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Analysis and modeling of dolomite sealing potential

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Abstract

One of the challenges toward understanding and predicting carbonate reservoir quality is the complex syn- to post-depositional diagenetic processes. Dolomitization is a critical modifier for carbonate reservoir quality in transforming the original grain-pore framework. Dolomitization especially leads to the redistribution of pore structure and connectivity, permeability, pathways, and reservoir producibility. Dolomite may behave as either a conduit or a barrier to flow depending on the original depositional texture, the chemistry of dolomitizing fluid, previous diagenetic stages, the timing and type of dolomitization, and the presence of anhydrite.

A quantitative conceptual model of dolomite sealing potential was established based on theoretical calculations of dolomitization for reservoir quality, supported by core and thin section data. The dolomite volume fraction-porosity relationships suggest that (1) generally, dolomitization can be divided into replacement and pore-filling (over-dolomitization) phases; (2) porosity preservation characterizes the former phase, and reduction of porosity for the latter phase; (3) grain-dominated limestone facies usually have less dolomitization potential (e.g., the dolomite fraction is usually < 0.8), whereas muddy facies have a higher dolomitization potential. Away from the dolomitizing fluid source, low flux and normal concentrations cause porosity preservation. Near the fluid source, high flux and high concentrations cause over-dolomitization. Tight dolomite can be an effective seal featuring high dolomite content, small pore throats, low porosity and low permeability.

3D geological models based on well logs and seismic data were built to help understanding the dolomitization mechanism, predict replacive dolomite and dolomite seal distribution. Modeling results very well proved the two phase's dolomitization and the sealing potential of tight dolomite.

Keywords: Dolomitization; Tight dolomite; Geological Model.

Introduction

Dolomitization is an important diagenetic process, because about 50% of oil and gas reservoirs in the world occur in carbonate rocks, and about 50% of the world's carbonate rocks are dolomitized [1]. Dolomitization usually strongly influences the redistribution of pore structure and connectivity, permeability pathway, and reservoir producibility. Dolomite can behave as either a conduit or a barrier to flow depending on the original depositional texture, chemistry of dolomitizing fluid, diagenesis stages, types of dolomitization, and presence of anhydrite [2].
Dolomitization is a complex process that a limestone is converted to a dolomite in different environments, usually through a dissolution-precipitation process facilitated by Mg-bearing fluids. Dolomitization can enhance, maintain, or destroy porosity relative to the parent carbonate rocks, depending on original depositional fabric and nature and volume of the dolomitizing fluids [3, 4]. Lynch and Trollope demonstrated the hydrothermal dolomitization enhanced the reservoir development and quality in Ordovician carbonates [5]. Lucia indicated that the dolomite porosity is inherited from the precursor limestone, and occluded by the process of overdolomitization based on several different data sets. Dolomite loses porosity more slowly than limestone during compaction and cementation processes, which makes dolomite to be good reservoir rock in many ancient carbonates [6, 7].

Although shale and evaporate are the most common seals, tight dolomite also can act as seal. The Mississippian system in most wells of the Nottingham Units is capped by a low permeability dolomite, which averages 6 meters in thickness [8]. The dolomite preserved the primary texture and contains some porosity but is impermeable to fluid flow [9]. Qian et al. studied the sealing capacity of the Ordovician carbonate rocks in Tazhong area of Tarim Basin and indicated that the Yingshan Formation dolomite limestone have certain sealing capacity.

A fundamental requirement for any effective seal is that the minimum displacement pressure (or capillary entry pressure) of the lithologic unit be greater than the buoyancy pressure of the hydrocarbon column in the underlying accumulation. The dolomites formed during pore-filling (overdolomitization) phase have much higher capillary entry pressure than those formed during replacement phase and limestone (Figure 1.1), indicating this tight dolomite could be a potential seal.

Coalson et al. (1994) studied the subtle seals and fluid-flow barriers in carbonates; consider the pore throat as the main factor for sealing capacity (Figure 1.2) [10]. Initial dolomitization leads to larger better sorted crystal and therefore larger pore throats. When dolomitization proceeds to overdolomitization, pore throats become very small and sparse. Hence, tight dolomites bear characteristics that meet the requirement of effective seals: high capillary entry pressures, small pore throat and low permeability.

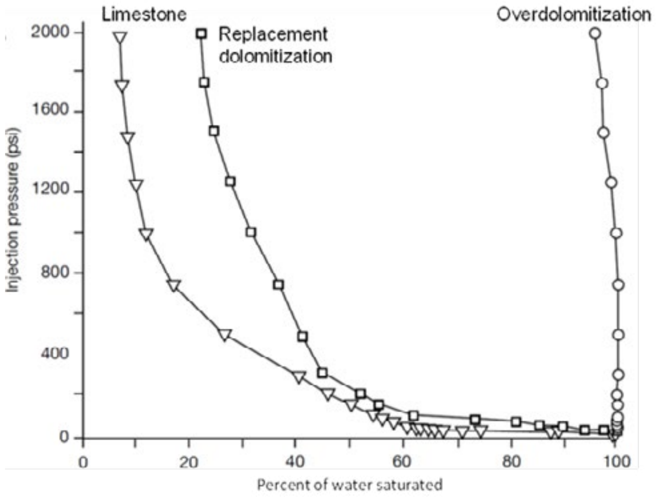

Figure 1.1: Hg-injection curve from representative lithologies in a sequence undergoing reflux dolomitization and overdolomitization (After Warren, 2006).

