SEISMIC EXPRESSION OF A CARBONATE-EVAPORITE SEQUENCE IN NORTHERN ALBERTA, CANADA†

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ABSTRACT

In exploring for reefs in the Middle Devonian evaporite basin in northern Alberta, geophysical criteria are used to define the reefs. In portions of the basin, carbonate buildups can be delineated by mapping drape features associated with salt removal. However, in areas where little or no salt removal has occurred, other seismic criteria must be used to interpret the stratigraphy. Variations in seismic parameters, such as amplitude, frequency, phase and velocity, are diagnostic of lithologic changes in the carbonate-evaporite sequence. In addition, the velocity anomalies associated with the carbonate buildups are used to predict porosity.

REGIONAL GEOLOGICAL SETTING

The Middle Devonian evaporite basin of Northern Alberta is bounded by a major barrier reef to the north and west, the Canadian Shield to the east, and the Peace River Arch to the south. Its east-west dimension is almost 500 miles, and it extends 300 miles from south to north.

The regional setting of the Middle Devonian Upper Elk Point Basin, the carbonate distribution and the outline of the area are shown in Figure 1. An extensive barrier reef, up to 1,000 feet thick, separated the open ocean to the northwest from a restricted basin to the southeast. Within the basin there are a number of sub-basins separated by extensive carbonate banks. Pinnacle reefs of varying sizes proliferated through these sub-basins.

During the mid 1960's, major reserves of gas, and light and medium gravity oil were discovered in this basin in pinnacle reefs in the Keg River formation in the Rainbow and Zama areas.

Exploration for reefs in a setting similar to that of the Rainbow and Zama discoveries led Industry to drill in the lesser known sub-basins to the east. One such area was the La Crete basin in northeast Alberta, where small reefs containing heavy oil were discovered in the late 1960's. This basin is similar to the carbonate basins to the west, but there are fundamental differences between them. These similarities and differences can best be illustrated by a geological cross-section along the west-east line, shown in Figure 1.

The cross-section (Figure 2), datumed on top of the Devonian, extends from the main barrier reef in the west, through Rainbow, and eastward across an extensive carbonate bank into the La Crete Basin.

Reef growth through the area varied considerably. In Rainbow, the pinnacles attained heights of up to 1,000 feet, whereas in La Crete they reached a maximum thickness of only 350 feet. The variation in thickness is due in part to the differential rate of subsidence of these two basins and

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in part due to proximity of the Rainbow Basin to normal marine waters.

Restrictions imposed by the barrier reef eventually resulted in the deposition and burial of the reefs by evaporites. The evaporites are mainly basin salts, anhydrite and dolomite at Rainbow, and predominantly salts at La Crete. Shortly after deposition, salt solutioning occurred around the reefs in Rainbow. This resulted in the draping of the Muskeg evaporites and the overlying Sulphur Point and Slave Point carbonates over the reefs.

Seismic Criteria

During seismic exploration in the Rainbow area, the Slave Point to Cold Lake isochron was used to delineate the reefs. The isochron thicks outlined the reefs, and the thins outlined the area of salt removal. Once this criterion had been established, successful exploration of the basin progressed at a fast pace.

In the La Crete basin, there is no evidence of draping of the overlying sediments over the reefs. This indicates that the salts were left intact. The Slave Point to Cold Lake isochron that was used so successfully in Rainbow to delineate the reefs could not be applied here. Other seismic criteria diagnostic of the response of the carbonate-evaporite sequence had to be recognized to outline the reefs. They are reflection amplitude, frequency change, phase reversal and velocity changes due to differences in lithology. The remainder of this paper will describe the techniques used to define the reefs in the La Crete Basin.

