

Impact of artificially matured organic matter on the dielectric and elastic properties of compacted shales

Matthieu Cauchefert*

Curtin University
Department of Exploration Geophysics
26 Dick Perry Avenue, Kensington, WA
matthieu.cauchefert@postgrad.curtin.edu.au

Stephanie Vialle

Curtin University
Department of Exploration Geophysics
26 Dick Perry Avenue, Kensington, WA
Stephanie.vialle@curtin.edu.au

Joel Sarout

CSIRO Energy
26 Dick Perry Avenue, Kensington, WA
Joel.Sarout@csiro.au

Matthew Josh

CSIRO Energy
26 Dick Perry Avenue, Kensington, WA
matthew.josh@csiro.au

Maxim Lebedev

Curtin University
Department of Exploration Geophysics
26 Dick Perry Avenue, Kensington, WA
M.Lebedev@exchange.curtin.edu.au

Bruce Maney

CSIRO Energy
26 Dick Perry Avenue, Kensington, WA
Bruce.Maney@csiro.au

Lionel Esteban

CSIRO Energy
26 Dick Perry Avenue, Kensington, WA
lionel.esteban@csiro.au

Jeremie Dautriat

CSIRO Energy
26 Dick Perry Avenue, Kensington, WA
Jeremie.Dautriat@csiro.au

SUMMARY

Unconventional gas shale resources recently became a standard in the American oil and gas industry and are studied throughout the world. However, gas shales are still poorly characterised with respect to other reservoir rock types. The different parameters of organic matter (OM) in organic shales needs to be better constrained in all their complexity and variability. This study focuses on the influence of OM maturity on the dielectric and elastic response of shale using a hydrous pyrolysis process to increase their maturity. We then incorporated the OM in a shale-like mineral matrix that was artificially compacted under control. Elastic properties and their anisotropy were measured during compaction while dielectric measurements were acquired post-compaction. The results showed that OM affects the onset of the liquid/plastic transition of compacting sediment. The immature OM lessens the development of P-wave anisotropy. On the other end, mature OM strongly decreases the imaginary dielectric permittivity at low frequencies while it increases electrical conductivity.

Key words: Shale, Organic matter, P-wave, Dielectric, Anisotropy, Hydrous pyrolysis

INTRODUCTION

Despite recent advances in petroleum technologies for exploration, prospecting and enhanced oil/gas recovery in unconventional shale reservoirs, this sedimentary rock type -the most abundant on Earth- still remains the least studied and poorly understood. Among the many reasons for under-representation of shales in scientific studies, we can include very low permeability, chemical reactivity with liquids and the difficulty to preserve natural samples (Ewy, 2015). OM adds another level of complexity as its content, type and maturity will determine the gas/oil storage capacity of the shale, influence most of its physical responses from various tools (lab, logs and models) and affect transport and mechanical properties of the formation(s), especially in near well conditions.

The rock physics literature investigating the effect of OM is often limited to its weight fraction content represented by the total organic carbon (TOC) and studies investigating other OM parameters aren't as frequent. Hence its real impact on the physical-chemical properties of shales is over-simplified. For instance, it was shown that shale elastic response and its anisotropy are considerably affected by OM maturity (Emmanuel et al., 2016), its orientation and distribution (Vernik and Nur, 1992; Sayers, 2013). Likewise, Delle Piane et.al. (2017) demonstrated that the presence of highly mature OM leads to unusually high conduction and dielectric permittivity within a shale, and Josh et.al. (2016) substantiate this finding with compacted synthetic shales and numerical simulation that both non-conductive and conductive OM can play a role.

The intrinsic complexities of natural shales (e.g. mineralogy, compaction-diagenesis history, heterogeneity) and the various parameters/properties involved in shale studies make it difficult to understand them properly. Through the study of artificial shales we can create and analyse samples with great repeatability under controlled conditions and focus on one or two variables of interest. In this paper, the variables in our samples are the organic content and its maturity. We collected immature peat samples and we developed a method to simulate natural maturation through hydrous pyrolysis and then incorporated immature and mature OM in synthetic shales that are subsequently compacted to study their dielectric and elastic behaviour. We will present how OM and maturity affect the liquid/plastic transition of compacting sediments, the development of elastic and dielectric anisotropy and the conductivity of shales.

