REEF DELINEATION BY MULTIPLE OFFSET BOREHOLE SEISMIC DATA COLLECTION: A CASE STUDY

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ABSTRACT

A new imaging method, closely related to prestack Kirchhoff migration, has recently been proposed for use with multioffset borehole seismic data. In order to test this method in a combined exploration/reservoir-description environment, a controlled case study was carried out during the fall of 1984. The purpose of the study was to evaluate the applicability of seismic reflection tomography (SRT)-processed borehole seismic profiles to two problems. The first is a structural problem: Can we perform an experiment in a dry hole to provide a clear indication of the presence and lateral offset of a nearby geological structure that is poorly resolved by surface seismics? The second is a stratigraphic problem: Can we provide any details on the lateral extent of internal units of a proven reef complex?

In this report we summarize the application of the method to the delineation of a Silurian pinnacle reef in the Michigan basin.

INTRODUCTION

Pinnacle reefs are major producers of gas and oil in Michigan. Estimates of recoverable reserves in the northern reef trend, for example, have been in the range of 400 to 600 million barrels of oil and 3 to 5 trillion cubic feet of gas. A brief and oversimplified description of their history follows (see Caughlin et al., 1976; Lee and Budros, 1982; and Nurmi, 1982, for more detailed accounts).

The reefs are of Middle Silurian (Niagaran) age and grew in an intracratonic structural basin which has been in existence for at least 500 million years (Figure 1). They are encased in an Upper Silurian (Cayugan) series of evaporites and carbonates (the Salina) that effectively act as both seal and source for the hydrocarbons (Figure 2). From bottom to top, the principal facies in the Salina Series consist of: A1 salt and A1 carbonate; A2 salt and A2 carbonates. Usually the Al sequence shows draping; the A1 salt is truncated and turns to anhydrite on the flanks of the reef; the A1 carbonate may or may not be truncated. The A2 salt can turn to anhydrite or only show inclusions of it, and the A2 carbonate usually drapes and overlies the reef, with a physical pull-up on top of the reef. The sequence below the reef may be compacted, with a physical pull-down of the base of the reef.

These simple geometrical considerations have led to some criteria in the interpretation of surface seismic data (and of dipmeter data) to identify reefs themselves, or to alert the explorationist to their proximity. Seismic criteria include (1) disruption of the seismic response of the A1-A2 sequence; (2) time thinning from the Dundee (an essentially flat shallow formation top) to the top of the A2 carbonate; (3) disruption of the Niagaran reflection; and (4) apparent pull-up of deep reflections.

Reliable determination of the thicknesses of the A1 and A2 sequence, and of the reef itself, is made difficult by the usual pitfalls in defining geometry from two-way times and by the variation of their velocity and density profiles due to post-depositional chemical changes. Further complications arise from a thick section of glacial deposits (about 600 ft, or 183 m, in the area of the experiment) and from the presence of surface sand dunes. Conversions occur at the base of the glacial layer to create “noisy” records, and statics (when not handled properly) play havoc with the seismic detection criteria.

The general consequence of all this is that although surface seismics can provide a fairly reliable proximity indication for Michigan basin pinnacle reefs, it often lacks the resolution to determine their exact location, and it is common to strike several dry holes before production begins.

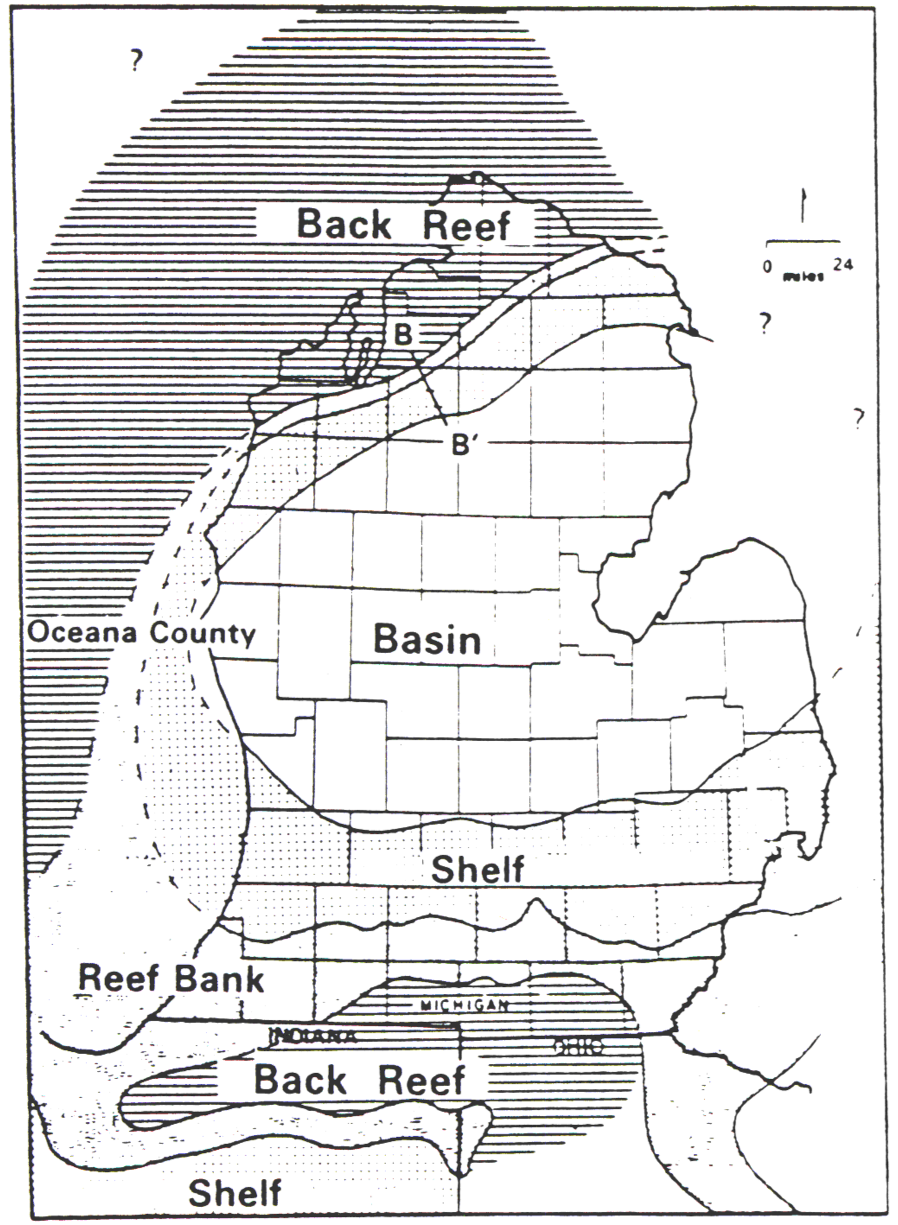

Figure 1. Niagaran environments of sedimentation, Michigan basin (from Briggs and Briggs, 1974, via Lee and Budros, 1982).

