PSOrigin of Silica in Pre-Salt Carbonates, Kwanza Basin, Angola*

Zsofia Poros¹, Elliot Jagniecki², John Luczaj³, Jeroen Kenter⁴, Benedek Gal², Thiago S. Correa², Elton Ferreira², Kathleen A. McFadden², Andy Elifritz², Matt Heumann², Michelle Johnston², and Veit Matt²

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Abstract

Various forms of silica (e.g., chert, chalcedony, mega-quartz) have been identified in pre-salt lacustrine carbonate reservoirs in the conjugate South Atlantic margins, offshore Santos and Kwanza basins. However, their mode of precipitation with respect to biogenic or burial diagenetic processes remains debated. The preponderance of microbial boundstone textures commonly associated with chert may suggest syndepositional chert formation through microbial mediation (Saller et al., 2016). Such relationships are commonplace in modern hot spring environments and alkaline lakes, where high dissolved silica concentrations promote rapid silicification of microbial mats (Renaut et al., 1998). Here we present a case study from offshore Kwanza, where chert is not a primary biogenic precipitate, but rather replacing a carbonate precursor of boundstone texture during burial diagenesis. The replacement process is partially fabric-preserving, hence the microbial texture of the chert. Petrographic observations suggest the following relative timing of events: 1) formation of microbial boundstone carbonate, 2) complete dolomitization and burial dolomite cementation, 3) silicification (i.e., partial replacement of microbial boundstone by chert), silica cementation (i.e., fibrous chalcedony followed by drusy and mega-quartz cements) and coeval corrosion. Silica cementation and corrosion may occur as multiple, repeating events. Fluid inclusion microthermometry, Raman spectroscopy, and petrography indicate that silica cements precipitated from high-T fluids (Th=98-123°C) associated with HC gases in the burial diagenetic realm. These observations imply that the high quality of these silicified carbonate reservoirs (k up to 100 mD, Φ up to 15%) is not only due to the presence of primary microbial framework porosity but also the enhancement of secondary vuggy pores generated by high-T fluid flow and corrosion. Thus, the recognition of potential migration pathways for high-T/hydrothermal fluids (e.g., faults), in association with build-up geometries on seismic profiles, may help to optimize the identification and characterization of these types of reservoirs.

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¹ConocoPhillips, Houston, Texas, United States (zsofia.poros@conocophillips.com)

²ConocoPhillips, Houston, Texas, United States

³University of Wisconsin, Green Bay, Wisconsin, United States

⁴Total, Houston, Texas, United States

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fabric partially preserved; silica>carbonate

Carbonate grain partially

associated with

Carbonate grain

RELATIVE TIMING OF DIAGENETIC EVENTS

Chemical compaction (stylolitization)

