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The Role of Carbonate Diagenesis in Exploration and Production from Devonian Pinnacle Reefs, Alberta, Canada

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Abstract: Carbonate diagenesis plays an important role in the exploration for, and hydrocarbon recovery from, pinnacle reefs of the Upper Devonian Nisku Formation of Alberta.

In the West Pembina area, the Nisku Formation occurs as a series of carbonate ramps prograding into the Winterburn shale basin. Discovered on a regional seismic line in 1977 by Chevron Standard Ltd., the play has matured into a pinnacle reef fairway 65 km by 180 km containing over 50 productive reefs with total reserves of approximately 325 MMstb oil and 500 BCF gas. Texaco's discovery, alone or jointly of 27 of these reef pools for a 30% net share in reserves has made understanding reservoir quality of importance to maximizing reserves on the reef trend.

Carbonate diagenesis exerts a major influence on the development of porosity and permeability in the reefs, and accounts for areal variability among different reefs in the trend. On an exploration basis, knowledge of diagenesis highlights areas for preferred drilling. For development, diagenesis and its effects upon reef petrophysics affects the selection of pools for water versus miscible flood enhanced recovery schemes.

The Nisku pinnacle reefs are built by rugose corals, stromatoporoids and algae with interbedded and matrix lime mudstones and wackestones. Three diagenetic processes affecting porosity and permeability within the reefs are early submarine cementation, dolomitization, and pressure solution.

The early submarine cements include spectacular multiple fibrous cements together with stromatolitic crusts and micritic cements. While these cements occluded some primary porosity, they provided a net beneficial effect by stabilizing the reef framework and muddy matrix and preserving intergranular and large interfossil pores.

Dolomite is the major determinant of reservoir quality. Fully dolomitized reefs average 10-20% porosity and up to 5 darcies permeability whereas partly dolomitized reefs have porosities of 2-5% and approximately 500 millidarcies permeability. Two dolomite types are present and both are believed to result from burial processes. Microdolomite rhombs 10 to 200 μm in size selectively replace micrite matrix in all reefs and are considered a shallow burial product which increases matrix permeability somewhat. Coarse sucrosic dolomite, with crystals from 50 to 400 μm in size, is not fabric selective and pervasively obliterates primary rock textures. This dolomite is a deep burial product which greatly increases intercrystalline porosity and permeability of the reefs, and accounts for reservoir variations along the reef trend.

Pressure solution has occurred throughout the burial history of the reefs. It is most noticeable as high amplitude stylolites concentrated along facies contacts and testifies to significant removal of potential reservoir section by solution. Additional leaching of skeletal fragments has created secondary porosity.

Understanding the interplay of these diagenetic processes upon the evolution of reservoir quality may have application to reef plays of other areas or geologic age.

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INTRODUCTION

The West Pembina Nisku reef trend of southern Alberta is a major oil and gas producing area within the Western Canadian Sedimentary Basin. The hydrocarbons are produced from numerous isolated Upper Devonian patch or pinnacle reefs. The play was opened in 1977 by Chevron Standard Ltd., who identified several geophysical anomalies on a 400 km regional seismic line shot across the province and drilled the discovery well Nairb Pembina A11-22-49-11 W5M (Exploration Staff, Chevron, 1979). From 1977 to date, the play has matured into a pinnacle reef fairway measuring 65 km by 180 km and containing over 50 productive reefs concentrated in an area measuring 2000 km^2. These Nisku pinnacle reefs are situated to the southwest of Edmonton, in the West Pembina area of Alberta extending from townships 46-52 and range 8-14 W5M (Figs. 1 and 2). The reefs range from 120 to 380 ha (300-940 ac.) in area with an average of one to three producing wells per reef.

Full exploitation of the play relies on the application of geophysics and a sedimentologic model to the discovery of the reefs, and an understanding of diagenesis as it affects primary productivity and enhanced oil recovery schemes. The paper examines the role of carbonate diagenesis in the development of the Nisku pinnacle reef reservoirs.

METHODS

This study is based upon the detailed analysis of 1720 m (5050 ft.) of core from 32 wells within the central area of the West Pembina play. Over 300 thin sections stained with Alizarin Red S and potassium ferricyanide have been examined to determine the carbonate paragene-

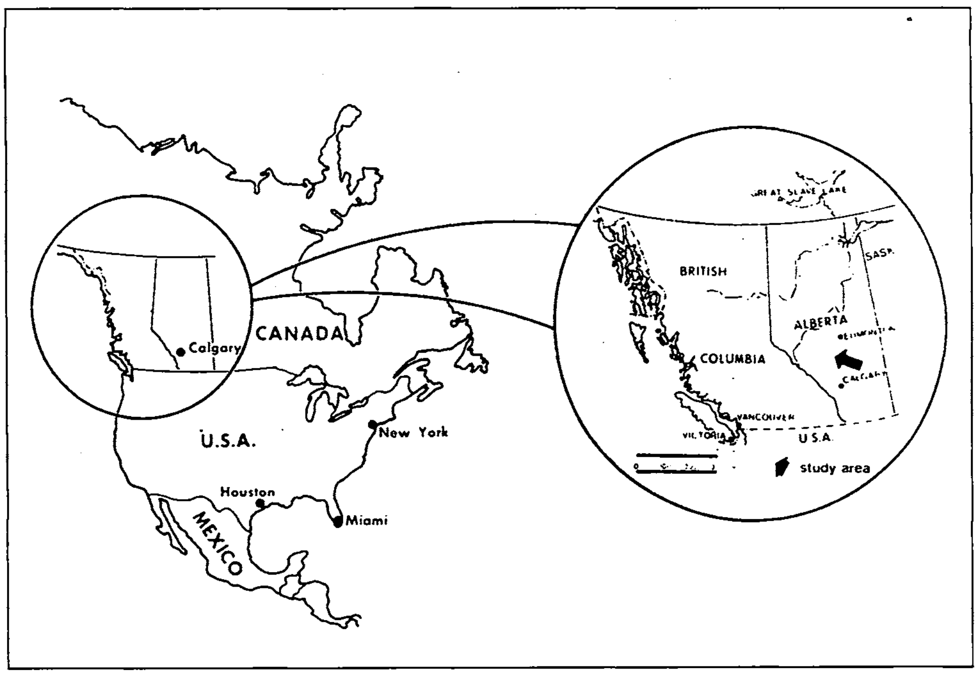


Figure 1: Location Map

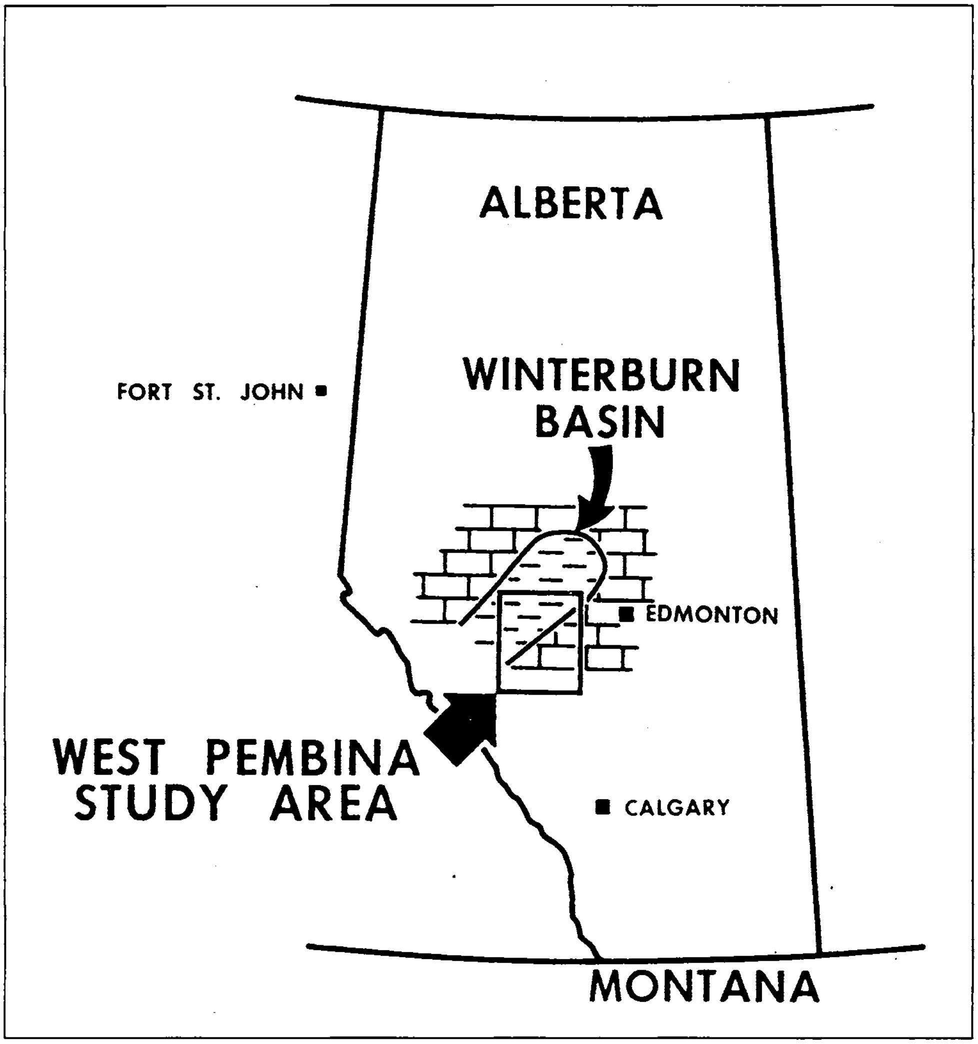


Figure 2: Location Map of the West Pembina area

sis. Additionally, for stratigraphic correlation over 250 petrophysical logs have been correlated with the core study.

