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LOCATING SWAN HILLS POROSITY AT JUDY CREEK USING SEISMIC INVERSION[1]

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ABSTRACT

The paper discusses the geology of the Judy Creek Field and describes one case where seismic data led to successful exploration even though porosity is not apparent in the amplitude of reflector corresponding to the Swan Hills Formation. An elementary model shows that low-velocity porous zones can be identified on sonic logs band-limited to seismic data frequencies. Inversion of seismic data using wavelet estimation and reflectivity-index computation over known production showed that model results can be extended to real data and porous carbonates seen as low-velocity pods. A well located on this concept was drilled and is now in production.

INTRODUCTION

The Swan Hills reefs are lucrative oil and gas producers with Judy Creek West having produced 373 million barrels ($59 \times 10^6 m^3$) of high quality 41°API (820 kg/m^3) oil. Explorationists have traditionally considered the Swan Hills a geological play because porosity is not apparent in the amplitude of the reflection from the Swan Hills. In this paper we show that the top of the Swan Hills Formation is clearly visible on seismic data after careful inversion, and porosity developments can be identified unambiguously on colour displays of interval velocity (acoustic impedance/empirical density section).

The area under discussion is situated at the southern end of the Judy Creek West Field on the boundary of Townships 62 and 63, Ranges 11 and 12, west of the fifth meridian (Figure 1). Judy Creek lies on the Swan Hills reef-fringed carbonate bank trend between Carson Creek to the south and Swan Hills to the north (Figure 2). The area is located approximately 100 km northwest of Edmonton.

STRATIGRAPHY

The Judy Creek oil field produces from the reef-debris unit of the Swan Hills reef which is Upper Devonian in age (Figure 3). Enveloping the Swan Hills are the deeper-water argillaceous limestones of the Waterways Formation which ranges from a dark argillaceous limestone to a calcareous shale. This shale was deposited after and transgressed over the platform and reef complexes. The contact between the Waterways and Swan Hills is an abrupt boundary where dark-coloured argillaceous limestones overlie light-coloured reefal limestone (Murray, 1965).

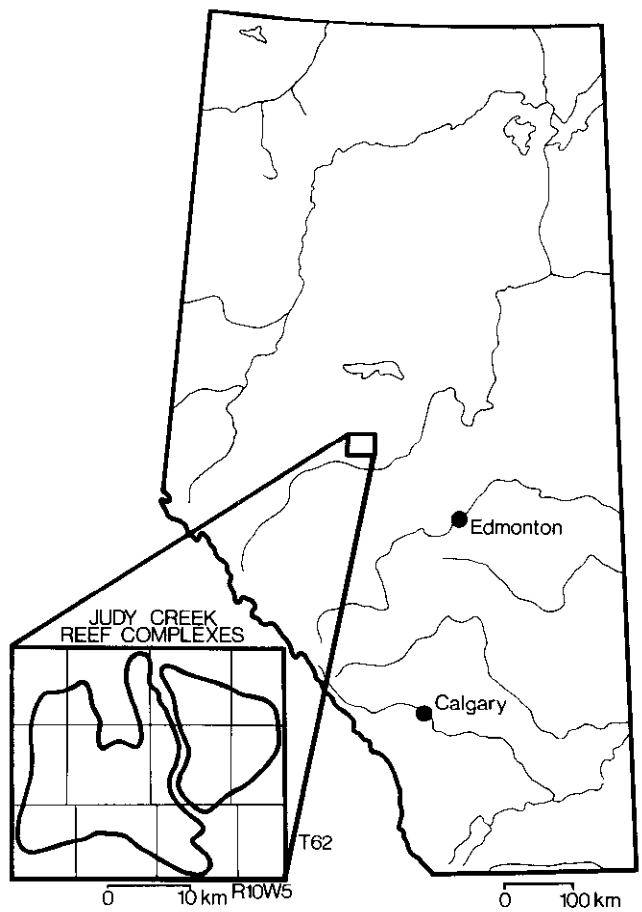

Fig. 1. Location map of Judy Creek reef complex.

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The Swan Hills overlies the Fort Vermilion Formation with an abrupt basal contact. Typical Fort Vermilion lithology consists of laminated anhydrite and calcareous shales. In the Judy Creek area of Fort Vermilion is more typically a calcareous shale.

The Swan Hills Formation can be separated into nine stratigraphic units (Murray, 1966). The important seismic stratigraphic units are outlined in Figure 4.

1) Open marine: a dense micritic limestone, 3 to 4 m thick.
2) Coral beds: mostly tight but may be a porous limestone 4.5 m thick. The eastern margin consists of porous stromatoporoid reef.
3) Deep lagoon: dense limestone 18 to 21 m thick, locally contains subspherical stromatoporoids.
4) Shallow lagoon: 18-m-thick dense limestones with sparry calcite, acoustically similar to unit 3, but this unit represents a transition to unit 5 and is bordered by porous stromatopoid reef facies.
5) Table reef: porous, dendroid and tabular stromatoporoid limestone beds, 9 to 18 m thick.
6) Lagoon: Amphipora limestone with low-to-fair porosity toward the edge of the band 24 to 26 m thick.
7) Brackish ponds and tidal flats: dense limestone with thin green shale streaks totalling from 9 m thick in the bank centre to zero at the edge.
8) Reef: porous stromatoporoid limestone beds 15 to 39 m thick at the margins.
9) Bank debris: porous calcarenite stromatoporoid limestone beds 12 to 24 m thick over the entire bank often diagenetically infilled with sparry calcite.