Massive dolomite bodies have long been documented in the study area because they strongly affect reservoir quality. A hybrid conceptual model was proposed for two possible dolomitization mechanisms: migration of dolomitization fluids from the salt basin driven by the tectonic compression; hydrothermal dolomitization by deep-seated water migrated upwards through fault and fracture systems. The occurrence of the massive dolomite was considered to be regional strati graphically discordant (i.e., crosscutting formation boundaries), which has enhanced porosity and permeability in tight carbonates that seal reservoirs [11].

Recent studies shed some light on the tight dolomite acting as seal. In this paper, we attempt to (1) delineate the spatial distribution of the massive dolomite through a regional scale geological modeling; (2) improve the understanding on the dolomitization effects on reservoir quality and predict the reservoir quality especially the dolomite seal through reservoir properties modeling; (3) Adding more quantitative elements into carbonate reservoir and seal prediction, and provide new insights to exploration by facilitating the identification of potential stratigraphic and diagenetic play concepts within the dolomite system.

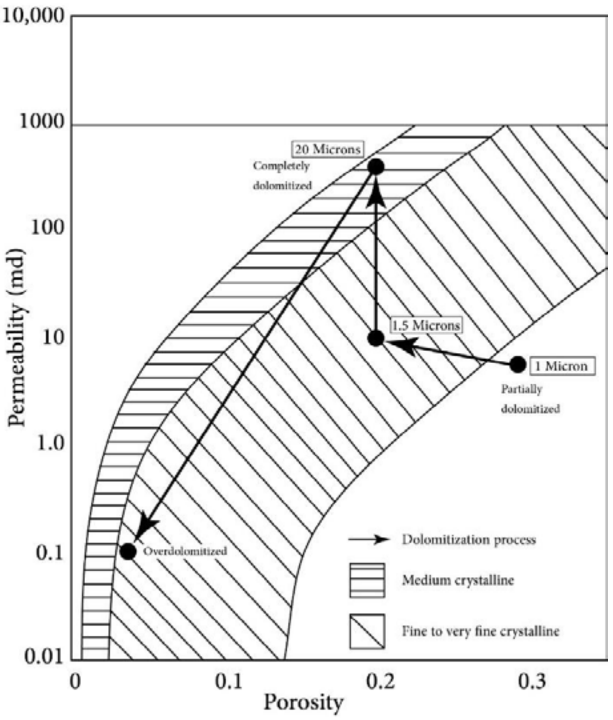

Figure 1.2: Porosity-permeability relationships for inter-crystalline porosity in a wide variety of carbonate rocks. Medium crystalline dolomites typically have better permeability (larger pore throats) at all porosities than do finer-textured dolomites. If dolomitization proceeds to overdolomitization, pore throats become very small and sparse (After Coalson et al., 1994).

Analysis of Dolomitization Effect on Reservoir Properties

Dolomitization strongly affects the reservoir quality by creating a new grain-pore framework at the expense of eliminating the original limestone fabrics. It usually strongly influences redistribution of pore structure and connectivity, permeability pathway, and reservoir producibility.

Chemistry of Dolomitization

Dolomitization can be summarized into the following equation [12]:

$(2-x)CaCO_3$ (Calcite) + Mg^{2+} + xCO_3^{2-} = $CaMg(CO_3)_2$(Dolomite) + $(1-x)\,Ca^{2+}$ (1)

The range of x can be any value between 0 and 1. Variable reaction stoichiometries may either reduce, leave unchanged, or enhance porosity. For example, if $x = 0.25$, 1 mole of dolomite ($64.365\ cm^3/mol$) is produced at the expense of 1.75 moles of calcite ($36.934\ cm^3/mol * 1.75\ mol = 64.6345\ cm^3$), the porosity is almost preserved (slightly increase).

Probably more important to the sealing capacity, the process of overdolomitization means that after all the calcite in the limestone has been replaced and converted into dolomite, dolomite precipitation persists due to the continuous supply of dolomitization fluid. Dolomite cementation will form in this case, blocking the pores and reducing the porosity. Overdolomitization can be expressed as:

$Ca^{2+} + Mg^{2+} + 2CO_3^{2-} \rightarrow CaMg(CO_3)_2$ (Dolomite) (2)

Theoretic Calculations of Dolomitization Effects on Reservoir Quality

We performed theoretic calculations of dolomitization effects on reservoir quality, assuming that the initial mineralogy is 100% calcite with 0.08, 0.17 and 0.26 porosity, for mudstone, grain-dominated packstone and grainstone, respectively. We set the x = 0.25 for the Eq. 1 to be consistent with the observations. The calculation results are shown in Figure 2.1.

