WATER-WEAKENING OF UNDER STRESS CARBONATES: NEW INSIGHTS ON PORE VOLUME COMPRESSIBILITY MEASUREMENTS

P. Carles, P. Lapointe (TOTAL S.A., Pau-France)

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SUMMARY

Reliability of laboratory pore compressibility measurements is a critical issue for numerous oil and gas reservoirs. The present paper first addresses the problem of water weakening effects on some types of carbonates. Several compressibility tests under isotropic conditions have been performed on carbonate rocks from different reservoir facies and at various oil and brine saturation states. Experimental work shows that this phenomenon not only affects chalk but more widely shallow-water type carbonates with preserved or enhanced porosity. In addition to the experimental aspects, a geological study based on thin sections and Scanning Electron Microcopy (SEM) image descriptions on samples before and after test gives new insights on the basic micro-mechanisms behind the water-weakening.

INTRODUCTION

Compaction drive mechanism consists in the expulsion of oil due to the reduction of pore volume as a response to pore pressure decrease during depletion. This mechanism could have a tremendous impact on additional recovery during natural depletion. Nevertheless further compaction could also lead to high level of surface subsidence, critical for off-shore structures as experienced on the Ekofisk field [1]. The contribution of compaction to oil recovery or subsidence depends on the compressibility of the reservoir rock under reservoir stress paths. For elasto-plastic rocks, the compressibility increases dramatically when the rock behaviour changes from elastic to plastic. The limit between the elastic and plastic behaviour determines the size of the elastic domain and is initially defined by one parameter called P_{c0}, the pre-consolidation stress. Compression tests are notably performed to determine this parameter. However conventional tests performed in the industry might underestimate the impact of the saturating fluid type on some carbonate behaviour.

Through the case study of the Alpha Gas Field, a limestone reservoir operated by TOTAL, this paper tackles the issue of water-weakening effects on some types of carbonates and revisits the pore volume compressibility to include the additional compaction due to water saturation. For this purpose, several compressibility tests under isotropic conditions have been performed on Alpha samples from different carbonate facies and at various oil and brine saturation states. In addition to the experimental aspects, a study of the sedimentological and diagenetic history of the limestones gives new insights on the carbonate facies the most susceptible to be weakened by the presence of water. Finally the possible micro-mechanisms behind the phenomena of water-weakening effect will be discussed.

ALPHA FIELD

The Alpha field is a shallow offshore gas field under production operated by TOTAL. The reservoir is developed within an isolated Oligo-Miocene carbonate platform located onto Eocene volcanic basement and Oligocene shallow marine volcano-clastics series. The carbonate platform is overlaid by deep marine shales Upper Miocene in age, 200m thick, which act as a seal. The carbonate buildup was drowned in the Upper Miocene, during the abrupt subsidence of the basement. Cores and thin sections cut from wells which penetrate the reservoir shows the following main lithofacies:

- Reef environment with specific characteristics related to barrier reef and inner platform reef;
- Near reef environments with abundance of bioclastic and coral debris;
- Inter reef environment characterized by bioclastic accumulations (shoal type) consisting of large benthonic foraminifera or red algae (Rhodoliths);
- Off reef or shelf environments.

Initial in situ mean effective stress is estimated at 70 bars and final in situ mean effective stress after depletion at 170 bar. The additional recovery due to compaction drive may be estimated between 0.5 and 1 % if the rock remains elastic during the field life and to more than 3% if the plasticity threshold is reached earlier. A detailed compressibility study was then implemented in order to remove this uncertainty.

