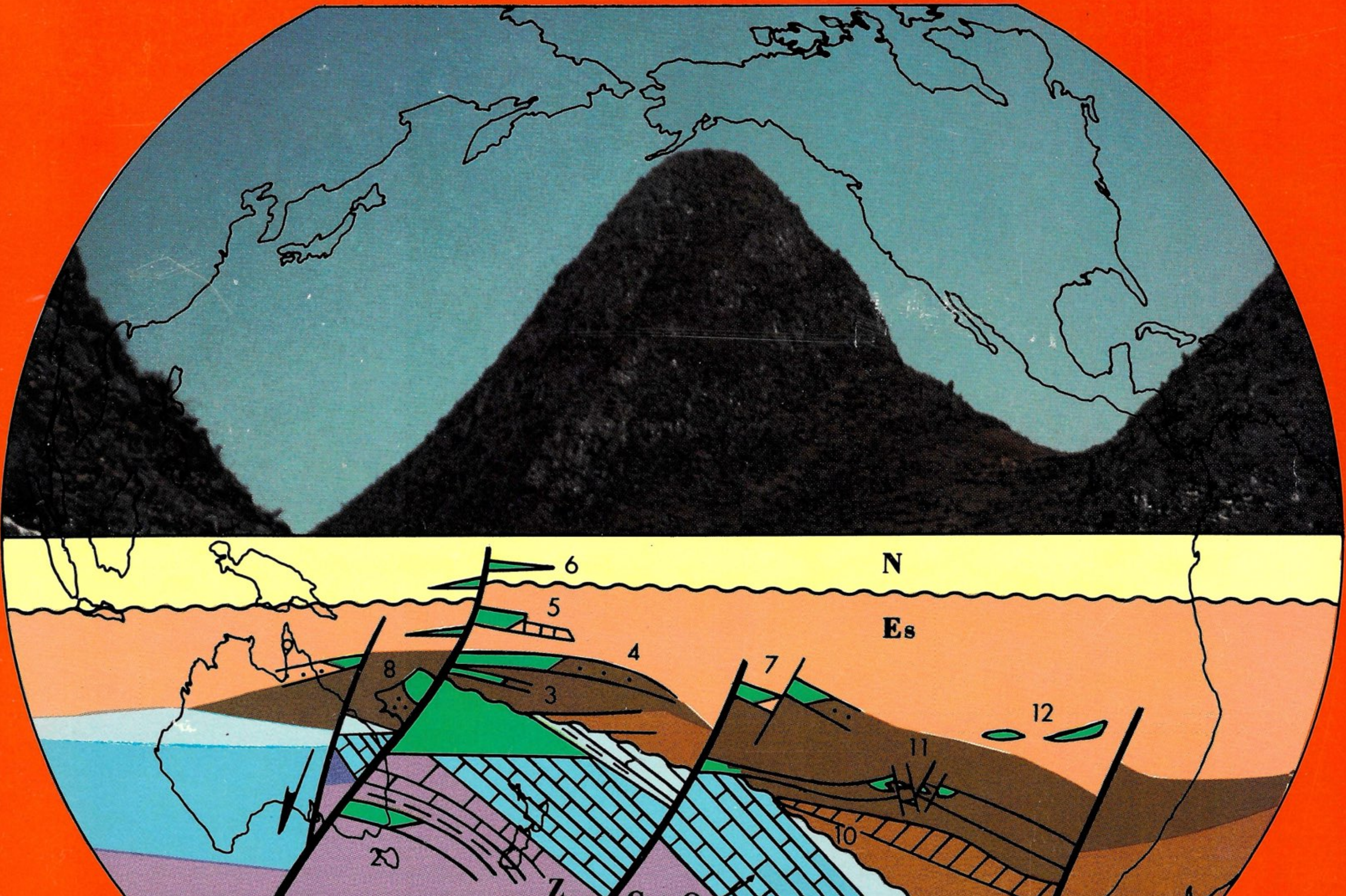
PETROLEUM RESOURCES OF CHINA AND RELATED SUBJECTS



CIRCUM-PACIFIC COUNCIL FOR ENERGY AND MINERAL RESOURCES
EARTH SCIENCE SERIES, VOLUME 10

Wagner, H.C., Wagner, L.C., Wang, F.F.H., and Wong, F.L., editors, 1988, Petroleum resources of China and related subjects: Houston, Texas, Circum-Pacific Council for Energy and Mineral Resources Earth Science Series, v. 10.

GEOPHYSICAL TECHNIQUES USED IN PETROLEUM EXPLORATION IN THE YING GE HAI AREA, ZHANJIANG, SW GUANGDONG PROVINCE, CHINA

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ABSTRACT

The China National Offshore Oil Company, Atlantic Richfield Company, and Santa Fe Minerals Asia have been jointly exploring in the Ying Ge Hai area, a 9,039 km^2 block south of Hainan Island in the South China Sea, since 1979. Drilling began in early 1983, and a significant discovery was made in mid-1983 and confirmed in 1984.

An advanced seismic acquisition system has been used to yield high resolution and deep penetration data capable of defining stratigraphic as well as structural traps. The system has 240 traces, on-line demultiplexing, a 2,400 m to 3,600 m cable, 10 to 15 m group intervals and a high-volume-tuned airgun array. Computer-assisted acoustic quality control is used on board to minimize noise.

Seismic processing parameters are determined after wavelet and resolution testing. The migrated stacked section is supplemented by color-attribute processing (such as pseudo-interval velocity and phase); depth conversion and RAP* processing have been especially helpful in stratigraphic seismic interpretation. Seismic attribute displays are calibrated with well log data. For testing, some data were subjected to 60-, 80-, or 120-fold processing with either a 2 or 4 ms sample rate. Measured far-field signature was used in deconvolution.

Vertical seismic profile logging allows a direct tie from the geological well logs to surface seismic. All well logs, seismic, and potential-field data are computerized in a data-base management system. Time, velocity, depth and thickness maps for both local prospects and regional prospects are routinely generated to assist the explorationists. Geological and geophysical modeling have helped to define well locations.

Using advanced interpretation and display techniques, such as computer grid residuals, bandpass filtering, and RAMTEK color displays, gravity and magnetic data anomalies have been closely tied to seismically derived trends.

INTRODUCTION

Atlantic Richfield Company (ARCO) has been interested in the hydrocarbon potential of the South China Sea for several years. In 1978, ARCO was invited to acquire seismic data and to make an exploration evaluation of a large contract area offshore from Hainan Island in the northwest portion of the South China Sea (Figure 1).

Regional seismic, gravity, magnetic, and geologic

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*The technology of several contractors will be shown and discussed in this paper. The processes or systems asterisked throughout this report are proprietary, patented, and copyrighted. The process or system names and their ownership are listed in the Appendix.

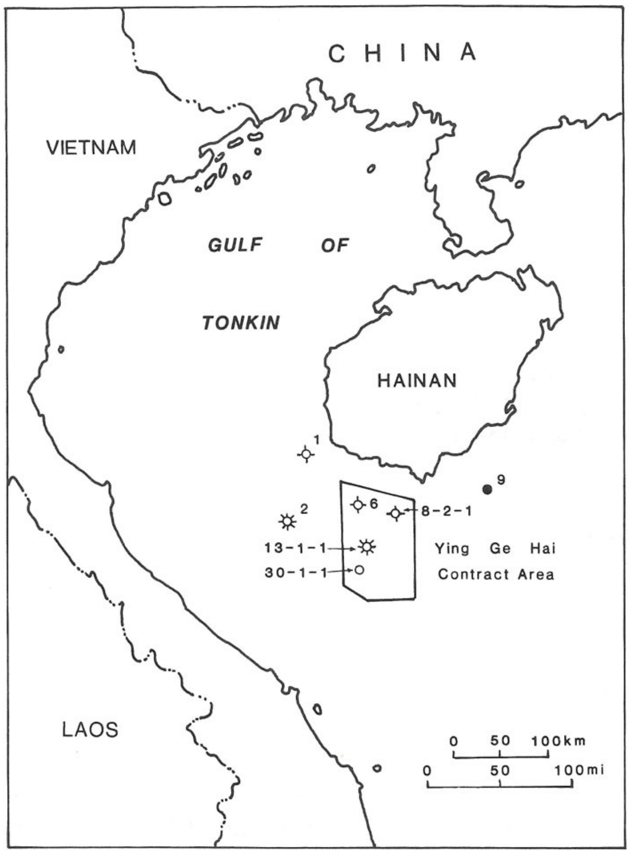


Figure 1. Map showing the Ying Ge Hai contract area, China.

surveys were done in 1979. Geophysical data were acquired, processed and interpreted by a team of explorationists from various ARCO companies and from the China National Offshore Oil Company (CNOOC). A comprehensive report was presented to CNOOC management in 1980. A contract was signed in September 1982 between ARCO China Inc. (ACI), CNOOC, and Santa Fe Minerals Asia to develop the Ying Ge Hai block, which covers an area of 2,233,567 acres (3,490 mi^2; 9,039 km^2), south of Hainan Island. ARCO China Inc. is the operator for the partners.

An operations office was set up in Zhanjiang in southwestern Guangdong Province, and drilling began in January 1983; detailed seismic work was done in the spring of 1983. A gas/condensate discovery was made during the summer of 1983; the discovery was confirmed by delineation drilling in mid-1984. Additional seismic data were acquired in the spring of 1984 and more are being acquired in 1985. ARCO continues to drill in the Ying Ge Hai area.

Early in the exploration of the block, ACI and Nanhai West Oil Company (NHWOC) realized that both structural and stratigraphic traps were possible. This contributed to a decision to use state-of-the-art technology in the exploration of the area. Today we have an integrated exploration process that utilizes computer data-base technology designed to evaluate fully the structural- and stratigraphic-trap potential of the Ying Ge Hai area.

The Ying Ge Hai block is a geologically varied area with sediments of Oligocene to Holocene age. The sedimentary section is from approximately 1,350 m (4,000 ft) to 12,000 m (36,000 ft) thick. There are six major geologic trends in the Ying Ge Hai area, and many apparent structural and stratigraphic traps are visible on the seismic data.

GEOPHYSICAL DATA ACQUISITION

By the end of 1984, NHWOC and Santa Fe Minerals have acquired approximately 14,300 km of seismic data and 10,000 km of gravity and magnetic data in the ARCO contract area. A summary of the parameters for seismic data acquisition in 1979 and 1983/84 are given in Table 1. In late 1982, an ACI and NHWOC task force decided on new parameters and a recording system to maximize penetration and resolution. An entirely new acquisition system was fielded in 1983, and advanced quality control equipment was added to monitor data quality and to improve the incoming data as the survey was underway.

Data acquisition in 1983 and 1984 utilized the CHINA-GECO *Alpha*. New systems were put on board the *Alpha* to accomplish deep penetration and high resolution seismic surveys. Special note should be taken of the 240-trace charge-coupled GECO cable, the high-energy airgun source, the comprehensive extended data header, and the on-line NORSK DATA* demultiplex system.

The CHINA-GECO *Alpha* is well suited for high technology operations. It is 91 m long, 15 m wide and has a gross tonnage of 2,908. The *Alpha* has a large amount of operational onboard room that enabled ARCO to install much equipment not normally available on smaller vessels. The *Alpha* has a 19-m wide heliport that allowed large helicopters to land and to transfer personnel, provisions, equipment, and tapes to the vessel while at sea. The *Alpha* can stay at sea for over 60 days, thus reducing port-call cost. Large airgun compressor capacity allowed greater than 3,000 in^3 volume operation with less than 10 seconds between impulses. The air pressure was 2,000 psi.

The GECO 240-trace charge-coupled cable allows group spacing as close as 2.5 m. ARCO used 10-m and 15-m spacing. The cable exhibits very low noise characteristics under tow. The cable reel is located

Table 1. Seismic Data Acquisition Parameters, Ying Ge Hai Area.

Parameter	1979	1983/84
Energy Source	Airguns	Airguns
Volume	1,760 in^3	3,101 in^3
No. Guns	27	27
Gun Depth	9 m	8 m
Firing Interval	25 m	20-30 m
SP Interval	25 m	20-30 m
Cable Length	2,375 m	2,400 to 3,600 m
No. Traces	96	240
Cable Depth	12 m	8 m
Group Interval	12.5 m	10 to 15 m
Geophones/Group	15	24
System	1-DFSV	2-DFSV
Demultiplex Online	No	Yes
Format	SEG-B (1,600 bpi)	SEG-D (6,250 bpi)
Effective Fold	48	60 to 120
Sample Rate	2 ms	2 ms

above a spare cable and repair shop deck. The cable can be lowered out of the weather for repairs, if necessary.

The NORSK DATA* on-line demultiplex system utilizes high-density tape drives and yields a 240-trace sequential output. This output can be plotted and used for quality control evaluation beyond that available on a conventional seismic vessel. The resulting onboard data are in a format similar to processed data and can be readily analyzed by ARCO Exploration Company onboard quality-control personnel to upgrade data-acquisition parameters during recording. Data are demultiplexed in "real time" and output to tape in 240-trace sequential mode at 6,250 bpi. This procedure results in 1,500 km of 240-trace, 2-ms sample data requiring less than 1,200 tape reels. Editing can be done during the demultiplexing step using the menu-driven NORSK-DATA* computer keyboard. The system has up to 32 megabytes of memory and an attached TRI-LOG plotter to display traces for quality control. It is estimated that the GECO on-line demultiplex system results in a net cost savings of 15% due to reduced processing center time and also allows considerable quality improvement while recording.