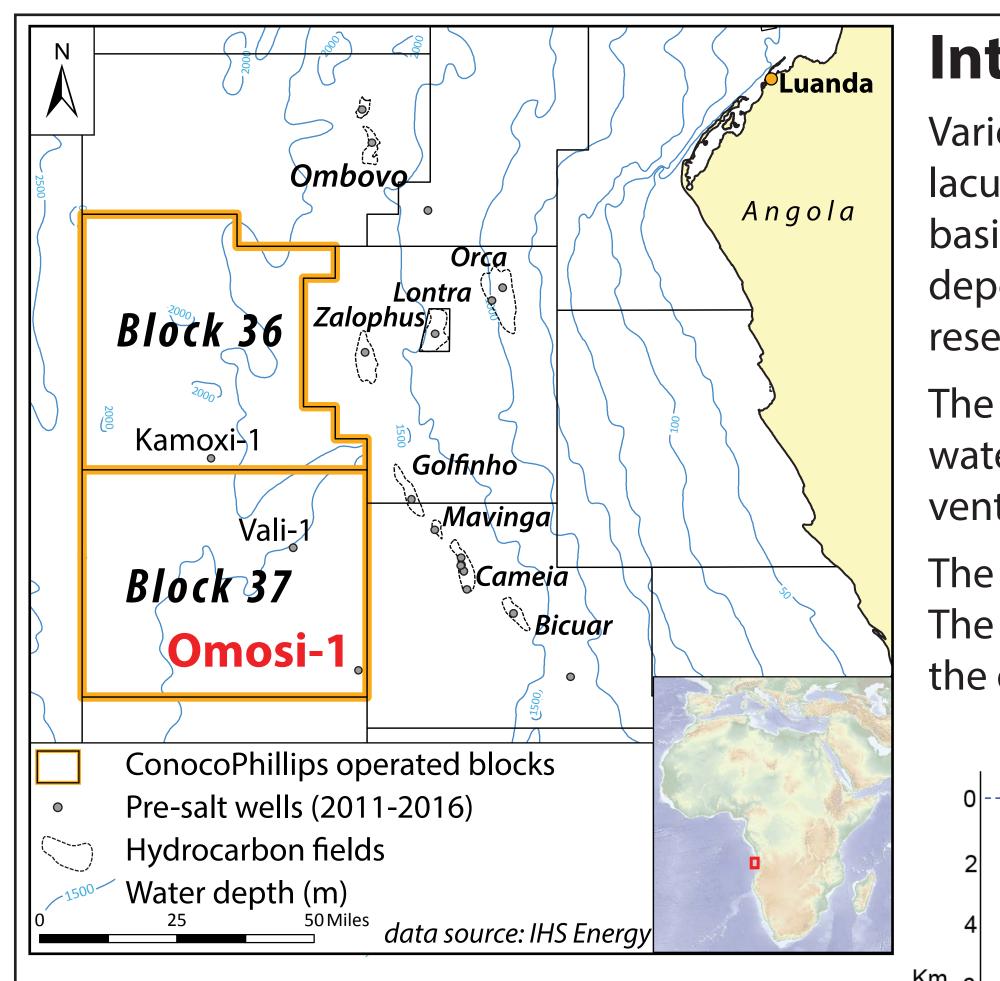
Calcite cementation (collomorph, followed by scalenohedral)





fabric destroyed, silica>>carbonate

¹ConocoPhillips (Houston, TX, United States); ²University of Wisconsin - Green Bay, WI, United States); *currently Total, ** currently Apache



An extensive lacustrine petroleum system was formed during rifting of the South Atlantic from Late Jurassic through Early Cretaceous time. Lacustrine carbonate sediments were deposited on basement highs during Syn-Rift and Sag phases on both sides of the conjugate margin.

The pre-salt reservoir facies comprise of: (1) Aptian-Barremian Upper Rift bioclastic grainstone (i.e., coquina) (2) Aptian Sag microbialite - spherulitic