GEOMETRY

The Swan Hills platform (Fort Vermilion) is approximately 4.5 m thick. The buildup of the Swan Hills reef-fringed bank reaches a maximum thickness of 135 m (Figure 5) (Murray, 1966).

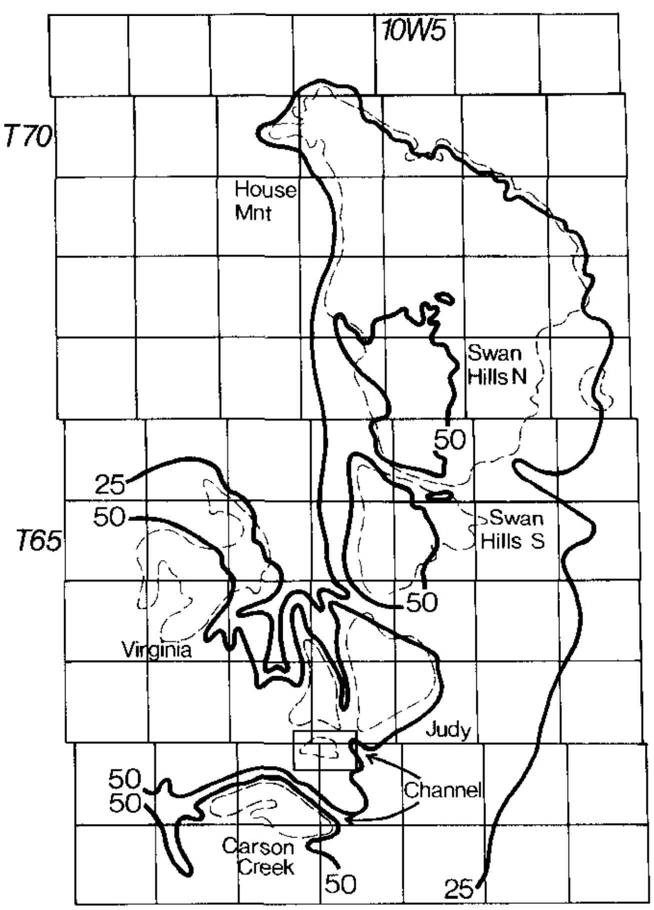


Fig. 2. Regional map of Swan Hills buildup. Dashed lines indicate known oil pools. Contour interval for thickness of reef buildup is 25 m.

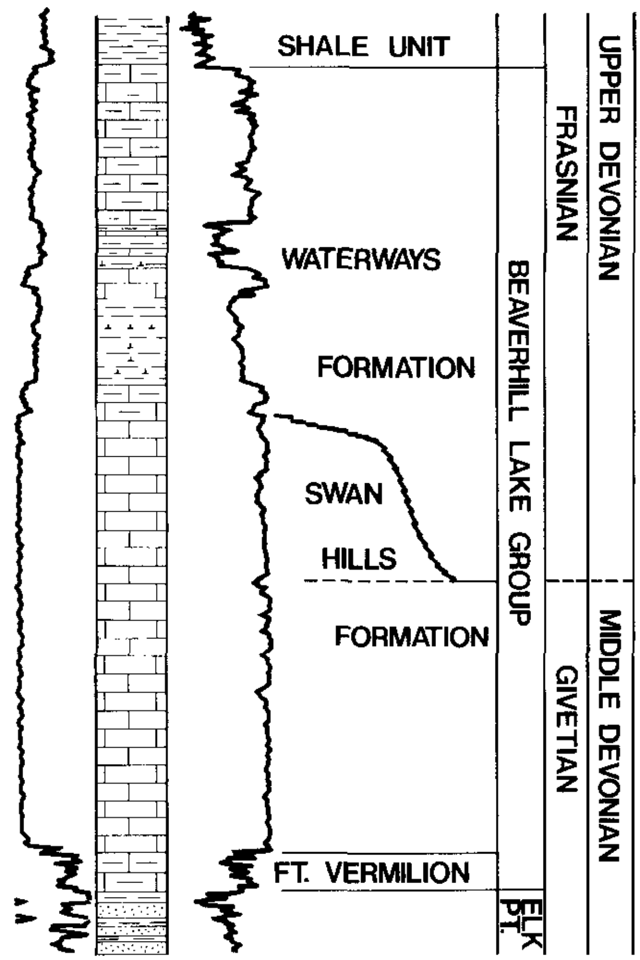


Fig. 3. Stratigraphic nomenclature of the Beaverhill Lake Group.