The CHINA-GECO *Alpha* has GECO airgun source and cable control systems that allow monitoring of an extraordinary amount of geophysical parameters during operations. ARCO Exploration Company quality-control supervisors utilize proprietary computer systems to monitor mechanical systems on board the vessel as well as the systems deployed behind the vessel. The ARCO/GECO source system consists of 27 airguns in 6 arrays yielding 3,101 in^3 of capacity. This translates to approximately 60 bar-meters of energy. The signal is sharp and has produced the high resolution, deep penetration profiles it was designed for. The GECO gun deployment and enclosed gun-to-cable systems result in a great reduction in gun-caused downtime that is common in a conventional system.

After close cooperation between ARCO/NHWOC and GECO technical experts during start-up operations, the *Alpha* became a quiet geophysical platform allowing high signal-to-noise ratio data to be recorded. The ARCO quality-control computers were interfaced into major onboard mechanical systems, and noise-frequency spectra and amplitude were analyzed. Mechanical systems were "fine-tuned" to produce the lowest amount of noise possible along the cable.

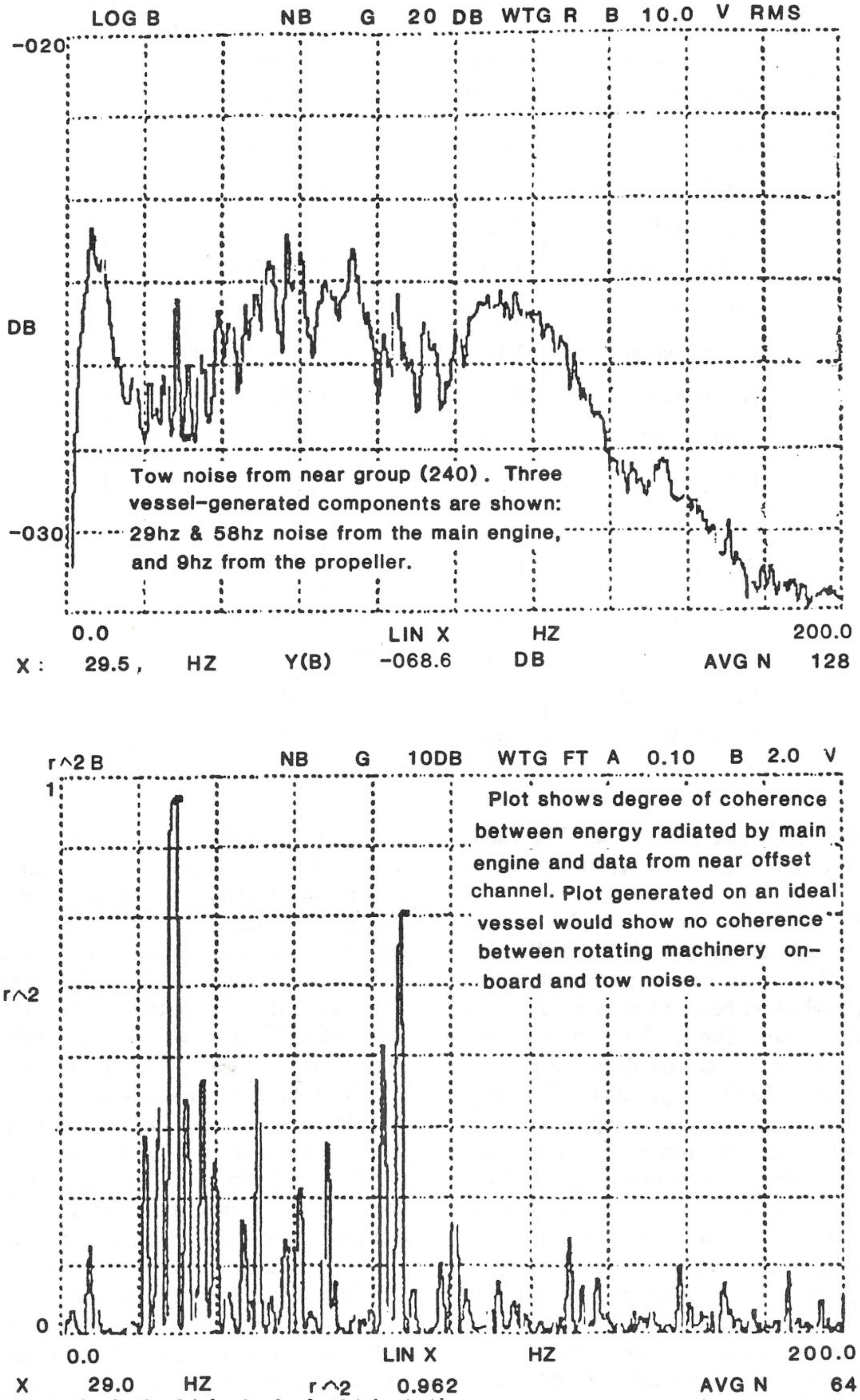


Figure 2. Onboard quality-control data-analysis charts.

Prior to field operations, the source signature, cable, and recording system response were simulated on ARCO computers allowing a match of the best components in the acquisition-parameter configuration. During recording, the field system closely approximated the computer simulation. The onboard quality-control monitoring by an ARCO acoustic engineer allowed sophisticated tuning of the system to best fit the area of operations.

Examples of the types of data analyzed by the ARCO acoustics engineers with the onboard computer are shown in Figure 2. The computer interfaced to the *Alpha* was a Scientific Atlanta Spectrum Analyzer. When data from this system are analyzed, the rpm of various machines and the pitch of the propeller can be adjusted to lower the power of noise peaks at certain critical frequencies. The *Alpha* mechanical system is "fine-tuned" by this method in order to allow for a high signal-to-noise ratio.

Table 2. Printout Model of Extended Header Recording System Aboard the CHINA-GECO M/V *Alpha.*

Day Time Location (lat/long) Shotpoint DFSI/DFSII record
Speed Gyro headings Water depth DFSI reel no. DFSII reel no.
Shotpoint spacing Antenna/source distance Airgun volume Array spacing DSS system output (volts/bar)
Tail buoy bearing Tail buoy range Digicourse streamer depth (at each group) Digicourse streamer heading (at each compass) Gun depth (at each array)
Manifold pressure Gun control system status - current Gun control system status - history
NOTES: Extended header automatically prints out data at every 40 shot points, but is available at each shot point. Extended header is useful onboard, but is invaluble to the processing geophysicist.

The GECO extended-tape header-recorded on-shot files are very useful in onboard quality control as well as in the processing center. If there are problems with lines or shots, they are generally obvious on the extended header. Table 2 shows information on this header. These data are automatically printed out every 40 shot points and are then included in the tape shipment to the processing center.

For 1983 seismic data gathering, well-site surveys, and rig moves, ACI and Nanhai-Geomex Surveys designed an ARGO/Syledis-B* navigation net especially oriented for use in the Ying Ge Hai area. The ARGO/Syledis-B* radio-positioning systems are integrated on the same tower but isolated from each other.

ARGO is the primary navigation system. Syledis-B (with boosters) is a medium range system used as a calibration for the ARGO. This integrated system performed well, depending on the atmospheric conditions and distance from shore. In 1984, ACI and Nanhai Racal made several improvements to the system. Shore-based stations were installed permanently, and an extensive ground plane was established at each location. In 1985, a switch was made to ARGO/MAXIRAN.

GEOPHYSICAL DATA PROCESSING

Acquiring seismic data using the best available technology is only the start of the geophysical data evaluation process. Production data processing must make full use of the raw data. In order best to use the data, ACI and NHWOC conducted extensive test processing in 1983 and 1984.

The data were processed by Western Geophysical Company in Denver, Colorado in 1983 and by the Geophysical Research Institute and Western Geophysical at Zhuoxian, PRC in 1984. The same software was used both years with some moderate upgrades being utilized in 1984. A summary of the testing sequence is shown in Table 3.

Production processing consists of source-signature deconvolution, velocity analysis, stacking, and F-D migration of the data. The sequence used for production processing is shown in Table 4. Processing was done entirely in the true-amplitude mode to allow the maximum amount of lithologic information to appear in the final processed data.

The signal-to-noise ratio of the 1983/84/85 data is very high. The frequency content is also high with 80 cps at 3.0 seconds not unusual. After testing, it was

Table 3. Data-processing Testing Sequence, Ying Ge Hai Area.

Sampling	*Migration*
240 traces	F-K migration
120 Adjacent Trace Sum⁺	Kirchoff migration (used on some lines)
2 ms sample rate	F-D migration⁺
4 ms sample rate	
4-2 ms supersample⁺	*Bandpass Filtering*
Deconvolution	Time varying filter
	Filter panels
Signature decon	Fan filter
Spike decon (various gaps)	Radial predictive filter
DBS + DAS	Time invariant filter (6-80)⁺
Signature/Spike DBS⁺	
	Time Variant Gain
Stack	
	RMS gain
Offset stack	Peaks gain
Beam Steering	RMS/peak gain after stack⁺
Weighted-offstack	
Normal stack (60, 120, 160 fold)⁺	*Other*
Multi-channel Coherent Noise Filter	Time var. spectral whitening (before and after stack)
Before stack	Mixing of shallow section
After stack (various trace windows)⁺	Depth Conversion
	Before migration
	After migration⁺

⁺Final parameter used

decided that the raw data could be processed with a 4 ms sample rate and then "supersampled" back to 2 ms in final display with little or no reduction in data frequency content. Extensive testing of 2 and 4 ms processed data has proven this concept to be true in the Ying Ge Hai area. Apparently, frequencies above 62.5 cps are retained in 4 ms processed data due to a high signal-to-noise ratio. Ying Ge Hai data do not generally have a strong noise aspect, partially as a result of acquisition quality control.

Processing is done using signature deconvolution. This source/array signature was recorded using digital sonobuoys during the acquisition phase. Source signature information is far-field, meaning that it was recorded in deep water using exactly the same field system with which the actual data were recorded. This method results in a close tie between the seismic field data and the VSP data from the wells.

POST-PRODUCTION PROCESSING

The term "post-production processing" is applied to the processing that was done beyond the time-migration stage. The purpose of this additional processing is to extract the maximum amount of structural and stratigraphic exploration information from the seismic data.

Relative Amplitude Processing (RAP*) is done on each line in both polarities. ARCO processing procedures specify the RAP* mode from the initial processing step with the sections gained up in final display only. RAP* sections are particularly useful in areas where there are lateral changes in lithology and/or density, such as in the Ying Ge Hai area.

Depth processing is done on a three-dimensional (3-D) basis. Velocity analyses are run every 1 to 2 km on all lines. All velocity data are then input by tape to

Table 4. Production Processing Sequence, Ying Ge Hai Area.

Parameter	1979	1983/84
Sample interval	4 ms	2 to 4 ms
Demultiplex	Proc. center	Done in field
Edit	Yes	Edit/zipper/sum
DBS (1)	Spike (4 ms)	Signature deconvolution
DBS (2)	--	Spike (4 ms)
Stack	4800%	6000/8000/12000%
Migration	F-D	F-D
Noise filter	--	MCCF*
Filter	Time varying	bandpass (6-80 cps)
Final display	4 ms	Supersample to 2 ms RMS gain applied
Other processing	True amplitude	RAP*
	Depth	Depth
Attribute	Test	Interval velocity Instantaneous phase Impedance Amplitude Frequency Cosine of inst. phase

Note: Relative amplitude was maintained throughout processing. Signature deconvolution was done with field-recorded far-field signature digital data. (Applies to 1983/84 data).

the ARCO computer data base. Velocity cross sections are made for each line and velocity timeslice. Velocity horizon maps are generated by the computer. The velocity values are smoothed and tied at line intersections. Then the velocity values are re-input to the processing computer and used to convert time-migrated lines to a depth mode. The ARCO Ying Ge Hai data base currently has over 5,000 velocity data files. The velocity data are of high quality in this area and drilled depths correspond closely to those predicted by seismic-reflection profile interpretation.

Seismic attribute processing has proven to be an important tool in the Ying Ge Hai exploration program. ACI, NHWOC, and Santa Fe use the SHADCON* program available from Western Geophysical Company which outputs color or black-and-white attribute displays. SHADCON* stands for "computer generated SHADed CONtouring of seismic data". Ying Ge Hai data have been attribute-processed for interval velocity, instantaneous phase, frequency, amplitude, impedance and cosine of instantaneous phase. The most useful attributes have been color interval velocity and black-and-white cosine of instantaneous phase. These outputs yield outstanding "stratigraphic" data. Attribute displays can be calibrated to the existing wells to allow for better low-frequency velocity curve input.

The SHADCON* program assigns user-defined colors at certain specified velocity-contour levels. The input data to the program have already undergone a transformation to pseudo-velocity, frequency, and phase. The transformation from trace amplitude to acoustic impedance requires an estimate of the reflection coefficients and velocity associated with dominant reflections in the seismic section. A very broad band-pass filter is also used. A continuous velocity estimate is generated from the seismic section. The theoretical-envelope function, dominant-frequency function, and phase function are all computed using the Hilbert transform of the input trace. A fast Fourier transform is used with the Hilbert transform. Output sections are then input to SHADCON*, and color levels are assigned to the appropriate parameter (i.e., hertz, degrees, meters/second).