EXPERIMENTAL METHODS

In this study, the experimental workflow is subdivided into three major components. First of all, OM is prepared before incorporation into the sample mixture. The synthetic samples are then compacted. Thereafter they are sliced in different directions to undergo dielectric testing.

Base materials

The choice of the different constituents of the artificial samples is crucial to the quality of the data to be acquired. Synthetic samples are not meant to be identical to natural ones but rather are a simplification of natural shales. All their mineralogical and petrophysical parameters can be controlled and we can focus on one or two variables. The components must be chosen according to the properties that will be measured and the natural characteristics to be reproduced. In the present case, dielectric and elastic properties of natural shales give us constraints for the sample compositions. A homogeneous mineral matrix that remains steady is required to highlight the influence of the considered variable: the organic phase. The resulting matrix has to feature vertical transverse anisotropy typical of shale formations and silt and clay-sized particles to reproduce the morphology of shale grain contacts. Even though some clay poor organic mudrocks with a low permeability are referred to as “black shales”, we chose to stick to the more classical definition of shales, i.e. a rock having a significant fraction of clay, as the clay/water interactions play an important role in the dielectric response of shales. In addition, strong electrical conductor such as pyrite must be avoided to not overshadow the dielectric behaviour of OM.

Hillier (2006) gathered an extensive database of mineralogical compositions of European shale formations of various ages (Cambrian to Quaternary). He computed the average composition of the collection. The mineral composition of our samples is based on this data. The resulting samples do not match any particular formation but instead represents an ‘average’ mineralogy that best suits the purpose of reproducing the dielectric and elastic behaviour of a typical shale. After rounding up and eliminating the minerals present in minor proportions, we came up with a mineralogy reduced to four groups: quartz, feldspar, carbonate and clay. The dominant minerals for the feldspar and carbonate groups have been selected: potassium feldspar (orthoclase) and calcite, respectively. Finally, kaolinite is chosen preferred to represent the clay group due to easy availability and a lower potential for swelling in presence of water. The proportion of each mineral for each sample of the study is detailed in table 1.

The organic material used for this study is a Canadian sphagnum peat moss from Nova Scotia. This material was chosen to reproduce OM containing type III kerogen (gas prone) and because it is the earliest precursor with the lowest possible maturity. Hence it represents the level 0 of maturity and the subsequent process of artificial maturation can yield a wide range of maturities from the same initial material. The Von Post classical method for artificial maturation is described by Stanek and Silc (1977). This tool assesses the humification of a peat sample. The degree of humification represents the degradation state of the peat, mainly due to microbial decomposition. As humification goes on, the elemental composition of peat changes towards immature kerogen. Namely the proportion of carbon increases at the expense of the oxygen fraction that diminishes whereas hydrogen tends to remain stable (Delicato, 1996). After examination, the OM at our disposition proves to be a poorly humified peat of rank H2. This corresponds to a high atomic O/C ratio of approximately 0.8 and an H/C ratio between 0.9 and 1.

Sample name	Dry mineral composition (wt%)				
	Quartz	K-Feldspar	Calcite	Clay (Kaolinite)	Organic (immature /mature peat)
Inorganic	20	10	10	60	0
Immature	18.2	9.1	9.1	54.7	8.9
Mature	18.3	9.1	9.1	54.7	8.8

Table 1: Mineral composition of each sample. ‘Immature’ stands for maturity 0, the sample containing immature peat whereas ‘Mature’ is the sample containing artificially matured peat. The inorganic sample is a comparison sample.

Organic matter preparation and maturation

The peat was initially dried at 85°C for a week and was then ground into a fine powder so it can easily be mixed homogeneously into the mineral matrix. About 90g of this powder was isolated to experience artificial maturation. To obtain a mature sample chemically similar to kerogen found in shale source rocks, a hydrous pyrolysis system has been developed. The principle of such system is to heat an organic sample under pressure and in the presence of water in a closed environment. Indeed it was shown that pyrolysis of immature source rocks carried out in the presence of water gives products with a chemical composition the closest to natural hydrocarbons (T.Barth, 1999). Moreover, several studies insist on the importance of the mineral matrix on the maturation of OM. Clay minerals especially have a great ability to adsorb organic compounds. The chemical interactions between OM and clays occur at this adsorbed interface. The greater the specific surface area of the clay, the greater is the resulting catalysis effect. Thus swelling clays shown in multiple studies to be the major catalyst (e.g. Wu et al., 2012). The relationship between the clay and the organic phase during maturation is further emphasized by the study of Rahman et al. (2017) where a greater contact between the two phases resulted in greater hydrocarbon production through pyrolysis.

