# LABORATORY ACOUSTIC MEASUREMENTS FOR RESERVOIR CHARACTERIZATION: CONSEQUENCES OF CORE ALTERATION

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## ABSTRACT

Core damage effects on laboratory measured elastic wave velocities have normally been ignored, largely because of the difficulties in quantifying these effects. By manufacturing synthetic rocks under stress, we have found that stress release during core drilling has several important consequences: Unloaded cores have largely reduced velocities compared to the rock *in situ*, and an associated velocity and attenuation anisotropy. Velocities are permanently reduced with respect to their *in situ* values even when the cores are reloaded back to *in situ* conditions. Core measured stress dependence is significantly larger than for the same material under virgin conditions in the Earth. Stress release induced microcracks may cause additional dispersion contributing to laboratory measured velocities with saturated cores.

## INTRODUCTION

Laboratory measurements of acoustic wave velocities are becoming more and more important as seismic monitoring of enhanced oil recovery processes (EOR) catches ground. Since the possible effects on seismic wave propagation depend on the actual EOR process and on the actual reservoir rock, up-front, reservoir specific studies are necessary to evaluate the feasibility of a reservoir monitoring programme (Wang and Nur, 1992). Clearly, underlying assumptions of all such core tests are that:

i) the core is representative for the formation *in situ*, and

ii) test conditions in the laboratory are representative for *in situ* conditions.

Both these conditions need to be fulfilled in order for effects of pore fluid, pore pressure and temperature changes associated with an EOR operation to be quantified. Further use of wave velocity measurements for reservoir characterisation purposes all lean on the same basis of core representativeness. Such applications include amongst others calibration of seismic depths, and evaluation of rock mechanical parameters. One exception should however be mentioned: Wave velocity anisotropy of unloaded cores is a technique for *in situ* stress direction determination actually based on core alteration (Ren and Hudson, 1985).

A main benefit of laboratory measurements is that they are performed under controlled conditions. If a sufficiently advanced laboratory is available, one can completely control the conditions (as fluid saturation, external state of stress, pore pressure, temperature, and to some extent also frequency) during a wave velocity measurement. What we can not control, is the properties and history of the rock sample. It has been retrieved from a certain depth in the Earth. During retrieval, the *in situ* stress (and pore pressure) has been removed, temperature has decreased, and the core has been exposed to non-native fluids. Further, it may have been damaged by the coring bit itself, during transport, storage and sample preparation. Core damage is by definition permanent: It can not be removed by bringing the sample back to *in situ* conditions.

The aim of this Paper is to present a systematic approach to quantification of core damage effects on laboratory measured wave velocities. For this, we will use a set of laboratory experiments where the rock sample has actually been controlled; i.e. a synthetic rock sample has been tailor-made (to resemble a specific rock in the Earth) and manufactured at controlled (simulated *in situ*) stress conditions. The coring procedure has been simulated by unloading, and the unloaded sample is reloaded back to the previous stress state. Comparison is made between measured P- and S-wave velocities prior to coring (representing the *in situ* velocities), after unloading, and after reloading (representing the core data). Furthermore the stress dependence of the velocities is also measured, and again comparison is made between virgin rock and cored rock. These experiments simulate only one core damage mechanism, namely external stress release. This is believed to be most significant for loss of core quality for rock mechanics measurements in high porosity, high permeability rocks such as sandstone (Holt *et al.*, 1994). It is hence expected to be important also for elastic wave velocity measurements (Holt *et al.*, 1996). Based on these experiments, we will discuss core damage effecs on velocity measurements for evaluation of reservoir monitoring feasibility.

## EXPERIMENTAL PROCEDURES

A synthetic sandstone is made by selecting a sand with a certain grain size (and shape) distribution, mimicking that of a target reservoir sand. We present here results obtained with one specific material, where the mean grain size (by weight) is 180μm, and the distribution is designed to give a resulting porosity of about 20%. The sand is mixed with a small amount of sodium silicate solution (in the case discussed here, 15ml silicate solution is used with 160g sand to produce a cylindrical sample of 1½" diameter and about 3" length). The amount of solution and its Na:Si mole ratio controls the mechanical stiffness and the strength of the synthetic rock. The wet sand pack is loaded in a rock mechanics test apparatus to the *in situ* stress state of the target reservoir (here: 30 MPa vertical (axial) and 15 MPa horizontal (radial) stress). It is then flushed with $CO_2$ gas, which leads to precipitation of amorphous silica between the sand grains (Kiesel and van Oehne, 1982). The process is completed within a few minutes. The porosity of the synthetic rock was measured to 20.0 % using He porosimetry at ambient conditions and estimated to 19.2% at simulated *in situ* conditions. All tests have been performed with air saturated cores.

