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EXPLORING FOR DOLOMITIZED SLAVE POINT CARBONATES IN NORTHEASTERN BRITISH COLUMBIA[1]

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ABSTRACT

In northeastern British Columbia a number of significant gas fields have been discovered in dolomitized Slave Point carbonates located along the edge of the mid-Devonian barrier-reef system. Reflection seismic techniques have been used extensively in exploring for these fields. A common exploration practice has been to detect the reef edge seismically and then drill on isochron thins and structural highs close to this edge. The remaining reserves, however, are proving more difficult to find, and this exploration technique does not always guarantee that the Slave Point Formation will be dolomitized in this location.

As with many other complex play types, combining geological concepts with geophysical exploration techniques can improve the explorationist's success ratio. In this example, a geological model (the Dorag dolomitization model — Budiozamani, 1973) provides a possible explanation for the localization of the Slave Point dolomites. In this model dolomitizing solutions are created by mixing fresh, phreatic water with salt water. This condition could occur if porous reefal Slave Point carbonates were exposed to fresh-water infiltrations adjacent to open-marine conditions. The edges of the mid-Devonian barrier reef and the edge of the Keg River embayments were areas that could have met these requirements. Thus the optimum condition for dolomitization should occur slightly basinward of the reef edge in the zone of possible mixing of fresh and salt waters. To increase the chance of encountering a potentially narrow band of dolomitized Slave Point reservoirs, exploration wells should be positioned on the edge of the carbonate reef slightly basinward of the isochron thin. An exploration example from a Keg River embayment area illustrates and supports this exploration concept.

INTRODUCTION

A number of commercial gas fields have been discovered in the northeastern part of the British Columbia Plains. Most of these reserves are located within dolomitized Middle Devonian carbonates. These gas accumulations tend to be structurally and stratigraphically trapped along the edge of the mid-Devonian barrier-reef system or within isolated reefs in the adjacent Petitot basin (Fig. 1). Reflection seismic techniques have played a significant role in helping explorationists locate these fields.

Although the larger gas accumulations within this area have probably been found, there still remains enough hydrocarbon potential to warrant additional exploration. However, the remaining reserves will be more difficult to find, as they are smaller and not necessarily located along well-established trends. Application of modern geophysical techniques and incorporation of geologic concepts that explain the occurrence of these dolomitized reservoirs may help the explorationists locate the remaining reserves.

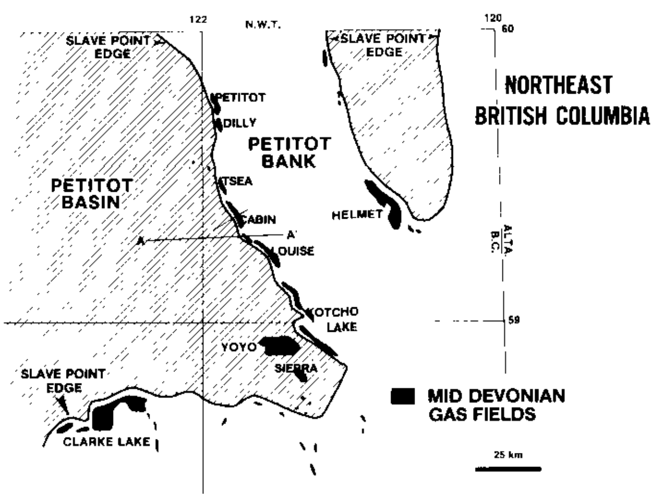

Fig. 1. Map showing the location of mid-Devonian gas fields of northeast British Columbia.

GEOLOGIC SETTING AND THE EXPLORATION TECHNIQUES COMMONLY USED

The geologic setting of the mid-Devonian carbonate-reef play is depicted on the schematic cross section A-A' (Fig. 2, adapted from Torrie, 1973). This section runs across the main reef system (the Petitot Bank)

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and into the forereef shale basin (the Petitot Basin). Significant gas accumulations have been discovered in porous, dolomitized Slave Point carbonates located along the edge of this barrier-reef system between forereef Otter Park shales and backreef tight limestones. Top seal is provided by the Muskwa and Fort Simpson shales. Large reserves of gas are also trapped in isolated reefal buildups within the basin where the offreef shales provide both the lateral and top seals. Dolomitization often enhances the reservoir properties of these pinnacle- and atoll-type reefs.