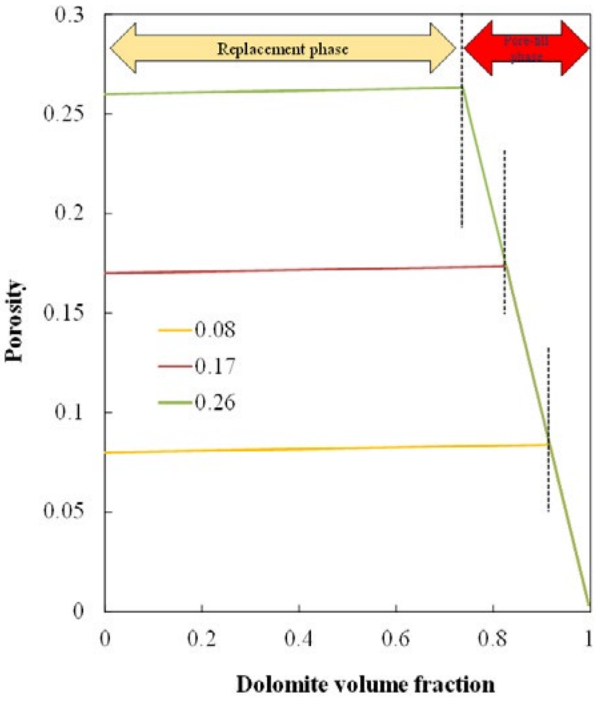

Figure 2.1: Calculated porosity variations as a function of dolomite volume fraction ((volume of dolomite)/ (volume of the rock)) with dolomitization reaction Eq. 1 and x = 0.25. The initial porosity is 0.08. 0.17 And 0.26 for mudstone, grain-dominated packstone and grainstone, respectively.

During the replacement phase, the porosity almost keeps unchanged (only slightly increases) for the dolomite fractions increasing from 0 to 0.73 for the grainstone, from 0 to 0.83 for grain-dominated packstone, from 0 to 0.92 for mudstone, respectively. During the pore-filling phase, the porosity decreases sharply for the dolomite fractions increasing from 0.73 to 1 for the grainy, from 0.83 to 1 for grain-dominated packstone, from 0.92 to 1 for mudstone, respectively.

Porosity Evolution during Dolomitization

The mechanisms of dolomitization are still controversial at present. Historically, mole-for-mole replacement of limestone by dolomite and an increase of 12.5% porosity were proposed for the porosity evolution during dolomitization [13]. The origin of porosity in dolomite is much more complicated than the simple mole-for-mole would suggest. Basically, later studies indicated that the dolomitization on porosity could be a function of (1) geological and tectonic settings, locations, (2) the original rock, (3) dolomitizing fluid chemistry, and fluid durations, and (4) the presence of gypsum or anhydrite cementation [14-19]. The contemporary view can be summarized as porosity preservation during the replacement phases, but porosity reduction during pore-filling phase [17].

Data from publications were analyzed and summarized in Figure 2.2 to illustrate the porosity evolution during dolomitization [17]. Lucia and Major described the transition from dolomite to limestone found in Plio-Pleistocene carbonate outcrops on Bonaire, Netherlands Antilles. The limestone is composed of grain-dominated fabrics with an average porosity of 25% and a range of 10-40%. The porosity values of dolomitic limestone range between 20% and 30%, a range similar to that of limestone porosity. Porosity decreases during overdolomitization, in an average of 11%, and range of 3-30%.

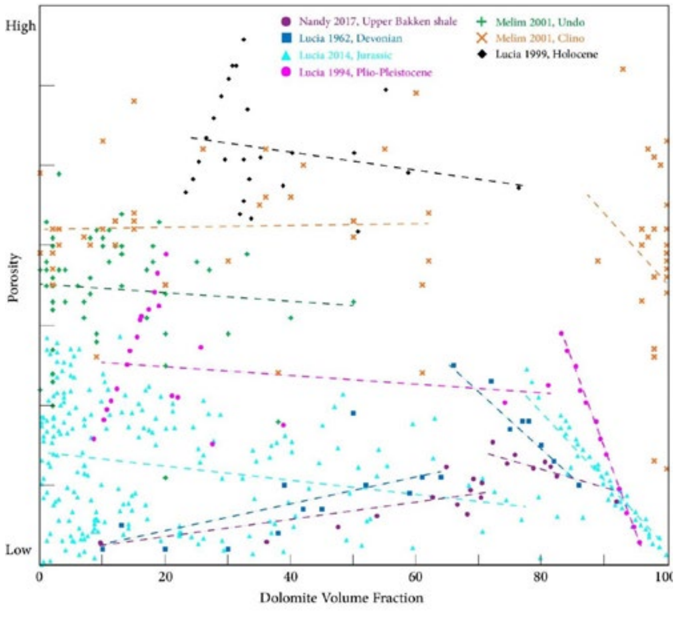

Figure 2.2: Effect of dolomitization of reservoir porosity based on literature data review. The dashed lines are linear regression of the data points in the same color.

