

## STRESS DEPENDENCE OF THE CEMENTATION EXPONENT

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### *Abstract*

The effects of simulated reservoir stress conditions on the cementation exponent of various outcrop sandstone samples and synthetic glass-beads samples were investigated. It was found that the cementation exponent can increase or decrease with increasing stress, dependent on sample porosity. The stress dependence of the cementation exponent of glass-beads samples turned out not to depend on porosity. The different behaviour of sandstone and synthetic samples is qualitatively explained by different types of grain to grain contacts. To assess the impact of these findings on core analysis, core data were compared with those obtained on the outcrop sandstones. The trends found with outcrop sandstones could be confirmed with the reservoir sandstones. The impact of these findings on hydrocarbon assessment is especially important for low porosity rocks ( $\phi < 12\%$ ). The results show that laboratory measurements at in-situ stress conditions are important to reduce uncertainties in hydrocarbon estimation. It is demonstrated that outcrop sandstone is well suited for experiments intended to help to better understand core resistivity. Results obtained on synthetic samples on the other hand have to be interpreted with great care as with such samples the behaviour of reservoir rock can often not be properly mimicked.

### *Introduction*

One of the empirical Archie equations [1] relates porosity  $\Phi$  and formation resistivity factor  $F$  of a rock through the cementation exponent  $m$ :

$$F = \Phi^{-m} \quad \text{with} \quad F = \frac{R_0}{R_w}$$

$R_0$  is the resistivity of the fully brine saturated rock sample and  $R_w$  is the resistivity of the brine. In this equation, the cementation exponent is considered to be a constant, at least for one and the same type of rock. The resistivity and the porosity of a fluid-saturated rock, however, depend on stress in ways that are not fully described by the above empirical relationship. Consequently, the cementation exponent is also a function of stress. Several cases are reported in the literature of  $m$ -values that increase [2, 3] or decrease [4] with increasing stress. As the cementation exponent is needed for the estimation of hydrocarbon saturation, changes of stress having an influence on

it should be taken into account. To this end, the effects of simulated reservoir stress conditions on the cementation exponent were investigated.

*Sample selection and experimental procedure*

Different outcrop sandstones (from Bentheim, Castlegate, Darley Dale and Fontainebleau) and synthetic rock samples made from sintered glass-beads were used for this investigation (see Table 1). Synthetic samples are often used for resistivity experiments, as they offer some advantages: the samples are easy to characterise; they are guaranteed to be clay-free; crucial parameters such as porosity can be controlled; and the grain shape is regular (in most cases spherical) - as it commonly is in the mathematical models that are developed to describe rock resistivity behaviour. To illustrate the structural differences between high and low porous sandstones on the one hand and between sandstones and synthetic samples on the other hand, in Fig.1 to 3 SEM (scanning electron microscope) photomicrographs of a high-porosity sandstone sample (Castlegate outcrop, Fig.1), of a low-porosity sandstone sample (Fontainebleau outcrop, Fig.2.) and of a synthetic samples (sintered glass-beads, Fig.3) are shown.

**Table 1: List of all samples**

Sample type	Origin	sample	porosity [%]
Outcrop sandstone	Castlegate	CG11	25.55
Outcrop sandstone	Castlegate	CG21	25.26
Outcrop sandstone	Castlegate	CG31	25.57
Outcrop sandstone	Castlegate	CG41	25.18
Outcrop sandstone	Castlegate	CG51	25.90
Outcrop sandstone	Bentheim	A1y	23.17
Outcrop sandstone	Bentheim	C1x	23.27
Outcrop sandstone	Bentheim	C1y	23.21
Outcrop sandstone	Bentheim	C3x	23.19
Outcrop sandstone	Bentheim	D2y	23.30
Outcrop sandstone	Bentheim	E3y	23.11
Outcrop sandstone	Darley Dale	DDA1	15.83
Outcrop sandstone	Darley Dale	DDB2	14.91
Outcrop sandstone	Fontainebleau	F11	6.68
Outcrop sandstone	Fontainebleau	F12	6.28
Outcrop sandstone	Fontainebleau	F31	7.21
Outcrop sandstone	Fontainebleau	F51	7.55
Synthetic sample	Glass-beads	K1i	19.23
Synthetic sample	Glass-beads	K2i	18.45
Synthetic sample	Glass-beads	WI	34.31
Synthetic sample	Glass-beads	WII	20.17
Synthetic sample	Glass-beads	WIII	13.42