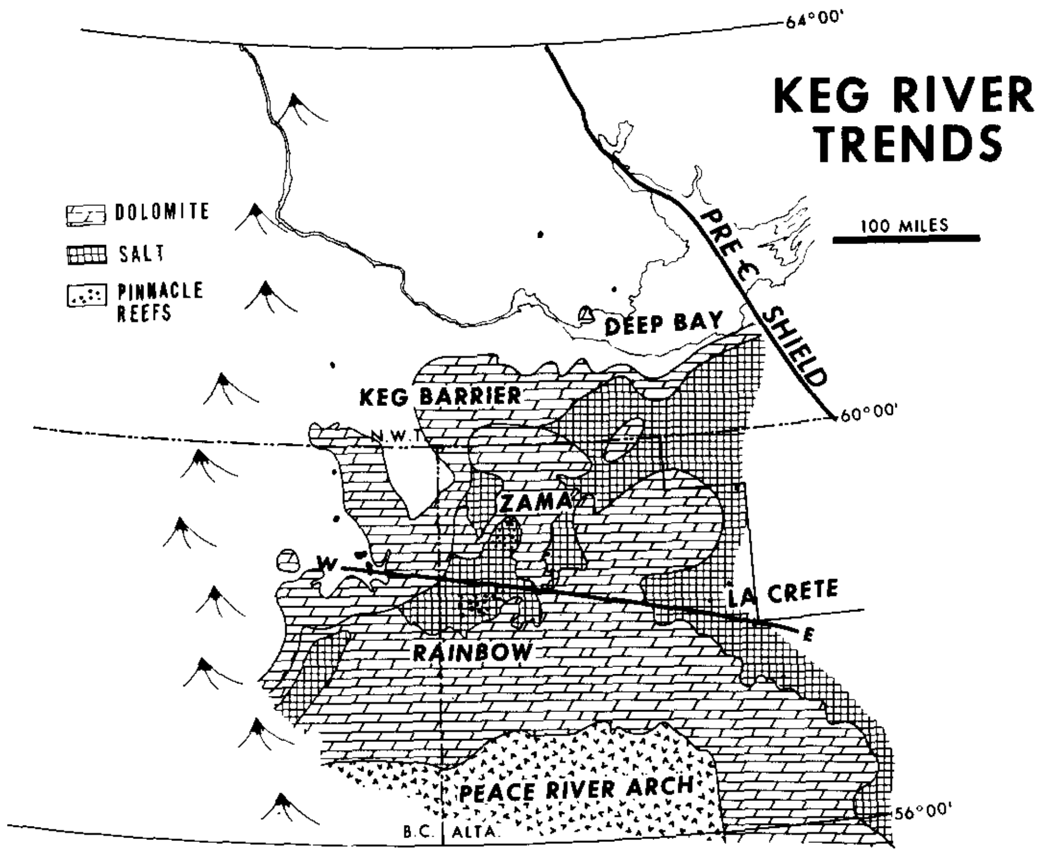


Fig. 1.

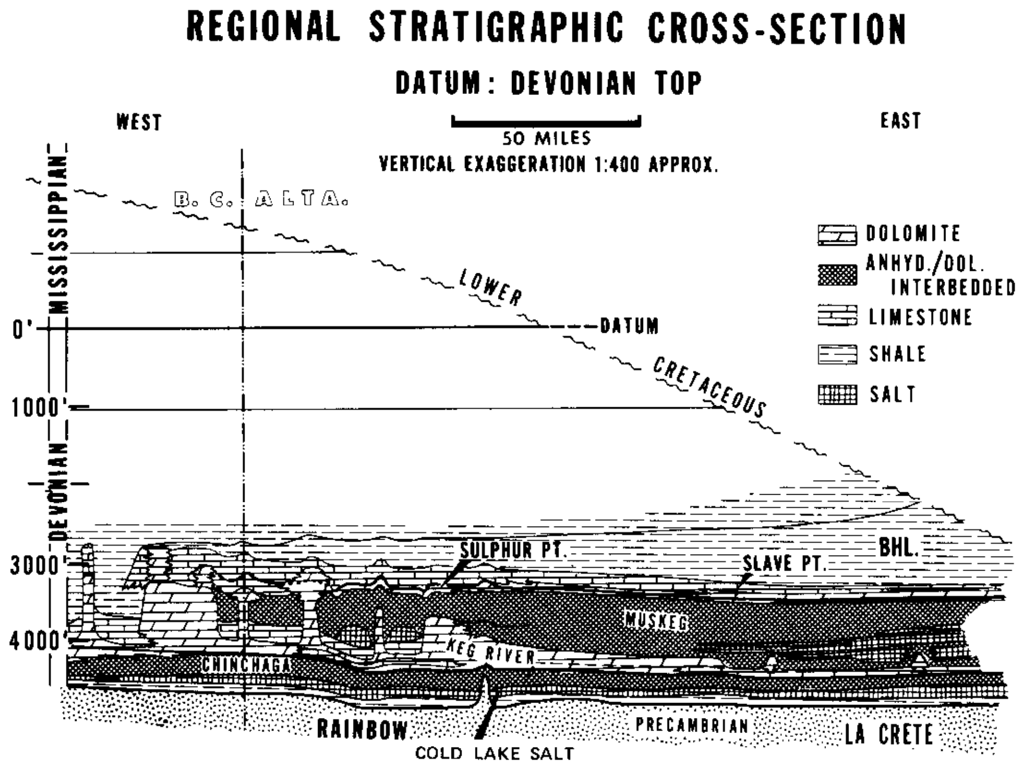


Fig. 2.