This information gathered in the literature helped to define the requirements of an OM maturation system. The choice of a closed system containing 90% peat and 10 % swelling clays (bentonite) with the presence of water was retained. We used a pressure vessel CF-0.2L from KD Instruments with a ceramic lining equipped with a pressure gauge and a pressure relief valve. A picture of the vessel

can be seen in Figure 1-a. The vessel was placed in an oven at 250°C. The temperature was set at the upper end of the temperature range where the vessel can be operated safely to maximize the rate of thermal OM cracking. Under these conditions, the water vapour pressure generated is 4 MPa. The sample was left for 3 days in the closed heated vessel and was then left to dry at 85°C. Finally we ground the obtained material to incorporate it into the sample the same way the immature peat was, according to the procedure detailed below.

Compaction procedure

At first, the dry powder minerals (and possibly OM) are put together. To keep track of the density and porosity during compaction, the exact amount and density of each initial constituent must be known. The initial minerals must resemble a homogeneous powder. Otherwise, they are ground and/or oven-dried. The density of each constituent is measured using a helium pycnometer. According to the proportion needed for the final sample and the required initial volume, each constituent is weighed with a ± 0.01 g. Thereafter the constituents are poured in a bowl together and undergo a thorough dry mixing.

Following this, the pore fluid is prepared from deionised water previously degassed for 24h under vacuum. Salts are then added to match the target brine composition. For the present sample set, a standard brine with 15g/L NaCl was used. The brine is then added to the dry mix of minerals. The liquid mix is subsequently stirred for at least 10min. The operator ensures no dry packs of grains remain in the mix. When the slurry visually seems perfectly homogeneous, the mix is stirred further as a precaution. Ideally the mix must have a high volumetric water content ($>75\%$) to prevent air bubbles being trapped in the sample.

The mixture is poured into the compaction cell. The cell is equipped with P-wave transducers that record ultrasonic signals in the horizontal, vertical and two different off-axis directions. The theoretical height of the initial sample derived from the volumes of the different constituents is verified using a Vernier calliper. Elastic moduli and the ϵ and δ Thomsen's anisotropy parameters can be computed from the picking of the first P-wave arrival time and the corrected sample dimensions, throughout the compaction process.