SHADCON* production processing can be very expensive. ARCO, NHWOC, and Santa Fe experimented with different processing parameters to maintain high resolution while decreasing the overall cost. As mentioned above, the Ying Ge Hai data allow 4 ms production processing and resampling back to 2 ms for final display due to the high signal-to-noise ratio. Attribute processing is accomplished with the added cost-reducing modification of processing every other trace with little, if any, decrease in spatial resolution. These steps have reduced the overall cost of color-velocity production-processing by a factor of four.

Early in 1983, it appeared that the color-phase display was greatly improving the resolution of the data over the standard seismic section. Western Geophysical Company and ARCO/NHWOC geophysicists decided upon a cosine of instantaneous phase display that is black and white and can, therefore, be reproduced quickly and inexpensively. The cost to produce this product was a fraction of that for color. In fact, the black-and-white section has turned out to be more useful in interpretation than the color; black and white is now done on every seismic line recorded. Black and white cosine displays do not contain relative amplitude information, however; but the output greatly improves lateral reflector continuity.

An example line (Figures 3-11) exhibits the various types of processing done in the Ying Ge Hai area. Post-production processing has been completed on a large number of lines. Attribute processing had been done on approximately 2,000 km of seismic data by the end of 1984.

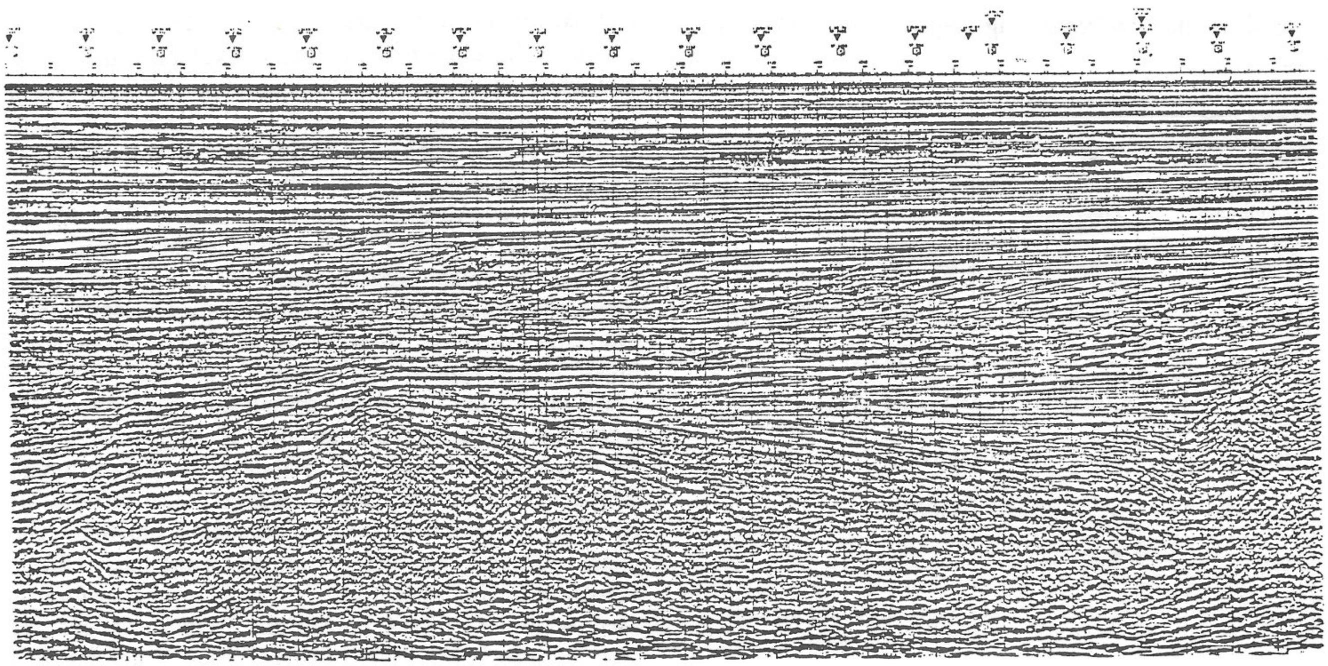


Figure 3. Time-migrated multichannel seismic-reflection profile using finite-difference migration for line C286A-83.

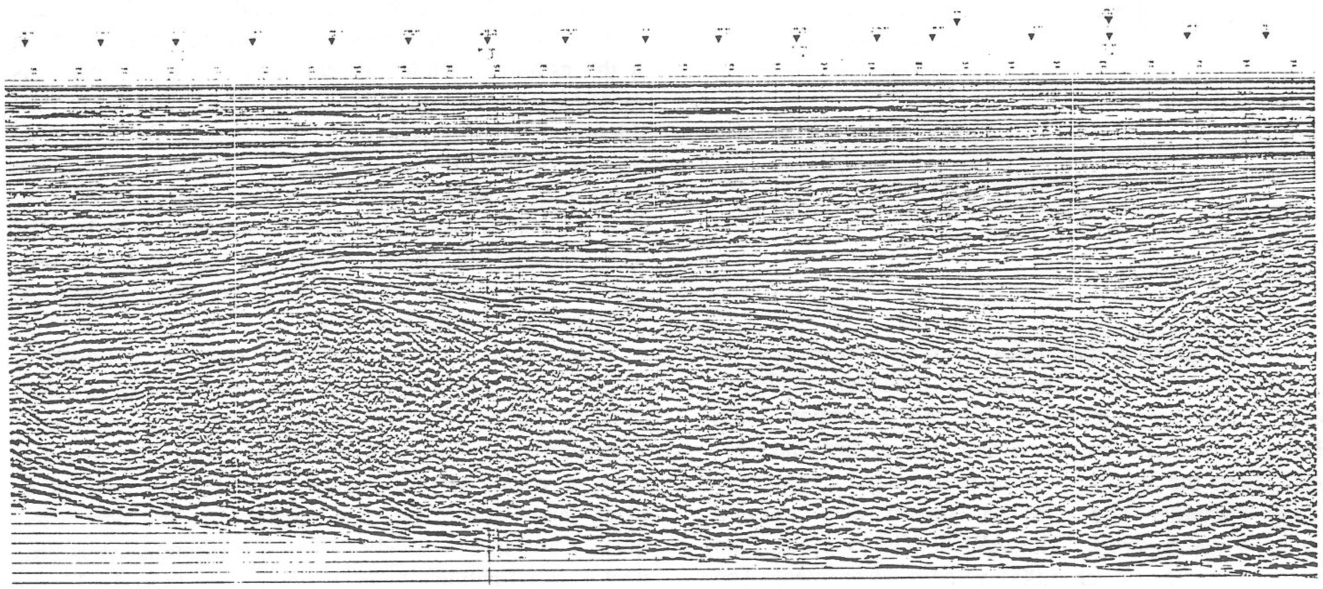


Figure 4. Depth-migrated multichannel seismic-reflection profile for line 286A-83.

EXPLORATION COMPUTER DATA BASE

ARCO, NHWOC, and Santa Fe now have a very large volume of geological and geophysical data in the Ying Ge Hai area, and it is increasing continuously. In 1983, the decision was made to put these data onto an exploration computer-data-base system to allow for advanced interpretation of the data in a more thorough and faster manner than would be otherwise possible. Such an exploration computer-data-base system was developed jointly by ARCO and NHWOC.

At present, the bulk of the data resides in the large ARCO computer system in Texas. In our Los Angeles exploration office, an IBM 4381 computer accesses these data for interactive use.

Because such a large volume of data must be

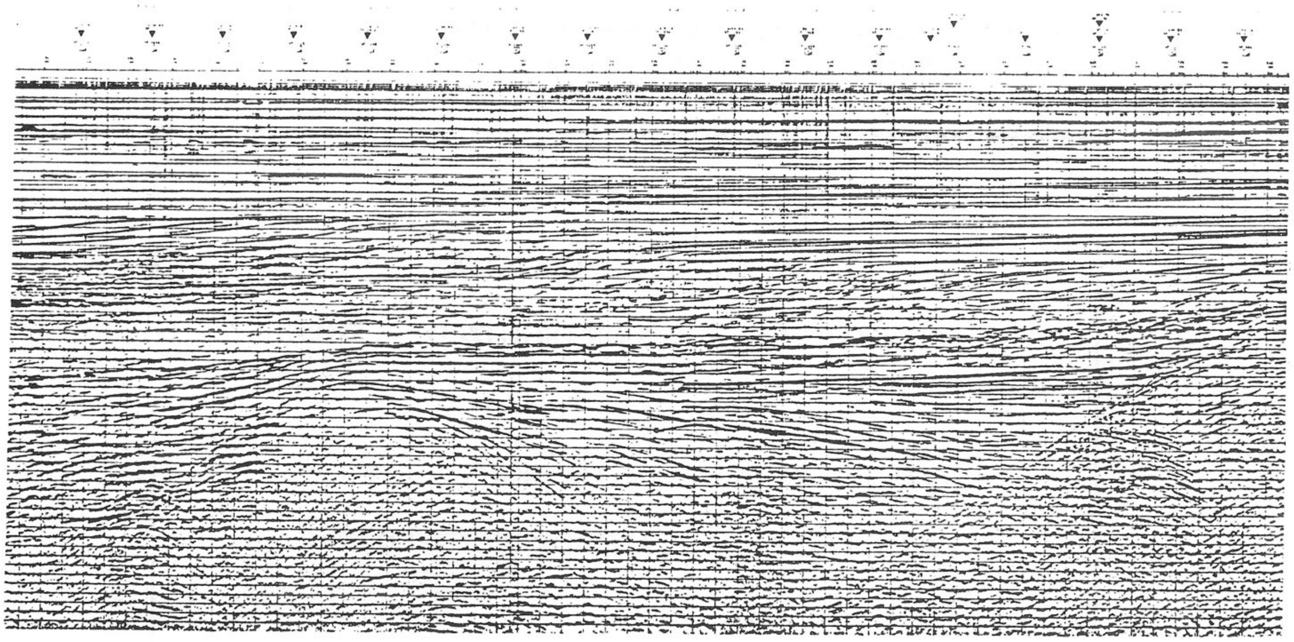


Figure 5. Relative-amplitude-processed (RAP*) multichannel seismic-reflection profile for line 286A-83.

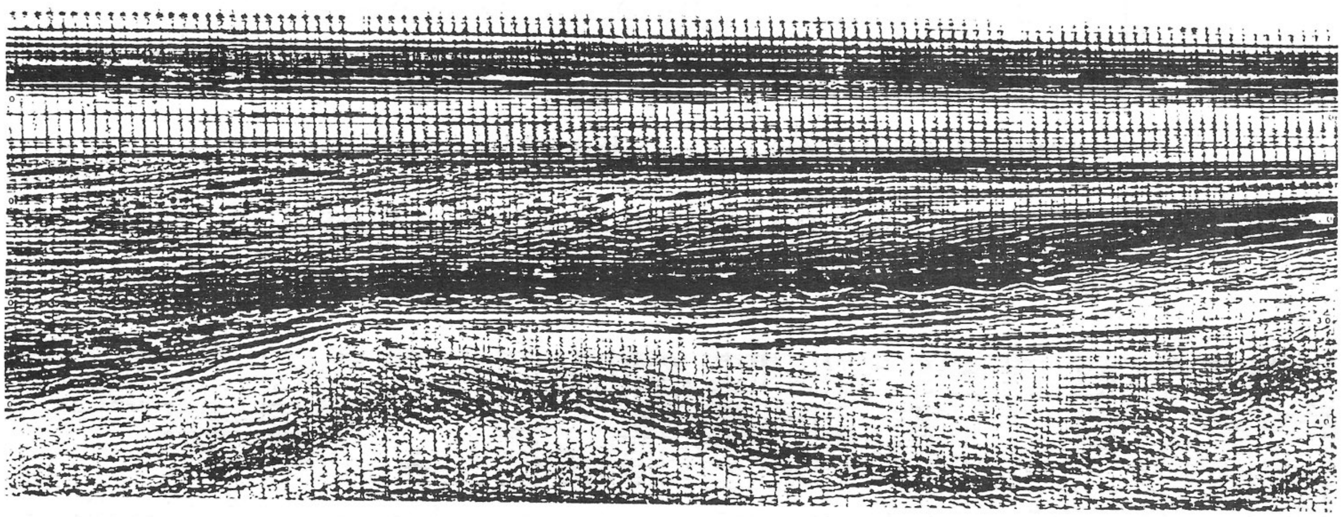


Figure 6. Multichannel seismic-reflection profile of line 286A-83 generated by using pseudo-interval velocity data (300 m/s velocity increment). [Original in color]

integrated for each prospect or regional evaluation, the computer is used in the interactive mode to facilitate interpretation of the seismic data and produce a wide variety of maps. Table 5 shows the process sequence for the input and output of data with this system.

Navigation data are first entered into the computer-data-base system. Seismic sections are interpreted, and the results are put into the data base. Actual seismic data can be accessed and selectively processed using the interactive screen. This is especially useful when modeling.

Velocity data can be entered by hand. Normally, however, velocity analysis tapes are accessed from the processing center. Vertical seismic profile and well log data are also accessed from the computer data base.

Output can be in several modes. Hardcopy output is instantly available at the interactive interpretation station. Plotters also can output any type of data, including

Table 5. Exploration Computer Data Base Process Flow Input/Output Sequence for Development of a Reservoir Evaluation Model in the Ying Ge Hai Area.

