High Resolution Seismic Reflection Survey Immediately North and West of the Deep Post Pit along the Carlin Trend, Carlin, Nevada

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SUMMARY

The high resolution seismic survey consisted of a single, nominal 24-fold common depth point (CDP) profile approximately 14,000 ft in length. The survey was designed primarily to image acoustic contacts from the base of the Tertiary Carlin Formation, which ranges in depth from tens of feet to several hundred feet in this area to well within the middle Devonian Popovich Formation at depths of 1500 to 2000 ft. Of secondary interest was the evaluation of state-of-the-art shallow high resolution seismic reflection techniques and equipment for incorporation into future exploration and prospect development along the Carlin Trend. As with previous surveys in this area, signal-to-noise ratio and propagation of high-frequency energy represent the most significant detriments to the overall effectiveness of the technique (Anderson, 1990; Kendrick and Cooksley, 1989). Preliminary background noise surveys in this area suggested that noise associated with mine operations is not sufficient to adversely affect the quality of seismic data collected along the proposed traverse of this profile (Miller and Erickson, 1995). Consistent with the goals of the survey, the vertically incident CDP stacked seismic section provided an enhanced picture of the drill inferred cross-section.

The vertically incident CDP stacked seismic section possesses many acoustic features consistent with those exposed in the north wall of the Deep Post Pit. Several relatively high amplitude and continuous reflection events can be interpreted across portions of the stacked section. The shallowest reflecting events were from within the Ordovician Vinini Formation and ranged in depth from 300 to 500 ft. The extremely complex geometry and lack of a reasonably abrupt acoustic contact between the Carlin and Vinini was likely responsible for the minimal reflection returns from depths less than about 300 ft. The deepest interpretable reflection was from a depth of around 1900 to 2000 ft, which is well within the Popovich. A discontinuous reflecting event traversing the length of the seismic section and possessing an apparent westerly dip is likely the acoustic trace of the Roberts Mountain Thrust Fault. The depth to this very discontinuous, yet acoustically unique, event ranges from just over 1100 ft on the western extreme of the profile to about 400 ft or maybe slightly less within the eastern third of the section. A confident interpretation of the fault becomes difficult in the extreme eastern quarter of the profile. Faulting is evident in several places across the section. For many of these faults, estimation of displacement, orientation, and/or classification cannot be uniquely determined by the seismic data alone, but require assistance from local drill data to accurately interpret. All faults interpreted on the seismic section are

acoustically evidenced by bed termination and/or offset, and in some cases acoustic point source signatures (scatter). The very complex nature of the geometries encountered (as expected) dramatically limited both confidence that interpreted coherent events are from within the plane of this 2-dimensional survey and the continuity of interpretations across the expanse of the profile.

Of secondary interest on this study was determination of 1) the feasibility of relatively non-invasive, and therefore cost-effective, state-of-the-art shallow high frequency seismic reflection techniques in a complex geologic setting with a very thick vadose zone, 2) current resolution (both vertical and horizontal) potential, 3) optimum equipment and parameters (excluding class A explosives), and 4) effective applications and limitations of this current technology along the Carlin Trend. Due to the de-watering necessary for the open pit mining method employed along the Carlin Trend, the water table in this area is estimated to be in excess of 1500 ft deep beneath the profile line. This extremely deep water table, relatively low moisture content of the near-surface, and the very unsorted nature of the unconsolidated material above bedrock, combined to attenuate most of the high frequency acoustic energy within the upper few feet. In spite of the extreme attenuation of the high frequencies along the survey line, reflections interpreted from over 1500 ft deep possessed a reflection bandwidth of more than an octave, a dominant frequency of around 60 Hz, and an upper corner slightly greater than 90 Hz. Normal moveout velocities (NMO, approximately equivalent to average velocity) ranged from 4000 to 7000 ft/sec within the interval imaged by these data. The practical vertical bed resolution for this area will vary from 40 to 60 ft, while the horizontal resolution, which is dependent on depth of the reflector and is defined by the radius of the first Fresnel Zone, is about 200 ft at 400 ft of depth and 300 ft at 1500 ft.

Based on walkaway noise tests in conjunction with the processed production data, the high frequency vibrator provided the largest percentage of recordable high frequency reflection energy and the deepest penetration of all other non-class A explosive sources tested. Based on the interval of interest and the velocity structure encountered during this study, a symmetric split-spread geometry with receiver intervals of no more than 40 ft and a maximum offset of at least 1500 ft would be optimum for the target depth range along this part of the Carlin Trend. The seismograph should possess A/D converters of at least 19 bits. Groups of at least three geophones should have 5 inch spikes (due to the loose near-surface) with each phone dug in at least a couple inches, or down to competent planting soils. Shallow seismic reflection techniques will be most effective along the Carlin Trend in areas with minimal cultural and mining noise, some background geology (i.e., some drill data) and other geophysics, in alluvial areas preferably close to stream beds and/or with several tens of feet of relatively well sorted unconsolidated sediments, and finally sites with subdued topography.

Incorporation of the seismic reflection data acquired and processed during this study with geologic interpretations of drill data and other geophysics data provide a very meaningful and useful picture of the subsurface for application to exploration and exploitation drilling programs along and adjacent to the Deep Post Pit. The CDP stacked seismic section possesses many coherent reflections that can be easily interpreted without any supporting geologic information. However, the geologic cross-section provided by Newmont geologists was critical for accurate inference of displacement and classification of faulting. Confidence in correlating interpreted reflections from the east end of the seismic section to the west end was increased by incorporating the geologic cross-section. The seismic data dramatically improved horizontal sampling in this area over drilling alone. This improved sampling and therefore resolution was critical in identifying minor structural features and delineating individual faults not previously suggested from drill data or other geophysical data sets alone.

INTRODUCTION

Seismic reflection has been actively used with a great deal of success in the petroleum industry for more than 70 years. Recent advances in the micro-electronic industry and an increasing need to image smaller and shallower targets for applications not only in the petroleum industry but also for applications in the engineering, groundwater, and environmental fields have led to significant advances in the use of seismic reflection for targets less than 1000 ft. Delineation of both structural and stratigraphic features on a scale of several feet has been document in the scientific literature with increasing frequency over the last 10 years (Gochiocco, 1992; Miller et al., 1992; Miller and Steeples, 1991; Steeples and Miller, 1990; Hunter et al., 1984). Seismic reflection has seen limited application to exploration and exploitation problems along the Carlin Trend over the last 10 years (Anderson, 1990; Kendrick and Cooksley, 1989).

