Increasing Oil Recovery Through Advanced Reprocessing of 3D Seismic, Grant Canyon and Bacon Flat Fields, Nye County, Nevada

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Abstract

Makoil, Inc., of Orange, California, with the support of the U.S. Department of Energy has reprocessed and reinterpreted the 3D seismic survey of the Grant Canyon area, Railroad Valley, Nye County, Nevada. The project was supported by Dept. of Energy Grant DE-FG26-00BC15257. The Grant Canyon survey covers an area of 11 square miles, and includes Grant Canyon and Bacon Flat oil fields. These fields have produced over 20 million barrels of oil since 1981, from debris slides of Devonian rocks that are beneath 3,500 to 5,000 ft of Tertiary syntectonic deposits that fill the basin of Railroad Valley. High-angle and low-angle normal faults complicate the trap geometry of the fields, and there is great variability in the acoustic characteristics of the overlying valley fill. These factors combine to create an area that is challenging to interpret from seismic reflection data. A 3D seismic survey acquired in 1992-93 by the operator of the fields has been used to identify development and wildcat locations with mixed success. Makoil believed that improved techniques of processing seismic data and additional well control could enhance the interpretation enough to improve the chances of success in the survey area.

The project involved the acquisition of hardware and software for survey interpretation, survey reprocessing, and reinterpretation of the survey. SeisX, published by Paradigm Geophysical Ltd., was chosen as the interpretation software, and it was installed on a Dell Precision 610 computer work station with the Windows NT operating system. The hardware and software were selected based on cost, possible addition of compatible modeling software in the future, and the experience of consulting geophysicists in the Billings area. Installation of the software and integration of the hardware into the local office network was difficult at times but was accomplished with some technical support from Paradigm and Hewlett Packard, manufacturer of some of the network equipment. A number of improvements in the processing of the survey were made compared to the original work. Pre-stack migration was employed, and some errors in muting in the original processing were found and corrected. In addition, improvements in computer hardware allowed interactive monitoring of the processing steps, so that parameters could be adjusted before completion of each step. The reprocessed survey was then loaded into SeisX, v. 3.5, for interpretation work. Interpretation was done on 2, 21-inch monitors connected to the work station. SeisX was prone to crashing, but little work was lost because of this. The program was developed for use under the Unix operating system, and some aspects of the design of the user interface betray that heritage. For example, printing is a 2-stage operation that involves creation of a graphic file using SeisX and printing the file with printer utility software. Because of problems inherent in using graphics files with different software, a significant amount of trial and error is introduced in getting printed output. Most of the interpretation work was done using vertical profiles. The interpretation tools used with time slices are limited and hard to use, but a number to tools and techniques are available to use with vertical profiles.

Although this project encountered a number of delays and difficulties, some unavoidable and some self-inflicted, the result is an improved 3D survey and greater confidence in the interpretation. The experiences described in this report will be useful to those that are embarking on a 3D seismic interpretation project.

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Introduction

Restatement of Proposal

This report summarizes the experience of Makoil Inc. and consultants working for Makoil in the execution of the project supported by Department of Energy Grant DE-FG26-00BC15257, "Increasing Oil Recovery Through Advanced Reprocessing of 3D Seismic, Grant Canyon and Bacon Flat Fields, Nye County, Nevada".

The grant proposal called for advanced reprocessing and interpretation techniques to be applied to a 3D seismic survey that covers Grant Canyon and Bacon Flat Fields in Railroad Valley, Nevada. The complexity of the geology of this area and related problems with seismic data interpretation because of geophysical complications are explained in several publications (French, 1998; Johnson, 1996; Johnson, 1994; McCutcheon and Zogg, 1994). A review of the original processing of the 3D survey supported the conviction that new processing techniques could improve the resolution of the seismic data to better define the geologic complexities of the area. New interpretation software would facilitate a more accurate structural analysis.

The first section of the report discusses the initial phase of the project, the seismic reprocessing steps and results. This is followed by a section describing the acquisition and installation of the computer hardware and software needed for the seismic interpretation. The report concludes with an evaluation of the software used to interpret the 3D seismic survey, and a summary of the interpretation results.

Scope of Project and Anticipated Results

Historically, the complicated geology of the Railroad Valley basin has been difficult to image and interpret with 2D seismic data. A 3D seismic survey, acquired over the Grant Canyon and Bacon Flat oil fields during 1993, improved the seismic resolution of the field structures. Still, the overall data quality was relatively poor. This fostered ambiguous structural interpretations and thwarted several attempts to increase oil production in the area. It was believed that if the quality of the 3D seismic data could be enhanced, more accurate structural renditions might lead to the discovery of additional oil reserves in the Grant Canyon/Bacon Flat area.

The acquisition parameters of the Grant Canyon 3D seismic data had been state-of-the-art during 1993 and are still typical of 3D surveys today. However, the seismic data processing of 1993 was lacking by modern standards. This suggested that the raw field data were of good quality for the area but amenable to enhancement through reprocessing. Reprocessing the 3D seismic survey was expected to improve the overall resolution of the seismic data and the subsequent interpretation.

Since 1993, seismic data processing has advanced significantly due to the exponential growth in computer speed, memory, and programming capabilities. In the past, many processing steps such as picking first breaks, muting shallow refractions, or analyzing CDP gathers and velocity stacks, required the visual inspection of reams of paper displays. To quality check/control (QC) the numerous processing steps, many hours of computer time also were required to change in-put parameters and rerun processing algorithms. Now, most processing steps are done interactively on screens using super-computers that quickly redisplay the effects of parameter changes. More time can be spent on productive analyses and QC of processing steps rather than shuffling paper.

It was anticipated that advancements in a number of data processing stages would combine to improve the Grant Canyon seismic data. The reprocessed data would benefit from better and faster algorithms used in a number of data processing steps, including mute, statics, phase correction, velocity analyses and migration. Because of the geological complexity of the area, the application of pre-stack time migration was predicted to provide a significant improvement over the post-stack time migration applied during the 1993 processing. The testing and application of depth migration algorithms were not tried due to budget constraints.