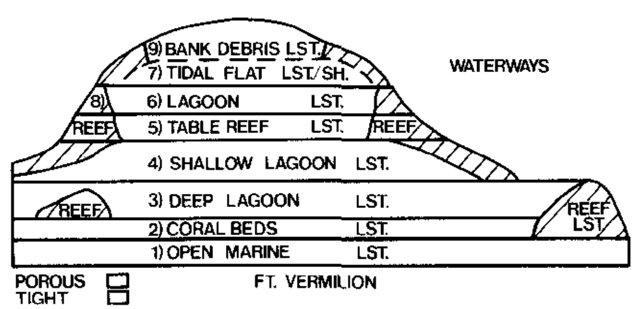
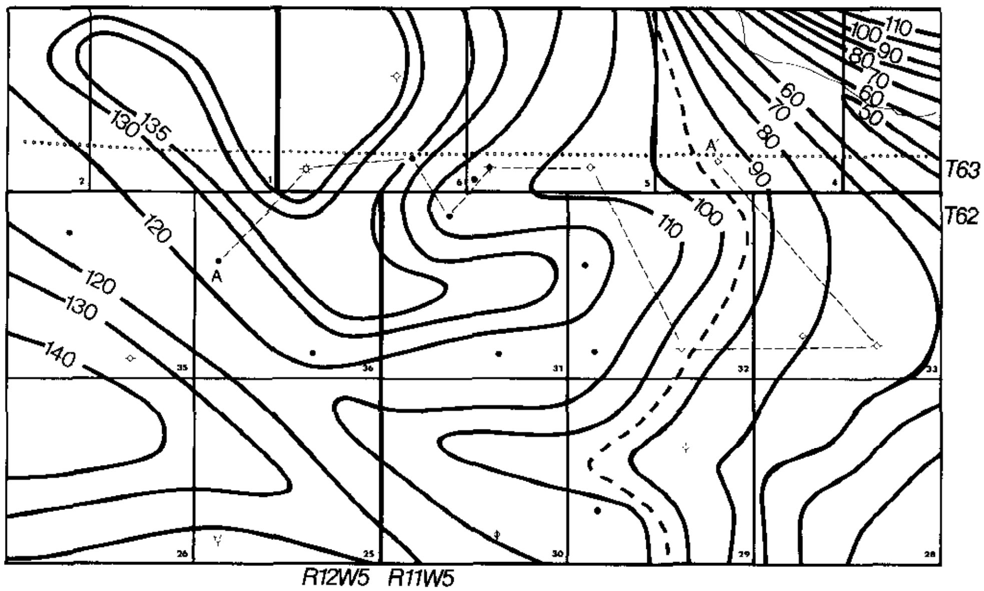


Fig. 4. Schematic reef profile for Judy Creek Swan Hills reef development.

The productive area of the field is approximately 25 km from north to south and 10 km east to west at the widest location, covering approximately 65 km^2. The east and south sides of the field are bounded by deep channels. Open marine conditions prevailed to the southeast while to the west is a poorly defined area where the Carson Creek, Judy Creek and Virginia Hills reefs converge. The northern part of the reef protrudes into a bay area which connected to an open marine environment. Figure 5 (Swan Hills isopach) and Figure 6 (Waterways isopach) define the reef configuration. The Waterways isopach provides a mould of the reef and is included as confirmation of the Swan Hills isopach as the latter is derived by subtracting the Swan Hills structure from the Elk Point structure. Unfortunately, few wells penetrate the Elk Point whereas all wells penetrate the Swan Hills, thus providing accurate data for the Waterways isopach.

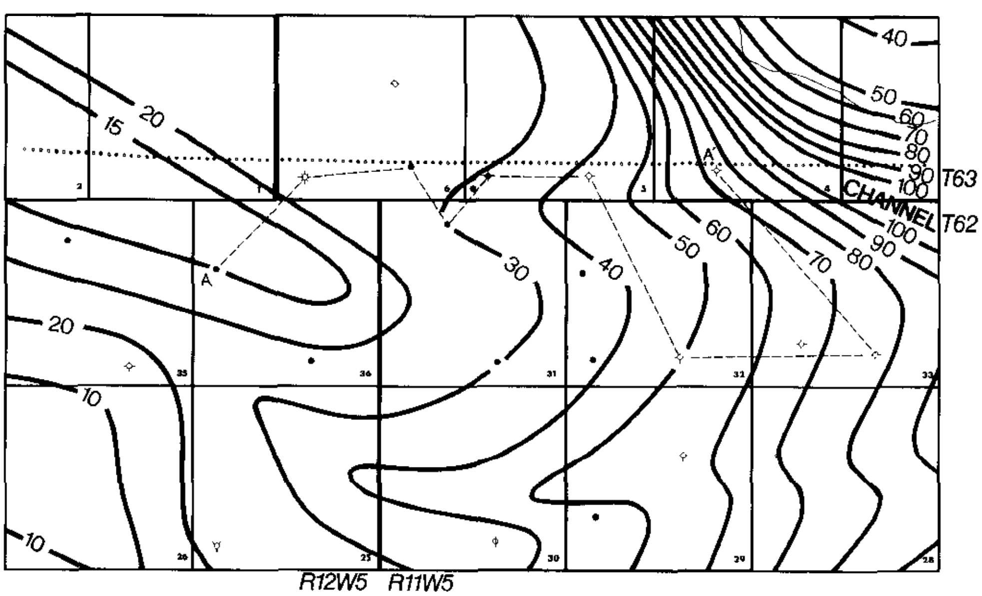
Porosity Distribution and Structure

The porosity distribution in the northern part of Judy Creek West (Figure 7) appears to be evenly distributed and predictable. However, drilling results in the south-



Seismic Profile .....
Cross Section -----
Edge of Bank Debris — — —

Fig. 5. Swan Hills isopach of a portion of the Judy Creek area. Contour intervals are 5 and 10 m.



Seismic Profile ......
Cross Section -----

Fig. 6. Waterways isopach of a portion of the Judy Creek area. Contour interval is 10 m.

ern portion of the field indicate a deterioration in reservoir quality by sparry calcite infill. This accounts for the limited success in predicting porosity trend development. In spite of these results, some excellent wells have been drilled where ultimate well reserves exceed 500 000 barrels (80 000 m^3) of oil.

Porosity development is of primary importance in Swan Hills exploration, but in the southern portion of Judy Creek West the structural element also plays a role in hydrocarbon entrapment where bottom water encroaches on the field. The regional structure on the carbonate platform is typically NW-SE, but in the reef areas, structure (Figure 8) is dominated by reef geometry. This is clearly illustrated by the counter-regional structure on the east side where the reef falls off into a deep channel.