Early seismic reflection work along the Carlin Trend by Newmont Exploration proved encouraging as a complement to drill data, but without geologic guidance from occasional drill holes, interpretations were somewhat speculative (Anderson, 1990). Interpretations of seismic data acquired in association with exploration of the Post Betze prospect (Kendrick and Cooksley, 1989) are dangerously liberal. Suggestions that seismic techniques, as used on that survey, can image extreme dip angles (> 45 degree) lack good technical foundation. Data from the Post Betze survey suffer from narrow bandwidth body wave energy, a relatively low dominant frequency, and an abundance of point source scatter (diffractions). Signal-to-noise ratio and resolution/bandwidth problems have limited the effectiveness of previous seismic surveys along the Carlin Trend.

This study was initiated to enhance interpretations of existing drill and gravity data by delineating and extending features to the north and east of the Deep Post Pit stratigraphically and structurally consistent with proven ore-bearing zones along this part of the Carlin Trend. Several east/west lines were originally planned to provide the necessary areal coverage, but due to the logistics of acquiring data in the area of interest only a single 14,000 ft line was completed (Figure 1). As part of this study, a series of background acoustic noise surveys were acquired at various places along the proposed lines as well as in the area around Troll/Mike where a previous seismic line had been acquired (Anderson, 1990). The noise survey near where the seismic lines were to be run indicated that noise generated as part of normal mining operations was not sufficient across 90 percent of the proposed line to be a detriment to the acquisition of useful seismic reflection data (Miller and Erickson, 1995). Only the extreme east end of the proposed line would suffer significantly from elevated mine noise.

During June 1995 the walkaway noise tests and production CDP profile were acquired along an approximately 3 mile long line extending from near the western boundary of section 15, through 14 and 13, and into 12 as far as the westernmost north/south haul road leading north from the Deep Post Pit (Figure 2). The walkaway test was acquired in a dry wash (drainage area) near station number 270 (Figure 2). After in-field evaluation of the walkaway data, equipment and parameters were selected that would provide the greatest potential of imaging the geologic targets of interest. The 876 shotpoint CDP profile was then acquired during the next four days. Source and receivers were deployed along a relatively straight line with careful attention to maximizing data quality and consistency in spite of changing surface and near-surface conditions.

This survey was undertaken in hopes of capitalizing on the experiences of past surveys and exploiting recent improvements in data acquisition equipment and techniques. Of primary concern was the economics and resolution of the seismic technique with the improvements of the last 5 years. The best seismic reflection acquisition program includes high explosives buried to the top of the water table. Unfortunately, the cost of drilling, permitting requirements, environmental concerns, and damage costs have minimized the use of borehole-placed high explosives as a seismic energy source in the United States over the last 10 years. Only minimally-invasive or non-invasive sources were tested during this survey. The high frequency vibrator used on this survey had been out of the experimental phase only a year or so at the time of this test. The weight drop source is an experimental modification of a 10-year-old design. The class C explosive source is, as well, an experimental model which has been extensively tested and proven an excellent high frequency source (Miller et al., 1994). The seismograph used on this survey had been on the market for only 18 months prior to its use here and possesses an instantaneous dynamic range equivalent to anything on the market. Everything considered, this represented a minimal cost study designed to determine if improvements in equipment and techniques could make shallow seismic reflection a specialized part of the exploration arsenal along the Carlin Trend, while improving the geologic understanding along this specific 3-mile transect north of the Deep Post Pit.

ACOUSTIC PERSPECTIVE OF GEOLOGIC SETTING

The study area is located along a spur of the Tuscarora Mountains (Thorenson, 1994). The structural complexity of the geology in the area directly north and west of the Deep Post Pit is evidenced by exposures in the north wall of the post pit (Figure 3). The intricate and severe folding and faulting possess geometries that could never be completely delineated with two-dimensional seismic reflection surveying alone. Thermal alteration, although geologically and mineralogically significant, does not alone represent a acoustically significant target. The near-surface along the line is characterized predominantly by a thin veneer of Quaternary alluvial and colluvial deposits overlying tuffs of the Tertiary Carlin formation which range in thickness from tens of feet to several hundred feet. Beneath the Carlin Formation lies the chert, mudstones, and limestones of the Ordovician Vinini Formation. Limestone/mudstone contacts within the Vinini should manifest themselves as very good reflectors, assuming the frequency of folding is not too great.

Separating the Ordovician Vinini from the Devonian Rodeo Creek is the Roberts Mountain Thrust fault. In some areas the fault could possess a sufficiently non-gradational contact to be uniquely imaged by seismic reflection. The Rodeo

Creek Unit is classified by siliceous mudstones, siltstones, and sandstones which possess distinct repetitive thin bedding and well-defined horizons. The transition from Devonian Rodeo Creek to the upper Devonian Popovich Formation is gradational and likely acoustically transparent. However, contact between some of the siltstones and limestones within the upper Popovich will likely possess acoustic impedance contrasts and assuming the layers do not dip excessively (i.e., > 40 to 45 degrees), should be imagible. Relatively strong reflecting events should be interpretable throughout most of the Popovich. Due to the gradational transition from the Popovich into the Roberts Mountain, it is unlikely the Devonian/Silurian boundary will be represented by a reflection interpretable on this survey. The folding, faulting, thermal alteration, and intrusives characteristic of this area increase the complexity and decrease the uniqueness of seismic data interpretations.

DATA ACQUISITION

Data for this study were acquired on a 48-channel Geometrics StrataView seismograph. The seismograph amplifies, digitizes the analog signal into a 24-bit word, digitally filters and scales displayed data, and stores the digital information in a demultiplexed SEG2 format. The StrataView has the ability to record an auxiliary pilot trace on channel 1 that can be either saved coincident with the other seismic data channels or used for in-field correlation with the other 47 channels. The recording of a pilot or auxiliary channel is only necessary for vibratory or coded impulsive sources. For straight impulsive sources all 48 channels recorded 2048 samples each with a sampling interval of 0.5 msec, providing 1024 msec records with a 1000 Hz Nyquist frequency. A total of 1024 msec of correlated data were recorded for the vibrator source as well, with a sampling interval of 0.5 msec. This floating-point seismograph possesses as high a dynamic range as commercially available anywhere.