The challenges associated with reprocessing and interpreting the Grant Canyon 3D seismic survey can be more readily appreciated with an understanding of the problems faced. A review of the geology and seismic velocity problems in the area are summarized below.

Geological Summary of the Grant Canyon and Bacon Flat Oil Fields

The Grant Canyon and Bacon Flat oil fields are mound-shaped structures located near the eastern edge of Railroad Valley about 265 km (160 mi) north of Las Vegas. Grant Canyon Field has produced 20 million barrels of oil from a closure covering about 1 sq km (0.4 sq mi) and the adjacent Bacon Flat Field has produced nearly 1 million barrels from a closure about half that size. The prolific oil fields produce from brecciated and karsted Devonian carbonate rocks. The reservoir rocks originated from one or more landslides that discharged from the adjacent Grant Range onto the floor of the ancestral Railroad Valley basin.

The landslide(s) occurred during Oligocene-Miocene time and the debris covered about 10 sq km (4 sq mi). The displaced Devonian rocks spread over exposed Pennsylvanian and Mississippian strata, as well as the flank of a large, late Cretaceous/early Tertiary intrusive. Early Tertiary basin-fill sediments also underlie the landslide debris in places. Subsequently, the landslide rocks were buried under fluvial and lacustrine deposits that filled the Railroad Valley basin during Tertiary Basin-and-Range rifting. Grant Canyon field is buried beneath about 900 m (3,500 ft) of basin-fill sediments and Bacon Flat field beneath about 1,500 m (5,000 ft).

Cretaceous to early Tertiary extension and the emplacement of the intrusive complicated existing paleo-structure. The intrusive also modified subsequent Basin-and-Range faulting in the Grant Canyon area. Because of this convoluted geological history, the Grant Canyon 3D seismic survey exhibits multiple unconformities, faults and other structural and depositional complexities. Fortunately, the challenge of unraveling the complicated geology and velocity field is aided by logs from 27 wells drilled within the survey area.

Summary of Geophysical Conditions in the Grant Canyon Survey Area

From east-to-west, the basin-fill sediments consist of coarse alluvial fan deposits at the edge of the basin that inter-finger with sands and shales basin-ward. The alluvial fans are comprised mostly of carbonate conglomerates with higher acoustic velocities than the inter-fingering sediments. This geometry has created considerable velocity gradients in the basin-fill strata, both horizontally and vertically, particularly within the upper 600 m (2,000 ft) of strata. Basin-fill velocities range from 1,500 to 5,200 m (5,000 to 17,000 ft) in the Grant Canyon survey area. These extreme velocity variations have skewed the appearance of the underlying structures as imaged by the seismic time data. For example, velocity surveys in two Grant Canyon field wells about 800 m (2,600 ft) apart have documented a velocity gradient that induced a time structure on seismic data equivalent to a structural change of about 300m (1000 ft) between the wells, before accounting for velocity (Johnson, 1996). On seismic data, apparent structures induced by velocity changes are indistinguishable from real structures without knowledge of the velocity field.

During the acquisition of the Grant Canyon seismic data, the abrupt variations in the basin-fill velocities introduced static shifts throughout the 3D data volume. Those static shifts caused the discrete wavelets comprising the data to be smeared together during the stacking and migration phases of seismic data processing. This data smear resulted in an overall degradation of data quality, reduced the frequency content of the data and impacted data continuity. This hampered the velocity analyses and subsequent data processing steps. Even during the 2000 reprocessing, the effects of velocity-induced statics could not be entirely removed from the data because the complexities of the acoustic velocity field could not be adequately determined. In both the 1993 and 2000 processing efforts, much of the hummocky or choppy data appearance, particularly in the zones of weaker data, likely can be attributed to velocity-induced statics and imperfect stacking and migration of the data.

Project Implementation and Results

Selection and Installation of Hardware and Software

Interpretation of 3D seismic data requires specialized computer software, which in turn requires some specialized computer hardware. The following paragraphs describe the process of selecting and installing the hardware and software used to interpret the Grant Canyon seismic survey. Also, there is a short critique of this part of the project that highlights points where problems could have been avoided or mitigated.

Selection of Hardware and Software

SeisX, published by Paradigm Geophysical Corp., was chosen as the software tool for interpreting the reprocessed seismic survey. The choice was based on cost plus intangible factors. The program was priced at $17,500, substantially less than other software packages with similar features at the time. In addition, SeisX can be upgraded and augmented with unix-based modeling software should that become necessary. The annual maintenance fee for SeisX was set at 18% of the intital cost, or $3,150/yr. The maintenance rate was comparable to other vendors, but the lower initial cost resulted in a lower annual fee. In addition, the program works with the

Windows NT operating system and this resulted in significant hardware savings over the cost of Unix equipment required by comparable programs. Finally, there are a number of geophysicists in the Billings area that use or have used SeisX; a situation that is favorable for finding help with other interpretation projects in the future.

Paradigm Geophysical provided some specifications for the hardware needed to run SeisX. These were used to shop for the required equipment. Two manufacturers, Hewlett Packard and Dell, sold computer models that were adequate for the project. Although the costs of base models were comparable, Dell provided more flexibility in the selection of a custom configuration. The specifications of the hardware recommended by Paradigm and the configuration that was ordered from Dell are provided below:

Hardware recommended by Paradigm Geophysical:

Single CPU, 200 MHz or greater Pentium Pro or Pentium with MMX
64 MB random access memory, 128 MB preferred
One of the following video card configurations:
  1 Colographic Mega Lightning or Pro Lightning card
  2 Matrox Millinium cards, 2 Mystique or 2 Diamond Stealth cards also work
  Most video cards will work, but video performance may be compromised
1 17” monitor, 2 monitors recommended, 256 color display, 1024 x 768 resolution
3-button mouse
Adaptec 2940 single-channel, ultra-wide SCSI controller card
2 GB, or greater, SCSI fast-wide, NTFS-formatted hard drive
CD-ROM drive

Software recommended by Paradigm Geophysical:

Windows NT 4.0 operating system
X Server, Paradigm recommended and supported only Exceed by Hummingbird
TCP/IP network protocol

Hardware purchased from Dell:

Single CPU, 600 MHz Pentium III
512 MB random access memory
Matrox G400 Max 2-monitor video card
2 P1110 21” monitors
Logitech 3-button mouse
2 18 GB SCSI hard drives with RAID controller
20/48X CD-ROM
Iomega Zip 250 drive

Software acquired:

Windows NT 4.0 and Service Pack 5, from Dell
Exceed, from Paradigm
SeisX version 3.4.2, from Paradigm

Additional software was obtained as required, and is discussed in subsequent paragraphs.