La Crete Basin

The La Crete Basin is outlined in Figure 3, and shows a bank margin on the west and numerous pinnacles in the centre; the east side of the basin outcrops along the Canadian Shield. The reefs to be used as examples for seismic modelling are located in the Rennie area.

One of the first seismic lines shot in this area is shown in Figure 4. It is a 6-fold CDP line shot with 3-hole patterns and approximately 1½ pounds of dynamite at 40 feet. The cable configuration used was an 1800-foot symmetrical split spread.

The geological data available suggested that shales of the Woodbend formation would be present at the surface, shales and limestones of the Beaverhill formation at approximately .35 seconds, a strong reflection from the Slave Point at .5 seconds, and strong reflections from either the Cold Lake salt or the Precambrian at .65 seconds. Somewhere between the last two events, at .5 and .65 seconds, we expected a response from the Keg River reefs, if they were present.

Seismic modelling, based on sketchy geological data and a rather optimistic choice of parameters, suggested that porosity in the carbonates would produce a high amplitude event.

The first well in the area, I.O.E. Rennie 3-22 (Figure 5), was drilled on one of these strong reflections. However, instead of finding the predicted carbonates, the well penetrated approximately 200 feet of basin salt. It was obvious that the seismic event, shown in the centre of the section at .575 seconds, was not a carbonate reef.

The velocity survey data from the well, in conjunction with a detailed model analysis of this strong reflector, indicated that:

a) the high amplitude was due to the fact that the reflection came from the interface of the Lower Muskeg Salt and the underlying anhydrite;

b) the frequency change and apparent sag were caused by the lateral thinning of the Lower Muskeg Salt;

c) the phase reversal was due to the termination of this salt.

It was now apparent that this strong reflection was the seismic expression of salt in this area. (Today it is an excellent example of a "bright spot".)

The second well, I.O.E. Husky Rennie 16-21 (Figure 6), was drilled at a location where the seismic expression of salt was absent. As expected, no salt was encountered; instead, the well penetrated approximately 250 feet of reef. The seismic section shows the basin salt on either side of the reef.

A detailed study of this well indicated that the seismic expression of a carbonate reef in this area was a definite cycle split in the Keg River formation. This is well illustrated on the seismic section in Figure 6, where the Keg River reflection consists of a broad, single reflection off-reef, as opposed to a definite cycle split on-reef. (This criterion became invaluable in exploring for reefs in salt leach areas and in the delineation of the main Keg River Reef bank reefs.)

Detailed examination of the reflectors associated with the Cold Lake salt and the Precambrian under the reef indicated two well-defined positive velocity anomalies on either side of the reef and a negative

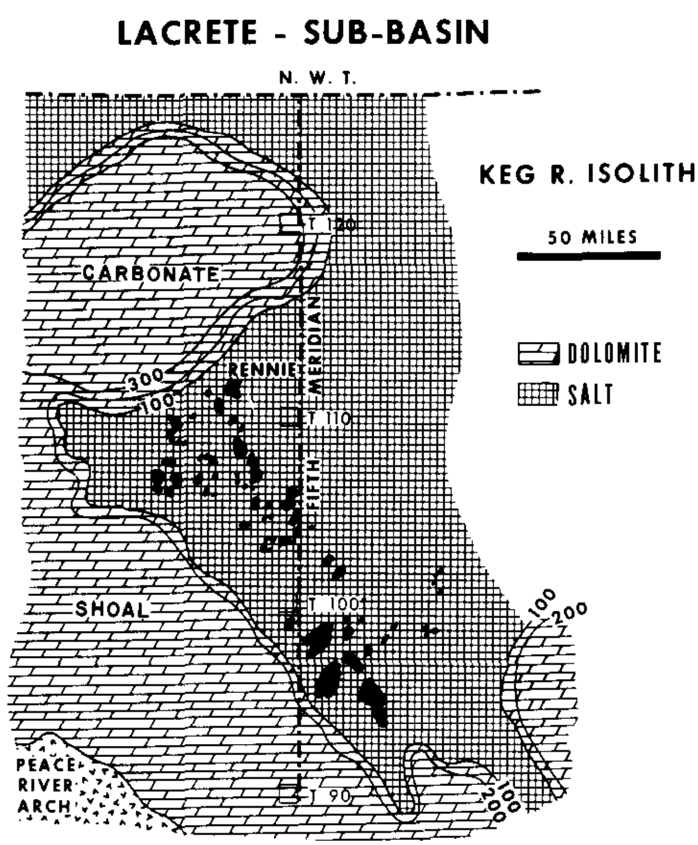


Fig. 3.

velocity anomaly, or sag, under the reef. In order to understand these events and their relationship to the lithology around the reef, a model based on the new well control and geophysical data was constructed.