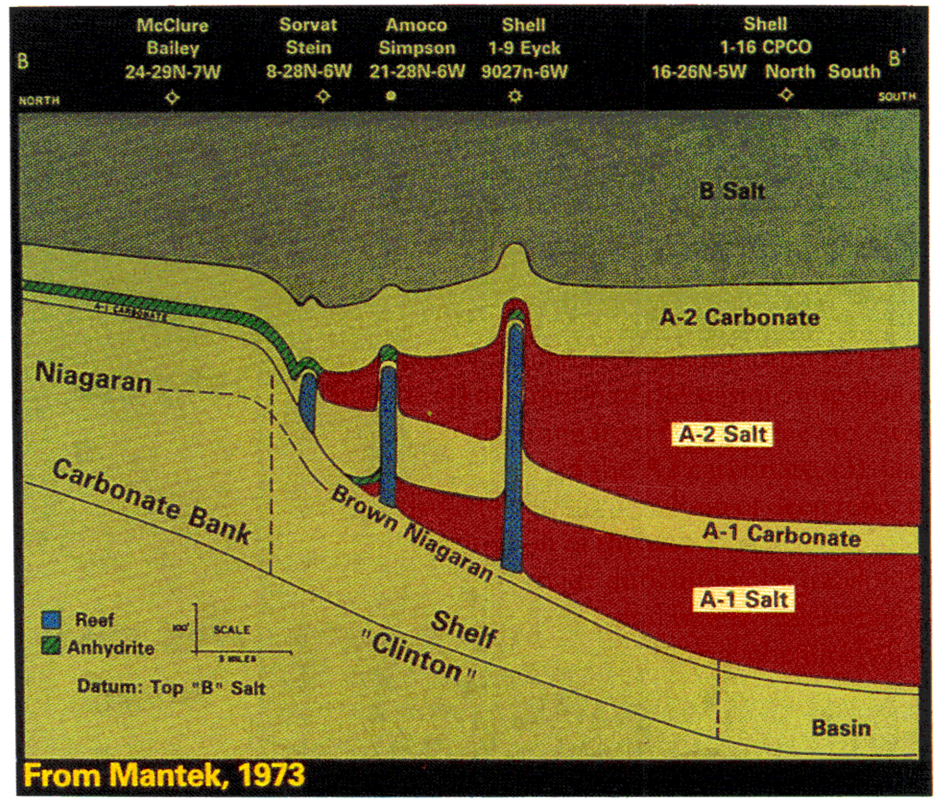

Figure 2. Cross section across a typical northern Michigan reef zone. See Figure 1 for location (from Mantek, 1973, via Lee and Budros, 1982).

THE STUDY

Our experiment was carried out in the vicinity of a proven reef in Oceana County, Michigan. The general trend of the reef is defined by two producing wells aligned from west to east and separated by approximately 1500 ft (457 m). Three dry wells flank the producing wells both to the north and south at offsets of about 1000 ft (305 m) in each direction (Figure 3). Our data were collected with a vertically polarized Well Seismic Tool from multiple receiver positions in one of the southern dry holes (well A). Source positions were chosen to provide a borehole seismic image along a north-to-south line parallel to a surface seismic line and about 400 ft (122 m) west of the nearest production well. The common depth point (CDP) seismic section indicates the difficulty in picking a precise reef location from surface-collected seismic data alone (Figure 4).

For geophone depths from 1400 to 4000 ft (427 to 1219 m), four offset profiles were recorded (Figure 5), one for a source 920 ft (280 m) to the south, and three for sources up to 1700 ft (518 m) to the north of well A. For 13 geophone depths from 1800 to 2400 ft (549 to 732 m), 28 walkaway profiles were recorded, seven to the south (up to 920 ft, or 280 m, offset), and 21 to the north (up to 3800 ft, or 1158 m). The south and north lines were recorded as allowed by local conditions, and well A is at about 350 ft (107 m) east of these lines.

Logs from the dry well and a standard vertical seismic profile (VSP) from the near offset are shown in Figure 6. They indicate that the top of the A2 salt occurs at 3330 ft, or 1015 m (650 msec two-way travel time), and that the top of the Al salt occurs at 3720 ft, or 1134 m (700 msec). Correlation with the CDP section suggests a static shift of 50 msec between the two, placing the top of the A2 at 600 msec and the top Al at 650 msec on the CDP section.

PROCESSING

In recent years, a number of “full wave equation” algorithms have been proposed for the migration of offset vertical seismic profiles. They include methods based on acoustic wavefield extrapolation using the Kirchhoff integral (Keho, 1984; Wiggins, 1984; Koehler and Koenig, 1984; Wiggins and Levander, 1984), phase-shifting in the frequency domain (Gazdag and Sguazzero, 1983), and finite-difference extrapolation (Whitmore and Lines, 1985; Change and McMechan, 1986). See Oristaglio (1985) for a more complete history. Miller, Oristaglio, and Beylkin (1984; 1986) proposed a general approach to seismic imaging (including VSP), which is closely related to these methods and to recent work on linearized inverse scattering (Born inversion; see e.g. Stolt and Weglein, 1985, for a summary).

This method, which is derived from the wave equation and the mathematics of the Radon (slant-stack) transform, seems particularly well-