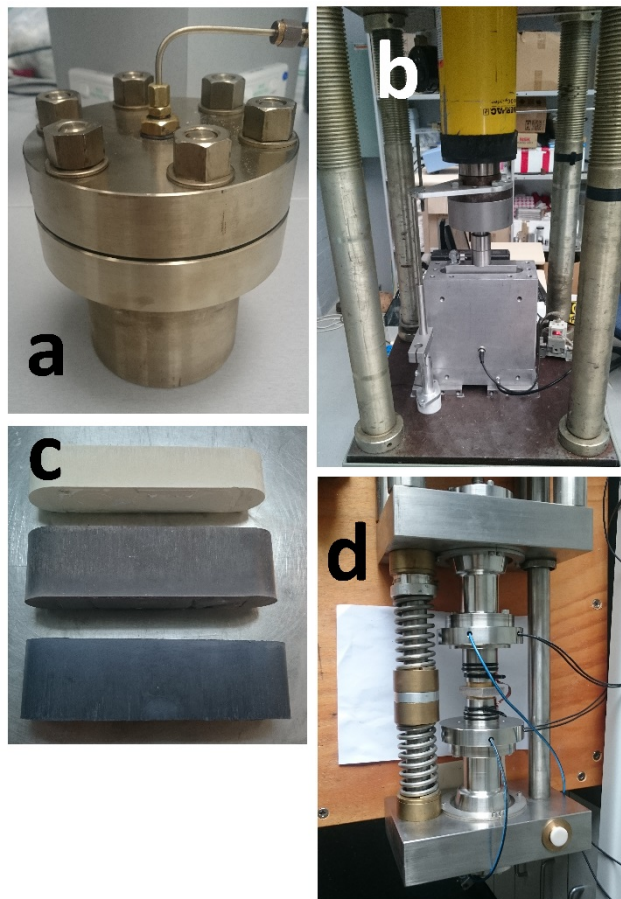


Figure 1: a) hydrous pyrolysis vessel. b) Compaction cell under the actuator. A transducer cable is visible on the cell wall. c) From top to bottom: sample inorganic, immature, and mature. d) Sample slice in the parallel plate dielectric apparatus

of charge carriers, respectively. It is heavily frequency-dependent with larger scale processes dominating the dielectric response at low frequency and small scale processes detectable at high frequency. There is a real ϵ'_r and an imaginary ϵ''_r part to the dielectric permittivity. The former can be regarded as a measure of the intensity of the polarization and the latter is related to the work exerted by the different mechanisms.

The stress applied by the piston is uniaxial in the vertical direction. The compaction is thus one dimensional and the horizontal section of the sample has a constant area throughout the experiment. A Linear Variable Differential Transducer (LVDT) is installed on the actuator and will record the shortening, and by extrapolation the volume, of the sample.

The compaction cell is installed under a reaction frame. The compaction is insured by an actuator which is brought into contact with the cell piston. The pore lines are installed and directed towards a scale that records expelled fluid masses. A picture of the cell in operation is reported in Figure 1-b. The load is applied on the sample with a regulator. The operator enters a target value for the stress and a selected stress rate. The regulator then controls through a feedback loop the actuator displacement accordingly. The loading path for the three samples is divided in two phase. An initial pressure of 1 MPa is maintained constant over several hours until the sample hits the liquid to plastic limit. The sample is then loaded up to 10 MPa of vertical compressive stress at a rate of 3.75 MPa/hour.

At the end of the compaction experiment the sample can be unloaded rapidly or by steps. The expansion upon unloading – relatively low – can be measured and corresponds to the compressibility of the mineral matrix. The cell is then disassembled and the sample extracted (Figure 1-c). The final weight and volume are measured and are used to double check the density and porosity values measured by the apparatus sensors. Finally the sample is sealed and put in a refrigerator to maintain saturation level before subsequent dielectric testing, explained in the following section.

Dielectric testing

The dielectric relative permittivity, ϵ_r , measures the electrical polarizability of a material under an alternating electric field. It is influenced by conduction and polarisation mechanisms, which can be explained as the translation and the reorientation

A vertical and a horizontal slice about 10 mm thick are extracted from each of the samples obtained after compaction. The two faces of a slice must be almost perfectly parallel with a constant thickness down to ± 0.1 mm to ensure a good coupling between the sample and the dielectric equipment. The slice is positioned between the parallel plate and pressed with a very small pressure to form a contact surface as can be seen in Figure 1-d. Next the measurement is run with an Agilent impedance analyser (4294A). The apparatus measures the real and imaginary part of the dielectric permittivity and can compute the equivalent electrical conductivity. The plates are also equipped with P-wave transducers to get unconfined ultrasonic data. Each slice is tested with direct contact to the parallel plate and through a plastic film. The first configuration gives information about the conduction processes while the second focuses on polarization processes.

RESULTS AND DISCUSSION

The compaction of the three samples was carried out in nearly the same conditions of initial porosity, maximum compressive stress, fluid salinity and loading paths as shown in table 2. The initial porosities are computed assuming the porosity equals the volumetric water content for a fully water saturated sample. The porosities during compaction are then computed assuming the volume decrease is attributed to loss of drained water only. The samples were CT-scanned to ensure the air trapped in the samples represents a negligible volume fraction ($\ll 1\%$). The only notable difference is the stabilization time at 1 MPa that lasted longer for the inorganic sample. We can see that each sample has a final unconfined porosity about 2.5% higher than the final porosity under stress, which is attributed to the elastic unloading of the sample. Despite similar conditions, the final porosity is lower for the inorganic sample and higher for the mature sample. The LVDT values used to compute the final porosities have an average error of 1.1% from the values measured with the Vernier caliper.

