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Use of SEISLOG for basin evaluation and field development

R.C. MUMMERY
Teknica Resource Development Ltd.
1100, 736 Sixth Ave. S.W.
Calgary, Alberta, T2P 3T7

Abstract: Generation of synthetic sonic logs (SEISLOGS) from seismic data can provide lithologic, porosity and in some case fluid content identifications in a variety of geological settings. In this period of high exploratory and development costs, SEISLOG data can significantly reduce exploration and development settings.

This paper briefly describes the techniques involved and illustrates examples from a variety of structural and stratigraphic settings. Carbonate examples include North Sea Chalk, fractured limestones in Venezuela, and porosity development in regional deposited limestones of Western Canada. The clastic examples are from Southeast Asia and include deltaic, transitional marine facies within Miocene age sediments.

INTRODUCTION

Seismic data have traditionally provided critical exploration information to define the location of structural anomalies in the sub-surface. In the last few years, interest has developed in using seismic data not only to map structural features, but as a means of determining the nature of the sub-surface stratigraphy. This paper discusses the application of a method used to convert the seismic traces into a series of synthetic sonic logs. These logs, called **SEISLOGS**, have a vertical axis in depth facilitating integration with sonic logs. A primary application of **SEISLOGS** is the delineation of productive units in the sub-surface. Secondary applications include the determination of lithology and facies distributions in basin evaluation studies. Examples from a variety of tectonic and stratigraphic settings including carbonates and clastics in onshore and offshore regions from around the world will be discussed.

THEORY

The inversion of seismic trace data to derive impedance logs in the time domain is not a new concept. However, the construction of pseudo-sonic logs from seismic data that are scaled for interval transit time in the depth domain was developed by Dr. Roy O. Lindseth in 1972. Conceptually, the inversion process is best understood when compared to the procedures used to construct a synthetic seismogram. Generation of a synthetic seismogram follows a route, herein called the FORWARD MODEL, that is essentially the reverse of inversion. In the FORWARD MODEL, the interval transit time data of the sonic log is transferred into the time domain and converted to reflection coefficients using the relationship shown in Figure 1.

The reflection coefficient series generated in this fashion is assumed to represent the re-

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$$Rc_1 = \frac{\rho_2 V_2 - \rho_1 V_1}{\rho_2 V_2 + \rho_1 V_1}$$

$$\approx \frac{V_2 - V_1}{V_2 + V_1}$$

Fig. 1 Reflection Coefficient Equation

flection coefficient series of the various lithologic interfaces of the stratigraphic sequence. Convolution of this reflection coefficient series with a suitable wavelet, produces a synthetic seismogram which can be correlated directly with seismic data (Figure 2). The quality of the correlation depends primarily on the accuracy of the sonic log and selection of an appropriate wavelet. This model presents an effective means of equating borehole units to their seismic equivalent. Although an excellent interpretation is possible at the well tie, the synthetic does not assist in evaluating the stratigraphic significance in changes of seismic character lateral to the well tie as effectively.

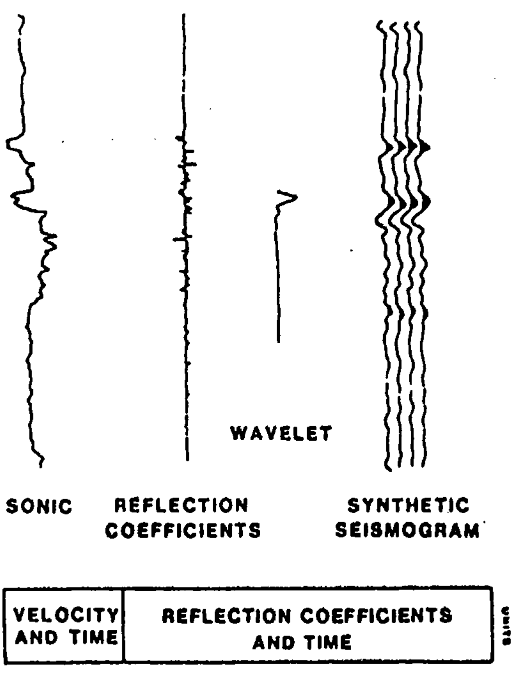

Fig. 2 Forward Model

The inverse model uses the seismic reflection coefficients to derive velocity using the relationship shown in Figure 3. This approach, in contrast to the FORWARD MODEL, assumes that the effects of the wavelet can be removed from the seismic trace and that the resulting reflection coefficient series is comparable to that of the stratigraphic sequence (Figure 4).

$$V_2 = V_1 \left(\frac{1 + Rc}{1 - Rc} \right)$$

Fig. 3. Inverse Model Equation

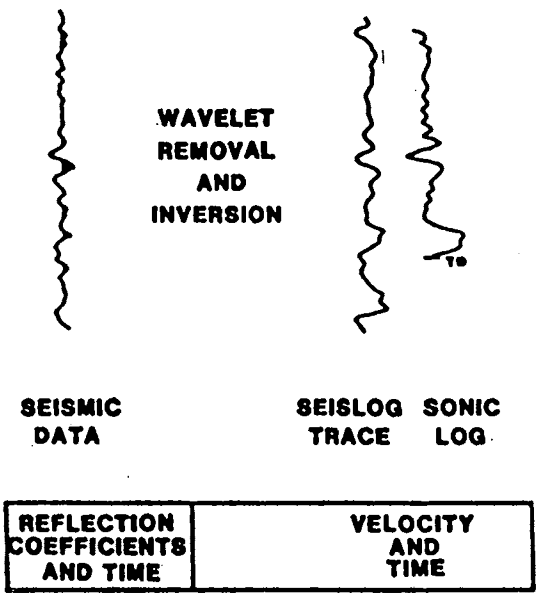

Fig. 4. Inverse Model. In the inverse model approximations of borehole sonic logs are constructed from seismic data after appropriate wavelet removal. These logs can be correlated with borehole sonic logs that have comparable bandwidth.

In order to calculate absolute velocity and depth from seismic data, we must first derive the reflection coefficient series and then estimate a velocity at some point in the series. When these calculations are made, powerful and detailed correlations can be observed between stratigraphic units measured with the sonic log, and those recorded by the seismic wave. In addition, accurate measurements can be made of interval velocities (transit times) and their relation to lithology-porosity variations quite large distances away from the well ties.

Figure 5 demonstrates the difference in frequency bandwidth between common seismic data and sonic logs. High resolution re-processing and frequency deconvolution can restore the amplitude of the higher frequencies in the seismic data so that the reflection coefficient series from seismic will match more closely that from well data.

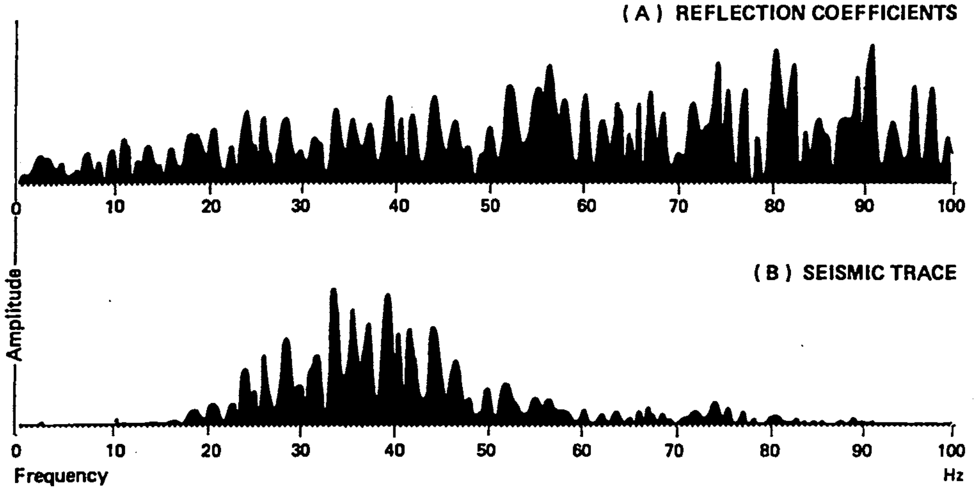

Fig. 5. Comparison of Amplitude Spectra from Well Data and Seismic

Because sonic logs contain data with frequencies of up-to 500 Hz, it is necessary to bandpass filter any sonic log before correlating it with seismic derived data. The effect of filtering out the higher frequencies is shown in Figure 6. The filtering of a sonic log aids in determining the resolution limits of units and acts as a model for constructive and destructive signal interference effects. Sonic logs are also displayed in a time velocity format which allows phase checks between well and seismic data necessary to determine the correct polarity of the final displays.

The impedance section (Figure 7) expressed in terms of velocity and time represents an intermediate step in the **SEISLOG** process. It is at this point that estimates of starting velocities for the series of reflection coefficients and any phase adjustments are made. This display contains only frequency data greater than 6 Hz obtained during a frequency deconvolution. In order to convert to depth, an estimate of velocity data from frequencies in a range from 0-6 Hz must be made. This information can be derived from stacking velocity data, well data or velocity modelling, and is then combined with the high frequency data.

A comparison of the low frequency components derived from stacking velocities with those derived from filtering a sonic log is shown in Figure 8. Both displays are expressed in terms of time and velocity. When the low frequency data is combined with the high frequency

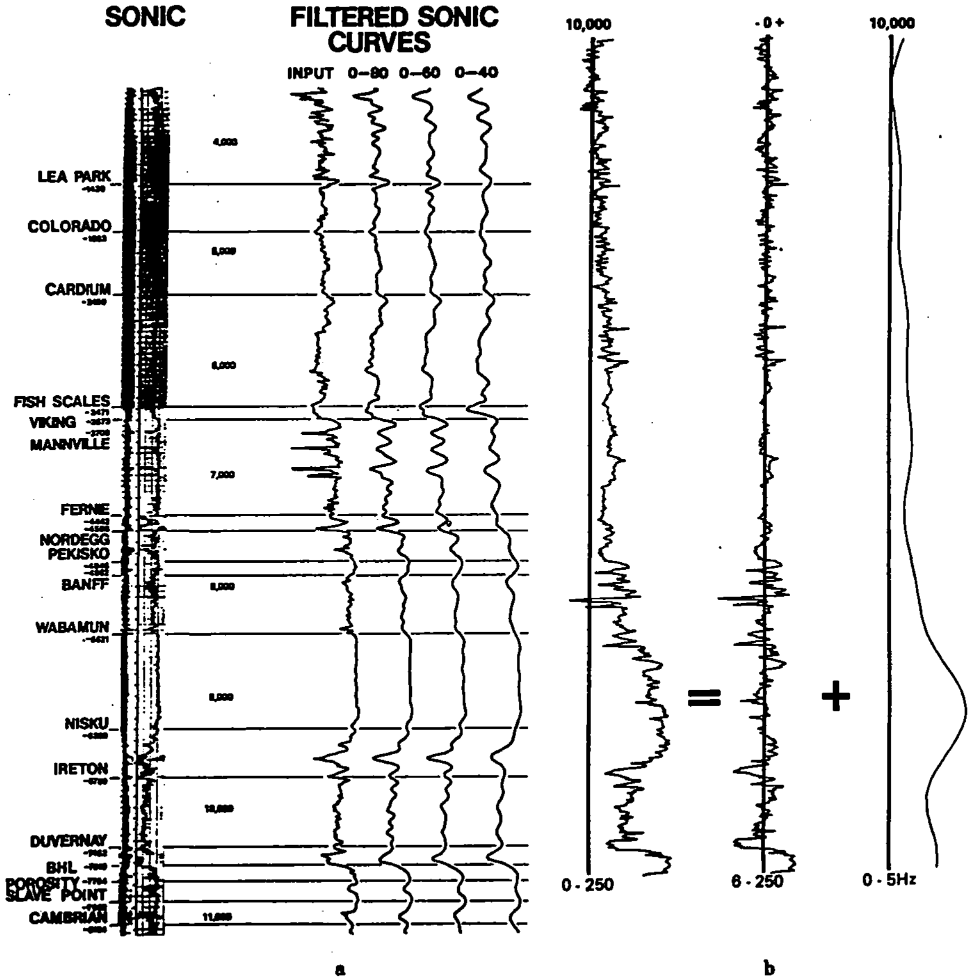

Fig. 6. Effect of Filters on Raw Sonic Data. (a) Loss of high frequency decreases resolution on sonic logs. (b) The basic velocity structure of a sonic log is provided by the very low frequencies, while the higher frequencies provide the detailed resolution.

information displayed on the impedance section we can then generate a depth transit time display.