LABORATORY TESTING PROCEDURE

The sampling is made according to the four main lithofacies described from the cores and thin sections analyses, and the check of the CT-Scan images of the core. Samples were labeled according to the facies distribution (table 2). A total of ten samples, referenced from Cp1 to Cp10, of 40mm diameter and 65 to 80mm length were cut. Each sample was protected in a rubber jacket to ensure the isolation of the pore pressure from the fluid used to apply a hydrostatic loading on the sample. The sample is dried at 60°C and set inside a confining cell. Vacuum is then created inside the sample. A fluid is injected into the sample to complete its saturation and to apply the desired pore pressure. For fully saturated samples (Cp1, Cp2, Cp3, Cp9, and Cp10), samples are saturated with mineral oil or brine. A given brine volume was injected in the samples Cp4, Cp5, Cp6, Cp7, and Cp8, to achieve a target residual brine and the sample was then oil-saturated. It has been verified that no water escaped from the sample at this stage.The end of saturation period is determined by the stabilisation of sample deformations under a pore pressure of 6 bars. The samples are then submitted to hydrostatic load under drained conditions. During the tests, stresses are applied at a slow rate (1 bar/min).The saturating brine is a standard lab brine. It was mixed for one month with powdered Alpha carbonate. The final brine analysis is given in table 1 below. Stabilizations are performed at the end of each loading phases. For brine saturated samples, the saturating brine is sampled and chemically analyzed at the end of each stabilization phase. Strains, and pore volume changes are monitored continuously through the test using standard petrophysics techniques. At the end of the test, the sample is cleaned and analysed for mineralogical composition. The whole rock mineralogical composition is very similar for all samples with dominance of the calcite fraction and minor dolomite.

TEST RESULTS

Pore Volume Compressibility

Corrections

It is admitted, and field simulations also confirm this, that the stress path inside the strained reservoir is close to a uniaxial path (vertical strain without radial deformations). Because the compressibility is measured in isotropic strain condition, the values are corrected to give the equivalent compressibility in these oedometric conditions (C_{poedo}). The theory of poro-elasticity provides a very good approximation of pore compressibility under uniaxial strain conditions, obtained from measured C_{pc} pore compressibility under isotropic confining conditions [2]:

$$C_{poedo}=C_{pc}\left(1-\frac{2\alpha(1-2\nu)}{3(1-\nu)}\right)-C_S$$

with:

- α the Biot's coefficient
- ν the Poisson's ration
- C_s the mineral compressibility

One of the characteristics of chalky samples is their viscous behaviour. The amount of strain occurring during creep phases makes the measured compressibility dependent on the test-loading rate. Therefore given compressibility results (table 2) are also corrected from the influence of the loading rate. This ratio and its impact is evaluated during the stabilization phases and is corrected using De Waal's equations [2-3].

Rock Behaviour

The general behaviour of samples is a first plateau at the beginning of loading, corresponding to the elastic strain phase. After this point called the pre-consolidation stress (P_{c0}), compressibility rapidly increases up: plastic deformations are reached. If the rock is oil-saturated (Cp1, Cp2 and Cp3) the pore compressibility remains low even after 170 bar of mean effective stress. For free-water zones, a plastic pore compressibility average of 1.45 10^{-4} bar^{-1} can be taken into account. However, the brine-rich samples reach the plastic domain after few amounts of depletion and their compressibility increases faster and higher than for the 100% oil-saturated samples. 5% of initial water saturation is sufficient to induce rheological behaviour changes. No correlations were found between facies and compressibility. However, the reactivity of the sample to the water is directly proportional to the initial rock porosity. The more porous the carbonates, the stronger are their compressibility during depletion. For the most porous samples the compressibility can reach up to 6.5 $10^{-4}bar^{-1}$.

Table 1. Brine chemical analysis

Before test analysis	Na mg/l	K mg/l	Ca mg/l	Mg mg/l	Cl- mg/l	SO4-- mg/l	HCO3 mg/l	PH
SATURATING BRINE	6346	1050	530	100	11948	210	158	7.74