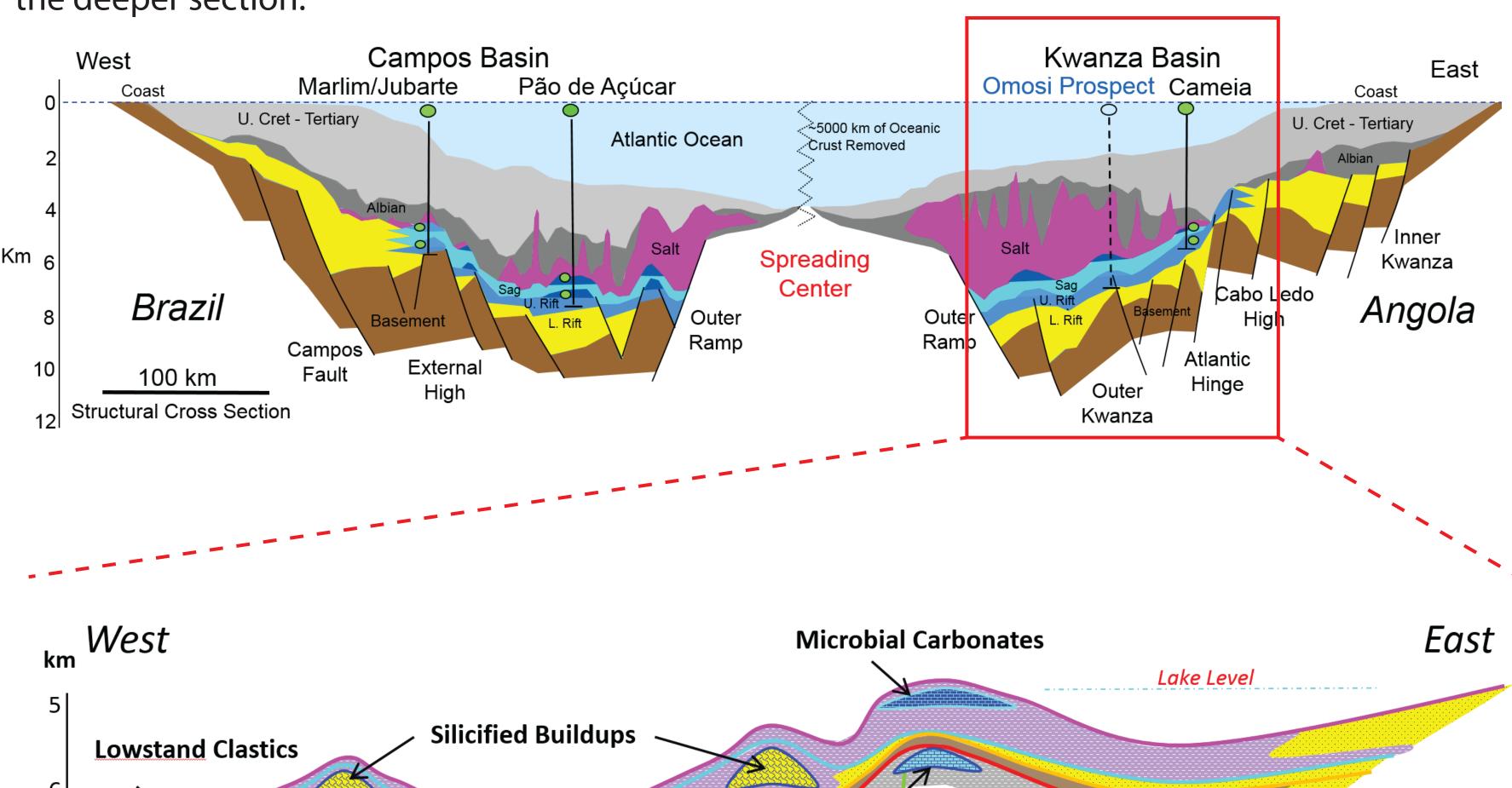
Reservoir quality of these carbonates is impacted by complex diagenetic processes. Finding the reservoir in a favorable diagenetic setting with improved reservoir quality is one of the key challenges of the play.

Introduction

Various forms of silica (e.g., chert, chalcedony, mega-quartz) have been identified in the pre-salt lacustrine carbonate reservoirs of the conjugate South Atlantic margins, offshore Santos and Kwanza basins. However, the origin of silica remains debated. The goal of this study was to identify the depositional and diagenetic processes, with emphasis on the silicification, that greately impacted reservoir quality of the carbonates.

The studied well, Omosi-1, is a vertical exploration well drilled in Angola Block 37 within the deep water of the Kwanza basin. ConocoPhillips operated the drilling of the well on behalf of its joint venture partners Sonangol P&P and Repsol.

The primary reservoir target was the Aptian Sag carbonate situated below a thick evaporite interval. The upper pre-salt section is dominated by carbonate rocks and arkosic siltstones to sandstones in the deeper section.



Petrophysical zones and Rock types

BHI textures were integrated with macro-and microscopic observations from 124 rotary sidewall core samples and cuttings and converted to depositional rock types (DRTs) where possible. These DRTs were compared to petrophysical rock types (PRTs) generated from the wireline logs and assumed to represent different reservoir quality classes. The following major rock types were identified in the carbonate units. (F1 - F4 following the Santos Basin nomenclature modified from Wright and Barnett (2015)):

