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Fluid Flow Properties of WAG Injection Processes

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Abstract

Immiscible water-alternating-gas (IWAG) experiments performed on equilibrated fluids are summarised together with the corresponding two-phase gas-oil and water-oil displacements.

Experimental studies at reservoir condition and also mechanistic experiments over many years have shown accelerated oil production and higher core flood oil recovery as a result of three-phase flow. The three-phase effects that are included and analysed are; trapped gas, and mobility for secondary processes (ex. water after gas injection). The oil recovery from the different oil recovery processes represented by; gas, water, and WAG core displacements are also compared. The oil recovery has been related to the trapped gas saturation, and the efficiency of the trapped gas on oil recovery is found to be varying with core wettability. Experimental results have shown that both gas and water relative permeability generally is reduced during three-phase flow.

Multivariate analysis has been used to investigate relations between variables like Sgt = f(k, φ, Sgi, krw^e), Sorm = f(k, φ, WI, Sorw, Sgt) and Sorg = f(k, φ, WI, Sorw, krg^e). The paper tries to address the question of what three-phase parameters influence oil recovery, and how these parameters are related. This is an important question for modelling and optimising the WAG process.

Introduction

The oil recovery method water-alternating-gas (WAG) has proved to be a successful way to improve oil recovery compared to pure water injection or pure gas injection. An increased oil recovery in the order of 5-10 percent of the initial oil in place has been reported as a typical effect[1,2].

The success of this injection method has several different explanations. WAG injection improves oil recovery by better sweep efficiency on both macroscopic and microscopic levels compared to gas injection or waterflooding. The macroscopic sweep is improved both in the horizontal and vertical direction. The water restricts the mobility of the gas which influences the horizontal sweep, and the vertical sweep is improved because the gas segregates to the top and the water slopes to the bottom. Microscopic displacement efficiency is improved because the residual oil saturation after gas injection is lower than after water injection and in the three-phase zone the residual oil saturation can be even lower than after gas injection. The trapping of gas and water in the three-phase zone near the injection well may influence the local pressure field and lead the injection fluids towards new pathways, i.e. an improved microscopic sweep.

An extensive database, accumulated over many years, is analysed containing fluid flow data for WAG special core analysis from different reservoir cores (from the North Sea and the Norwegian Sea) and outcrop rock (Berea). The three-phase data consist of sequential flows, like initial water-, secondary gas- and tertiary water injection (W1G2W3) and initial gas-, secondary water- and tertiary gas injection

(G1W2G3), and data from WAG experiments (short slugs of gas and water injected). The database also includes primary two-phase data represented as initial water injection (W1) and initial gas injection (G1).

Three-phase data and the connection between three-phase variables are investigated. WAG data is compared to sequential flow, W1G2, W1G2W3, W1G2W3G4, G1W2 and G1W2G3, and these three-phase experiments are compared to two-phase data. Multivariate analysis is also used to examine relations between three-phase variables.

Results and discussion

Three-phase effects - Residual oil saturation for different processes and wettabilities. Earlier results have shown that the residual oil saturation after WAG flooding, Sorm, is significantly lower than for water- or gas injection [3-5]. As seen from figure 1 and 2 the data considered in the current paper confirm these findings for WAG vs. gas injection or water flooding.

Secondary processes, secondary gas after primary water injection or secondary water after primary gas injection, has been shown to mobilise additional oil and results in lower oil saturation than the primary processes.[3] This conclusion is confirmed by the all data in table 1 independent of wetting state or rock properties.

The flooding experiments on a water wet core (E6) in figure 3 show Sor for a primary process (highest Sor), secondary processes (lower Sor) and WAG (lowest Sor).