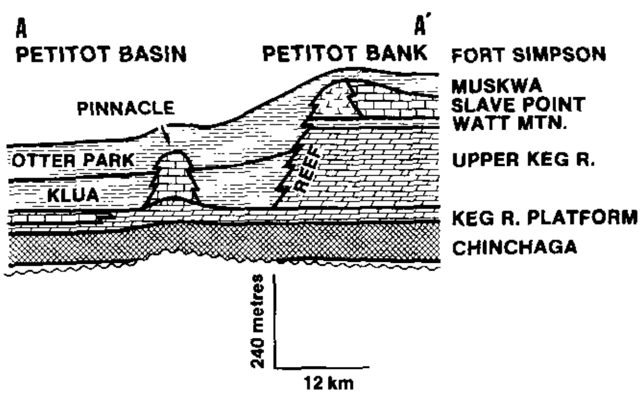

Fig. 2. Schematic cross section showing the geological setting of the mid-Devonian carbonate reefs of northeastern British Columbia (adapted from Torrie, 1973).

Since the discovery of the Clarke Lake field in 1957, seismic data have been successfully used to locate the edge of the main Slave Point - Keg River barrier reef. The seismic line on Figure 3 was shot across the reef edge and shows the typical geophysical response from this type of geologic configuration. A strong Slave Point reflector originates from the shale/top of carbonate reef interface. This reflection rapidly drops structurally to the left of the section as the line crosses the reef edge and extends into the forereef shale basin. Associated with this drop is a corresponding thickening of the overlying shale section represented by the low-reflection energy zone above the mid-Devonian carbonate reflector. An isochron map between the easily recognizable top of Devonian reflector and the mid-Devonian carbonate reflector shows this rapid increase in shale thickness, which corresponds to the edge of the reef. A common exploration practice has been to define and map the reef edge seismically and drill the structural highs along this edge. The gas well shown in the seismic line (Fig. 3) is located on such a position. Success depends on the Slave Point Formation's being dolomitized at these structurally high locations. This exploration practice has been used to discover several gas fields along the mid-Devonian reef complex. Early success was due partly to the existence of a rather wide zone of dolomitized Slave Point carbonates that

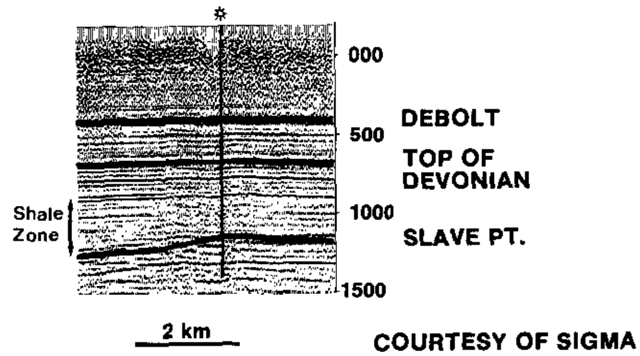

Fig. 3. Seismic expression across the edge of the Slave Point - Keg River barrier reef (Sigma participation survey).

provided a broad drilling target along the edge of the barrier reef.

The geophysical expression from isolated reefs within the basin is similar except that the top of mid-Devonian reflector drops off rapidly in all directions from the crest of the buildups. These reefs are easily seen as "bulls'-eyes" on top of Devonian to top of mid-Devonian isochron maps. The key to locating these smaller reefs is obtaining a very dense grid of modern seismic coverage across the prospective pinnacle fairway.

When one examines the geological map (Fig. 4) that shows the occurrence of dolomitized Slave Point carbonates, an additional play type is seen to occur. As was shown on Figure 2, Slave Point dolomites commonly occur along the edge of the Slave Point Formation. This map, however, shows that a number of wells have also encountered Slave Point dolomites behind the main Slave Point reef front. These dolomitized reservoirs too have been found to contain gas reserves.