Walkaway Noise Tests

The walkaway noise tests were conducted near station 290 along the western slope of an alluvial valley. Most shots recorded during the testing phase were gathered into 192 trace files with individual traces ordered so source-to-receiver offsets increased incrementally out to a maximum of over 1500 ft. Some offsets tested were as great as 2400 ft. Sources and source configurations tested included the Bolt LSS-6 land air gun (1500 psi gun pressure through 20 cubic inch gun), rubber band accelerated weight drop (Bison EWG equivalent), IVI MiniVib (including several sweep designs correlated against ground force and synthetic), and the 8-gauge auger gun (Healey et al., 1991). Receivers (three Mark Products L28E 40 Hz) were selected based on field conditions, necessary acoustic frequency band, and previous experience.

On-site testing concentrated on source configuration, source/receiver geometries, and recording parameters (Table 1). Testing was designed to maximize the performance range of each of the sources so qualitative judgments could be made from the recorded shot gathers as to the equipment and parameters that produced the highest signal-to-noise ratio and resolution potential as well as identify which characteristics were influencing data quality the most at this site. Effectiveness of vertically stacking multiple shots per station in signal-to-noise enhancement was evaluated for impacting impulsive sources (i.e., air gun and weight drop). For analysis purposes only, single shots without vertical stacking were recorded for the vibrator and auger gun. The source-to-receiver offsets ranged from 8 to over 1500 ft with adjacent stations separated by 8 ft. The data quality and testing procedure was sufficient to allow selection of optimum parameters and geometries for acquisition of data at this site targeting reflectors between 100 and 2500 ft deep.

TABLE 1
Sources and Configurations Tested

Weight drop		
100	single shot	
101	stack of 5 shots	
Air gun		
102	single shot	
103	stack of 5 shots	
Auger gun		
160		
Vibrator		
110, 120, 130, 140 ,150	single shot synthetic	N1, N2, N3, N4, N5
111, 151	stack of 5 synthetic	N1, N5
112, 122, 132, 142, 152	single shot ground force	N1, N2, N3, N4, N5
113, 153	stack of 5 ground force	N1, N5

Vibrator sweep index

N1	30-250 Hz	5 seconds	calibrated	6500 lbs	1/4-1/4 sec taper
N2	30-250 Hz	5 seconds	calibrated	1500 lbs	1/4-1/4 sec taper
N3	30-250 Hz	5 seconds	uncalibrated	6500 lbs	1/4-1/4 sec taper
N4	30-250 Hz	5 seconds	calibrated	2750 lbs	1/4-1/4 sec taper
N5	30-250 Hz	5 seconds	calibrated	2750 lbs	1.0-1/4 sec taper

Analysis and selection of optimum equipment and parameters could only be made with confidence after thorough analysis and data reduction. The test data were gathered according to common source configuration and then displayed in trace offset ascending order. Digital filtering, AGC scaling, f-k filtering, and source static corrections were made to the shot gathers prior to hyperbolic curve fitting, refraction analysis, spectral analysis, and wavelet analysis. Careful consideration was given to the signal-to-noise ratio in light of the distance the test site was from active mining areas. Estimations of resolution potential were made for each source wavelet and bandwidth of reflection energy with respect to propagation distance. All factors considered, the reflections interpreted on walkaway noise tests matched theoretical curves reasonably well, possessed marginal signal-to-noise, similar arrival patterns and velocities to pre-test models, and were consistent enough file-to-file to justify collection of the production data set.

Production CDP Profiles

Production parameters were designed in accord with analysis of walkaway data. Minimum QA/QC of field data necessitated in-field correlation capabilities, digital display filters, and a real-time noise monitor. Analysis of noise effects during walkaway tests resulted in the designation of a maximum allowable background noise threshold of 0.1 mV peak-to-peak. Identification of various unique reflection arrivals on walkaway data allowed confident selection of equipment, parameters, and geometries to be used for the CDP portion of the survey.

The production portion of the survey took 4 days and included 876 shotpoints acquired along one nearly 3-mile-long line. Using a vibrator as the seismic energy source allowed input power and spectral control while maintaining a relatively undisturbed and uninvaded ground surface. The vibrator's pad was generally located on relatively undisturbed material vacant of brush and other materials that might negatively effect source coupling. Prior to recording each shot, the pad was seated to the ground by running a sweep under routine down pressure (around 6,500 lbs for this survey). Three linear sweeps (30 to 250 Hz) were then vertically stacked after correlation with the ground force and saved for each shot point. The sweeps were 5 seconds each in duration and correlated with the ground force into a 1 sec record. The seismograph recorded for a total of 6 seconds for each sweep, sampling every 0.5 msec. Identification of various unique arrivals on the walkaway data allowed for confident selection of parameters and geometries used for the CDP portion of the survey.

Based on the walkaway data and the dynamic range of the recording instrument, the source/receiver geometry was end-on with a source-to-nearest-receiver separation of 215 ft and a furthest offset of 780 ft. The seismograph was configured to target reflections shallower than 750 msec that possessed average velocities from 3000 to 9000 ft/sec. The three 40 Hz geophones were planted into competent material in a 3 ft in-line array to help attenuate source-generated air-coupled waves as well as cultural noise. Each receiver was monitored intermittently for continuity (≈3,000 ohms) and leakage (>1,000K ohms) and each phone underwent a modified twist and tap test to ensure an optimum plant prior to recording. The analog spectrum was in part shaped by the vibrator sweep and drive force in an attempt to enhance the higher frequency components of the recorded energy. This emphasis on pushing the high side of the spectrum was necessary if any interpretations of unique reflectors with geometries evident in the pit was to be possible.

DATA PROCESSING

All data processing was done on an Intel Pentium-class microcomputer using *WinSeis* and *Eavesdropper,* both commercially available algorithms. Display parameters were determined based on scale of existing data sets, optimum exaggerations, and workable formats.