REGIONAL GEOLOGY

The reefs belong to the Nisku Formation of the Winterburn Group and are Upper Devonian (Frasnian) in age. The carbonates of the Winterburn Group are overlain by the limestones and dolomites of the Wabamun Group (Famennian) (Fig. 3). The formal stratigraphy of the Nisku Formation in this area is given in a paper by the Exploration Staff, Chevron (1979) and is illustrated here in Figures 4 and 5.

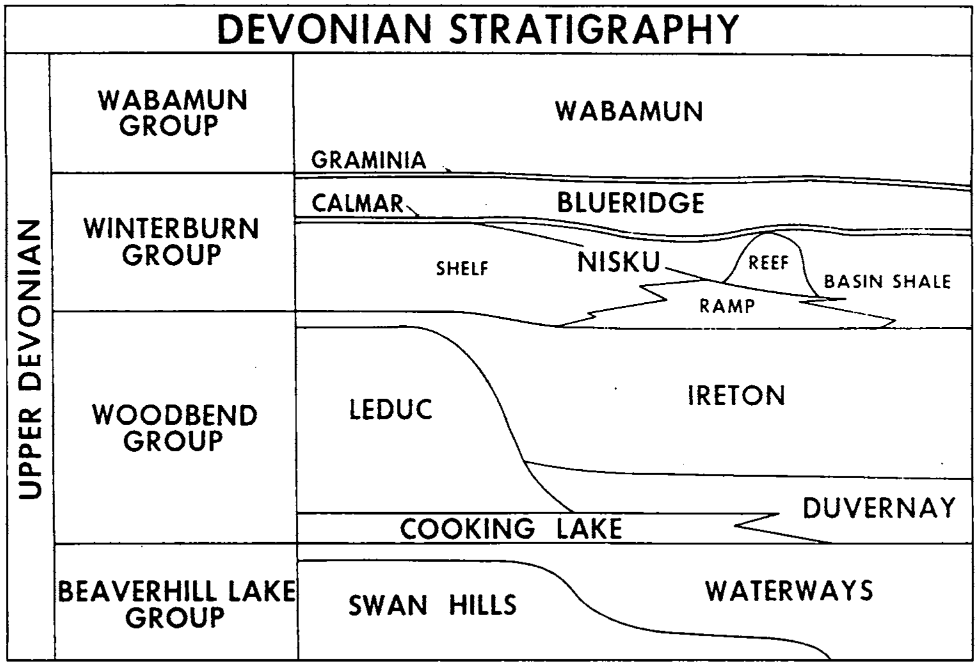


Figure 3: Devonian Stratigraphy

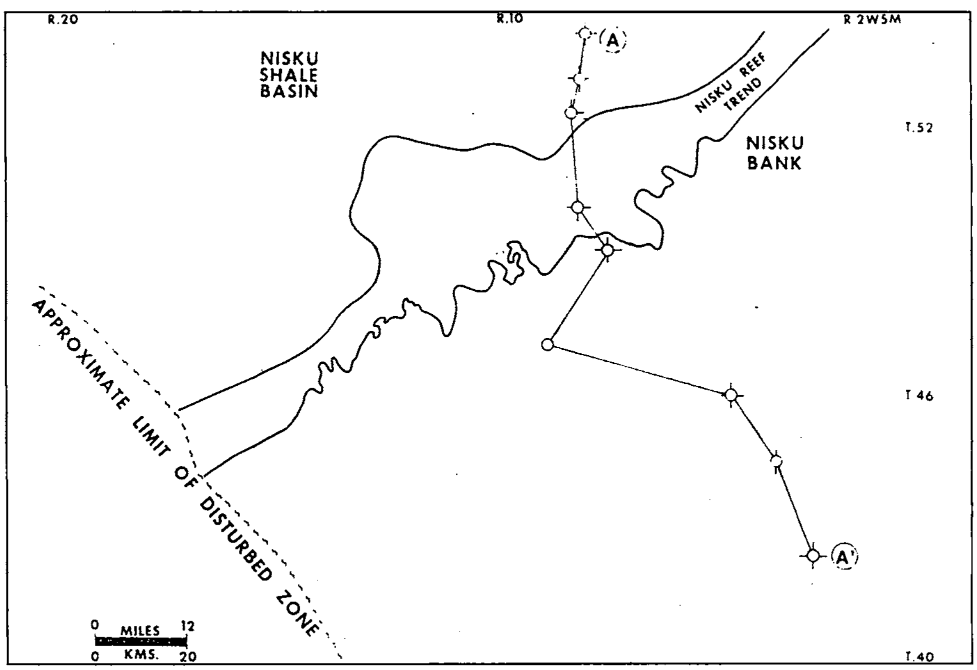


Figure 4: Index Map

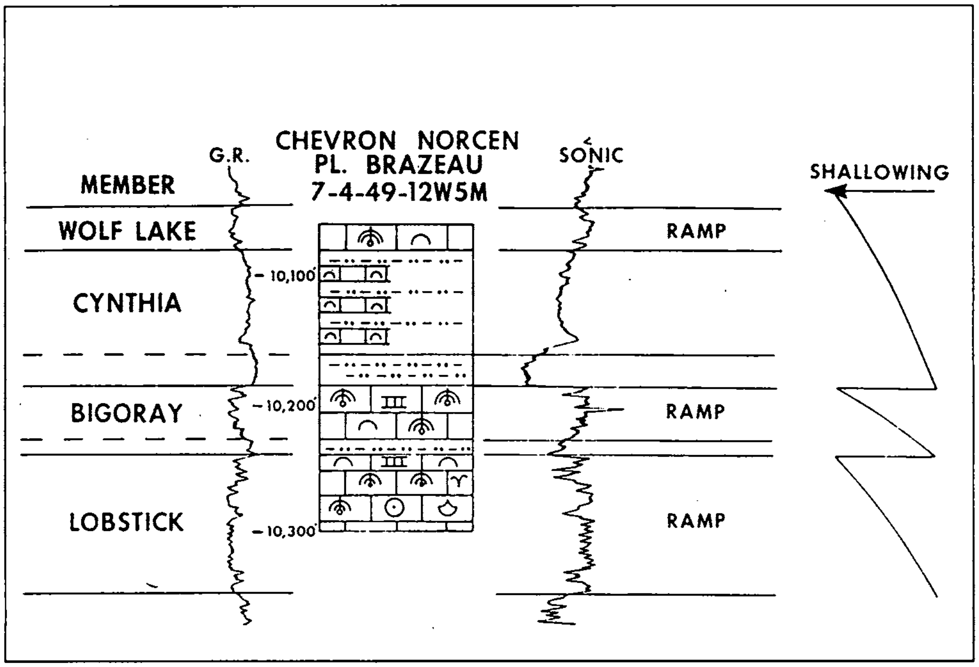


Figure 5: Ramp Sequences within the Nisku Formation

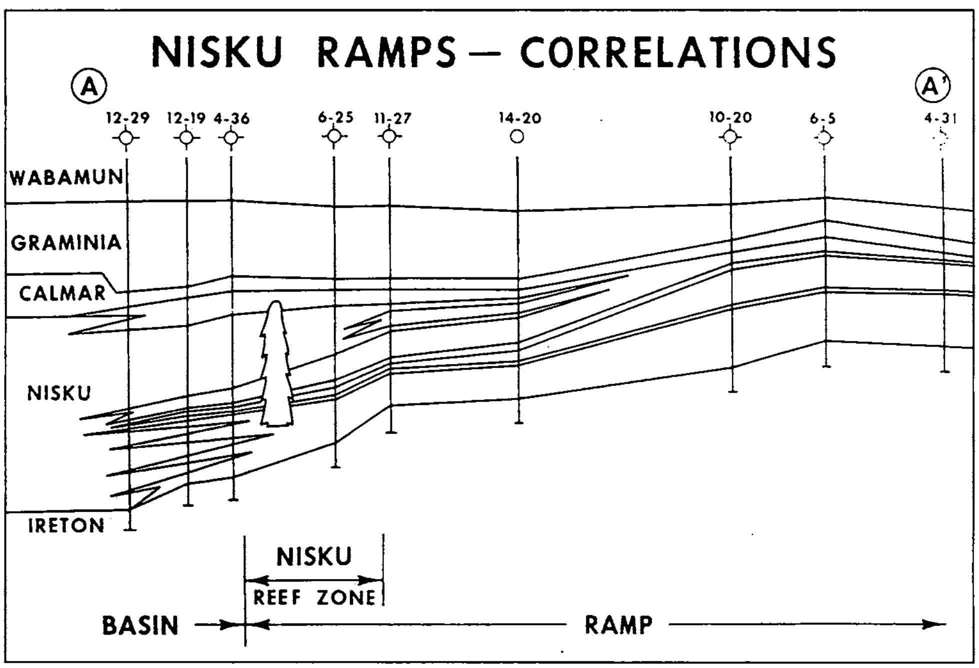


Figure 6: Nisku Ramps — Correlations

The Nisku Formation on a broad scale developed as an approximately 102 m thick carbonate wedge (Figure 6), consisting of open shelf and peritidal carbonates which prograded over the basinal Ireton shales in an overall regressive phase of sedimentation.