Prior to any measurement, all samples were cleaned by hot extraction. Thereafter the sample porosity at ambient conditions was determined by the buoyancy method. The formation resistivity factor and the porosity were determined as a function of isostatic stress during the same loading cycle. For this purpose the brine-saturated rock sample was mounted inside a pressurised rubber sleeve between two plungers (Hassler-type core holder). The pore pressure was drained to 1 atmosphere. The confining isostatic stress on the sample was increased stepwise up to a maximal stress value of 700 bar. The vertical displacement of the sample as a function of stress (due to compaction) was measured by a displacement transducer. The change of the pore volume as a function of stress was monitored via the amount of expelled brine displayed in a burette. The resistance of the sample was measured with a resistivity bridge connected to two blackened platinum electrodes mounted on the sample ends. For each loading step equilibrium was waited for before recording the data. The brine resistivity was measured separately. All measurements were performed at room temperature. From the thus obtained data, the changes in formation resistivity factor, porosity and cementation exponent with stress were calculated.

### *Results and Discussion*

For all samples, porosity and formation resistivity factor were determined as a function of isostatic stress up to 700 bar. Table 2 lists the relative changes in porosity and formation resistivity factor between 50 and 700 bar. The variations in the relative decrease of porosity with increasing stress are small for the different sandstones, whereas big differences in the relative increase of the formation resistivity factor are observed.

**Table 2: Relative change in porosity and formation resistivity factor as a function of stress**

sample type	% change in porosity between 50 and 700 bar	% change in F between 50 and 700 bar
Castlegate	-7%	+11%
Bentheim	-4%	+5%
Darley Dale	-8%	+20%
Fontainebleau	-7%	+100% to +300%
Glass-beads	-4% to -6%	+1.5% to +4%

The respective relative changes in formation resistivity factor and porosity with stress determine the stress dependence of the cementation exponent. In Fig.4, porosity, formation resistivity factor and cementation exponent as a function of stress for Castlegate (as an example for a sandstone with high porosity) and Fontainebleau (as an example for a sandstone with low porosity) are shown. Note that even small porosity

contrasts between different samples from one type of sandstone are reflected in their resistivity behaviour.

The stress dependence of the cementation exponent of the sandstones samples is clearly governed by porosity. In Fig.5 the change in cementation exponent between 50 and 700 bar is plotted versus the initial porosity of the measured samples. The data points for sandstone samples more or less follow a curve that is crossing the zero line between 15 and 20%. For samples with lower porosity than ca. 15% an increase of the cementation exponent with stress is observed, whereas for samples with higher porosities than ca. 20% a small decrease is obtained. The non-linear increase in the dependence of the cementation exponent on stress for decreasing porosity suggests similarity with a percolation threshold phenomena proposed elsewhere [5].

For the glass-beads samples, stress showed to exert a similar effect on porosity as for the sandstone samples. The increase in the formation resistivity factor with stress, however, was considerably smaller for the glass-beads samples than for any sandstone sample and did not depend on the initial porosity (see Table 2), resulting in a likewise porosity-independent decrease of the cementation exponent with stress (Fig.5).

Considering the differences in microstructure between the various sample types, a qualitative interpretation of the observed features can be attempted: The resistivity of a rock sample is strongly determined by shape and distribution of pores and pore throats. Sandstone samples show irregular pore shapes (Figs.1 and 2) and tangential grain to grain contacts, forming pore throats. Particularly at low porosity, these grain to grain contacts control the pore structure (Fig.2.). The stress-induced closure of such a tangential contact, cutting off a certain conductivity path completely, can have a much more drastic influence on resistivity (without affecting porosity very much) than the mere decrease of pore diameter in the big pores of a high-porosity sandstone. For low-porosity sandstones a critical number of tangential grain to grain contacts might be exceeded, resulting in the observed drastic increase in resistivity.

