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TESTING THE CORRELATION BETWEEN SEQUENCE STRATIGRAPHY, SEISMIC REFLECTORS AND DIAGENETIC CHANGES IN CARBONATES

Final Report

Phase 1: April 1, 1992 – March 31, 1994
IMPLICATIONS FOR THE DISTRIBUTION OF POROSITY AND PERMEABILITY
Phase 2: April 1, 1994 – March 31, 1996
EVALUATION OF FLUID FLOW DURING EARLY AND LATE DIAGENESIS

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DISCLAIMER

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INTRODUCTION

This final report summarizes the result of the project entitled "Testing the correlation between sequence stratigraphy, seismic reflectors and diagenetic changes in carbonates". The project was conducted in two phases.

Phase 1 was subtitled "**Implications for the distribution of porosity and permeability".** The duration of this first phase was from 1 April 1992 – 31 March 1994.

Phase 2 was subtitled "**Evaluation of fluid flow during early and late diagenesis".** The duration of the second phase was from 1 April 1994 – 31 March 1996.

The project was initiated to test the hypothesis that early diagenesis, like facies, is related to fluctuations in sea-level and follows a predictable pattern. Initial results from investigations on two core borings from Great Bahama Bank (GBB) indicated that diagenetic overprint follows the sequence stratigraphic framework.

In the first phase of the project the goal was to demonstrate how variability in diagenesis is related to fluctuations in sea-level and, by unraveling this relationship, to increase our predictability of porosity and permeability in carbonates. In order to achieve this goal we performed a thorough study of the diagenesis of the prograding platform carbonates, in particular the timing and the mechanisms of aragonite dissolution, compaction, cementation by low-Mg- calcite and celestite and perhaps most important dolomitization. The comparison of the physical properties (porosity, permeability, density and velocity) with the lithologic and diagenetic facies helped assess the correlation between diagenesis and logs and seismic reflection pattern.

Recognizing the importance of fluid flow in the process of transforming the sediment to the rocks, phase two had its main objective to assess the fluid flow during early and late diagenesis. In particular, the hypothesis that the development of the depositional geometries, the facies and the development of fluid pathways are related. To better constrain mechanisms and variations of the fluid flow in the prograding sequences

of western GBB we designed three experiments. 1) To assess the fluid flow an attempt was made to reoccupy the two drill sites on GBB for water sampling and temperature measurements. The holes could not been found and a piston coring experiment was used instead. It allowed measurement of geochemical gradients in the top sediments along the platform margin and slope. 2) Numerical modeling of the fluid flow through GBB should help identify the primary driving mechanisms for flow in the platform. The seismic geometries and results of the geochemistry and diagenesis were used to constrain the model. 3) To test our findings in an ancient example the correlation between diagenesis and sequence stratigraphy was studied in the Devonian Miette platform in Canada. In addition, we continued our efforts to quantify the controls on sonic velocity in carbonates.

SUMMARY OF RESULTS

The four year project produced a wealth of information in regards to the understanding of the processes governing diagenesis, petrophysics and the fluid flow in carbonate depositional systems. In the following we briefly outline our major findings; a more comprehensive description and discussion of the results is presented in the published papers.

Diagenesis:

The cores CLINO and UNDA studied in this project provide important insights into several aspects of carbonate diagenesis. Perhaps the most important was the opportunity to examine platform-derived carbonates that have not been subjected to diagenesis in meteoric fluids. These unique data set has documented that diagenetic models which are associated with the conditions established during large Pleistocene sea-level fluctuations are not representative of conditions affecting older sediments and those deposited in deeper water settings. These findings are:

1) The most important finding is that diagenesis is not random but occurs within the sequence stratigraphic framework as do different facies. Diagenesis is therefore at least initally controlled by changing sea level and thus be predictable within the sequence framework (Melim et al. 1995; Anselmetti and Eberli, 1993; Eberli et al., 1997).

2) Another new finding of the project is the documentation of early marine burial diagenesis that produces a petrographic fabric previously believed to be meteoric in origin, occurring in deeper-water facies of the cores never affected by freshwater (Melim et al, 1995). These findings suggest that there is a considerable amount of alteration associated with modified seawater. The end product of marine burial diagenesis looks very similar to that of phreatic meteoric diagenesis: A limestone composed of low-Mg calcite and minor dolomite with micrite envelopes, moldic porosity, blocky spar cementation and aragonite neomorphism. This observation forces a reevaluation of the criteria for recognizing meteoric diagenesis in ancient carbonate sequences. Without clear physical evidence of subaerial exposure (e.g., caliche horizons or vadose cements) or chemical evidence of meteoric fluids (e.g., depleted oxygen isotopes) workers should be very careful about identifying meteoric diagenesis.