INPUT	
NAVIGATION DATA TAPES	
SEISMIC DATA - TAPES OR DIGITIZED SECTIONS	
VSP DATA TAPES	
VELOCITY DATA - TAPES OR DIGITIZED VELANS*	
WELL LOG DATA - TAPES OR DIGITIZED LOGS	
OUTPUT	
VELOCITY MAPS	TIMESLICE OR HORIZON
REGIONAL MAPS	TIME-DEPTH-ISOCHRONS-ISOPACHS
PROSPECT MAPS	TIME-DEPTH-ISOCHRONS-ISOPACHS
3 DIMENSIONAL MAPS	ISOMETRIC DISPLAYS
GEOLOGICAL/GEOPHYSICAL CROSS SECTIONS	

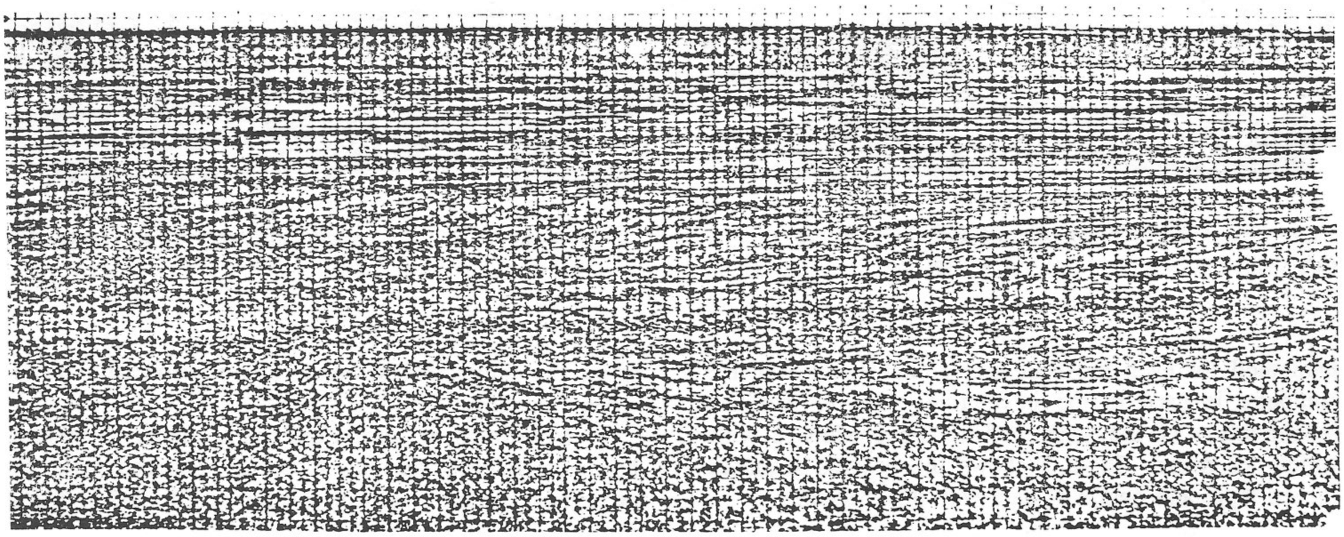


Figure 7. Multichannel seismic-reflection profile generated by the amplitude envelope method, line C286A-83. [Original in color]

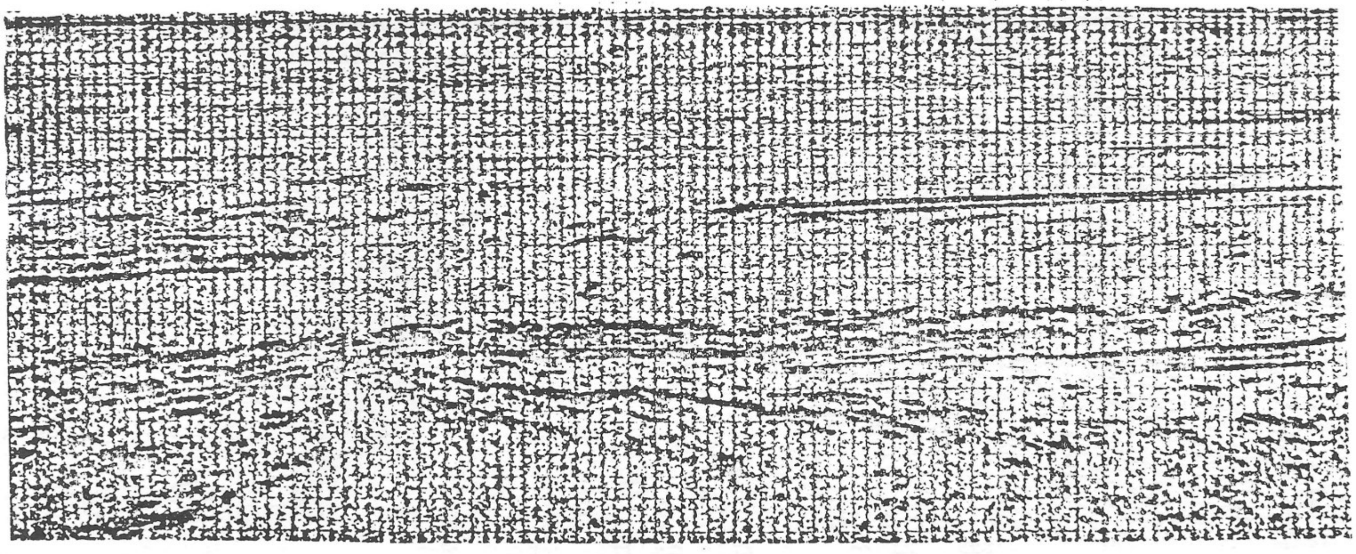


Figure 8. Multichannel seismic reflection profile generated by using dominant-frequency data, line C286A-83. [Original in color]

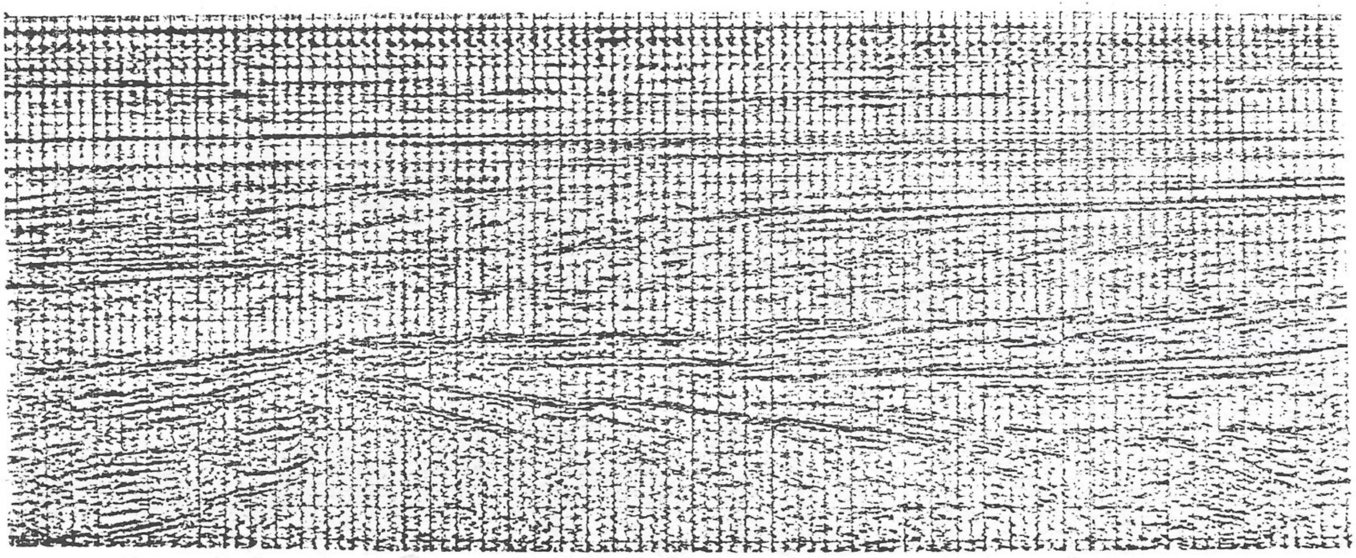


Figure 9. Multichannel seismic-reflection profile generated by the pseudo-impedance method, line C286A-83. [Original in color]

seismic sections, well cross sections, and maps. Data can be output to tape for use elsewhere. Figures 12 and 13 show example outputs of a time-related structure contour map and of a velocity time-slice map, each generated from the computer-data-base system.

Manipulation of the data is done in real-time and displayed on the interactive screen. The explorationist can alter the input/output parameters before plotting, which saves time and money. The primary reasons for using a computer-data-base system are to manage effectively a large amount of exploration data and to derive more useful interpretations of the data than could be done by hand in the time available.

Confidence in the geological and geophysical interpretations of this mass of data by the explorationist increases with computer data-base use. The greater confidence is probably due to the fact that the explorationist knows he is using more data to make his decisions than he could possibly handle alone, and that he has personally chosen the parameters for his work.

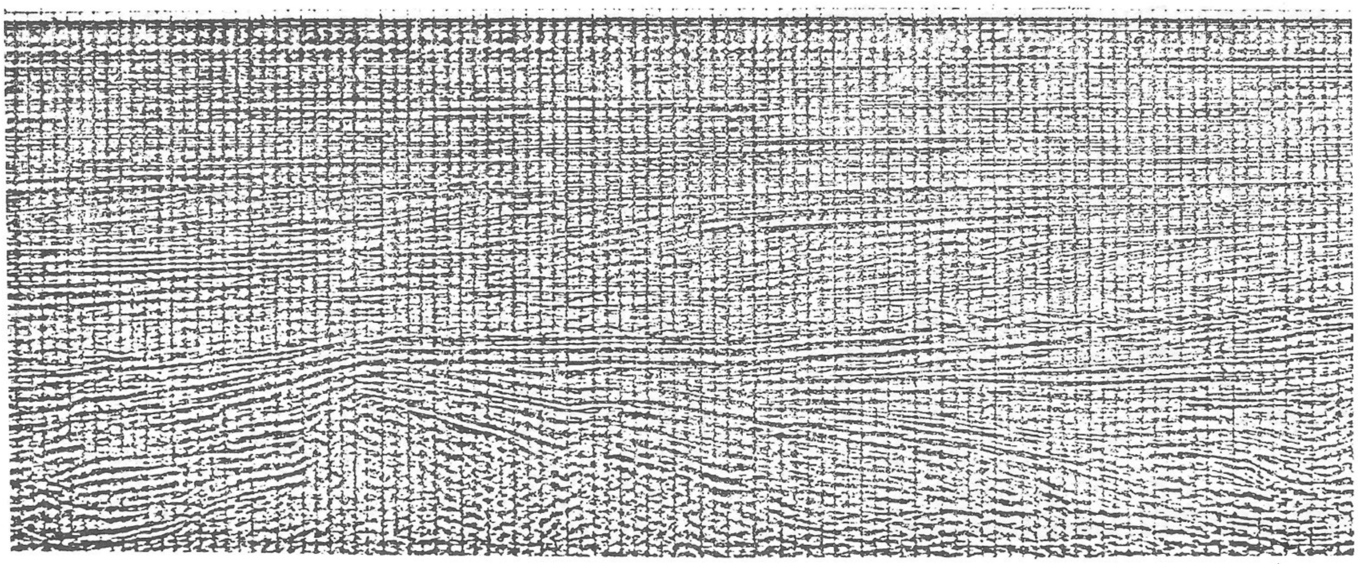


Figure 10. Instantaneous-phase-generated multichannel seismic-reflection profile for line C286A-83. [Original in color]

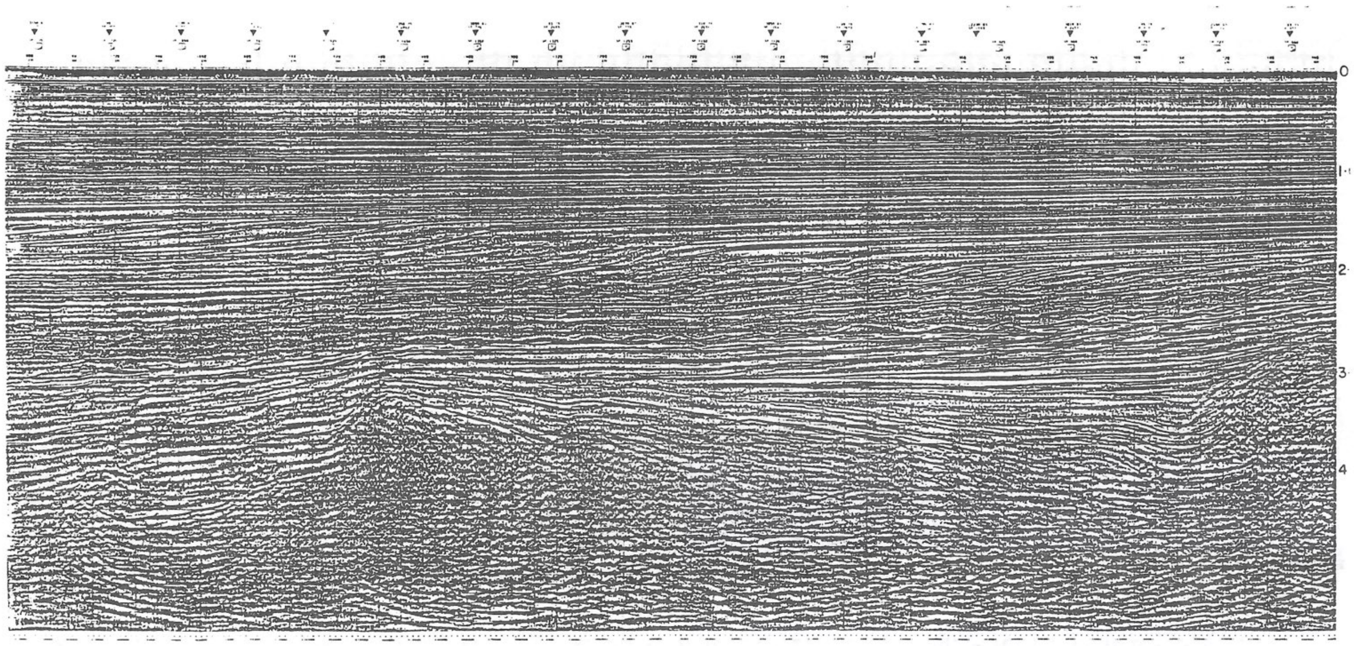


Figure 11. Cosine of instantaneous-phase-generated multichannel seismic-reflection profile for line C286A-83. [Black and white]

VERTICAL SEISMIC PROFILING

Vertical Seismic Profiling (VSP) has been used to log drill holes in the Ying Ge Hai area with great success. The VSP tool allows a one-to-one tie between the surface seismic data and the geology in the borehole.