Walkaway Noise Tests

Comparisons of various source, receiver, and instrument settings and configurations as well as overall signal-to-noise, frequency content, and velocity structure are the intent of the walkaway noise tests. The level of testing is dependent on the objectives of the project and the degree of difficulty in obtaining the required resolution and signal-to-noise ratio. Processing of data for this test was limited to trace organizing, gain balancing, source static, and digital filtering. Vibrator data comparisons from this study include in-field correlation with various sweep specifications, pilot traces, and data characteristics. Spectral analysis contributed to optimizing the acquisition specifications. The data are gathered and displayed in a source-to-receiver offset order according the specific source configuration.

Production CDP Lines

The CDP data processing flow was similar to those used in petroleum exploration (Table 2). The main distinctions relate to the conservative use and application of correlation statics, precision required during velocity and spectral analysis, and extra care taken during muting operations. A very low percentage allowable NMO stretch (< 20%) was extremely critical in avoiding wide-angle reflections, maximizing resolution potential, and avoiding distortion in the stacked wavelets (Miller, 1992). Many processing techniques that have not routinely been effective on shallow data sets (including f-k migration, deconvolution, and f-k filtering) were tested to evaluate their potential on this data set.

For most basic shallow high resolution seismic reflection data the processing steps/operations are a simple scaling down of established petroleum-based processing techniques and methods. However, processes such as deconvolution have basic assumptions (Yilmaz, 1987), including high signal-to-noise ratio, random reflectivity series, and large number of reflections. With the small time window and the marginal signal-to-noise all of these assumptions are violated to some degree by this and most shallow data sets. Processing/processes used on data for this report has/have been carefully executed with no *a priori* assumptions and designed to simply enhance what can be interpreted on shot gather data, not to create through processing.

TABLE 2
General Processing Flow

format from SEG2 to KGSSEGY
spectral analysis (frequency vs amplitude plots)
digital filtering (bandpass with spectrum balance 20-40 150-300)
trace balance (250 msec window)
fk filter (slope filter targetting ground roll and refractions)
first arrival muting (direct wave and refraction)
surgical muting (removal of groundroll based on trace-by-trace arrival)
bad trace edit (removal of all low signal-to-noise traces)
assign geometries (input source and receiver locations)
sort into CDPs (re-order traces in common midpoints)
velocity analysis (whole data set analysis on 200 ft/sec increments)
NMO correction (velocity from 4250 ft/s to 6500 ft/s)
static correction (10 msec max shift, with 400 msec correlation window)
CDP stack
trace balance (150 msec window)
migration (velocity of 5000 ft/s)
digital filtering (20-40 150-300)
display

Processing flow for CDP stacked data. Parameters were determined by analysis for each prior step as well as through iterative analysis of particular operations.

Uncompensated variations in the near-surface velocity structure manifests itself as erroneous apparent structures, reduced resolution, and apparent stratigraphic variations. A first arrival statics operation proved effective in reducing long wavelength (several times larger than the length of the spread) artifacts of a horizontally varying near-surface velocity function. Geometric analysis of reflection hyperbola (the basis for the zero-offset corrections necessary in establishing apparent NMO velocities used for common midpoint summation) was adversely affected in places along the line by relatively severe inter-spread statics. Some of the apparent non-uniform reflection curvature was a direct result of small-scale bed terminations, out-of-the-plane reflection interference, and possibly gradual horizontal lithologic changes. Sub-spread length features can be smoothed or slightly distorted by the hyperbolic zero-offset (NMO) correction and therefore may be slightly de-focused on CDP stacked sections. Iterative surface-consistent statics and velocity analysis effectively reduced much of the zero-offset trace misalignment that resulted from the inter-spread static.

Vibrator

The use of vibratory sources increases the potential for spectral shaping of the recorded wavelet, minimizes the environmental impact, and increases the signal-to-noise ratio, while increasing the complexity of in-field and/or post-acquisition processing when compared to non-coded impulsive sources. Vibratory techniques were first developed over 30 years ago as an alternate method (non-impulsive) of introducing acoustic energy into the ground (Crawford et al., 1960). This oscillatory energy method known as "vibroseis" uses a controlled vibrating source to generate a sinusoidal wavetrain of continuously varying frequency delivered to the ground over a specific time period (Sheriff, 1991). The sweep (sinusoidal source input function) trace or pilot is correlated with each time series trace. The record time of each data trace is slightly longer than the sweep (pilot) time to allow sufficient "listen" time for two-way travel of the entire sweep. The correlation process effectively produces a time series trace comparable to impulsive source records with respect to full-wave field recording.

Both in-field and post-acquisition correlation were equally effective on this line. In-field correlation requires on-site determination of the optimum pilot trace. Once the data have been in-field correlated against the sinusoidal wavetrain (pilot) the process cannot be easily reversed. Since the vibrator is instrumented with one accelerometer on the base plate and one on the mass, three possible pilot trace choices exist: ground force (mathematically determined based on weighted output of base plate accelerometer and mass accelerometer), filtered ground force (tracking filter derived from synthetic), and the synthetic (theoretical drive function). Depending on near-surface conditions and selected parameters, any one of the previous pilot trace options could produce the broadest band, most representative seismogram. Field and post-acquisition testing included combinations of several sweeps correlated to each of the three possible pilot traces. The overwhelming improvement in the data when the ground force was correlated with the data traces provided the necessary confidence to select in-field correlation with the ground force as optimum for these conditions and data requirements.

RESULTS

Unequivocal identification of reflection energy on field files is essential for accurate interpretation of CDP stacked sections. Raw field files acquired during the production portion of the survey from each line have intermittent identifiable reflection events between 150 and 600 msec. The reflections have an average dominant frequency of approximately 60 Hz and an apparent NMO velocity ranging from 4000 to 6500 ft/sec. These would result in an approximate depth to the reflector of between 300 and 2000 ft. The signal-to-noise ratio on some raw field files is good, allowing confident identification of reflections on many of the raw field files.

The CDP stacked sections possess broken coherency with a series of apparently discontinuous reflection events between about 100 msec (about 200 ft) and 700 msec (about 2500 ft). An interpretation of the reflection events on the CDP stacked section without the benefit of the geologic cross-section would differ predominantly with respect to fault displacement and estimation of offset (Figure 4). It would also be relatively difficult to distinguish the most reasonable structural trends without drill guidance.