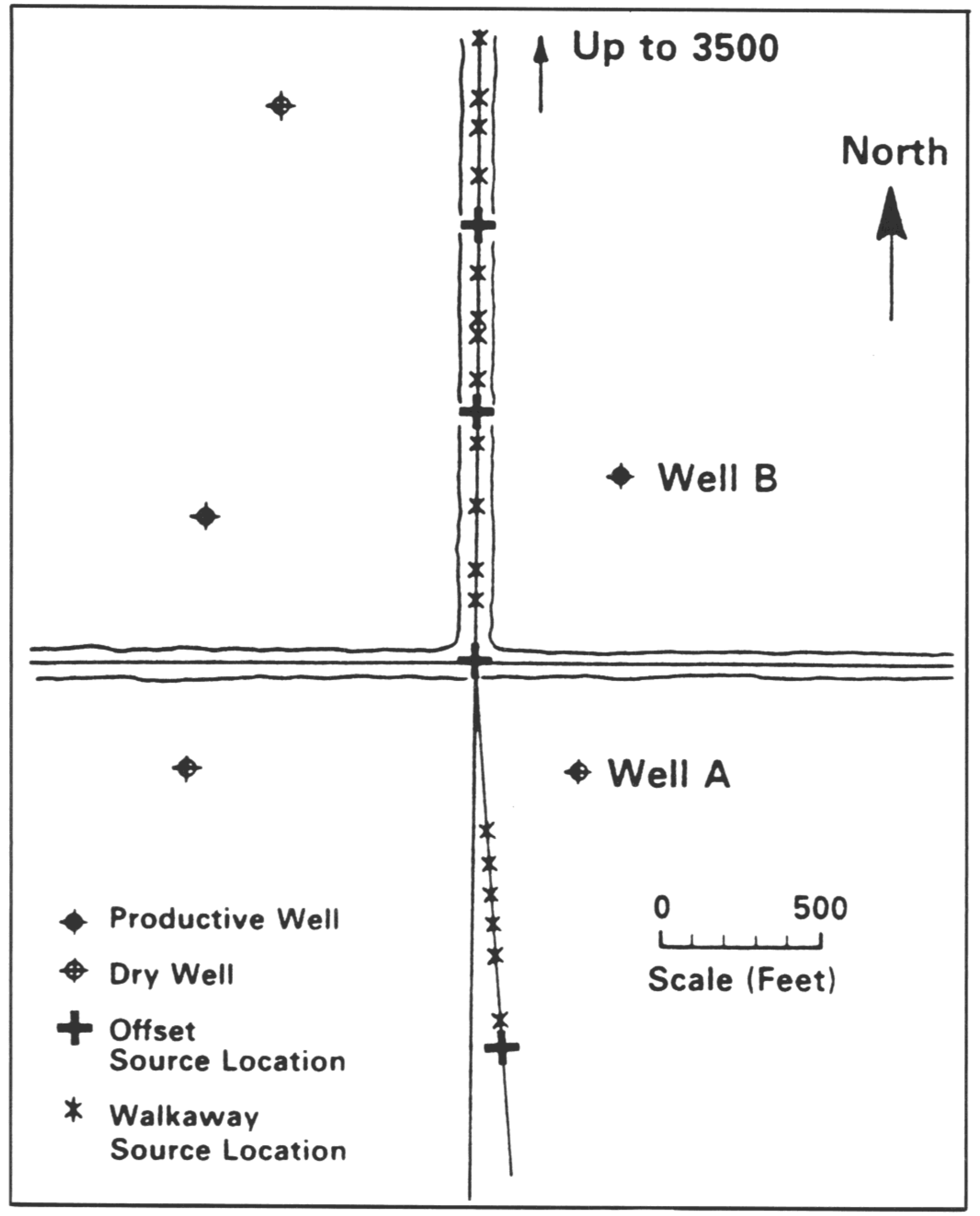

Figure 3. Plan view of the experiment showing well locations and line placement.

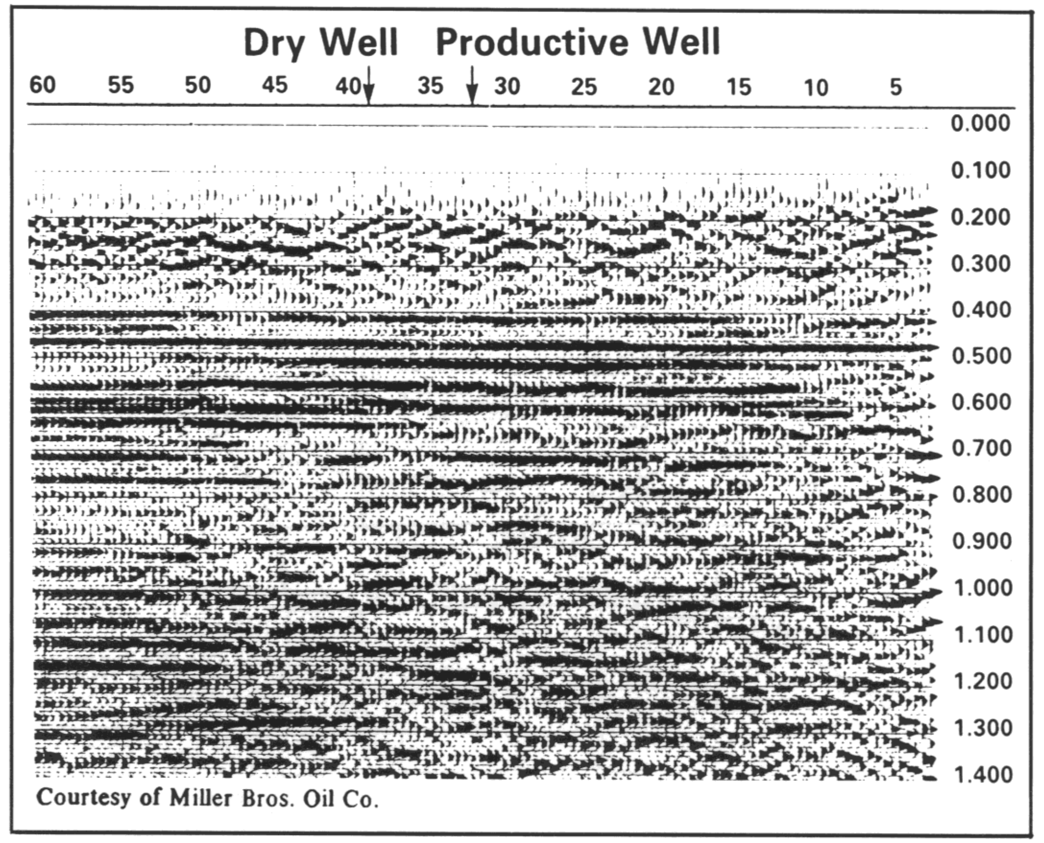

Figure 4. Surface seismic section (coherency filtered CDP stack). The line runs from north to south with well B at shotpoint 32, and well A at shotpoint 39.