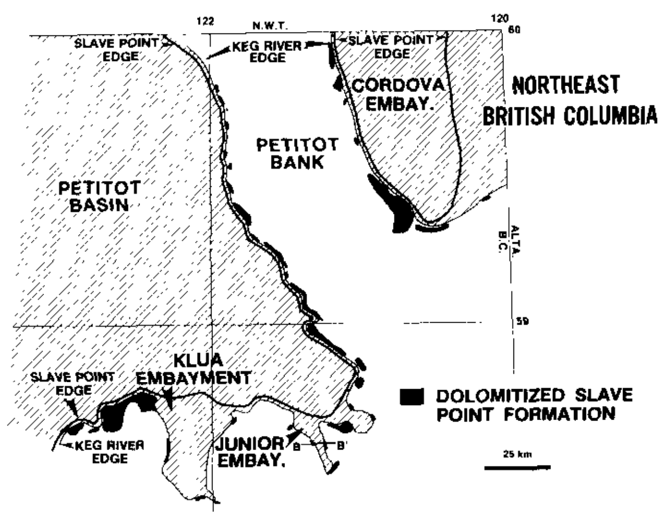

Fig. 4. Geological map showing the occurrence of dolomitized Slave Point carbonates.

Cross section B-B′ (Fig. 5) shows the geologic setting of the dolomitized Slave Point play type that exists behind the main Slave Point edge. On this cross section the Slave Point carbonate is shown to be locally dolomitized above the edge of the underlying Keg River reef / Klua shale forereef boundary. Although the Keg River Formation can also be dolomitized, gas tends to be trapped in the updip porous Slave Point dolomites.

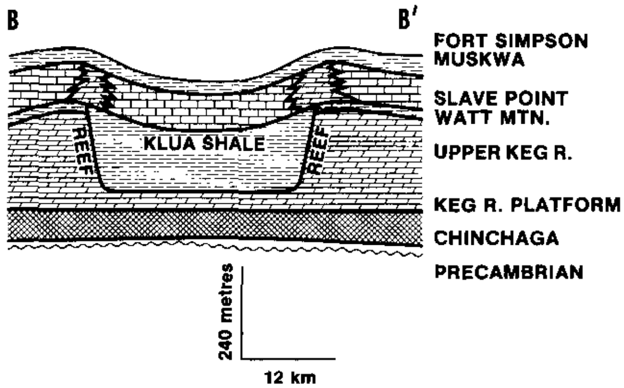

Fig. 5. Schematic cross section showing the geological setting of the Keg River embayment areas in northeastern British Columbia.

The key to locating these dolomitized Slave Point carbonates is to first locate the edge of the underlying Keg River reef. Once again, seismic information has proved to be a useful tool in exploring for this play.

The seismic response across one of these Klua shale embayment areas is shown on the section in Figure 6. As with the previous seismic example, the top of Devonian and mid-Devonian Slave Point carbonate reflectors are seen as strong amplitude reflections (just below 0.6 sec and 1.0 sec respectively). But the Slave Point reflector does not drop off as dramatically at the reef edge; instead, additional reflectors are present below the Slave Point reflector (left part of section at 1.1 sec). Here the upper Keg River carbonate has been replaced by the Klua shales. These reflections result from the Slave Point carbonate / Klua shale interface and the Klua shale / Keg River carbonate interface. The mapped limits of these Klua shale reflectors mark the edge of the upper Keg River carbonate reef. This edge is a prospective locale for dolomitized Slave Point carbonates, as the dolomitized zone tends to be positioned above the upper Keg River reef edge (Fig. 5).

Once the limits of the Klua shale embayment area have been mapped, the top of Devonian to Slave Point isochron map can be used to highlight maximum reefal buildup along the edge of the Klua shale (once again, maximum reefal growth corresponds to isochron thins). Wells located in structurally high positions along these isochron thins have sometimes encountered gas accumulations in dolomitized Slave Point carbonates. Unfortunately, however, this has not always been the case.

For example, two exploration wells were located on isochron thins (Fig. 7) and structural highs (Fig. 8) close to the edge of the Klua shale reflector. The seismic lines in Figures 6 and 9 across these locations are indicated on the maps. The well located on the isochron thin and structural high on the seismic line in Figure 6 encountered a gas-bearing dolomitized Slave Point reservoir. The same isochron-thin and structural-high criteria are present at the location shown on the seismic line in Figure 9. Nevertheless, this well encountered tight Slave Point limestones. Locating a well along isochron thins in structurally high positions in the vicinity of the reef edge, then, does not guarantee that porous, dolomitized Slave Point reservoirs will be found.