Several problems inherent to two-dimensional seismic reflection in areas with complex geology are evident on the stacked section (Figures 5, 6, 7, and 8). First is the appearance of relatively flat coherent events that seem to terminate without an apparent geologic reason. This effect is a combination of the physical size of the subsurface sampling area (Fresnel Zone) and changes in the relative angle of reflected energy with respect to the ground surface from flat or minimal dips (< 20 degrees) to layers with large dip angles (> 35 to 40 degrees). The acoustic representation of, for example, a tight syncline anticline sequence has a somewhat linear stairstep look where the nodes and anodes of sinusoidal structures are horizontally exaggerated with no visible expression of the flanks of these type structures. An example of this type of phenomena is evident between 450 and 600 msec centered on CDP 760.

The second problem, from which it is more difficult to develop a unique interpretation, is out-of-the-plane reflections and scatter. This acoustic problem usually manifests itself as a short-duration coherent event that generally does not possess a reasonable stacking velocity and that generally interferes strongly with legitimate primary vertical reflections. A significant number of the apparent reflections near the eastern extreme of the line are likely from out of the plane. This suggestion is based on their inferred dip angles, the extreme inconsistency with expectations of structure in that area, and interpreted reflectors on the western part of the line.

The end-on, west to east acquisition geometry was designed to enhance coherency of reflection events by increasing the density of horizontal traces within the optimum window and to improve the accuracy of velocity control. The down side of end-on acquisition is the loss of dip control on events with predominantly east dips. Since the general dip was suggested to be westerly, the source pushed the receivers in the up dip direction, providing more focused reflected energy. A significant amount of scatter and most extreme dip angles interpreted on the stacked section possess west dips. This is not to say few easterly dips are actually present, the survey is just not as sensitive to the westerly dips.

The shallowest event the can be interpreted with any degree of confidence is the Roberts Mountain Thrust which is an acoustically strong, yet very disjointed and angular event (Figures 5, 6, 7, and 8). The acoustic appearance of the fault is likely a result of the structurally disturbed and altered zone that characterizes that interface. The thrust fault could be vertically offset in several places depending on interpretation. Clearly between station 175 and about station 300 a zone of faulting that is unresolvable with seismic reflection is evident. The structural complexity resulting from not only the faulting, but also the distortion of bedding planes makes this area appear acoustically chaotic on the CDP stacked section. Several significant individual faults exist between stations 370 and 450. These faults clearly offset the Roberts Mountain Thrust. The thrust fault shallows on the eastern end of the line to a point where it is not imagible with this data set. It is estimated to be at a depth of around 200 ft near station 670. There is no clear expression of the thrust east of station 670.

The reflecting event at about 450 msec on the western end of the line is interpreted here to be the contact between the Rodeo Creek and the Popovich. The event appears to be relatively high amplitude with a gentle yet continuous westerly dip. The fault zone between stations 180 and 300 makes a high-confidence tie across the section impossible. The Rodeo Creek Formation does not appear to have any geologic interfaces with sufficient acoustic impedance to be represented as a reflection or the dip angles of those interfaces are too severe to image with this technique. The abundant short and extremely undulating events could be reflections, but without more horizontal consistence, interpreting them would be extremely speculative. Faulting interpreted to offset the Roberts Mountain Thrust can be extrapolated to the Rodeo Creek/Popovich contact. Diffractions are tell-tale evidence for the faulting of this reflector. Only two faults can be interpreted with confidence between about stations 450 and 750. An apparent fault can be interpreted at about station 580 that offsets all the units below the Roberts Mountain Thrust. The data quality is not sufficient to extend the fault vertically beyond the Rodeo Creek. A second fault that offsets the Rodeo Creek and deeper units is beneath station 510. This fault extends from the Vinini/Rodeo Creek contact to depth. The Rodeo Creek/Popovich contact on the eastern end of the stacked section is represented by a step sequence of reflection events. This step sequence is the result of large east dip angle. The very smooth reflections with unrealistic apparent dip are probably from out of the plane of the survey and could be anything from fault planes to dipping beds. The basal contact of the Rodeo Creek seems acoustically much more significant than geologically inferred.

The three sections of the Popovich Formation appear to be acoustically represented on the stacked section. Several reflection events are interpretable across the middle of the section within what is interpreted as the Popovich. The faulting as interpreted through the Rodeo Creek is also evident through the Popovich. Steep east dips have resulted in acoustic discontinuities in the interface separating the upper and middle Popovich between station 675 and 705 as well as between 750 and 780. The eastern extreme of the entire acoustic column is saturated with out-of-the-plane events and edge effects artifacts. The fault interpreted as the termination of the Popovich is interpreted based on the abrupt change in wavelet characteristics.

Everything considered, the seismic section possesses several reflection events that can be interpreted with confidence. Faults with relatively narrow fault zones and minimal offset (i.e., around 50 to 100 ft) appear to be uniquely imagible with seismic reflection techniques. The push to the higher frequency portion of the spectrum has resulted in significantly more unique reflection events than on previous surveys and much higher resolution. However, out-of-the plane energy and steep dips were the biggest detriments to the generation of geologic cross-section that allowed a direct extrapolation of the structures in the Deep Post Pit wall northward.

Preliminary Stacked Sections

With the diversity of processing steps and processes available for seismic reflection data, decisions concerning parameters, order of processing, and even which processes to use are very subjective. Considering the extremely complicated nature of the subsurface material, it is very likely that with any one particular processing flow certain areas along this line may be optimally enhanced while the same flow at a different location may have a negative impact on coherent reflection. It is, therefore, reasonable to provide three different processed sections, two that are the result of preliminary processing.

Preliminary processed sections provided to Newmont geologists in September of 1995 were processed through a complete flow but lacked fine tuning of certain parameters which were deemed necessary to improve the accuracy of the subsurface image. The final sections included in this report are the result of several variations in processing parameters and secondary processes in comparison to the preliminary sections. The preliminary sections (processing flow #1, [Figures 9 and 10] and processing flow #2, [Figures 11 and 12]) are included so if improvements in the acoustic cross-section seemingly evident to the processing geophysicist in the final sections are not consistent with and/or provide a less meaningful geologic picture, the preliminary sections can be incorporated into the geologic picture. The preliminary sections also provide a reference point so relative changes in data quality and reflection accuracy can be ascertained.