Exploration Objective

The east-west cross-section along the northern edge of Township 62 (Figure 6) is shown in Figure 9. The section demonstrates the required objective of locating porosity within the Swan Hills reef-fringed bank. The bank-debris unit of the Swan Hills is correlated and the

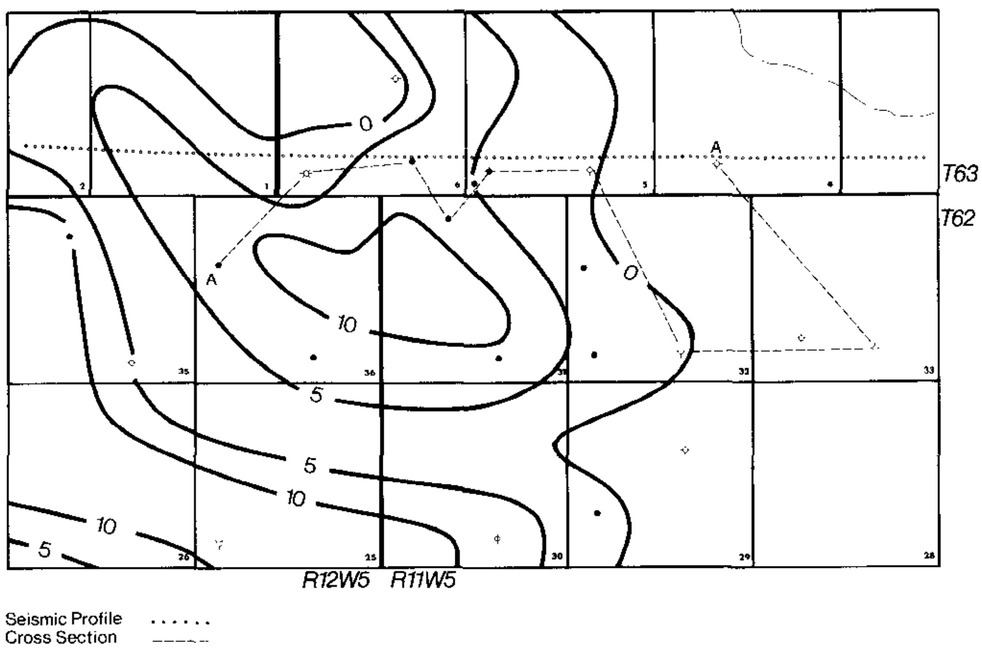


Fig. 7. Porosity isopach of reef debris of a portion of the Judy Creek area. Contour interval is 5 m.

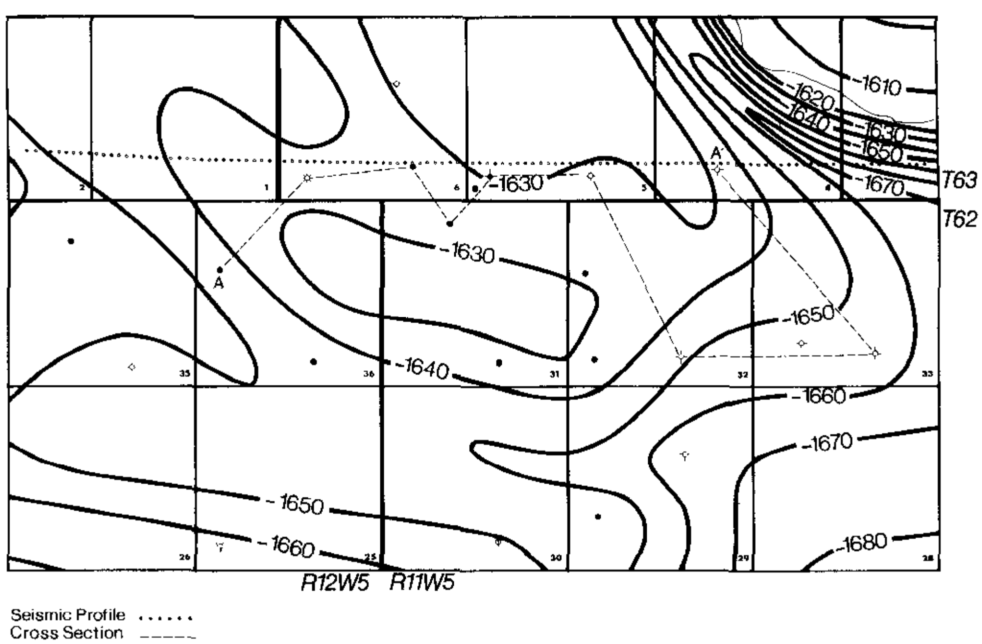


Fig. 8. Swan Hills structure of a portion of the Judy Creek area. Contour interval is 10 m.

porosity is marked on the stratigraphic section.

To the west where the reef-fringed bank is structurally highest within the mapped area, porosity is virtually nonexistent within the uppermost Swan Hills (bank-debris). Porosity in this unit develops and improves gradually towards the east with maximum development in section 31 of township 62, R11, W5M. A rapid porosity development then occurs east of section 31 in the upper Swan Hills while simultaneously the unit thins as the reef facies is replaced by Waterways in the surge channel separating the two Judy Creek reef-fringed banks.

The cross-section illustrates a systematic development of porosity. However, geological mapping alone proved inadequate for economically viable exploration and additional control was required.