Table 2. Main results

		Cp1	Cp2	Cp3	Cp4	Cp5	Cp6	Cp7	Cp8	Cp9	Cp10
Well		**Alpha1**	**Alpha1**	**Alpha2**	**Alpha2**	**Alpha3**	**Alpha1**	**Alpha1**	**Alpha1**	**Alpha1**	**Alpha2**
Lithology											
Facies		Mixed	Red Algae	Mixed	Red Algae	Large Foram.	Mixed	Reef	Mixed	Reef	Large Foram
Mineral density											
Rhos		2.731	2.728	2.762	2.735	2.728	2.728	2.724	2.719	2.712	2.732
Saturation state during the first loading up to 170 bar of mean effective stress											
Oil	*%*	100	100	100	95	95	90	70	70	0	0
Brine	*%*	0	0	0	5	5	10	30	30	100	100
Porosity at initial effective reservoir stress condition (70 bar of mean effective stress)											
Φ	*%*	36.5	25.7	34.7	39.2	29.4	37.5	31.8	31.7	17.9	26.8
Porosity at 170 bar of mean effective stress											
Φ	*%*	35.9	25.4	34.3	37.1	28.6	34.5	31.1	30.8	17.8	26.3
Pore compressibility at 170 bars of mean effective stress											
Cpp	$10^{-4} bar^{-1}$	2.20	0.97	1.19	6.69	2.78	6.32	3.53	2.63	0.41	1.82
Cam-Clay parameters											
$\mathbf{P_{c0}}$	*bar*	181	200	218	121	178	121	185	178	347	245

At the end of the test, in order to analyse the elasto-plastic behaviour of the same sample under various fluid type saturation, the oil-saturated samples were unloaded, and reloaded again up to 400 bars three times, unloaded then brine-flooded and then loaded again up to 650 bar. Figure 1 shows clearly the brine effect on the rock: when unloaded and reloaded up to 400 bar, the oil-saturated sample behaves elastically. In other word, the pore volume exhibits the same trend (phase 3 on Fig. 1). However when the sample is water-flooded and reloaded (phase 4) the pore volume variation curve does not superimpose the previous trend and exhibits a stronger decrease before reaching 400 bars. Plastic behaviour appears since 200 bars of mean effective stress. As soon as brine is present, the sample suffers additional and irreversible deformation.

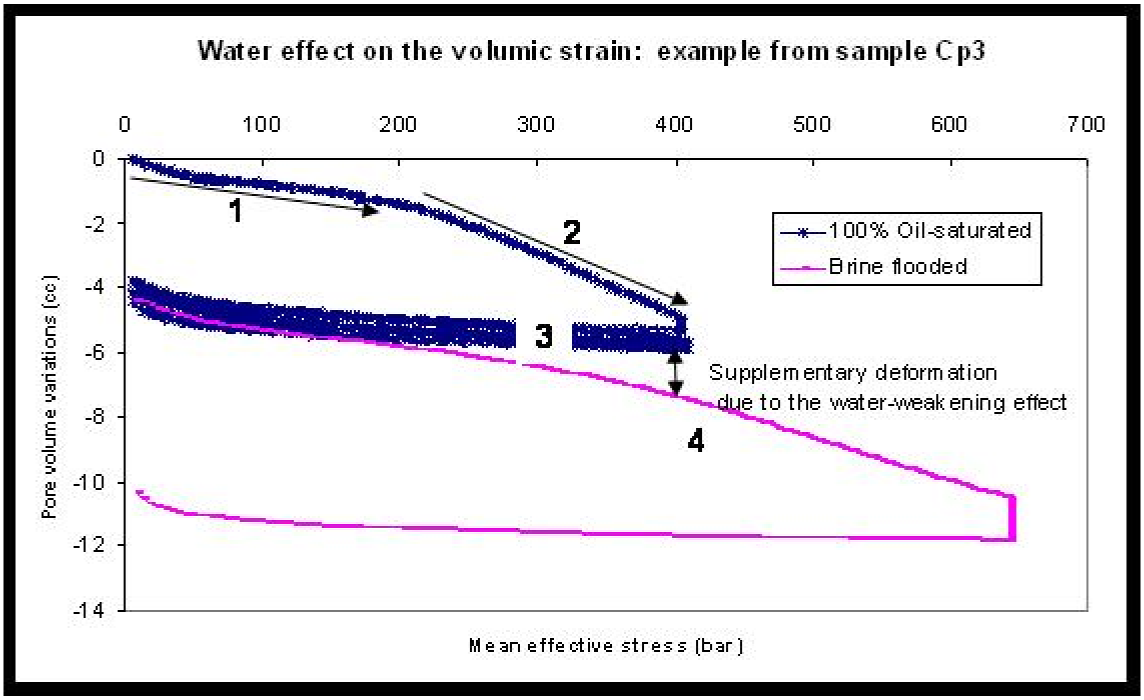

Figure 1. Compaction curve for Cp3 *(1 = elastic deformation, 2 = plastic deformation, 3= unloading, reloading, 4 = reloading but brine flooded)*

Cam-Clay model

Under isotropic stress condition, the Cam-Clay (short of CAMbridge CLAY) model [4] admits that both the elastic and the plastic variations of the void ratio vary linearly with ln P' (P' being the mean effective stress). The slopes of the elastic and plastic consolidation lines are respectively denoted κ (swelling coefficient) and λ (compressibility coefficient) (Fig. 2).