The interpretations of the preliminary sections (Figures 9, 10, 11, and 12) in this report are the same as those provided originally during September. It is evident that the interpretations at that time incorporated only minor aspects of the geologic cross-section derived from drilling. The major fault sequences were placed with the help of the geologic cross-section but interpreted bedding is only influenced in terms of gross trends.

The three interpreted seismic sections provided in this report all possess slightly different geologic interpretations. These interpretations are provided only as a general guide as to how a geophysicist would view this data set, keeping in mind that virtually none of the subtle geologic characteristics familiar to geologists working this area are taken into consideration. Depending on processing and the significance the interpreter puts on specific wavelet characteristics, any of the interpretations presented could be representative of the subsurface.

RECOMMENDATIONS

Time-to-depth information, a very critical piece of the geophysical picture, is missing here. Attempts to acquire uphole information from a recently drilled corehole was not successful. It would be very helpful to have a walkaway VSP to confirm interpretations presented here that are based on stacking velocities only. This data set is continuing to undergo reprocessing in attempts to enhance in the in-plane reflections and to improve the trace-to-trace consistency of the interpreted reflections. This reprocessing includes optimum window low-fold stacks designed to minimize static problems. As well, the data are evaluated and compensated for refraction variability. Any interpretations/correlation of these stacked data with borehole geology should involve both geologist and geophysicists. The high frequency vibrator definitely pushed the high frequency components of the stacked reflection profile higher than on previous surveys in this area. It would be advantageous on any future surveys to increase the applied peak force.

REFERENCES

Anderson, R.G., 1990, TS Ranch reflection seismic tests: Data interpretation: Newmont Exploration Limited, Geophysical Department, 24 pp, 4 plates.

Crawford, J.M., W. Doty, and M.R. Lee, 1960, Continuous signal seismograph: *Geophysics*, v. 25, p. 95-105.

Gochiocco, L.M. 1992, Modeling studies of interference reflections in thin-layered media bounded by coal seams: *Geophysics*, v. 57, p. 1209-1216.

Healey, J., J. Anderson, R.D. Miller, D. Keiswetter, D.W. Steeples, and B. Bennett, 1991, Improved shallow seismic-reflection source: Building a better Buffalo [Exp. Abs.]: Soc. Explor. Geophys. v. 1, p. 588-591.

Hunter, J.A., S.E. Pullan, R.A. Burns, R.M. Gagne, and R.S. Good, 1984, Shallow seismic-reflection mapping of the overburden-bedrock interface with the engineering seismograph—Some simple techniques: *Geophysics*, v. 49, p. 1381-1385.

Kendrick, P., and J.W. Cooksley, 1989, Seismic exploration of the Gold Strike Mine area, Carlin Gold District, Nevada: Cooksley Geophysics, Inc., 31 pp.

Miller, R.D., N.L. Anderson, H.R. Feldman, and E.K. Franseen, 1995, Vertical resolution of a seismic survey in stratigraphic sequences less than 100 m deep in Southeastern Kansas: *Geophysics*, v. 60, p. 423-430.

Miller, R.D., and J. Erickson, 1995, Noise survey at Newmont Gold's Mines north of Carlin, Nevada: Kansas Geological Survey Open-file Report 95-20.

Miller, R.D. S.E. Pullan, D.W. Steeples, and, J.A. Hunter, 1994, Field comparison of shallow P-Wave seismic sources near Houston, Texas: *Geophysics*, v. 59, p. 1713-1728.

Miller, R.D., V. Saenz, and R. Huggins, 1992, Feasibility of CDP seismic reflection to image structures in a 220-m deep, 3-m thick coal seam near Palau, Coahuila, Mexico: *Geophysics*, v. 57, p. 1373-1380.

Miller, R.D., 1992, Normal moveout stretch mute on shallow-reflection data: *Geophysics*, v. 57, p. 1502-1507.

Miller, R.D., and D.W. Steeples, 1991, Detecting voids in a 0.6-m coal seam, 7 m deep, using seismic reflection: *Geoexploration*, Elsevier Science Publishers B.V., Amsterdam, The Netherlands, v. 28, p. 109-119.

Sheriff, R.E., 1991, *Encyclopedic dictionary of exploration geophysics*, 3rd ed.: Society of Exploration Geophysicists, Tulsa, Okla., 376 pp.

Steeples, D.W., and R.D. Miller, 1990, Seismic-reflection methods applied to engineering, environmental, and groundwater problems: Soc. Explor. Geophys. Investigations in Geophysics, Investigations in Geophysics no. 5, Stan Ward, ed., *Volume 1: Review and Tutorial*, p. 1-30.

Thorenson, R.F., 1994, Geology of the Post deposit, Eureka County, Nevada: Newmont Exploration Limited, 16 pp.

Yilmaz, O., 1987, Seismic data processing; S.M. Doherty, Ed.; *in* Series: Investigations in Geophysics, no. 2, Edwin B. Neitzel, Series Ed.: Soc. of Explor. Geophys., Tulsa, Oklahoma.

Figure 1. Site map.