Installation

The Dell workstation was to be installed in an office where several other computers, printers, and a plotter were present on a local network. The network also included an internet router connected to a T1 line. The workstation needed to be part of the network in order to use the plotter for output. Most of the other computers on the network are Macintoshes.

In addition to the SeisX software, several other pieces of equipment and software were prerequisite to installation of the workstation. The 2-monitor configuration recommended for SeisX required, in turn, acquisition of workstation furniture. Because the network included Macintosh equipment, interface software would be required so the workstation could communicate with them. SeisX was originally designed to run on workstations using the Unix operating system. To accommodate a Windows system, an interface program, Exceed, published by Hummingbird, would be required.

Based on the advice of other workstation users, we obtained a U-shaped table with room for two people to work at the monitors and surrounding table space large enough to conveniently arrange printed maps, cross sections and seismic sections.

Communication with the Macintosh computers on the network was accomplished by installing PC Maclan on the workstation. Installation of the program was straightforward but proper configuration of Windows networking software caused some difficulty. Because of the nature of the local network to the internet, the computers used to access the internet required a permanently assigned internet address. Although the workstation was not going to be used for internet access, the Windows NT operating system uses internet network protocols and the workstation therefore also required a permanent internet address in order to communicate on the local network. A description of this aspect of network configuration was not found in the on-line or printed manuals that were available, so resolving the problem required several days and some outside help.

When the workstation was ordered from Dell the single-monitor video cards recommended by Paradigm had been replaced with a newer 2-monitor card. Although the new card had not been tested using SeisX and Exceed, the fact that it was from the same manufacturer led us and Paradigm to believe that it would be compatible. This belief turned out to be erroneous. The problem was compounded because the incompatibility did not manifest itself in an identifiable manner; the program would fail to start and report a licensing error.

Considerable effort was expended to solve this problem. Initially, Paradigm sent a preliminary copy of Version 3.5, a forthcoming SeisX release, to replace Version 3.4.2. This failed to cure the situation so configurations of Exceed and Windows NT were modified several times, culminating in a system failure that required reinstallation of the operating system. The RAID setup did not protect from this and caused confusion about formatting during reinstallation. Also, after the operating system was reinstalled it was discovered that some of the required network software was not available on any of the installation disks. The software was found on the Dell internet site, but because the network functions of the workstation were disabled, the software had to be retrieved using another computer.

Once the workstation was operating, attention turned to changing the video cards. Paradigm provided 2 single-monitor cards to replace the 2-monitor card, all from the same manufacturer. After the replacement, it was possible to start the program but screen colors were modified in ways that made the program unusable. Again, considerable effort was expended on changing software settings, including establishing a special internet connection that allowed Paradigm technicians to log onto the workstation and control it directly. When these efforts failed, Paradigm sent a technician with the older-model video cards to replace the newer cards. The program then worked.

After the workstation was installed and configured to work on the local network, we found that it could not establish a connection with the plotter. Various network-configuration settings were changed without success. A call to Dell technical support likewise did not help. Then a call was placed to Hewlett Packard, because both the plotter and the plotter network interface were manufactured by them. After some trial and error, they determined that the nature of the local network, which required a permanent internet address for the workstation, in turn required a permanent address to be assigned to the plotter interface device. This possibility had been overlooked because other computers on the local network, Macintoshes, used different network protocols to communicate with the plotter and did not have connection problems. The Hewlett Packard technician explained the process to change the internet address of the plotter interface device, not a straight-forward procedure, and communication between the workstation and the plotter was established.

Shortly after interpretation work began using SeisX it was discovered that the program had no capacity for directly printing output. Printing output from SeisX is accomplished in a 2-stage process. First SeisX generates a CGM file, then separate, print-utility software opens and prints the CGM file. This situation was not contemplated when we were shopping for interpretation software, and is not addressed in the specifications sheet for SeisX that was provided by Paradigm. The lack of printing functions in SeisX is probably a consequence of the evolution of the program from the Unix operating system.

We arrived at a 2-fold solution for printing because of limitations found with the printing-utility software. CGM print utilities turned out to be surprisingly expensive, $600-$1,500, and some had steep annual maintenance fees. This is probably a function of limited demand and commensurate high per/unit cost of development and support. Just CGM was purchased for $800, without the annual maintainence option. All of the utilities had little or no capability for editing or annotating output. SeisX, likewise, has limited editing functions available. However, a special edition of a popular graphics editor, Canvas, published by Deneba, can open CGM files. Although this program allows extensive editing, the special edition version was unacceptably slow on the workstation. Still, the CGM file could be converted into a modified Canvas file and then edited easily using the Macintosh version of Canvas. The CGM print utiltiy was used to make routine work prints. To prepare final output for display the CGM file had to be converted to a Canvas file, then opened, polished, and printed using the Macintosh software.

Shortly after the workstation was put into service it became evident that a tape drive would be needed for data loading and archiving. By request the reprocessed Grant Canyon seismic survey was provided by the processor, Western Geophysical, on a compact disk. However, most other surveys are stored on tape cartridges. A used tape drive that cost $400 was obtained and installed without difficulty.

Summary

The installation of the hardware and software was generally more difficult than expected. Some aspects, like communication with other computers on the local network, were less trouble than anticipated. Some seemingly simple items, like communicating with the plotter, were surprisingly hard. Some problems were self-inflicted by a lack of knowledge about the Windows NT operating system. Technical support played an important role in the installation process of both hardware and software.