The results of comparing Sor and wettability for different processes suggest that maximum oil mobilisation can be achieved when gas is injected first in a water wet core (G1W2G3), as seen in figure 4. It has previously been reported that minimum oil saturation is lower when gas is injected first in an immiscible WAG process[3]. Data for the sequence starting with water (W1G2W3) show the opposite behaviour; higher oil recovery for more oil wet cores when water is injected first. This can also be seen from figure 3 where the water wet core shows lower residual oil saturation when gas is injected first (G1W2) compared to a sequence starting with water (W1G2). Residual oil saturation for intermediate wet cores have previously been shown to have little dependence on which phase is injected first in a WAG scenario[4]. This is confirmed by figure 4 where the trends intersect near neutral wettability.

The microscopic displacement efficiency of gas injection is higher at a more neutral or slightly oil wet wettability than for a water wet situation, as seen in figure 5. This trend has also been observed earlier[4,6].

Trapped gas, Sgt. Residual oil saturation is lower when trapped gas is present during a water flood, when compared to water flood with no trapped gas[7]. Data from an earlier paper[4] suggest that the sum of residual saturations for oil and gas show a tendency towards being equal to the residual oil saturation after water flooding,

$$\text{Sorw} = \text{Sorm} + \text{Sgt}. \qquad (1)$$

A simple relationship that quantifies the effect of trapped gas, eq. 2, has been used in several earlier papers[7]. The effect of gas trapping in this data summary is shown in figure 6, and has been used to calculate the constant R, table 2.

$$\text{Sorw} = \text{Sorm} + R * \text{Sgt}, \qquad (2)$$

Water wet cores have a values ranging between 0,36 and 1,00. Weakly water wet cores have lower a values, ranging between 0,32 and 0,92, and cores with neutral wettability have somewhat lower values, ranging between 0,00 and 0,85. This suggests that the effect of trapped gas on three-phase residual oil can be very efficient at any wettability, but there is a trend to less impact of trapped gas as wettability shifts towards more oil wet condition. These observations are consistent with the conclusions from several other

papers[7-11], but are opposite to the behaviour reported recently by Caubit et al[6]. Different parameters influencing residual oil saturation will be further discussed in the multivariate section.
For secondary water injection the value of R range from 0,00 to 1,00, for tertiary water injection from 0,32 to 0,85 and for WAG from 0,55 to 1,00. The data indicate that WAG injection gives the highest effect of trapped gas on residual oil.

The literature on both two-phase and three-phase flow suggest that the trapped gas saturation is strongly dependent on the maximum gas saturation during the displacement process[3,11]. The data in the current paper also show a strong relation between trapped gas and initial (maximum) gas prior to trapping, as seen in figure 7 and 8.

The data is plotted together with different values of C (constant of Land type). The Land type constant[12] is given as

$$C = \frac{1}{S_{gt}} - \frac{1}{S_{gi}} \quad \text{, where} \qquad (3)$$

Sgt is the trapped gas saturation and Sgi is the initial gas saturation.

The average C value and average Sgt value for different processes are listed in table 3. Comparison of the C values gives:

$$C(W2) > C(W3) > C(WAG). \qquad (4)$$

The low C value estimated from the WAG processes could be due to the fact that the initial gas saturation is only measured before the last water cycle, and can therefore possibly be underestimated.

The average Sgt values for W3 and WAG processes are approximately the same whereas the average Sgt value for W2 is higher. This could be influenced by the maximum gas saturation being higher during a W2 process than for W3 and WAG processes. The difference between two-phase and three-phase gas trapping has been extensively discussed in the literature[6-8,13-15]. In several papers the trapped gas saturation for two-phase is higher than for three-phase[8,10,11,13], while other papers have found that trapped gas saturation is equal for two- and three-phase[6, 14, 15]. There is currently no explanation for the non-consistent trend, but in general two-phase trapped gas is always higher or equal to the three-phase trapped gas.