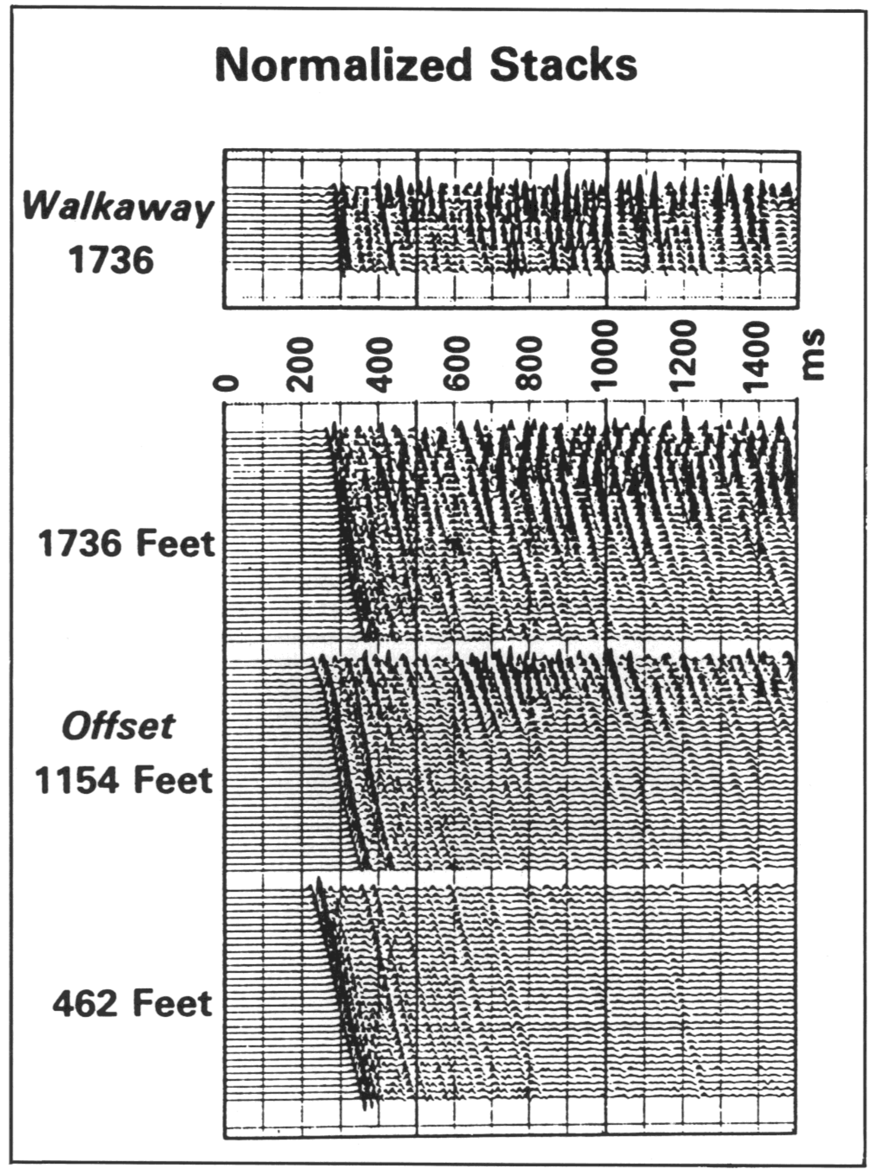

Figure 5. Stacked raw data. Each playback is normalized by file. Depth range is 1400 to 3960 ft (427 to 1207m) for the offset VSPs, 1800 to 2400 ft (549 to 732 m) for the walkaway.

suited for use with multi-offset borehole seismic-data collection where one must combine data from several experiments and contend with heterogeneous velocity structures. The connection with the Radon transform and the methods of ordinary x-ray tomography suggests the term "seismic reflection tomography" (SRT). It should be emphasized, however, that the method is substantially a variation of the classical diffraction stack.

The integral equation for seismic reflection tomography derived by Miller, Oristaglio, and Beylkin (1984; 1986) translates to a summation processing: *For all image points x, compute*

$$image\ (x) = \sum_{s,g} W(r,x,s)\, u_{sc}(r,s,t).$$

Here, s and r are sources and receivers, t = τ(r,x) + τ(x,s) is travel time, computed by ray tracing from s to x to r through a background model, and u_{sc}(r,s,t) is the singly scattered wavefield generated by the scattering object. W is a product of weighting factors which handle geometrical spreading, source and receive-angular spacing as viewed from the image point, and source-receiver offset angle. An additional factor equal to the vertical component of the unit vector along the receiver ray was included to attempt to compensate for the vertical polarization of the geophone.

The SRT algorithm requires that two essential inputs be derived from the experimental data: the singly scattered data field u_{sc}(s,r,t); and the reference velocity model for use in the computation of travel times τ(x,y).

An acceptable approximation to the first item is provided by the traditional VSP processing steps of velocity filtering and waveshaping. (See Hardage, 1983, for a discussion of basic VSP processing.) In the present case the presence of high-amplitude events on traces where the ratio of source offset to geophone depth is large makes these steps difficult (Figure 5). These events appear to occur at the contact between the Antrim Shale and the Traverse carbonate, at about 1800 ft (549 m). They affect a few geophone levels above and below this contact, suggesting possible waveguide effects. For the offset profiles, the separation of events was performed with an interactive F-K filter. Unwanted events of high amplitudes on the shallowest traces were muted before the filtering, as most of them occur later than the reflections in interest. Upgoing events were then waveshaped using a filter designed from the extracted downgoing wavefield. Due to difficulties presented by the combination of the high-amplitude noise events and the smaller number of receiver stations available for estimation of the downgoing (incident) wavefield, the walkaway data were more difficult to process. In the end, they gave similar results. The image shown was generated using the three northern offset profiles only.

The second requisite item is provided by a log and VSP-based velocity analysis. Formation tops for a flat velocity model were tentatively pinpointed from the gamma-ray log of well A, and velocities were assigned from the lithology. Those velocities then were refined by requiring that the first arrival times derived from ray tracing through the model match those measured from the data. Static corrections for each source location were estimated by a similar process, replacing each actual source position, s, by a virtual source position, s^t, at the base of the weathered zone.

When elastic parameters were introduced into the model, some events could be interpreted by ray-tracing as P-to-S conversions at the base of the weathering. An example is the event going down from 400 msec to 450 msec in the walkaway at 1736 ft (529 m; top of Figure 5). A sonic log was derived from the model and used to generate the synthetic seismogram shown in Figure 6.