A display can be made using the computer that lays out the various well logs in depth on a horizontal scale and the surface seismic section through the well in time on the vertical scale. The VSP is the tie between geology and geophysics because this logging tool measures seismic time and signal at specific depths in the well, commonly at about 50 m (150 ft) intervals. The VSP records all the signal—not just check-shot information. The VSP data are processed much like a seismic section. The final result is shown in Figure 14. Here

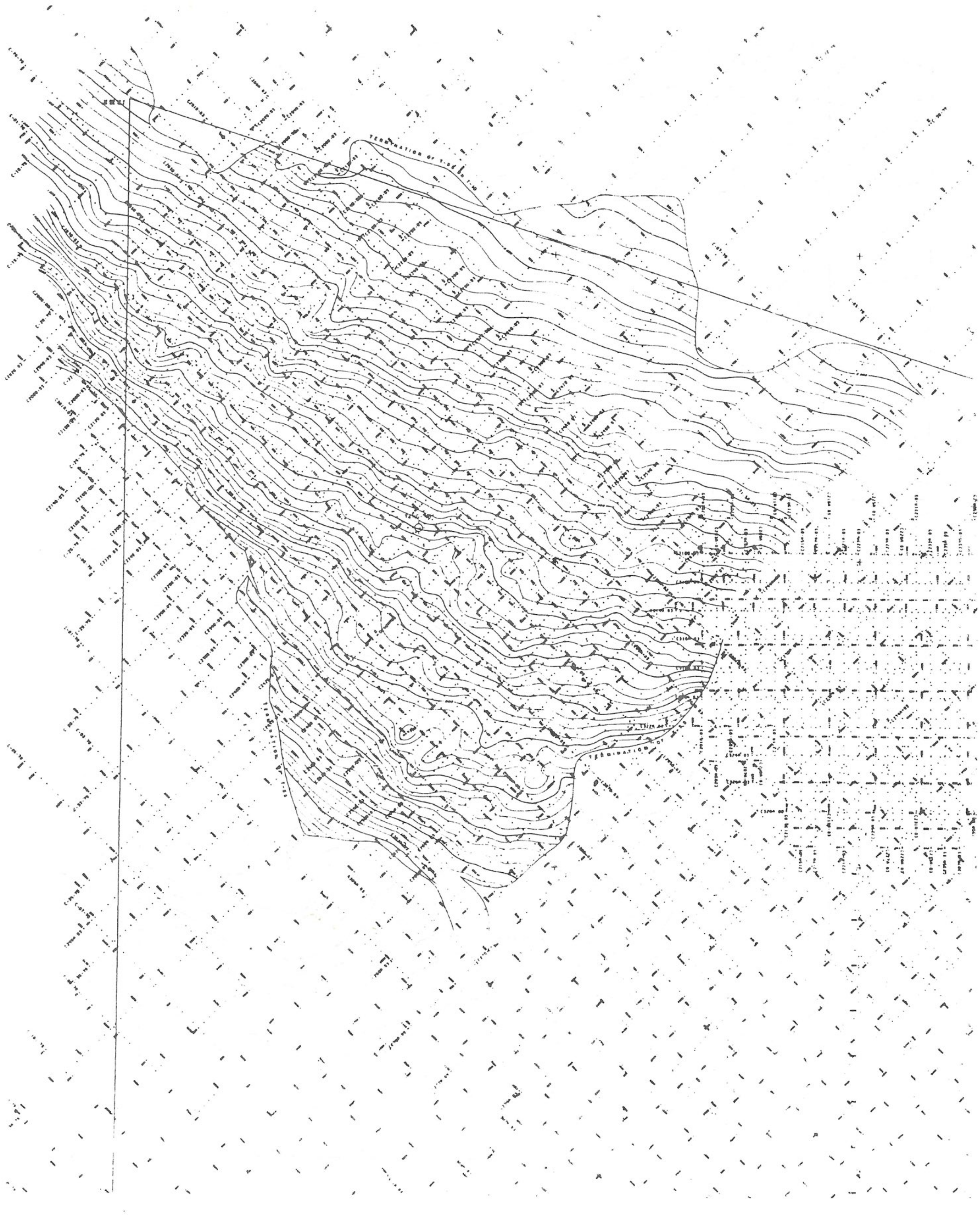


Figure 12. Computer-generated time-related structure contour map in the NW part of the Ying Ge Hai contract area.

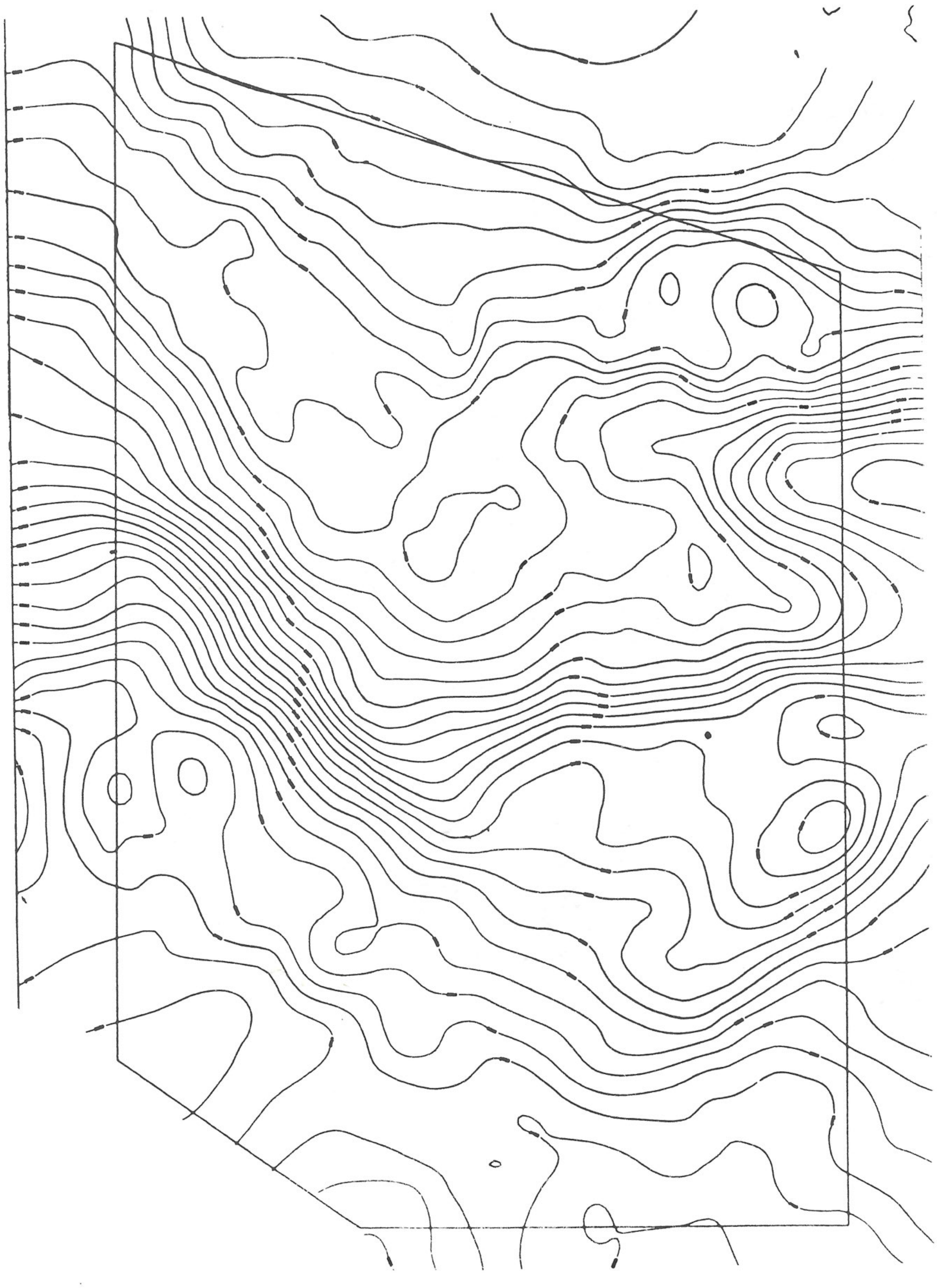


Figure 13. Computer-generated velocity time-slice map of the Ying Ge Hai contract area.

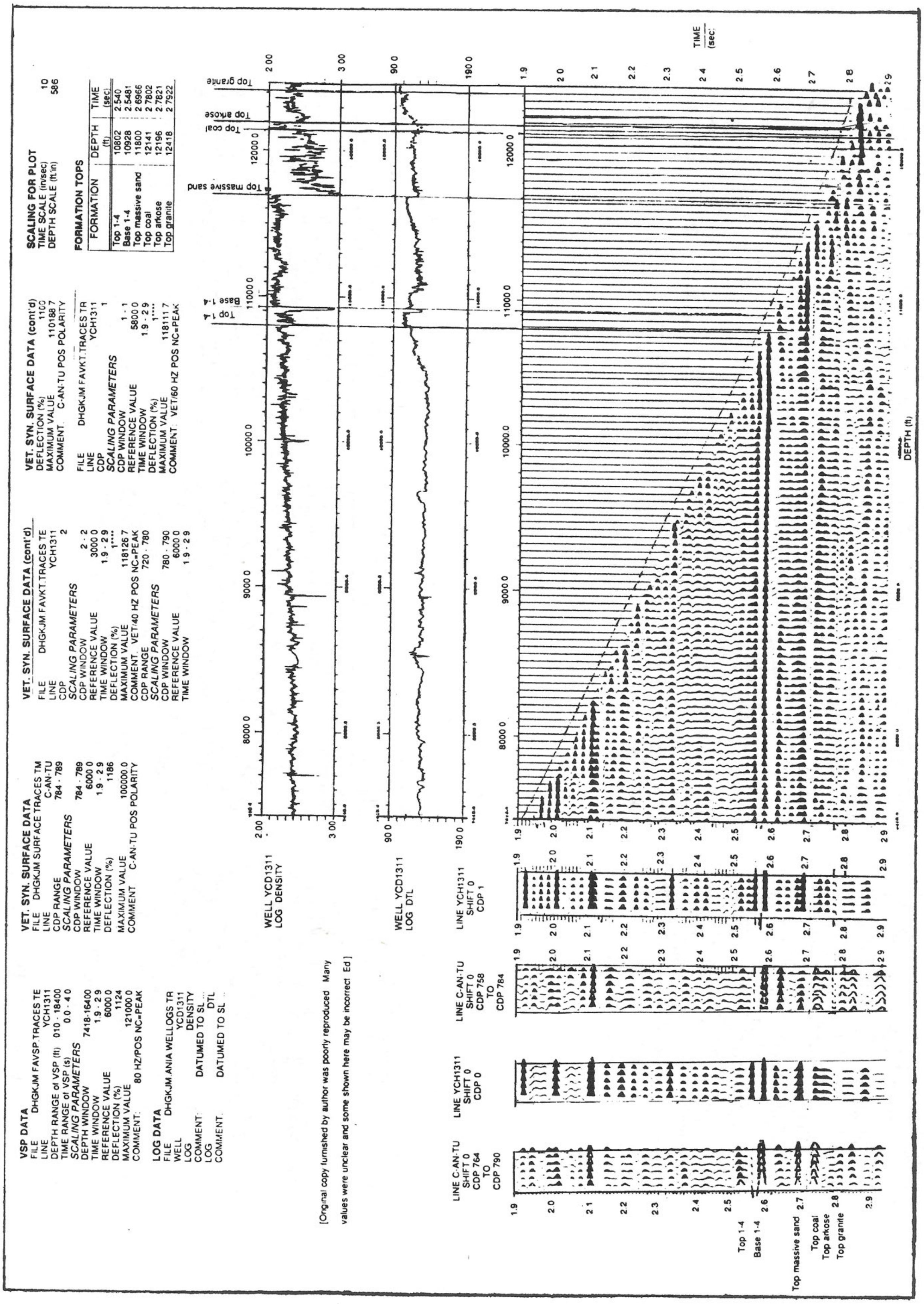


Figure 14. Vertical seismic profile (VSP) "Bridge" display of the Yacheng 13-1-1 VSP/AGC.