Figure 9 shows a depth transit time display (inverse of velocities). The transit times can be contoured and coloured to conform with a standard stratigraphic code which is shown in Figure 10. Greens represent the lowest velocities and blues the highest. This display also shows a filtered sonic log on the left side which can be used to correlate units and establish lateral velocity variations that can be due to porosity development or facies changes.

Let's turn to some case studies. We will examine 3 carbonate examples and 3 clastic examples.

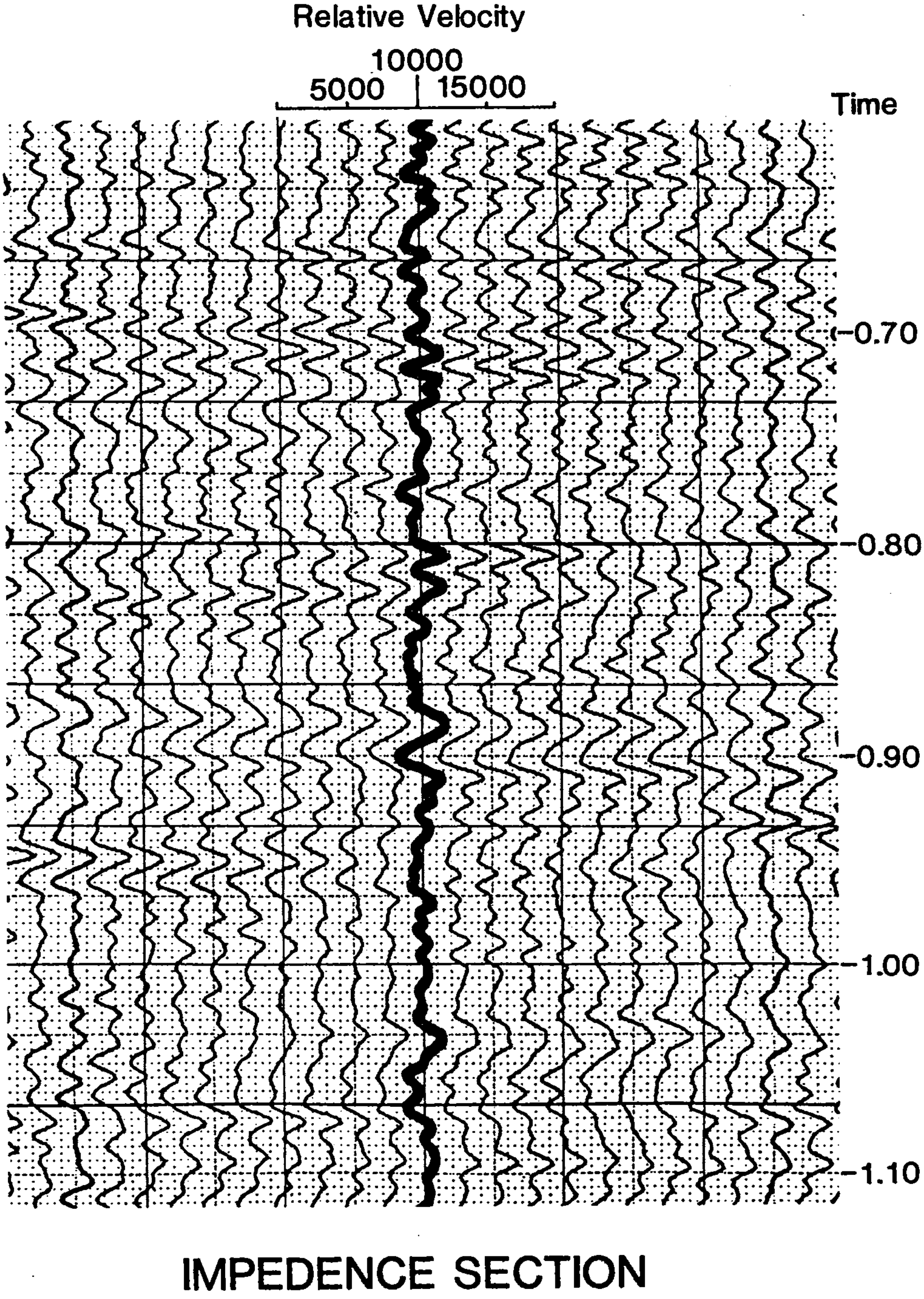

Fig. 7. Impedance Display

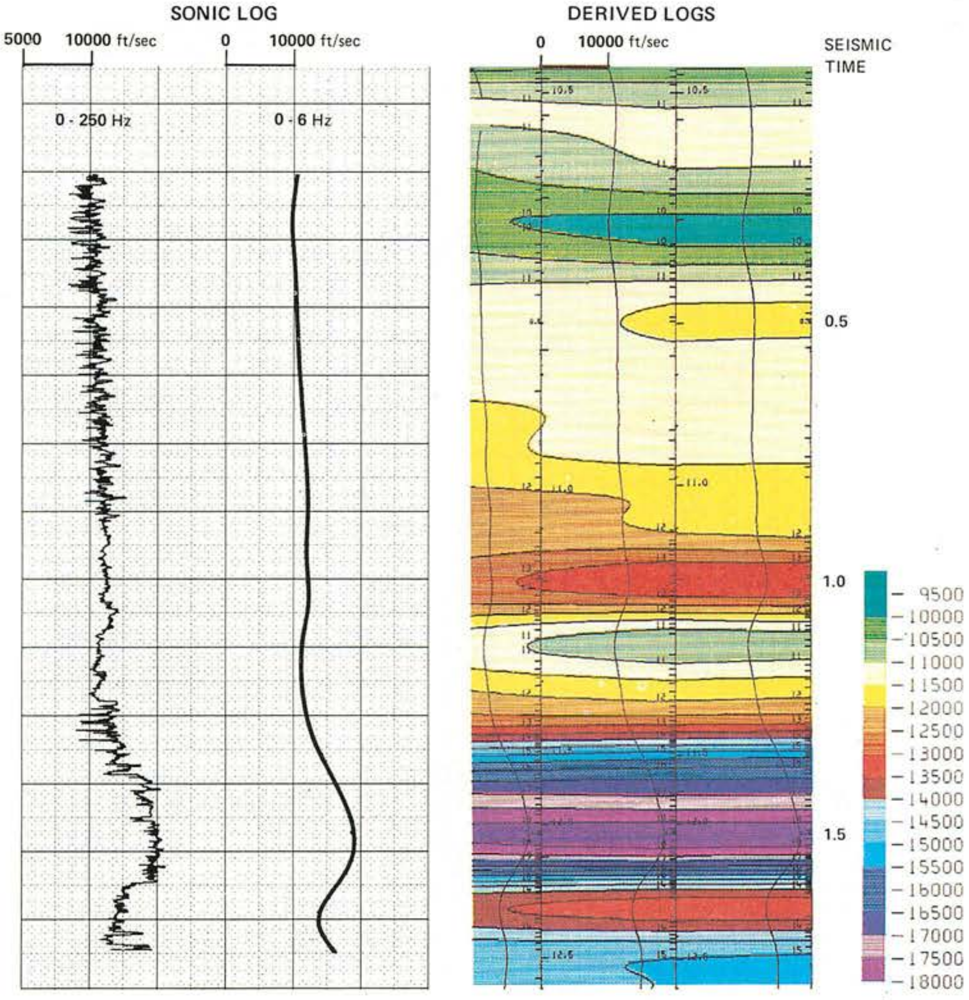

Fig. 8. Comparison of Low Frequency Components from Well Data with that Derived from Stacking Velocities