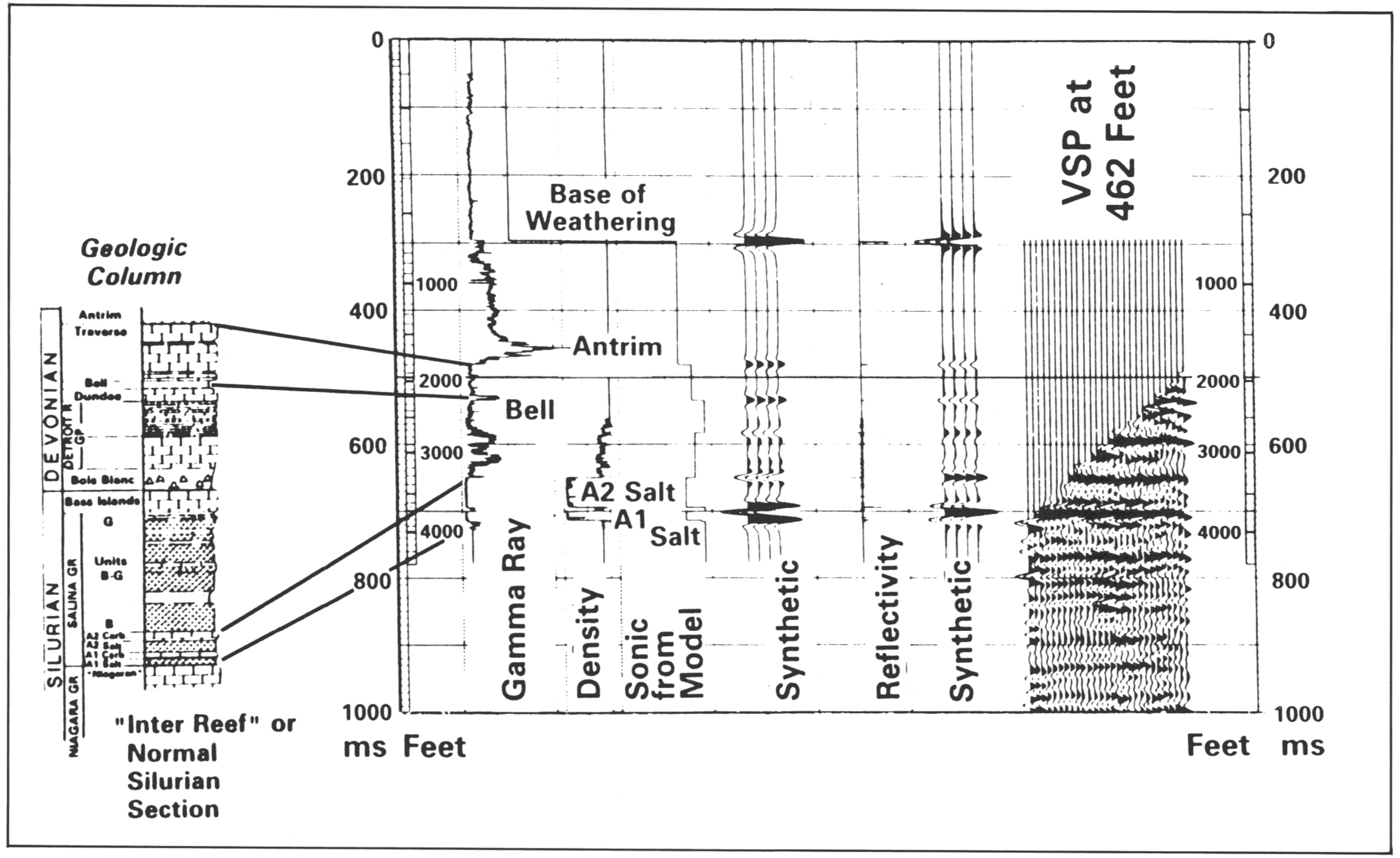

Figure 6. Relationships between geology and the VSP data at 462 ft (141m) offset.

THE IMAGE

Figure 7 shows the SRT borehole seismic profile (BSP) displayed in depth together with gamma ray logs for both wells. The reflection from the top of the Al salt matches the logs of the dry well (A) at its projected location in both time and polarity. As we move north toward the productive well (B), it shows draping and a change of character, and a new reflection appears below it. This new reflector matches the top of the high-porosity, light-hydrocarbon-bearing, dolomitic formation in the productive well. A thin bed of anhydrite separates this zone from the above low-porosity mixture of limestone and dolomite. The black peak of the SRT profile indicates a decrease in acoustic impedance at the top of the high-porosity zone.

Figure 8 shows a detailed drawing taken from Gill (1973) illustrating the expected relationship between the various facies in the reef complex. In particular, it shows the conventionally accepted division of the reef formation into three distinct growth stages corresponding to biohermal development below wave base, wave-resistant organic reef development above wave base, and tidal and supratidal-island development in a hypersaline environment (cf. Lee and Budros, 1982).

Figure 9 shows a corresponding enlarged section of our borehole seismic profile together with detailed logs from both wells. The three growth stages are evident on the Global™ log of the productive well with the organic reef stage corresponding to the porous reservoir between depths 3680 and 3790 ft (1122 to 1155 m). The continuous event that connects the top of the A1 salt to the tight dolomitic zone at 3550 ft (1082 m) suggests a correlation between the A1 carbonate and the upper part of the supratidal-island stage of the reef complex. This supports Huh's (1973) suggestion that some of the growth of the northern reef complexes occurred during the deposition of the Al carbonate (cf. Lee and Budros, 1982, p. 10).

Figure 10 shows the same borehole seismic profile displayed in two-way time together with the surface CDP section. Aperture for specular reflections on the BSP is a function of the location of the sources and receivers, and of the dip of the reflector. The apparent decay of the flat reflectors in the upper right of the BSP occurs at the aperture limit for 0-dip specular reflections. The measured dip on the top A2 event is 0 degrees. The measured dip on the top reservoir event is 15 degrees. The transformation from depth to two-way time was based on the velocity model used in processing the BSP.

The events occurring at 4000 ft, or 1219 m (730 msec) and 4300 ft, or 1311 m (760 msec) on the BSP probably correspond to the top Gray Niagaran and base Clinton. These events are evident at the left edge of the CDP section (Figure 4), but they break up near shotpoint 47 (- 1500 ft on Figure 10). That shotpoint coincides with the base of a hill which ascends to shotpoint 35 (+ 300 ft). This breakup, along with the mistie of these events between the CDP section and the BSP, suggests a possible problem with elevation statics on the CDP section.

For comparison, Figure 11 shows the image obtained from the same borehole seismic data (largest offset only) by means of the method that is the current standard for commercial processing of offset VSP in the industry as a whole (reflection point mapping). See Wyatt and Wyatt (1981) implementation by Schlumberger.