F1: various textures with shrubs

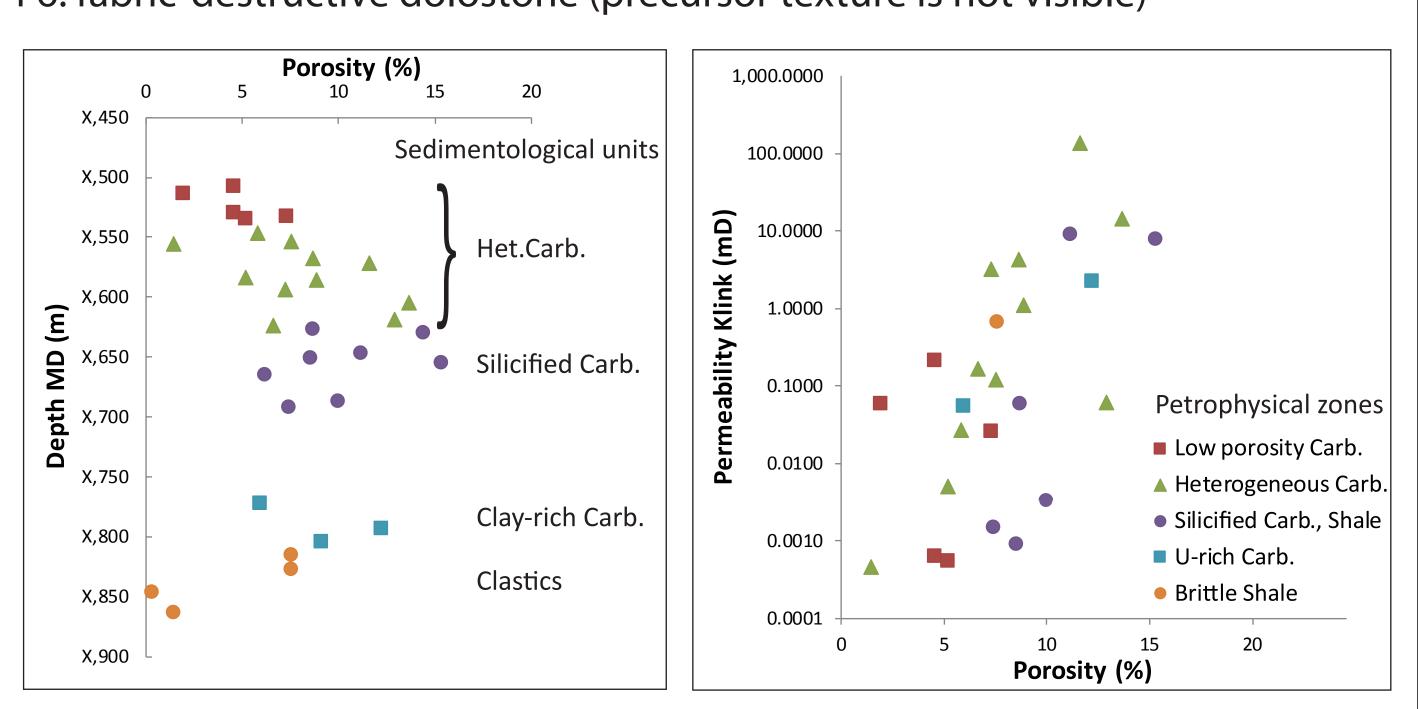
F2: various textures with spherulites

F3: laminated mudstone with early silica nodules

F4: reworked grainstone/rudstone

F5: microbialite

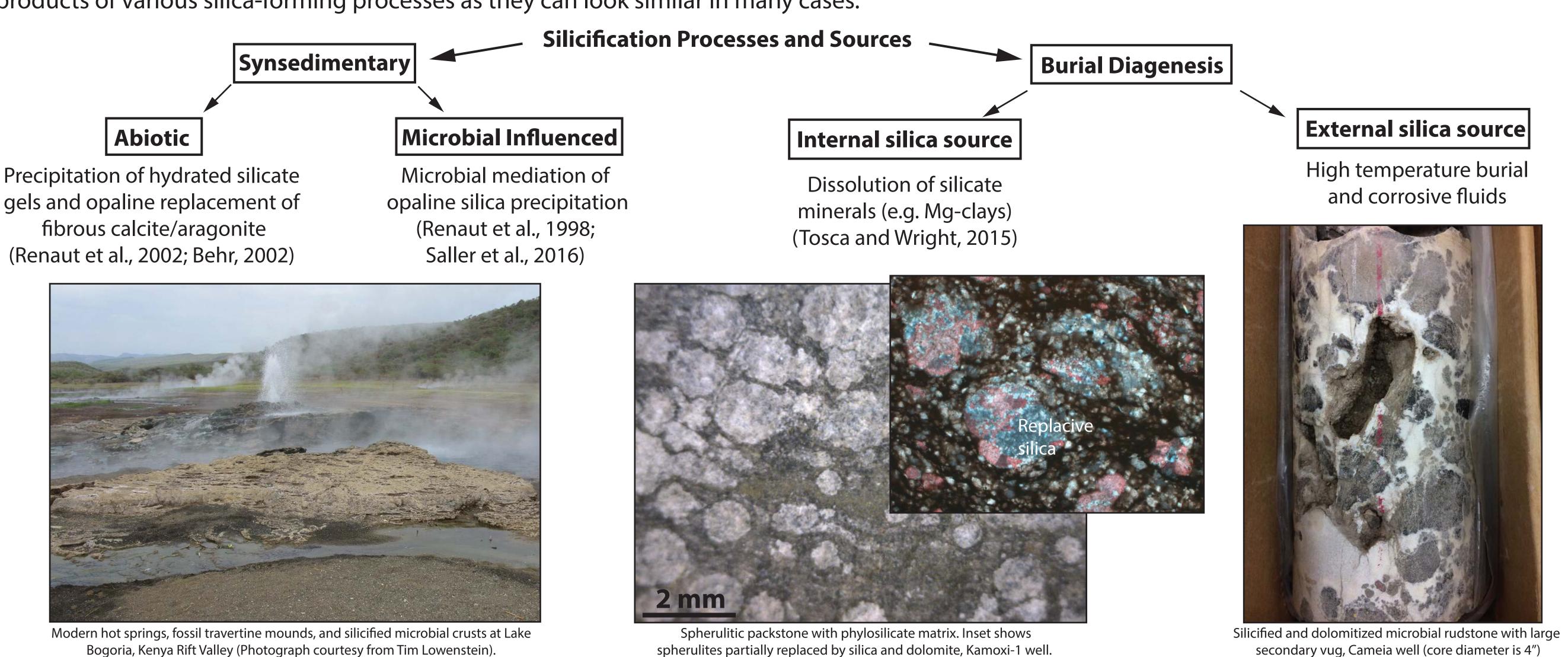
F6: fabric-destructive dolostone (precursor texture is not visible)



RCA data, measured at 2800 psi net confining stress, showing Porosity versus Depth and Porosity versus Permeability. Reservoir quality of the carbonate units varies between 1.5-15% porosity and 0.0005 to 140 mD permeability (Klinkenberg corrected). Note the increasing porosity trend with depth in the upper carbonate

Problem Statement

Silicification of the pre-salt carbonates in the Kwanza Basin may have been a result of synsedimentary or burial diagenetic processes, or both. Silica precipitation is common in modern hot spring and alkaline lake environments in East Africa, Kenya Rift Valley, where evaporative concentration and cooling of thermal waters with high dissolved silica precipitate hydrous silicate gels and opaline silica that encrust microbial mats. However, silicification also occurs during burial diagenesis from silicate mineral dissolution or by external high temperature fluids. The challenge is to differentiate the 📗 🗓 🔻 products of various silica-forming processes as they can look similar in many cases.



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Space and Time: Implications for Global Exploration and Production: Geological Society of London, Special Publications, v. 418, p. 209-219.