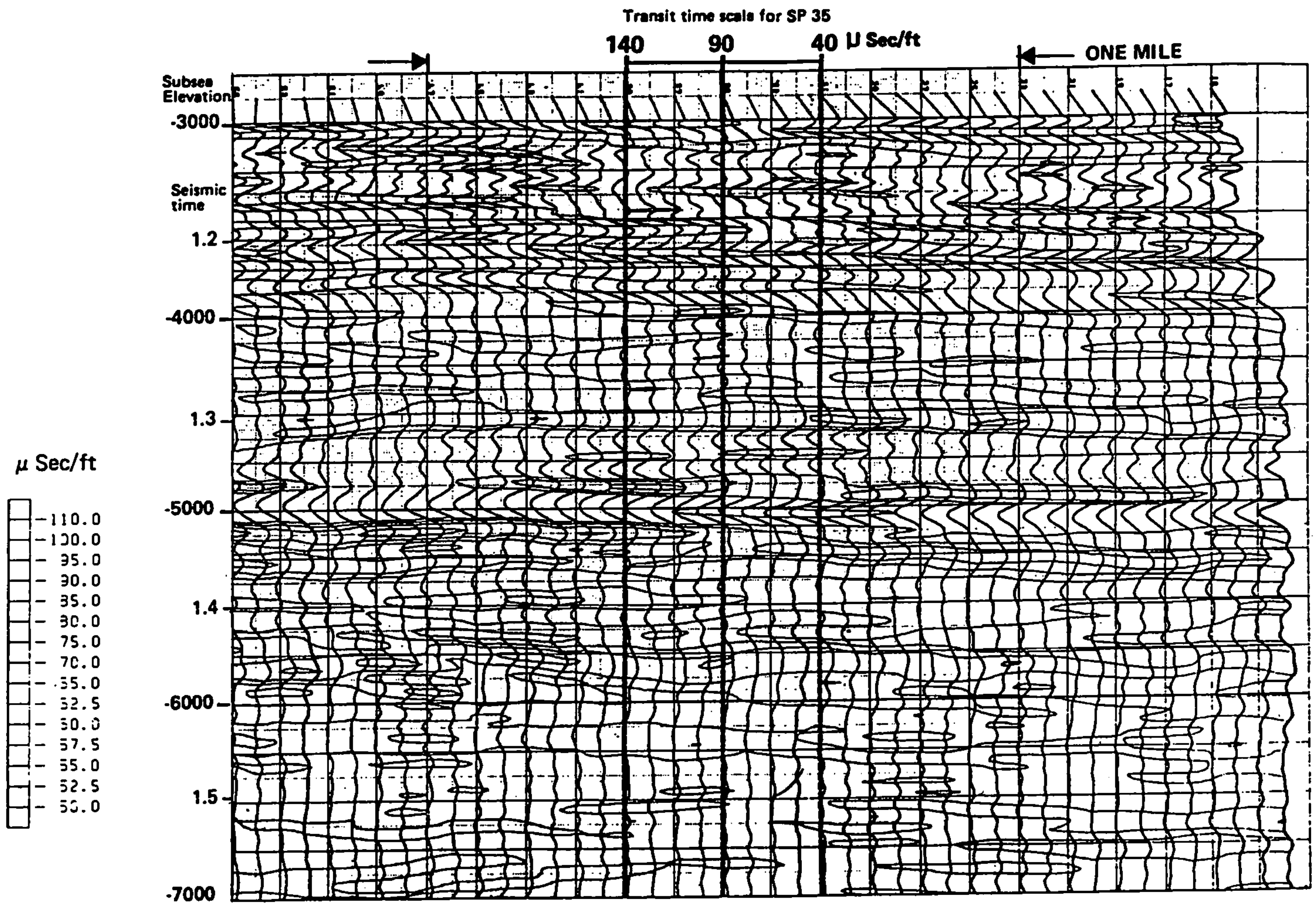

Fig. 9. Machine Contoured Uncoloured Synthetic Sonic Log (SEISLOG). Contours of isotransit-time outline geologic members and map facies changes within the section.

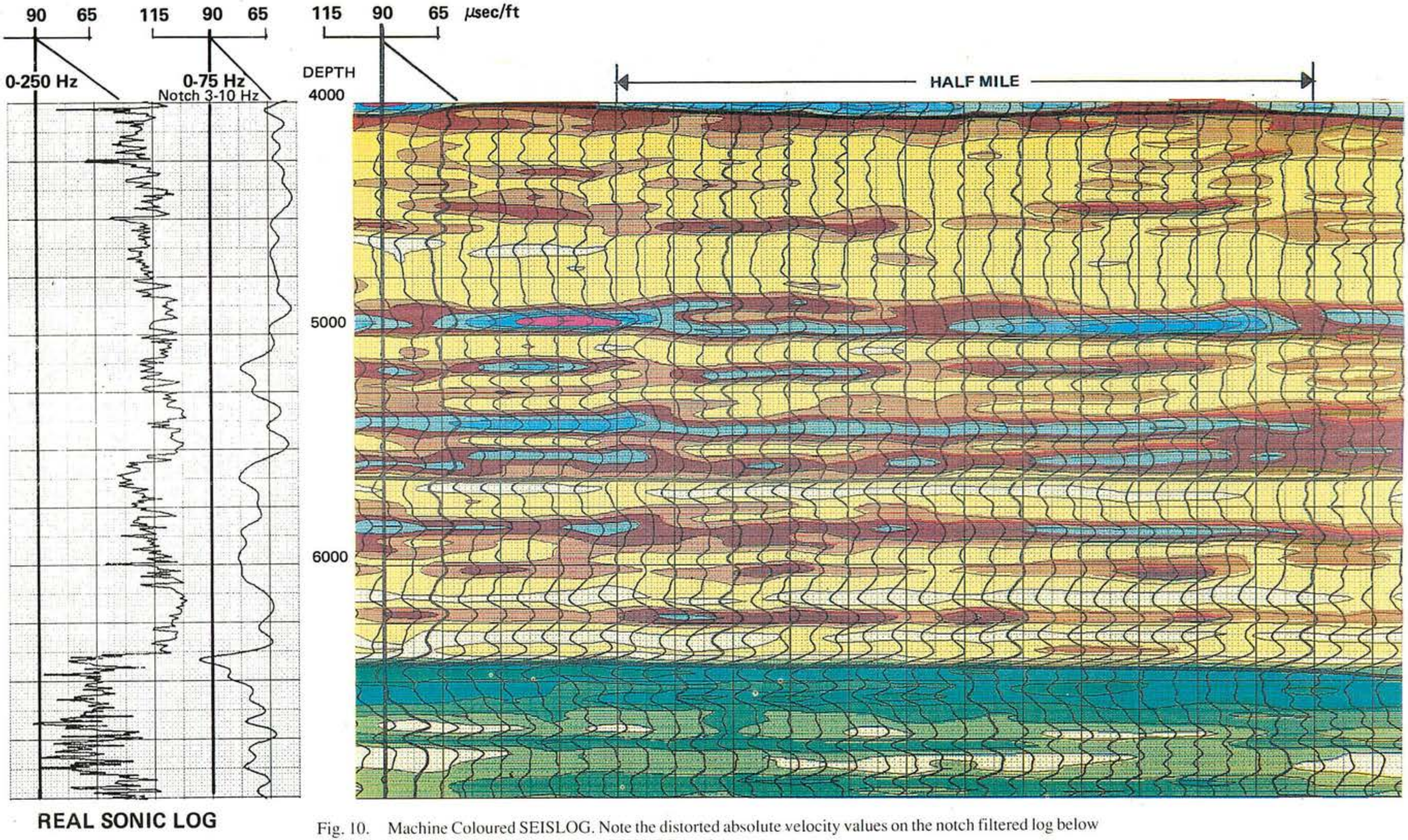

Fig. 10. Machine Coloured SEISLOG. Note the distorted absolute velocity values on the notch filtered log below 6000 ft. A similar response exists on the SEISLOG section.

CARBONATE EXAMPLES

Our first carbonate example is a Devonian reef located in the Central Alberta portion of the Western Canada Basin.

The reef is located at about 1.15 seconds on the conventional seismic display (Figure 11). To an experienced geophysicist, this feature displays subtle characteristics typical of the seismic response associated with reefs such as drape, discontinuity in reflections and character change. However, the outline of the reef mass cannot be clearly defined.

Figure 12 shows the colour coded **SEISLOG** display of the area marked on the seismic section. The major unconformity between Cretaceous clastics and Devonian carbonates occurs at 1.1 seconds on the seismic section and just below –2,000 feet on the **SEISLOG** display. The abrupt colour change from lower velocity greens, yellows and oranges of the clastic section to the higher velocity blues and purples of the carbonates can be clearly seen. On the **SEISLOG** display the reef mass is clearly defined.

Figure 13 shows an interpretation of the **SEISLOG**, based on well data in this area. One of the **SEISLOG** traces has been marked on the right side of the display. Each trace is centered on the 90 microseconds/foot baseline of the transit time scale. Just to the left of this trace, the filtered sonic log for a well near this location, has been drawn on the section to show the remarkable similarities in character and transit times between it and the seismic derived **SEISLOG** trace.

The top of the reef complex is labelled **Leduc**. Well information in the area indicated that the production is mainly in the upper porous part of the reef, displayed by the lighter blue colour below the diamonds tape on the left. The reef margins were considered tight. **SEISLOG** displayed a lateral extension of the reservoir at the reef edge coloured yellowish green. **SEISLOG** was able to extend the producing field and located new reserves in an area written off by conventional seismic and delineation well data. In addition to oil production from the reef, gas has been produced from Upper Devonian carbonates above the reef. This production is more extensive and has been correlated to the pale blues between the solid tapes above the **Leduc** marker.

The area outlined in red demonstrates the excellent match between well data on the left and the **SEISLOG** trace on the right and gives confidence to the detailed correlation with formations in the area.

Our second carbonate example is also from Western Canada. **SEISLOG** studies over this existing gas field (Figure 14) were able to extend this pool into an area that would not have been evaluated on the basis of well data alone. These two maps (Figure 14) shows the result of incorporating **SEISLOG** data in the interpretation. A conventional seismic display (Figure 15) which was oriented east-west across the northern part of the gas pool is provided as a comparison to the **SEISLOG** display (Figure 16). On the conventional display, the top of the producing horizon, Crossfield, is identified near 1.35 sec. Production is obtained from dolomitized porosity in an algal bank within the Crossfield member of the Upper Devonian Wabamun carbonates.

Several critical features stand out in the **SEISLOG** display (Figure 16). The change

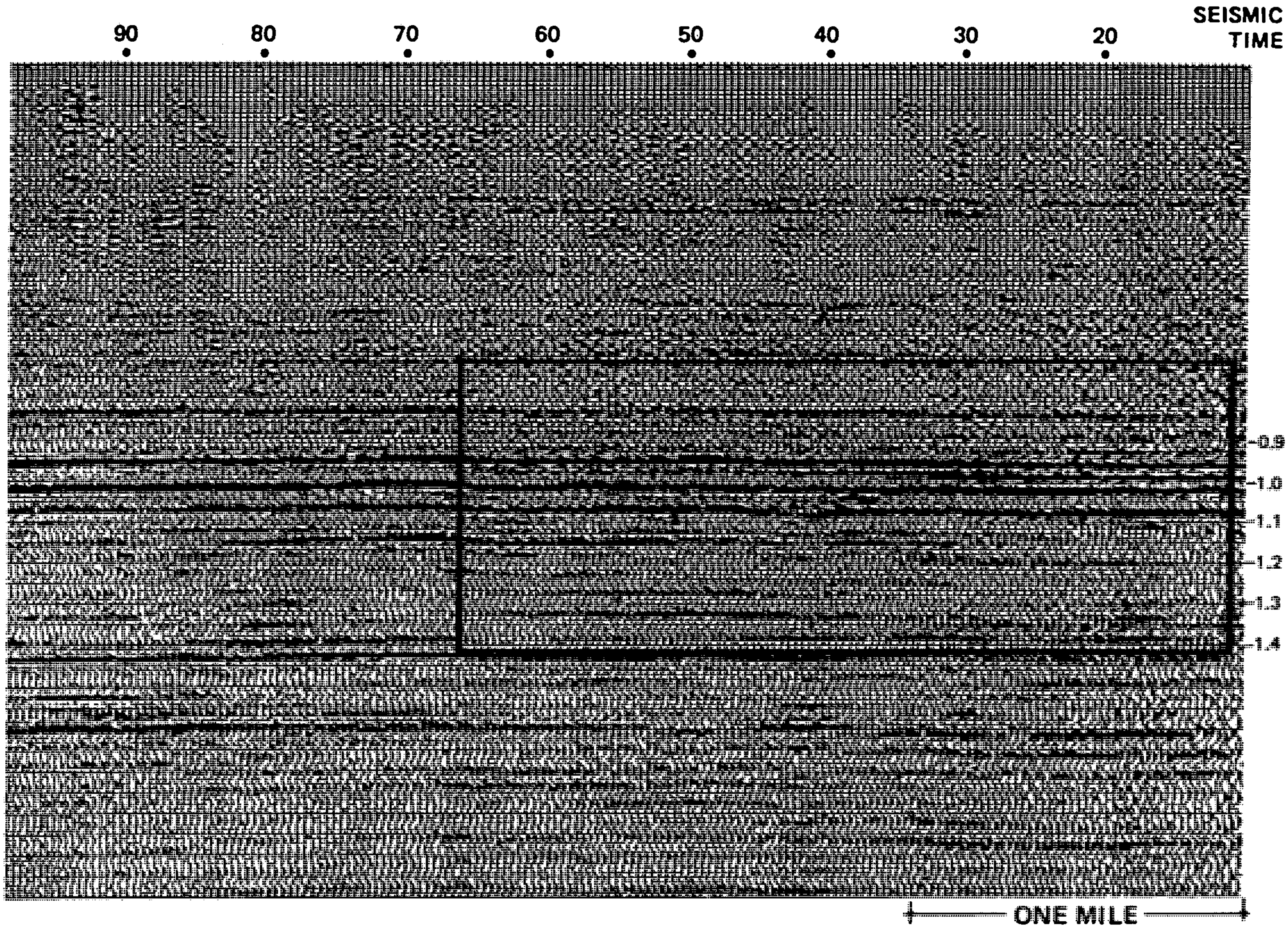

Fig. 11. Conventional Seismic Across Alberta Reef. The section is divided about 1.1 sec between Cretaceous clastics above and mainly Devonian carbonates below. The reef lies about 1.2 sec.