The stress path during coring is simulated as shown in Figure 1: For a vertical borehole, the vertical stress is released first, while the horizontal stress is released only after the core has entered inside the core barrel. Thus, during a certain period of time, the difference between the vertical and the horizontal stress may be large enough to cause yielding or even failure; i.e. mechanical damage of the core material. The figure also shows the stress path during reloading of the core to the *in situ* state, and subsequent uniaxial compaction testing. During the tests, which have been performed in the Formation Physics Laboratory at SINTEF Petroleum Research using a TerraTek apparatus, P- and S-wave velocities are measured at various stages along the sample axis ("vertical" direction), and the P-wave velocity is also measured across the sample diameter (radial or "horizontal" direction). Pulse transmission measurements have been performed using broadband (Panametrics) transducers operating at their centre frequency of 0.5 MHz.

## EXPERIMENTAL RESULTS AND INTERPRETATION

***Effects of unloading and reloading.***

During initial loading of the uncemented sand, wave velocities increase until the *in situ* stress state is reached. The axial and radial P-wave velocity (averaged over 6 different tests) at this stage are 2200 m/s and 1995 m/s, respectively. When cementation is completed after $CO_2$ injection, these velocities have increased to 3460 and 3325 m/s, respectively. In addition, an S-wave has appeared, with a velocity of 1805 m/s. The observed velocity anisotropy reflects the anisotropy of the *in situ* stress state. Notice that cementation increases the velocities with 55-65% and reduces P-wave anisotropy from about 10% to about 3%. The resulting velocities are in the same range as those measured from logs in the target reservoir. The average velocity values are listed in Table 1.

The effect of coring simulation is to reduce the wave velocities strongly. As can be seen from Figure 2, the axial P- and S-wave velocities decline as the axial stress is reduced (in particular when the axial stress release exceeds 10-15 MPa), whereas the radial P-wave velocity primarily decreases when the radial stress is removed. Thus, the velocity changes reflect the stress changes. After complete unloading no axially propagating waves are detected due to too large signal attenuation, but from the first measurements during reloading, it is apparent that the axial P-wave is slower than the radial P-wave in the completely unloaded specimen. Thus, the velocity and attenuation anisotropy of the unloaded core reflects the *in situ* stress state, but with the <u>slowest</u> velocity in the direction of the previous <u>maximum</u> principal stress. This confirms the basis for the Differential Wave Velocity technique proposed by Ren and Hudson (1985).

As can be seen from Figure 3, the wave velocities do not reach their previous values after completed reloading. The average axial P-wave velocity is 3050 m/s, the average radial P-wave velocity is 2950 m/s, and the average axial S-wave velocity is 1650 m/s (also given in Table 2). Thus, all velocities are permanently reduced with 9-12%. The explanation for these observations is that grain bonds have been broken during coring simulation. Most grain bonds have been broken in the direction where the unloading was a maximum; i.e. where the previous stress was largest. This explains the inverted velocity anisotropy in the unloaded specimen. Since the deviatoric stress was high during the coring simulation, grains have also been permitted to move and rearrange their mutual positions. This explains why reloading does not reinstall the previous velocities: Due to the induced shear displacements, the broken surfaces do not fit together when reloaded.

***Stress dependence.***

The static behaviour of the simulated core is also altered as a result of the unloading – reloading cycle. Two types of comparative experiments have been performed, where i) the virgin material is loaded in uniaxial strain, simulating reservoir compaction, and ii) the reloaded simulated core is loaded in exactly the same way, simulating a laboratory test on a core. In both cases, the axial stress was increased from 30 to 60 MPa. The simulated core is softer (statically) than the virgin rock Holt *et al.* (1998), in particular during the first part of the loading. This softening is related to the microcracks opened and the shear sliding induced during the coring simulation, as discussed above. In these tests, the samples were also loaded in 2 additional uniaxial compaction cycles, to see if cyclic tests on cores may be used to recapture the virgin compaction behaviour. The static stiffness in the $2^{nd}$ and $3^{rd}$ cycle is about 2 times higher than in the $1^{st}$ cycle, but is <u>not</u> representative for the virgin compaction behaviour.

Wave velocities have been measured during all uniaxial compaction cycles. In the virgin material (Figures 4 and 5), all velocities increase 2-3 % in the first cycle when the axial stress is increased from 30 to 60 MPa (see also Table 2). In the simulated core, however (also in Figures 4 and 5), the velocities increase near 10 % during the $1^{st}$ $K_0$ cycle. At high stress levels, the difference between virgin and core material is gradually wiped out. Repeated stress cycling does not change significantly the stress dependence (Figure 6): There is a slight velocity increase, in particular at low stresses for the simulated core. There is a bit more pronounced velocity decrease at low stresses for the virgin material. This must imply that grain bonds (or grains) are broken during the compaction cycles. The results indicate that stress dependence of wave velocities (e.g. King, 1966; Dvorkin and Nur, 1996) as seen by practically all published core studies of sandstone may largely be a result of core damage, and that cyclic loading does not reinstall representative *in situ* velocities nor representative *in situ* stress dependence.

***Experiments with natural cores.***

It is of course not possible to verify these findings experimentally on natural rocks unless a very detailed *in situ* monitoring programme is carried out. As an example of natural core behaviour, wave velocity measurements with a dry, vertical sandstone core from about 3000m depth are shown in Figures 7 and 8. This sandstone was cored from the reservoir simulated by the synthetic sandstone; i.e. the *in situ* stress conditions were assumed close to those used in the manufacturing of the synthetic sandstone. This particular sample had 14.6% porosity at ambient conditions; i.e. lower than that obtained with the synthetic cores. The natural core was intact and visual inspection did not show any signs of damage. Core plugs were 1 ½" diameter and approximately 3" length, as for the synthetic samples.