Synthetic samples show mostly well defined pore throats (see Fig.3), which are, due to their convex shape, not very susceptible to stress. These differences in grain to grain contacts illustrate, why an increase of stress reduces porosity in rather the same way for high and low porous sandstones and for synthetic samples, whereas the effect on resistivity is much more pronounced for those type of contacts present in sandstones and predominating low-porous sandstones.

#### *Impact on core analysis*

To investigate the representativeness of the results obtained on outcrop sandstone for reservoir sandstone, the measurements were compared to data obtained earlier from core analysis on reservoir rocks. In Fig.6 the formation resistivity factor is plotted versus the porosity for all different samples and for different stress values. The data points obtained from a particular sample follow a common trend with respect to stress, regardless of whether the sample came from an outcrop or a core. The shifts between

samples are presumably caused by microstructural differences. The huge effect of a small porosity decrease on the formation resistivity factor of low-porosity samples is again illustrated by this graph - note the change in slope at ca  $\phi=12\%$  which supports once more the existence of a critical porosity value [5].

Further analysis of the data revealed that the core samples show also a change in sign of the stress dependence of the cementation exponent, which is related to their initial porosity. In Fig.7 the change in cementation exponent with stress is plotted versus the initial porosity of the samples. Again, the stress dependence of the cementation exponent is more important at low stress; therefore the data have been evaluated separately for two stress regimes (Fig.7.a: ambient conditions to 100 bar, Fig.7.b: 100 bar to 700 bar). From Fig.7.a it can be seen that the data points for sandstone and core samples follow a curve that crosses the zero line at around 20% porosity. In most cases samples with lower porosity exhibit an increase of the cementation exponent with stress, whereas samples with higher porosities exhibit mostly a decrease. Although a trend is clearly observed, it is shifted for some types of samples, suggesting a dependence on lithology.

#### *Impact on saturation estimation*

The Archie equations (see above) [1] describe also, how the saturation exponent  $n$  mediates the relation between the resistivity index  $I$  (the ratio between the resistivity of the partially water saturated to that of the fully water saturated sample) to the water saturation  $S_w$ :

$$I = S_w^{-n}$$

The graph in Fig.8 compares the water saturation  $S_w$  (as obtained from the second Archie relation with  $n=2$ ) with the 'corrected' water saturation  $S_w'$ . The corrected and uncorrected water saturations have been calculated using the Archie equations. The correction factor depends on the difference in cementation exponent as a function of stress as shown in Fig.7.

The obtained results reinforce the importance of performing laboratory measurements at representative stress conditions (corresponding to in-situ stress). Errors of more than 10% in terms of hydrocarbon saturation can easily be introduced for low-porosity rocks when resistivity measurements are not performed at representative stress conditions.

#### *Conclusions*

- The cementation exponent of sandstones depends on stress, the sign and the magnitude of the dependence being related to porosity.
- The effect of stress is particularly important for sandstones with low porosity.

