CSEG JOURNAL, V. 8, NO. 1 (DEC., 1972) P. 1-13, 11 FIGS., 1 TABLE

VELOCITY - DENSITY VARIATIONS AROUND KEG RIVER REEFS, ALBERTA†

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Subsurface well velocity-density data has been compiled and analyzed within individual stratigraphic units over Middle Devonian Keg River reefs in the Rainbow sub-basin of northwestern Alberta. Within these Middle Devonian and basal Upper Devonian units velocity anomalies in the order of 5 per cent (+1000 ft/sec) and corresponding density anomalies of 2 per cent (+0.06 gm/cm^3) generally have been found to exist directly above Keg River reefs; an exception being the Muskeg Formation in which the velocity-density decreases above-reef by approximately 4 per cent (—850ft/sec) and 1.5 per cent (—0.04 gm/cm^3) respectively. The success of seismic frequency-amplitude analysis and gravity exploration in Keg River reef exploration in the Rainbow area may in part be due to the presence of these anomalies. For example, the magnitude of the above-reef density variations appears sufficient to account for approximately one-third of the total gravity anomaly often observed above Keg River reefs. Studies concerning the nature of the velocity-density variations reveal a relation may exist between vertical fluid movement, dolomitization and leaching of Keg River reefs, solution of the Black Creek Salt in the vicinity of Keg River reefs, and the source of the velocity-density anomalies; however, no complete geologic model is offered at this time.

INTRODUCTION

The Middle Devonian Rainbow sub-basin of northwestern Alberta (Figure 1) trends northeast-southwest over an areal extent of approximately 1200 square miles and centres on Twp 108, Rge 8, W6M. Within the Rainbow sub-basin several isolated Keg River reefs have been delineated.

Although not as "spectacular" in terms of magnitude and vertical extent as anomalies which exist around Upper Devonian Leduc reefs (Davis, 1972) velocity and density variations have been found in the geologic section (Figure 2) adjacent to and above Keg River reefs as determined from well logs in the Rainbow area. These localized velocity and density variations which exist in the geologic section surrounding Keg River reefs may be related to the diagenetic processes of solution, dolomitization and anhydritization (Langton and Chin, 1968; Barss *et al.*, 1970) which have involved the reefs themselves. The purpose of this paper is to examine the velocity and density variations which exist around Keg River reefs and to discuss the various geologic and geophysical implications thereof.

VELOCITY VARIATIONS AROUND KEG RIVER REEFS

Sonic logs from 134 wells in the Rainbow area (Figure 1) were digitized and analyzed on the digital computer in terms of seismic velocity over seven geologic intervals extending from the Muskeg Formation upward to the Fort Simpson Group as shown in Figure 2. A trend surface analysis (Krumbein and Graybill, 1965, p. 320) was used to separate the velocities over all of the geologic intervals into regional and residual components as exemplified in Figures 3-8.

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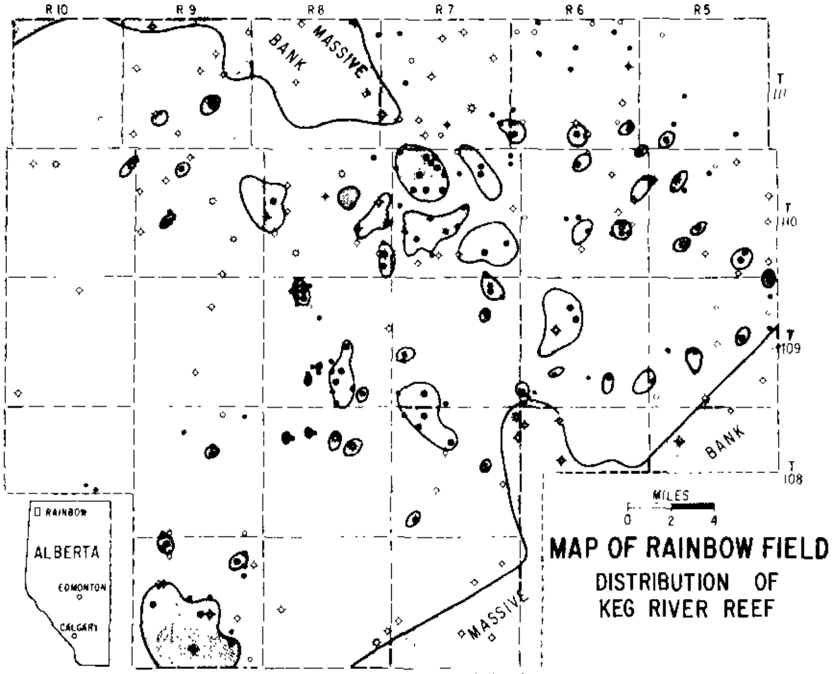

FIG. 1. Rainbow sub-basin

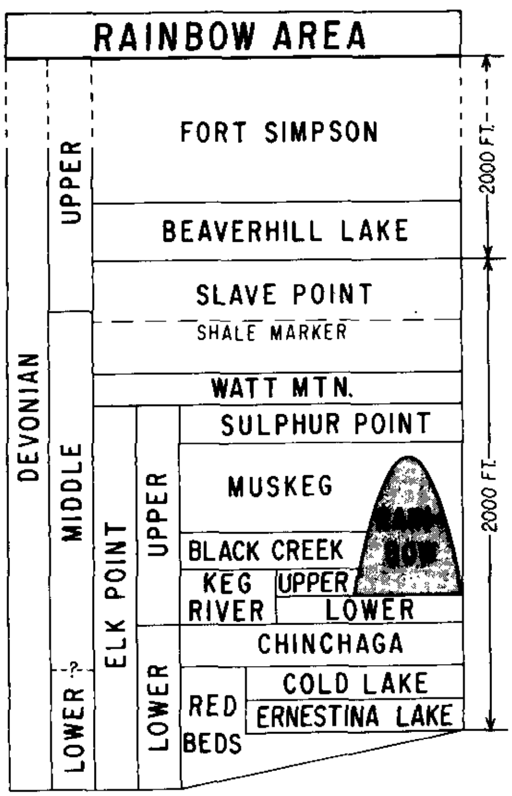

FIG. 2. Stratigraphic column of study area.