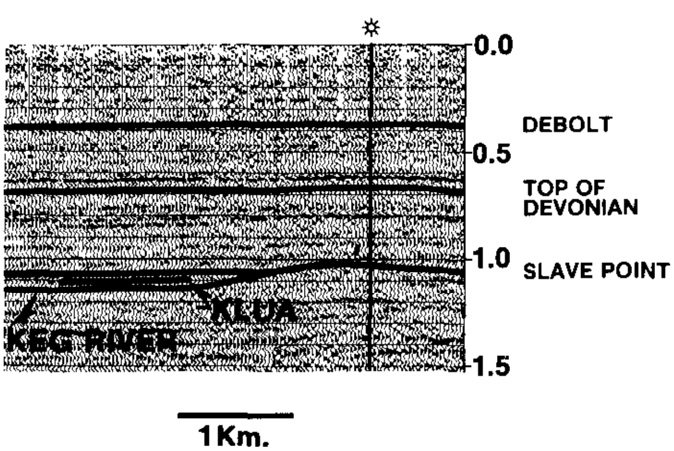

Fig. 6. Seismic expression across a Keg River embayment

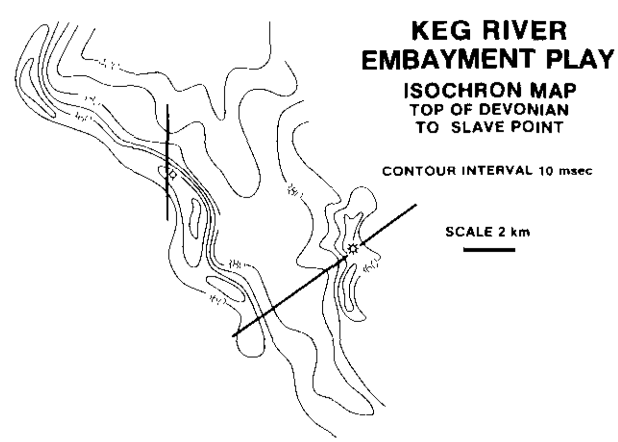

Fig. 7. Top of Devonian to Slave Point isochron map used to highlight reefal developments.

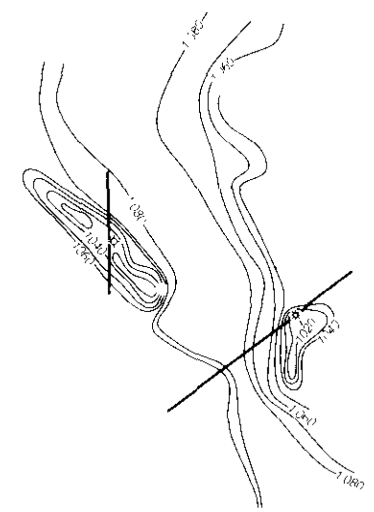

Fig. 8. Slave Point structure map used to locate structural closures along the reef edge.

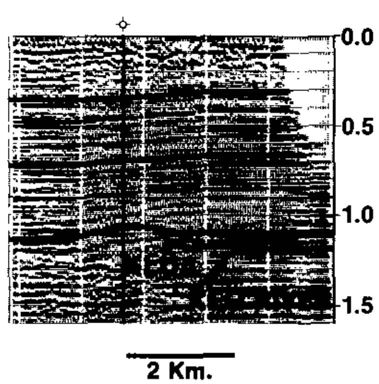

Fig. 9. Seismic expression across a Keg River embayment.