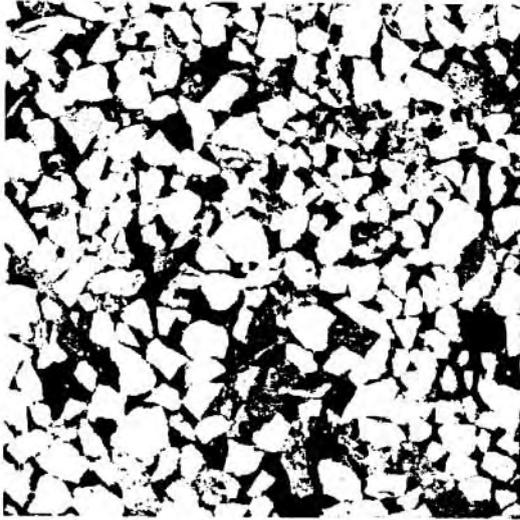
- Below a certain critical porosity value (around 12%) the resistivity and thus the cementation exponent exhibit a strongly non-linear dependence on stress, suggesting the presence of a threshold phenomena.
- Laboratory measurements of rock resistivity should preferentially be performed at simulated reservoir stress conditions. Significant errors in terms of hydrocarbon saturation can be introduced when resistivity measurements are performed at non-representative stress conditions.
- The results suggest that outcrop sandstone samples are very well suited for resistivity measurements that can be related to cores.
- On the other hand, results obtained with synthetic samples which are often reported in the literature, have to be interpreted with great care, as such samples are not necessarily representative of core material.

#### *Acknowledgements*

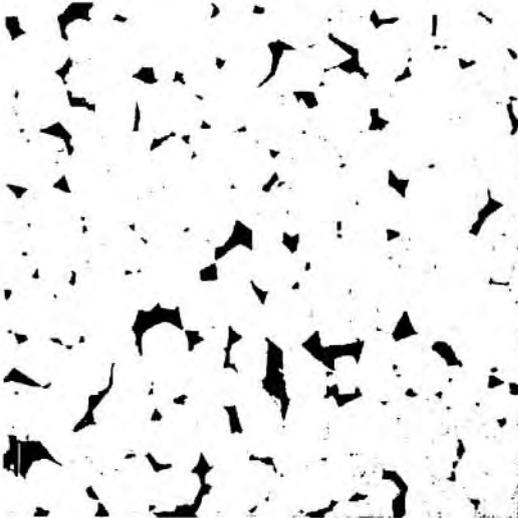
The author thanks Shell Internationale Research Maatschappij B.V. for granting the permission to publish this paper.

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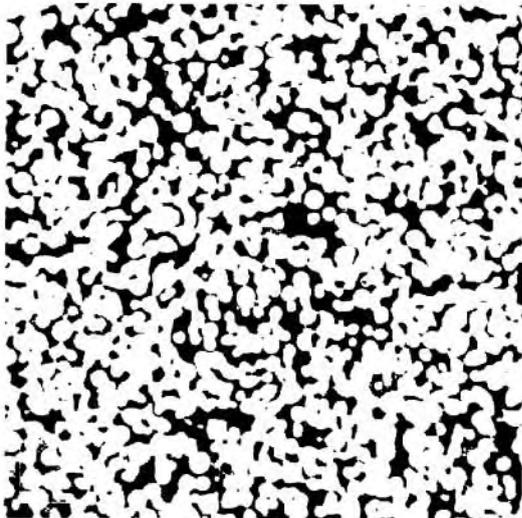
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**Fig. 1 SEM photomicrograph of Castlegate sandstone (porosity 25.5 %).**