Relative permeability. If water or gas relative permeability is reduced in three-phase flow, the reduction is considered to be reduced flowing fraction of the phase due to three-phase trapping. When examining end-point relative permeabilities it can be concluded that the data show reduced mobility in the three-phase flow situation (three-phase hysteresis) both for krw(Sorm) < krw(Sorw) and for krg(Sorm) < krg(Sorg). However, as the endpoint saturation may vary for the individual processes, the conclusion is not trivial to describe in figures or tables. To explain the results further a method has been applied that compares the relative permeability at the same phase saturation. Using linear extrapolation the endpoint relative permeability for W1 can give an apparent endpoint relative permeability at the endpoint saturation for the W2 and W3 processes. This procedure makes it possible to compare relative permeability for the different processes from only endpoint information. In addition the numerical difference between the endpoint relative permeability, ex. krw^e, from primary processes to a three phase process quantifies the reduced three-phase relative permeability.

As an example, a positive value for the kr difference between the measured value for krw^e at W1 and the calculated apparent value for W3 could indicate three-phase hysteresis in krw. All the core floods except E5 and E8 show significant signs of three-phase hysteresis for W3, as seen from figure 9. E5 shows no hysteresis and E8 has a negative value for difference with respect to W3. The core in E5 is water wet and the wettability for E8 is not known. For W2 only the five first floods have values and three of them indicate lower permeability in presence of trapped gas. The core floods E5 and E2 show negative delta values. E5 is as mentioned water wet, but E2 is more oil wet. For strongly water wet cores other papers have stated that the wetting phase is primarily a function of the wetting phase saturation[3, 11]. More oil wet cores have generally showed stronger three-phase hysteresis[5, 11].

Analysis of the relative permeability for gas shows that four of the core floods have strong three-phase relative permeability reduction. The data showing this relationship for krg^e at G3, are E1, E4, E5 and E18 The method for comparing endpoints as described earlier has also been applied to gas relative permeability data. The difference between the calculated and measured value for krg indicate three-phase hysteresis for all G3 and WAG cases, and lower permeability in presence of gas in all but the E1 case for G2, as seen in figure 10. The core in E1 is strongly water wet. This analysis is in agreement with earlier results reported, where hysteresis in relative permeability was found for the non wetting phase[3]. The krg value was strongly reduced for gas injection after waterflood compared with primary gas injection[3]. The E1 case is in agreement with the previous indication of only small changes in relative permeability between initial and tertiary gas injection for water wet cores, but more strongly reduced relative permeability for oil wet cores[11].

Multivariate analysis. Multivariate analysis was performed to explore the parameters influencing residual oil saturation and the relation between the parameters, figures 11, 12 and 13. A previous paper has also considered multivariate analysis to investigated connections between three-phase parameters, but for different parameters like experimental measured differential pressure and with a different objective of correlating directly measured quantities and derived parameters from unsteady state core floods[16].

Sgt = f(k(abs), φ, WI, Sgi, $krw^e/krw^e(W1)$*):* The relation between Sgt and k, φ, WI, Sgi and krw^e (normalized) was investigated. The analysis within the limitation of multivariate method shows that Sgt is positively correlated to Sgi and krw^e. The dependency of Sgi has been discussed earlier, but to a more surprise strong correlation of higher Sgt for high krw^e was found, though, the results agree with our earlier reported trend[7] of lower trapped gas at less water wet condition.

Sorm = f(k(abs), φ, WI, Sorw, Sgt): The dependence of three-phase residual oil saturation, Sorm, on the parameters k, φ, WI, Sorw, and Sgt was analysed. Sorm was found to be positively correlated to Sorw and negatively correlated with Sgt. These results fit well with the relation[7] Sorm = Sorw – R * Sgt and papers stating that trapped gas will result in lower residual oil saturation[3,6,7].

Sorg = f(k(abs), φ, WI, Sorw, krg^e*):* Sorg was found to depend on porosity and was negatively correlated with krg^e. This could indicate that cores with high porosity have more trapping of gas. The relation between low Sorg and high krg^e is as expected from the general shape of the relative permeability curve.