Figure 7 shows a model of a carbonate buildup, flanked by anhydrite and salt, and the simplified seismic response in terms of velocity anomalies. This model indicates that the two velocity anomalies on the sides of the reef are caused by the surrounding anhydrite halo. Off-reef, they are related to a difference in velocities between anhydrite and salt; on-reef, they are related to the difference in velocities between anhydrite and reef. The negative velocity anomaly, or sag, in the centre is related to the velocity in the carbonate. Because there is a direct relationship between porosity and velocity, porosity in the reef can be predicted from the depth of sag.

Figure 8 shows a lithology-porosity crossplot from Rainbow on which porosities of limestones and dolomites are expressed in terms of transit time, or the reciprocal of velocity. This chart, together with the seismic sections, can be used to predict the porosity in the reef.

Referring to Figure 7, it is obvious that a flat response, or lack of sag under the reef, indicates that the velocity in the reef is the same as that of the surrounding anhydrite, i.e., 19,000 feet/second. This is equivalent to a sonic transit time of 52.6 u sec/ft., or a porosity of approximately 5.5%. On the other hand, a negative velocity anomaly which dips as far as the salt line indicates a transit time of 69.0 u sec/ft., or a porosity of approximately 18%. No velocity anomalies of this magnitude have been observed. Using the seismic parameters and velocities shown in the model, a more quantitative relationship,

LA CRETE REEFS
ALBERTA, CANADA

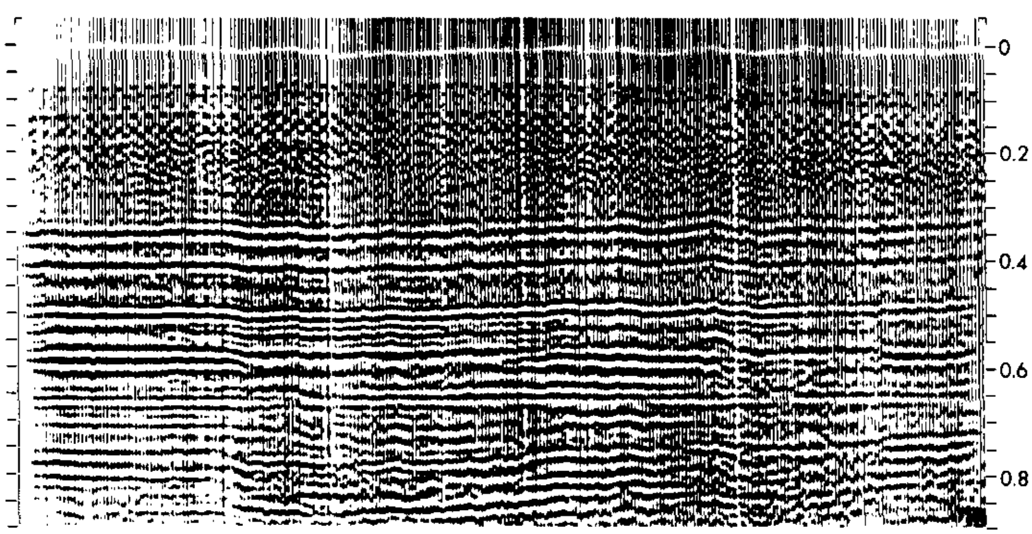


Fig. 4.

expressing porosity in the reef in terms of the magnitude of the negative velocity anomaly, can be developed.

The next three illustrations show other examples of seismic responses to lithology in the La Crete area.

Figure 9 shows a carbonate buildup, identified by the cycle split, in the centre of the section. A strong reflection, indicating salt in the off-reef position, is visible on either side of the reef. Note the frequency change as the salt thins, and a phase reversal where the salt terminates on the flanks of the reef. Three velocity anomalies on the horizons below the reef are clearly visible; the double velocity anomaly indicates the anhydrite halo around the reef and the sag indicates an average velocity through the reef of less than 19,000 feet/second, or, in this case, a porosity of approximately 10%.

Figure 10 is another example of seismic response to salt, anhydrite and carbonate. Note the strong reflection in the centre of the section, at approximately .6 seconds, representing salt. The termination of the salt and the velocity anomaly on the Precambrian cycle to the left of the section indicates what appears to be an anhydrite halo. However, from the extent of this event and the single Keg River cycle, a possible salt leach area is interpreted.