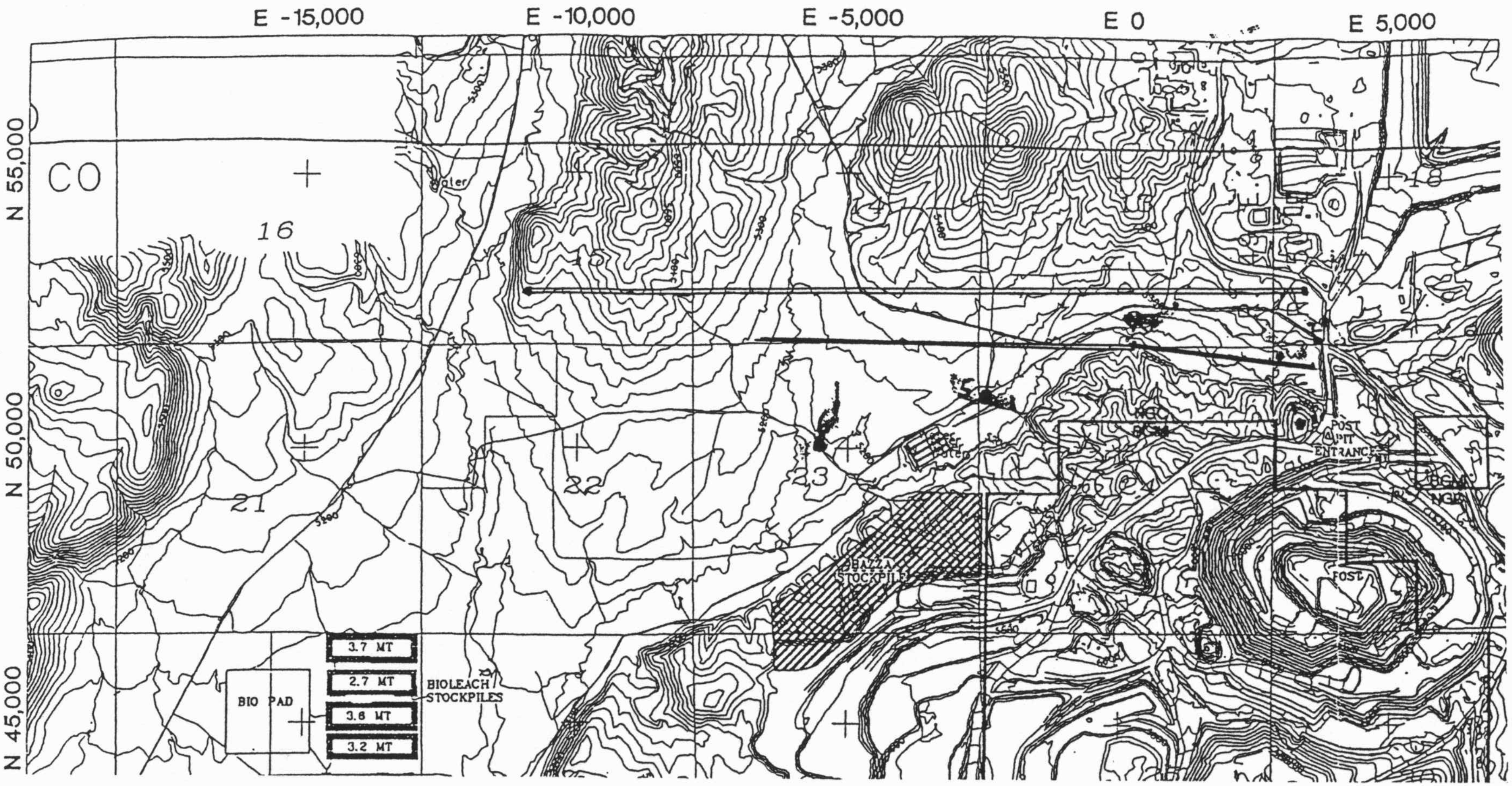
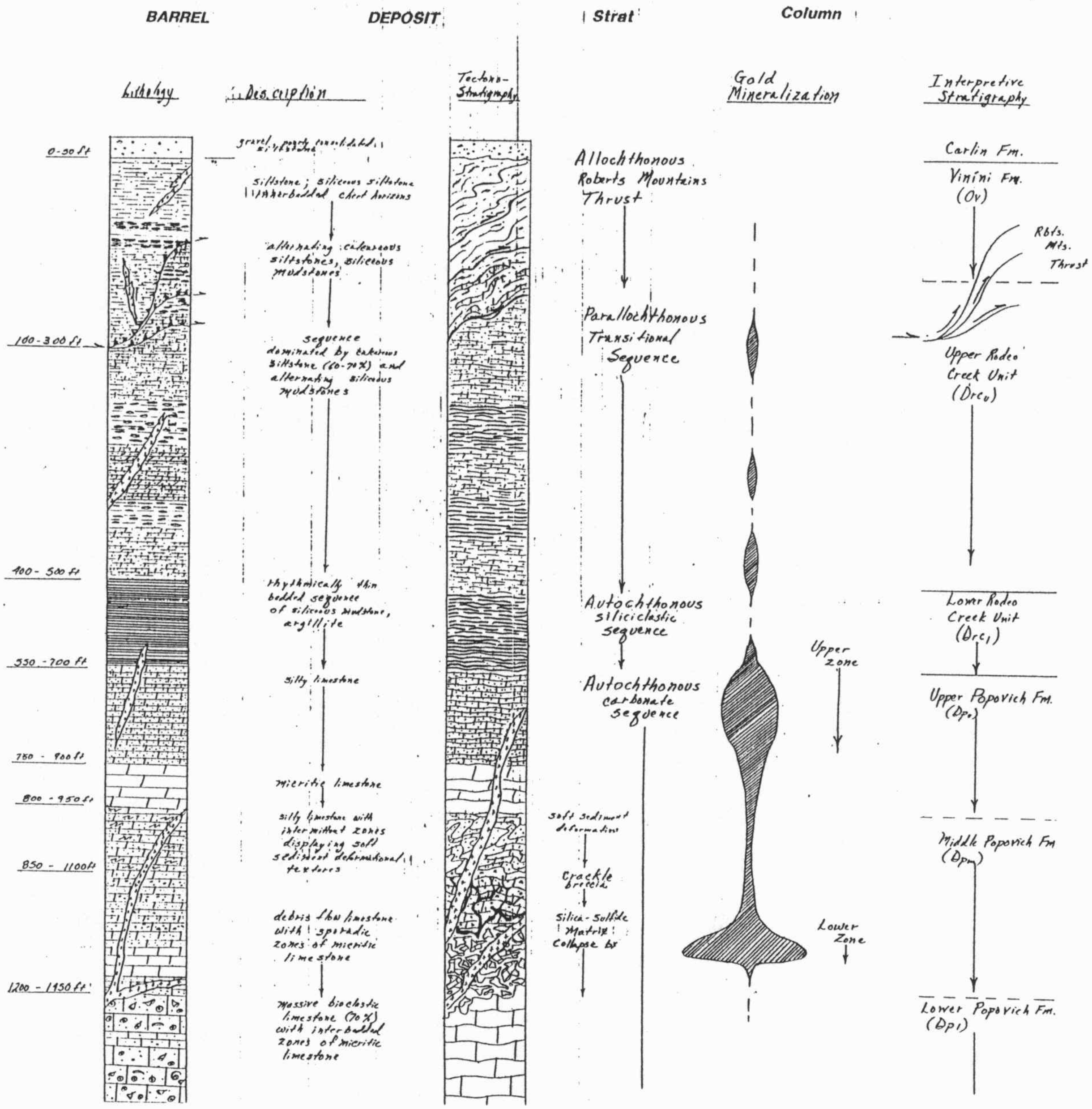


Figure 2. Stratigraphic column.