This overall regression is differentiated into three shallowing-up sequences in which are developed carbonate ramps. The first two ramp sequences correspond to the Lobstick and Bigoray Members. The Cynthia Member is a deep carbonate ramp representing incipient drowning of the earlier carbonate ramps. A well developed tidal flat sequence (Wolf Lake Member), the last carbonate ramp, occurs at the top of the Nisku Formation (Figure 5). The development of these major carbonate ramps is controlled by the rate of carbonate production, relative rise in sea level, and basin subsidence. The Nisku Formation represents a cyclic and reciprocal pattern of sedimentation with individual ramps wedging out into the Winterburn Basin (Exploration Staff, Chevron 1979; Anderson, 1982). The Nisku reefs are developed within these carbonate ramps which occur in a fairway rimming the Winterburn basin (Figure 2).

DEPOSITIONAL SEQUENCES WITHIN THE NISKU

CARBONATE RAMPS

Lobstick Member

The Lobstick Member, the first carbonate ramp, has well defined gamma ray/sonic log characteristics and is easily correlated throughout the study area (Figure 5). This unit in the central West Pembina varies in thickness from 20 to 60 m. The Lobstick Member consists of bedded nodular bioclastic limestones, siltstones and calcareous siltstones. In part, this unit may be dolomitized. The carbonates contain noticeable amounts of oncolites which increase in abundance up through the unit. Besides oncolites, the biota consists of brachiopods, bivalves, bryozoans, gastropods, stromatoporoids, ostracods and crinoids. Hardground surfaces developed during low rates of sediment accumulation and/or periods of non-deposition. Originally the sediments within the Lobstick Member were mud-supported and grain-supported bioclastic silts, sands and gravels with siliciclastic silts and lime mud areas. These rocks are interpreted as a shallow carbonate ramp; the biota indicates normal open marine shelf conditions. Overall the Lobstick Member represents a shallow-up sequence.

Bigoray Member

The Bigoray Member, consists of carbonates similar to the underlying Lobstick Member. This unit varies in thickness from 10 to 30 m and consists of argillaceous bioturbated limestones which possess a well developed biota of corals, stromatoporoids, brachiopods, gastropods and crinoids. Once again oncolites are present and show an increase in abundance towards the top of the unit. This unit is easily recognized by its well defined gamma ray/sonic log curve. The Bigoray Member is separated from the underlying Lobstick Member by a basal siltstone unit (Figure 5).

The Bigoray basal unit represents periods when the production of carbonate material was hindered by the influx of terrigenous material into the depositional system probably during a stable sea level or slight lowering of the sea level. The upper unit represents renewed carbonate deposition with the development of a subtidal shallow carbonate ramp.

Cynthia Member

The Cynthia Member varies in thickness from 15 to 35 m in the study area and can be divided into two main units (Figure 5). The lower unit (2-10 m thick) consists of black bioturbated calcareous mudstones which are interpreted to represent relatively deep water anoxic conditions (Anderson, 1982).

The upper unit (on average 25 to 35 m thick) consists of argillaceous bioclastic limestones and calcareous shales with a sparse but diverse biota of corals, brachiopods, gastropods and stromatoporoids. Commonly thin silty bioclastic limestones occur intercalated with grey calcareous siltstones and in places show fining-up sequences. The bioclastic-rich layers commonly show scoured surfaces and variable grain-supported fabrics.

These carbonate layers are interpreted as episodic storm-generated units formed below normal wave base. Based upon the lack of shallow water structures, the presence of a diverse but sparse normal marine fauna, well preserved in-situ fossils, burrows and interbedded fine carbonates and terrigenous sediment, a deeper ramp to basin margin setting is invoked for the Cynthia Member (Wilson, 1975 p. 355-356; Read, 1980, p. 1597).

Water depths in the Cynthia Member may have been greater than 50 m. This value is similar to the 40 to 90 m water depths in the Persian Gulf where argillaceous carbonate muds are developed around Holocene buildups. The transition from the lower calcareous mudstone to the upper deep-ramp argillaceous limestones reflects a change from deeper anoxic basinal waters to shallower oxic waters of the deep-ramp basin margin.

Wolf Lake Member

The Wolf Lake Member (Figure 5) consists of tidal flat sediments which are comparable to modern carbonate flat deposits (Figure 7) on Andros Island, Bahamas (Hardie, 1977). Nine basic recurring lithologies (Figure 8) can be recognized within this tidal flat sequence. The Wolf Lake Member is interpreted as a tidal inner carbonate ramp.

NISKU REEFS

The Nisku reefs grew on the underlying stable Lobstick and Bigoray carbonate ramps (Figure 6). These reefs differ greatly in their constituent facies compared with the larger and better known Devonian atoll-type reefs of the Swan Hills and Leduc Formations. In these latter reefs, geological studies have shown that the 'atoll' reefs are comprised of different lateral facies, including foreslope, reef margin, reef crest, and several back reef or lagoon facies. In comparison, the Nisku reefs are too small to have developed significant internal differentiation. The facies pattern seen within the Nisku reefs is mainly a vertical zonation in which three zones can be easily recognized: Lower and Upper Zeta Lake Member (reef carbonates), and the capping Wolf Lake Member (previously discussed).

Lower Zeta Lake Member

The lower reef zone (Figure 9) of the Nisku reefs consists predominantly of dendroid and fasciculate rugose corals. The rugose coral genera are *Smithiphyllum, Thamnophyllum,* and