Geophysical Methods in Predicting the Occurrence of Porous Slave Point Dolomites

Ideally, the explorationist would like to know where the Slave Point carbonates are dolomitized before drilling any wildcat wells. One approach would be to detect the porous, dolomitized Slave Point reservoirs directly on seismic data. In considering this possibility, the first approach is to examine a number of seismic lines that cross both dolomitized Slave Point reservoirs and tight Slave Point limestones, hoping to find a consistently recognizable seismic-response difference between the two areas. As porous dolomites have lower velocity and density values than tight limestones, one might expect a loss in amplitude going from the shale (low velocity and density) / tight limestone (high velocity and density) reflections to the shale / porous dolomite (moderately high velocity and density) boundary. If the porous dolomite zone was completely encased in tight limestone, a recognizable reflection response might result from the limestone/dolomite (negative interface) and the dolomite/limestone (positive interface) boundaries.

A number of seismic lines that crossed these areas of interest were examined for any of these reflection characteristics. Although amplitude variations and other localized reflection changes were present, there was not a consistent relationship between these geophysical reflection variations and the presence or absence of porous, dolomitized Slave Point carbonates. Unfortunately, the reflections resulting from the shale / porous dolomite interface appear similar to the reflections resulting from the shale / tight limestone interface. It is also difficult to separate low-amplitude reflections that might result from tight limestone / porous dolomite interfaces from other noise-related events.

Separating porous dolomites from tight limestones directly on seismic data has proved a difficult task in this area. Part of the problem results from the rather high background noise present on these land seismic data. Separating the dolomites from limestones in this formation is further complicated by the irregular limestone/dolomite interfaces, which can vary from horizontal to vertical over a very short distance and generally tend to be transitional boundaries. Potentially, inverse modelling (*e.g.*, Seis-log) techniques on modern high-resolution data could yield positive results in separating seismically the porous Slave Point dolomites from tight Slave Point limestones, but no substantiation of this technique for this play is known to the author.

Geologic Methods in Predicting the Occurrence of Porous Slave Point Dolomite

If the geological events that caused localized Slave Point dolomitization were understood, then the explorationist could use the associated geological model to help predict where other porous dolomites might be located. Unfortunately, there are a number of theories concerning the possible cause of dolomitization.

Therefore a unique solution for Slave Point dolomitization is elusive and at best speculative. By selecting the dolomitization model that best fits the geology of the mid-Devonian carbonate complex, however, and using it along with the existing exploration techniques, it may be possible to fine-tune the wildcat locations and increase the success ratio in exploring for this difficult play.

Before selecting an appropriate geological dolomitization model from the literature, a brief discussion on the geology of Slave Point dolomites is in order. In doing this, reference is made to some core-analysis work from a typical dolomitized Slave Point field, the Clarke Lake field, by J. W. Young and R. P. Glaister of Esso Resources Canada Ltd. The following is a brief summary of their findings:

The Clarke Lake carbonates have had a long and complicated diagenetic history involving several stages of cementation, chalkification, alteration to dolomite, and fracturing. In most backreef areas, or where Klua shale is present, the Slave Point has remained as limestone with calcite cement infilling any original porosity. In the reef-edge facies cementation was incomplete. Here, early chalky porosity (Fig. 10) developed within the micrite matrix and in the stromatoporoidal reef material. Magnesium-bearing fluids were able to pass through these zones of chalky porosity, dolomitizing the groundmass and forming enlarged intercrystalline pores. At the same time, stromatoporoids and some of the other fossils were leached out, creating excellent vuggy porosity (Fig. 11). A later, less significant stage of white, coarsely crystalline dolomitization followed. It appears to be associated with fracturing of the earlier-formed dolomites.

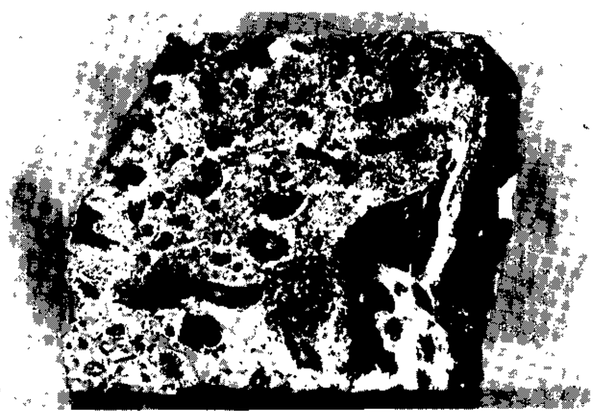

Fig. 10. Slave Point core from the Clarke Lake field showing early chalkification.