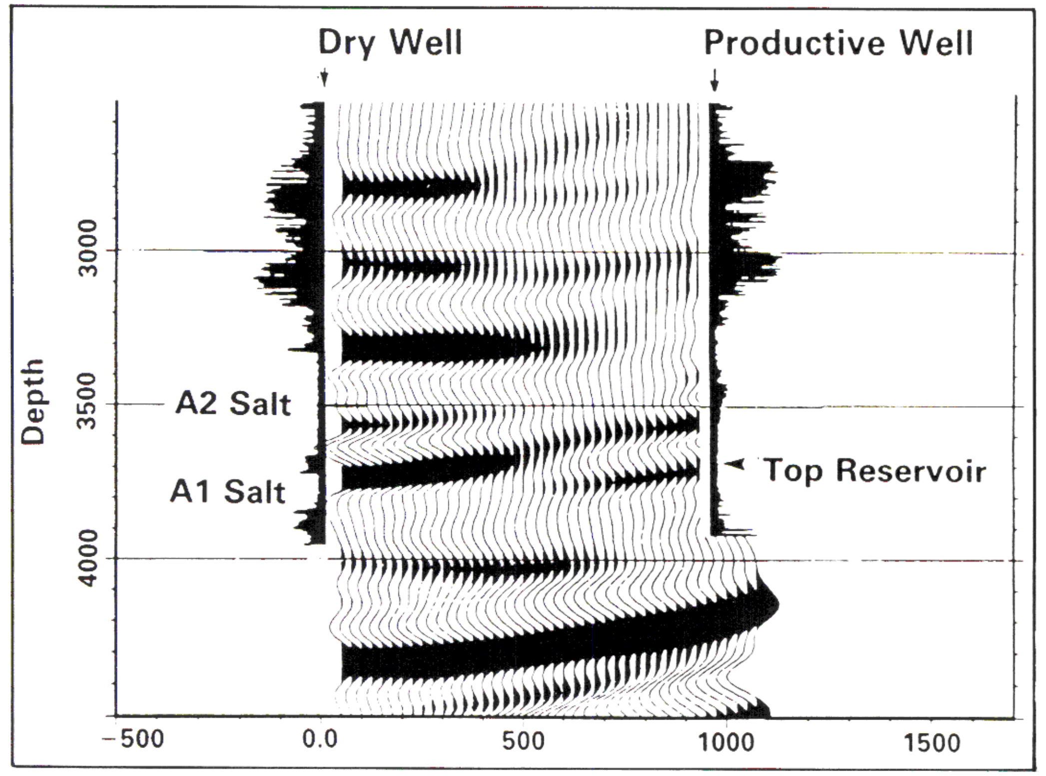

Figure 7. Gamma-ray logs and SRT-processed Borehole Seismic Profile (BSP) displayed in depth.

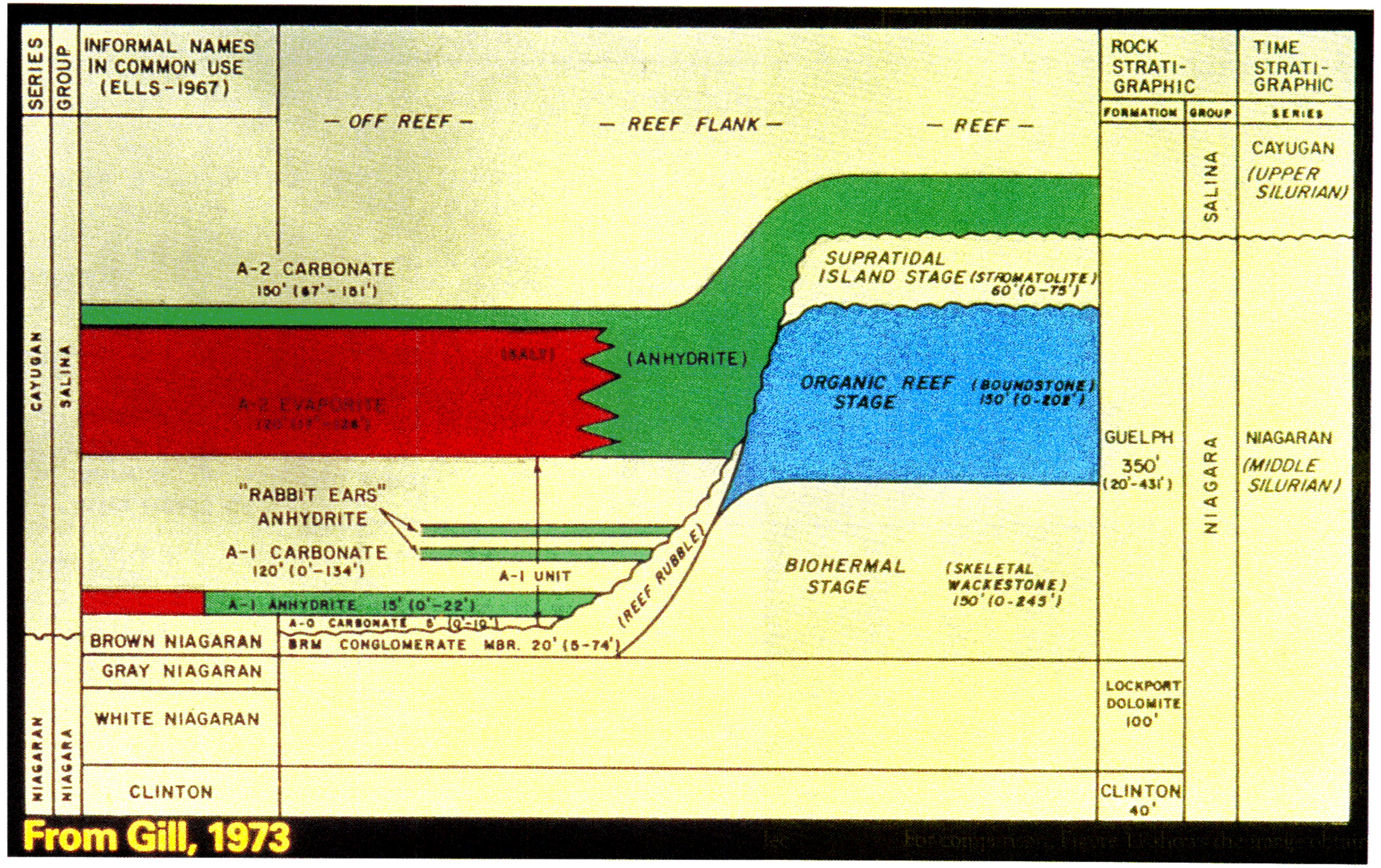

Figure 8. Stratigraphic relationships and nomenclature in the pinnacle reef trend, southeast Michigan (from Gill, 1973, via Lee and Budros, 1982). Note three reef growth stages.

Global™ is a Schlumberger trademark. See Mayer and Sibbit (1980).