Hardware support from Dell was limited. Response time when called was good, but definitive answers were seldom available. Although it was not surprising that questions about the video card, network, and plotter connection could not be answered directly, it would have been helpful if some direction could have been provided. On the single occasion that Dell provided tangible assistance, regarding network software, it was necessary to download the needed software from an internet site using a Macintosh on the local network. It seems odd that critical networking software was not provided with the workstation on a backup disk. Hewlett Packard technical support was substantially better. It was not difficult to locate a specialist in their support system, and with the help of the technician an obscure network problem was fixed which allowed the workstation to communicate with the plotter.

Support of SeisX software by Paradigm was mixed. The support personnel were helpful when called but were slow to investigate problems that were outside direct assistance with the program. For example, the difficulty with video card compatibility required research with the card manufacturer and the publisher of Exceed.

With the perfect vision of hindsight, it is possible to identify several points that would have improved the installation process. A Hewlett Packard workstation should have been purchased instead of the Dell equipment. The quality of technical support from HP, and their familiarity with our network-plotter configuration more than offset the cost difference between their workstation and that of Dell. We should have insisted on on-site help from Paradigm when it became clear that the program would not start as expected. This would have been cost effective for all of us. Also, Paradigm provided no indication that additional software would be needed to create printed output. When an inquiry was made, they provided a short list of printer utilities, but more useful information was obtained in discussions with other SeisX users and by searching the internet. Because this project did not have our undivided attention, the delays associated with these installation problems amounted to several months.

Reprocessing the Grant Canyon 3D Survey

Survey Parameters

The acquisition and original processing of the Grant Canyon 3D seismic survey was supervised by Apache Corporation's Denver office. The data were acquired during December 1992 and January 1993 by Western Geophysical Company, Survey Party 780. The 3D survey was designed to acquire 24-fold seismic data and was centered over the Grant Canyon and Bacon Flat oil fields with a sufficiently large perimeter to image the flanks of the fields.

The survey area is rectangular, about 6.26 km (3.89 mi) east-west by 4.72 km (2.93 mi) north-south, and covers an area of 29.5 sq km (11.4 sq mi). The long dimension is rotated about 20 degrees counter-clockwise. The surface terrain is low-relief alkali flats with a pediment surface in the southeast corner of the survey area that gently rises toward the Grant Range. The data were acquired using Vibroseis with a sweep frequency range of 10-80 Hz, except in a patch of muddy ground about 2.5 sq km (1 sq mi) in size near the center of the survey. In that area, a pattern of 6 mini-holes, with a total of 1 kg of dynamite, was utilized for the energy source.

Receiver groups were spaced 36.5 m (120 ft) apart and receiver lines were spaced 220 m (720 ft) apart. Perpendicular to the receiver lines, source lines were spaced 220 m (720 ft) apart with source points spaced 36.5 m (120 ft) apart. When source lines crossed a receiver line they were offset laterally 110 m (360 ft), creating a "brick pattern" with the receiver lines. The 3D data were acquired using overlapping rectangular patches comprised of 768 live receivers.

Horizontally, this layout resulted in 87,637 data bins 18.3 by 18.3 m (60 by 60 ft) square in the form of 258 paralleling east-west lines (in-lines) spaced 18.3 m (60 ft) apart, and 342 similarly spaced north-south lines (cross-lines). The small bin size was chosen to ensure sufficient sampling to resolve the complicated geology, image steep dips without aliasing, and aid in velocity analyses during processing. Vertically, a sample rate of 2 milliseconds obtained data samples about every 3 m (10 ft) assuming an average velocity of about 3,000 m (10,000 ft) two-way seismic time.

Description of the 1993 Seismic Data Processing

Western Geophysical Company's Denver processing center processed the Grant Canyon survey over a five-month period from January to June 1993. Custom Geophysical Services, Inc. supervised the seismic processing and chose or approved the processing sequence and parameters. The following processing steps were applied:

1.SEGD format conversion: sample rate 2ms, record length 3.0 s
2. Geometry computation
3. CMP sort, field static computation (datum elevation 1,433 m (4,700 ft), correction velocity 1,830 m/s (6,000 ft/s))
3. Offset-consistent gain compensation
4. Deconvolution: Surface consistent minimum phase, 2 ms predictive distance, 220 ms operator length, 1 window, 0.01% pre-whitening.
5. Model based wavelet processing (MBWP)
6. Phase match dynamite to vibroseis
7. Refraction statics
8. 1st Velocity analysis
9. 1st Autostatics
10. 2nd Velocity analysis
11. 2nd Autostatics
12. 3rd Velocity analysis: checked with constant velocity stacks
13. Trim statics: 12 ms maximum shift
14. Normal moveout and first break supression
15. Dip moveout (DMO): progressive stack
16. Spectral whitening: 10-78 Hz
17. FX deconvolution
18. Migration: Stolt 3D (minimum DMO velocity), Finite difference 2D by 2D (residual DMO velocity)
19. Time-variant filter: 21-60 Hz from 0-0.6 s, grading to 15-44 Hz from 0.9-3.0 s
20. Gain

Pertinent details of the 1993 seismic data processing are included in a later section comparing the results of the 2000 Reprocessing.