Rock fabrics from the Jurassic reservoir were originally described by Powers [20]. For all dolomite samples earlier than Holocene, porosity is generally preserved or slightly decreased until the dolomite volume fraction of ~ 0.8. From that point on, porosity decreases sharply. The similarity between the porosity of grain-dominated limestone and dolomite suggest that dolomite porosity is inherited from the precursor limestone. The loss of porosity in the dolomite is attributed to variations in the porosity of the precursor and to the addition of dolomite cements after the replacement phase (overdolomitization) [17]. Lucia and Major described the transition from dolomite to limestone found in Plio-Pleistocene carbonate outcrops on Bonaire, Netherlands Antilles. The limestone is composed of grain-dominated fabrics. The porosity values of dolomitic limestone has a range similar to that of limestone porosity. However, porosity decreases during overdolomitization. Core data from two wells of Clino and Unda from Melim et al. on the study of Neogene carbonates, Great Bahama Bank, and X-ray diffraction derived dolomite content and core analysis porosity data of samples from wells of Elm Coulee Field also show the similar trend [21, 22]. The lithology of the dolomitic limestone is mainly pack/grainstone which preserves the porosity of the limestone. Porosity decreases sharply after entering into the overdolomitization phase.

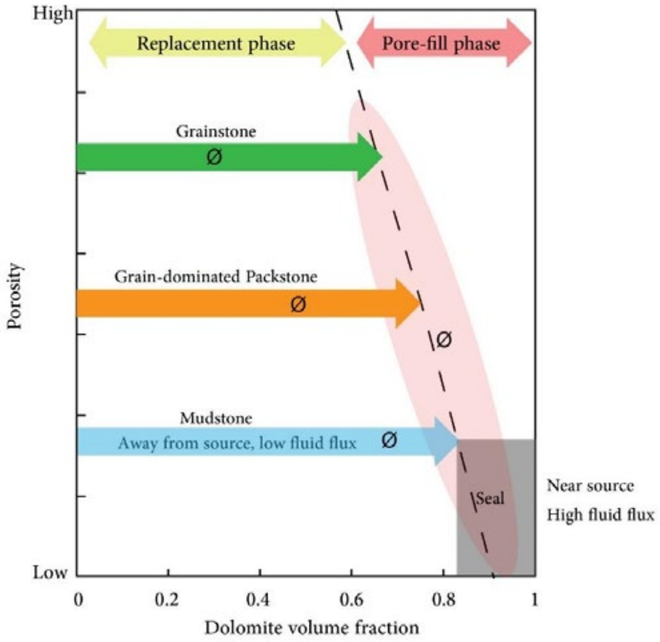

Figure 2.3: Summarized relationships for the porosity as a function of dolomite fraction for grainstone, grain-dominated Packstone and mudstone. Dolomitization potential increases from grainy to muddy facies. Near fluid source, high flux, high concentration overdolomitization (seal); away from the source, low flux, normal concentration, porosity preservation.

It can be summarized that porosity is a function of dolomite fraction. Dolomitization potential increases from grainy to muddy facies (Fig. 2.3). Overdolomitization (dolomite seal) tends to develop in areas near fluid source with high flux and high concentration. Replacement (replacive dolomite) tends to develop in areas away from the dolomitization source with low flux, normal concentration and porosity preservation.

The complex dolomite from petrographic analyses also suggest that dolomite in this area may involve different formation mechanisms of two diagenetic stages. Replacive dolomite characterized by a gradual transition from very coarse crystalline cement to fine crystalline particles (Figure 2.4a and c). Very coarse crystalline dolomite with intercrystalline porosity and sometimes with anhydrite cement (Figure 2.4b and d) may be related to hydrothermal origins.