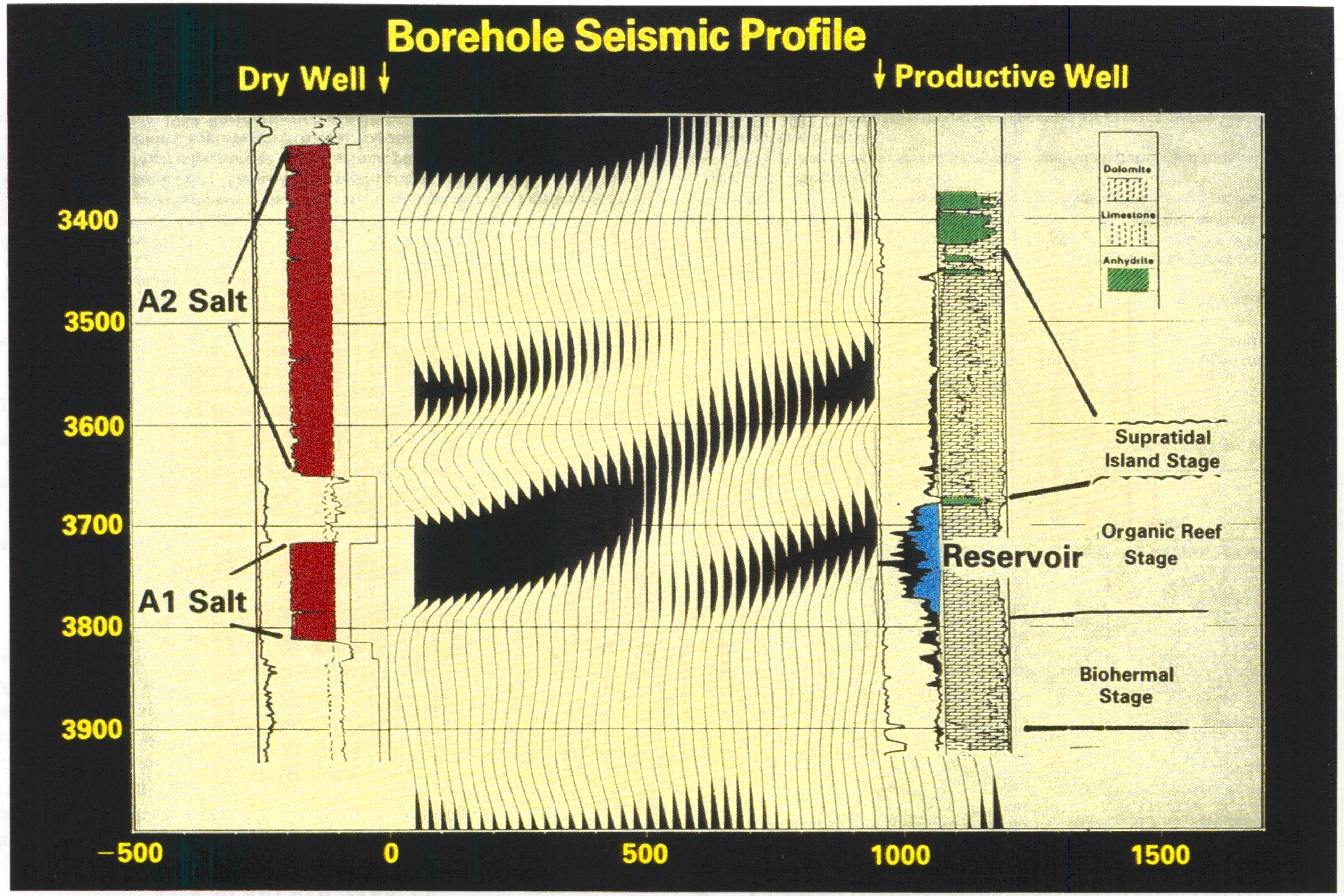

Figure 9. *Details of logs and Borehole Seismic Profile (BSP) in the reef zone. Top of the gas-filled organic reef stage is evident both on the Global™ log for the productive well and on the Borehole Seismic Profile.*