Description of the 2000 Seismic Data Reprocessing

Custom Geophysical Services and Western Geophysical Company were chosen to reprocess the Grant Canyon 3D seismic survey because both companies originally processed the seismic data during 1993. Several of the people that were involved with the initial processing have remained at each company and participated in the data reprocessing. Firsthand knowledge of the problems and shortcomings of the original processing effort facilitated choosing the steps and parameters to reprocess the seismic data. The reprocessing sequence is outlined below:

1. SEGD format conversion: sample rate 2ms, record length 3.0 s
2. Edit bad traces and apply, QC and correct geometry
3. Grid define and CDP sort
4. Testing and application of minimum-phase filter, to help pick first breaks on single-fold data
5. Spherical divergence compensation

6. Deconvolution: Surface consistent zero phase spike decon, 160 ms operator length, 0.01% pre-whitening.
7. Trace Balance
8. Time variant spectral whitening (10-80 Hz)
9. Refraction statics
10. Model based wavelet processing (MBWP) and phase match dynamite to vibroseis
    a. QC of phase match and adjustment of static shifts
11. 1st Velocity analysis: approximately every 1.25 km (0.5 mile)
12. 1st Autostatics
    a. QC of phase match and adjustment of static shifts
13. 2nd Velocity analysis: approximately every 1.25 km (0.5 mile)
14. 2nd Autostatics
    a. Final QC of phase match and adjustment of static shifts
15. Offset selection for pre-stack time migration: 16 offset ranges
16. Normal moveout correction, mute offsets
17. Dip moveout (DMO) of the 16 offsets
18. FXY deconvolution of the 16 offset DMO stacks
19. Trace interpolate to fill holes in the offset stacks
20. Time-varient filter: 10-80 Hz to 2.0 s, taper to 10-60 Hz at 3.0 s

21 Minimum function X-Stolt migrations

22. Sort to CMP: 16 fold
23. Remove pre DMO, NMO correction
24. 3rd Velocity analysis: approximately every 1.25 km (0.5 mile)
25. Re-stack composite minimum function migration
26. Residual finite difference migration
27. Time variant filter and scaling: low frequency open; 75-65-45 Hz high- frequency cut-off at 0-1-2 s, respectively
28. Output as SEG-Y to CD: at 1,433 m (4,700 ft) final datum

Also, a second migrated data set was produced applying the following steps:

26. De-migrate step 25 (above) with minimum function
27. Migrate with full field Stolt algorithm
28. Time variant filter and scaling: low frequency open; 75-65-45 Hz high-frequency cut-off at 0-1-2 s, respectively
29. Output as SEG-Y to CD: at 1,433 m (4,700 ft) final datum

Results and Discussion of the Seismic Reprocessing

The seismic reprocessing effort associated with this project is described in an appended proprietary report submitted by Elias Ghattas, Custom Geophysical Services, Inc. The report is titled, “QC Reprocessing Report – 2000, for Grant Canyon 3D, Nye County, Nevada, for Makoil, Inc.,” and amply illustrates the results of the various reprocessing steps. A summary of the report follows, comparing the 2000 reprocessing to the original 1993 processing and detailing significant improvements associated with specific data reprocessing steps.

A primary goal and accomplishment of this project was to improve the overall quality and interpretability of the Grant Canyon 3D seismic survey by reprocessing the data. Improvements in a number of processing steps enhanced the resolution of the 2000 reprocessed seismic data. Gains made during early steps of the reprocessing augmented the results of subsequent steps. The 2000 reprocessing benefited from the use of better processing algorithms than were available during 1993. Interactive computer screens and faster display capabilities permitted substantially more analyses and QC throughout the processing flow. Some unexpected gains in data quality resulted from the discovery of geometry errors in the original survey, as well as some processing application errors, that went unnoticed during the 1993 processing.

Extraordinary advances in computing speed, capabilities and algorithms since 1993, resulted in a superior reprocessing job in half the time and for less cost than the original effort. The 1993 DMO (post-stack) migration alone took a week of computer number-crunching time and was very costly, which limited any subsequent modifications to velocity analyses or other input parameters. At that time, pre-stack time migration, a better solution to migration, was prohibitively expensive. Because of greater processing speed and much lower cost, the 2000 reprocessing not only utilized pre-stack time migration but also experimented with various input parameters and the compared different migration algorithms during reprocessing.

Geometry QC/edits. “First arrival refraction reduction” (FARR) displays were employed to examine shot and receiver positions and polarity reversals of receiver groups. Edits could be made using interactive displays rather than tedious manual editing. Improvements over the 1993 processing can be attributed to more robust computer algorithms and displays, which together provided more accurate geometry analyses. Maps of attributes that contributed to the geometry QC during reprocessing included ‘source/detector locations,’ ‘CMP fold,’ ‘minimum and maximum offset distributions,’ and ‘average X and Y distances to cell centers.’

Phase Match Vibroseis and Dynamite Data. Model-based wavelet processing (MBWP) was used to extract wavelets and compute phase differences between the vibroseis and dynamite data. During data acquisition, two shot-points were duplicated using both sources to facilitate phase comparisons between the two types of data. The common shot-points aided QC of the MBWP design and application. During the 2000 reprocessing, the phase match between the two data sources was performed earlier in the processing sequence and the MBWP phase analysis was more rigorous than that used during 1993. After stack, overlapping CDP gathers were compared and cross-correlated to verify the phase match. Furthermore, the phase was rechecked several additional times during subsequent processing steps (refer to listed steps of 2000 reprocessing) which was not done during the 1993 processing.

Refraction Statics. The application of refraction statics helped resolve the long wave statics and improved the short wave (high frequency) statics. The improvement in high frequency statics facilitated and enhanced the results of subsequent operations of automatic surface-consistent residual statics and velocity analyses. Picking first breaks on shot records and the flagging of noisy or reversed traces has become automated, providing faster analyses for editing and also exposing some additional geometry errors missed during the geometry QC. Better first break picks improved the refraction statics analyses. To further QC the refraction statics during the 2000 reprocessing, variations in computed near-surface velocities were compared to maps of topography and surface geology for consistency and validation. This was not done during the 1993 processing.

Phase Correction of the 3D Survey Data. Surface-consistent deconvolution was applied using a spike deconvolution operator of 160 ms length as a first step toward correcting the data to zero phase. The 160 ms operator length was shown to be superior to an operator length of 80 ms and comparable to an operator length of 240 ms, with preference for the shorter operator. The 10-80 hz frequency spectrum of the raw data began to dissipate above 40 hz and the spectrum was whitened to boost the amplitudes of the higher and lower frequencies (Step 8) prior to applications of velocity analyses and autostatics. Western Geophysical then applied proprietary MBWP to further adjust the data to zero phase (Step 10). Periodically during subsequent processing steps, MBWP was used to recheck phase and readjust any static shift in the data. During the 1993 processing, minimum phase deconvolution with a 220 ms operator length was used followed by spectral whitening. MBWP was applied after the spike deconvolution but only one time. This was presumed to adequately correct the phase of the data. The phase was not checked and readjusted subsequent times as was done during the 2000 processing. Better zero phase conversion and periodic QC during the 2000 reprocessing enhanced data resolution and facilitated and improved the subsequent velocity and autostatics applications.