Trend surface analysis assumes that the regional variations occur in a simple pattern that can be approximated by some polynomial function. The polynomial may represent a linear plane (1st order surface), a quadratic (2nd order surface), or higher terms. The residual values are obtained by subtracting the observed values from the fitted surface. The statistical "fit" of the polynomial surfaces used in establishing regional components can be evaluated in least squares terms, whereby, the sum of squares of the residual departures from the fitted surface are minimized. The statistics involving the low-order polynomial surfaces used in establishing regionals in this study are shown in Table 1.

The results of the regional-residual separation are:

a) The regional Muskeg component (Figure 3) reflects a "basinal" distribution of regional velocity. The lower "regional" velocities occur in the basin centre.

b) The residual component maps indicate velocity anomalies centred above many of the prominent Keg River reefs. These anomalies appear to be detectable in some cases into the Beaverhill Lake interval. The magnitude of these anoma-

Table 1. Trend surface statistics.

Horizon	Parameter	Std. Dev.	F Test		
			1st Order	2nd Order	Fcritical (99%)
Ft. Simpson					
	Velocity	167 ft/s	18.5	5.49	1.52
Beaverhill Lk.					
	Velocity	267 ft/s	4.05	.94	1.52
Slave Point					
	Velocity	286 ft/s	1.99	1.91	1.52
	Density	.024 gm/cm^3	.15	3.86	1.54
Shale Marker					
	Velocity	409 ft/s	6.48	3.15	1.52
	Density	.026 gm/cm^3	4.85	3.40	1.54
Watt Mtn.					
	Velocity	849 ft/s	17.15	14.29	1.52
	Density	.026 gm/cm^3	.91	3.45	1.54
Sulphur Point					
	Velocity	633 ft/s	2.38	7.23	1.52
	Density	.03 gm/cm^3	.69	4.28	1.54
Muskeg					
	Velocity	617 ft/s	6.19	10.73	1.52
	Density	.028 gm/cm^3	2.38	4.72	1.54
B. Muskeg					

lies, apart from the Muskeg residual interval velocities, tends to decrease upwards as depicted in Figure 15.

c) Anomalies of greatest magnitude appear to occur in the basin centre.

d) Not all the Keg River reefs have associated anomalies. The lack may in part be due to well control on which this study is based.

In geophysical terms, the velocity anomalies above Keg River reefs at Rainbow would enhance the Slave Point - Muskeg interval velocity in the order of 5 per cent (1000 ft/sec) relative to the off-reef section. The velocity increase would presumably be a contributing factor also to the seismic frequency increase (Fitton and Long, 1967, Lindseth, 1970, p. 9.4) and the amplitude increase (Hriskevich, 1970, p. 2274) associated with Keg River reefs.

DENSITY VARIATIONS AROUND KEG RIVER REEFS

Borehole compensated density logs from 117 wells in the Rainbow area were digitized and analyzed over similar geologic intervals as in the velocity study. However, due to lack of density information above the Slave Point, control could not be extended above that horizon. The results are shown in terms of regional-residual density components of each of the geologic intervals analyzed (e.g. Figures 9-14). The statistics involved are given in Table 1.

The results of the regional-residual separation parallel those of the velocity study. The magnitude of the anomalies observed above many of the Keg River reefs is shown schematically in Figure 15. The magnitude of these density variations, geophysically speaking, is sufficient to account for approximately one-third of the gravity anomaly often observed above a Keg River reef. For example, considering a typical reef and above-reef section to consist of cylindrical masses with fixed average off- to on-reef density contrasts (Figure 16), the maximum gravity anomaly associated with each cylinder can be calculated according to Nettleton (1940, p. 144) as:

$$\Delta g_z = 2\pi\gamma\Delta\rho \{h + (R^2+D^2)^{1/2} - (R^2+(D+h)^2)^{1/2}\}$$

where

Δg_z is the gravity anomaly on the axis of a vertical cylinder,

$\Delta\rho$ is the density contrast,

D is the vertical distance or depth to the top of the vertical cyclinder,

R is the radius of the cylinder,

γ is the universal gravitational constant, and

h is the cylinder height.

The total maximum gravity anomaly of .450 mgal derived by summing the individual effects compares favourably with the .5 mgal anomalies observed by Soukoreff in the field (see Hriskevich, 1970, p. 2272). It is apparent from Figure 16 that .130 mgal of the total .450 mgal theoretical gravity anomaly may be derived from the above-reef source. But what of the geologic nature of this source?

NATURE OF THE VELOCITY-DENSITY VARIATIONS

The velocity-density variations observed must reflect localized above-reef lithologic changes in the geologic section extending from the Muskeg to the Beaverhill Lake. How do these velocity-density variations compare in terms of the source models advanced by Yungul (1961) and Haye (1967) to account for the density increase often predicted above reefs? Haye's (1967) model attributes the density anomalies to compaction of the above-reef section with the underlying reef acting as a stress concentrator. The density-velocity decrease in the Muskeg above Keg River reefs, if due in fact to lithologic change rather than pore fluid content, would tend to oppose Haye's proposed "compaction-anticline" source. The decrease occurs in the section immediately above the reefs where presumably the greatest stress concentration should occur.

Correlation of marker horizons in the Muskeg between on- and off-reef areas has been established (Fuller and Porter, 1969; Barss *et al.*, 1970, p. 45). These correlations indicate infill of paleotopography subsequent to reef growth during much of early Muskeg time. Infill is supported largely by evaporite facies analysis, onlap of basal Muskeg beds onto the reef (absence of intertonguing of reef and basal Muskeg beds), and the abundance of normal marine fauna in the reefs along with the absence of reef detritus in the evaporites.