The velocities increase strongly during initial loading (Figure 7), as was seen with the simulated core of the synthetic sandstone in Figure 3. The axial P-wave velocity increases faster than the radial one during loading, which indicates that more coring induced (primarily horizontal) cracks are closed as a result of the *in situ* vertical stress being larger than the horizontal. After the axial stress reaches 30 MPa (which is close to the *in situ* vertical stress prior to depletion in the actual reservoir), a uniaxial compaction experiment is performed. The axial P-wave velocity (Figure 8) increases with about 5% as the axial stress is increased to 60 MPa. Qualitatively, the results agree with the stress dependency observed in the synthetic sandstone (Figures 5 and 7). Again, cycling did not lead to a significant change in velocity nor stress dependence, whereas it, as in the case of the synthetic rock, caused the static stiffness to increase by a factor of ~2. Thus, these results seem to confirm the validity of the approach taken by using synthetic rocks formed under stress to simulate core damage effects on wave velocities.

## DISCUSSION

The possibility to monitor for instance a waterflooding operation in an oil reservoir depends on the seismic contrast between the waterfront and the unswept oil. In practice, such differences may be due to (Wang and Nur, 1992):

i) the effect of water vs. oil as a saturating fluid
ii) the effect of cooling at the injection front
iii) the effect of an increased pore pressure at the injection front

Furthermore, since one is monitoring changes occurring throughout the entire reservoir during its life-time, it is important to be aware of global changes that are caused by production-induced changes in the reservoir boundary conditions, such as an altered state of stress.

The main experimental result found here is that velocities are much less stress sensitive in a virgin material than in a simulated core. This observation is valid both in loading (depletion) and unloading (repressurization) (Fjaer and Holt, 1999). All experimental data shown here are obtained with one particular type of synthetic core, formed at the simulated *in situ* stress, and tested in dry conditions. If the material is less well cemented, a somewhat larger stress dependence appears also in the virgin case, but the difference between the cored and the virgin material still persists (Holt *et al.*, 1996). If the rock in the Earth is buried deeper (loaded) after diagenesis, the stress sensitivity *in situ* is not likely to become larger, whereas after uplift (unloading), enhanced stress sensitivity may be found. The important factor here is if the rock has passed a stage where cement bonds are starting to break as a result of stress alteration from the state where diagenesis occurred; what we will refer to as a damage state. If so, stress sensitivity will result. Implicitly, this also means that a well-cemented (strong) rock is not likely to be particularly stress sensitive *in situ*. If the strong rock is encountered at a large depth, so that the stress release during coring brings it past its damage surface, then the cored rock is likely to show significant stress sensitivity. This implies that a relation between velocity and porosity may be completely erroneous if based on unloaded core specimens, as demonstrated by Rathore *et al.* (1989) in a study of similar synthetic rocks. Even reloaded cores will according to the present study not reveal the true velocity - porosity relationship. This relationship depends on the compaction and the degree and type of cementation (Dvorkin and Nur, 1996) and has not been addressed here.

As mentioned, all tests above are performed with dry core samples and no pore pressure. In reality, reservoir rocks have pore pressures, and if they are prone to EOR treatment, they will also be liquid saturated *in situ*. The effect of pore pressure reduction is not the same as of external stress increase. The effective stress principle for wave velocities is not fully understood (King, 1966; Ringstad and Fjaer, 1997). In the following we have assumed that the rock framework contributes to the P-wave velocity as a function of the difference between the external stress and the pore pressure, whereas the pore fluid contribution can be calculated by the isotropic Biot-Gassmann model (Biot, 1962; Gassmann, 1951). By doing this, wave velocity anisotropy is considered as a secondary factor compared to the fluid effect. Pore fluid properties are altered with pressure, as outlined by Batzle and Wang (1992). Using their empirical relationship, the effect of pore pressure decline was calculated for a virgin compaction experiment. The result is shown in Figure 9. The case considered is oil saturation at 100ºC, and the temperature dependence is assumed to be associated only with the fluid properties. As seen, the stress dependence of the saturated rock is even smaller than that of the dry material. The Figure also shows the effect of brine saturation, which leads to an increased P-wave velocity compared to the effect of oil. The velocity of the brine-saturated rock is only slightly temperature dependent, according to the results of Batzle and Wang (1992). If the injection front cools the oil saturated rock, the P-wave velocity will increase near the front. A temperature drop to 20ºC leads to a velocity increase of about 2% (Figure 10). Thus, the effect of different saturating fluids and the effect of cooling seem to be the main mechanisms permitting seismic monitoring of a water injection front.