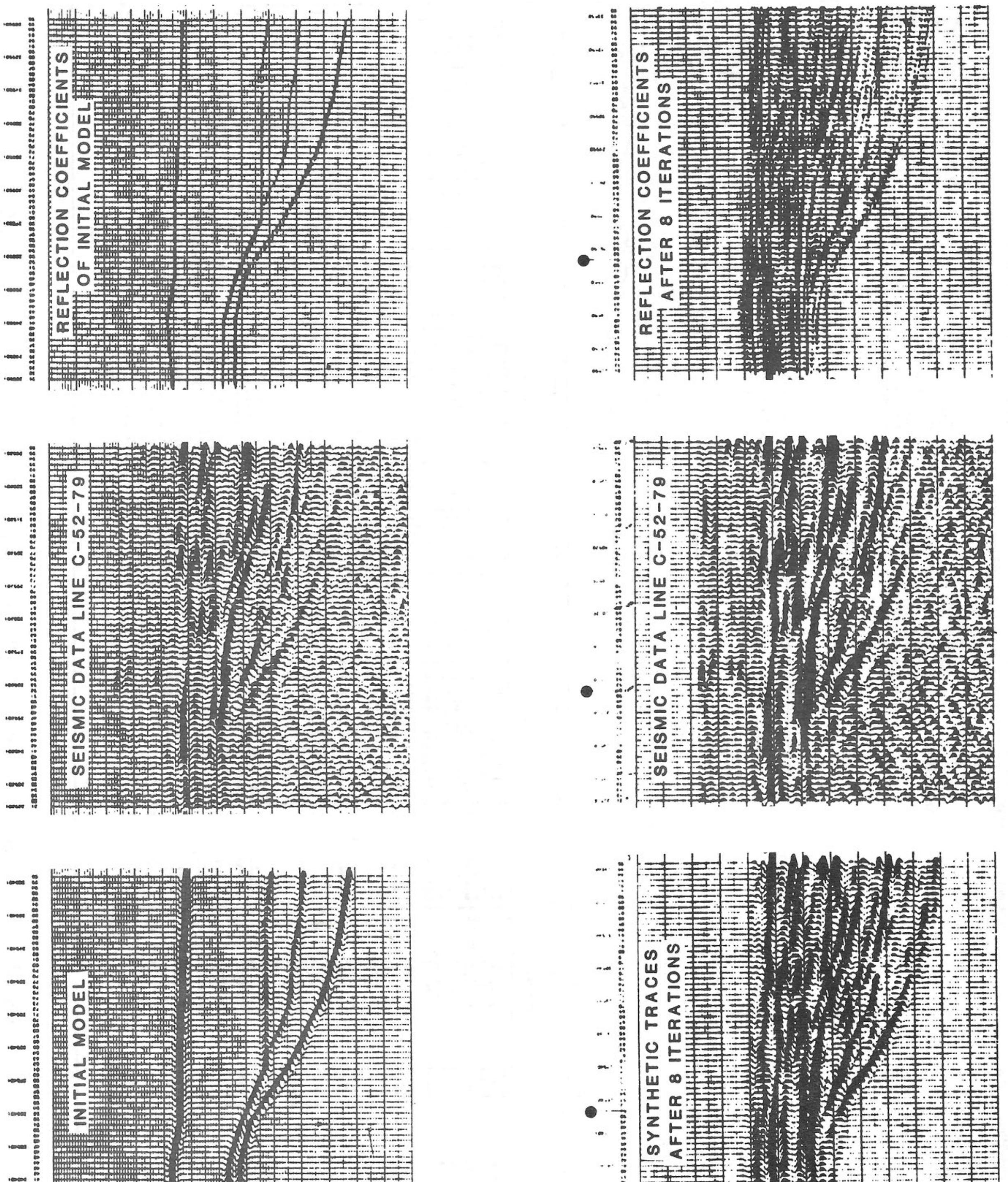


Figure 15. Progression profiles reflecting modeling sequence in line C-52-79, Ying Ge Hai project area.

we can see that the VSP becomes a seismic section indicating the appearance of the geological interfaces as they would occur on a seismic-reflection profile if measured at the well interface itself.

A most important aspect of the VSP is its ability to look below the drill bit. The VSP records energy coming up from below as a result of the surface shot as well as the energy coming down to the phone in the borehole. This feature is very useful for calibrating reflections or rock interfaces for the drillers to use in planning deeper drilling. VSPs can also be used to distinguish multiples from primaries. This information can be used in processing the surface seismic data better and in the mapping process as well.

SEISMIC MODELING

Seismic trace modeling is an important part of exploration today, particularly in stratigraphically complex areas. The geologist and geophysicist work closely together to test possible geological models in an effort to match the field seismic section and, thus, to gain confidence in the exploration interpretation of the seismic data prior to and after drilling.

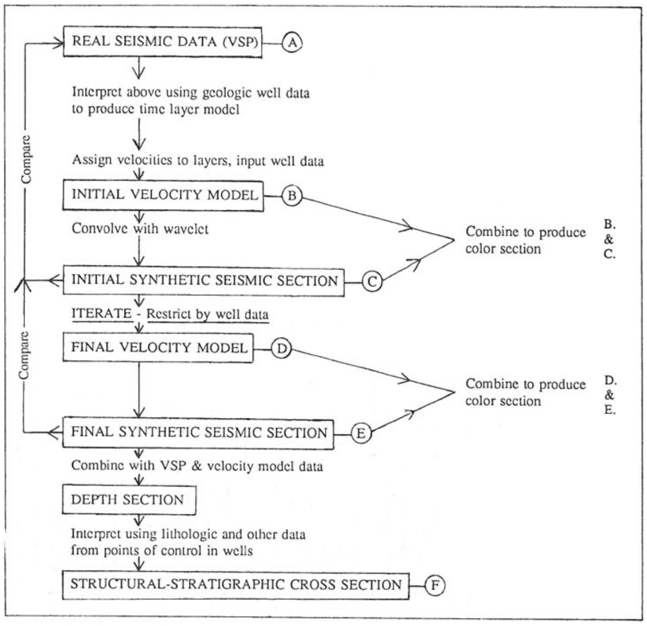
Once the geologist has drawn the proposed model, the geophysicist inputs velocity and density data that represent the various layers of the model. Then the model is convolved or processed with a seismic wavelet. The result is a synthetic seismic section that is compared to the actual surface-recorded data.

State-of-the-art modeling programs are often complex; but they alone can determine the seismic-energy raypaths. These programs produce very accurate representations of the subsurface when the geological and geophysical parameters are correctly input. ARCO uses these programs in our exploration system in the U.S.A. Two other types of models, which are different in approach have also been incorporated into the Ying Ge Hai exploration program.

One type of stratigraphic modeling is the Seismic LIthologic Modeling (SLIM*) program available from Western Geophysical Company. In this method, the best available geological and geophysical data are input to the program along with the geologist's model. SLIM* varies from the conventional, direct method for inversion of seismic traces in that it allows the insertion of broad-band frequencies and noise into the final result.

Table 6 shows the flow diagram of the SLIM* process. It is an iterative process in that a number of passes are made to improve the correlation of the final model to the surface seismic record. However, the program continues to honor the basic input data. The final output is shown in Figures 15 and 16 for a Ying Ge Hai area prospect. As the final model is only as good as the

Table 6. Flow Diagram for the Seismic Lithologic Modeling (SLIM) Process.



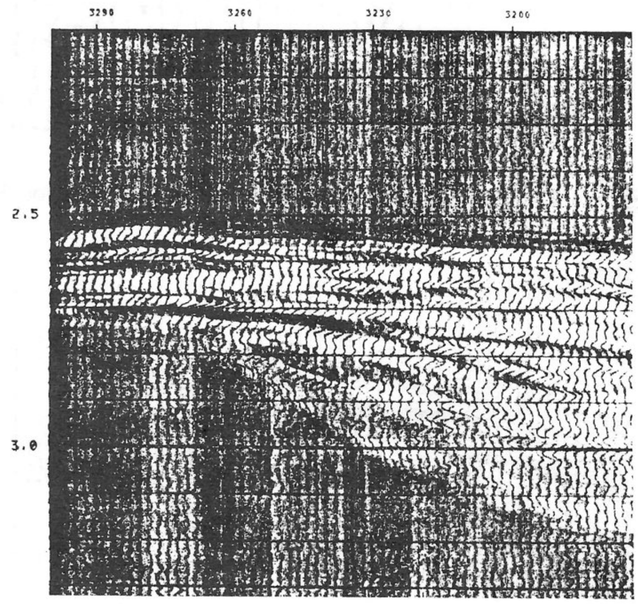


Figure 16. Final output after application of 8 iterations in the "SLIM" method to line C-52-79, Ying Ge Hai area. [Original in color]

input data, the VSP information is particularly useful in the SLIM* process.

The other method of seismic modeling is more direct and simple than either of the above methods. It can be done in the local office on a micro-computer. An example of this type of modeling is the Seismic Amplitude Modeling (SAM*) program available from Keyser Geophysical. This innovative program can be run on an

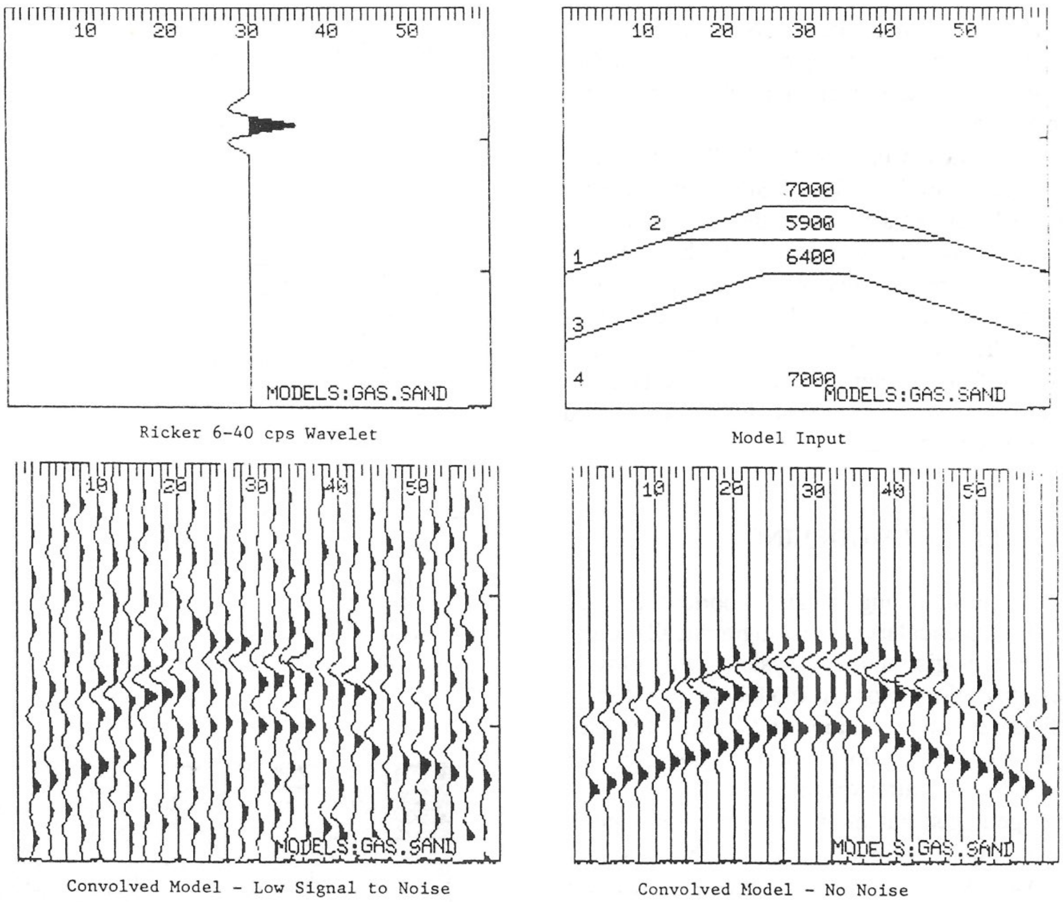
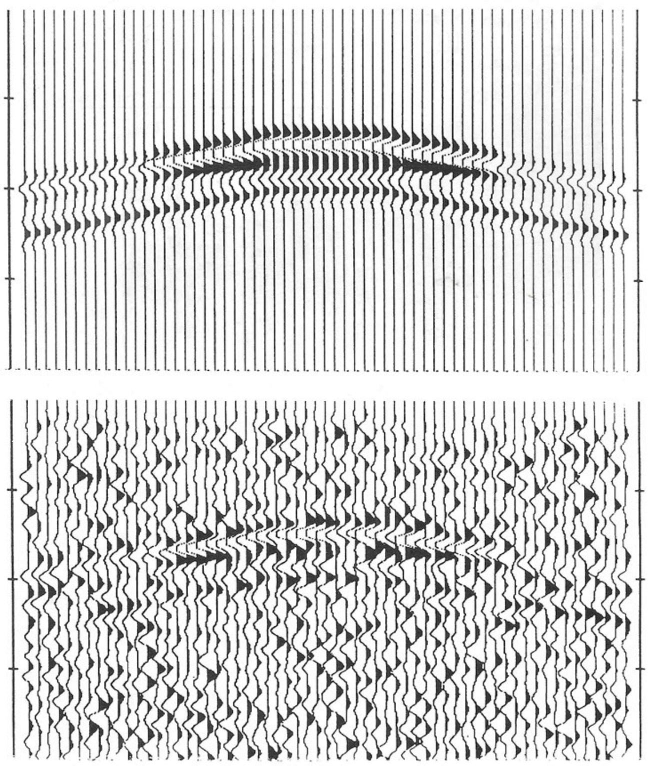


Figure 17. Example one of a "Seismic Amplitude Modeling" (SAM) program run on an Apple computer.