It seems possible that the paleotopography which existed during Muskeg deposition

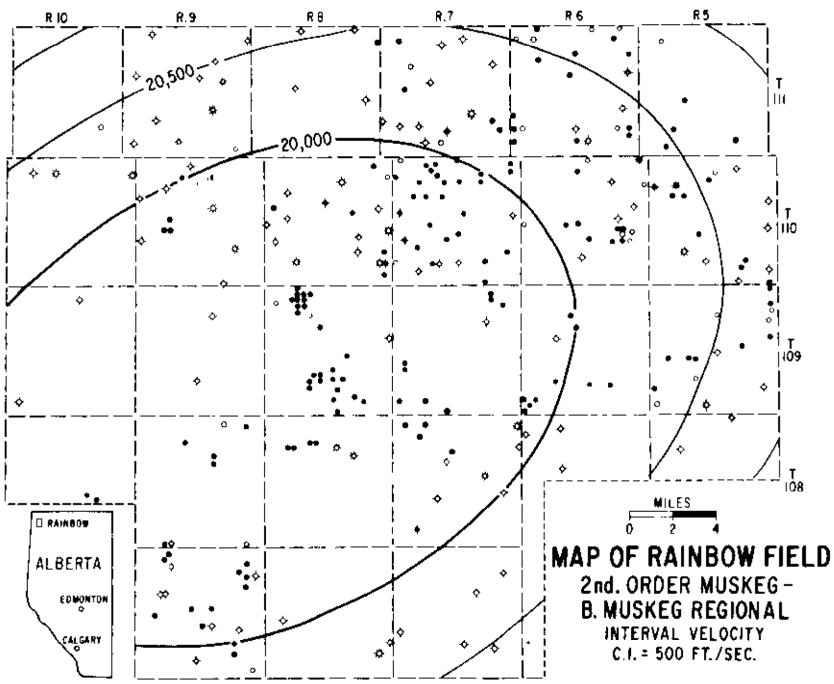

FIG.3. Muskeg regional interval velocity.

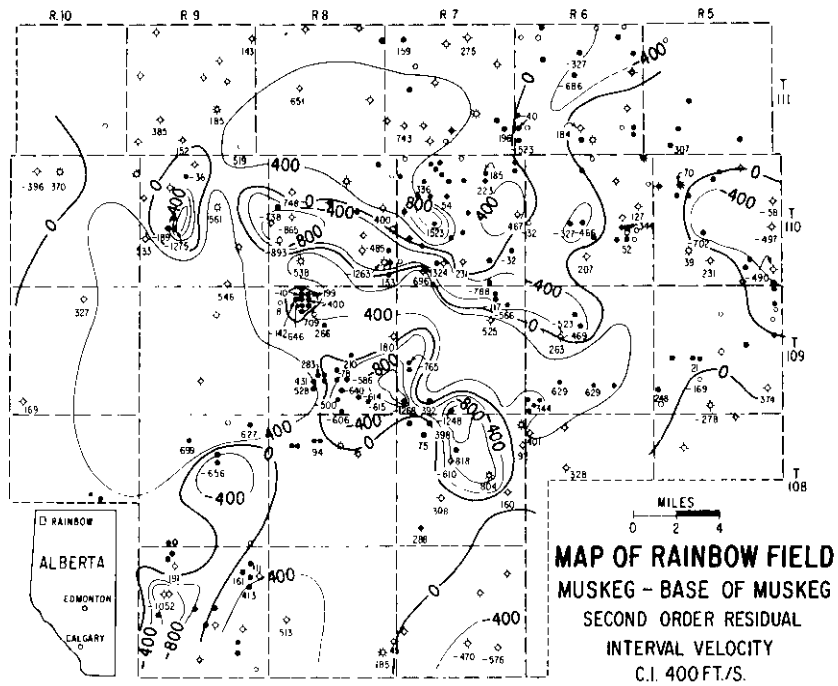

FIG 4 Muskeg residual interval velocity.

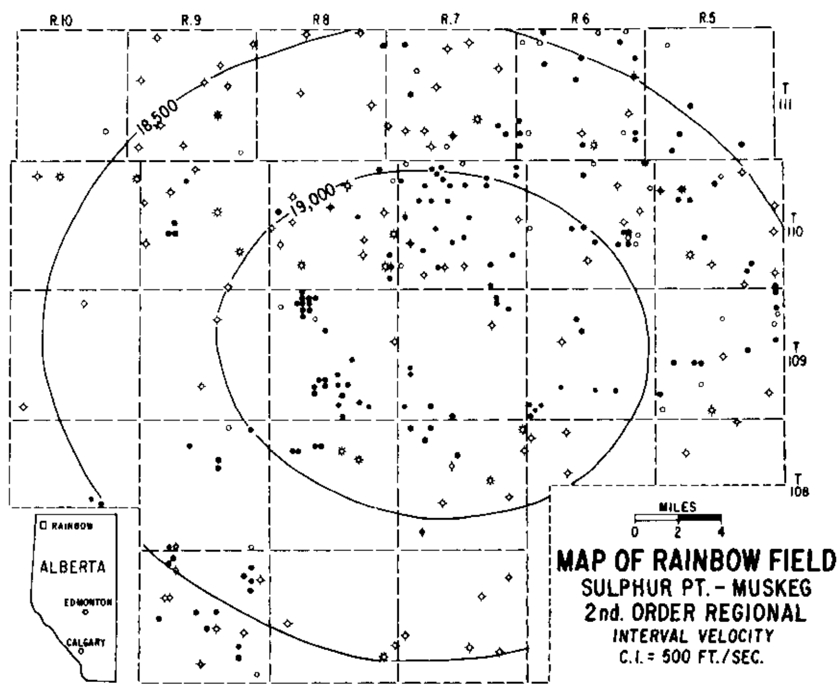

FIG. 5. Sulphur Point regional interval velocity.