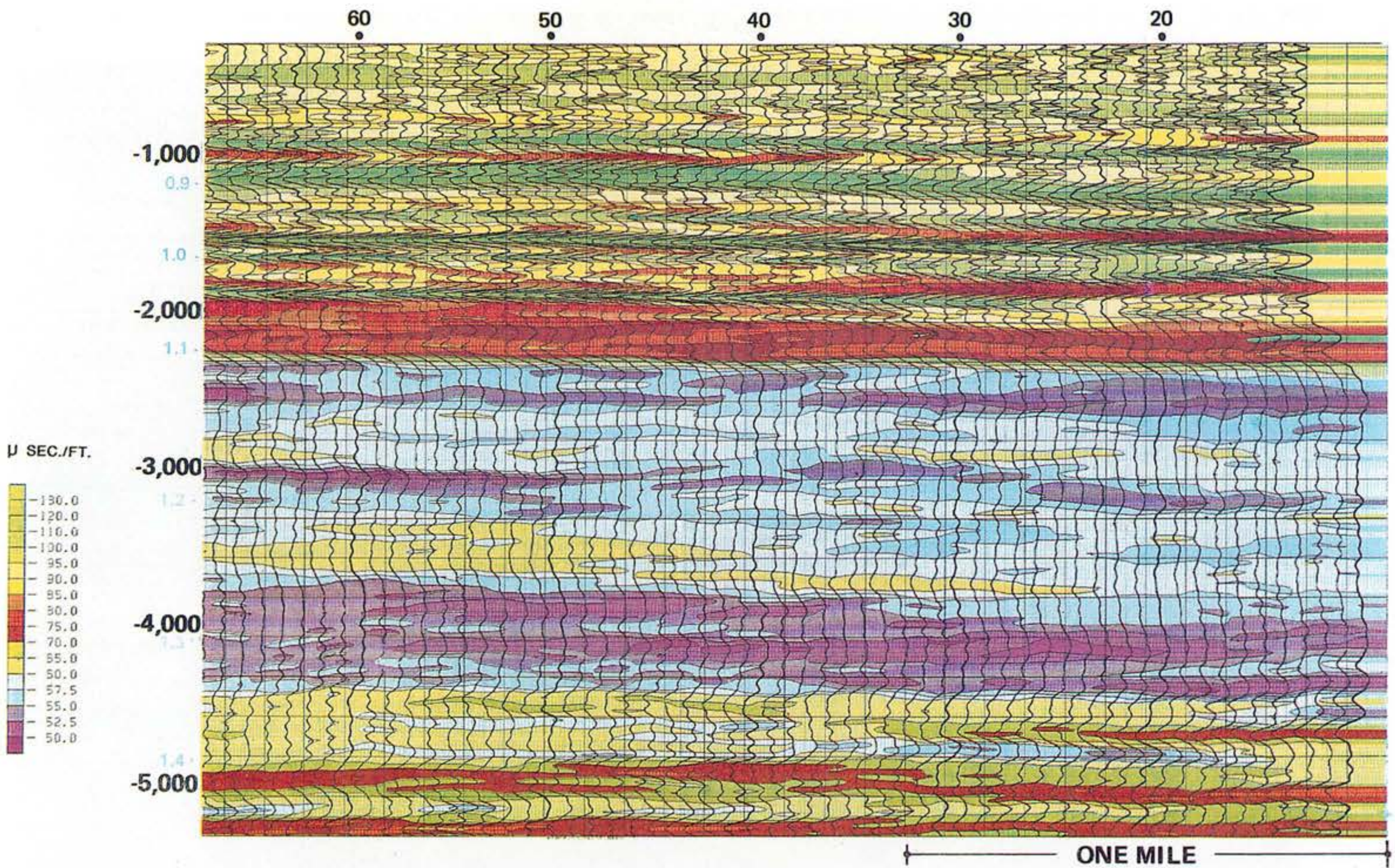

Fig. 12. SEISLOG Display of Seismic. Inversion of a window of the seismic data. Transit times have been contoured and colour coded as indicated by the colour bar to the left. Each trace is a synthetic sonic log. The unconformity separating clastics from Carbonates is clearly visible as a distinct colour change near 2000 ft. The reef is the irregular dark blue mass near 3000 ft. Both sections are uninterpreted, displaying the seismic data presentation after processing ready for interpretation.