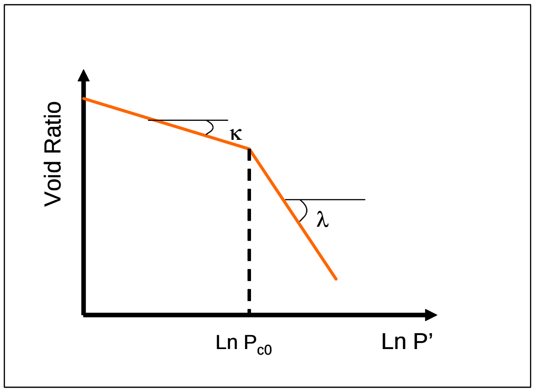

Figure 2: Compaction behaviour of a Cam-Clay material

The consolidation stress (P_{c0}) is defined as the mean effective stress corresponding to these tangents intersection. In practical terms, P_{c0} is the largest hydrostatic loading ever experienced by the material. In other words it corresponds to the stress "memory" of the rock.

Pre-consolidation stress determination

Whatever the saturation type is, the samples exhibit a clear elasto-plastic behaviour. The global behaviour of the samples can be described according two phases (Fig. 2):

1) At the beginning of the tests the samples have an elastic behaviour such that the void ratio decreases linearly with the logarithm of mean effective stress (phase 1 on Fig. 1).
2) Then the samples reach the plastic domain: the void ratio decreases also linearly with the logarithm of mean effective stress but with a higher slope than previously (phase 2 on Fig. 1).

For all the tested samples, the curves display the same behaviour as the one predicted by the Cam-Clay model. They were used to determine the model parameters. Table 2 summarizes the values calculated for P_{c0} obtained from the different tests. The pre-consolidation stress is constant for oil-saturated samples whatever their in situ porosity. With the presence of water (even for 5% water-saturated samples) the samples exhibit pre-consolidation stress values varying from 121 to 347 bar. As shown in figure 3, the pre-consolidation stress for partially to fully brine-saturated samples is inversely correlated to the in situ porosity of the samples. Obviously brine reduces the strength of the carbonates by modifying the pre-consolidation stress (P_{c0}) and increasing the plastic deformations.

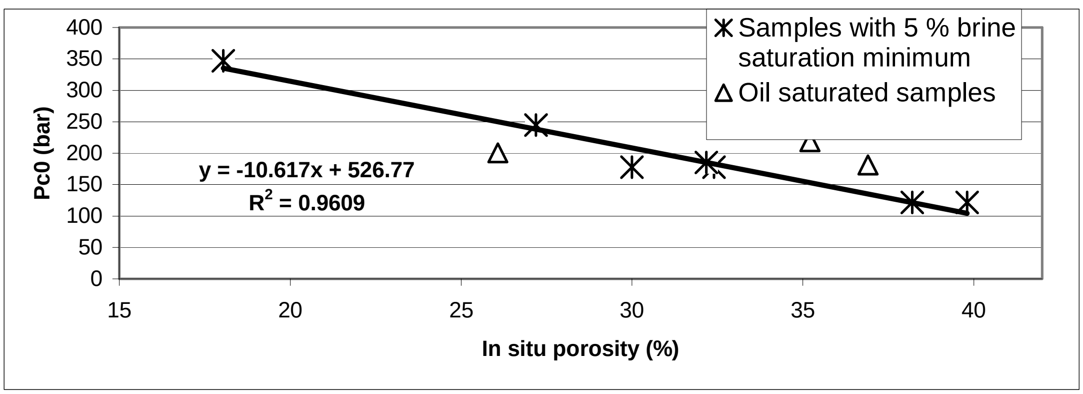

Figure 3: Correlation between pre-consolidation stress and porosity

IMPACT OF THE COMPRESSIBILITY TESTS ON THE CARBONATES

A set of thin sections was prepared before the test and compared to a second test prepared after the test was completed. This examination was cross-checked with Scanning Electron Microcopy (SEM) in order to investigate the possible lithological or architectural changes of the facies components (grains and cement) at different scales (Fig.4).