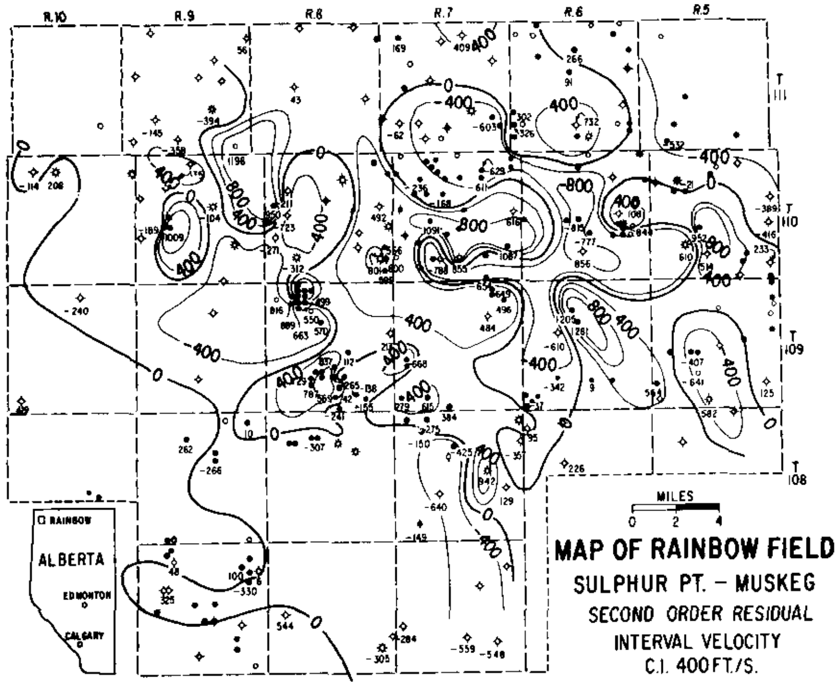

FIG. 6. Sulphur Point residual interval velocity.

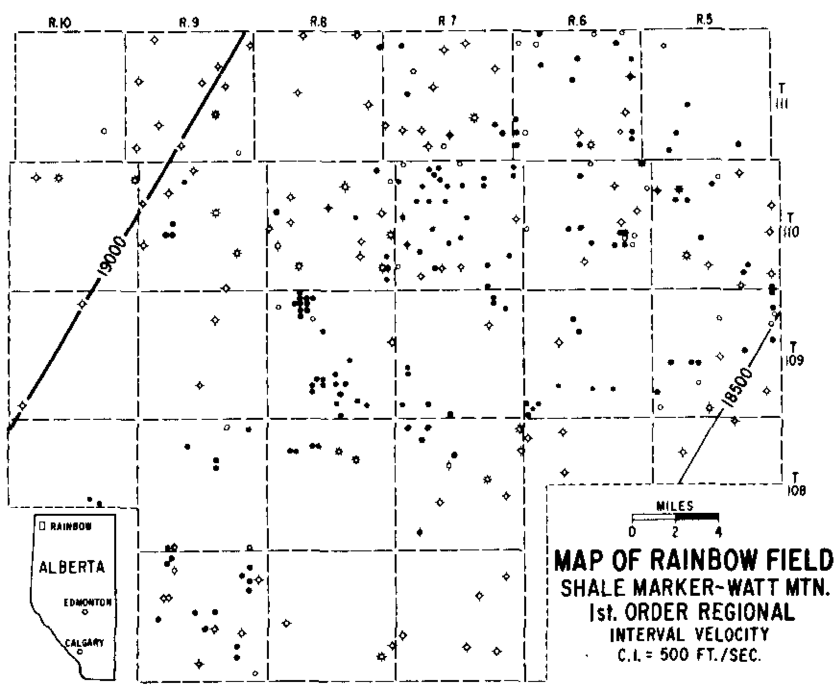

FIG. 7. Shale Marker - Watt Mountain regional interval velocity.

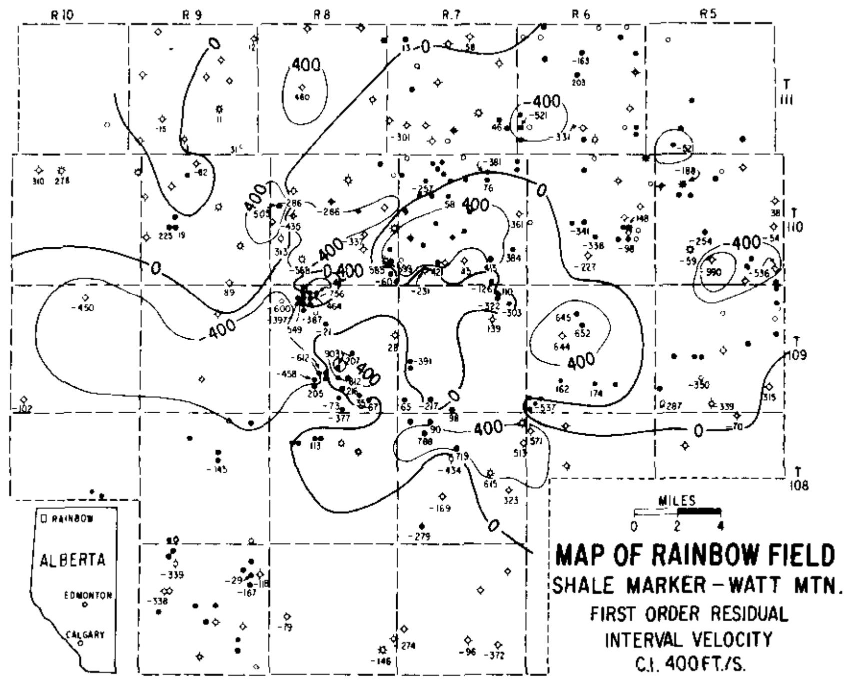

FIG. 8. Shale Marker - Watt Mountain residual interval velocity.