Figure 11 is another excellent example of a high amplitude discontinuous reflection with phase reversal at approximately .575 seconds. The lithology of this reflector can be predicted with great confidence. Without doubt it is the Lower Muskeg Salt infilling the lows between two reefs seen on the left and on the right of the section.

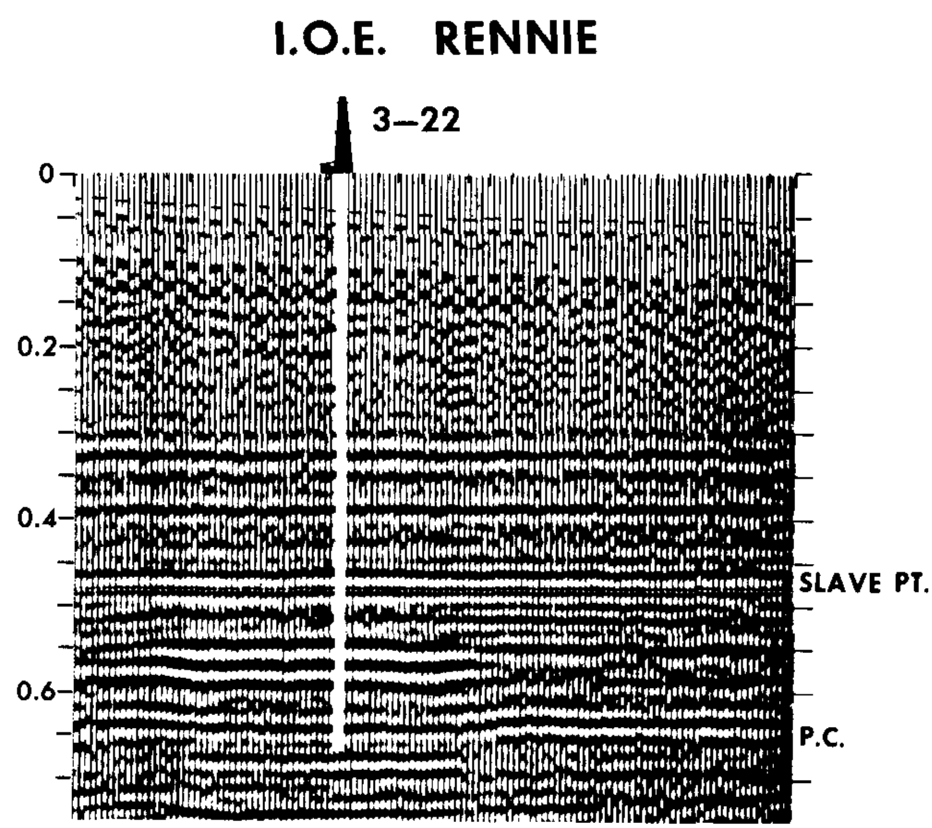


Fig. 5.