Mutes and Velocity Analyses. First arrival waves and refractions, high amplitude “noise” in the shallow data, were only partially muted during the 1993 processing. Muting was deliberately minimal prior to DMO (dip move-out) with the intent of readjusting the mute after the DMO process. The second muting step was inadvertently omitted during the processing sequence which left refractions in the data. Stacking in the refractions smeared shallow data and produced lower-frequency, high amplitude events in the seismic data above 0.5 s. This oversight was corrected during the 2000 reprocessing. The mute pattern has become easier to design on the screen using Western Geophysical’s Omega system and several different muting applications were tested and compared to optimize the mute selection. The reprocessed data exhibited substantially higher frequencies overall, particularly in the basin-fill strata. This greatly improved velocity analyses and revealed stratigraphy that was previously obscure. Apparently as a result of optimizing the mute, multiple low frequency events (having the appearance of reverberations) present on the 1993 processed data, particularly in the Paleozoic strata, were not evident on the reprocessed seismic data. This facilitated well ties and interpretation of the Paleozoic strata. It also solved the mystery of why some thick, uniform carbonate intervals appeared to be layered or “banded” on the 1993 data.

Pre-stack Time Migration. Pre-stack time migration (PSTM) repositions individual signal wavelets in a seismic data volume back to their points of origination before the data is stacked together. This is a more correct approach to data migration than first compiling inaccurately-located wavelets into common mid-point (CMP) stacks and subsequently migrating the stacked wavelets. Two versions of PSTM were produced during reprocessing, a conventional PSTM and a full-field Stolt PSTM. Both data volumes were clearly superior in resolution and overall quality compared to the 1993 post-stack DMO time migration. During interpretation, there was a noticeable improvement when tying well tops to corresponding seismic horizons, using time/depth relationships generated from sonic logs. In theory, the full-field Stolt PSTM more closely reflects the true positions of structures than either the conventional PSTM or the DMO post-stack migration, and this version was used for the seismic interpretation.

Evaluation of Seismic Interpretation Software

Since the preferences of software users vary and are not all addressed equally by software creators, individual users will find that some seismic interpretation programs are more compatible with particular projects or interpretation styles than others. Software should be evaluated with that in mind, appreciating that all brands have desirable and undesirable features.

This overview is not intended to analyze all of the capabilities of the SeisX seismic interpretation software or compare the program directly with competing software. Some strengths and weaknesses of SeisX are pointed out that aided or impeded the interpretation of the Grant Canyon 3D seismic survey. From this discussion the reader may gain insight and better evaluate options to deal with similar interpretation issues.

Paradigm SeisX Software

Seismic interpretation programs incorporate different data picking routines and displays, but all provide basically similar interpretation capabilities. The present-day PC programs now can accomplish much of what the more expensive Unix-based workstations do, but still lack the elaborate interactive 3D visualization capabilities of Unix platforms. As previously mentioned, a PC-compatible system was chosen over a Unix-based system due to cost considerations.

The interpretation software chosen was a version of SeisX designed to run with Windows NT. SeisX was developed by Photon Systems Ltd, Canada, and has been marketed since 1994 as a Unix-based system by Photon and its successors, Cogniseis and Paradigm Geophysical. Windows NT-compatible versions have been available since 1997, which incorporated a Unix-to-PC software interfacing program. SeisX was appealing because it was available in a PC version but had been designed for a Unix platform. Therefore, the seismic interpretation capabilities of SeisX are typical of the more expensive Unix-based systems rather than PC-based systems.

Initially Paradigm supplied SeisX Version 3.4.2, the current version at the time of purchase. Later, SeisX Version 3.5 was provided to us as part of the effort to fix the graphics card problem discussed earlier. Version 3.5 was never widely distributed and some of the problems that we encountered during the past year have been addressed and fixed in SeisX Version 3.6, in the process of being released.

Overall, the SeisX seismic interpretation software performed well. The option menus are arranged logically and it did not take long to become proficient with the various interpretation steps. The program offered a number of desirable options for extrapolating an interpretation throughout a data volume.

SeisX Program Stability

SeisX 3.5 had a propensity to "crash" inexplicably and often. Crashes occurred as often as several times per hour or as infrequently as once or twice a day, usually for no apparent reason. This required reopening SeisX and regenerating the maps and displays previously being used. It was aggravating and time-consuming; however, except for the displays on the monitors, the seismic interpretation in progress did not appear to be affected by the crashes and was recoverable. Several users of earlier versions of SeisX advised us of similar experiences with crashes. It is not known if this problem will persist in Version 3.6.

Often the monitor displays turned a variety of kaleidoscopic colors when different options were selected. This affliction is called "color flashing" and occurs when colors mapped by multiple subroutines exceed the color range available for color mapping. The problem was remedied by clicking on the refresh and redraw buttons to regenerate the original colors for the seismic and base map displays. Although disconcerting, the color changes did not affect the ongoing interpretation and were quicker to fix than the periodic crashes. Version 3.6 has an expanded color range and should be less prone to color flashing.

Data Loading

SeisX was designed to read seismic data in standard SEG-Y format and data loading was relatively straightforward, employing a fill-in-the-blanks survey parameter sheet. Well log data were more difficult to load since the standard LAS format files first had to be converted to a "Photon ascii" format, which did nothing more than change the position of some of the LAS header data. Coordinates for data importing were limited to X-Y values in meters or feet.

SeisX Monitor Displays

A typical dual-monitor layout was employed for the seismic interpretation, with seismic data displayed on one monitor and a base map displayed on an adjacent monitor. The map and seismic displays are fully interactive, with the map showing a plan view of the interpretation as it proceeds on the seismic line. A number of options are available for scaling and annotating the monitor displays. However, annotation sizes had to be chosen differently for the seismic and map displays to produce suitable well symbols and text, and this complicated plotting the displays (discussed below).