Sonic Velocity Model

A sonic log from well 2-6-63-11W5, which has a 7-m-thick porous zone, was used in a model study to show that the porous zone can be identified in band-limited seismic reflection data. Figure 10 shows four pairs of sonic logs. In each pair, the right curve is the original sonic, integrated at 2 ms, with lower velocity in the porous zone. In the curve on the left, porous zone velocity has been altered to correspond to impervious reef. The first pair on the left is unfiltered. The other pairs have been filtered with bandpass zero-phase filters of 5-50, 5-70 and 5-80 Hz. All sonic logs after filter show a clear reduction in velocities corresponding to porous reef. This provides a reason to hope that careful inversion of seismic data might reveal porous zones.

Seismic Profile

The seismic line shown in Figure 11 was recorded in 1985 using a dynamite source, 1200% subsurface coverage, 16.5 m group intervals and a split spread of 1600 m. The traverse of this line has been shown in Figure 6. It was designed to tie a variety of wells — productive, tight and off-reef (to the east). There is good reflection quality and continuity in the section. The Swan Hills, at a time of about 1.6 s, has a frequency range of 10 to 60 Hz and shows the eastward dip into the channel. However, amplitude changes that could be related to porosity are not apparent because the changes in velocities over a small zone are smoothed by the propagating wavelet (Jain 1986, model 3). Jain and Wren (1977) described a method of computing this wavelet and reducing it to a spike. The resulting reflectivity-index trace is used in their technique to compute interval velocity in the medium which is found to match the sonic velocities on real data. Jain (1986) has shown that replacement of the wavelet by a spike enhances resolution, and porosity changes over thinner zones can be observed more easily than on a normal seismic section. Figure 12 shows an inversion section for a portion of Figure 11. The character match with the filtered sonic for the well 2-6 located as shown is very satisfactory in the zone of interest.

Figure 13 shows the reef zone in detail. The sonic logs are shown on the top. The conventional seismic section is shown in the middle and the inversion section at the bottom. Lines of projection from the cross-section to the inverted seismic line are also shown. The distance between traces is 33 m. The seismic section shows the drop to the east into the channel but does not define the

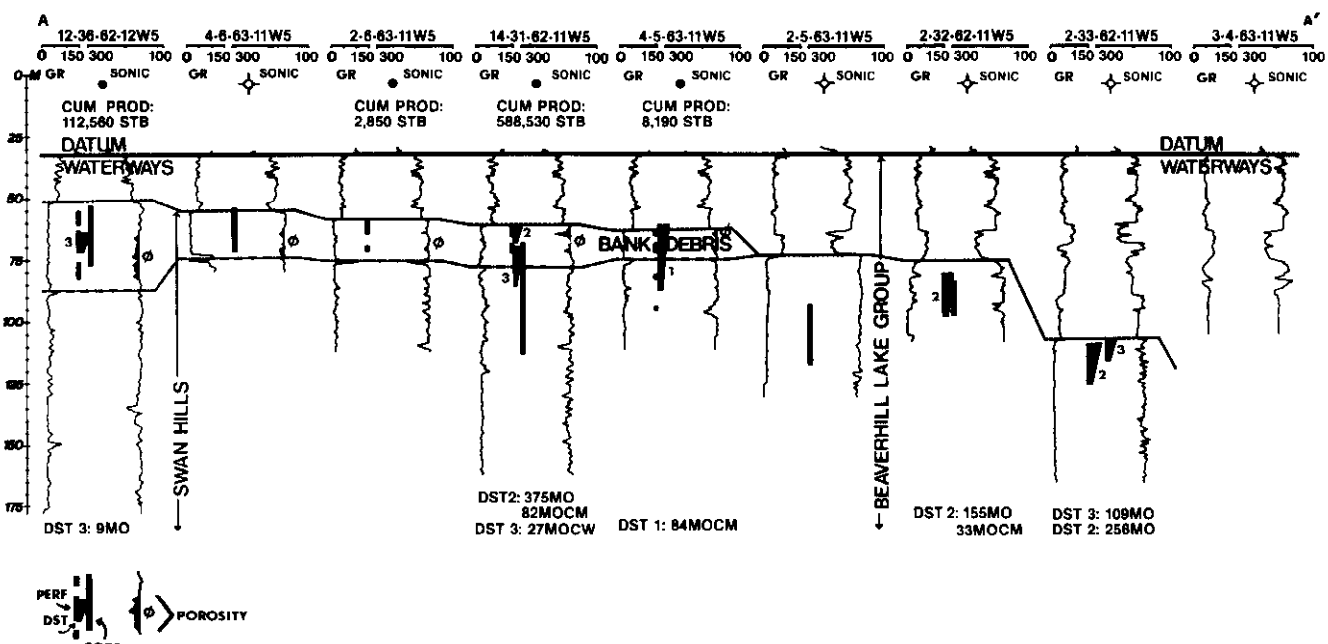


Fig. 9. Stratigraphic section along well profile shown in Figure 6. Gamma-ray (GR) and sonic logs are shown for each well. Perforated, drill-stem tested and cored intervals are also indicated.

reef porosity. On the inversion section, one can now define the separation between the Swan Hills and the top of the Beaverhill Lake (Waterways) and identify the Swan Hills buildup in the section by means of a 'shelf' in between low-velocity Waterways and high-velocity impervious carbonates. The log traces superimposed on the inverted section are taken from sonic logs integrated in time and displayed at the same scale as the inversion sections. Starting from the right-hand side, the match is good with the logs for wells 3-4, 2-33, 2-32 and 2-5. As the reef builds up to 4-5 and 14-31, the porosity zone in the Swan Hills matches the low-velocity zone in the inverted traces.

A broad area between 4-6 and 2-5 identified by a thick zone of lower than normal velocities (red) looks very favourable for Swan Hills porosity. A well was drilled at 2-6, resulting in a Swan Hills oil well which produces at the rate of 200 bopd (1.3 m^3/h).