This paper deals primarily with core damage aspects. The stress-release induced core damage may also affect the velocity of laboratory saturated core samples. As we have seen, cores will even after being loaded back to *in situ* conditions have permanently reduced velocities, which means that there are still microcracks present in the samples. A wave passing through a fluid saturated sample which contains microcracks will experience a larger amount of dissipation and dispersion due to local (squirt) flow between cracks and pores. This mechanism yields a higher wave velocity at high frequencies than in the absence of microcracks. This is particularly important for ultrasonic waves, which are conventionally used in laboratory tests. The transition frequency is according to Budiansky and O'Connell (1980) proportional to the 3rd power of the crack aspect ratio. The presence of cracks will thus move the transition in the direction of lower frequencies. Thus, even if the laboratory tests are carried out in the seismic frequency range, squirt flow influence on the results may occur. It is commonly observed in laboratory tests that squirt flow is the dominating attenuation and dispersion mechanism in sandstones (Winkler, 1985; Jones, 1986). It still remains to be seen to what extent this holds for a rock under virgin conditions *in situ*.

We have looked exclusively at core damage caused by external stress release. Other sources of core damage may affect wave velocities as well, such as invasion of non-native fluid, and possible degradation by local effects of thermal stress release. These mechanisms need further consideration.

## CONCLUSIONS

The experiments presented here demonstrate a systematic approach to evaluation of core damage effects on elastic wave velocities. We have found that stress release during core drilling is likely to cause large velocity reductions and associated velocity anisotropy of unloaded cores, permitting estimation of *in situ* stress directions. Permanently reduced velocities are also seen when the cores are reloaded back to *in situ* conditions. This indicates a systematic difference between velocities measured *in situ* (from seismic or log measurements) and velocities measured in the laboratory. There is however a number of other sources of such a discrepancy, like effects of frequency, temperature, and length scale.

Core damage is a main source of stress dependence of wave velocities. Using uncorrected stress dependence measured on laboratory cores to e.g. estimate changes in velocities during oil recovery for reservoir monitoring purposes is likely to yield erroneous results.

The overall advice for laboratory testing is to bring the rock as close as possible to the *in situ* state, with respect to stress, fluid saturation, temperature and measurement frequency. The velocity of a dry rock sample will be underestimated because of stress release induced damage, while the velocity of a liquid saturated rock may yield a positive bias because of microcrack induced squirt flow. Normally laboratory tests are performed at room temperature, whereas velocities measured at reservoir temperature (in particular in oil saturated rocks) may be significantly lower. Even if all these precautions are made, permanent core alteration will cause the laboratory measured stress dependency to be erroneous. In order to assess this more correctly, a theoretical model is required, based on e.g. controlled laboratory experiments like those discussed here.

## ACKNOWLEDGEMENTS

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## TABLES

Table 1: Velocities of axial P-waves ($v_{pz}$), radial P-waves ($v_{pr}$) and axial S-waves ($v_{sz}$) at various stages of the tests with synthetic sandstone and with a natural core. The numbers for the synthetic rocks are averaged over 3 virgin compaction experiments and 3 coring simulation experiments.

| | **Stress state [MPa]** | **$v_{pz}$ [m/s]** | **$v_{pr}$ [m/s]** | **$v_{sz}$ [m/s]** |
|---|---|---|---|---|
| **Uncemented sand** | $\sigma_z$=30 $\sigma_r$=15 | 2200 | 1995 | n.a. |
| **Cemented synthetic sandstone** | $\sigma_z$=30 $\sigma_r$=15 | 3460 | 3325 | 1805 |
| **Unloaded synthetic sandstone** | $\sigma_z$= 0 $\sigma_r$= 0 | < 1800 | 1800 | < 1200 |
| **Reloaded synthetic sandstone** | $\sigma_z$=30 $\sigma_r$=15 | 3050 | 2950 | 1650 |
| **Loaded ($K_0$) synthetic virgin rock** | $\sigma_z$=60 $\sigma_r$=23 | 3515 | 3340 | 1915 |
| **Loaded ($K_0$) synthetic core** | $\sigma_z$=60 $\sigma_r$=23 | 3455 | 3235 | 1835 |
| **Unloaded natural core** | $\sigma_z$= 0 $\sigma_r$= 0 | 1500 | 2040 | 1520 |
| **Reloaded natural core** | $\sigma_z$=30 $\sigma_r$=15 | 3650 | 3680 | 3040 |
| **Loaded ($K_0$) natural core** | $\sigma_z$=60 $\sigma_r$=17.5 | 3960 | 3890 | 3270 |