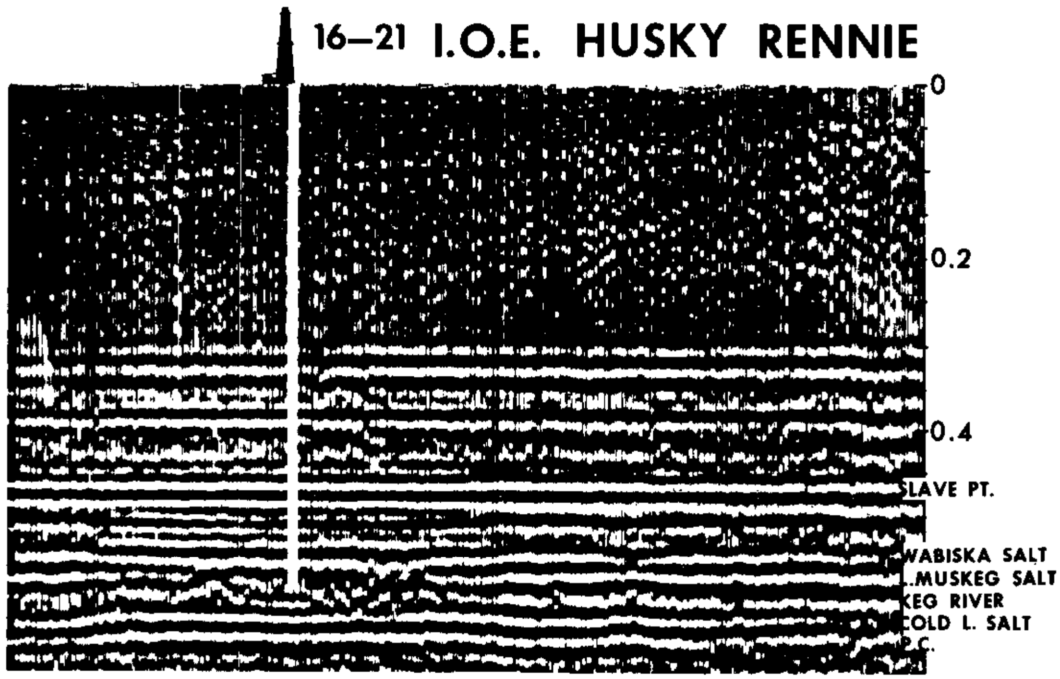

16–21 I.O.E. HUSKY RENNIE
0
0.2
0.4
SLAVE PT.
WABISKA SALT
L.MUSKEG SALT
KEG RIVER
COLD L. SALT
P.C.

Fig. 6.

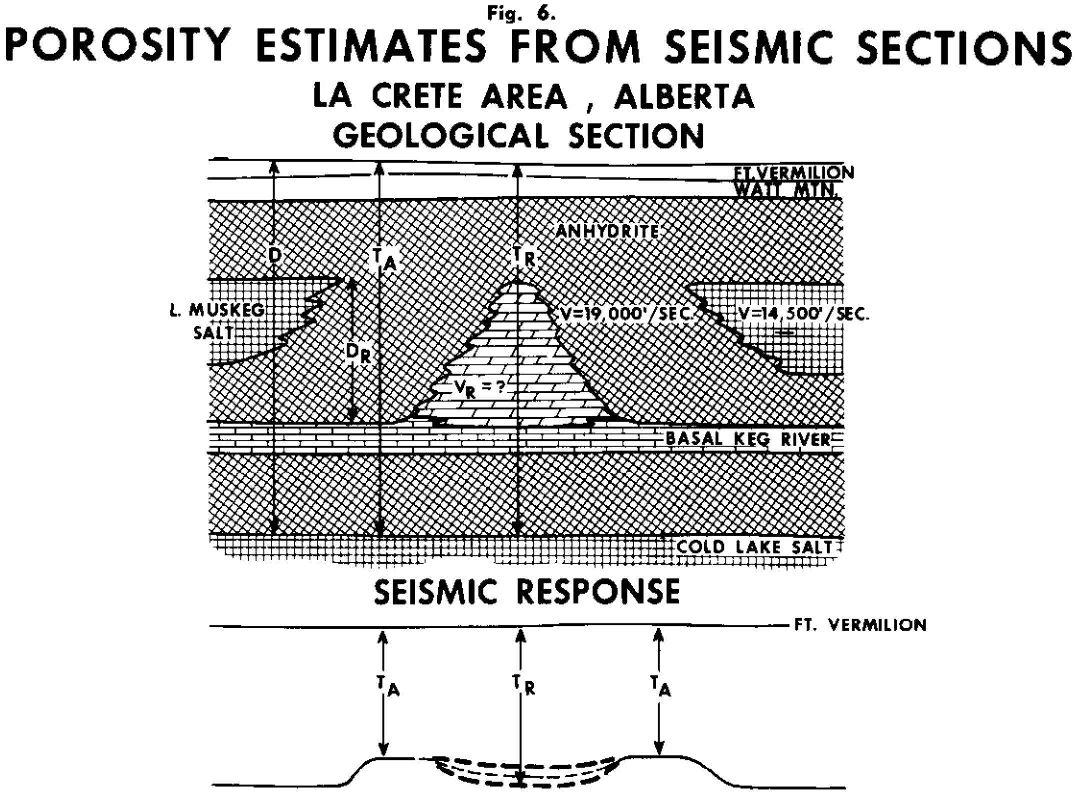

POROSITY ESTIMATES FROM SEISMIC SECTIONS
LA CRETE AREA , ALBERTA
GEOLOGICAL SECTION
FT.VERMILION
WATT MTN.
ANHYDRITE
D
T_A
T_R
L. MUSKEG SALT
D_R
V=19,000'/SEC.
V=14,500'/SEC.
V_R = ?
BASAL KEG RIVER
COLD LAKE SALT
SEISMIC RESPONSE
FT. VERMILION
T_A
T_R
T_A

Fig. 7.