Known existing reservoirs were identified with similar characteristics on other seismic profiles. Some other prospects were downgraded when they did not show similar features on interval velocity sections.

Conclusions

Detailed geological analysis coupled with careful use of seismic reflection data including inversion was instrumental in the location of a successful well at Judy Creek. The study shows the importance of considering various geological and geophysical factors in a successful exploration effort.

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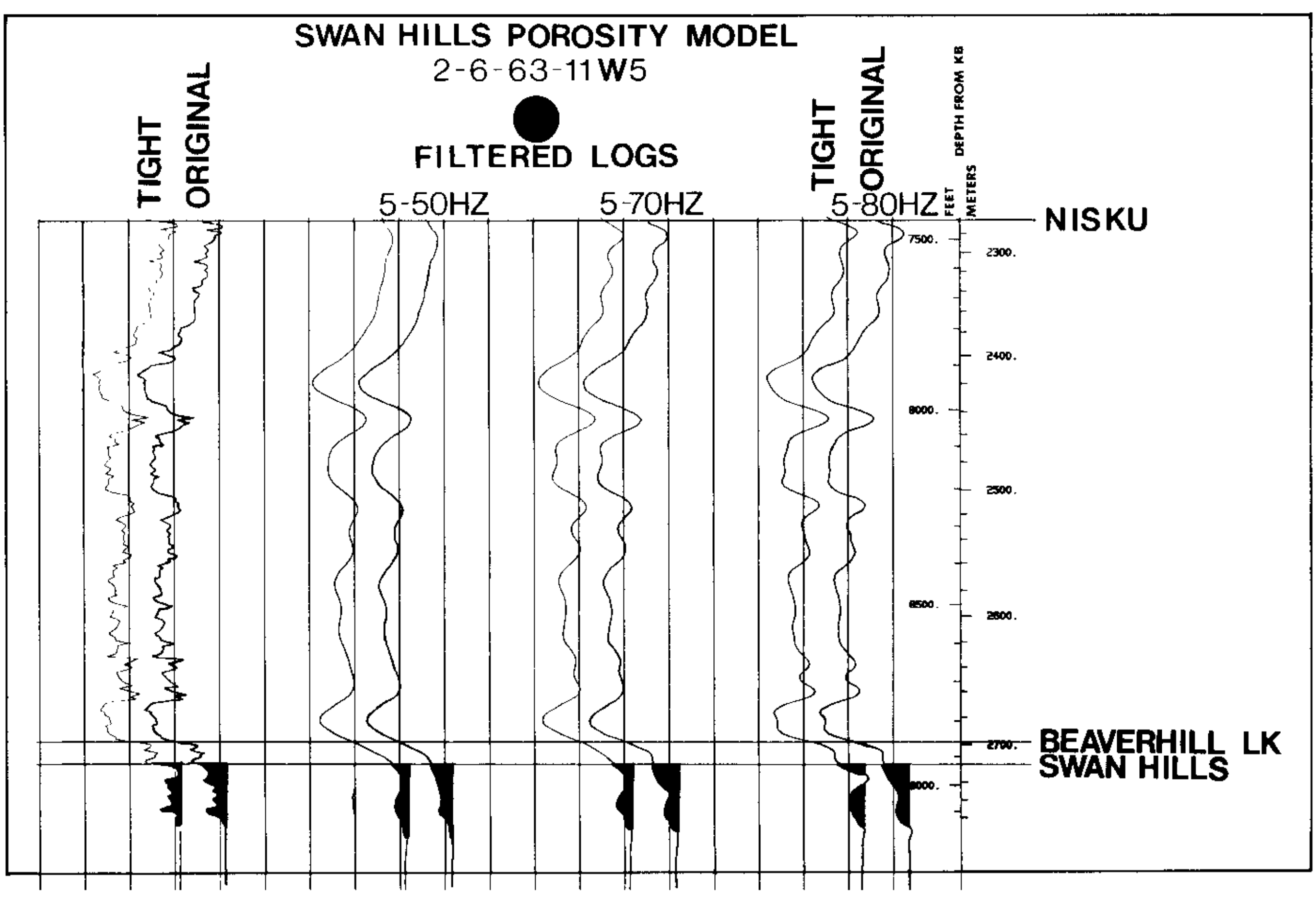

Fig. 10. Velocity model showing velocity anomaly due to porosity after filtering with three different zero-phase filters. The right curve in each pair is original sonic with porous section and the left curve corresponds to the tight reef. Vertical lines are separated by 1522 m/s for each curve.