APPLE computer and allows the geologist and geophysicist to run models with many sets of parameters quickly. An example of the results of a SAM* program is shown in Figures 17 and 18. A printout is immediately available on a high-resolution graphics printer. This program offers a wide variety of processing options and can even input noise to more closely approximate the field seismic section by varying the signal-to-noise ratio.

GRAVITY AND MAGNETIC DATA

The potential-field geophysical tools, gravity and magnetic data, have not been considered to be as useful in recent years as seismic data. The gravity and magnetic data in the Ying Ge Hai area seem to indicate that this is a processing, interpretation, and presentation problem rather than a problem with the basic methods.

The Ying Ge Hai gravity and magnetic data grid is

Figure 18. Example two of a "Seismic Amplitude Modeling" (SAM) program run on an Apple IIe computer.

extensive. Like the seismic data, it too resides in the computer data base. Cross correlations between the two methods have been used to produce regional maps that indicate that all the geologic trends, and many of the prospects, were also seen on deep seismic lines. Gravity and magnetic data are particularly useful in basement correlations.

The gravity and magnetic data can be made available as output on an advanced RAMTEK color computer display system. The examples in Figures 19 and 20 show gravity and magnetic data displayed like seismic attributes in color. We have found these tools to be very helpful on a regional as well as a prospect basis.

OTHER EXAMPLES OF DATA OUTPUT

Two sets of Ying Ge Hai seismic data are shown in Figures 21 to 27. Special processing of the seismic data has defined what appears to be stratigraphic trapping in both areas. Figures 21 and 22 show stacked-migrated and color interval-velocity versions of line C313-83. Velocities generally increase as the color darkens. Note the lateral changes in velocity. Figures 23 and 24 show black-and-white examples of a stacked and migrated profile using the finite difference migration method, and an example of the cosine of instantaneous phase method for line 278A-33. Figures 25 to 27 show three different versions of the color interval velocity for lines 278-33 and 278A-33. The three different color sections display different color "windows" or ranges of interval velocity (100 m/s, 200 m/s, and 300 m/s). Note the changes that occur in the geological "picture" with the different color "windows". [Close scrutiny of the black and white reproductions reveals all that the color has shown. Ed.]

CONCLUSIONS

Geophysical and computer data-base technology have been applied in the Ying Ge Hai area as a result of a commitment to a thorough, state-of-the-art approach to structural and stratigraphic exploration.

Advanced acquisition, processing, modeling and interpretation techniques have been used to extract the maximum amount of structural and stratigraphic information from the data.

Geological and geophysical data have been entered into an extensive exploration computer data-base system which is then used to assist in interpretation in a more comprehensive and quicker manner than would be possible by hand.

Figure 19. Computer-generated gravity-anomaly map of the Ying Ge Hai area. [Original in color by R6-R2 RAMTEK process]

Figure 20. Computer-generated magnetic-anomaly map of the Ying Ge Hai area. [Original generated in color by the RTP RAMTEK process]

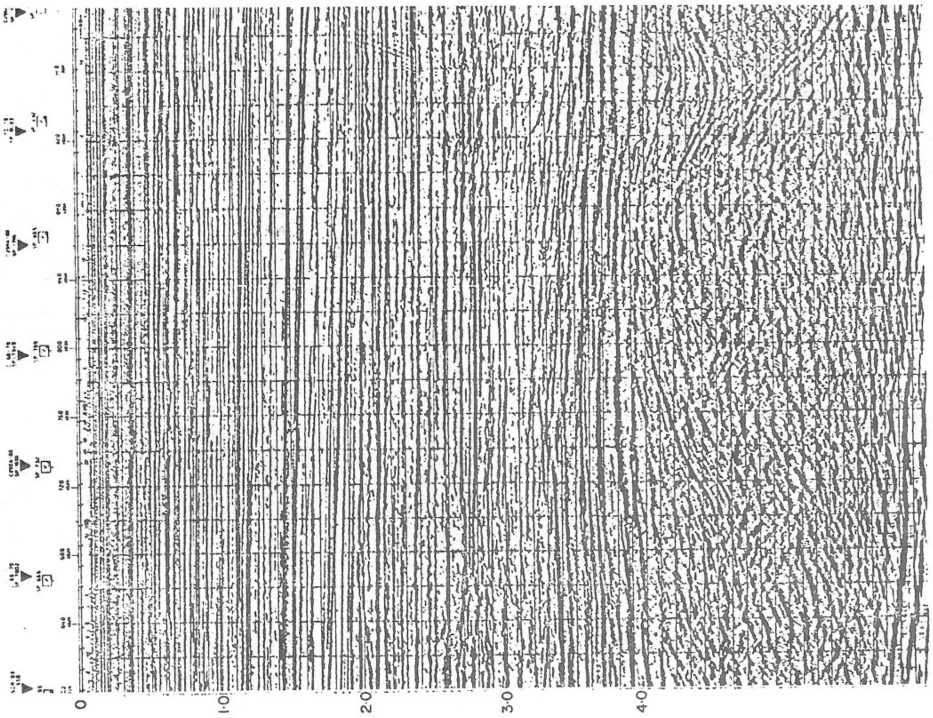


Figure 21. Multichannel seismic-reflection profile of line C313A-83 that has been stacked and migrated by the finite difference method.

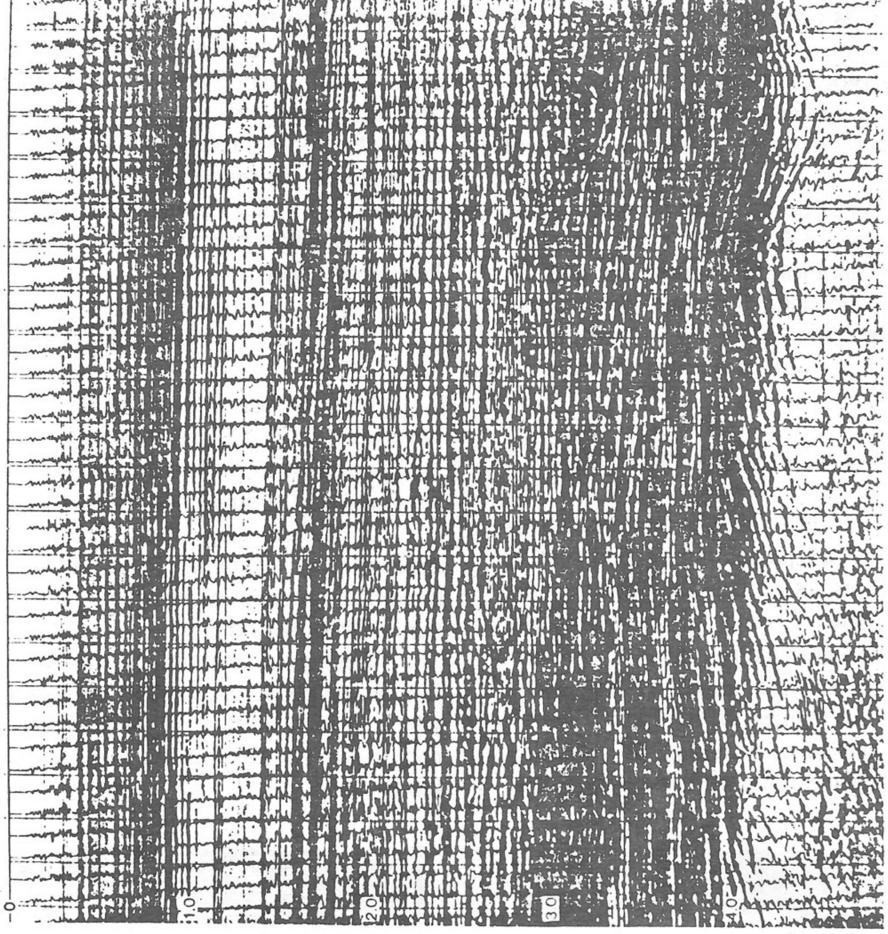


Figure 22. Multichannel seismic-reflection profile of line C313A-83 that has been generated with a 300 m/sec interval velocity increase. [Original in color]

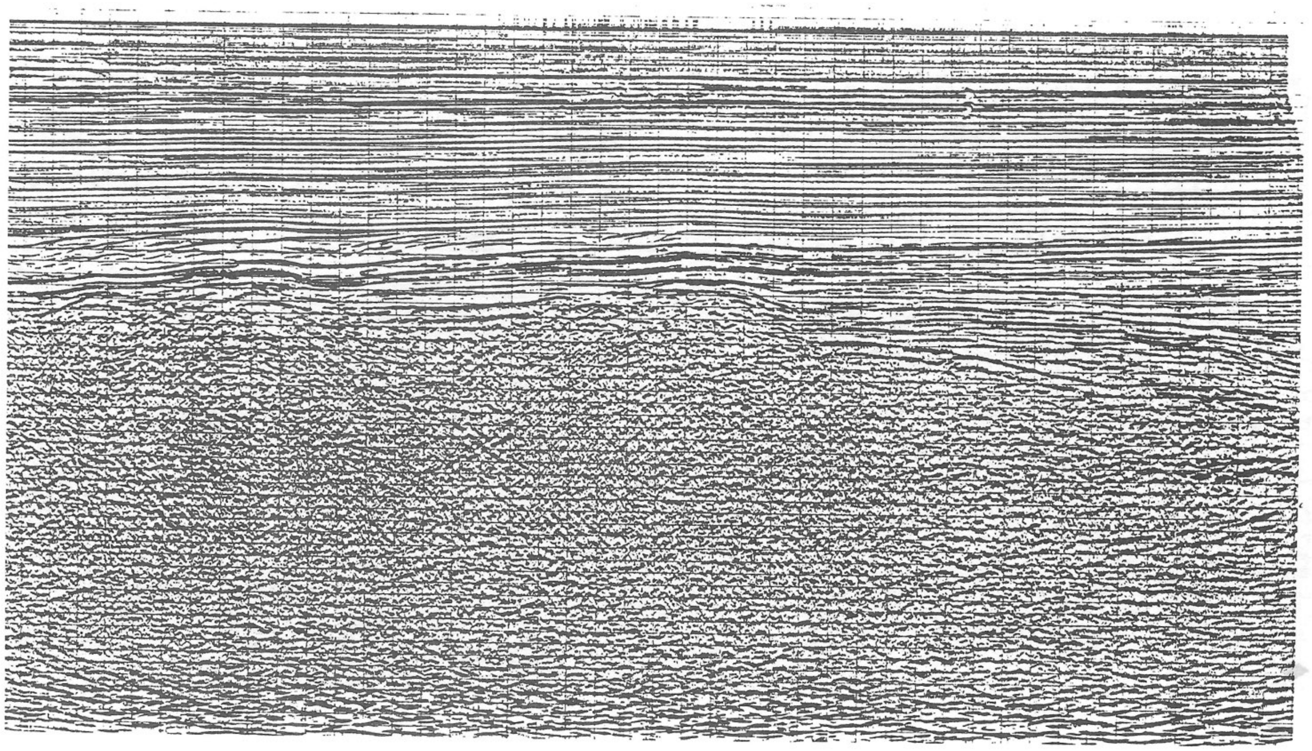


Figure 23. Multichannel seismic-reflection profile of line C278A-83 that has been stacked and migrated using the finite-difference-migration method.