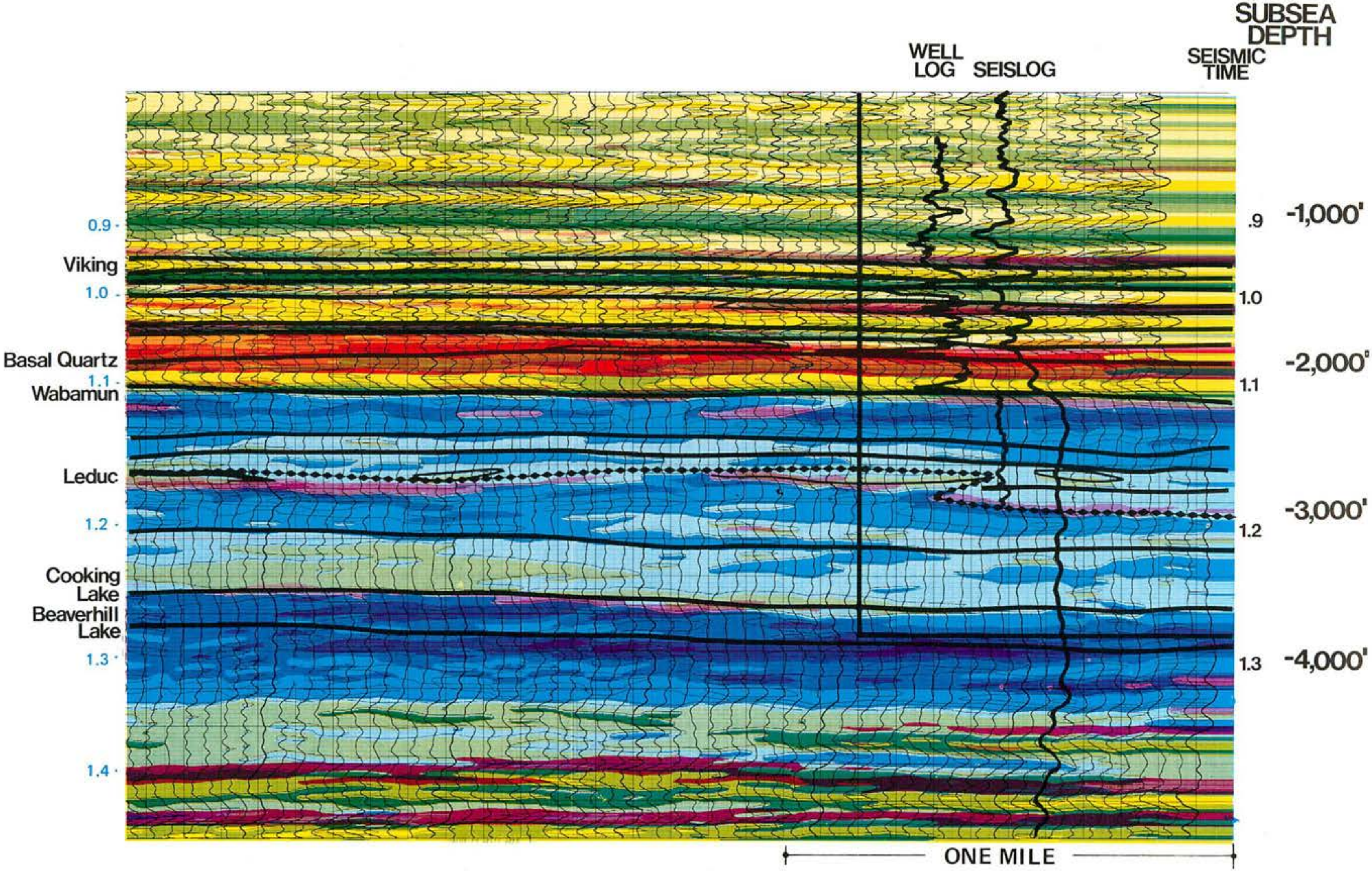

Fig. 13. Interpreted Depth SEISLOG Display of a Devonian Reef in Western Canada

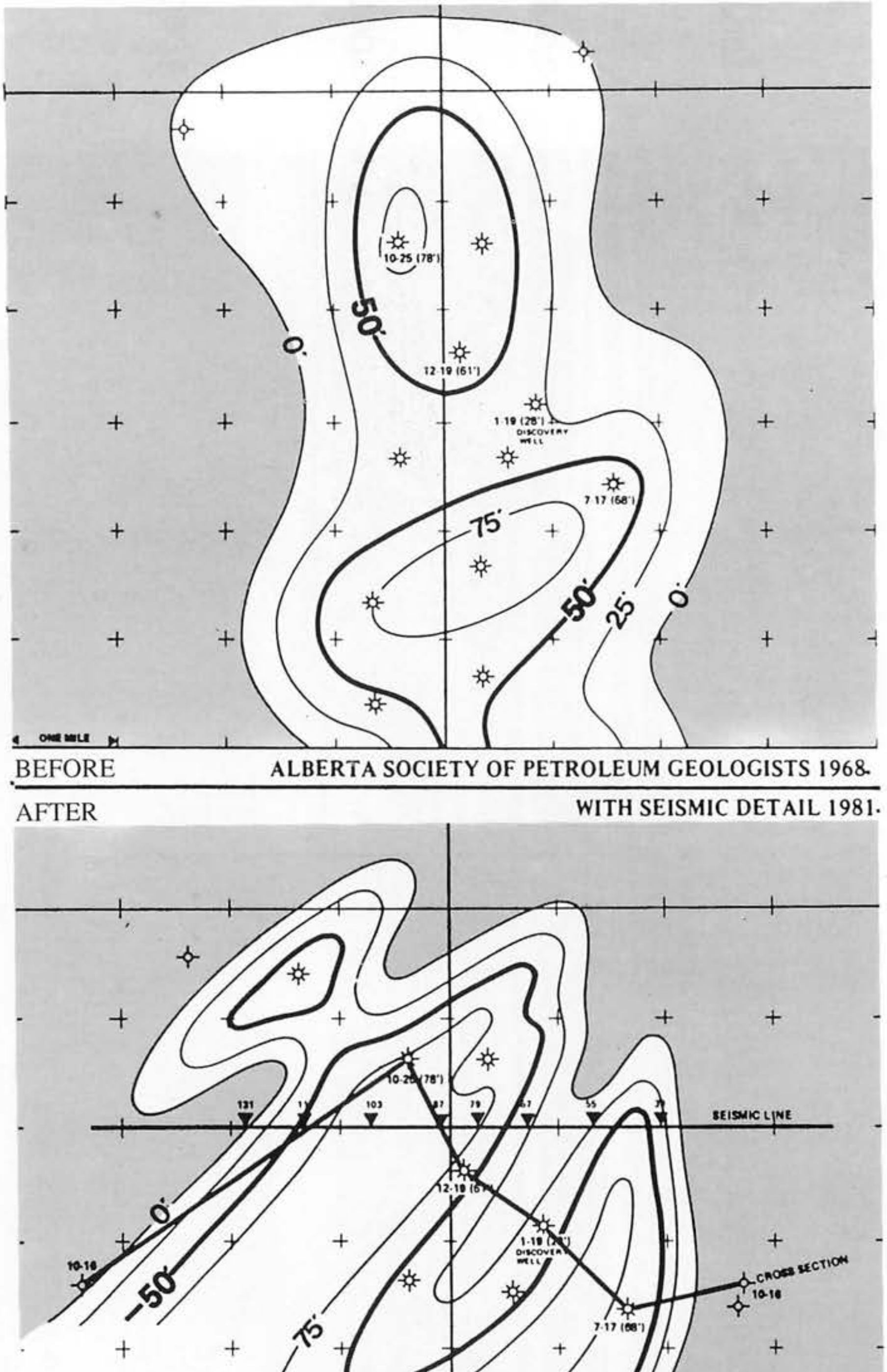

Fig. 14 Location Map of Seismic Across Regional Carbonate Unit before and after SEISLOG.
BEFORE : The orginal pool outline was contoured from only net pay values in each of the 13 wells. Reserve estimates, production rates and further in-fill drilling are commonly defined using such limited data.
AFTER : Supplementing well control with stratigraphic seismic data can result in a great increase in available reservoir detail.
The 'Before' map illustrates net gas pay, and the pool outline from only well control. The 'After' mapincorporates porosity-feet values from single seismic line with well control.

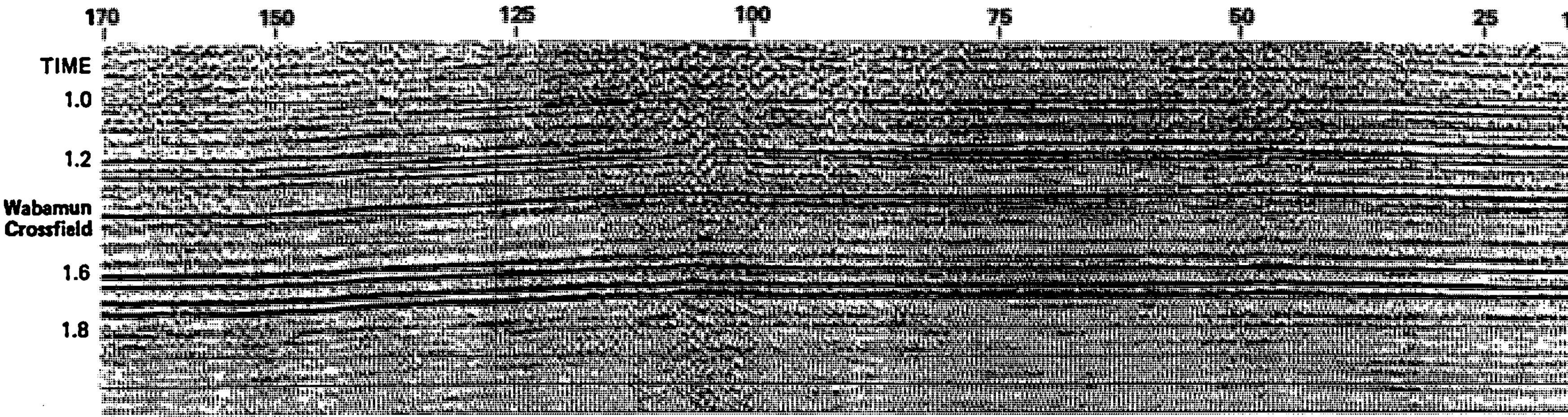

Fig. 15 Conventional Seismic Across Regional Carbonate. Seismic line across a gas field. Production is obtained from dolomitized porosity in an algal bank in Devonian carbonate section. The zone of interest is the Crossfield.

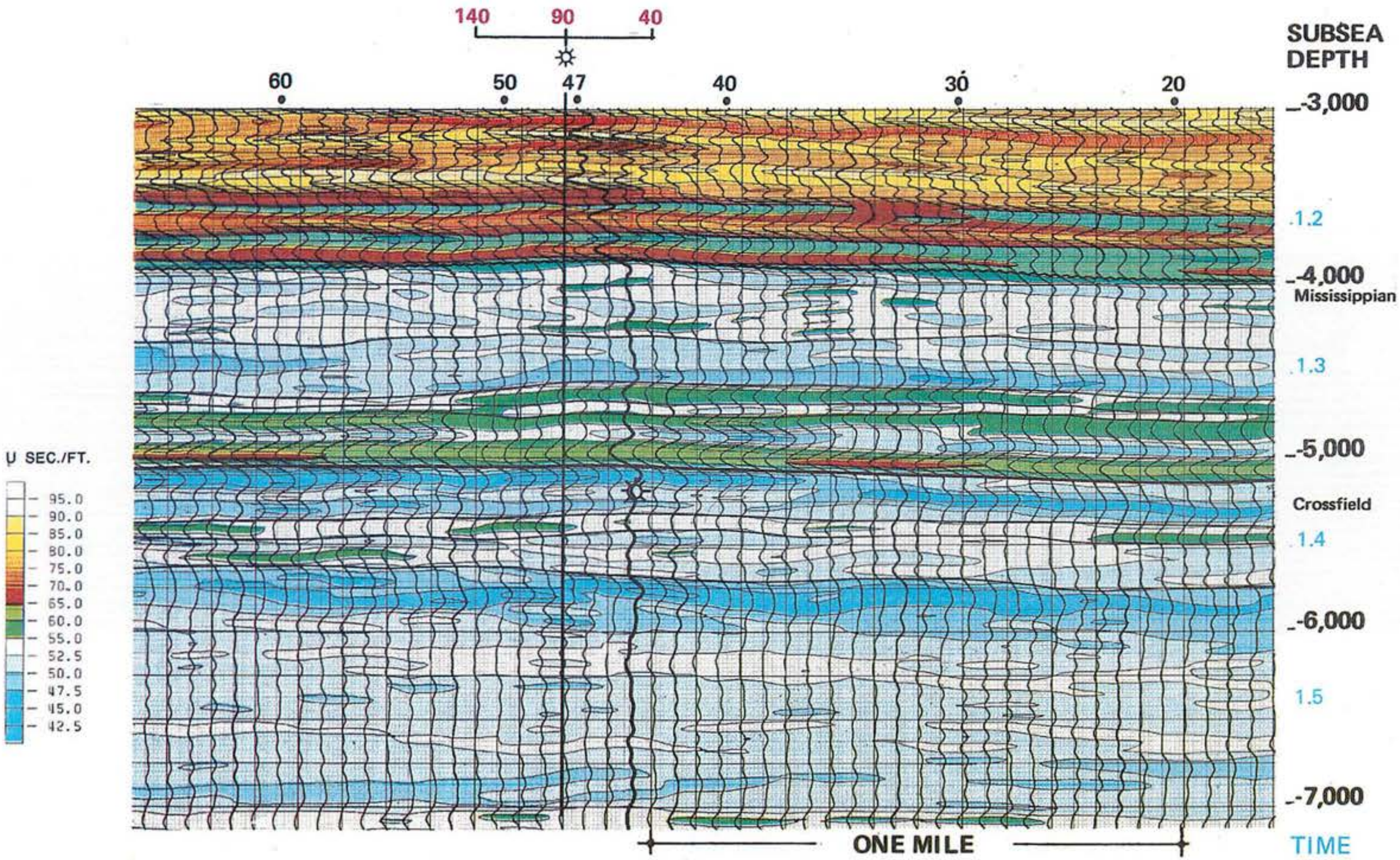

Fig. 16. A SEISLOG display of part of the seismic data shown in figure 15. The zone of interest is labelled Crossfield near -5250 feet.

from Cretaceous clastics to Mississippian-Devonian carbonates is represented by the colour changes from reds-yellows to higher velocity blues near –4,000ft. Low velocity shales in the Lower Mississippian are displayed by green colours near –5,000 ft. The producing zone is labelled Crossfield near –5,250ft. The pool was originally thought to extend from left (west) of the section to about shotpoint 55 on the basis of conventional seismic data. The **SEISLOG** study indicated that the pool might extend east to shotpoint 35. The gas symbol on the heavy trace at shotpoint 47 marks the porosity anomaly. A well was subsequently drilled at this location and encountered gas pay in the Crossfield zone. In this field study, calibration of the transit time values on the **SEISLOG** section with borehole measurements in wells provided data to accurately map porosity-foot values. This provided excellent control for development of this gas pool, and more accurate calculations of gas reserves in place.

The third carbonate example is from the North Sea (Figure 17). Two structures, **Dan** and **Anne** were defined using conventional seismic, shown in Figure 18. The map is based on the top Chalk, which is the reservoir in the region. The Chalk is Lower Tertiary (Danian) to Upper Cretaceous (Maastrichtean) in age. Chalk thickness and structure were similar on both features, however, **Dan** field has produced over 20mm barrels of oil, and the **Anne** structure was deemed uncommercial. **SEISLOG** processing was performed of the seismic line shown which crosses both structures and ties two wells.