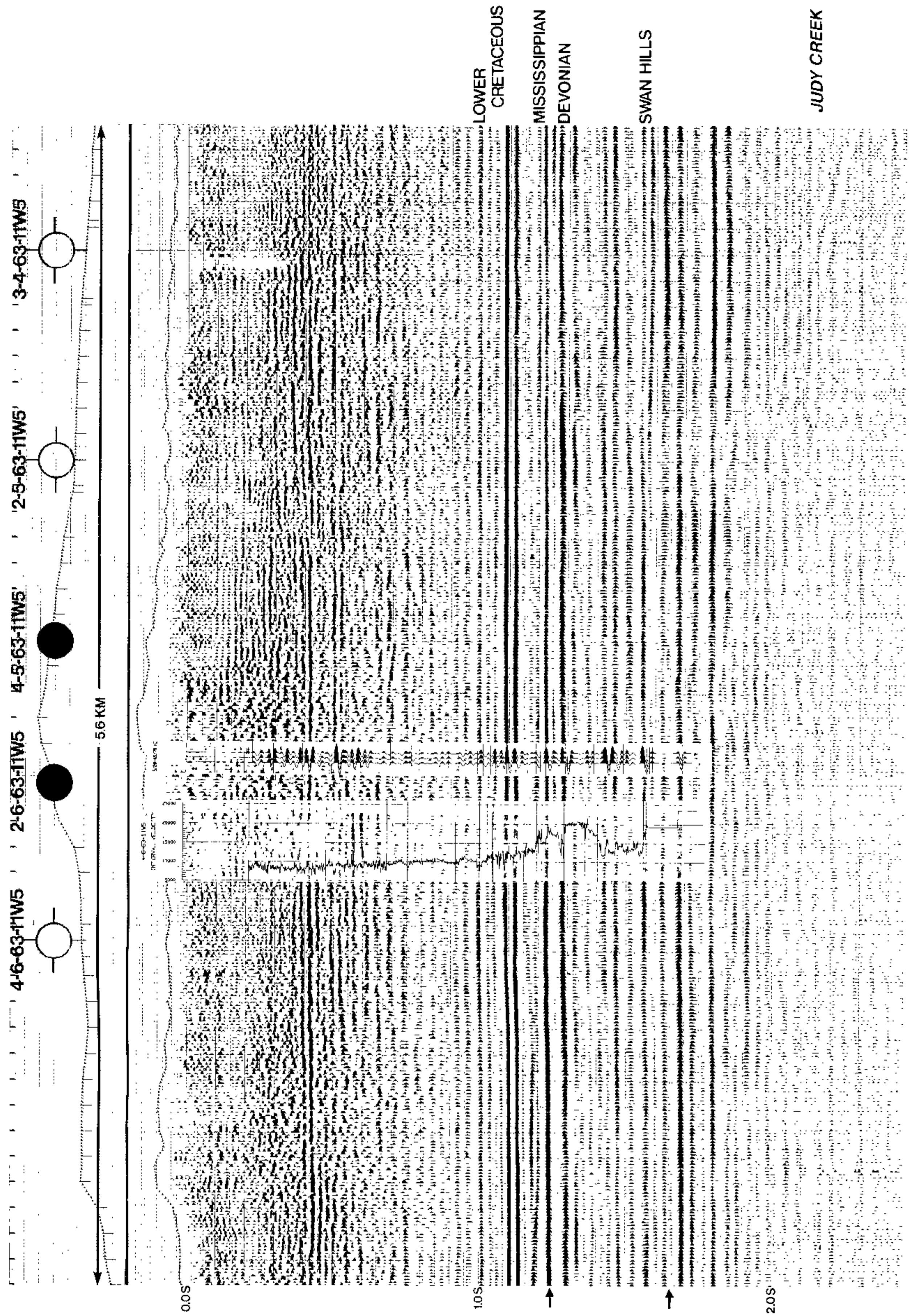

Fig. 11. Seismic section corresponding to stratigraphic section of T63 in Figure 9. Vertical scale is time in seconds.