The samples were selected throughout the four main facies described (Table 2):

- Large benthonic foraminifera (named as “large foram.”): it consists of large accumulation of *Lepidocyclina* or *Spyroclypeus* associated with bioclastic debris as smaller foraminifera, echinoderms, mollusks pieces of branching red algae (Fig.5A).
- Red algae (named as “red algae”): it consists of the accumulation of crustose coralline algae (*Melobesoidae*) as rhodoliths (Fig.5E). The associated cortege comprises abundant encrusting foraminifera, bryozoans, echinoderm debris and mollusks. A part of this micrite is of endostromatolitic nature ensuring a minimal binding for the sediment.
- Reef or Coral facies (named as “reef”): hermatypic coral has been identified as preserved forms or debris. Corrallinacean and cyanophycean algae play a major role at this stage binding loose coral fragments.
- Mixed facies (named as “mixed”): in several occurrences, it is rather unclear to determine one of the above mentioned facies (Fig.5H) and may refer to a highly disorganized patch reef or near reef facies.

For all these facies, matrix consists of minute bioclastic debris, micrite clots or bridges binding grains and scattered microsparite or dolomite crystals (Fig.5C). Dolomite content varies from 1 to 35% of the original rock. Few vugs are partly cemented by microspar. As a general statement, porosity remains high for these rocks, testifying for minor burial and minor diagenetic changes.

The comparison of the two thin section sets leads to several observations:

- Large benthonic foraminifera exhibit a remarkable loss of volume. Original facies (Fig.5A) shows micritization of the walls, internal cells coated by thin rim cement with remaining open porosity space. Cells shape exhibits centrifugal convexity. The external shape of the foraminifer is partly coated with a thin rim cement often discontinuous made of small euhedral calcite crystals. After stress (Fig.5B), the changes are characterized by a shortening of the micritized pillars, a drastic pore volume reduction of the cells with a partial disappearance of internal calcite coating (probably related to pressure-solution) and a crushing characterized by convexity inversion, becoming centripetal. The rim cement coating the external shape of the foraminifera is generally broken, calcite crystal are partly re-mobilized within the new “matrix” and apparently partly leached.
- Red algae appears less susceptible than the foraminifera to volumetric changes. After stress (Fig.5F), Red algae appears preserved compared to foraminifera, their internal structure prevents from collapsing. Nevertheless, associated encrusting foraminifera show frequent loss of porosity by reduction of their cells volume.
- Coral remnants do not show a specific change, they moved within the matrix, participating to the general compaction due to stress.
- After the brine saturated test (Fig.5D), the matrix appears compacted with a drastic loss of volume. Micritic binding is broken and grains compacted with some evidence of pressure dissolution. Isolated dolomite or calcite crystals are locally forced into softer grains

(Fig.5G, Fig.5H). Microsparite rims are frequently mechanically and/or chemically disrupted. After stress, dolomite rhombohedra look preserved under microscope, but SEM examination (Fig.4D) evidences some changes. The dolomite rhombohedra are displaced and develop abnormal contacts with other grains.

An observation made under SEM on several samples complete and precise the microfacies analyses. The photos below (Fig.4) illustrate the recurrent differences encountered in the rock structure before and after brine-saturated test. It shows particularly evidences of microporosity loss within the micritic cement (4A versus 4B) and fracturing for dolomite and calcite crystals (4C versus 4D).