Petrography of the Upper Carbonate Units

Silicification to various degrees was observed in multiple facies, most commonly in F1, F2, and F5. Silicification may or may not be fabric-preserving. In samples where the precursor carbonate texture is still recognizable, the following paragenetic sequence was established:

- 1) Circumgranular calcite cementation (collomorph followed by scalenohedral)
- 2) Complete dolomitization of the pre-cursor carbonate

worked spherulites

calcareous mudstone

Sedimentological units versus petrophysical zones (PRT's). Note that

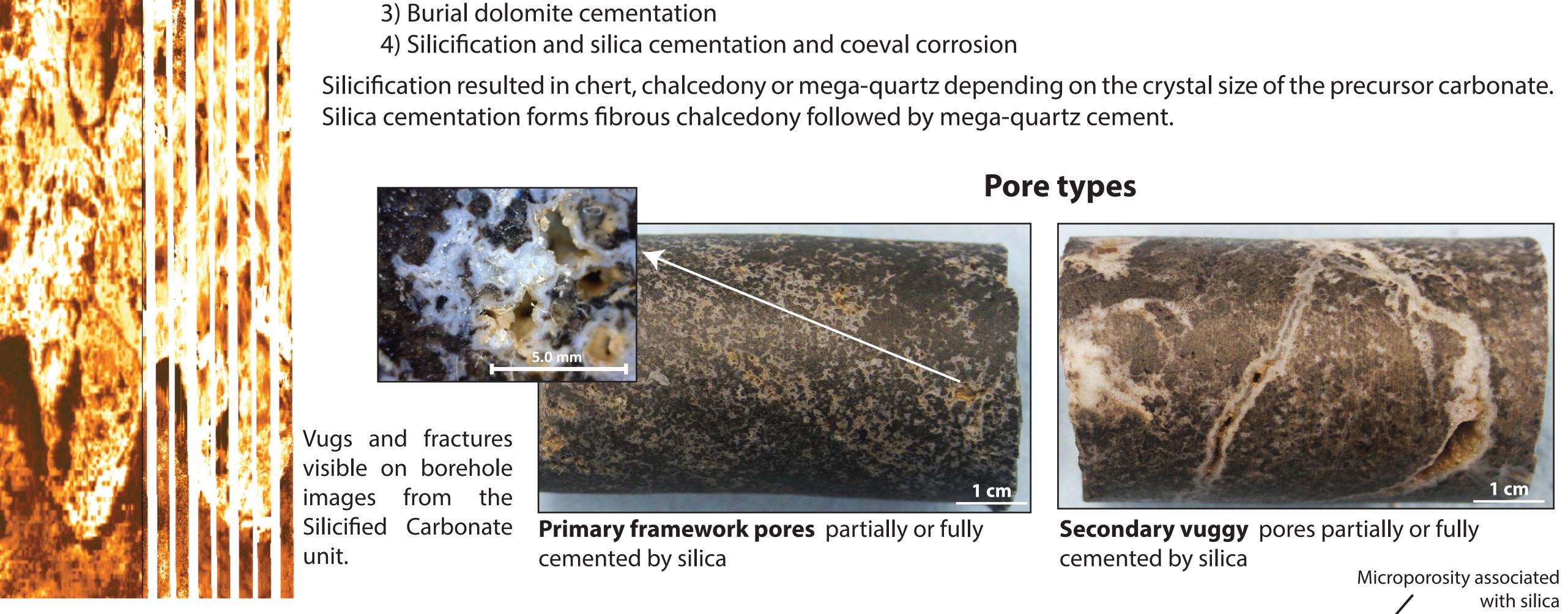
percentages of QFM (Quartz, Feldspar, Mica) from the spectroscopy tool

(track #2) capture both the diagenetic silicification of the carbonate uni

and the detrital silica in the Clastic unit.

Sequence Model

hin-bedded argillaceous to



In addition to the abundant microporosity associated with silica, the two other major pore types in the upper carbonates are 1) primary framework pores and 2) late secondary vuggy pores. Even though they can be similar in terms of size and shape, it is still possible to differentiate them. Primary framework pores follow the grain boundaries, while vuggy pores often cut across them and they are often connected by fractures. Both pore types can be found open, fully or partially cemented by silica, dolomite, sulfides or solid bitumen.