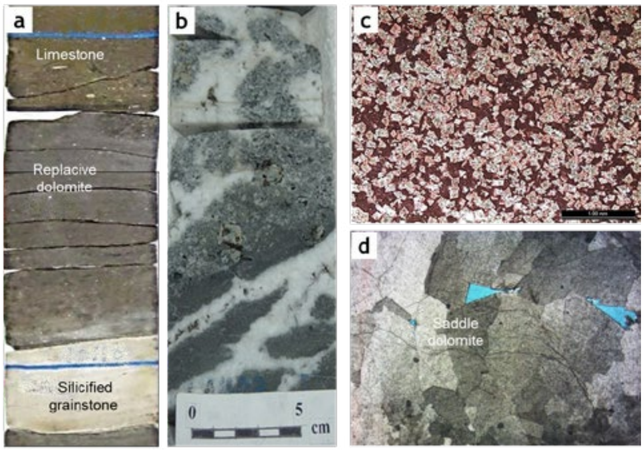

Figure 2.4: Typical dolomite in the study interval with core images and thin-section photomicrographs. (a) Silicified grainstone is sandwiched between grainy dolomite (typical replacive dolomite). (b) Coarse crystalline dolomite with intercrystalline porosity forms in hydrothermal veins (c) Partially dolomitized limestone, with very fine sucrosic dolomite crystals. (d) Coarse saddle dolomite with characteristic curved crystal edges and cleavage planes. Intercrystal pores occur locally.

Dolomite Seal Modeling

Regional mapping indicates that the regional stratigraphically discordant dolomite bodies cross-cut formation boundaries. The dolomite volume is most pervasive adjacent to the intrashelf salt basin and decreases with distance to the north (Figure 3.1).

Three-dimensional (3D) geostatistical modeling provides a comprehensive description of subsurface reservoirs. It is an effective way of characterizing subsurface reservoir architecture, facies geometry and reservoir properties mainly based on field data such as well logs, cores and seismic data [23, 24]. Since late 1990s, the technology of reservoir modeling integrated with seismic data has been developed and widely used in reservoir characterization [25]. Araktingi et al. discussed a workflow of using seismic data in reservoir characterization and fluid-flow predictions integrated with well logs [26]. Yang et al. discussed about incorporating seismic acoustic impedance with well log derived porosity to generate the porosity model in a gas field [27]. Strebelle et al. employed multiple-point geostatistical technique in describing a deep water turbidite reservoir under the condition of using seismic data [28]. Michelena et al. established a workflow to estimate facies probabilities from log and seismic data and use the information to constrain reservoir facies modeling.

A stochastic geological model was built to characterize the massive dolomite distribution and predict the dolomitization effect on reservoir quality using Sequential Gaussian simulation algorithm. The model covers an area of about 6.6 x 103 km2 with 500 m by 500 m grid spacing in X and Y direction. The modeling interval is consist of 132 layers of 10 zones, in a total number of 3.9 x 107 cells.

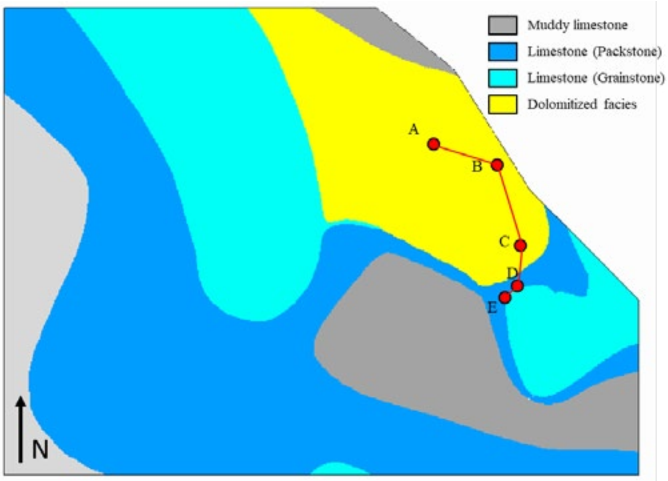

Figure 3.1: Regional lithofacies distribution. Red dots represent well locations.

Structural model shows the topographic elevations generally increase from east to west (Figure 3.2). The massive dolomite mainly occurs in the northeastern part of the study area, with its maximum thickness in the "dolomite center" near the southern margin of the intrashelf salt basin to the north. Towards the south and west, the dolomitized intervals progressively decrease in thickness to the "dolomite front," forming a wedge-shaped geobody (Figure 3.3).

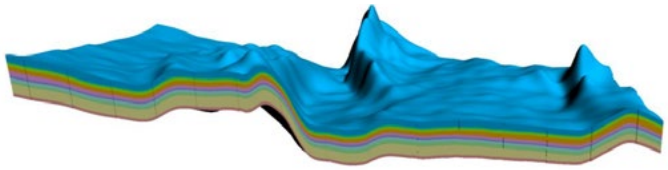

Figure 3.2: Structure gently goes deeper towards east (view from south).

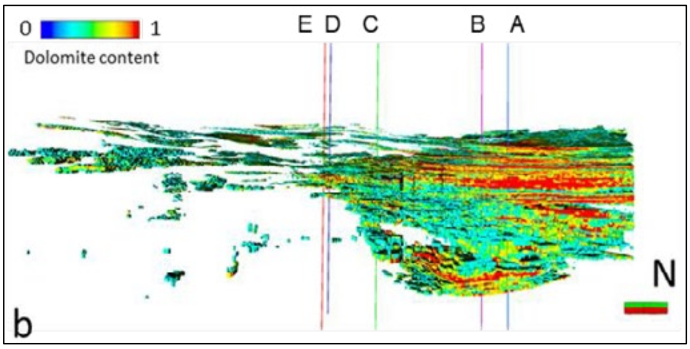

Figure 3.3: 3D Modeling results showing the massive dolomite distribution in a wedge-shaped geobody (flatten at top surface) and the internal dolomite content (view from east, vertical exaggeration × 10).