**FIGURES**

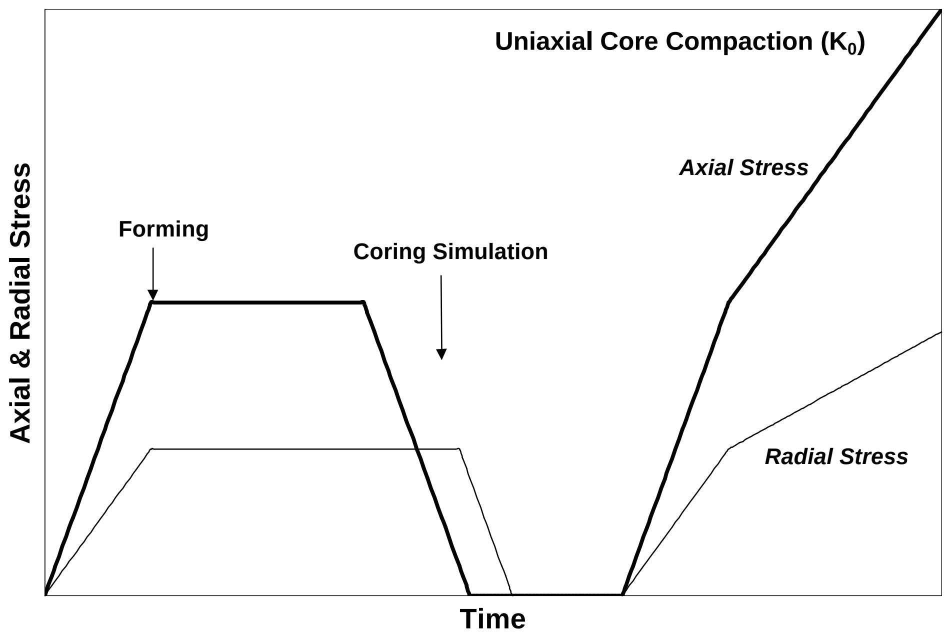


Figure 1: Stress path during forming of a synthetic sample, during coring simulation, during reloading to the previous stress state, and during a subsequent uniaxial compaction test.

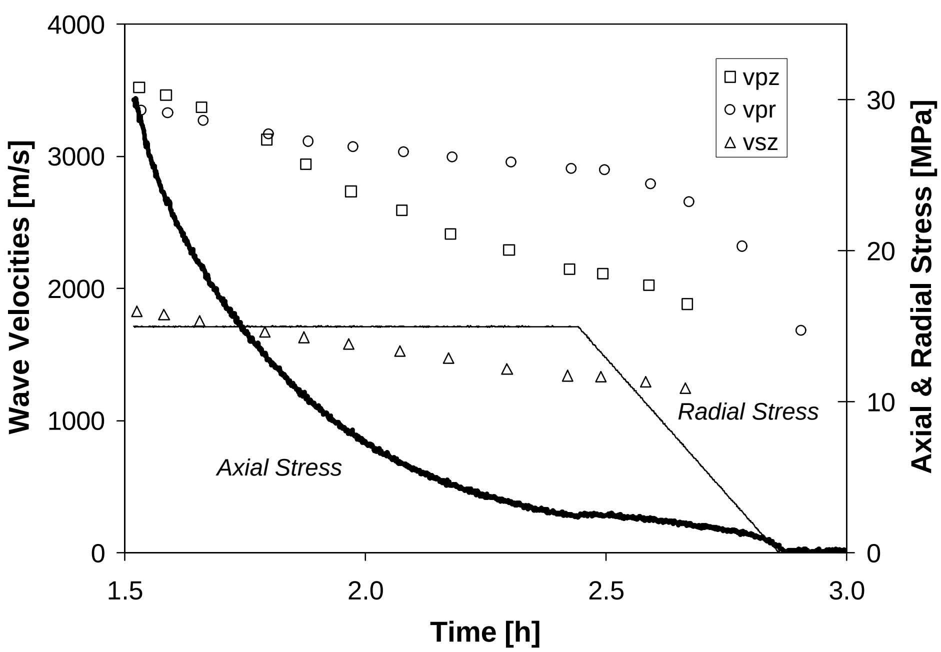


Figure 2: Axial P- ($v_{pz}$|), radial P- ($v_{pr}$) and axial S- ($v_{sz}$) wave velocities, and axial and radial stresses, vs. experiment time during unloading (coring simulation) with a synthetic sandstone formed under 30 MPa axial and 15 MPa radial stress.

