for comparison to model simulations. The estimated water-level rise of about 62 ft in well MR-615 (open only to the Orangeville Shale, model layer 5), however, indicates that the large magnitude (20 to 80 ft) of water-level rise simulated in

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**Table 1. Hydraulic properties used to simulate the ground-water flow system before and after the Pymatuning earthquake (shaded blocks indicate change in property between pre-quake and post-quake simulation)**

<table>
<thead>
<tr>
<th>Geologic unit</th>
<th>Estimates of horizontal hydraulic conductivity from pumping tests (feet per day)</th>
<th>Final values used to simulate</th>
<th>Storage value specific yield (dimensionless) or specific storage (per foot)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Pre-quake conditions</td>
<td>Post-quake conditions</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Horizontal hydraulic conductivity (feet per day)</td>
<td>Horizontal hydraulic conductivity (feet per day)</td>
<td>Vertical hydraulic conductivity (feet per day)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Overburden/weathered rock 1</td>
<td>0.004</td>
<td>NC</td>
<td>Specific yield = 0.01</td>
</tr>
<tr>
<td>Near-surface fractured zone 2</td>
<td>0.023</td>
<td>NC</td>
<td>3 x 10^-1</td>
</tr>
<tr>
<td>Meadville Shale 3</td>
<td>0.004</td>
<td>NC</td>
<td>3 x 10^-1</td>
</tr>
<tr>
<td>Sharpville Sandstone 4</td>
<td>0.004</td>
<td>NC</td>
<td>3 x 10^-1</td>
</tr>
<tr>
<td>Orangeville Shale 5</td>
<td>0.004</td>
<td>NC</td>
<td>3 x 10^-1</td>
</tr>
<tr>
<td>Berea Sandstone 6</td>
<td>0.004</td>
<td>NC</td>
<td>3 x 10^-1</td>
</tr>
<tr>
<td>Bedford Shale 7</td>
<td>0.004</td>
<td>NC</td>
<td>3 x 10^-1</td>
</tr>
<tr>
<td>Cuyahoga Sandstone 8</td>
<td>0.004</td>
<td>NC</td>
<td>3 x 10^-1</td>
</tr>
<tr>
<td>Alluvium beneath major streams Parts of layers 1-7</td>
<td>0.004</td>
<td>NC</td>
<td>3 x 10^-1</td>
</tr>
</tbody>
</table>

1 Initial estimate was from pumping-test data from wells completed in fractured-shale units.
the model for geologic units beneath the near-surface fractured zone may not be unreasonable.

Although it is difficult to directly compare the results of model simulation of hydraulic head in specific geologic units to water levels in household-supply wells that are open to several units, in general, the simulations of post-quake water-level changes lend plausibility to the hypothesis that the changes were caused by an abrupt increase in vertical hydraulic conductivity of the shale. Simulation results corroborate observations that (1) water levels declined rapidly within the first few hours after the earthquake in the shallow fractured zone, (2) water levels increased rapidly within the first few hours after the earthquake in deeper units that subcrop beneath the valley and ridge slope, and (3) water levels declined gradually for 3 months after the earthquake in all units; greatest declines were beneath the ridge top. In the deeper units, even after 3 months of decline, water levels are still higher than pre-quake levels, which also is consistent with observations that new flowing artesian wells and springs continue to flow in June 1998.

The simulated changes in hydraulic conductivity in the ground-water model also caused changes in simulated streamflow that are generally consistent with observations. During the first 24 hours after the earthquake, model simulations indicate ground-water discharge should have increased streamflow an average of 0.3 ft$^3$/s from pre-quake conditions. In comparison, streamflow at the Little Shenango River at Greenville increased an average of 0.4 ft$^3$/s during the first 24 hours after the earthquake.

**Figure 10.** Comparison of water-level change "observed" in wells and simulated in layer 2 of the ground-water flow model from before the earthquake through January 29, 1999. (Observed levels were estimated from historical measurements and reports from homeowners and drillers.)

**Figure 11.** Examples of simulated water-level changes in different geologic units after the earthquake.

**COMPARISON TO OTHER STUDIES**

Previous reports of earthquakes causing hydrologic effects in Pennsylvania have been limited to the observation of water-level fluctuations in wells lasting only several minutes (Vorhis, 1967). Longer-term hydrologic changes lasting for days, weeks, or months, such as those reported after the Pymatuning earthquake, have been documented outside of Pennsylvania by a number of other investigators (Rojstacer and Wolf, 1992; Wood and others, 1985; Eaton and Takasaki, 1959; and Nicholson and others, 1988). For example, an earthquake in northeastern Ohio in 1986 caused hydrologic effects similar to those observed after the Pymatuning earthquake. Nicholson and others (1988, p. 192) attribute those hydrologic effects to the squeezing and expansion of aquifers caused by the earthquake. In northern California, the Loma Prieta earthquake of October 17, 1989 (magnitude 7.1), caused ground-water levels in the upland parts of watersheds to decline by as much as 70 ft within weeks to months after the earthquake. Rojstacer and Wolf (1992) concluded that those declines resulted from an earthquake-induced increase in the hydraulic conductivity of bedrock. Similarly, an increase in hydraulic conductivity caused by the Pymatuning earthquake in northwestern Pennsylvania is believed to have resulted in the hydrologic changes reported in the vicinity of Greenville and Jamestown.