The **SEISLOG** displays of the seismic data demonstrate the difference between the structures. The **A-2 well** (Figure 19) is located on the **Anne** structure and tested 450 BOPD from the upper Chalk. The **M-8X well** (Figure 20), in the **Dan** field flowed 4,500 BOPD and had over 100 m of pay. The velocity in the upper Chalk section varies dramatically between the two displays. Gas in the upper zones, had reduced the impedance of the normally high velocity Chalk. Stratigraphic studies have shown that the Chalk is homogeneous in composition, thus velocity changes can be related to porosity-permeability changes and fluid content variations. Comparison with well data indicates that blues represent tight Chalk, and oranges and yellow represent reservoir zones. The greens at the crest of the structures result from gas effects which dramatically lower the normally high chalk velocity. The reservoirs are more extensive and thicker in the **Dan** field (Figure 20) than over the **Anne** structure (Figure 19). Thus **SEISLOG** would have been able to rate these structures on the basis of potential reservoir and ensured that the **Dan** structure was drilled first.

CLASTIC EXAMPLES

Let us now turn to some clastic examples. Three examples will be discussed from the southern part of the South China Sea Region (Figure 21). One is from the Gulf of Thailand, while the others are from offshore Malaysia and offshore Indonesia. One area is under production, and the other two are in the delineation and development phases. The reservoirs are Miocene sandstones and contain gas and gas-condensate. We are not at liberty to disclose the exact location of the lines and I will acknowledge the companies at the end of this paper for the use of their data.

Our first example is from offshore Malaysia (Figure 22), the depth window displayed is from –4,500 feet to just over –8,500 feet, and the green colours represent the lowest velocities and the dark blues the highest. A representative **SEISLOG** trace has been darkened near the centre of the interpreted display. These synthetic sonic logs, which have been generated from the seismic data, were compared with well data in the area to establish the correlations used

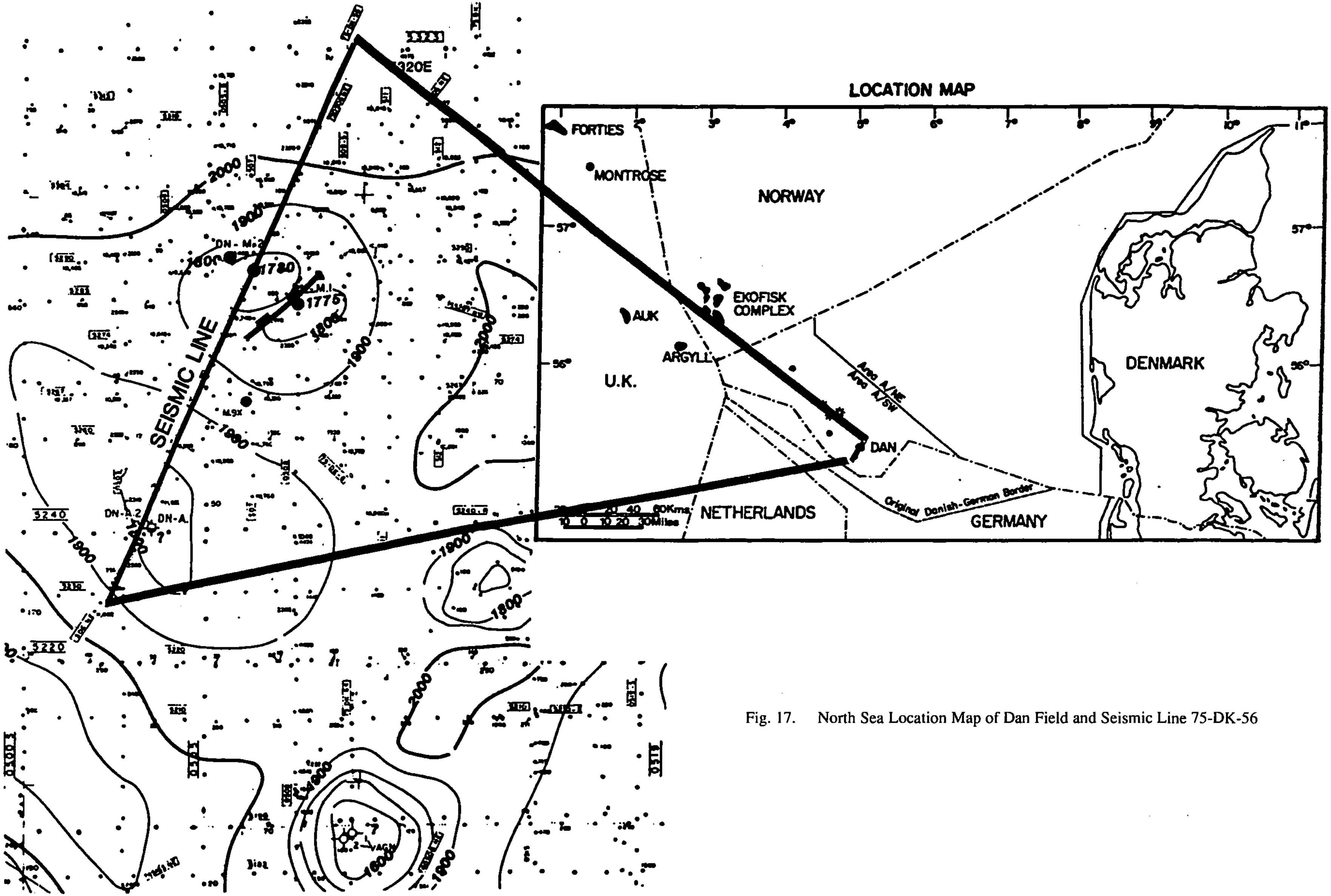

Fig. 17. North Sea Location Map of Dan Field and Seismic Line 75-DK-56

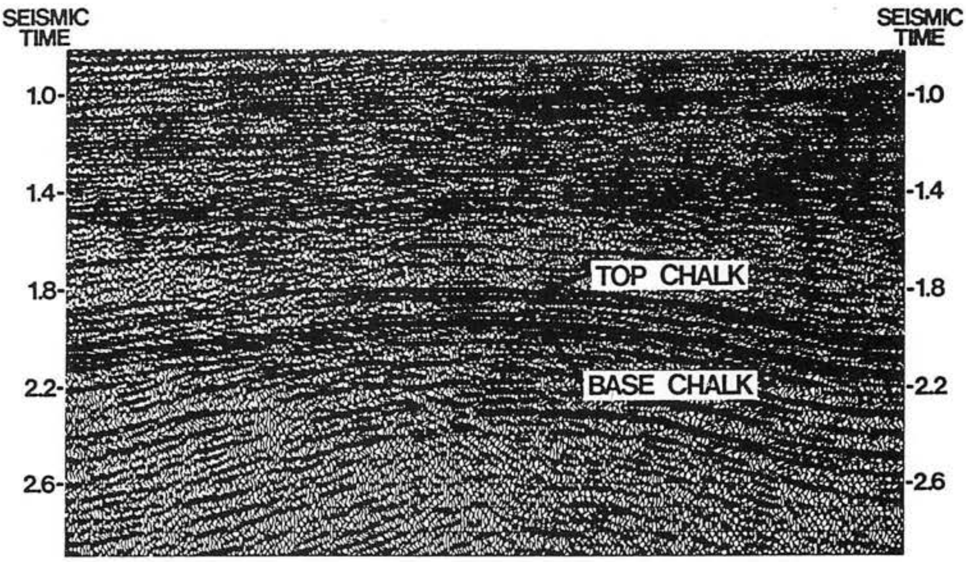

Fig. 18. Conventional Seismic in North Sea (Dan Field, Seismic Line 75-DK-56)

for the interpretation. The upper part of the stratigraphic section consists of marine shales of the Upper Miocene Bekok Formation overlying a clastic complex of the Miocene Terengganu Group, which starts at about –6,500 feet. The upper part of the clastic complex consists of interbedded sands and shales overlying a lower sequence of massive sands separated by major shale units. The sequence continues to just above –8,000 feet where it changes to silts and shales, resting on basement.

Many details within the sedimentary package can be observed. The massive sand sequence has been interpreted as a set of coastal barrier-beach complexes. The yellow coloured unit near the middle of the display represents the main reservoir unit. The oranges and browns represent sands with less porosity and hence higher velocity. The reservoir sands at the top of the massive sands complex have reasonable lateral continuity, with some local variation in porosity. The trap in this area is predominantly structure although **SEISLOG** indicates wells may vary in productivity due to reservoir quality variations. Most of the faulting displayed on the section is in the lower part of the sequence and only one fault (on the right) appears to transect the Upper Miocene section.

Finally, the upper section appears to be in a shallow marine environment, predominantly shales but with a few thin laterally extensive marine sands displaying higher velocities. These sands are yellow in colour and a few of these have been outlined.

Our second clastic example is from Natuna Sea area of offshore Indonesia (Figure 23). In contrast to the previous display (Figure 22), the upper section contains a high percentage of coal, coloured grey. This line is from an existing field and two of the main producing zones are identified on the right-hand side of the interpreted section.