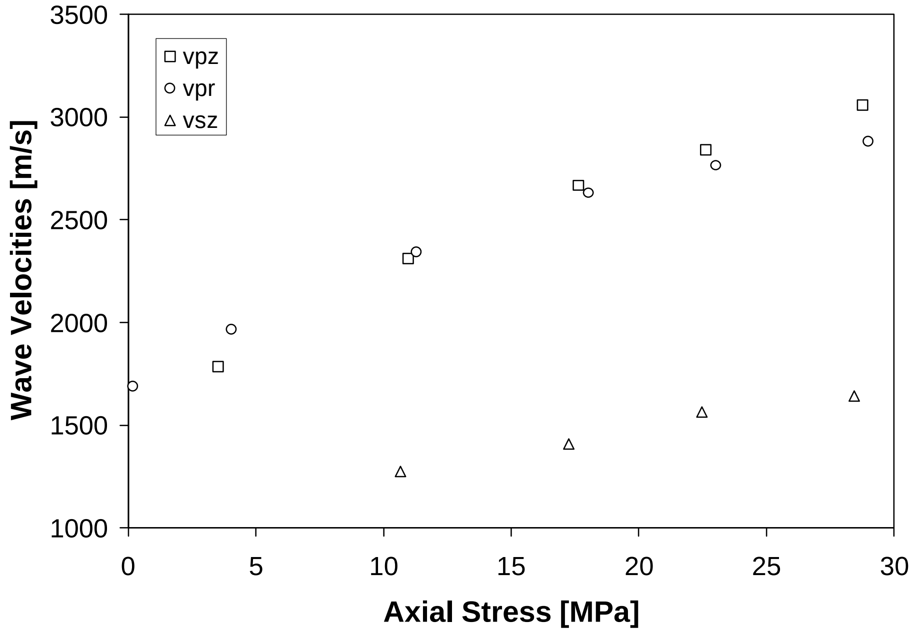


Figure 3: Axial P- ($v_{pz}$|), radial P- ($v_{pr}$) and axial S- ($v_{sz}$) wave velocities during reloading of the synthetic sandstone for which data are shown in Figure 2. The specimen is reloaded to 30 MPa axial and 15 MPa radial stress, maintaining a constant ratio of 2 between the two stresses during the whole reloading period.

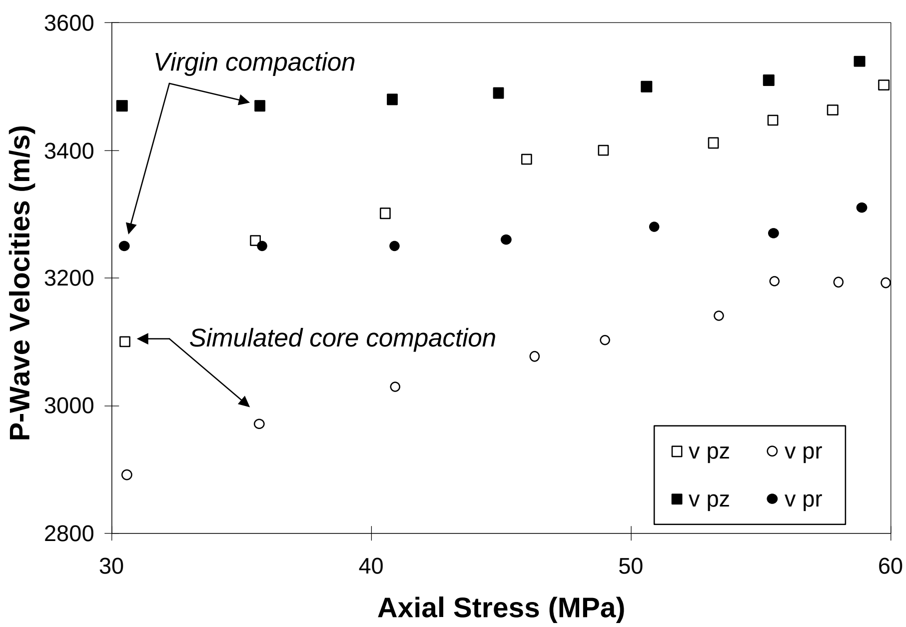


Figure 4: Axial and radial P- wave velocities ($v_{pz}$ and $v_{pr}$) vs. axial stress during uniaxial compaction of virgin (filled symbols) and simulated synthetic core (open symbols).

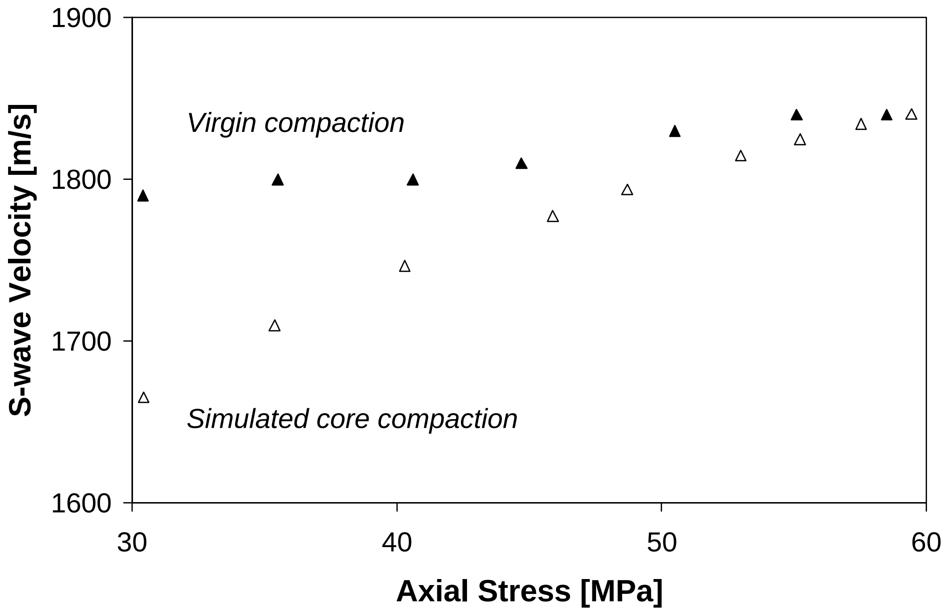


Figure 5: Axial S- ($v_{sz}$) wave velocities vs. axial stress during uniaxial compaction of virgin (filled symbols) and simulated synthetic core (open symbols).