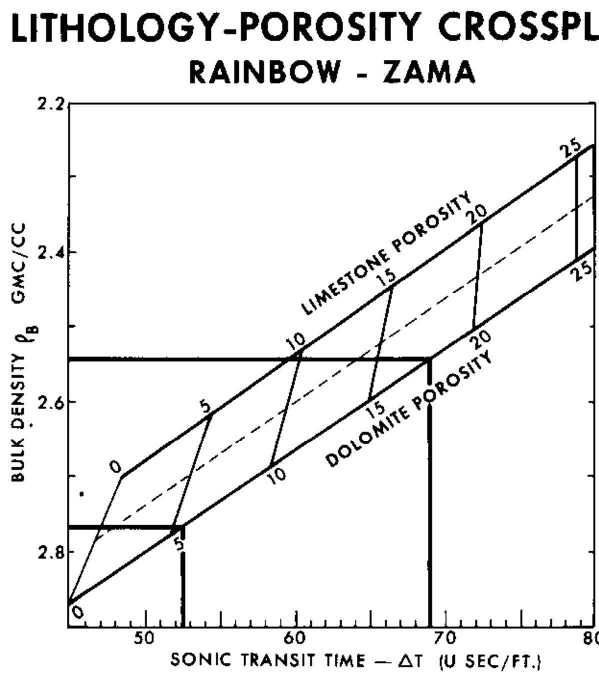
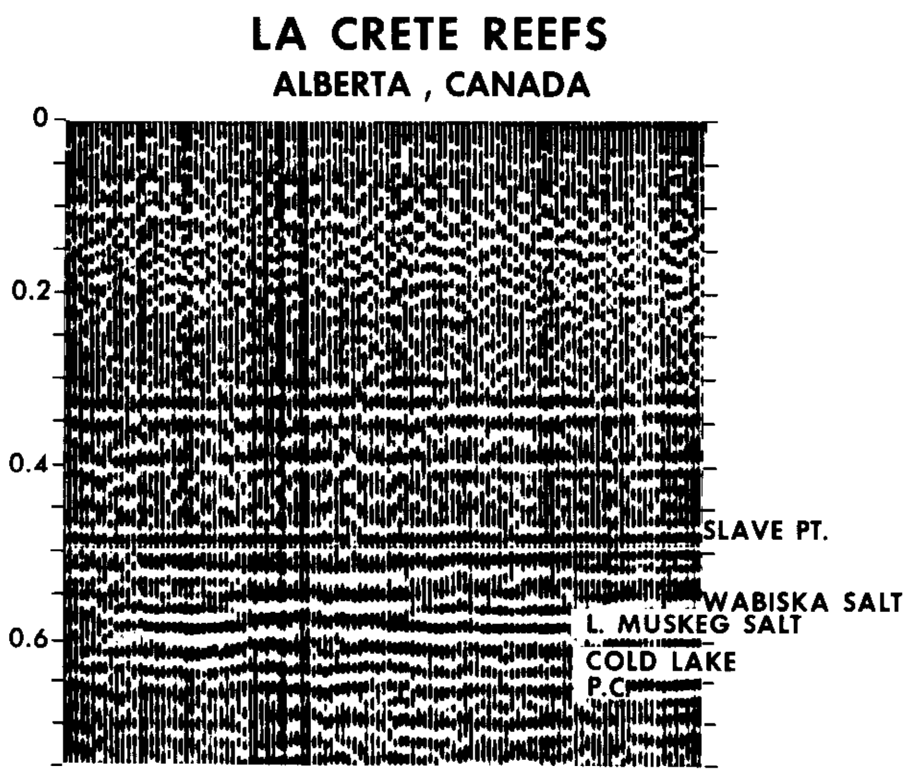

LITHOLOGY-POROSITY CROSSPLOT
RAINBOW - ZAMA
BULK DENSITY ρ_B GMC/CC
SONIC TRANSIT TIME — ΔT (U SEC/FT.)
LIMESTONE POROSITY
DOLOMITE POROSITY
2.2
2.4
2.6
2.8
50
60
70
80

Fig. 8.