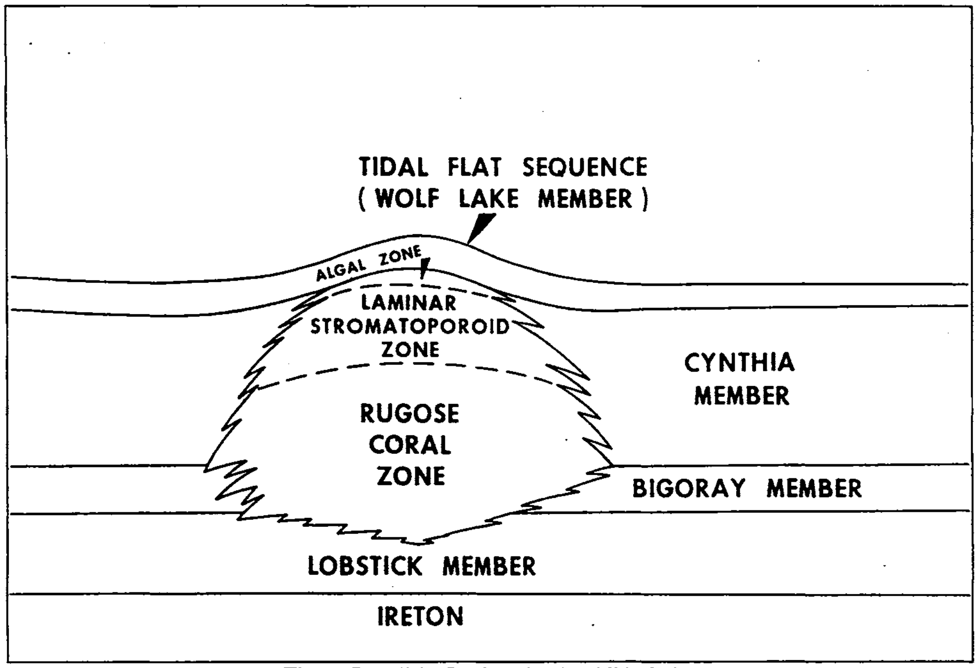


Figure 7: Nisku Reefs and related lithofacies

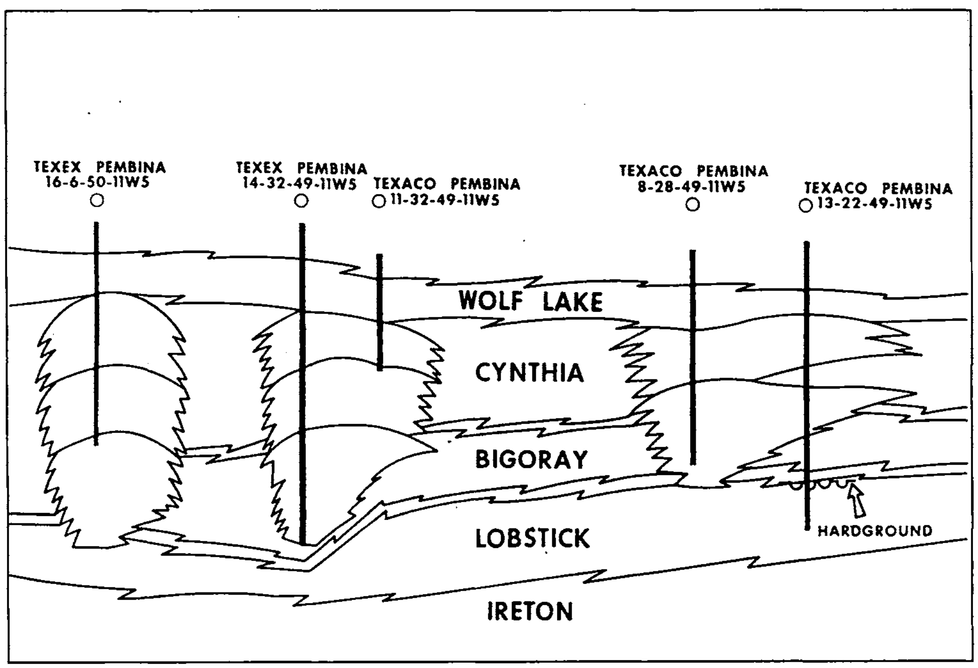


Figure 8: Nisku Reefs

Disphyllum; in addition there are minor amounts of the tabulate corals *Syringopora* and *Favosites*. Subordinate stromatoporoids, mainly possessing a laminar skeletal morphology, add strength to the existing reef frame. Three main pore types are biomoldic, intraskeletal, shelter, fracture, and vug. This lithofacies is very homogeneous.

Upper Zeta Lake Member

Towards the top of the reef, thin to thick laminar anastomosing stromatoporoids are the dominant framebuilders (Figure 9). *Amphipora* is absent or rare. Fasciculate and dendroid rugose corals are the minor framebuilders but may be present in quite large numbers. The problematic alga *Renalcis* occurs scattered throughout the reef sediment. In places calcareous algae (Figure 9) may strengthen the reef frame through formation of dense growths of stubbily-digitate to bulbous masses of *Solenopora,* which is related to the crustose corraline red algae which dominate Recent algal reefs. The reef frame may also be encrusted by thick layers (<10 cm's) of *Rothpletzella* and *Wetheredella.* This lithofacies again, like the Lower Zeta Lake Member, is homogeneous. Main pore types are moldic, intraskeletal, vug and fracture.

DIAGENESIS OF NISKU REEFS

The diagenesis of the Nisku reefs is complex, with individual reefs being subjected to varying degrees of alternation during their geologic history (Figure 10). The pinnacle reefs contain interskeletal, intraskeletal, and interparticle marine cements, marine internal sedi-

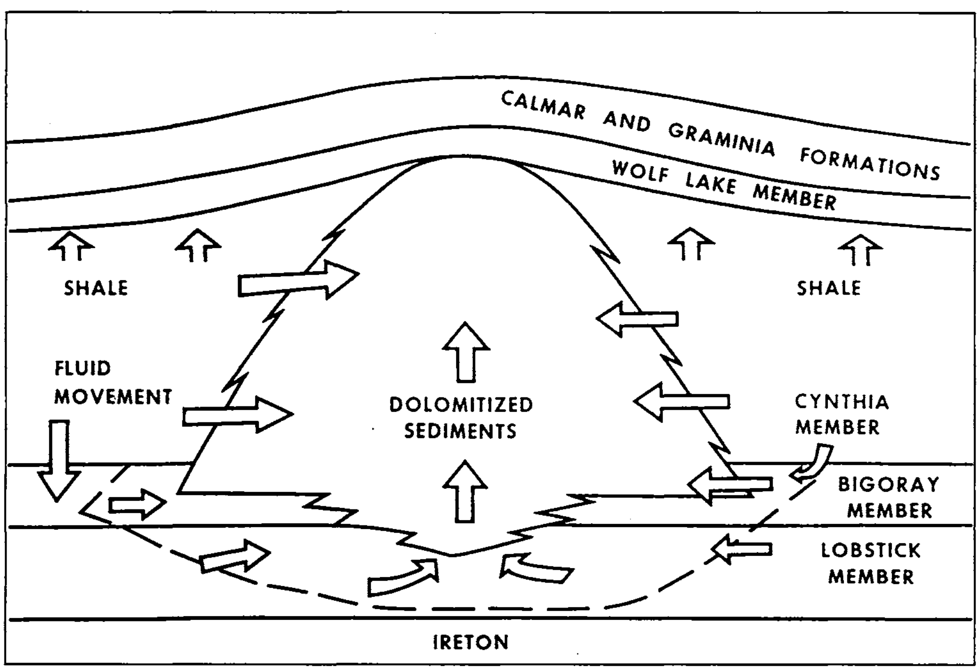


Figure 9: Dolomitization — Burial Model

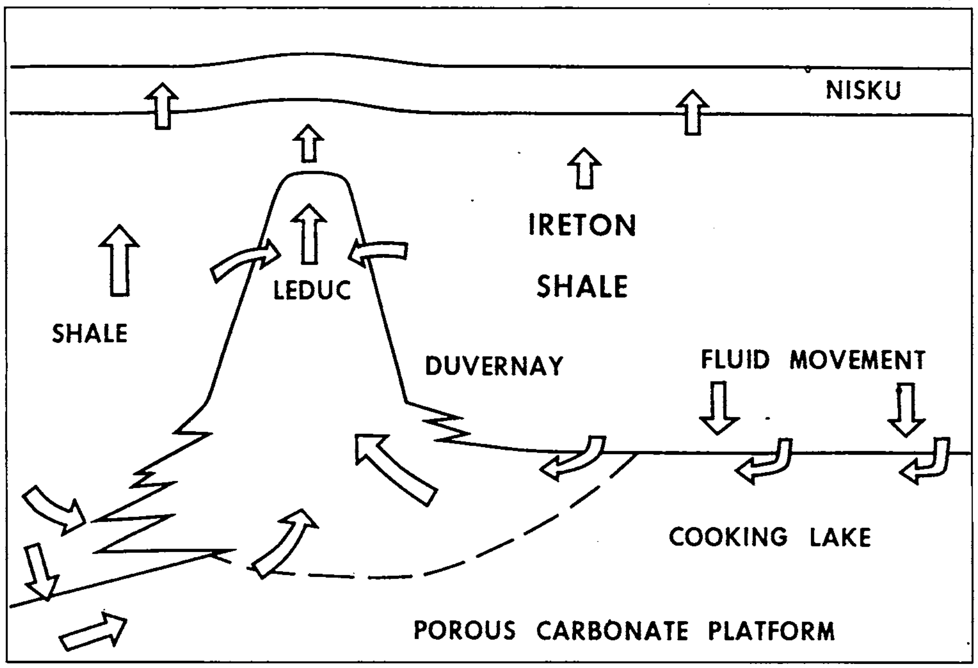


Figure 10: Deep Burial Dolomitization

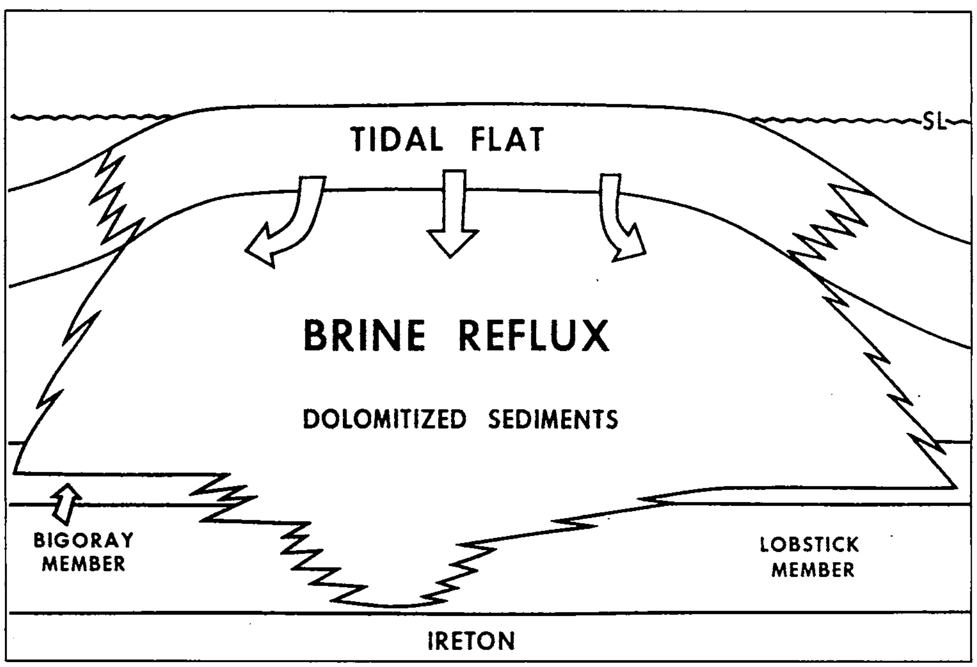


Figure 11: Dolomitization — Reflux Model

ments, sparry calcite mosaics, meteoric calcite cements, dolomite and anhydrite. The cements, associated diagenetic fabrics and geologic history of the Nisku reefs indicate that they were subjected to marine, meteoric and burial diagenetic regimes (Figure 10).