A limitation of SeisX 3.5 is that this version used the same color scheme for both seismic displays and map displays. Earlier versions of SeisX reportedly offer separate color choices for maps and seismic displays, as does Version 3.6. In Version 3.5, the color scheme chosen for the seismic data display was the color scheme automatically utilized for the base map interpretation values, and vice versa. A common blue-white-red color scheme used for the seismic interpretation provided inadequate resolution for the map display, where multiple color bands often are used to illuminate the contoured data and accentuate interpretation problems. Since interpretation discontinuities were not readily apparent on the base map, they were identified using adjacent-line overlays described later in the "horizon interpretation" sub-section.

SeisX Plots

Plots are a useful part of any 3D seismic interpretation effort and essential for the presentation of results. Plotting SeisX monitor displays was a challenge, one drawback of SeisX being a Unix-based interpretation system. Like other Unix-based systems, SeisX 3.5 does not provide direct plotting capabilities and file format options are limited. Plots first had to be saved as "CGM" files and subsequently plotted using software developed by another vendor. More problematic than the added software expense and additional steps and time required to generate plots, was a general scaling incompatibility between SeisX and the chosen plotting software.

Scaling problems result from an incompatibility between interpretation software, plotting software and/or plot drivers. Available CGM plotting software varied from $600 to $3900, a significant percentage of the seismic interpretation software cost. In addition, most required stiff annual licensing fees. Lacking guidance and the time required to thoroughly research the options, our choice of plotting software was based primarily on cost. It would be a service to the customer if plotting problems associated with Unix software could be resolved by built-in plot routines, as provided by some PC-based interpretation systems.

To generate and plot the CGM files, we utilized Just-CGM Version 2.2 software by Justcroft Technical Systems. This software performed adequately but was strictly a plot utility. After a plot was generated, nothing could be changed. Even simple edits to a plot title required modifying the display in SeisX, saving the display as a new CGM file, and then opening the new file to view the changes and create the plot.

There was a lack of uniformity between the appearance of the SeisX monitor displays and the Just-CGM plots, so editing the SeisX displays for plotting was done by trial and error. For example, normal-sized well symbols and seismic shot-points on monitor displays appeared huge on plots; normal-sized contour values and text on monitor displays were microscopic on plots. Once acceptable plotting parameters were selected the parameter file could be saved and recalled. However, the sizes of some annotations, such as contour values, are incorporated into the SeisX mapping routine. To accommodate the various plots, contour maps had to be regenerated with different parameters.

Using our particular plotting software and plotter, scales specified in the SeisX display did not transfer to the plots. They varied by a factor of about 1:1.428, determined empirically. A plot of a 1:24,000 scale map was accomplished by entering a value of 1:16,800 for the SeisX map scale. Similarly, SeisX scale values of 11.2 traces per inch (tpi) horizontally and 7.14 inches per second (ips) vertically, produced the more typical seismic display scale of 16 tpi and 5 ips. Unfortunately, the entered values - not the actual plot sizes - were automatically annotated on the maps and seismic plots, which impacted the professional appearance of the plots.

Seismic Interpretation Using SeisX.

Horizon Interpretation. Interpreting the data with SeisX involved clicking a 3-button mouse to draw interpreted horizons across vertical seismic lines (profiles) extracted from the data volume. Vertical lines included in-lines, cross-lines, or arbitrary lines that cut through the data volume. Arbitrary lines could be created easily by clicking and dragging the mouse over the base map, with simple editing of pivot-points between multiple linear segments. Also, SeisX has options for quickly generating multiple arbitrary lines in parallel, radial (spokes-of-a-wheel) or fan-shaped patterns. The parallel feature permits any number of parallel lines to be displayed in a direction other than the orthogonal layout of the in-lines and cross-lines. The radial feature enables the viewing and extrapolation of seismic events outward in all directions from a well or locally-interpreted area. The fan feature may seem redundant to the radial display, but fans cover arcs less than 180 degrees and provide focused orientations and closer line spacing to facilitate detailed viewing and interpretation. All of the arbitrary line displays proved very useful and, after being created, the displays refreshed much more quickly than in-line or cross-line displays. This allowed for rapid panning through the data sets to view the structure and interpretation on adjacent lines, a very useful 3D visualization tool.

A variety of choices are available for auto-picking or manual-picking the vertical sections. The auto-picking features would have been useful on more coherent data. However, most of the Grant Canyon 3D seismic reflections are hummocky or discontinuous. Although auto-picking was employed on two shallow valley-fill reflections, considerable manual editing was required. Other horizons were picked manually due to the overall reflection discontinuity of the data and because most of the key horizons were unconformity surfaces with naturally variable reflection character that could not be auto-picked. The draw-and-erase features of the software worked quickly and predictably during the interpretation of vertical lines.

Particularly useful while interpreting in-lines or cross-lines was an option that permitted horizon interpretations from any number of paralleling lines to be overlaid as dashed lines on the current line being picked. In areas of weak data or discontinuous reflections, this feature facilitated interpretation because the general shape of a few adjacent horizon picks could be followed. During reviews of horizon interpretations, overlaying a large number of adjacent line picks accented changes in structural dip and also provided an interpretation and editing tool that emphasized discontinuities in the interpretation.

Horizon picking options and draw-and-erase features were more limited and slower when working with “time slices,” horizontal slices that provide “map” views of the seismic data volume. First, files of time slices had to be built and the size of a created file could be very large depending on the choice of the time interval between slices. A 20 ms interval worked well for the interpretation. Interpretation picks could only be made in a continuous “streaming” mode as the mouse was dragged along. This was not a particular problem until editing. Editing picks made on time slices was painfully slow as each interpreted bin of data had to be individually clicked with the mouse to be erased. Also, picks of reflection events could not be overlaid on adjacent time slices to help guide the interpretation through the layers of horizontal slices. As a consequence, virtually all interpretation was performed on vertical seismic lines. The horizontal time slices do show the developing interpretation wherever the time slices intersect picks made on the vertical lines. Therefore, the time slices are useful to periodically to check the continuity of the interpretation and its conformity to the spatial patterns of seismic events.