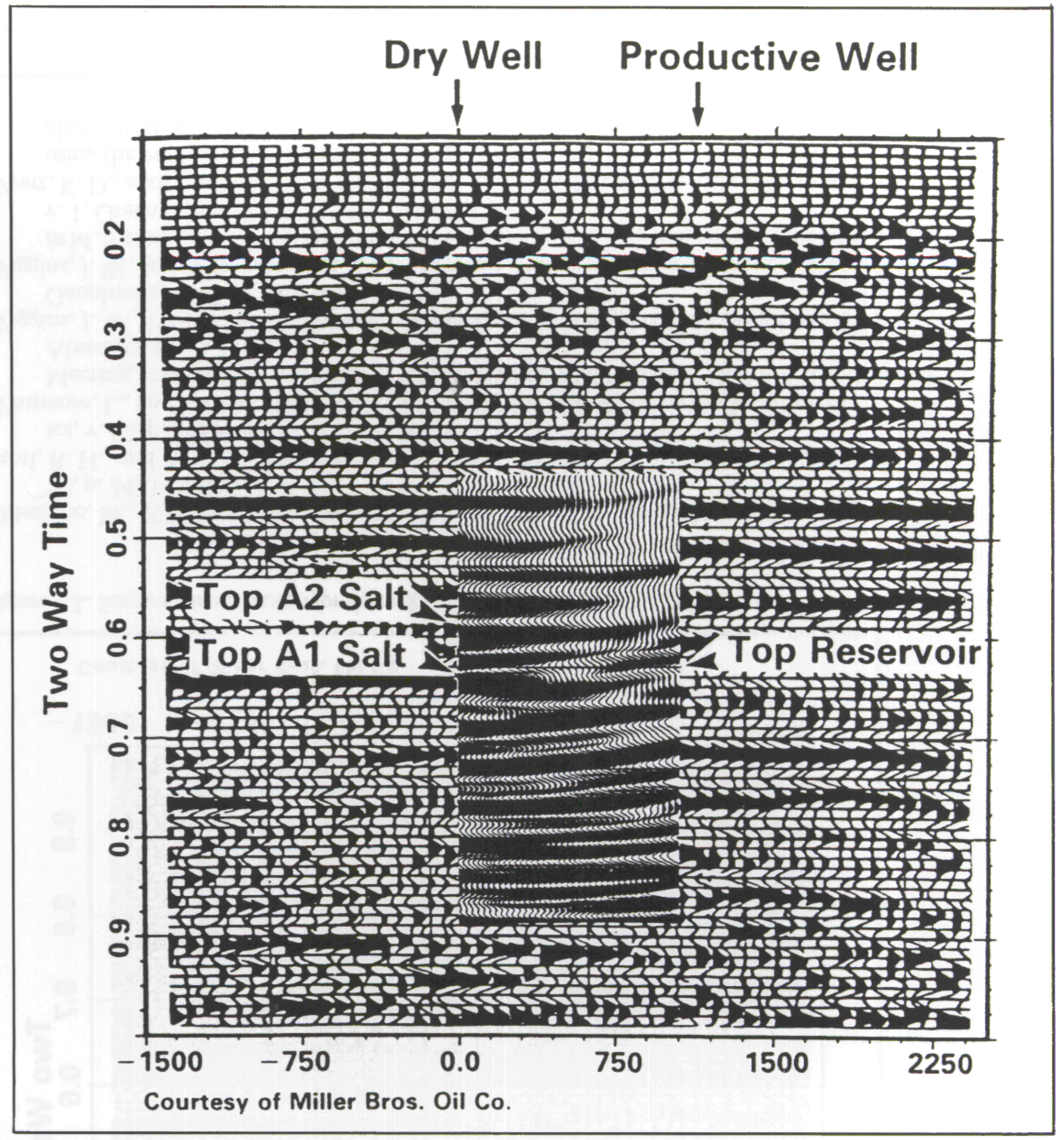

Figure 10. *SRT-processed Borehole Seismic Profile (BSP) displayed in two-way vertical traveltime and superimposed on the surface seismic section. The polarity of this section is opposite to that of Figures 7 and 8.*

CONCLUSION

Successful migration of multi-offset borehole seismic profiles seems to depend on issues that are familiar from surface seismic-data collection: geometry (fold of the coverage—especially in terms of the range of dips resolvable at each image point), velocity analysis (including statics), and deconvolution. The present study shows that the complicating factors present in field data can be handled smoothly by making full use of VSP and logs. In the specific case of Michigan pinnacles, we seem to see both a useful exploration tool and a method for shedding new light on some long-standing geological questions.

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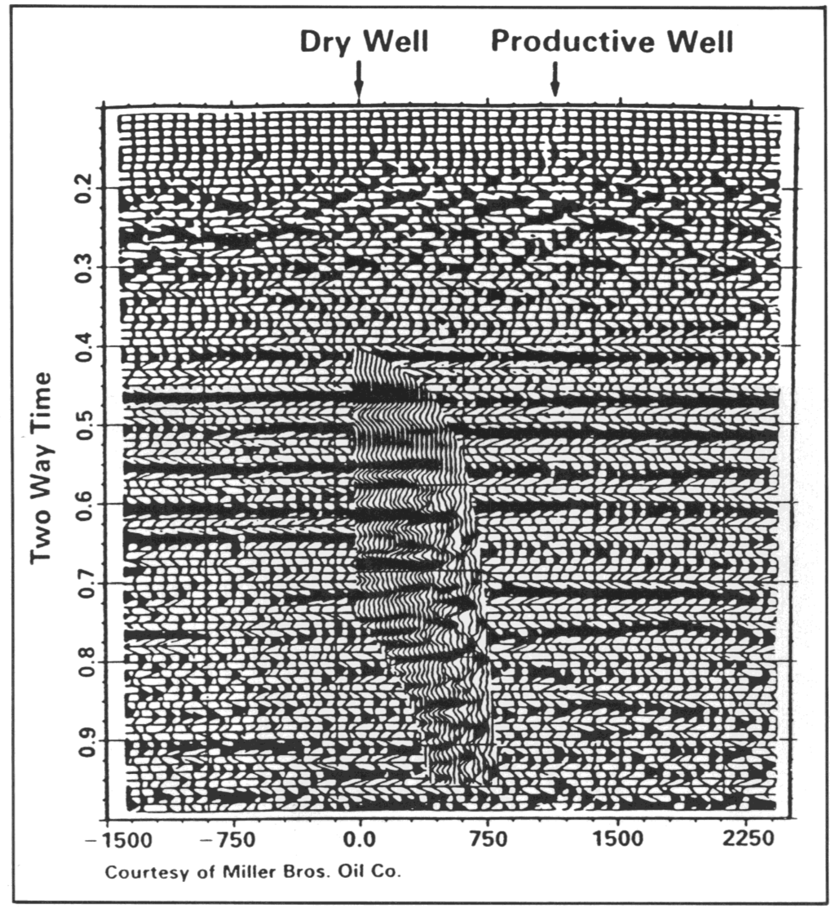

Figure 11. Profile obtained from offset VSP at 1726 ft (529 m) using the reflection-point mapping method.

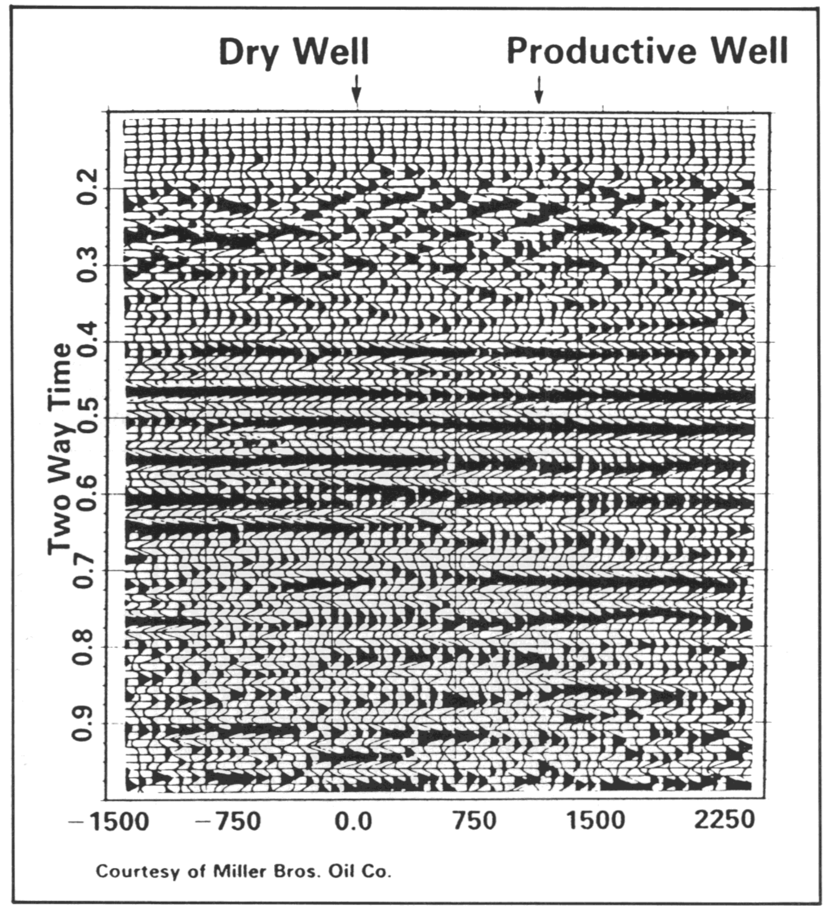

Figure 12. Surface seismic section for the region displayed in Figures 10 and 11.

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