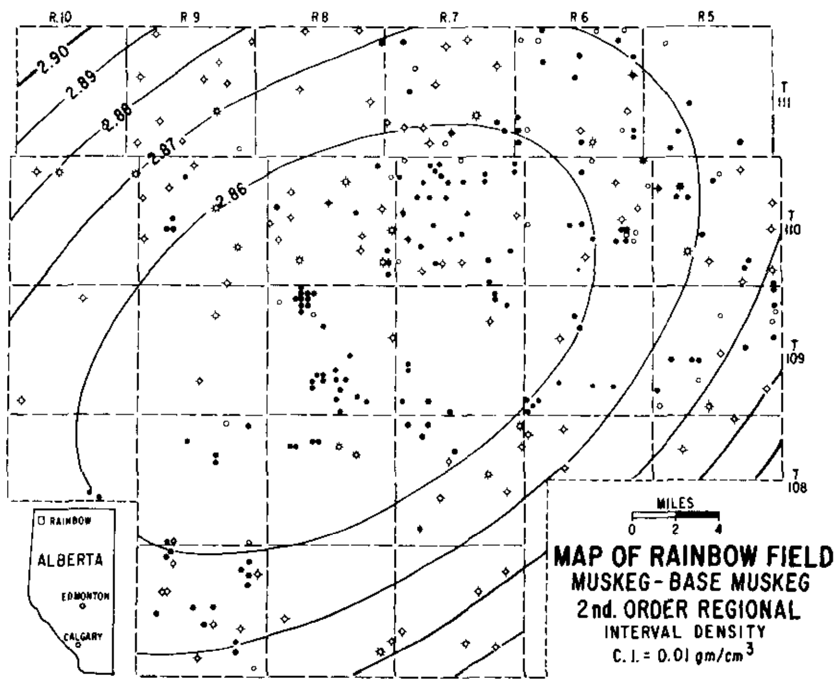

FIG. 9. Muskeg regional interval velocity.

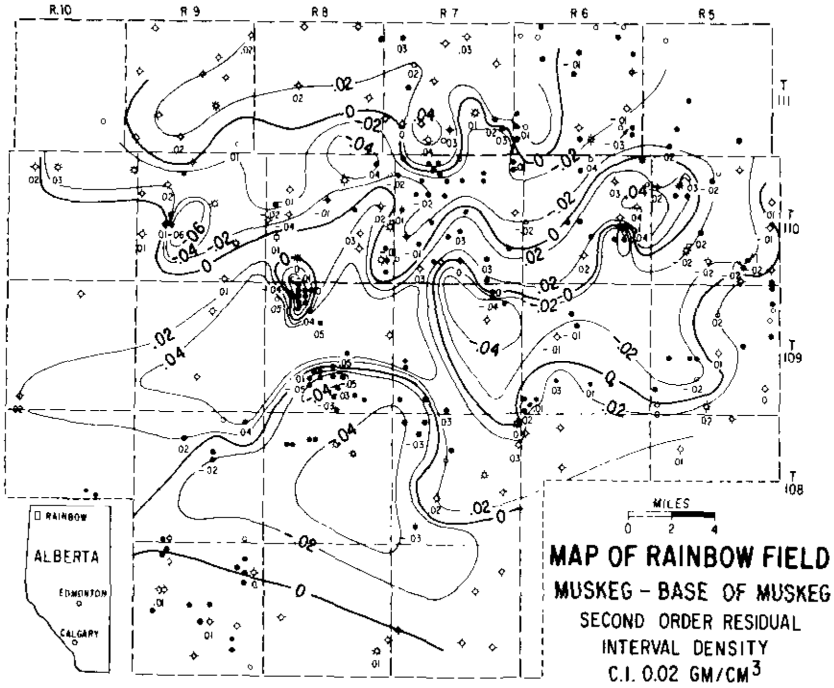

FIG. 10. Muskeg residual interval density.

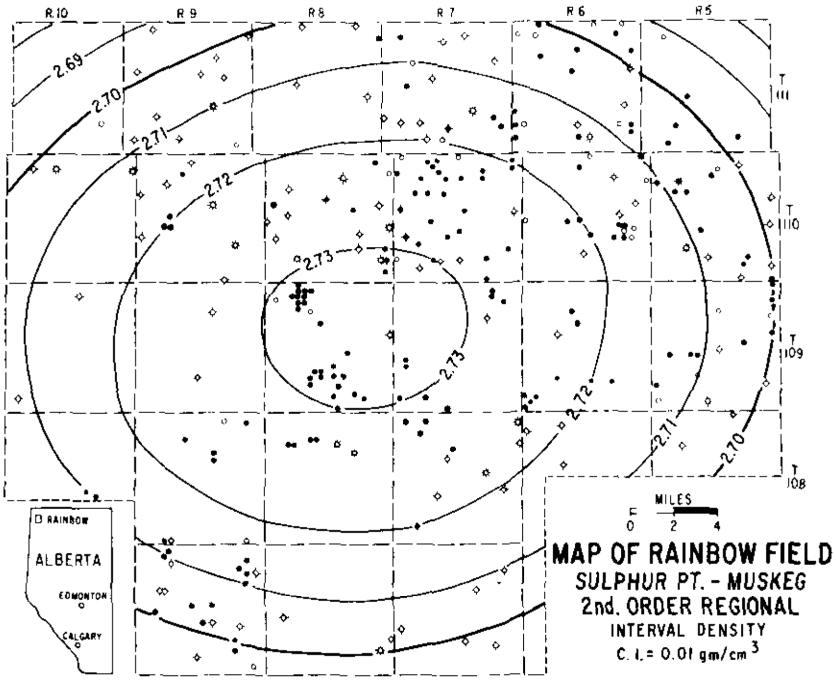

FIG. 11. Sulphur Point regional interval density.