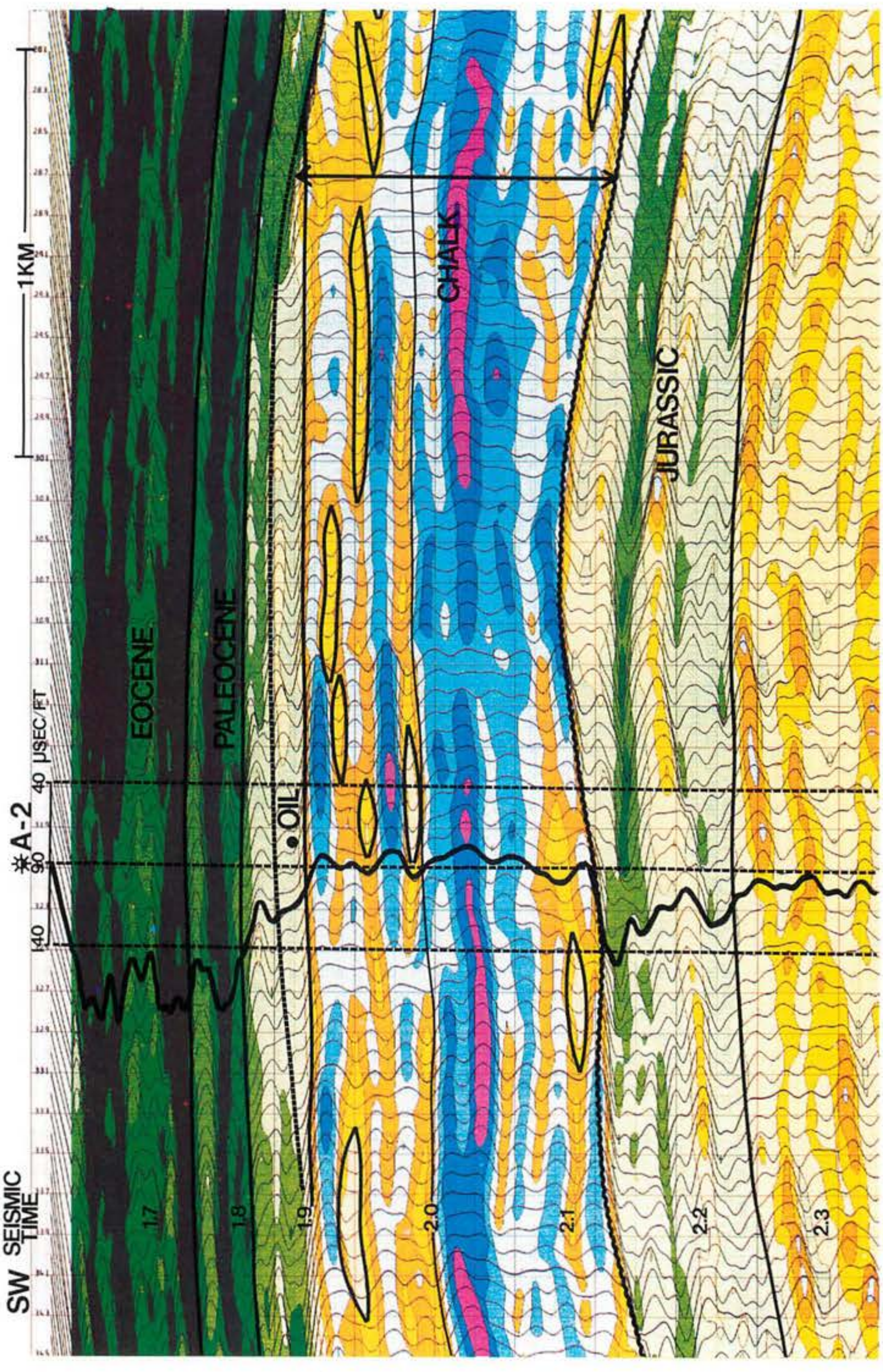

Fig. 19. SEISLOG Display at A-2, Anne Structure, North Sea

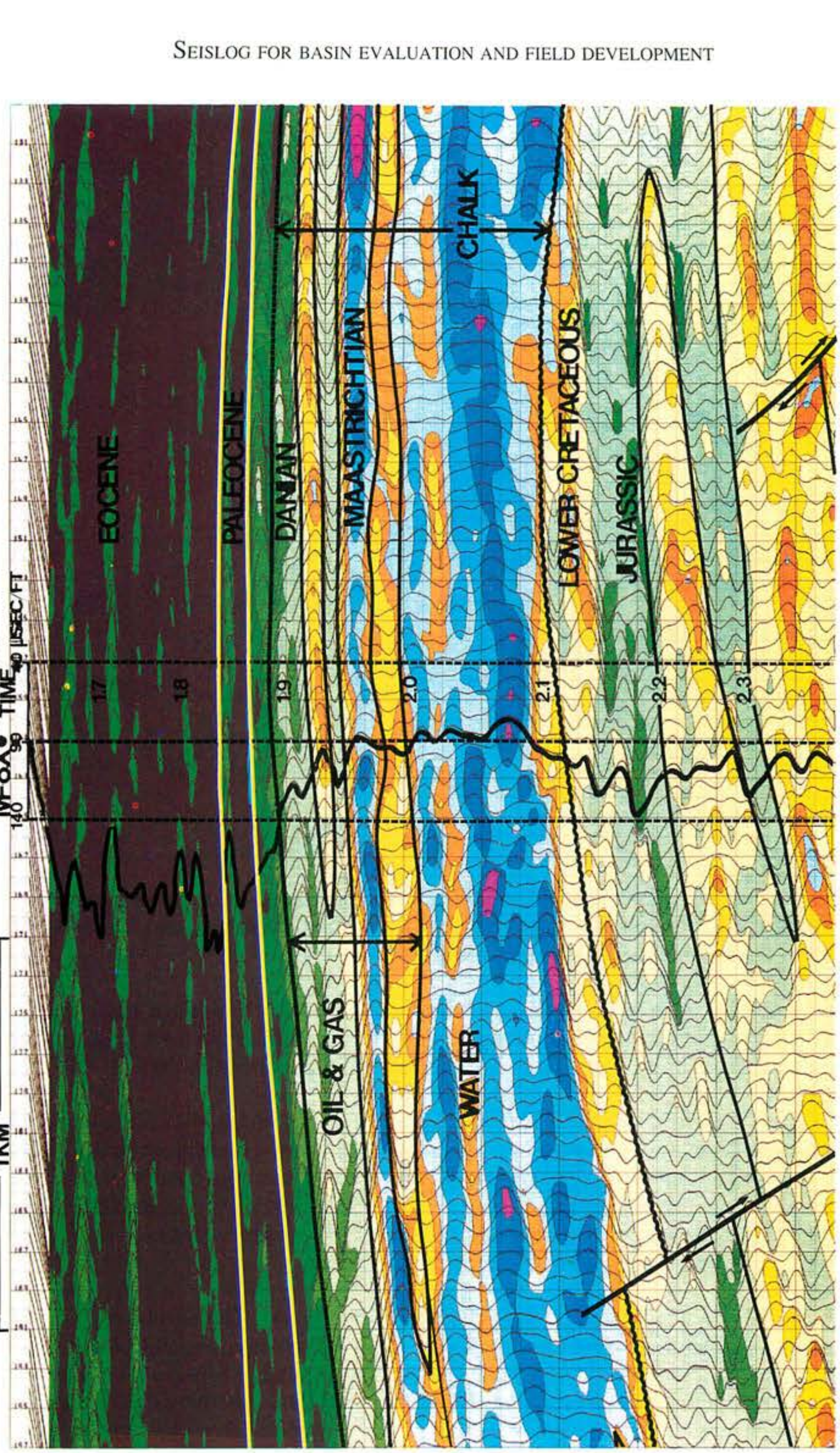

Fig. 20. SEISLOG Display at M-8X, Dan Field, North Sea

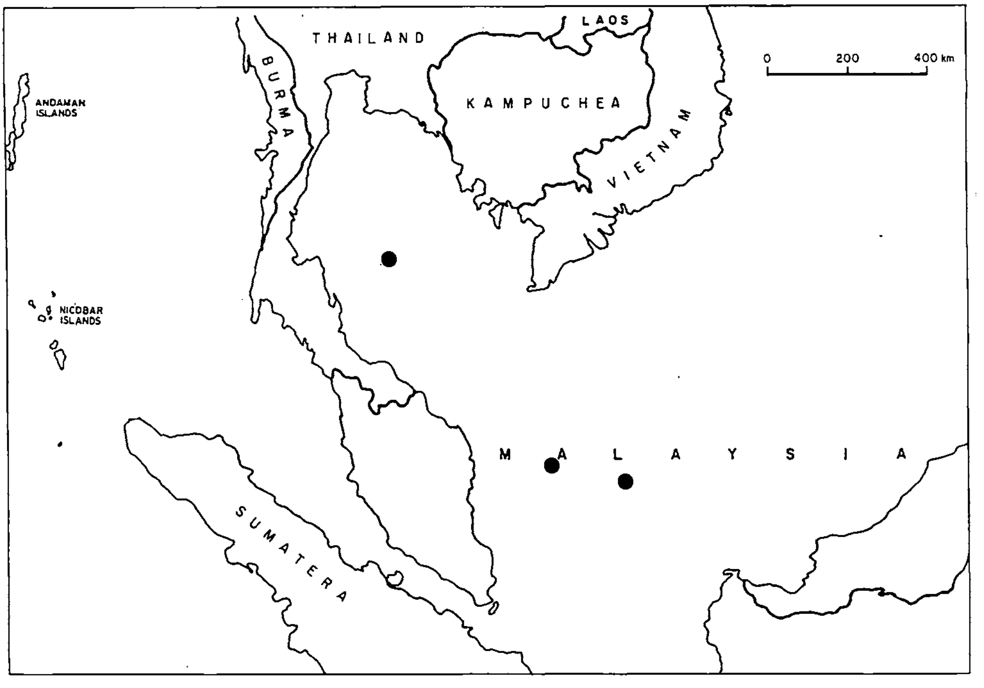

Fig. 21. SE Asia Location Map of Clastic SEISLOG Examples

A major gas zone occurs at about –4,000 feet, and the main gas-condensate zone has been identified near –5,000 feet. Basement is below the section displayed, and the stratigraphic sequence is thicker than in the previous area.

The depositional environment of the Miocene sands in this region has been interpreted as lower delta plain to transitional marine. Faulting is evident in the area, however, many units, especially the lower velocity shales, display good lateral continuity.

The area outlined on Figure 22 shows the rather abrupt limits of the producing units. Faulting appears to play a role in the trapping of hydrocarbons in the region. **SEISLOG** also indicates rather homogeneous reservoir conditions in the condensate zone bounded by solid tape on the top and dashed tape on the bottom. Reservoir units may extend to the downside of the fault, however, the low velocity unit is thinner, and may be water bearing because of its down dip position relative to existing production.

Our final example is from the Gulf of Thailand (Figure 24). This display is quite different in appearance from the previous ones. The depositional environment of the Miocene sands in the area is interpreted as upper delta plain to continental. There is a high coal content in the section, coloured dark green. The yellow-coloured sands are more discontinuous and variable in thickness than in the other areas.