**Fig. 2 SEM photomicrograph of Fontainebleau sandstone (porosity 6.3 %).**



**Fig. 3 SEM photomicrograph of a synthetic glass-beads sample (porosity 20 %).**

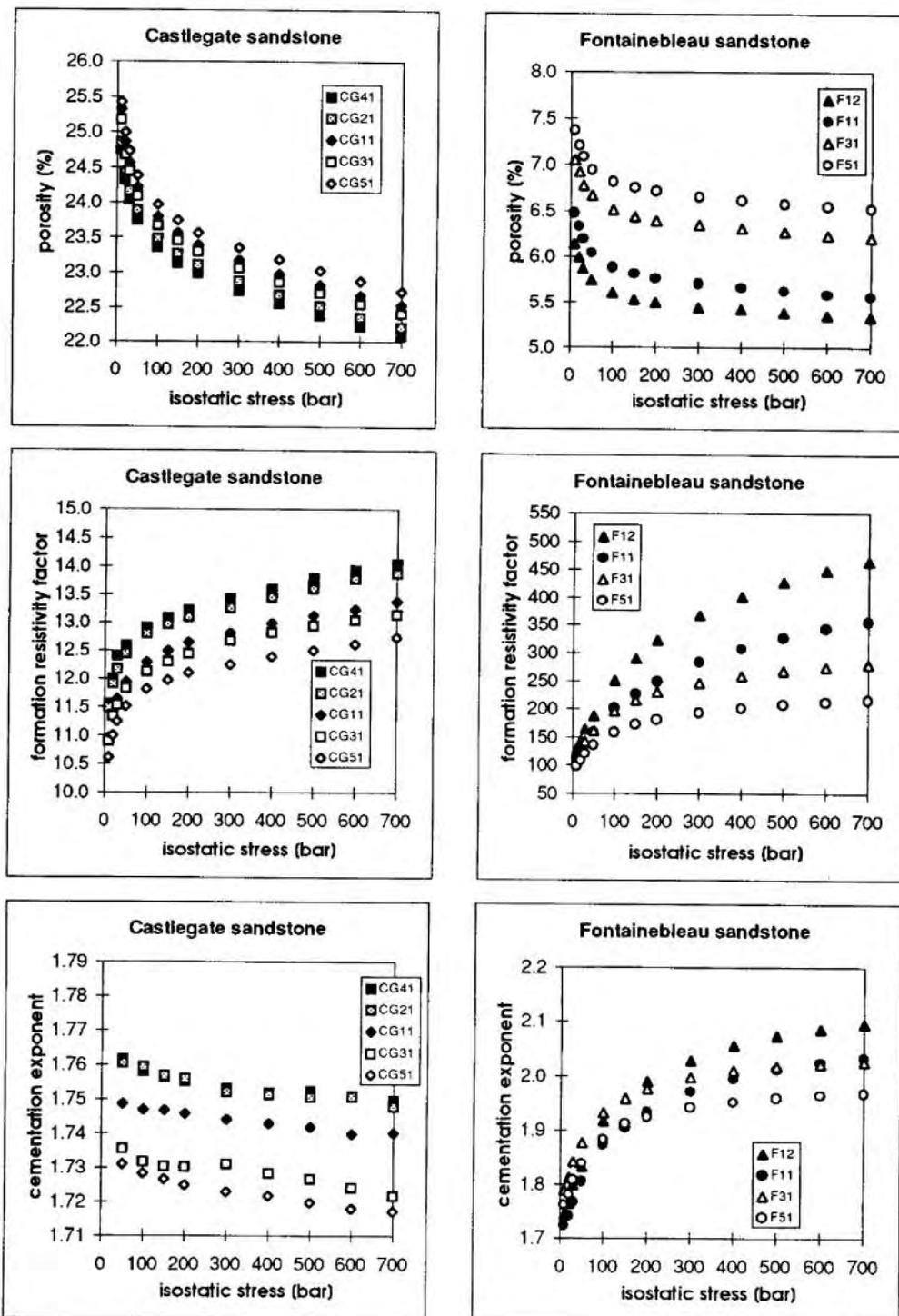
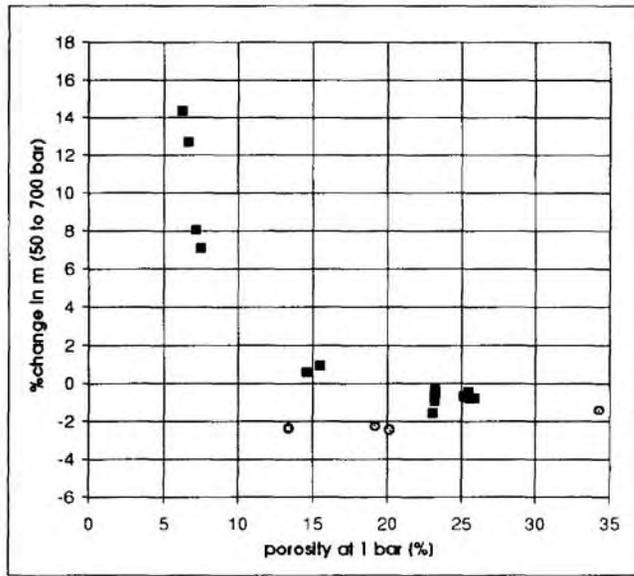
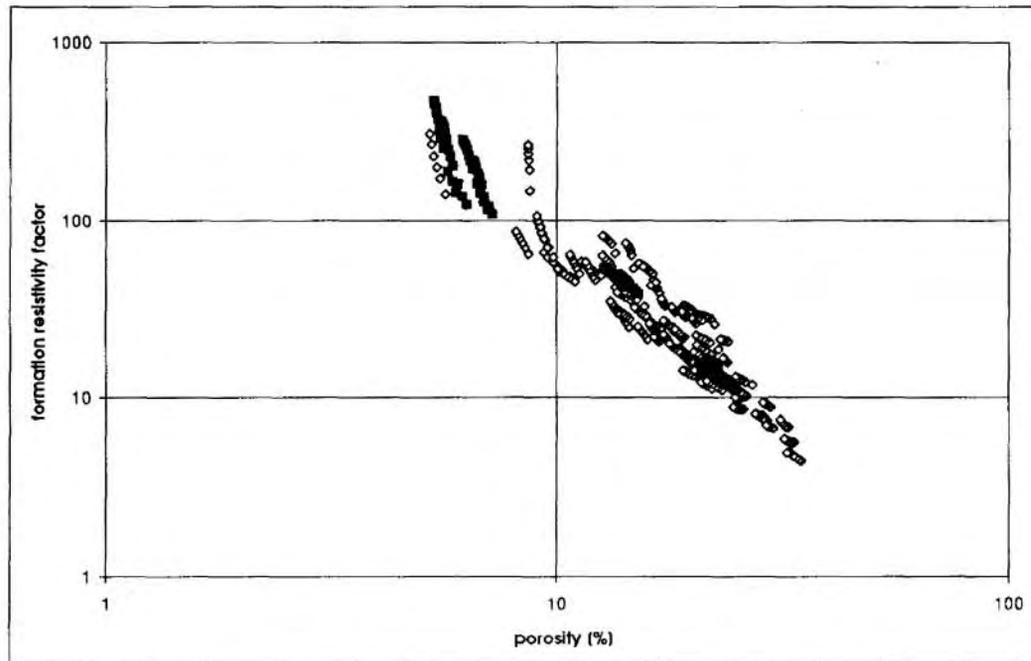