Conclusions

Comparison and analysis of WAG related data indicate the following trends:

- Residual oil saturation after WAG flooding is significantly lower than for water- or gas injection.
- Secondary processes result in lower oil saturation than primary processes.
- Minimum oil saturation is lower when gas is injected first in a sequential flow (G1W2G3) in a water wet core, and minimum oil saturation is lower when water is injected first in a sequential flow (W1G2W3) in a more oil wet core.
- Residual oil saturation after initial gas injection is lower for more oil wet cores than water wet cores.
- Trapped gas the strongest effect on the residual oil saturation in water wet cores.
- WAG injection gives higher impact of the trapped gas on residual oil than W3 and W2 processes.
- There is a strong relation between trapped gas saturation and initial (maximum) gas saturation.
- The average trapped gas saturation is higher for two-phase than for three-phase.
- Three-phase hysteresis is found for the water relative permeability in some of the core floods.
- Significant three-phase hysteresis is found for gas relative permeability in almost all cases, but a strongly water wet core show less hysteresis.
- The three-phase hysteresis effect for gas relative permeability is greater than for water relative permeability

Multivariate analysis:

- Trapped gas, Sgt is related to Sgi, k(abs) and krw^e.
- Three-phase residual oil saturation, Sorm seems to be correlated with Sorw and negatively correlated with Sgt and k.
- Residual oil saturation after gas injection, Sorg was strongest correlated to porosity.

Acknowledgement

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Nomenclature

R: Constant expressing the ability of trapped gas to reduce residual oil saturation
C: Land constant
k(abs): Absolute water permeability
krg^e: End-point gas relative permeability
krw^e: End-point water relative permeability
WI: Amott wettability index
Sgi: Initial gas saturation
Sgt: Trapped gas saturation
Sor: Residual oil saturation
Sorg: Residual oil saturation after gas flooding
Sorw: Residual oil saturation after water flooding
Sorm: Three-phase residual oil saturation
φ: Porosity

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Table 1: Residual oil saturation for different processes.

Dataset	Experiment	G1	W2	G3	W1	G2	W3	G4	WAG	WAG
1	E1	0,213	0,079	0,075	0,44	0,438	0,391			
2	E2	0,236	0,158	0,156	0,147	0,141	0,089			
3	E3	0,334	0,302		0,324	0,226	0,225		0,245	0,2244
4	E4	0,23	0,18	0,17	0,32	0,24	0,24		0,21	
5	E5	0,23	0,201	0,191	0,377	0,359	0,303		0,194	0,141
6	E6	0,35	0,16		0,28	0,18			0,05	
7	E7	0,069	0,069		0,213					
8	E8	0,157			0,265	0,05	0,05	0,025		
9	E9				0,14	0,06	0,04	0,04		
10	E10				0,17	0,07	0,07	0,04		
11	E11				0,111	0,111				
12	E12	0,265		0,086						
13	E13	0,275	0,139							
14	E14	0,302	0,241							
15	E15	0,296	0,26							
16	E16	0,152		0,07					0,039	
17	E17				0,284	0,113	0,111		0,094	
18	E18	0,275		0,139						

Table 2: The effect of trapped gas on three-phase residual oil represented by the constant R for different wettabilities and processes.

Wettability	**R**
Water wet	0,36 - 1,00
Slightly water wet	0,32 - 0,92
Neutral	0,00 - 0,85
Process	**R**
W2	0,00 – 1,00
W3	0,32 - 0,85
WAG	0,55 – 1,00

Table 3: Trapped gas according to the Land equation represented by the Land Constant (C) and trapped gas saturation, Sgt for different processes.

Sequence	**C average**	**Sgt average**
W2	2,77	0,2249
W3	2,28	0,19889
WAG	1,59	0,19908
Total	**2,44**	**0,21**