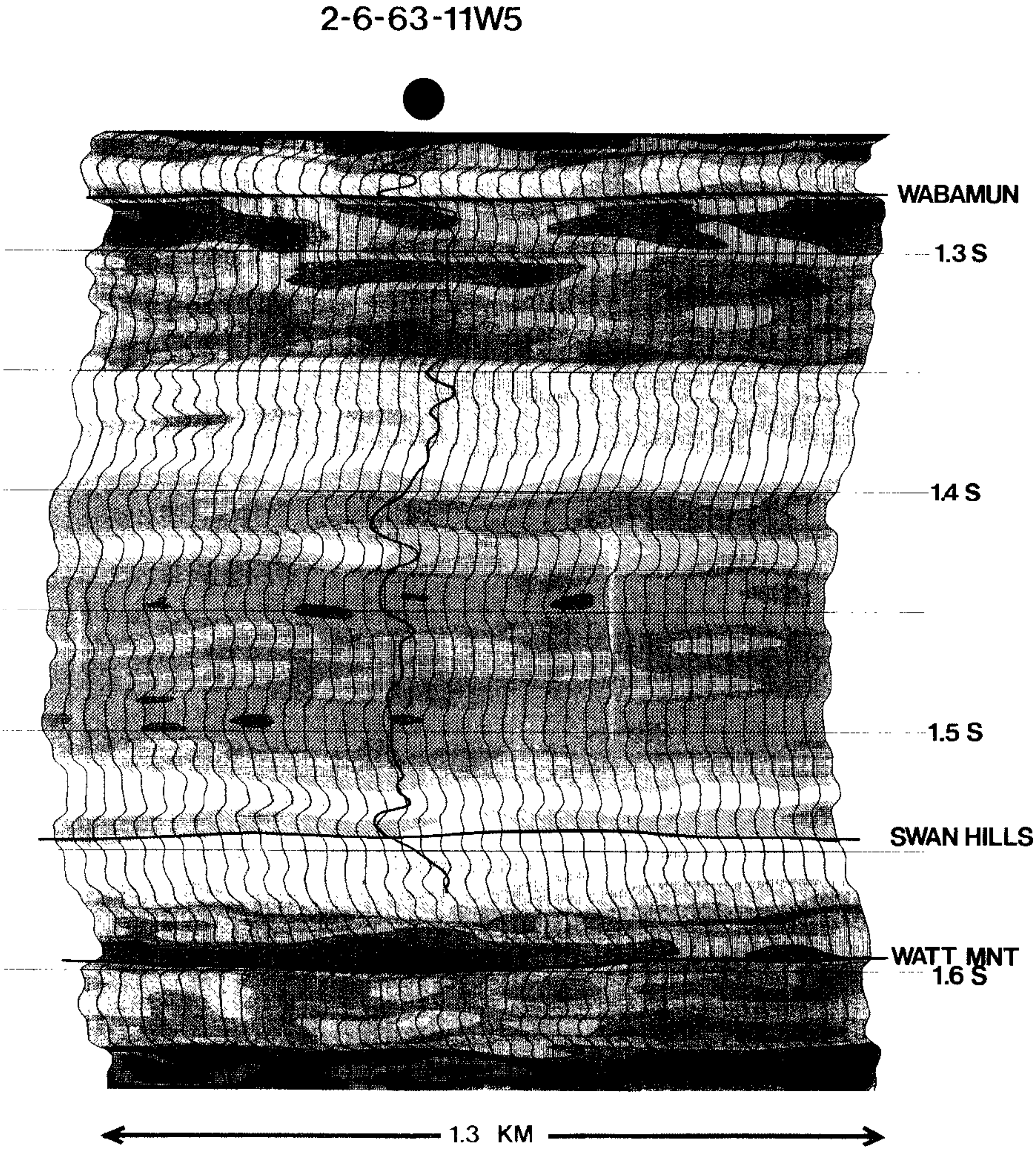

Fig. 12. Velocity section for a portion of line in Figure 11. The portion shown is indicated by arrows in Figure 11. The contour interval is 250 m/s. Vertical scale is time in seconds.

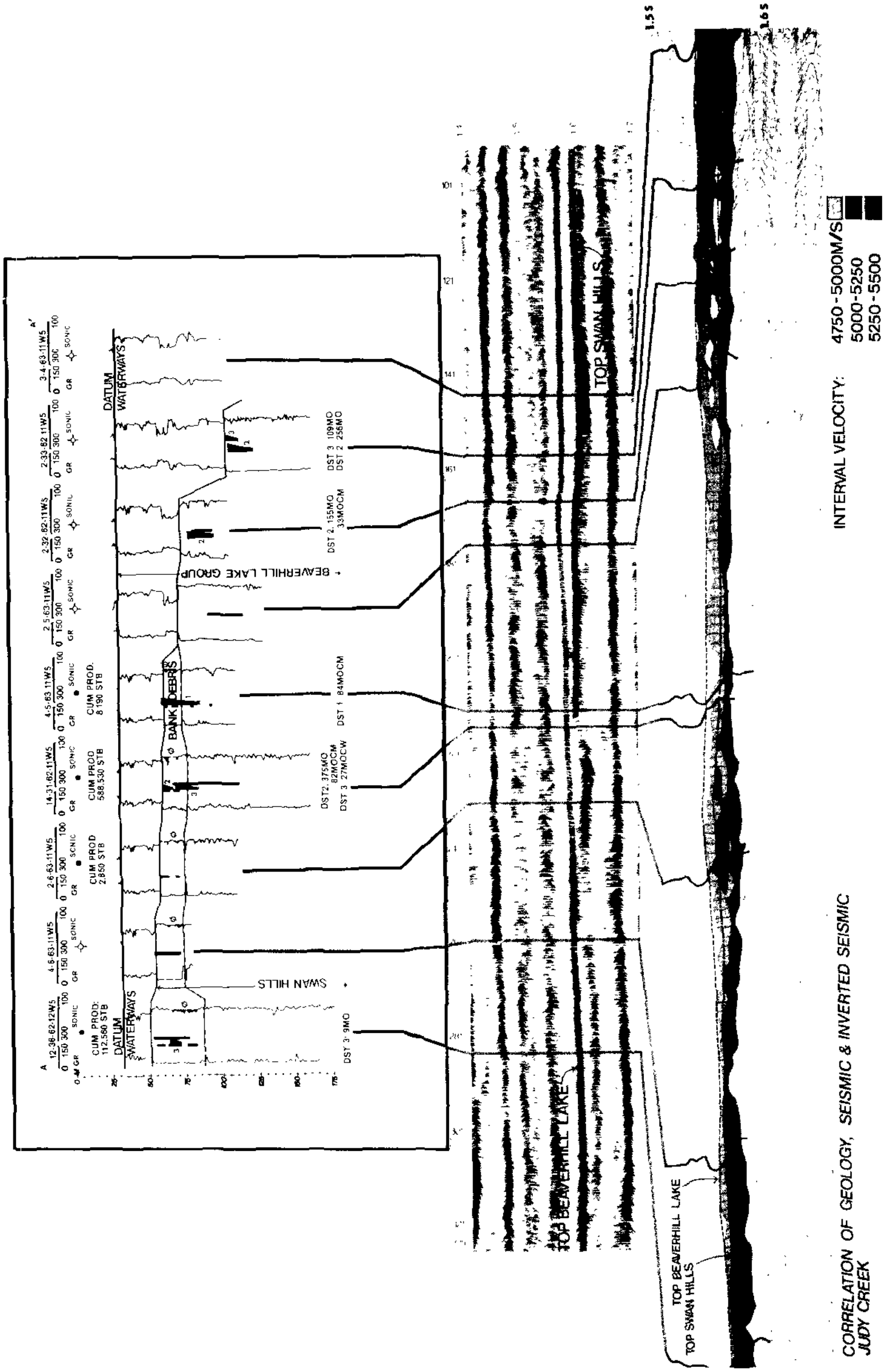

Fig. 13. *Stratigraphic-seismic-velocity sections illustrating location of porous zones (medium-shade zones in velocity section).*