MARINE CEMENTS

Fibrous Calcites

A distinctive feature of the Nisku is the spectacular development of thick layers (<3 cm) of multigenerations of fibrous calcite cements. The fibrous cement is ubiquitous being well preserved in limestone reefs and in relict form in dolomitized reefs. The cement is white to grey, has undulose extinction, irregular crystal boundaries and numerous inclusions. Some of the cement is radiaxial calcite (Bathurst, 1959). The cements are considered to be marine in origin because they are the first cement generation, occur in primary shelter voids, and contain dusty internal sediment. Also their fabrics are very similar to modern marine cement types.

Rim Cements

This cement is a syntaxial cement, containing inclusions, on crinoid grains within the internal reef sediments. The local occurrence of marine lime mud resting with a sharp contact on the cement suggests a marine origin. Similar cements have been described by Grover and Read (1983) who postulate that they had a percursor high-Mg calcite mineralogy.

Micritic Cements

Hardgrounds locally truncate bioclastic mudstones and wackestones within the reefs. This suggests that the lime mud matrix of these sediments has been cemented by early marine micritic cements (Shinn, 1969; Taft *et al.,* 1968; Goldring and Kazmierczak, 1974). Additionally the presence of reworked reef clasts with a lime mud matrix implies early micritic marine cements.

METEORIC

Thin Dog-tooth Spar

A drusy dog-tooth spar occurs as thin crusts within intraskeletal pores. Commonly this non-ferroan cement grows from the septa and dissepiments of the corals into intraskeletal space. Similar low-Mg calcite drusy calcite cements within emergent Pleistocene reefs have been precipitated by meteoric fresh water (Gvirtzman and Friedman, 1977).

Cross-cutting Spar

Calcite mosaics associated with the disphyllid corals of the Nisku reefs often consist of coarse crystals (up to 2mm in size) which extend out from the coral skeletons into void filling cement. Similar fabrics have been recorded in the Pleistocene reefs of Bermuda by Pingitore (1976) who termed this fabric 'cross-cutting' mosaic. This calcite mosaic has been interpreted to be indicative of phreatic cementation.

SHALLOW TO INTERMEDIATE BURIAL CEMENTS

Zoned non-ferroan and ferroan clear sparry calcite cements are present, postdating fibrous calcites, within interskeletal, intraskeletal, interparticle, shelter, and fracture pores. These calcites are interpreted to have formed during a shallow to intermediate burial stage that can be related to a vadose phreatic origin, deep phreatic (mixed fresh and marine water) and shallow subsurface (connate water) zones (Walls *et al.*, 1979). Ferroan calcites can either be formed in the reducing environment of the phreatic zone (Neal, 1969; Bathurst, 1976) or the deep subsurface (Oldershaw and Scoffin, 1976; Walls *et al.*, 1979).

DOLOMITIZATION

Three distinct dolomite phases can be recognized within the Nisku reefs: matrix selective dolomites, pervasive dolomites, and saddle dolomites, reflecting dolomitization over a long period of time.

Matrix-selective Dolomites

A major proportion of the dolomites consist of grey matrix-selective, finely crystalline (20 to 150 μ) dolomites. The dolomites are typically subhedral to euhedral rhombs with hypidiotopic to idiotopic textures. Crystals of this dolomite type may also contain cloudy centres. This matrix dolomite shows a dominant fabric selectivity to the micritic matrix within the reefs. Matrix dolomites are often concentrated along stylolite seams and individual crystals may be corroded and dissolved at stylolite sutures.

The origin of this type of dolomite is problematic, mainly due to the lack of a present day analogue and also due to disagreements over the mechanisms of dolomitization. However a similar dolomite fabric has been recorded in Pliocene-Pleistocene limestones on Carribean islands (Land 1973, Supko, 1977, Sibley, 1982). Here dolomitization occurred before the fossils were replaced by low magnesium calcite. In the Caribbean examples the diagenetic features reflect dolomitizing pore solutions that are close to calcite equilibrium, and is consistent with a dolomite model where the fluids are less saline than normal seawater (ie. brackish). This system is encompassed by the mixing-water model of dolomitization popularized by Back and Hanshaw (1970), Land (1983) and Sibley (1980). But the fabrics would also be representative of dolomitization as a result of hypersaline brines if they were undersaturated with respect to high-Mg calcite (Sibley, 1982).

In the Nisku reefs the matrix dolomitization took place prior to stylolitization as indicated by suturing and concentration of dolomite rhombs along stylolites implying formation at shallow depths. The reefs are overlain by a tidal flat sequence suggesting a hypersaline reflux origin for this dolomite (Sears and Lucia, 1980). Progradation of the tidal flat carbonates (Wolf Lake Member) resulted in dolomitization of the reefs which were engulfed by these sediments (Figure 11).

Pervasive Sucrosic Dolomites

The second dolomite type, which is the most volumetrically abundant is characterized by coarsely crystalline (50 to 400 μ), brown sucrosic dolomites. The dolomites are typically anhedral to subhedral with xenotopic to hypidiotopic textures. This dolomite type is not

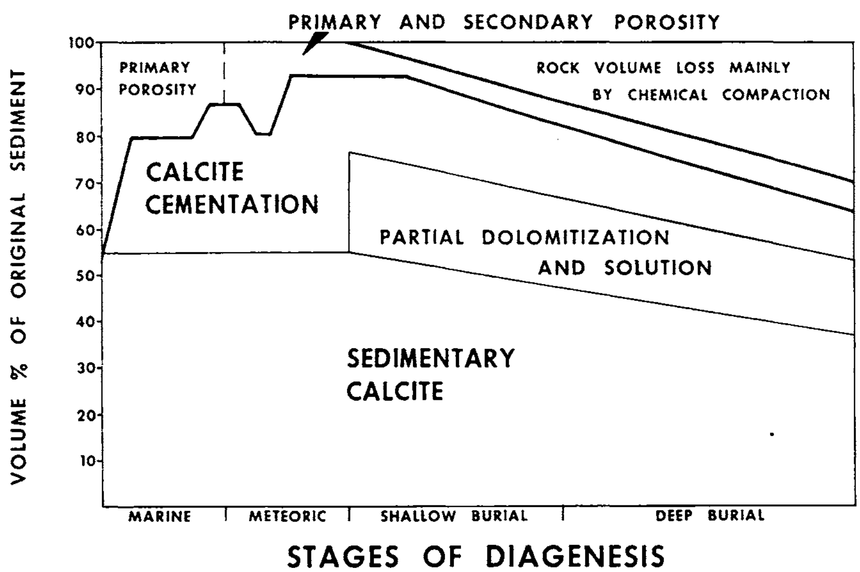


Figure 12: Partially Dolomitized Nisku Reef

fabric selective and pervasively obliterates primary rock textures. These coarse pervasive sucrosic dolomites occur throughout structurally downdip reefs and on the margins of updip reefs. The pervasive dolomites obliterate the stylolites which postdate the matrix dolomites, but pre-date a second latter stylolitization event. This dolomite is interpreted to represent a deep burial product (Anderson, 1983). Petrographic analysis suggests a continuous phase of dolomitization with the pervasive dolomites being the result of recrystallization of the matrix dolomites (Anderson, 1983) and continued growth of dolomite crystals on dolomite percursors with solution of calcite. Synchronous with dolomite cementation and recrystallization, there was extensive calcite dissolution with corresponding development of porosity and permeability.