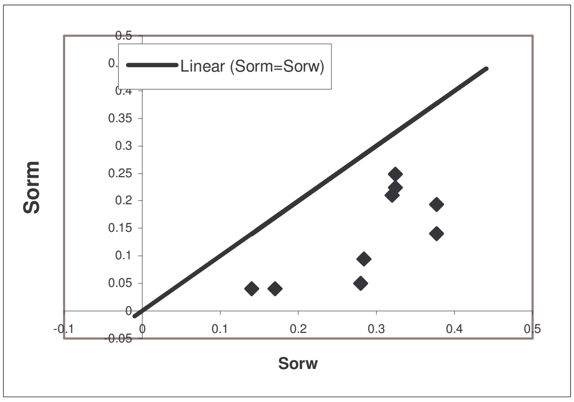


Fig. 1: Three-phase residual oil versus Sorw

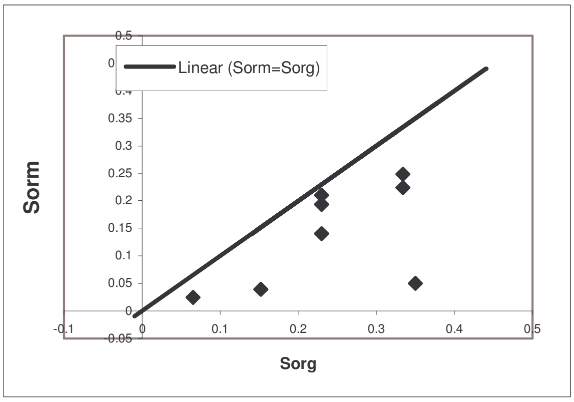


Fig. 2: Three-phase residual oil versus Sorg

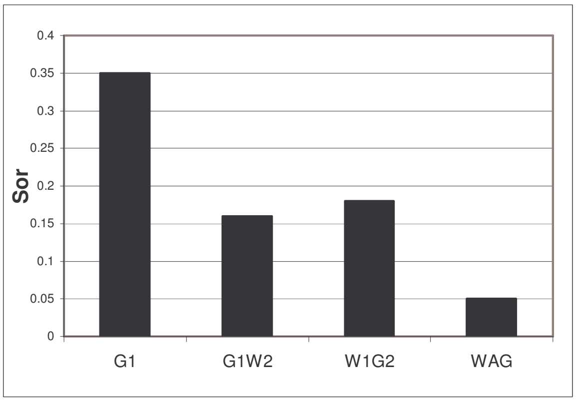


Fig. 3: Sor for different processes in a water wet core.

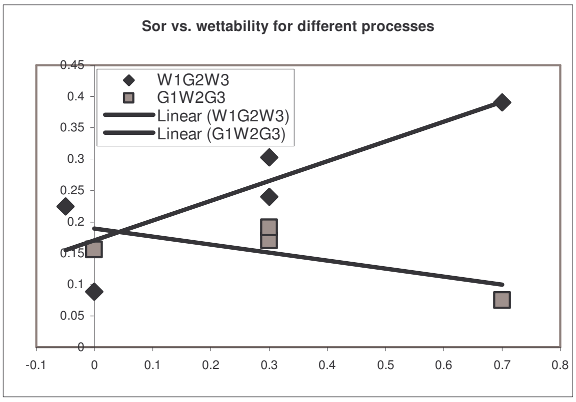


Fig. 4: Sor versus wettability for different processes.

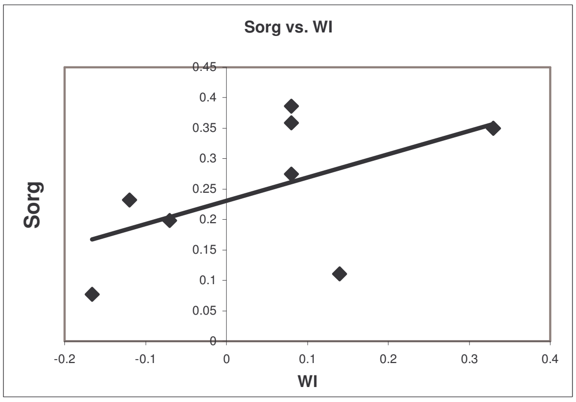


Fig. 5: Residual oil after gas inj. versus wettability,

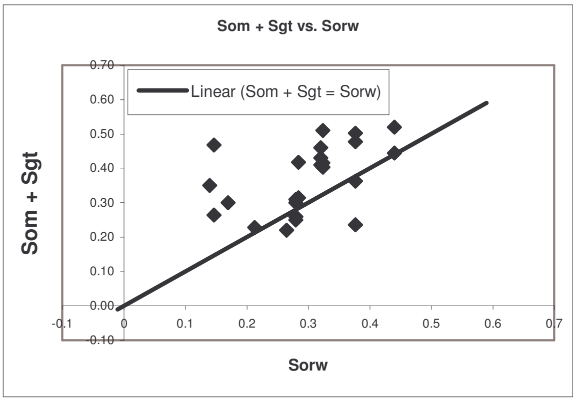


Fig. 6: Effect of trapped gas on residual oil.