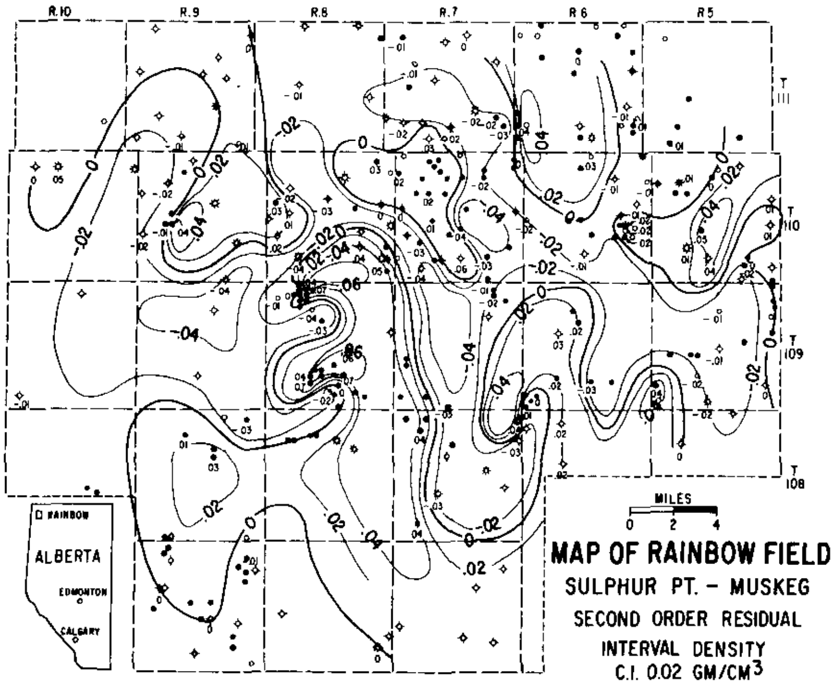

FIG. 12. Sulphur Point residual interval density.

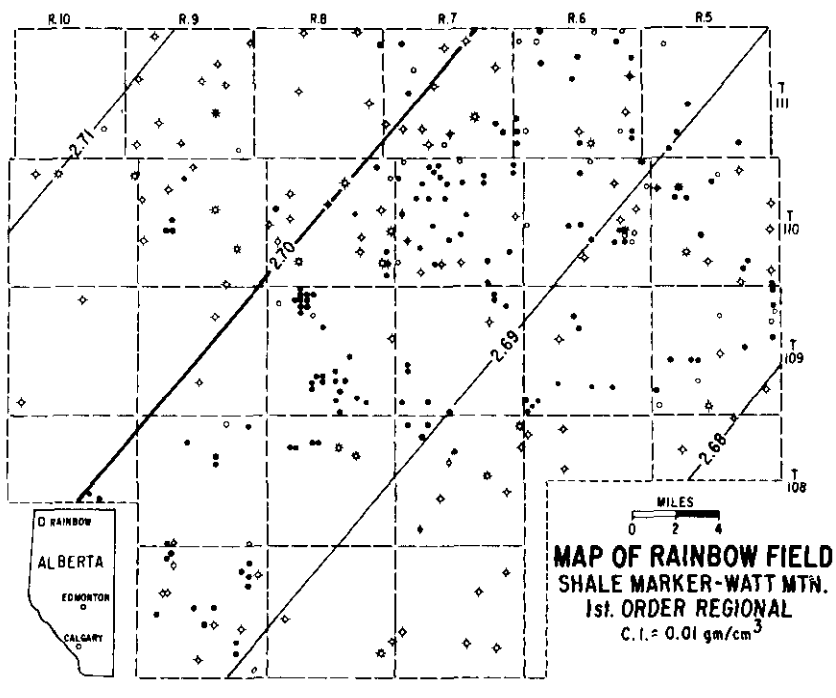

FIG. 13. Shale Marker - Watt Mountain regional interval density.

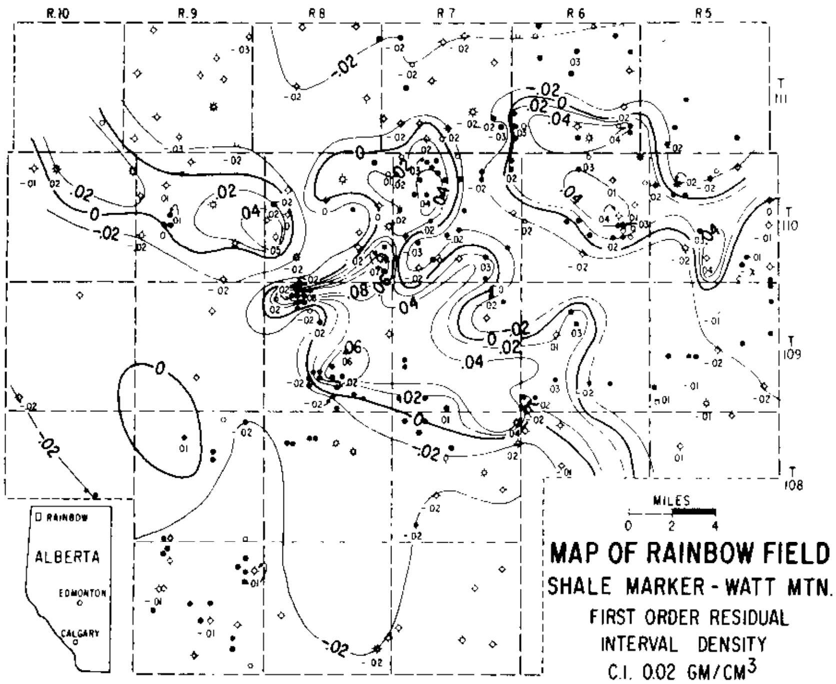

FIG. 14. Shale Marker - Watt Mountain residual interval density.