3) The third important finding is in regards to dolomite formation. Several phases of dolomite formation occurred in Pliocene and Miocene aged portions of the Clino and Unda cores producing three different types of dolomites were found in these young sediments and rocks. The dolomitizing fluid in all cases seems to be modified sea water . This finding indicates that early dolomite formation can produce a variety of dolomite fabrics at various places within the strata. The earliest is 1-3% isolated dolomite rhombs that formed on or near the sediment-water interface. In permeable sediments, microsucrosic dolomite continued to form during marine burial diagenesis (up to 20% dolomite) while dolomitization ceased in low permeability sediments. Isotopic analysis of leached dolomite samples have revealed heavy oxygen isotopic compositions ($\delta^{18}O$ = +3.7±.3‰) indicative of sea water dolomitization. Hardgrounds were preferentially dolomitized, usually with dense micritic dolomite, probable due to prolonged exposure at the sea floor with the increased availability of organic matter. Isotopic analyses of leached dolomite from the hardground at 536.3 m (1759.6 ft) are consistent with the formation of dolomite from cold waters near the hardground surface as the oxygen isotopic composition decreases gradually with increasing depth consistent with a geothermal gradient of approximately 40°C/km, typical of continental crust. The relatively isotopically depleted nature of the carbon isotopic composition of the dolomite at the hardground suggests that perhaps dolomitization is being driven by the oxidation of organic material. The third dolomite forms up to 100% dolomite in the middle reef and platform section (292.82-360.28 m) of Unda and extends into the overlying slope facies. Leached dolomite samples from this interval also indicate seawater-derived fluids ($\delta^{18}O$ = +3.9±0.1‰).

4) Data from three Bahamian and South Florida cores with deeper water facies showed that, contrary to current models, there is no phreatic meteoric diagenesis that can be attributed to large-scale sea-level lowstands (Melim, 1996). The diagenetic active meteoric lenses in the Bahamas and Florida are restricted to within 60 m, and perhaps less, of the land surface. Models that currently assume a constant rate of alteration in meteoric fluids need to accommmodate this variation with thickness of the vadose zone. The results also questiojn the use of plaeophreatic lenses as records of eustatic sea level, as large-scale falls may not leave any record.

Fluid Flow:

Results from the Bahamas Drilling Project strongly suggest the presence of active fluid circulation beneath Great Bahama Bank. This recognition is based not only on consideration of the geochemistry of deeply buried carbonates which have apparently been altered in principally marine derived solutions, but also from the geochemical analysis of interstitial waters retrieved from deep within the carbonate platform. Such flow mechanisms have profound implications as regards diagenesis of the carbonate sediments in all carbonate platforms. We have considered mechanisms such as Kohout convection, hydraulic head differences between the bank and adjacent seaways, and variable salinity of the water on the platform top. For the bank configuration studied and for boundary conditions that are representative of current conditions near North Andros Island, geothermal flux is the dominant driving force for fluid circulation. Head differences across the island of up to 0.6 m have essentially no effect on the fluid circulation patterns. Recharge on the island has a local effect, but bank scale circulation is relatively insensitive to recharge rate. Finally, simulations in which permeability of the various zones were varied, demonstrate that temperature gradients along the bank edges are particularly sensitive to variations in permeability. Evaluation of these models suggests that the temperature difference between the open ocean and the carbonate platform is the most important control. Control of the flow patterns within the platform are controlled by variations in anisotropy and differences in permeability between various different facies.

Petrophysics:

Results of the project have advanced the understanding of the controls of petrophysical properties in carbonates, especially for sonic velocity, porosity, and permeability. The major accomplishments are:

1) The controls on sonic velocity ion carbonates can now be explained by considering not only porosity but also specific pore types. These findings are based on a large data set from the two cores (Unda and Clino) on Great Bahama Bank, Florida Bay, and the Cretaceous Maiella platform. A study conducted in this project was able to relate the specific carbonate pore-types form by several post-depositional processes, such as cementation or dissolution (Anselmetti and Eberli, 1993, 1997). The elastic properties of the different pore types explain why rocks with the same porosity can have completely different velocities. This relationship between the acoustic properties and diagenesis is a key element for the interpretation of log data.