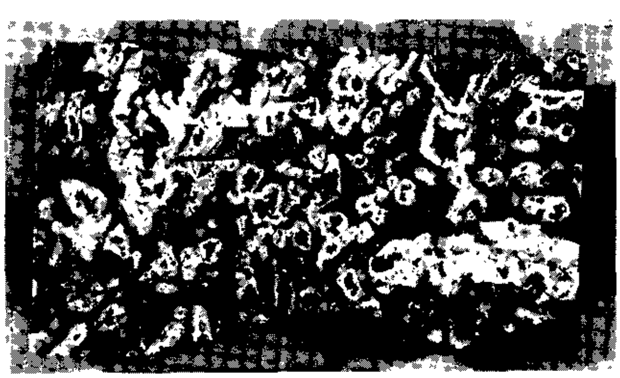

Fig. 11. Slave Point core from the Clarke lake field showing porous dolomites.

These observations from Clarke Lake cores indicate that most of the dolomitization occurred rather early in the diagenetic history (before calcite cementation could completely infill all the pore spaces in the reefal facies). The dolomitization also appears to be closely related to the stromatoporoid-rich reefal facies, where primary and chalky porosity development provided the passageway for the dolomitizing fluids. This close relationship between the reef-edge facies and the occurrence of dolomite is also evident on the geological map (Fig. 4) of Slave Point dolomites and is implied on the cross sections (Figs. 2, 5).

In selecting an appropriate geological model to explain the localized Slave Point dolomitization, the penecontemporaneous dolomitization models found in sabkha-type environments can be discarded, as there is no evidence of the anhydrites, gypsums or supratidal carbonate deposits commonly associated with this mode of dolomitization. The reflux model suggests that dolomitization occurs when heavy brines with high Mg/Ca ratios pass through porous carbonates beneath sabkha or saline basins (Deffeyes *et al.*, 1965). This method of dolomitization, however, cannot be applied here, as the Slave Point dolomites are overlain by marine shales.

Late-stage dolomitization related to faulting can also be rejected as a primary mechanism for Slave Point dolomitization, because evidence suggests that i) most of the dolomitization occurred before complete calcite cementation, and ii) the dolomites appear to be facies-related rather than structurally related.

The model that best fits the early, facies-related Slave Point dolomitization is the Dorag dolomitization model (Badiozamani, 1973). It suggests that dolomitizing solutions are created by mixing fresh, phreatic water with salt water. This condition can exist whenever a porous carbonate rock is partially exposed above sea level. Under these subaerial conditions, rain water can percolate through the porous carbonate and mix with the marine waters. Fluctuations in sea level allow for the continual mixing of both the fresh and Mg-rich salt waters. These fluctuations also supply the pumping mechanism that forces the fluids through the porous host rock. As fluctuations in sea level occur continually, the lengthy time required for dolomitization is also met.

Preferential dolomitization of the stromatoporoid-rich reefal facies fits the model's requirement for a porous carbonate host rock close to marine waters. The requirement for early dolomitization before complete calcite cementation can be met as well, since the Dorag dolomitization model could start shortly after deposition. For this model to work, however, a source of fresh water must be present.

The schematic cross section (Fig. 12) shows how the Dorag dolomitization model can be applied to the Petitot bank edge. Exposure of the main reef complex above sea level allows fresh water to percolate through the porous reefal facies. Where these waters mix with adjacent sea water, dolomitization can occur. On the other hand, the tight back-reef facies would not become dolomitized because fluids could not pass through this tight formation.

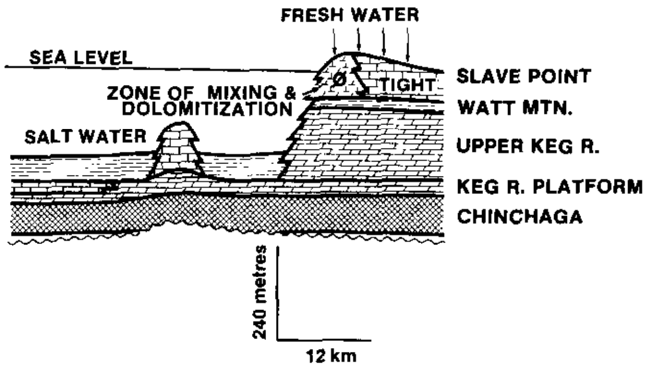

Fig. 12. Schematic cross section showing how the Dorag dolomitization model can be applied to the Petitot Bank edge.