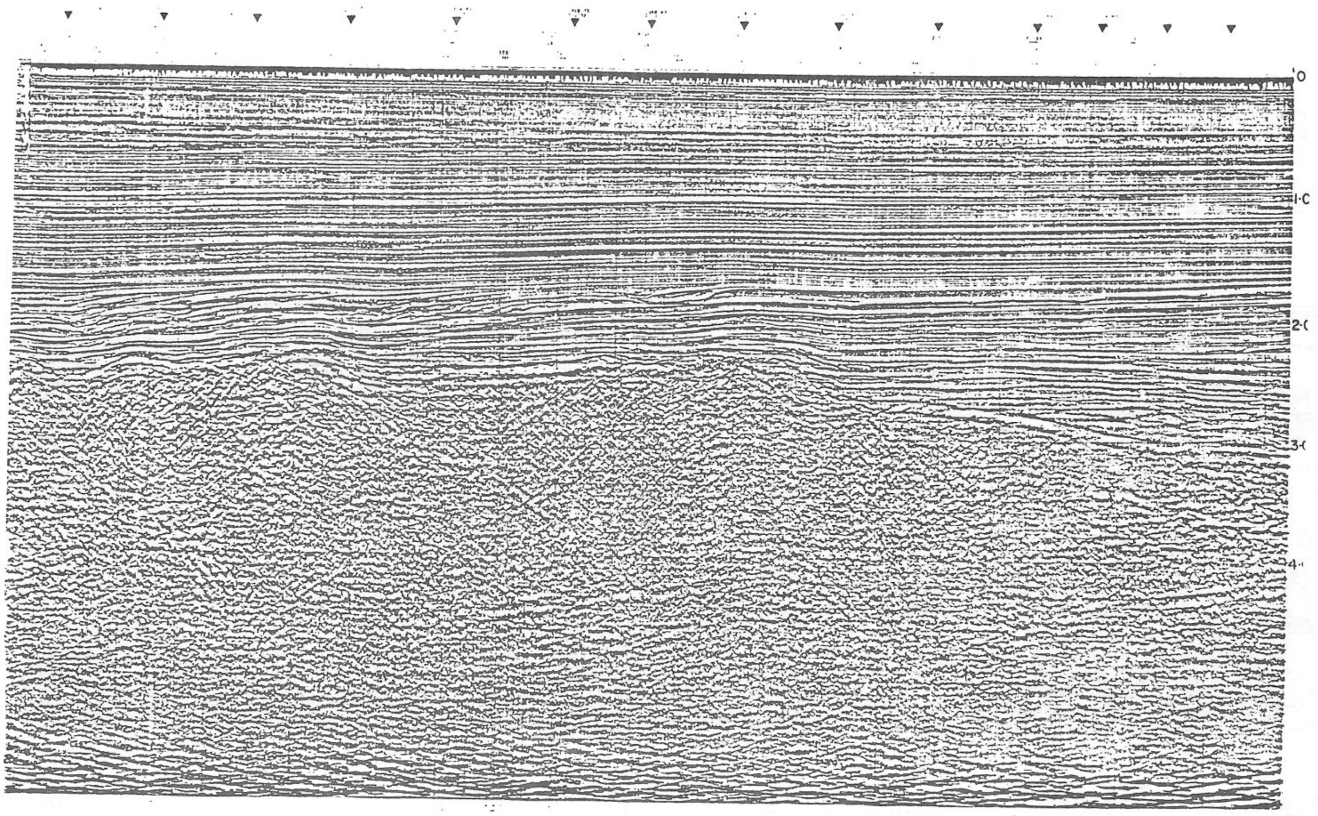


Figure 24. Multichannel seismic-reflection profile of line C278A-83 that has been stacked and migrated using the cosine of instantaneous phase method.

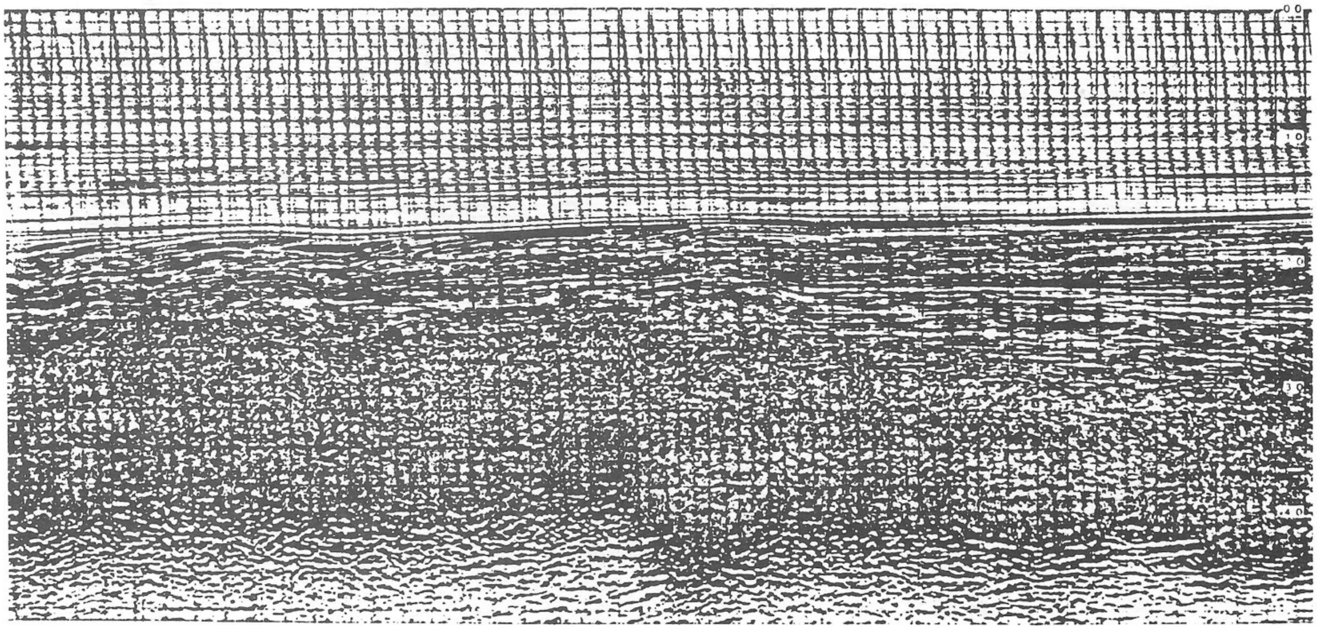


Figure 25. Multichannel seismic-reflection profile of line C278A-83 that has been stacked and migrated using the pseudo-interval-velocity method with a 100 m/s velocity-increase window. [Original in color]

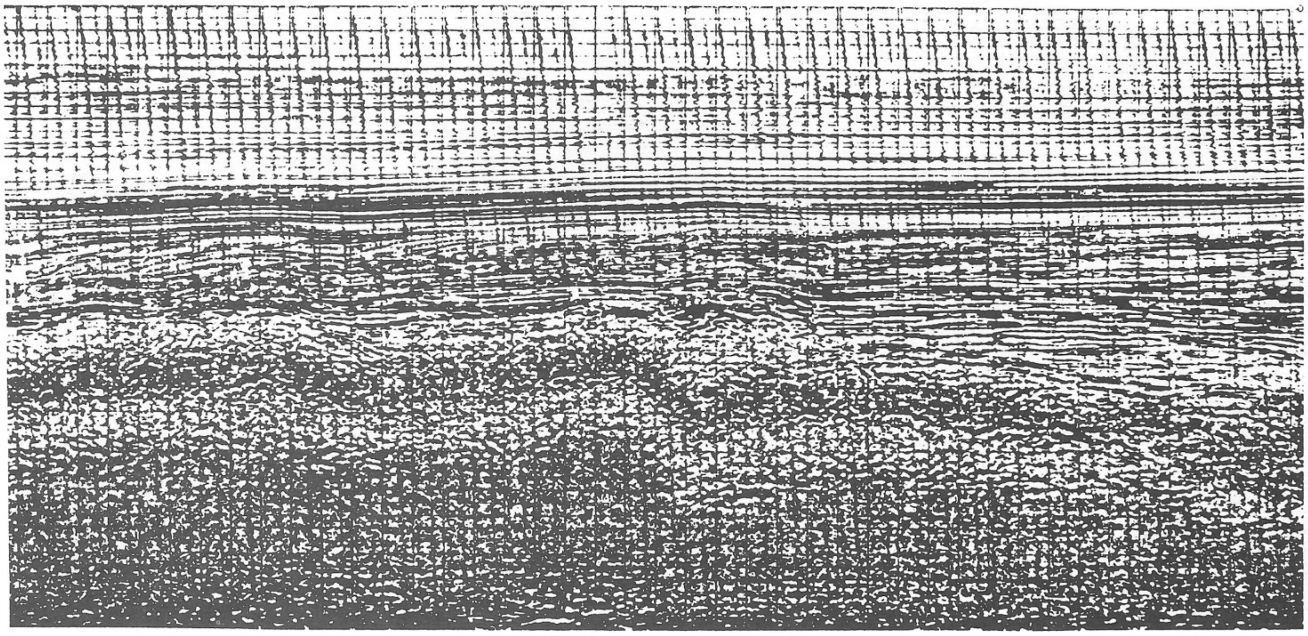


Figure 26. Multichannel seismic-reflection profile of line C278-83 that has been stacked and migrated using the pseudo-interval-velocity method with a 200 m/s velocity-increase window. [Original in color]

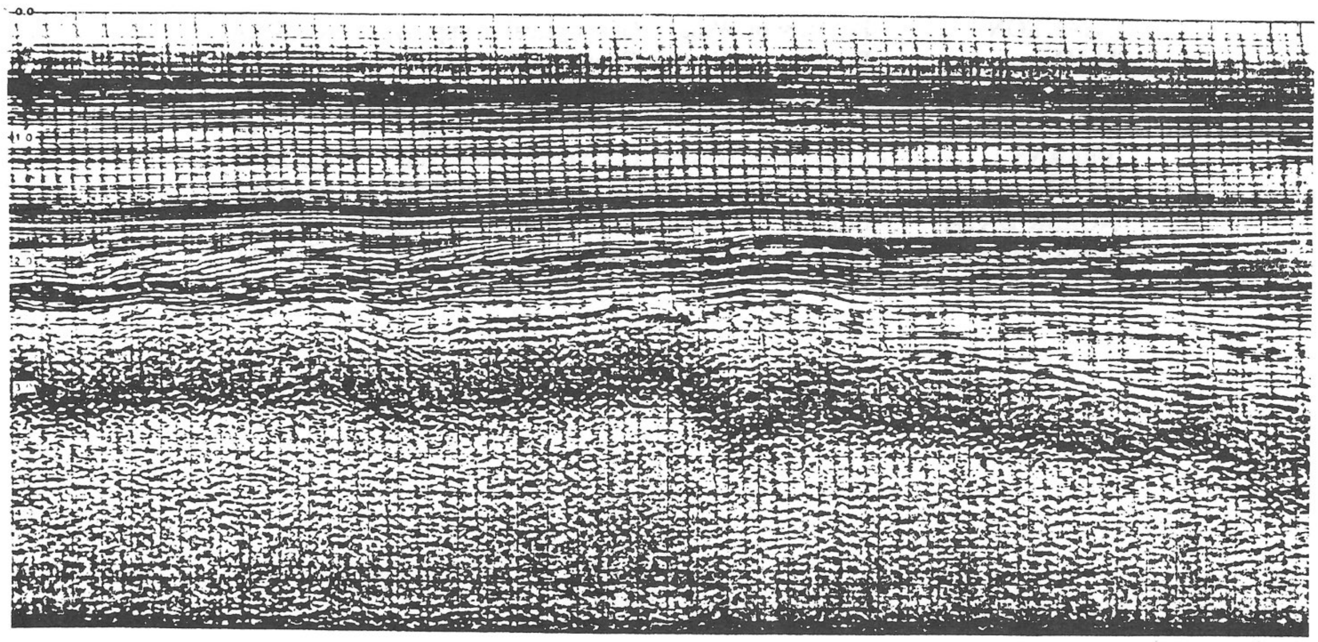


Figure 27. Multichannel seismic-reflection profile of line C278A-83 that has been stacked and migrated using the pseudo-interval-velocity method with a 300 m/s velocity-increase window. [Original in color]

No attempt will be made to try to convince the reader that the acquisition, processing, and interpretation technology used in the Ying Ge Hai area has been inexpensive. However, special attention throughout the exploration process to cost-effective methods has resulted in an outstanding multi-faceted exploration product that has proven to be cost-effective.

The use of advanced technology brings with it complex interpretation problems. Analysis of a four-way dip closure is no longer sufficient to find oil and gas in a basin. Experience with this technology, followed by drilling to prove-up the applications, is essential to the continued use of high-tech, high-cost exploration systems. The use of technology mentioned in this paper, along with high-technology interpretation by experienced seismic interpreters, has resulted in the definition of relatively deep stratigraphic traps which have been proven by drilling in the Ying Ge Hai area.

Not all of these techniques will yield useful data in all areas. ARCO China, NHWOC, and Santa Fe submit, however, that today's exploration requires a comprehensive technology approach, especially when stratigraphic traps are thought to be important in the area.

ACKNOWLEDGMENTS

The author wishes to thank ARCO China, Inc., CNOOC-NHWOC, and Santa Fe Minerals Asia for permission to publish this paper. Special thanks also go to ARCO China, NHWOC, and Santa Fe Minerals geologists and geophysicists who developed the technology system discussed herein and continue to acquire, process, and interpret data in a high-quality manner.

Thanks are also given to the geophysical contractors who worked with us to design and implement this technology. The primary contractors were: China-GECO, Keyser Geophysical, Nanhai-GEOMEX Surveys, Nanhai Racal, and Western Geophysical Company of America. The Geophysical Research Institute and Western Geophysical staffs in Zhuoxian deserve our thanks for a difficult processing job in 1984.

Special thanks go to He Han-yi, Chief Geophysicist of NHWOC/ACAC in Zhanjiang. He Han-yi developed this geophysical system with the author and is largely responsible for the success in applying attribute processing in our stratigraphic exploration method.

APPENDIX

The author wishes here to state his appreciation and to acknowledge permission to discuss the proprietary technology of the processes or systems listed below:

SHADCON	- Property of Western Geophysical Company	(U.S.A.)
SLIM	- Property of Western Geophysical Company	(U.S.A.)
SAM	- Property of Keyser Geophysical Company	(U.K.)
RAP	- Property of Western Geophysical Company	(U.S.A.)
VELANS	- Property of Western Geophysical Company	(U.S.A.)
MCCF	- Property of Western Geophysical Company	(U.S.A.)
NORSK DATA	- Property of Geophysical Company of Norway	(NORWAY)
ARGO/Syledis-B	- Property of Nanhai-Geomex Surveys	(P.R.C.)