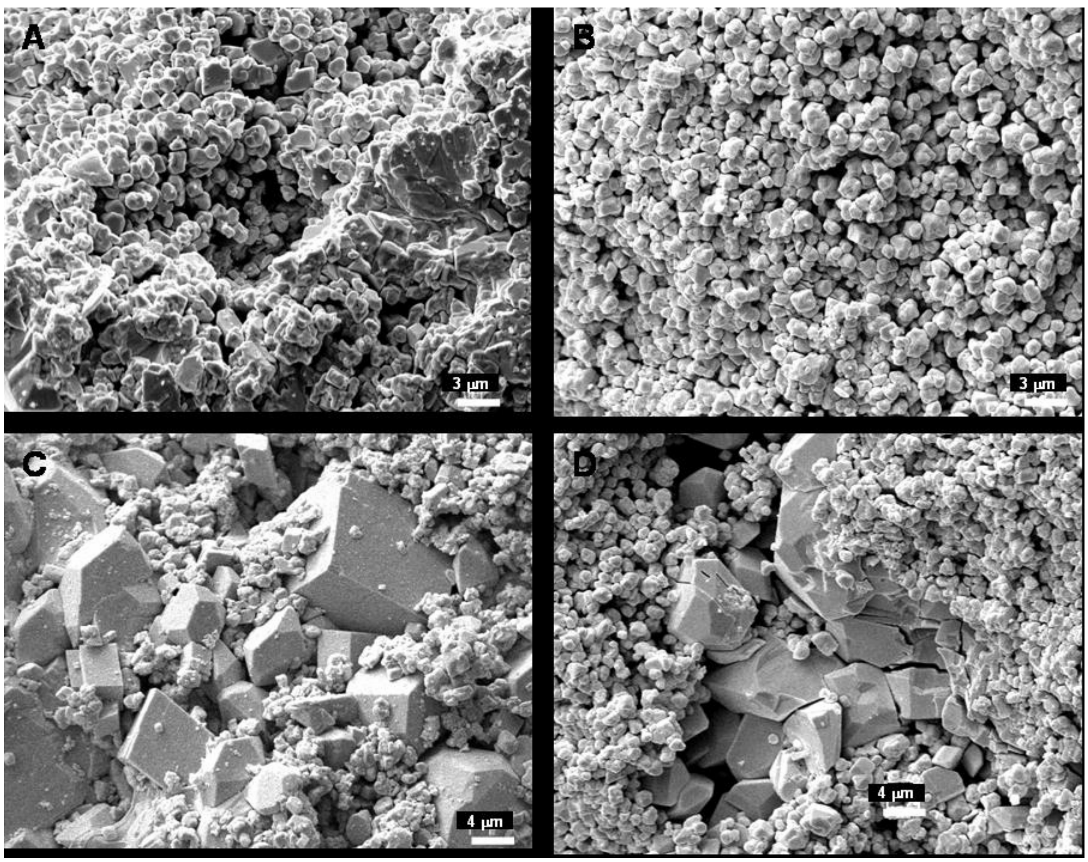

Figure 4: SEM photos. ***A:*** *Cp8 before test,* ***B****: Cp8 after brine-saturated loading,* ***C****: Cp4 before test,* ***D****: Cp4 after brine-saturated loading*