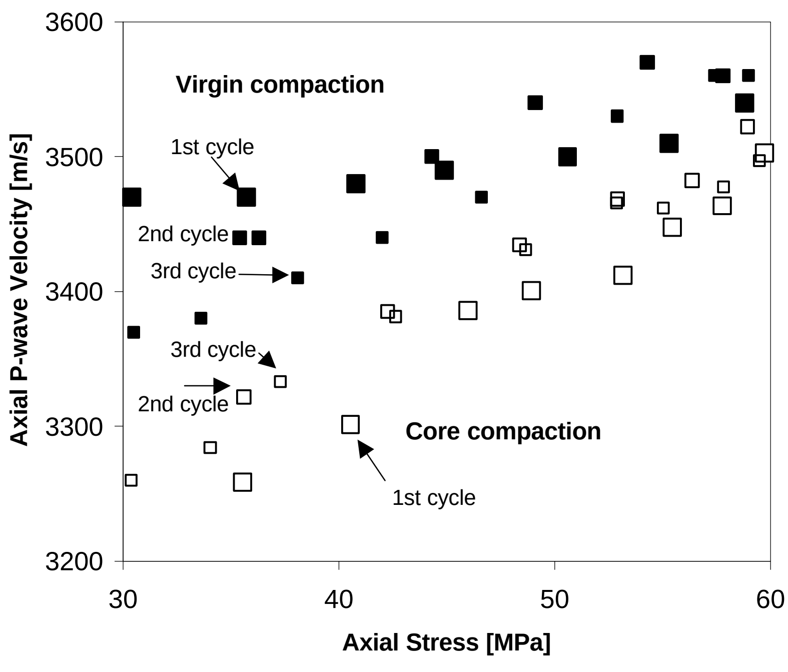


Figure 6: Axial P- wave velocity vs. axial stress during 3 uniaxial compaction cycles of a virgin material (filled symbols) and a simulated core (open symbols) of synthetic sandstone formed under stress. (Note: Decreasing symbol size with increasing cycle no.).

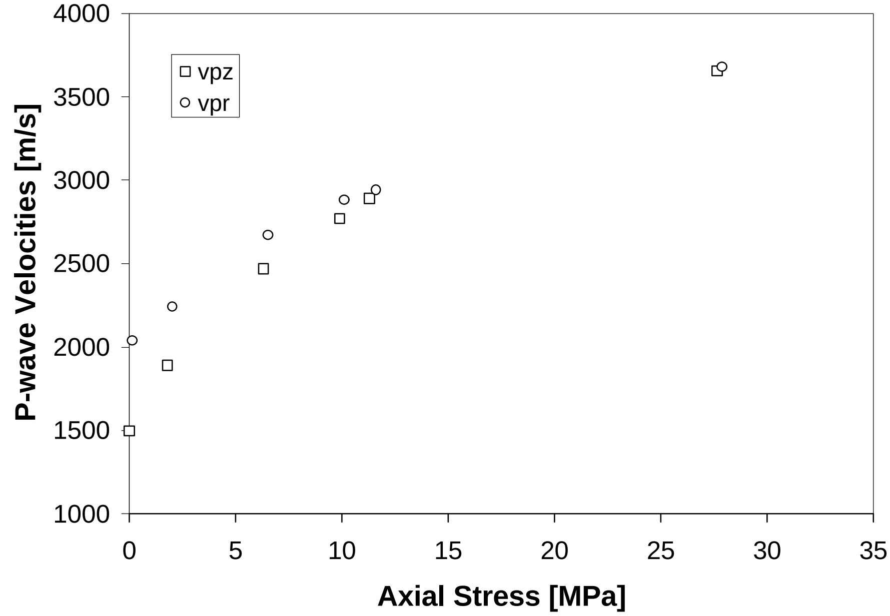


Figure 7: Axial (vpz) and radial (vpr) P-wave velocities of a natural core during loading from zero to 30 MPa axial stress. Loading is performed with axial = 2 x  radial stress. The sample axis is parallel to the vertical direction *in situ*.