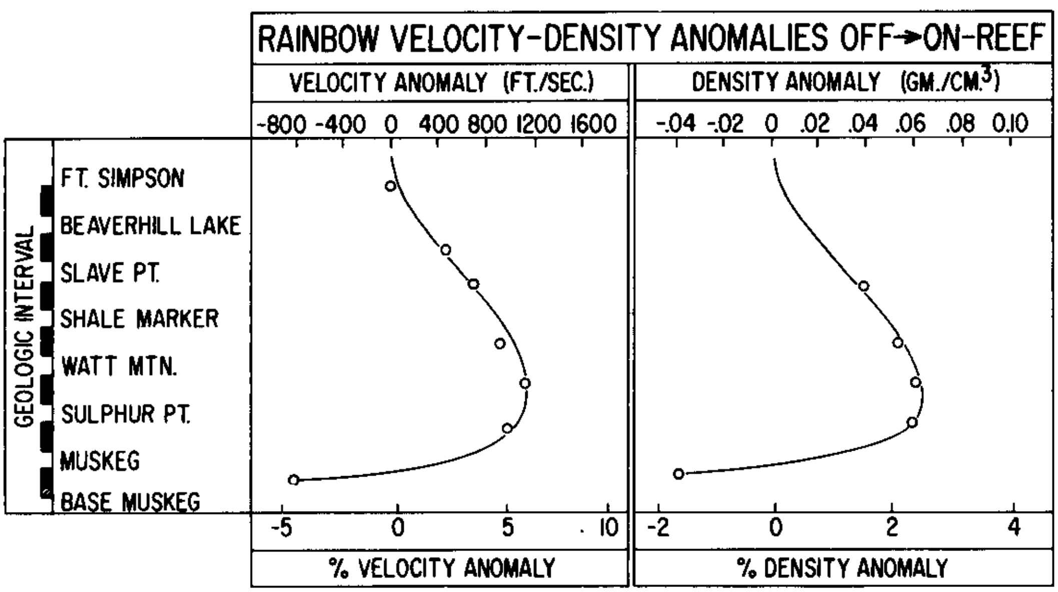

FIG. 15. Typical magnitude of velocity - density variations around Keg River reefs.

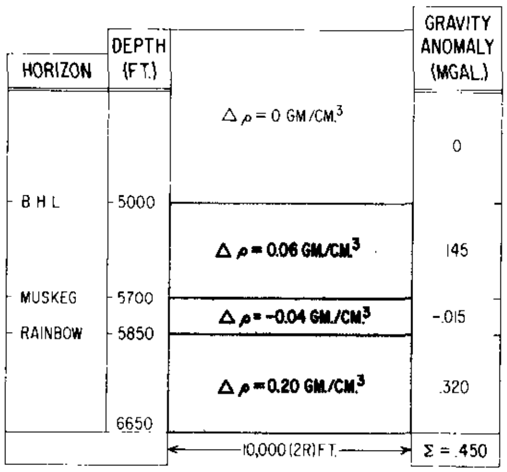

FIG. 16. Theoretical gravity anomalies over Keg River reefs

owing to the presence of underlying Keg River reefs may have localized a porous, permeable carbonate facies within the Muskeg above many of the reefs (particularly within the basin centre). Possible evidence for such a facies localization within the Muskeg above Keg River reefs is given by Hriskevich (1970, p. 2279) in describing an almost complete Muskeg section of fine-medium grained saccharoidal dolomite encountered in the A-pool discovery well 7-32-109-8W6M.

It is thus possible that a depositional source as suggested by Yungul (1961), whereby the reef even after burial creates a topographic expression on the sea floor resulting in "selective" deposition of material over the topographic high, may account for the velocity density anomalies in the Muskeg. However, evidence for paleotopography reflecting underlying Keg River reef does not exist at time of deposition of the Sulphur Point as indicated by Barss *et al.*, (1970, p. 30). In fact, the presence of disconformities at the base and top of the Sulphur Point Formation are suggested. A possible model to explain the velocity-density variations is thought to include vertical fluid movement in the Muskeg evaporite localized by underlying Keg River reefs.

At least 275 feet of Black Creek Salt was once present throughout the area as evidenced by well control. Its present distribution can be mapped seismically. In many areas of close proximity to the reef flanks salt solution has caused anomalous thickening of the Muskeg sediments (Figure 17). Solution of the Black Creek Salt thus began relatively "early" during Muskeg time. It is postulated that continued solution of the Black Creek Salt may have involved vertical fluid movement focused by underlying Keg River reefs (Figure 18). Original porosity and permeability within the Muskeg and the Keg River reefs would play an important role in channelling of these fluids. The vertical fluid movement may have localized post depositional diagenetic anomalies in the geologic section from the Muskeg upward to the Upper Devonian Beaverhill Lake. A similar model has been introduced by Jodry (1969) in explaining the dolomitization of Silurian reefs in Michigan.

Thus a relation between the solution of the Black Creek Salt, dolomitization and leaching of Keg River reefs, and the source of the velocity-density variations observed in the geologic section above Keg River reefs may exist. Further investigation of this hypothesis may prove useful in understanding the diagenetic processes of solution, dolomitization, and anhydritization associated with Keg River reefs.