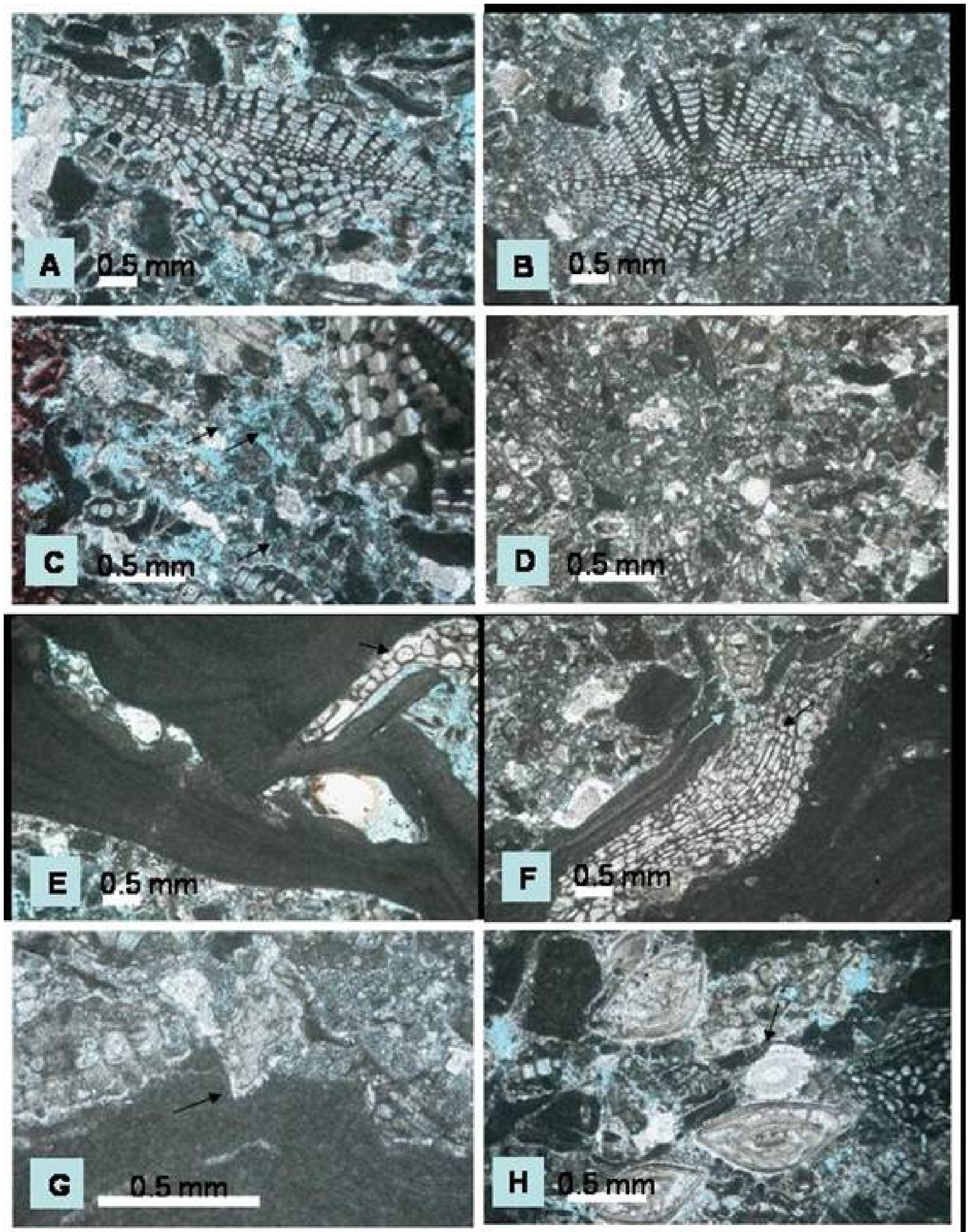

Figure 5: Photomicrographs of thin sections. **A** –Cp1, Mixed. Large benthic foraminifera (*Lepidocyclyna*) before stress. High porosity appears in blue. **B** -Cp1, Mixed. Shows the same sample after brine-saturated test. The foraminifera chambers have suffered compaction, pillars appear prominent, micritic bridges have been crushed and, the porosity is reduced. Microsparite cement lining the foraminifera is disrupted and participates to the matrix. **C** -Cp1, Mixed. Porosity is quite high; the rock is mostly cemented by micritic bridges (Arrows). **D** -Cp1,

Mixed. Under brine-saturated stress, the micritic bridges are easily destroyed. Porosity decreases dramatically. **E** -Cp2, Red Algae. Before stress, rhodoliths appear as composite red algae balls with encrusting foraminifera with irregular cells, often globular (arrow). **F** -Cp2, Red Algae. After brine-saturated test, rhodolith small size cells look apparently unchanged. However outer layer is broken (light blue arrow) and peripheral encrusting foraminifer cells exhibit a volume decrease (black arrow). **G** –Cp1, Mixed. After brine-saturated test, some grains are interpenetrating other bioclastic remnants (black arrow), along with a disorganization of the rim cement. **H** – Cp2, Red Algae. After brine-saturated test, porosity is less reduced here if compared to the previous 5B or 5D microphotographs. Abundance of grains prevents from crushing; interpenetrations of the grains provide a more rigid framework with possible incipient pressure solution (black arrow).