Primary framework porosity partially cemented by silica

Secondary vuggy pores c across grain boundary

Burial corrosion (vuggy pores, diss. enlarged fractures/stylolites, multiple event Replacive silica phase Precursor carbonate phase Carbonate replacement by silica (mostly chert and chalcedony) (Th=95-125° Chert Silica cementation (mostly mega-quartz) (Th=105-125°C) Collomorph carbonate cement Fibrous chalcedony Dolomite cementation-2 assoc. with solid bitumen (Th=95-115 $^{\circ}$ C) Scalenohedral calcite cement Mega-quartz | Fluid Inclusion Analyses 90 95 100 105 110 115 120 125 Homogenization temperature (Th, °C) Dolomite cement phase-1 Dolomite cement phase-2 Chalcedony Mega-quartz Distribution of homogenization temperature of primary aqueous fluid inclusions from various cement phases.

After silicification

Fluid inclusion microthermometry, Raman spectroscopy, and petrography indicate that replacive chalcedony and mega-quartz cement precipitated from high-T fluids (Th=98-123°C) associated with hydrocarbons (mostly CH₄ and CO₃) in the burial diagenetic realm. The two dolomite cement phases formed before and after the silica show a slightly lower temerature, thus silica cementation likely represents a localized maximum heating event in the reservoir.

A - aqueous liquid (L) + vapor (V) fluid inclusion in replacive chalcedony - vapor-only fluid inclusion in a drusy mega-quartz cement. The inclusion is part of a primary fluid inclusion assemblage (FIA) C - corresponding Raman spectra of the above inclusions. The two-phase aqueous inclusion (A) shows low density methane in the vapor phase. The liquid water peak/hump expected between 3000-3600 cm⁻¹ is masked by fluorescense. The vapor-only inclusion (B) shows a high density mixture of various gas phases, mostly CH₄ and CO₂ and smaller amounts of other aliphatic gases and possible traces of aromatic and S-bearing gas species. (Qtz - Raman bands corresponding to the host quartz).

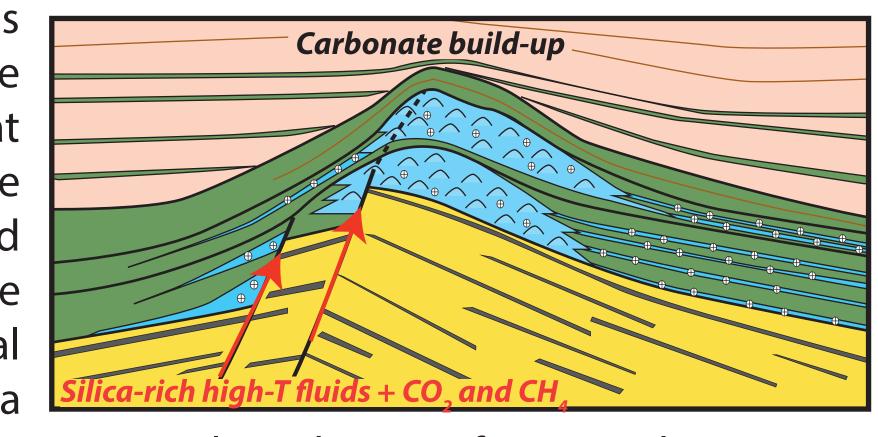
Conclusion and Applications

Microbial features and degree of silicification

fabric preserved; carbonate>>silica

Silicification and porosity evolution

This study couples the observed silicification and corrosion at Omosi-1 to diagenetic processes linked to high temperature CO₃- and CH₄-bearing fluids that migrated along faults during late burial stage. Fluid-rock interaction caused by these ascending fluids is the likely mechanism that triggered carbonate dissolution and simultaneous silica precipitation, favored by the inverse solubility relationship of carbonate and silica from changes in pressure and pH, and supported by core observations of high-T overprint of the primary (microbial/spherulitic/shrubby) texture and pore system. The previously published model (Saller et al. 2016) arguing for a microbial formation of chert is not supported by this data. Textural features in chert that resemble a



microbial origin are a result of silica replacement of precursor microbial carbonate. The recognition and prediction of potential migration pathways for high-T corrosive fluids (e.g. faults), in association with build-up geometries on seismic profiles, may help to optimize the identification and characterization of these types of reservoirs.