The replacement nature of the dolomite, and the fact that in part it originated after an initial phase of stylolitization implies that this dolomite was not a near surface phenomenon but that the extensive dolomitization occurred during intermediate to deep burial. Geochemical calculations indicate that the migration of hydrocarbons into the Nisku reefs occurred during Upper Cretaceous time when the Nisku Formation was buried to a depth of 2100 m. Consequently, the main phase of dolomitization began during the Mississippian and continued until the sediments were buried to the oil window level in the Cretaceous (Figure 10). This is consistent with other Devonian reefs of Western Canada (Mattes and Mountjoy, 1980). The major source of the dolomitizing fluids came from the basin shales surrounding the Nisku reefs (Figure 12). The magnesium for dolomitization originated from the formation fluids derived from connate sources or from clay mineral transformations during compaction (Mattes and Mountjoy, 1980).

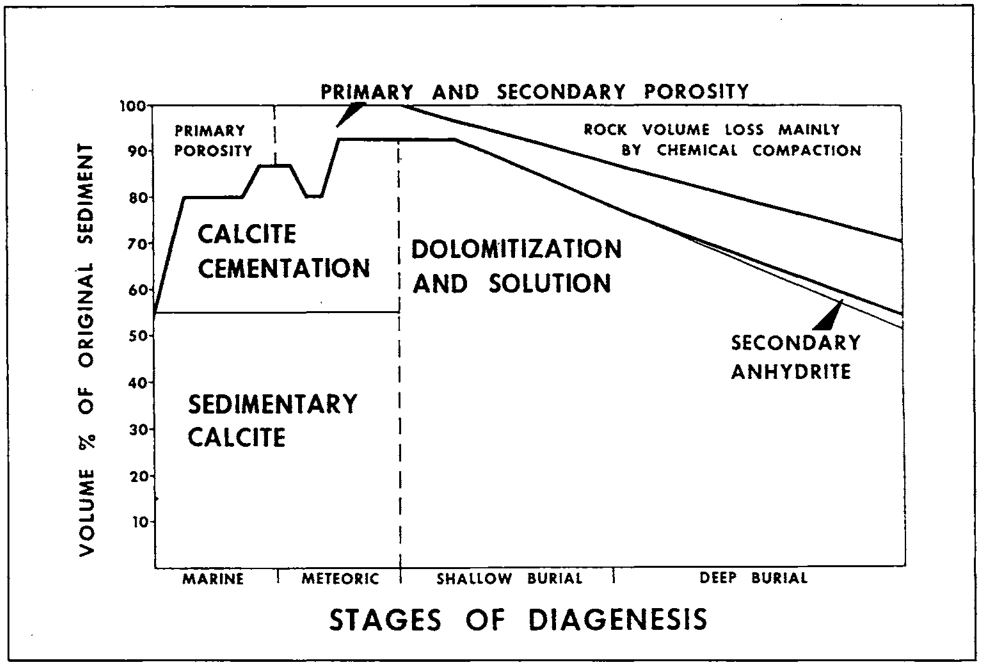


Figure 13: Fully Dolomitized Nisku Reef

Saddle Dolomite

Biomoldic porosity, vugs and fractures are occluded (totally or partially) by saddle dolomite which is a white to clear coarsely crystalline dolomite characterized by curved crystal faces and cleavage, and sweeping extinction. The saddle dolomite is present either as a cement within voids or as a replacement mineral. The geochemical parameters under which saddle dolomite is believed to precipitate are formation temperatures of 60 to 100°C, saline epigenetic waters under mild pH, and intermediate to high reducing conditions (Beales, 1971, Choquette, 1971).

ANHYDRITE

White anhydrite which is characterized by large bladed to lathlike crystals (several millimetres long) and/or acicular crystals (a few tens of microns long) forming a felted fabric, infills vugs, biomoldic porosity, and fractures. Geochemical data suggests that the anhydrite is a late stage event (Figure 18), postdating dolomitization (Machel, 1983) and occurring at great burial depths in the range of 2.5 to 5 km (Hutcheon *et al.*, 1982; Kirker and Nahnybida, 1980). Anhydrite precipitation results from mobilization of evaporites within the Paleozoic carbonate sequence of the Winterburn Shale Basin.

STYLOLITIZATION AND FRACTURES

Stylolites are abundant in both the limestone and dolomite reefs. Major stylolites occur at lithologic boundaries and the base of multiple-cemented zones. High amplitude stylolites, contain thick stylocumulates and testify to significant removal of potential reservoir section in limestone reefs by solution. Stylolites truncate the multiple fibrous calcite cements and probably supplied free carbonate for the precipitation, in part, of the zoned sparry calcite mosaics in shallow to intermediate burial regimes.

In the dolomite reefs, an early phase of stylolites postdates matrix dolomites (Figure 18), but are overgrown by the pervasive dolomites which in turn are truncated by a later phase of stylolitization (Figure 18). The timing of stylolite formation occurred throughout the burial history of the reef rather than a distinct diagenetic stage.

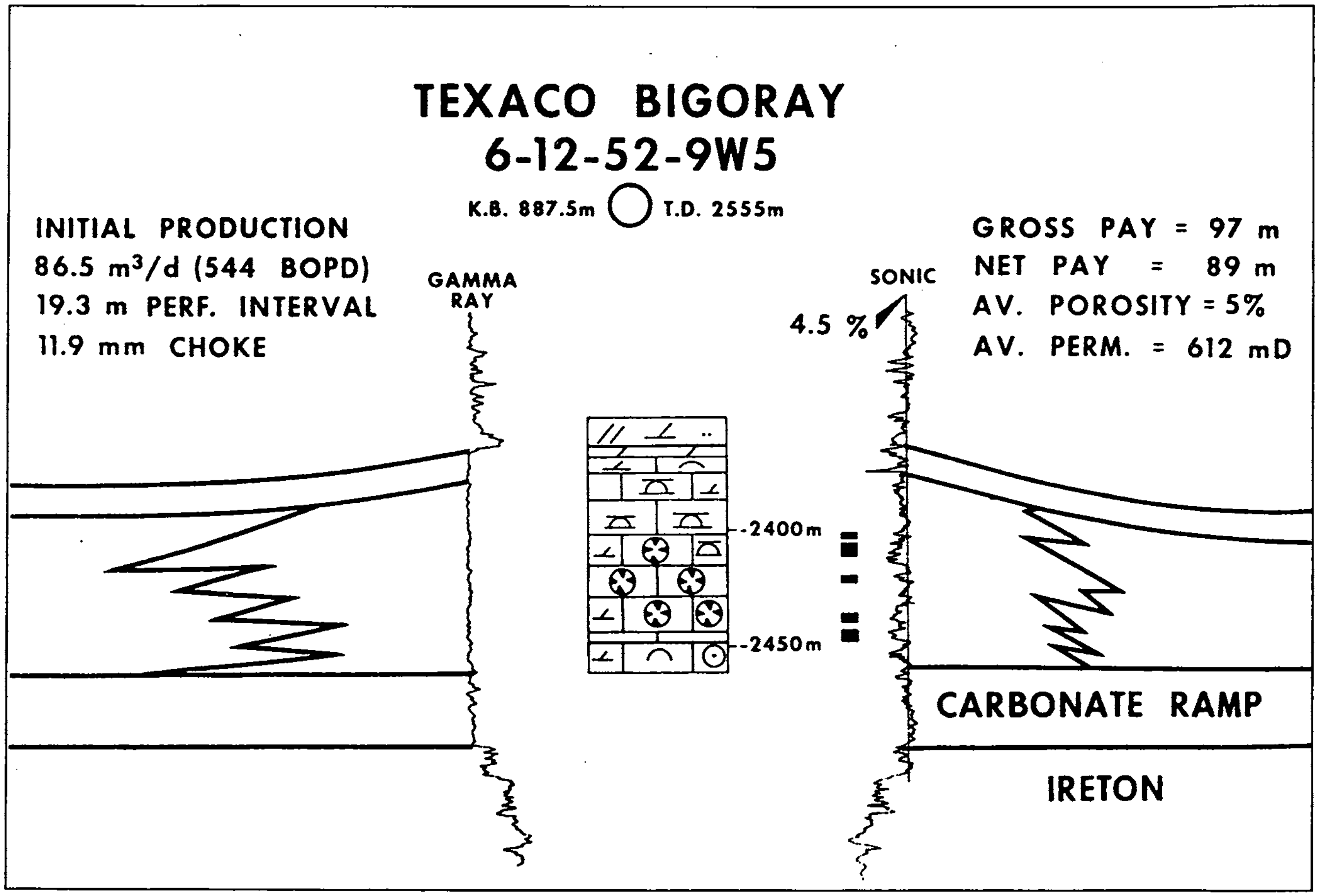
Fractures occur throughout the Nisku reefs and offset or are themselves offset by stylolites. They postdate the dolomitization, suggesting late deep burial tectonism (Figure 18).

DIAGENETIC HISTORY OF THE NISKU REEFS AND IMPLICATIONS TO RESERVOIR QUALITY

The paragenesis of the Nisku reefs is illustrated in Figure 17. This diagenetic history is discussed sequentially below.