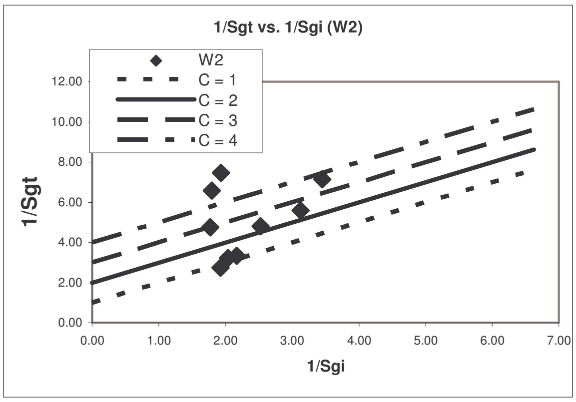


Fig. 7: Land relation (1/Sgt versus 1/Sgi) for W2.

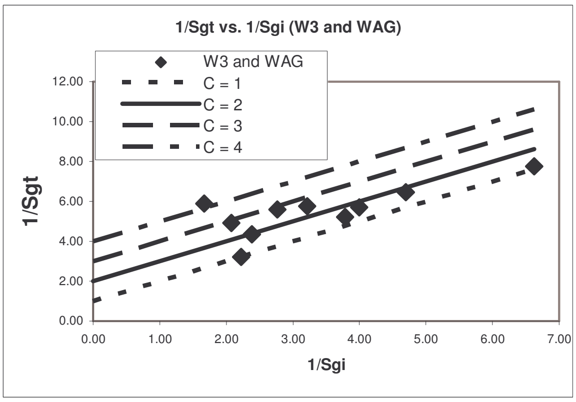
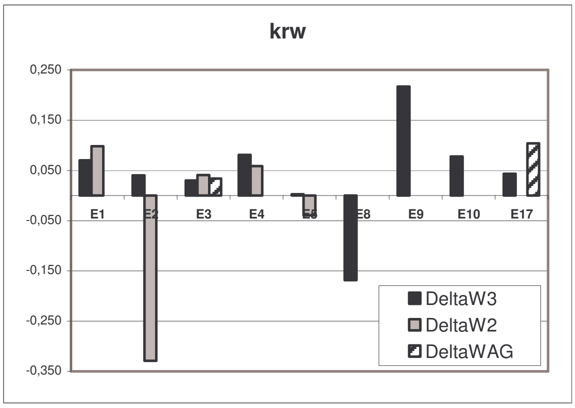


Fig. 8: Land relation (1/Sgt versus 1/Sgi) for W3 and WAG.