Fault Interpretation. Like interpreting horizons, picking faults was accomplished by clicking and dragging the mouse. Each click of the mouse produced a node on the interpreted fault line with linear segments between nodes. Arcuate faults required multiple clicks producing multiple nodes. To accelerate the interpretation of faults, fault cuts were picked using relatively few nodes. Just as for horizons, fault picks from adjacent lines could be superimposed on the line being interpreted and this aided fault plane continuity. In order to switch between picking faults and picking horizons, separate icons on the main menu bar had to be chosen to access the fault or horizon option menus, and then the respective picking option had to be selected. This was tedious for interactive fault/horizon picking or editing. As a result, some faults were not picked on every line of the survey. However, the presence of the fault would be reflected by an abrupt shift or “stair-step” between adjacent horizon picks.

To avoid the slow process of toggling between horizon and fault interpretation modes, a fault surface was picked on multiple lines and horizons were subsequently interpreted, or horizons were picked and the faults were added. In the latter case, the option to display horizon interpretations on adjacent profiles proved useful to extrapolate both the orientation and throw of the fault. Faults could be interpreted on time slices but, like horizons, the picks on adjacent time slices could not be superimposed for guidance, and editing was a nuisance. Only limited fault picks were made on the time slices to help guide the fault interpretation subsequently performed on the profiles.

Maps and Gridding Operations. Contour maps of interpreted horizons could be created after applying a gridding operation to the interpreted picks. This process was quick and the contours “flowed” smoothly. A number of grid cell-size and data smoothing options are available to accommodate variations in data quality or the contouring detail desired. Contouring orientation can be biased somewhat by selecting elongate cell sizes. The generated grids can be combined (subtracted, multiplied, etc.) to produce isochron maps or other contoured displays.

Adding arbitrary data points, for example to expand a velocity grid beyond an area of existing well values, is not an easy task in SeisX Version 3.5. The X-Y locations of fictitious “wells” must first be entered into the well file, and the desired values keyed in as “well” data. According to Paradigm, Version 3.6 will offer a simple "click on the map" method for adding data points.

Overview of interpretation results

A number of horizons were analyzed and interpreted during the data interpretation phase of the project. Four basin-fill surfaces were picked to help unravel the structural history of the Railroad Valley basin and possibly identify drape over underlying obscure structures. They included two seismic horizons approximating the middle valley fill and lower valley fill unconformity surfaces described by McCutcheon and Zogg (1994, p. 204), plus shallower and deeper sub-parallel events. Two separate landslide masses were identified and mapped, the one responsible for the Grant Canyon and Bacon Flat reservoir rocks as well as a younger slide. The Pre-Tertiary basin floor unconformity surface of Pennsylvanian/Mississippian rocks was mapped. It is a distinct, high-amplitude event where there is density contrast with basin-fill strata, but is nebulous where covered by carbonate landslide debris. The surface of the deeper Devonian strata and a sub-parallel lower Devonian (Ordovician?) horizon also were picked. The underlying flank of the intrusive was interpreted. It was most evident in the Grant Canyon field area as a detachment surface truncating unconformable Paleozoic strata.

In contrast, the 1993 processed data was more difficult to interpret and the interpretation was more limited. Only the surfaces of the Grant Canyon/Bacon Flat landslide mass, the Paleozoic basin floor and the underlying intrusive were mapped. All exhibited less clarity on the 1993 processing. In particular, the intrusive surface was more difficult to interpret due to the presence of low-frequency, high-amplitude noise reverberating through the data.

As a result of the interpretation of the 2000 reprocessed seismic data, several prospects have been identified. The prospects are currently being refined and critiqued. At this time, one of the prospects appears sufficiently promising to warrant evaluation by drilling.

Conclusions

Our experience in this project is described in two broad catagories: the installation and use of the computer hardware and software employed for seismic interpretation, and the results of reprocessing the seismic data.

A number of lessons were learned in the process of installing the hardware and software:

- Although not for beginners, installation can be done by those with a medium level of computer literacy.
- Select software and hardware components based on the quality of support that is provided. Unfortunately, the choice of operating-system software is limited, but the choice of computer hardware can be important. Hewlett Packard provided exemplary technical support.
- Unanticipated difficulties can be a major cause of delay in the intallation process. Consulting specialists may be needed to overcome some problems.

- Installation and initial use of seismic-interpretation software can be a complex process. It is important to select a vendor that can provide on-site assistance and to have access to experienced users.
- The SeisX seismic interpretation software performed well and was relatively easy to employ with little training.
- Problems with SeisX caused frustration but did not appear excessive relative to other competing software used by us or colleagues. All interpretation programs to have various problems and limitations that will be perceived differently by each user.

There are inherent limitations to how well the seismic tool can resolve the complicated geology of Railroad Valley, Nevada, but previously acquired seismic data likely can be improved by reprocessing the data due to recent advances in seismic data processing. This was shown to be the case for the Grant Canyon 3D seismic survey acquired during 1993. The reprocessing effort conducted during 2000 significantly improved the resolution and quality of the seismic data. As anticipated, this resulted in a more accurate and comprehensive seismic interpretation of the Grant Canyon and Bacon Flat fields and surrounding area.

The better overall clarity of the reprocessed seismic data not only facilitated data interpretation, but also has raised the level of confidence in the interpretation product. Several new prospect ideas emerged during analysis of the 2000 reprocessed seismic data that were not evident from the 1993 processed data. As an unexpected benefit from reprocessing the data, some geometry and processing oversights that impacted the quality of the 1993 processed data were discovered and corrected, further enhancing the 2000 reprocessing effort.

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Appendix

QC Reprocessing Report – 2000, for Grant Canyon 3D, Nye County, Nevada, for Makoil, Inc., by Elias Ghattas, Custom Geophysical Services, Denver