Initially the Nisku reefs underwent fairly extensive early marine cementation. At the end of Nisku deposition the reefs were all at or near sea level, and consisted of well cemented buildups. In modern reefs, there is virtual elimination of porosity by submarine cementation within 1 metre of the reef-water interface (Ginsburg *et al.*, 1971, Ginsburg and Schroeder, 1973, Friedman *et al.*, 1974, Land and Goreau, 1970). The large amounts of fibrous calcite present within the Nisku reefs suggest that porosity in the reefs was significantly reduced due to this early cementation (Figure 14). Cement types indicative of the meteoric (subaerial) environment are exceedingly rare, implying that subaerial exposure of the reefs was brief and they did not undergo extensive karst development and leaching with concomitant porosity enhancement. Pore-filling blocky zoned calcites suggest that the reefs underwent shallow to deep burial. Consequently, the remaining porosity was further reduced by calcite cementation (Figure 14) within the shallow to deep burial diagenetic regime. The limestone reefs within the trend are examples of where this paragenetic sequence was halted. These have low porosities (2-5%) and permeabilities (<500 md), with initial production rates reflecting the lower productivity of the limestone wells (Figure 15).

Three distinct phases of dolomitization can be recognized: matrix selective dolomite, pervasive dolomite, and a pore filling white saddle dolomite. Dolomitization, within the Nisku reefs took place over a long period of burial starting at shallow depths and progressing through to deep burial. Isotope values for both pervasive and matrix dolomites indicate formation at elevated burial temperatures (Anderson, 1983). Dolomitization and porosity development is simultaneous and most of the dolomite, together with secondary porosity, formed during the late Paleozoic and early Cretaceous (Figure 17). Dolomitized reefs increase in number down structural dip with limestone reefs being concentrated up-dip to the southwest (Figure 16). Thus the later dolomite is controlled by fluids derived from the basin moving up-dip during the regional tilting of the strata to the southwest during the late Paleozoic and early Mesozoic (Anderson, 1983). Basinal derived fluids depleted in Mg^{2+}, moving up-dip, only partially dolomitized the reefs to the northeast.