Fig.4. Porosity, formation resistivity factor and cementation exponent as a function of isostatic stress for Castlegate and Fontainebleau sandstone samples



**Fig.5**  
*Relative change in the cementation exponent between 50 and 700 bar, plotted versus the porosity at atmospheric conditions for sandstones (black squares) and synthetic samples (grey dots)*



**Fig.6.**  
*FRF vs. porosity for different outcrop sandstone samples (black squares) and for core samples of various origin (thombs); every data point corresponds to a fixed value of stress, every sequence of data points belongs to one sample, the only variable within the series being stress*

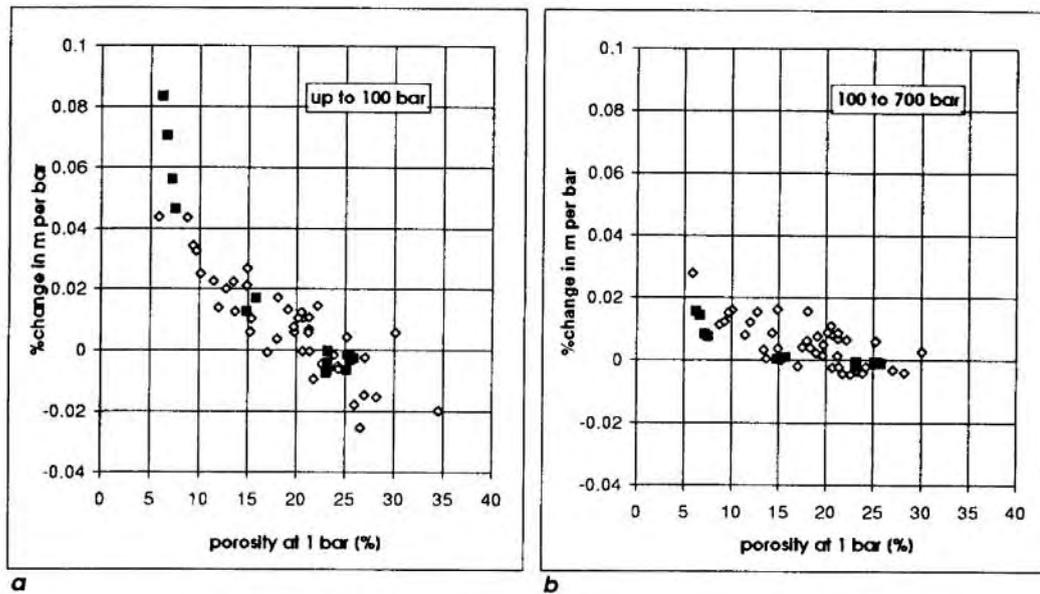


Fig. 7. Percentage change in cementation exponent per bar as a function of ambient porosity; Fig. 7.a shows the stress regime from ambient conditions up to 100 bar, Fig. 7.b from 100 bar up to 700 bar; black squares represent sandstone samples, rhombes represent core samples from various reservoirs

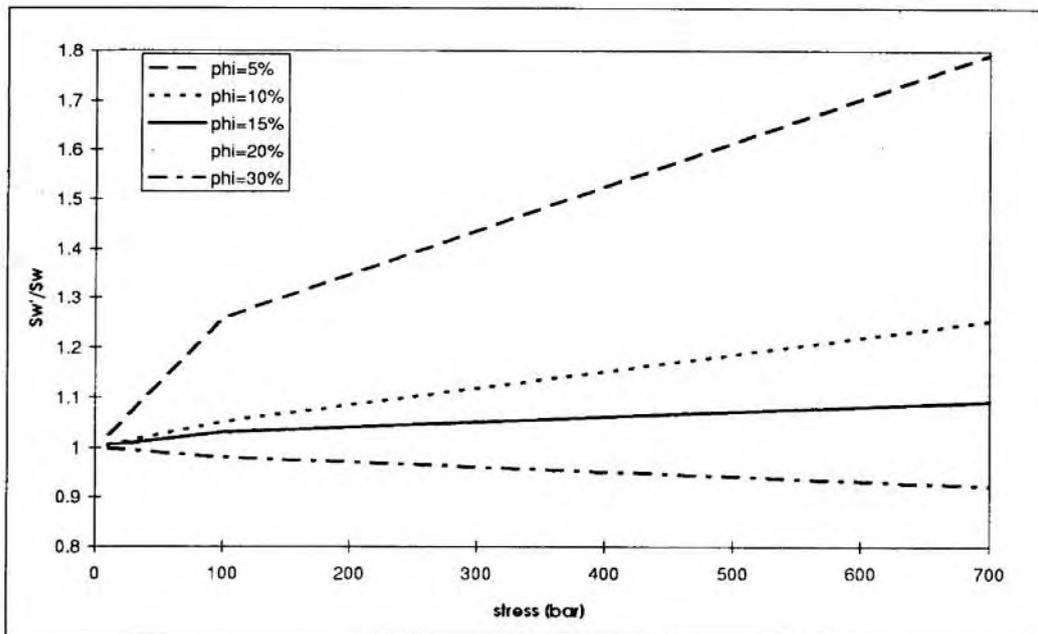


Fig. 8. Ratio of the water saturation corrected for the stress dependence of  $m$   $S_w^c$  to the uncorrected water saturation  $S_w$ , plotted versus the effective isostatic stress for various porosities