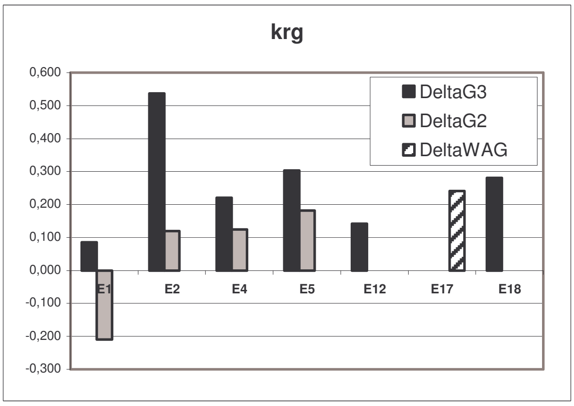
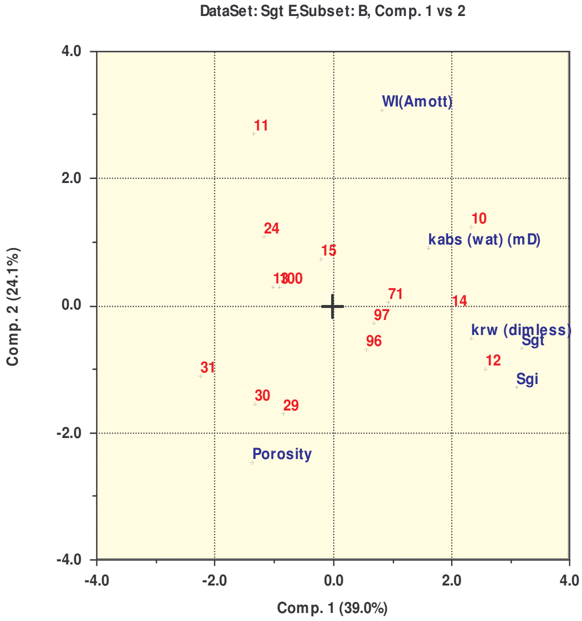


Fig. 9: Change in krw^e from W1 to. W2, W3 and WAG. *Fig. 10: Change in krg^e from G1 to. G2, G3 and WAG.*



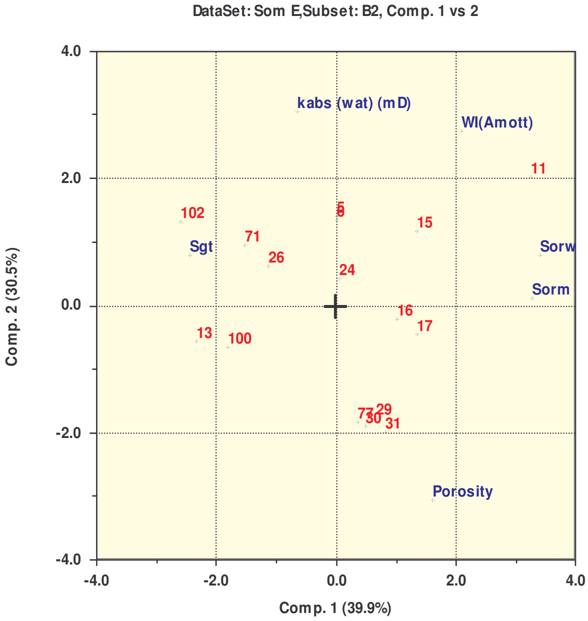


Fig. 11: Bi-plot showing Sgt is positively correlated to Sgi, k(abs) and krw^e

Fig. 12: Bi-plot showing Sorm is positively correlated to Sorw and negatively correlated with Sgt.

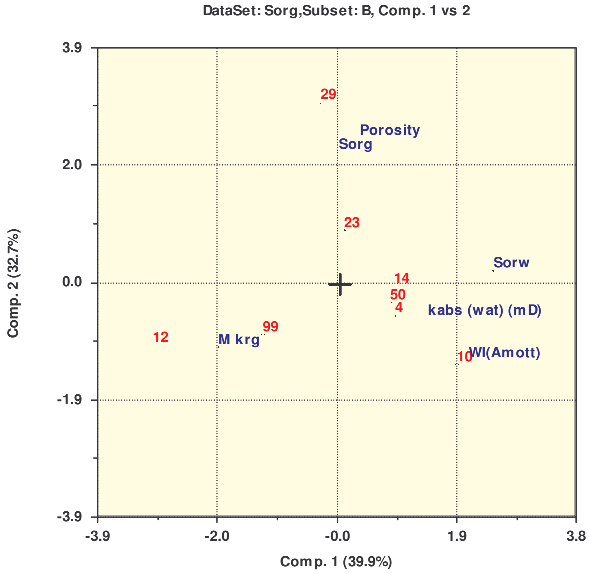


Fig. 13: Bi-plot showing Sorg is strongest correlated to porosity