Fiigure 14: Nisku Limestone Reef

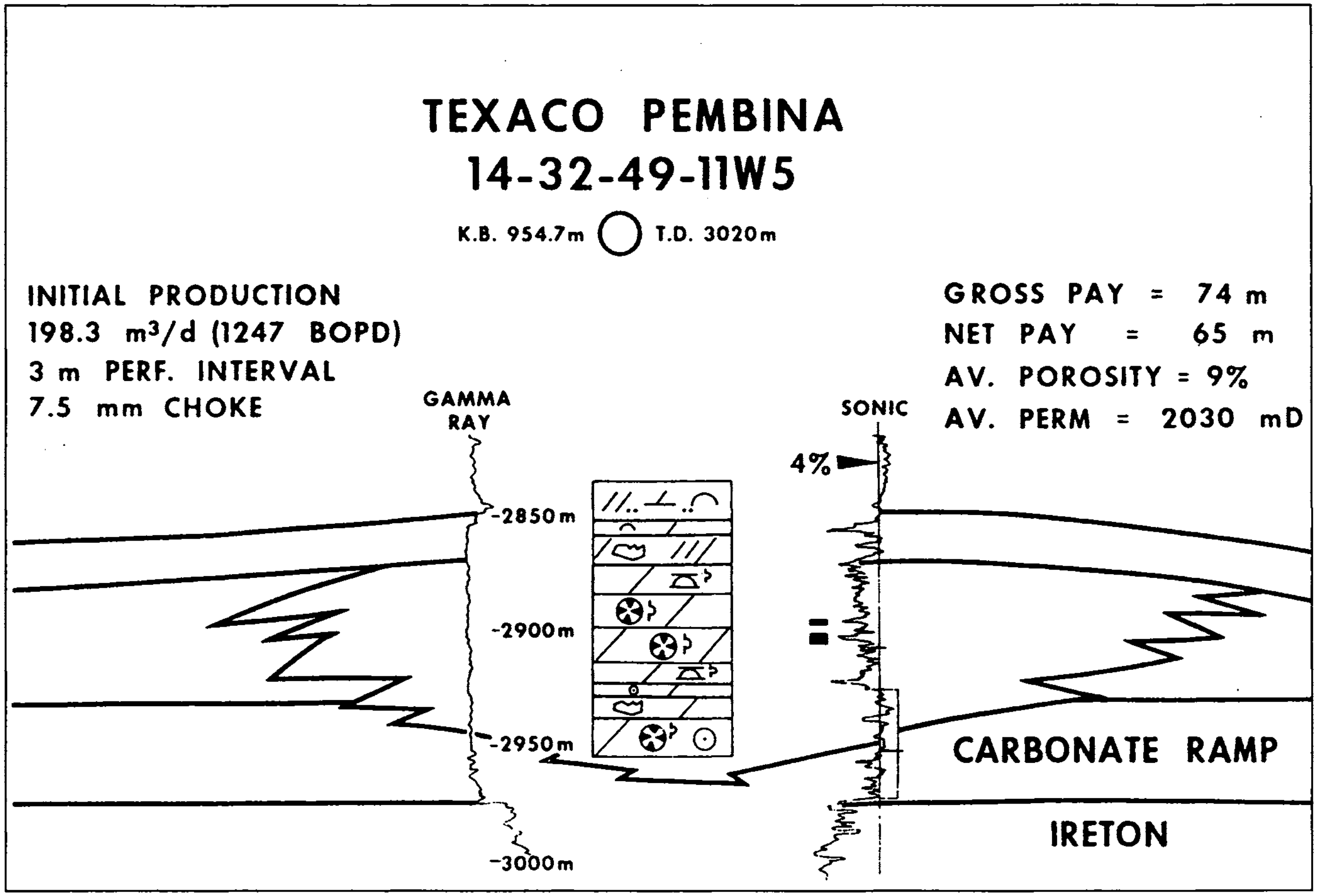


Figure 15: Fully Dolomitized Nisku Reef

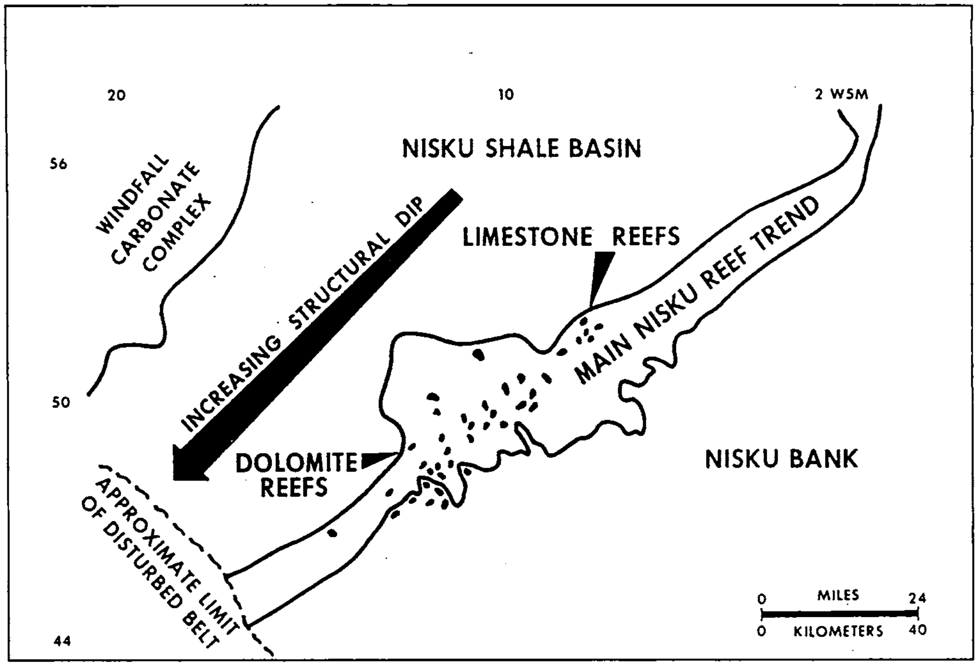


Figure 16: Reef Distribution

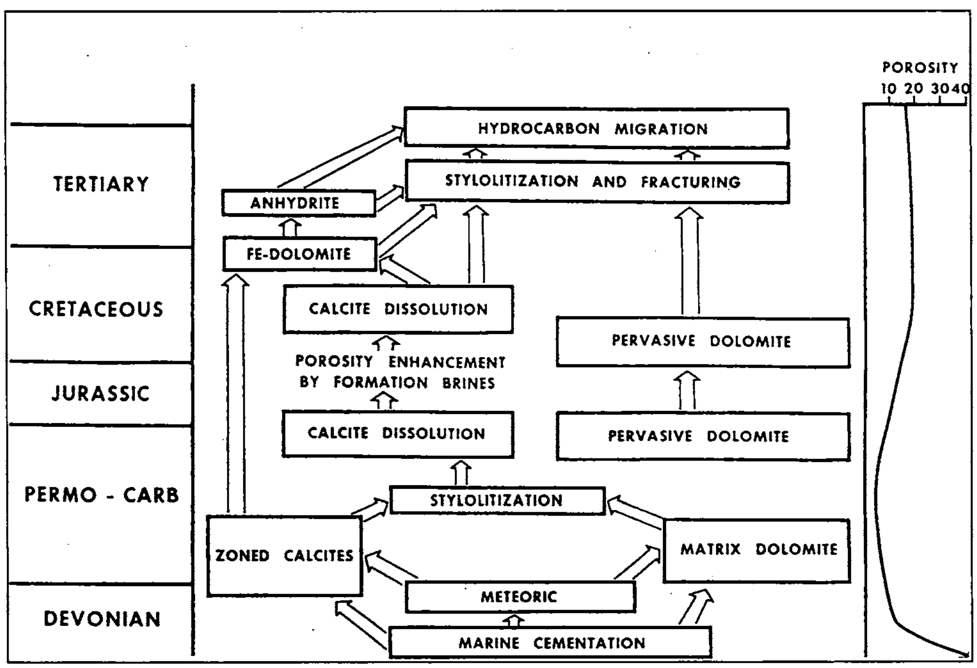


Figure 17: Paragenesis of the Nisku Reefs

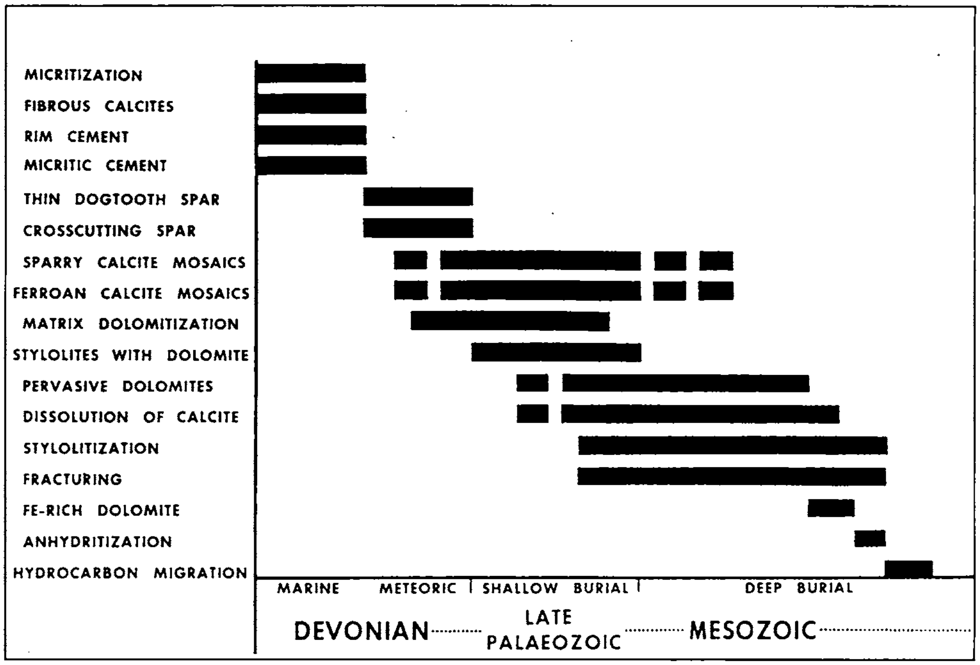


Figure 18: Diagenesis — Nisku Reefs

Dolomite is, therefore, the major determinant of reservoir quality. Fully dolomitized reefs average 10-20% porosity and up to 5 darcies permeability with appreciably higher initial production rates compared with limestone reefs (Figure 15).

Although dolomitization enhanced porosity and permeability, there are two mineral phases, which albeit not volumetrically abundant, are still important in terms of reservoir quality. These are saddle dolomite and anhydrite. Both these minerals occur infilling void space either partially or totally. If the pore space is totally occluded, local tight zones occur within the reefs. The presence of such tight zones is of great importance in consideration of enhanced oil recovery and their extent and distribution clearly needs to be documented.

Saddle dolomite predates the anhydrite and commonly occurs within biomoldic porosity and fractures. Detailed logging suggests that it does not occur in pool wide layers but is limited in extent.

Paragenetic and geochemical studies (Hutcheon *et al.,* 1982; Kirker and Nahnybida, 1980) indicate that the anhydrite which infills voids and fractures formed after the last phase of dolomitization which has been dated to have ended by the early Cretaceous. Anhydrite precipitation would, therefore, have taken place during the Mid-Cretaceous, postdating dolomitization (Figures 13, 17). As fluid migration, involving connate waters, would have taken place through fractures and remnant porosity, cementation by anhydrite would be random and would not have occurred in layers. By consideration of this detailed diagenetic model involving paragenetic and geochemical data, it is possible to postulate the lack of extensive lateral permeability barriers associated with anhydrite development. The higher production rates, reflecting optimum porosities and permeabilities within the dolomite Nisku reefs, indicate that the larger reefs are ideal candidates for miscible flood schemes as opposed to water flood schemes which are ideally suited to smaller dolomite reefs and limestone reefs with their lower porosities and permeabilities.

The understanding of the interplay of these diagenetic processes and their paragenetic sequences helps to describe individual reefs in terms of porosity and permeability development, distribution of poroperm values, occlusion of porosity within reefs, and the effect of diagenesis on reservoir quality in relation to enhanced oil recovery.

CONCLUSIONS

1. The West Pembina Nisku reefs of Alberta, Canada contain both dolomite and limestone reefs throughout the reef fairway.
2. The reefs underwent fairly extensive early marine cementation, and calcite cementation at shallow to intermediate burial depths. These processes resulted in significant porosity reduction.
3. Three basic types of dolomite are present within the reefs, and dolomitization occurred over a long period of burial, starting in near surface regimes and proceeding to intermediate/deep burial diagenetic regimes.
4. Matrix selective dolomites formed under near-surface to shallow burial depths, as indicated by the presence of dolomite crystals and dissolution of individual crystals along stylolites.
5. Pervasive dolomitization and calcite dissolution occured almost simultaneously with the dolomites representing progressive burial at elevated temperatures, within the time span of Late Paleozoic to early Cretaceous.
6. Optimum porosities and permeabilities occur within fully dolomitized reefs and correlate with the distribution of dolomite reefs along trend. Secondary porosity and dolomitization increases down structural dip.

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TABLE 1

STRATIGRAPHY OF THE FOUR REGIONS OF THE KINABALU SUTURE ZONE
THE DENT-SEMPORNA AREA AND THE SANDAKAN PENINSULA

STRATIGRAPHY Kinabalu Suture	BANGGI KUDAT	KINABALU RANAU	LABUK TELUPID	UPPER SEGAMA	DENT SEMPORNA	SANDAKAN
RECENT	ALLUVIUM	ALLUVIUM	EROSION SURFACES	ALLUVIUM	ALLUVIUM	ALLUVIUM
PLEISTOCENE	TERRACES	PINOSUK GRAVEL tilloid		TERRACE ALLUVIUM OLIVINE BASALT	TERRACE ALLUVIUM	TERRACE ALLUVIUM
PLIOCENE	TIMOHING epineritic BONGAYA neritic	N D nondeposition		Felsic to intermediate volcanics	TOGOPI neritic GANDUMAN paralic–deltaic	N D
LATE MIOCENE	BALAMBANGAN LIMESTONE ?		BONGAYA paralic TANJONG paralic KALABAKAN diamict.	TANJONG paralic–deltaic TABANAK CONGL. volcanism	SEBAHAT paralic–neritic TABANAK CONGLOMERATE	SANDAKAN KAPILIT TANJONG epineritic–paralic ?
MIDDLE MIOCENE	SOUTH BANGGI neritic	WARIU olistostrome os	N D	KUA-MUT os AYER os	TUNGKU paralic tuffaceous AYER os	GARINONO KUAMUT olistostrome
EARLY MIOCENE	CROCKER turbidites mass flow ss	CROCKER turbidites mass flow ss olistostrome	KULAPIS CROCKER turbidites	N D	LABANG neritic ?	N D
OLIGOCENE				LANGUSAN neritic to bathyal tuffaceous ?	KULAPIS turbidites ?	
EOCENE		TRUSMADI turbidites olistostrome		CHERT–SPILITE ophiolite melange	?	
PALEOCENE	CHERT–SPILITE ophiolite melange		CHERT–SPILITE ophiolite melange		CHERT–SPILITE ophiolite melange	CHERT–SPILITE ophiolite melange
LATE CRETACEOUS		CHERT–SPILITE ophiolite melange				
		CRYSTALLINE BASEMENT continental or mixed crust Jura . older		MADAI-BATURONG LS. Early Cret. CRYSTALLINE continental Jurassic	BASEMENT or mixed and	MADAI-BATURONG LS. crust older

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