2) Permeability in Miocene to Quaternary Carbonates on Great Bahama Bank is, similarly as velocity, controlled primarily by pore types rather than porosity (Melim et al., in press). In particular, the connectivity of macropores is the key to predicting permeability. For example, moldic pores that are isolated from other pores are not contributing to permeability but if they are well-connected in a continuous pore network, like in many of our samples, these molds contribute or even control permeability. Pore types can again be related to diagenesis, as the different diagenetic environments commonly produce a dominant pore type (e.g., marine burial diagenesis often results in connected moldic porosity). The vertical trend in the cores Unda and Clino is characterized be alternating high and low permeability zones, documenting that overburden has little influence on permeability to depths of 670 m. The vertical permeability distribution displays a large variability with high and low permeability zones alternating on a small scale. This intercalations has strong implications for modeling of fluid flow in carbonate platforms as previous workers have assumed an anisotropy ratio of 2.5 (horizontal/vertical) while this study has found one of to 10^3 or 10^4. This also suggest that much of the fluid flow is along depositional units rather than in a vertical direction.

3) Our results produced an immediate application for the hydrocarbon industry that helps predict diagenetic and permeability trends from standard log data. Based on the observation that both sonic velocity and permeability are related to pore-types, we developed a method that provides information about the pore type distribution in bore holes. In this method a "velocity-deviation log" is calculated by combining the velocity and neutron-porosity logs Eberli and Anselmetti, 1999). The time average equation between velocity and porosity is used to transform the neutron-porosity log into a synthetic sonic log that displays velocity values which would be expected from the log-porosities. The difference between the real sonic log and the synthetic sonic log can be

plotted as a "velocity-deviation log" that reflects the different pore types and their different rock-physical signatures. Positive velocity-deviations mark zones in the drilled section where velocity is higher than expected from the porosity values; these are zones where frame-forming pore types dominate. Negative deviations show intervals where the rock lacks a rigid frame, such as in carbonates with high intercrystalline or microporosity. By tracing the velocity-deviations continuously downhole, zones can be identified with different pore types and the related constructive or destructive diagenetic processes. In addition, this method can be used to make permeability predictions, since pore type influences the permeability of the rock. We view this finding as major step forward in solving the problem of predicting permeability with remote geophysical tools.

Relationship Between Diagenesis, Facies, Petrophysics and Seismic Sequences:

Results of the projects clearly show how the intertwining of processes controlling the distribution of facies, diagenesis and petrophysical properties produces seismic reflection s that image the seismic sequence architecture (Anselmetti and Eberli, 1993, 1997; Anselmetti et al., 1997). The driving mechanism that sets the stage for all subsequent processes is sea level. Changing sea level determines the location, input, type and amount of sediment into the system and it controls the near surface hydrologic system. Post-depositonal processes (diagenesis) follows the intial template as it transforms the sediment into rock. During this transformation the rock receives its petrophysical characteristics as it enhances the contrast between different sedimentologic packages (Anselmetti and Eberli, 1993, 1997; Melim et al. in press). Hardground development is probably the most significant change as it creates a hard, dense layer that is then overlain by loose sediment providing an abrupt velocity change and thus the necessary impedance contrast for a seismic reflector. Further velocity variations are created during later diagenesis by selective cementation, dissolution and compaction, which enhances or decreases small original sedimentologic velocity changes leading to the required velocity contrasts for a seismic reflection pattern. As such the project results provide new insights into the relationship between the petrophysical properties of carbonate deposits and their facies and diagenesis.

To test our findings from the modern, we studied the platform margin of the Devonian Miette Buildup (Alberta, Canada), and found a very similar pattern, indicating that our results from the Neogene are relevant for ancient deposits. Diagenesis in the

Miette Buildup began very early and continued into the shallow to deep burial environment. Dolomitization is the most important diagenetic element in the Miette Buildup. A comparison of the dolomite distribution across the Miette Buildup margin and in cores Clino and Unda from Great Bahama Bank reveal amazing similarities. In both cases, the deeper water facies contain ubiquitous but minor dolomite while the platform margin has been extensively dolomitized with the dolomite extending above the platform facies into the overlying slope facies. This implies dolomitization after deposition of the slope facies in both examples. Geochemical evidence suggests that dolomite was formed at low temperatures, and the correlation between dolomitized layers and specific locations with respect to genetic units and stacking patterns indicate an early diagenetic origin, unrelated to strong evaporation. Dolomitization significantly enhanced the primary porosity.

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