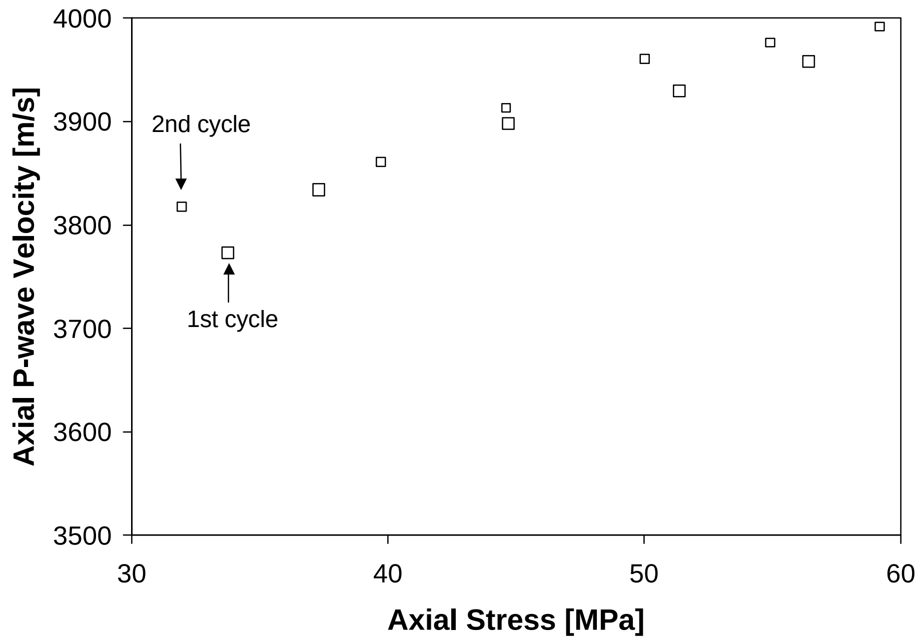


Figure 8: Axial P-wave velocity during cyclic loading of a natural sandstone core in uniaxial strain conditions.

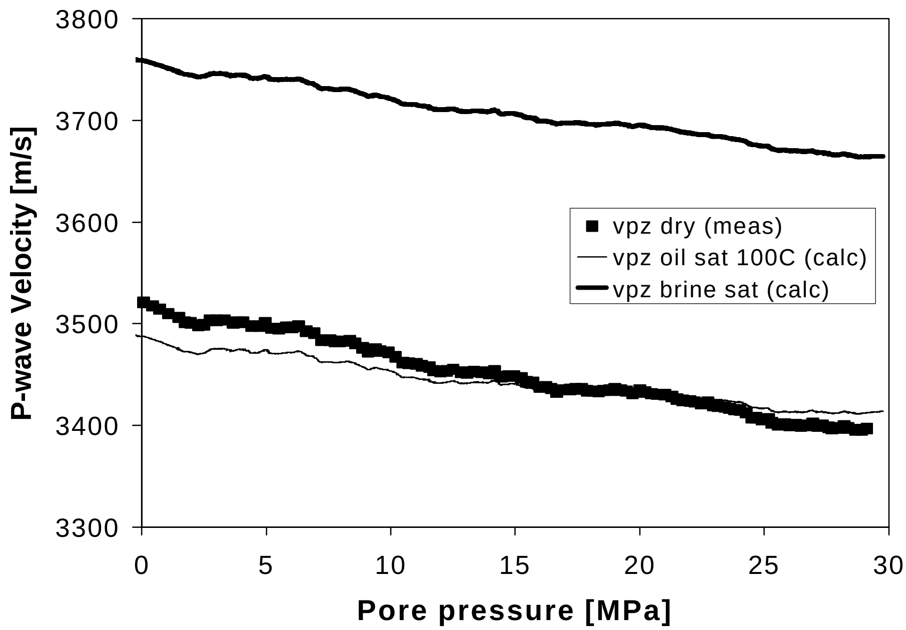


Figure 9: Estimated (axial) P-wave velocity vs. pore pressure for a synthetic sandstone in dry, oil (at 100ºC) and brine saturated conditions during virgin uniaxial compaction.

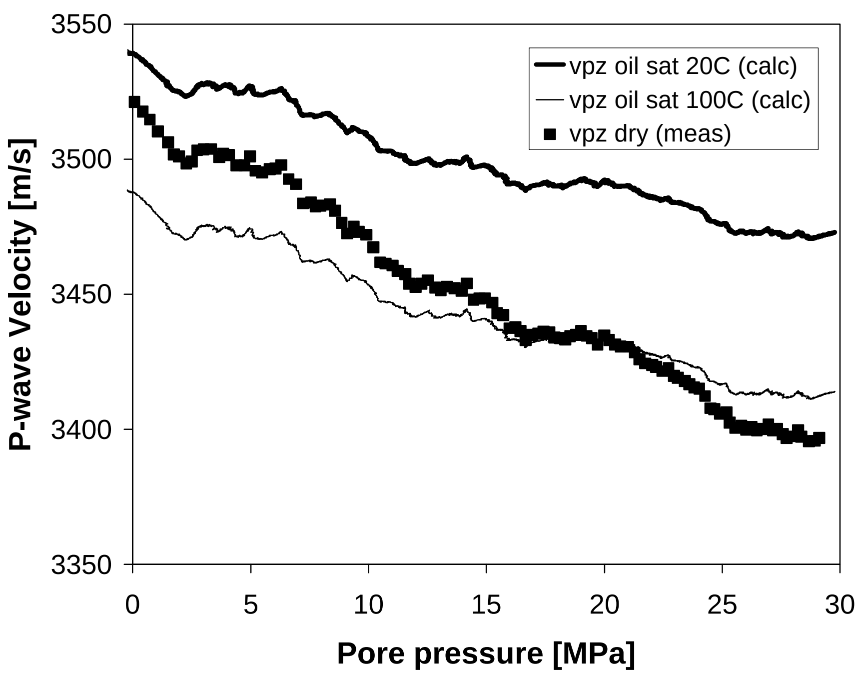


Figure 10: Estimated (axial) P-wave velocity vs. pore pressure for a synthetic sandstone in dry and oil saturated conditions during virgin uniaxial compaction, for oil temperatures of 20 and 100ºC.