DISCUSSION

The series of tests presented above shows that oil-saturated Alpha samples are stiffer than water-saturated samples despite the residual water saturation contained in oil-saturated samples (estimated to 1-2%). This water-weakening effect was well documented in the last decades with the subsidence and well instability problems experienced by the North Sea chalks [5-6-7-8-9]. These experimental works on Alpha reservoir rocks show that this phenomenon not only affects reservoir chalk but more widely carbonated reservoirs with preserved or enhanced porosity.

Experiments on Alpha samples were performed at various saturation states. The pre-consolidation stress (P_{c0}) gives a good indication of the rock structure alteration. P_{c0} corresponds to the highest mean effective stress experienced by the material. All the samples being broadly at the same depth and having suffered the same geological and therefore stress history they should have the same pre-consolidation stress. As expected, test results show that P_{c0} is constant for oil-saturated samples whatever their in situ porosity. However, as soon as water saturation reaches 5%, P_{c0} is not a constant value anymore but varies significantly from a sample to another. The intrinsic properties of the rock are clearly modified with the presence of water. It is in agreement with the conclusions raised from the observation of the thin sections and SEM images before and after test. After being water-saturated tested, the rock has clearly lost part of its structure with evidence of broken micritic bonding, disrupted microsparite rims and even fractured dolomite or calcite crystals.

The fact that the pre-consolidation stress and the plastic compressibility for water-rich samples are strongly correlated to the in situ porosity but not to the water content raises two important points: as soon as the water weakening mechanism is activated, the phenomena is independent of the water content of the sample and the severity of the sample weakening is linked to the water accessibility onto the grain surface.

Since the 90's new studies and specific mechanical tests on chalk gave new insights on the possible mechanisms at the origin of the water-weakening. Capillary forces were one of the micro-mechanism proposed in the literature to explain the weakening phenomena [10-11]. The principles behind the capillary forces theory are that surface tension of water menisci between grains creates a structural bond. Nevertheless our results show that water weakening is activated since 5% of water saturation. The same threshold saturation was observed during experiments on chalk [12]. It is in contradiction with the fact that water saturations of 5-10% are generally considered optimum for the mechanism of capillary suction [13].

Hellmann et al. (2002) [14-15] have enlarged the debate by supporting a mechanism based on pressure solution. The pressure solution mechanism is of chemical origin with stress-enhanced reactions between water and calcite. During our brine-saturated tests, the saturating lab brine (analysed at the end of each loading phase) did not exhibit any significant variations of chemical composition or pH. However, microscopic traces of dissolution such as partial disappearance of internal calcite, and grains compacted with some evidence of pressure dissolution, were visible from thin sections on the samples after brine-saturated test. This phenomenon occurs at a very tiny scale. Nevertheless even such partial and microscopic dissolution could be sufficient to induce the breakage of micritic bridges between the grains, and grain to grain sliding.

In addition to this chemical process, the adsorption pressure mechanism [12] may contribute strongly to the deformation. This mechanism is based on the supplementary stress added to the grains by the adsorbed water molecules on the grain surface. Such purely mechanical phenomenon is consistent with the homogeneous deformation of the foraminifer’s cells as well as the fracturing of the dolomite crystals occurring during loading of the brine-saturated sample. However this micromechanism is difficult to demonstrate by experiments or imaging techniques. Only the mathematical transcription of the stress redistribution at the grain scale and a precise knowledge of the molecules interactions at grain surface could validate or invalidate this hypothesis. If adsorption pressure is confirmed to be the preponderant mechanism, reservoir saturation state and above all rock wettability will become critical in predicting carbonate mechanical behavior.

CONCLUSIONS AND TECHNICAL CONTRIBUTIONS

The results of this work suggest that the mechanical properties of some carbonated reservoirs are strongly dependent on the saturating fluid type. The chemical nature of the pore fluid plays a crucial role in determining the compressibility. These results and their impact in the reserves prediction lead to two important technical conclusions:

- Laboratory compaction test procedure should be adapted for carbonates. Tests have to be performed by trying to reproduce the in situ saturation state and when possible the wettability of the reservoir.
- Any changes of saturation state during the reservoir production history (such as water injection) should be taken into account. The right pore volume compressibility corresponding to this saturation state should be used in reservoir modeling.

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