The presence of green, waxy Watt Mountain shales (Maiklem, 1971) supports the concept of the main barrier reef being above sea level. These shales are thought to have been deposited above sea level as residues from meteoric solutioning. The lack of good Watt Mountain shales in the pinnacles suggests they were below sea level at this time, which may explain why the upper portions of most of the pinnacles and atolls are not dolomitized.

This model can also be applied to the dolomitization that appears to be located along the edge of the Keg River embayments. The schematic cross section (Fig. 13) illustrates this concept. This model suggests that the Slave Point Formation would be exposed to fresh water influx only when it was underlain by the Keg River reefal development, as differential compaction within the shale embayment area would keep the Slave Point Formation below sea level. The backreef facies of the Slave Point Formation would also remain as limestone, because they are normally tight and not in close contact with the dolomitizing marine waters of the embayment area. According to this model, only porous carbonate zones in close communication with both fresh and marine waters would be dolomitized. The result could be a very narrow dolomite zone that would be restricted to the reefal edge. This zone may not always occur directly under the structural highs and isochron thins, but would preferentially be located along the reef front / basin edge where fresh and magnesium-rich marine water mixing would occur.

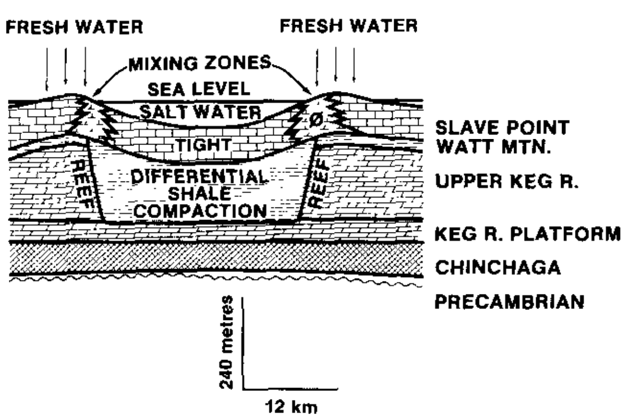

Fig. 13. Schematic cross section showing how the Dorag dolomitization model can be applied to the edges of the Keg River embayment.

The Dorag model meets the basic requirements for dolomitization and the geological constraints peculiar to this geologic play. The model indicates that dolomitized zones should occur in reefal facies that were subjected to fresh-water infiltration adjacent to open-marine conditions. The edge of the main barrier reef and the edge of the Keg River embayment were areas that could have met these requirements.

Exploration Applications of Dolomitization Model

To show how this dolomitization model can be used to assist exploration for Slave Point dolomites, reference is made to the Keg River embayment example. As seen on the top of Devonian to Slave Point isochron (Fig. 14) and the Slave Point Structure map (Fig. 15), two wells were located on structural highs and isochron thins but only one successfully encountered dolomitized reservoir rock within the Slave Point Formation. In the Dorag model, the optimum position for dolomitization should be in a reefal facies close to open-marine waters. Thus, the best position for finding dolomitized reservoirs should be at the edge of the carbonate buildup close to the embayment (*i.e.*, slightly basinward of the isochron thin). As is shown on Figures 14 and 15 and on the seismic line (Fig. 16), a well was drilled on this position. The well encountered dolomites within the Slave Point Formation and tested substantial quantities of gas.

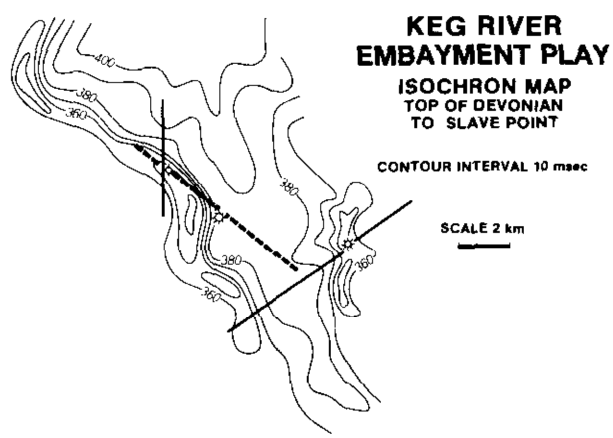

Fig. 14. Top of Devonian to Slave Point isochron map (Fig. 7) showing new seismic line and a new well location.