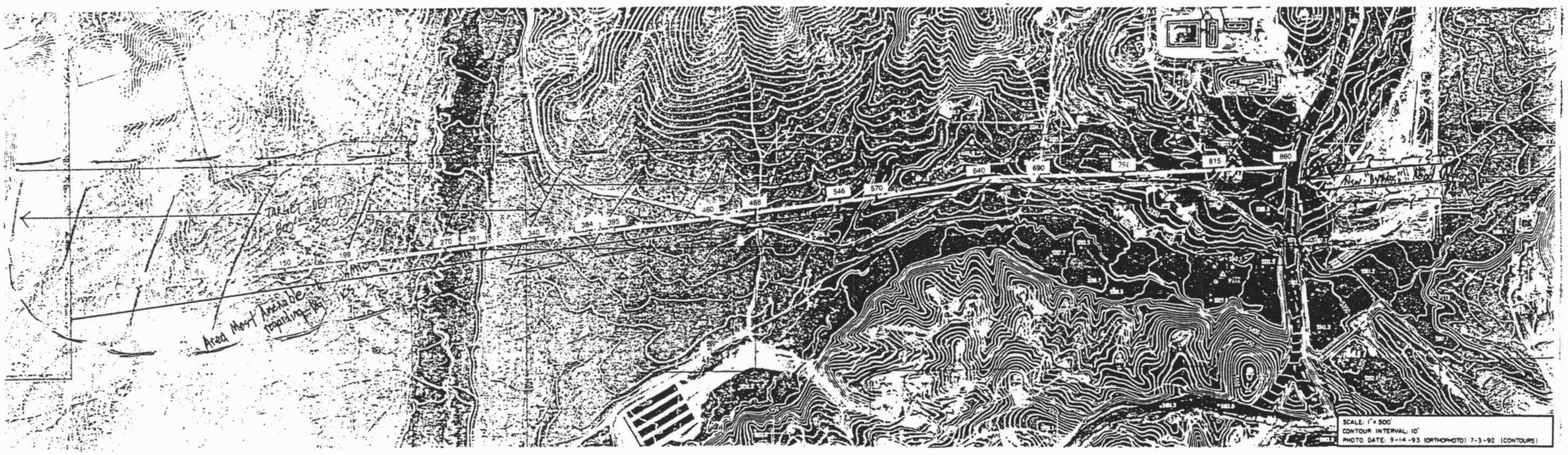


Figure 3. Shotpoint map.

Figure 4. Drill geologic cross-section.

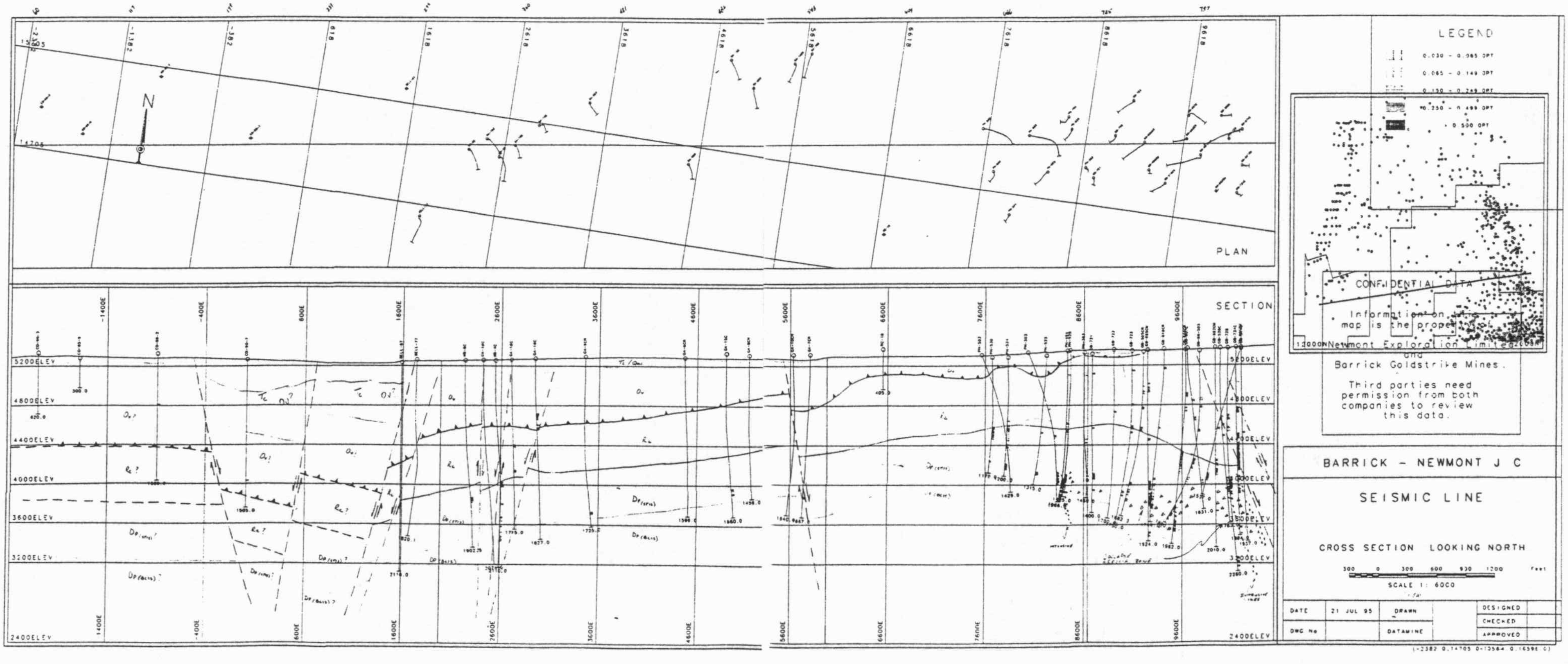


Figure 5. Uninterpreted flow #3.

Figure 6. Interpreted flow #3.

Figure 7. Uninterpreted flow #3—post migration smoothing.

Plot History

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Figure 8. Interpreted flow #3—post migration smoothing.

```
**Plot History**

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