Properties modeling results also prove the proposed two phase's dolomitization model. Fig. 3.4 show the dolomite content, porosity and permeability change along the cross section from "dolomite center" to "dolomite front." Areas with high dolomite content tend to have relatively low porosity and permeability, also supported by thin sections.

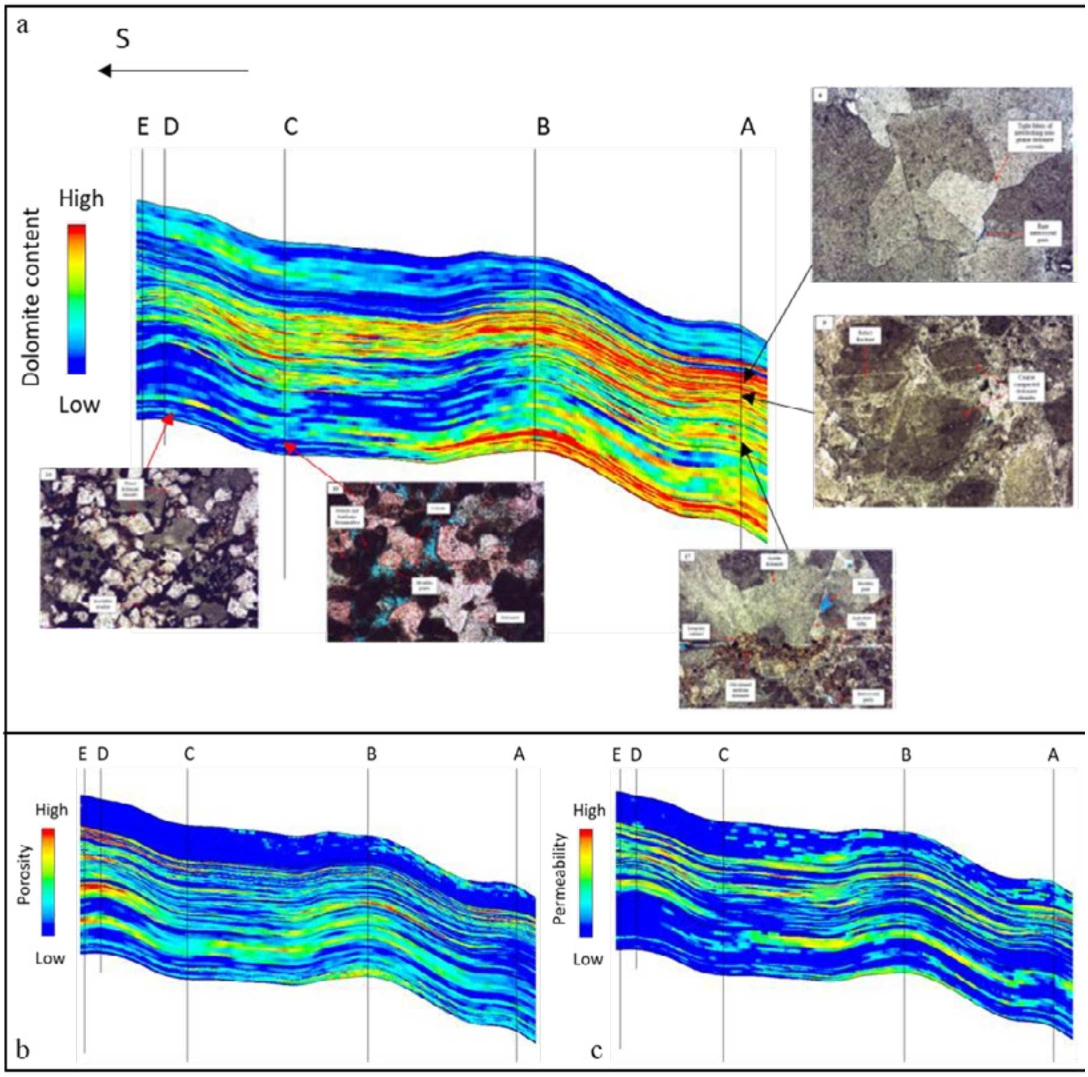

Figure 3.4: Cross sections show porosity, permeability and dolomite content lateral change with thin section analysis in well locations. Tight dolomite (high dolomite content, low porosity and low permeability) mainly developed in the dolomite center (well A, near source). Replacive dolomite (relatively lower dolomite content, higher porosity and permeability) mainly developed in the dolomite front (well D and E, away from the source).