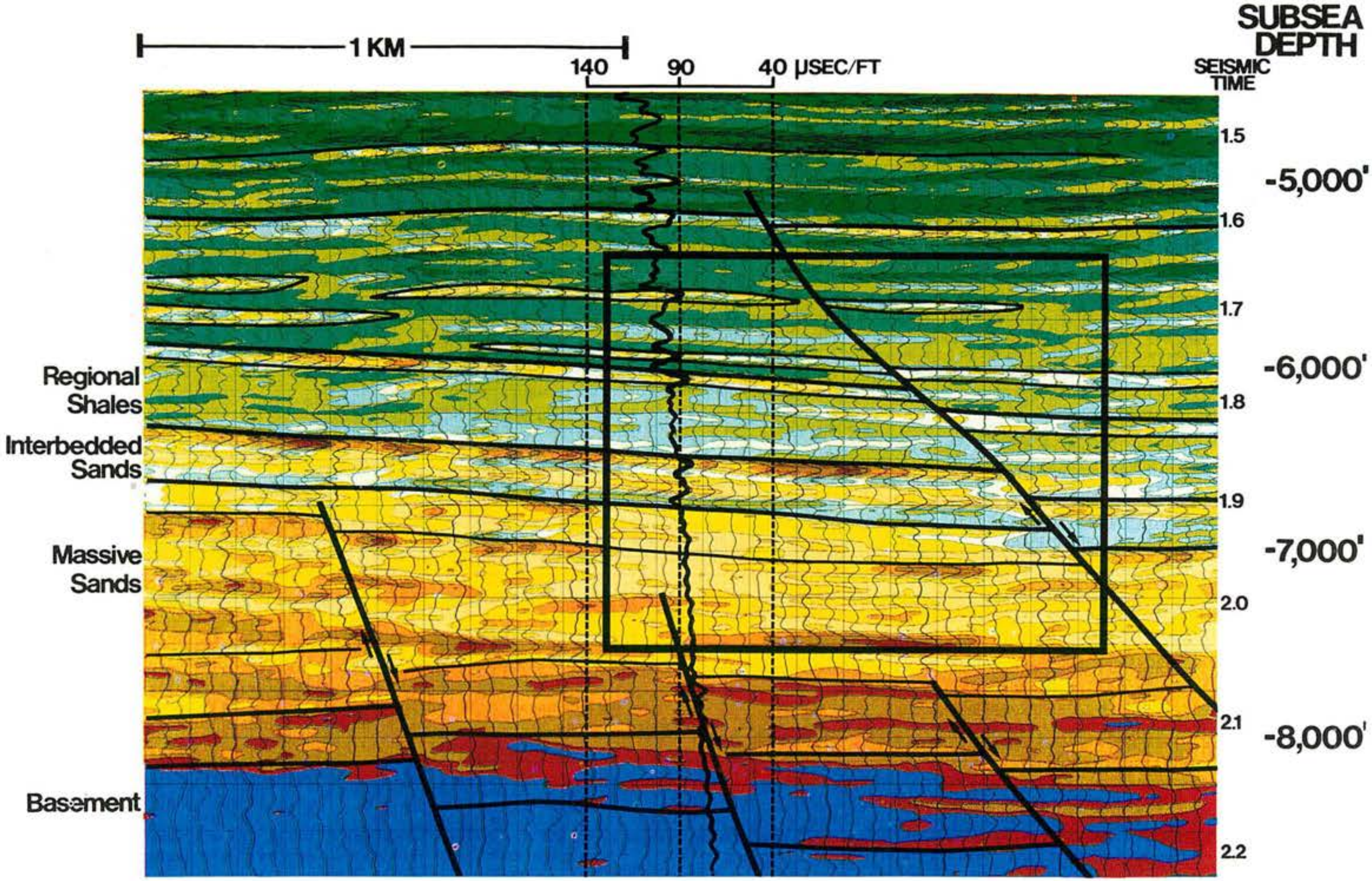

Fig. 22. Depth SEISLOG Display Offshore Malaysia

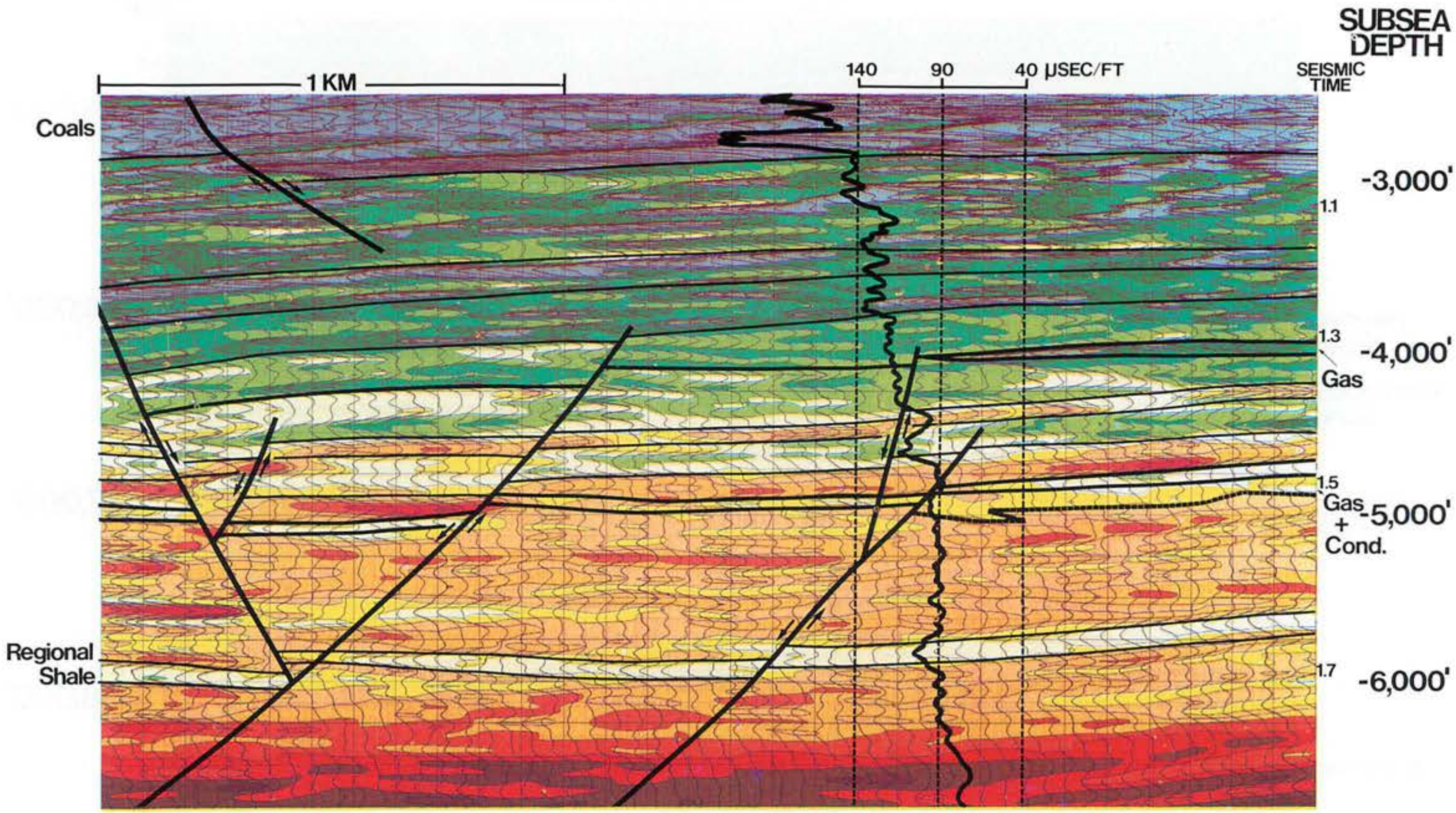

Fig. 23. Depth SEISLOG Display Offshore Indonesia.

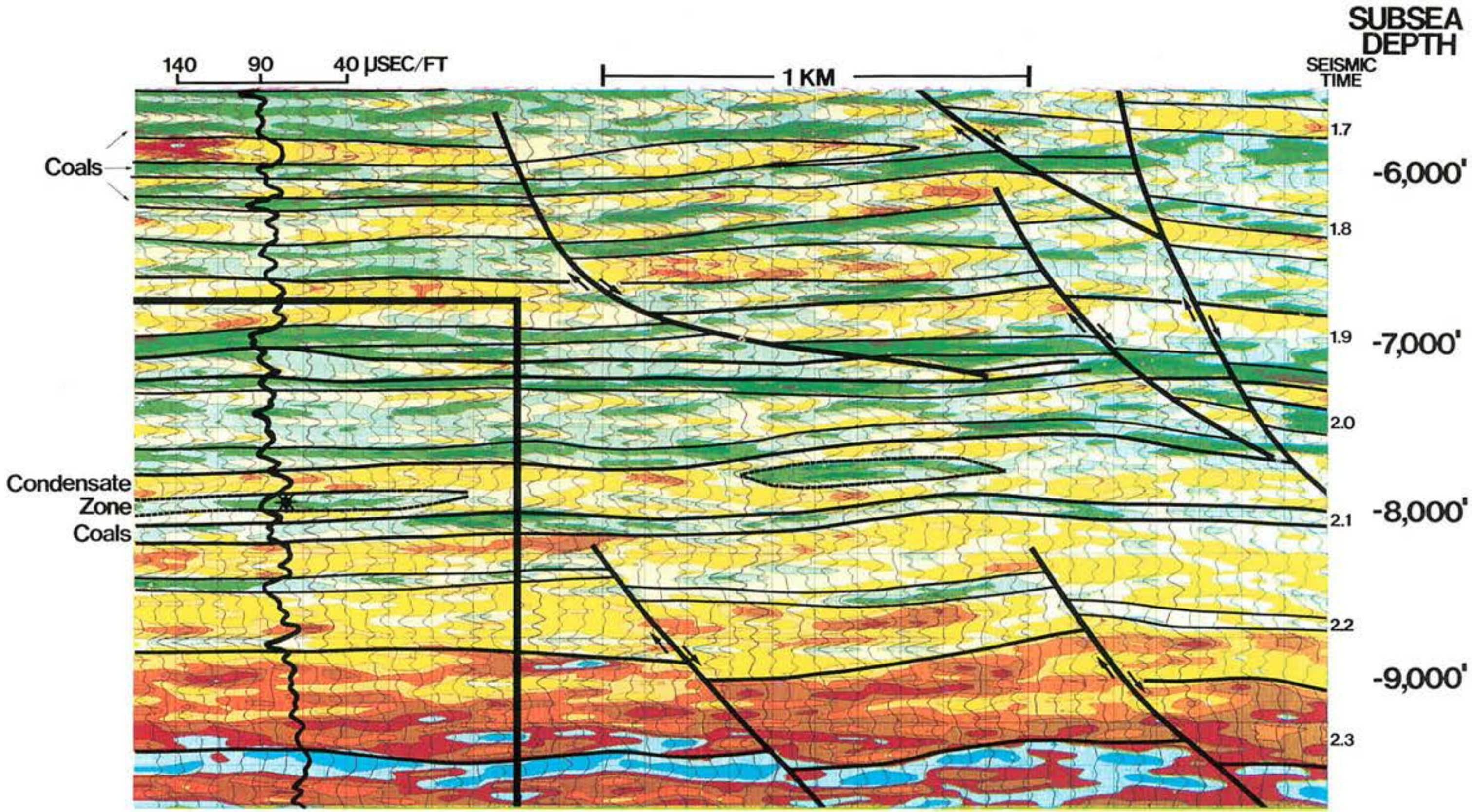

Fig. 24. Depth SEISLOG Display Gulf of Thailand.

Well data near the left side of the section indicate a number of coal and gas zones throughout the sequence. Many are below the resolution limits of the data, however, one of the major condensate producing zones has been outlined near –8,000 feet. Many of the faults in the section show expansion on the downthrown side. Differentiation between gas sands, coals, and carbonaceous shales on the basis of velocity data alone is almost impossible. However, using facies models one can predict that shales and coals will have more continuity than sands in this depositional environment.

The outlined area on the display shows that the condensate zone near the centre of the slide is best developed within the middle of a higher velocity sand lens. The velocity of this zone is similar to overlying and underlying coals and shales, however, its continuity is restricted. In this area, stratigraphic changes form the main trapping mechanism. A similar, but untested zone, can be seen near the middle of the section on the right and this would be the optimum spot to locate a well rather than in a structurally higher location further to the right. **SEISLOG** studies reveal that delineation drilling based on structure alone would result in a significant number of dry holes or marginal producers.

CONCLUSION

In conclusion, I hope that these examples, from a variety of tectonic and stratigraphic settings, have been able to demonstrate the importance of obtaining detailed stratigraphic information from seismic data. Creation of pseudo-sonic logs from seismic traces is a powerful tool in both exploration and development programs. In exploration ventures, one can use this information to rate structures that might appear similar according to conventional seismic. **SEISLOG** data can also be used to predict the stratigraphy of an area before drilling and thus help in planning the well program. In delineation and production phases, the **SEISLOG** method can predict reservoir continuity, optimize platform locations and can save dry hole money.

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