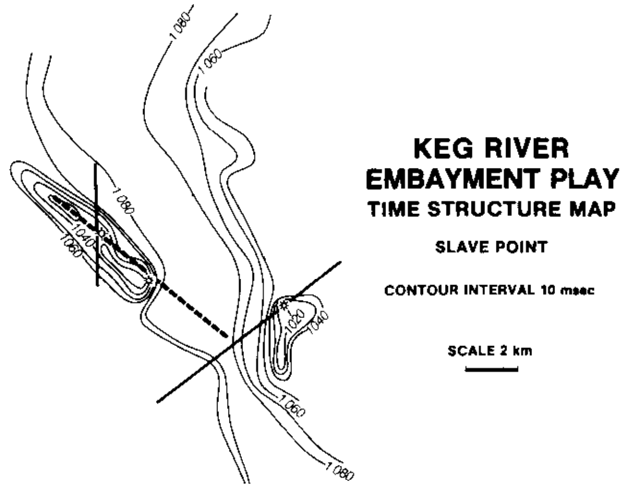

Fig. 15. Slave Point structure map (as Fig. 8) showing new seismic line and new well location.

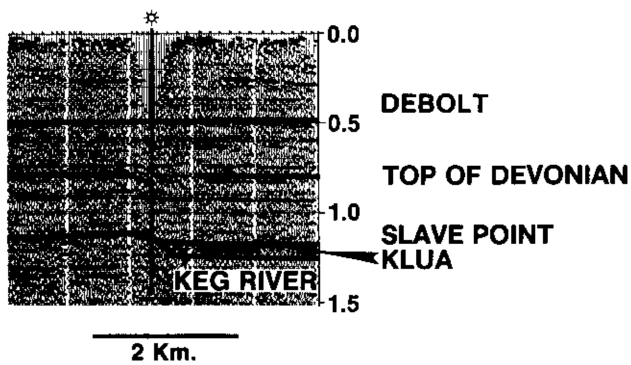

Fig. 16. The seismic line shown in Figures 14 and 15, and the new well location.

Using a geological model to explain why the Slave Point is locally dolomitized does not ensure that similar locations will always prove to be dolomitized. Applying it, however, might improve the chances of this happening and thus should be considered when locating a wildcat well on a Slave Point reef-edge play in northeastern British Columbia. According to the model, the optimum position for encountering dolomitized Slave Point reservoirs is slightly basinward of the isochron-thin and structural-high locations.

CONCLUSIONS

The Slave Point carbonate play in northeastern British Columbia has been successfully explored by geophysical techniques. Geophysicists have used reflection seismic methods together with isochron and structure maps to locate both the edge of the mid-Devonian reefs and isolated pinnacles within the basin areas. These areas have tended to be excellent locales for discovering gas reserves. However, the remaining undiscovered reserves are proving more difficult to find. Most of the undiscovered reserves may possibly occur along narrow zones in dolomitized Slave Point reservoirs associated with Keg River embayment areas.

As with many other complex play types, combining geological concepts with geophysical exploration techniques can improve the explorationist's success ratio. In this example a geological model (the Dorag dolomitization model) gives a possible explanation as to why the Slave Point dolomites are located where they are. Knowing this, the explorationist is better able to predict where else they might be. Although there still remains a high risk of encountering dolomitized Slave Point reservoirs, the optimum position is predicted to occur along the edge of the carbonate reef slightly basinward of the isochron thin. The standard geophysical techniques used for locating the reef edge are still valid, but the actual well locations should be shifted slightly basinward when exploring for these narrow zones of dolomitized Slave Point gas accumulations. It is hoped the risks involved in exploring for these dolomite reservoirs will be further reduced if it can be demonstrated that inverse seismic modelling techniques can detect these isolated zones directly on seismic data.

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