LA CRETE REEFS
ALBERTA , CANADA
0
0.2
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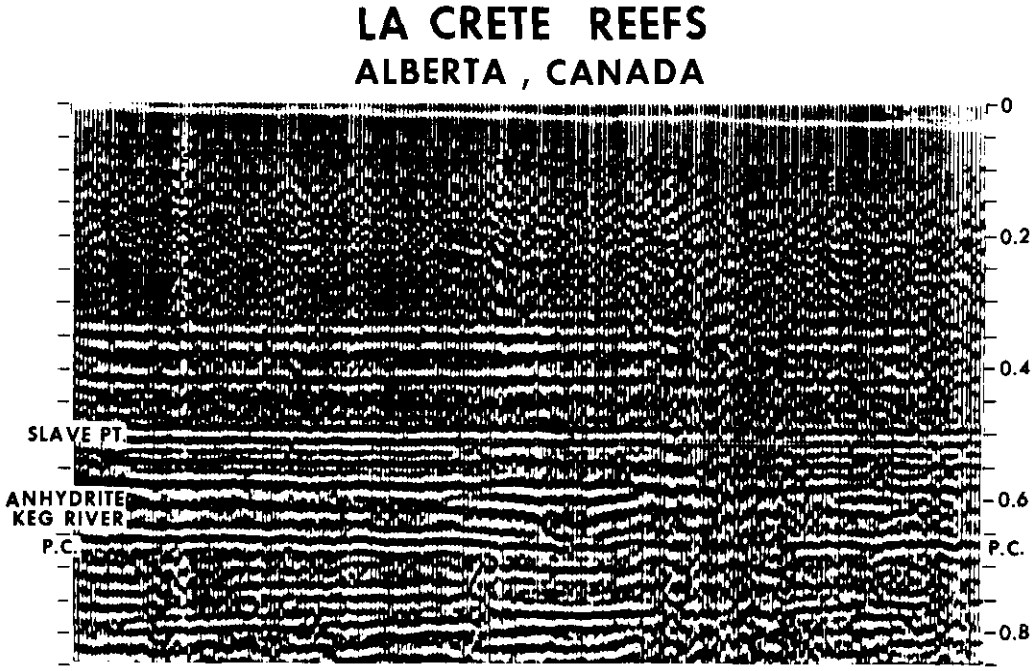
SLAVE PT.
WABISKA SALT
L. MUSKEG SALT
COLD LAKE
P.C

Fig. 9.


LA CRETE REEFS
ALBERTA , CANADA
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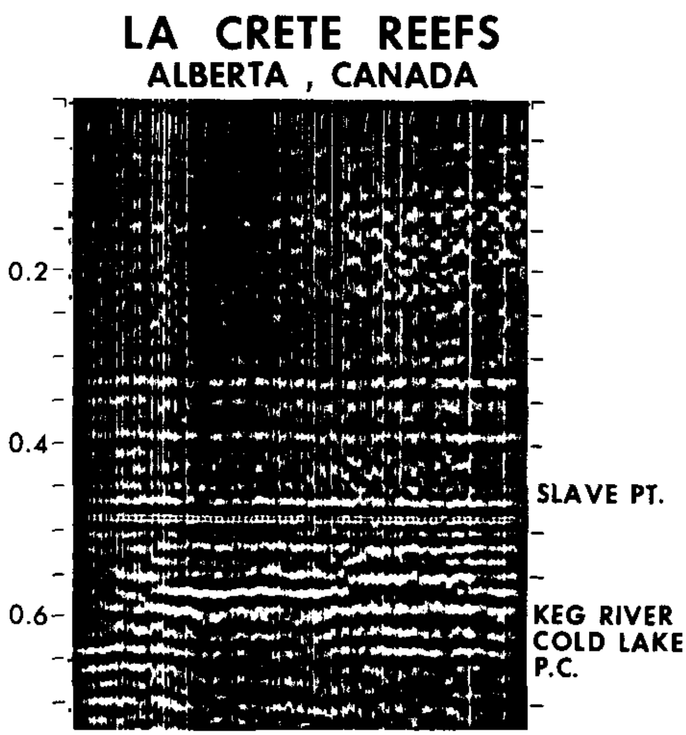
SLAVE PT.
ANHYDRITE
KEG RIVER
0.6
P.C.
P.C.
0.8

Fig. 10.


LA CRETE REEFS
ALBERTA , CANADA
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SLAVE PT.
0.6
KEG RIVER
COLD LAKE
P.C.

Fig. 11.

Conclusion

The conclusions of this study can be summarized as follows:

1. The isochron which was used so successfully in Rainbow could not be applied in the La Crete Basin.

2. The high amplitude reflection with frequency change and phase reversal is the Lower Muskeg Basin salt.

3. Reefs can be identified by:

a) the disappearance of the salt reflection.

b) a cycle split in the Keg River formation.

c) a negative velocity anomaly under the reef.

4. The magnitude of the negative velocity anomaly can be used to predict the range of porosity in the reefs.

Successful evaluation of the potential of this basin progressed at a fast pace once these criteria were fully understood and applied to the seismic interpretation.

Acknowledgement

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