To further exploring of tight dolomite sealing potential, a detailed dolomite model was performed by integrating seismic properties for a specific interval (interval A) within the study area (Figure 3.5). The grid spacing in X and Y direction is 100 m by 100 m. The total number of cells is about 1.1 E x 107.

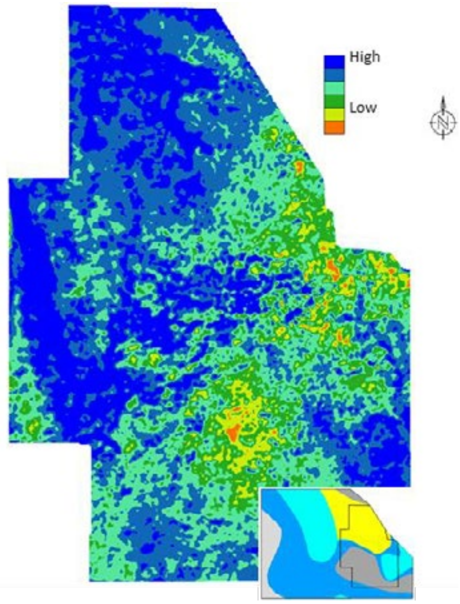

Figure 3.5: A detailed dolomite modeling area with acoustic impedance (AI) within the large AOI.

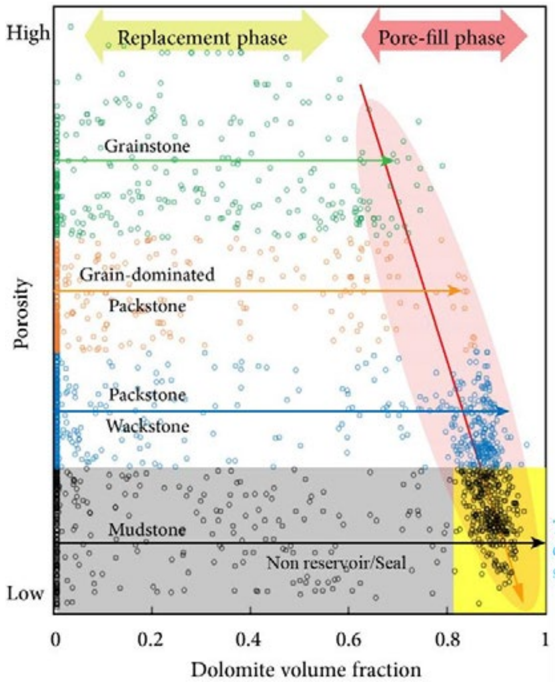

Figure 3.6: Relationships for the porosity as a function of dolomite fraction for grainstone, grain-dominated packstone, wackstone and mudstone of interval A.

As shown in Figure 3.6, dolomitization potential increases from grainstone to mudstone, very well matches the proposed model. Non reservoir or seal can be defined by porosity cut-off (mudstone) among which tight dolomite seal has a dolomite volume fraction approximately larger than 0.8.

Figure 3.7 and 3.8: show relatively good correlations among porosity, acoustic impedance (AI) and dolomite content [29]. Therefore, we adopted AI as the additional data source to the dolomite model and porosity model. A number of algorithms were tested and co-kriging method was selected to generate the models with and without AI constrain (Figure 3.9).

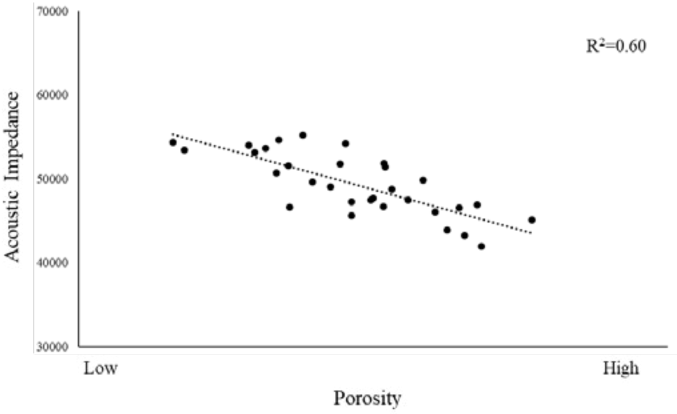

Figure 3.7: Porosity vs. AI at well locations (32 data points).

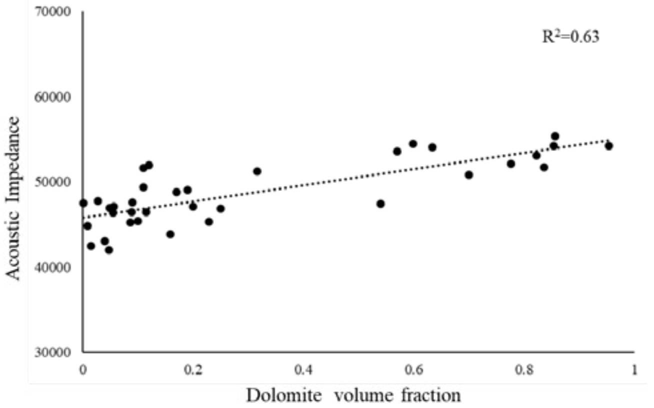

Figure 3.8: Dolomite content vs. AI at well locations (35 data points).