CONCLUSIONS

From this study the following conclusions may be drawn:

- In the Rainbow sub-basin velocity-density anomalies generally exist in the Middle and basal Upper Devonian sediments above Keg River reefs. These anomalies extend from the Muskeg Formation, which envelopes the reefs, upward to and including the Beaverhill Lake Formation. The velocity-density of the Muskeg Formation appears to be lower (-850 ft/sec and -0.04 gm/cm³) in the above-reef section. Within the Sulphur Point to Beaverhill Lake interval these anomalies have an average overall magnitude of +1000 ft/sec (5 per cent) and +0.06 gm/cm³ (2 per cent) respectively.
- The velocity density anomalies are focused directly over the Keg River reefs. The magnitude of the individual ano-

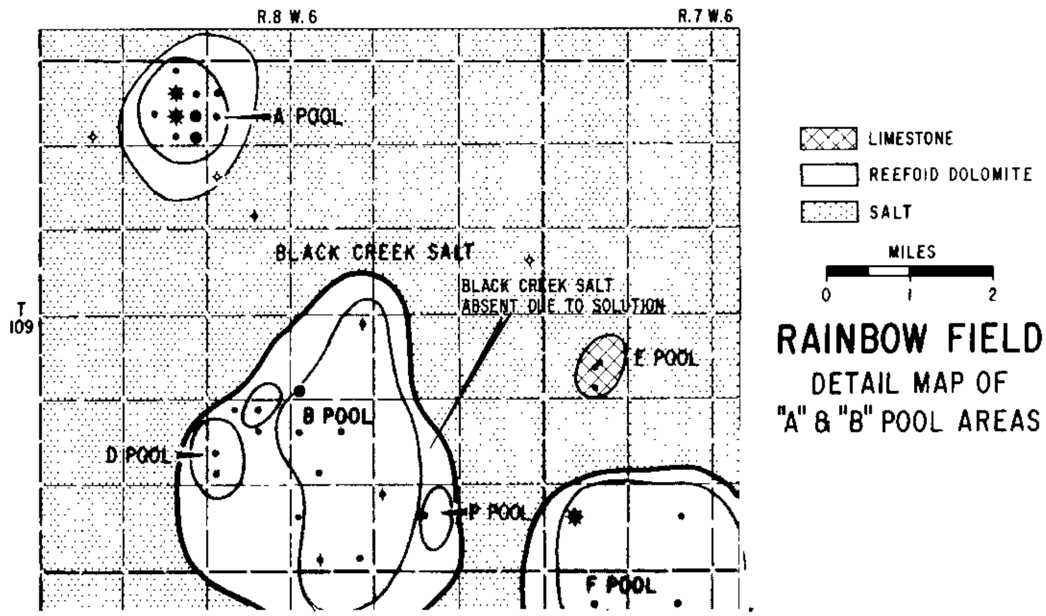

FIG 17 Relation of Black Creek Salt solution to reef proximity.

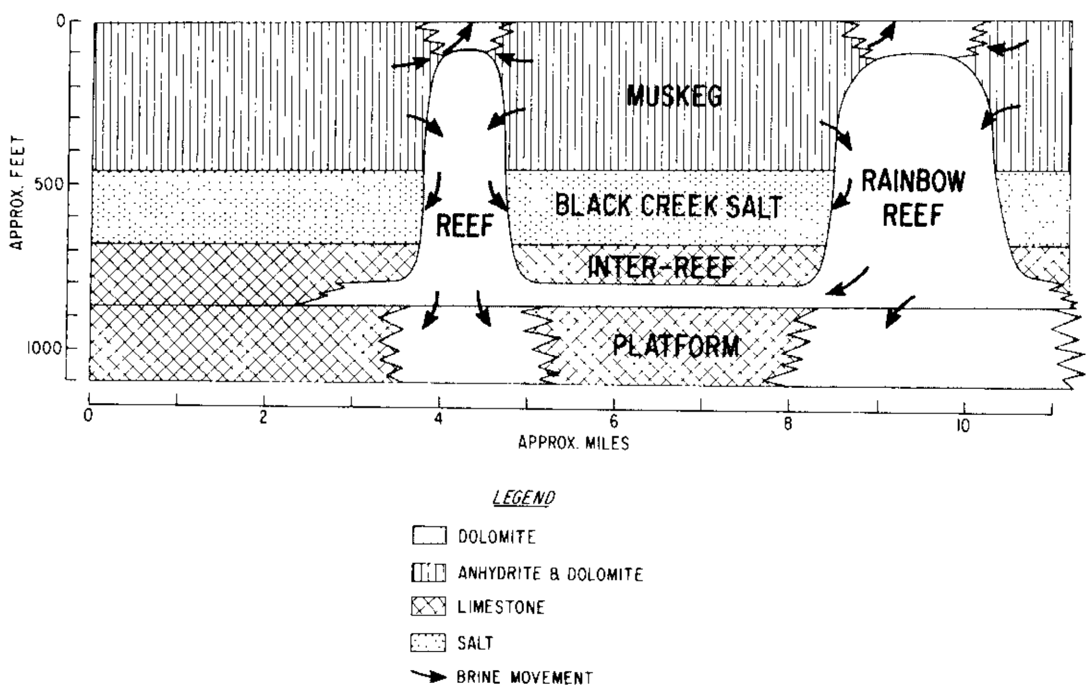

FIG 18 Schematic Keg River cross section

malies, apart from the Muskeg, decreases upward. The anomalies within each of the individual stratigraphic units appear to be of greatest magnitude in the vicinity of the Rainbow sub-basin centre.

— The additional 4-5 per cent velocity increase in the above reef interval would presumably be a contributing factor to the seismic frequency (Fitton and Long, 1967; Lindseth, 1970, p. 9.4) and the amplitude anomalies (Hriskevich, 1970, p. 2274) associated with Keg River reefs. In terms of gravity exploration the magnitude of the above-reef density variations are sufficient to account for approximately one third of the total gravity anomaly often observed above Keg River reefs.

— The density-volocity reversal within the above-reef Muskeg would appear to contradict Haye's (1967) compaction anticline source of the variations. In Muskeg time it is possible that depositional changes as suggested by Yungul (1961) did occur above Keg River reefs. However, it is more difficult to invoke depositional changes as the source of the anomalies which occur above the Muskeg. A possible explanation for the source of the velocity-density anomalies is thought to include vertical fluid movement focused by underlying Keg River reefs.

ACKNOWLEDGMENTS

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