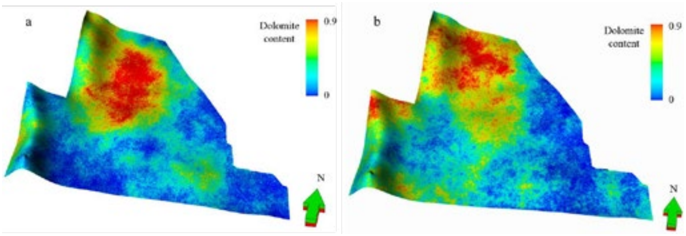

Figure 3.9: One layer of part of the dolomite model, warm color represents high dolomite content. (a) is the model generated only based on well logs while (b) is the model incorporated well logs with seismic properties. They both obey the data at well locations. But in areas between wells, (a) mainly relies on geostatistical analysis while (b) has more detailed information from seismic properties.

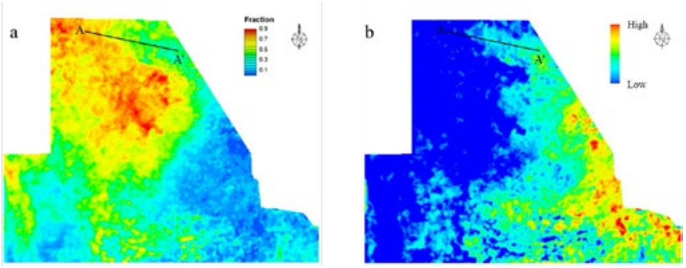

Figure 3.10: Average dolomite content and porosity distribution of the study interval from seismic constrained models.

Overall, dolomite is well developed in interval A especially in the northwest area. Limestone and dolomitized limestone with relatively lower dolomite content have good reservoir quality in the eastern part of the study area. The tight dolomite developed in pore-fill phase as well as some muddy dolomitized limestone have good potential of acting as lateral (Figure 3.10). This configuration presents a good reservoir-seal combination, which constitutes a diagenetic play concept (Figure 3.11).

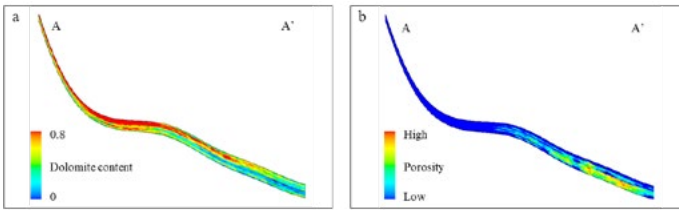

Figure 3.11: West-east cross section profiles (AA') of dolomite and porosity models showing the reservoir pinch out up-dip into the west with the dolomite content increase and porosity decrease, cool color in porosity model represents non-reservoir (using porosity cut-off), warm color indicates higher porosity value. Dolomite content profile generally shows the two phases of dolomitization in blue and red colors.

Conclusions

Stratigraphically discordant massive dolomite bodies have long been observed and documented in the study area because of its significant impact on reservoir quality. Dolomite can behave as either a conduit or a barrier to flow depending on the original depositional texture, chemistry of dolomitizing fluid, diagenesis stages, types of dolomitization, and presence of anhydrite.

The dolomite volume fraction-porosity relationships suggest that (1) generally, dolomitization can be divided into replacement and pore-filling (over-dolomitization) phases; (2) porosity preservation characterizes the former phase, and reduction of porosity for the latter phase; (3) grain-dominated limestone facies usually have less dolomitization potential (e.g., the dolomite fraction is usually < 0.8), whereas muddy facies have a higher dolomitization potential. Away from the dolomitizing fluid source, low flux and normal concentrations cause porosity preservation. Near the fluid source, high flux and high concentrations cause over-dolomitization. Tight dolomite can be an effective seal featuring high dolomite content, small pore throats, low porosity and low permeability.

A detailed dolomite model of a thin layer of interval A within seismic coverage indicates that there is a good potential for diagenetic trap, which formed by porous limestone reservoir and up-dip tight dolomite and muddy dolomitized limestone seal in this heavily dolomitized study area.

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Conflict of Interest Statement

We declared that we have no conflicts of interest to this work. We declare that we do not have any commercial or associative interest that represents a conflict of interest in connection with the work submitted.

Author's Contribution Statement

Sihai Zhang wrote the main manuscript and analyzed the potential of a diagenetic play in. Yin Xu built the dolomite seal model. Peng Lu prepared "Analysis of Dolomitization Effect on Reservoir Properties". All authors reviewed the manuscript.

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