Sample name	porosity (%)				maximum vertical stress (MPa)	pore fluid salinity (g/L)	First phase @1MPa (hours)
	initial	At the end of the first phase	final under stress	final unconfined			
inorganic	79.42	46.7	34.9	37.4	10.2	14.5	11.7
Immature	78.99	50.6	36.5	38.8	10.2	15.1	6.5
Mature	78.84	50.9	37.2	39.5	10.2	15.3	6.2

Table 2: information summary from the compaction experiments.

The inflection of the porosity curves (Figure 2) at the end of the first phase (constant stress at 1MPa) shows the transition from the primary to secondary consolidation phase, when the pore pressure dissipates and the mineral matrix starts to bear most of the load. The porosity decrease over time is very similar for the two organic samples. On the other hand the inorganic sample has a slower porosity decrease rate during the 1 MPa phase but reaches a lower porosity at the end of the first phase. This is attributed to the fact that the first phase was almost twice as long for the inorganic sample. For technical reasons the second phase had to be started at the transition between primary and secondary consolidation for the organic samples. However we can see that the transition (inflection of the curve) occurs at a lower porosity and at a later time for the lean sample than for the organic samples. This suggests that the OM plays a role in the porosity decrease rate during the primary consolidation and the onset of the transition to the secondary consolidation, regardless of the maturity of that OM.

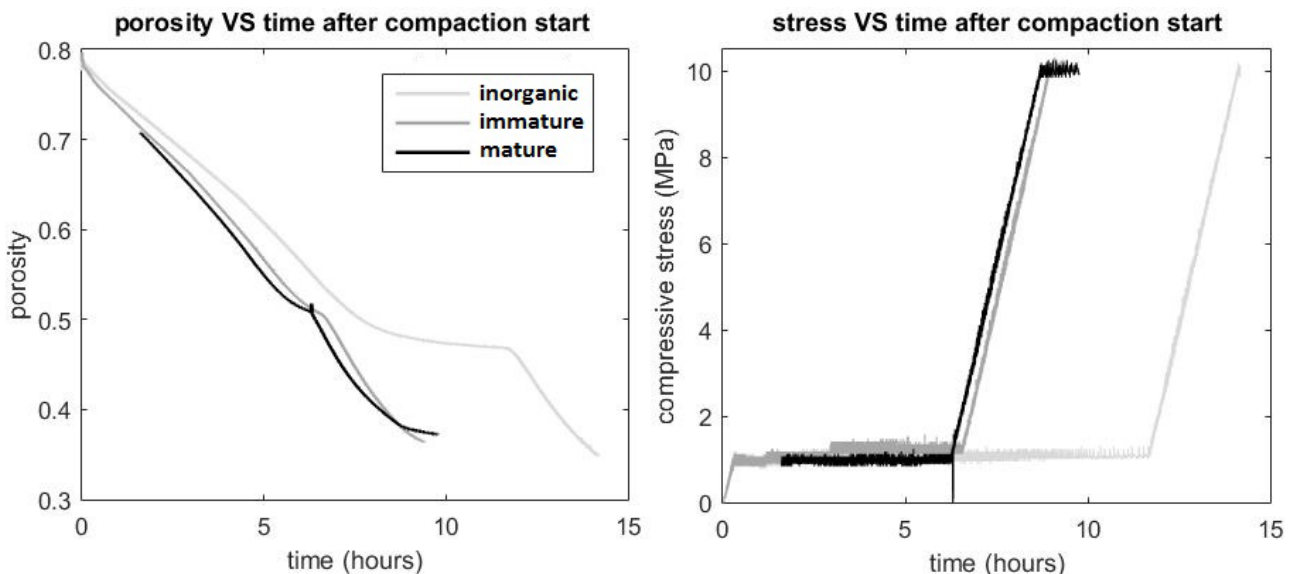


Figure 2: Porosity (left) and compressive stress (right) evolution over time during the compaction experiments.

The two phases of compaction are also visible on the ultrasonic data, as shown in Figure 3. The P-wave travel time is affected both by the velocity increase of the compacting material and the distance change between source and receiver, as two of the transducers are embedded in the piston, moving down during compaction.

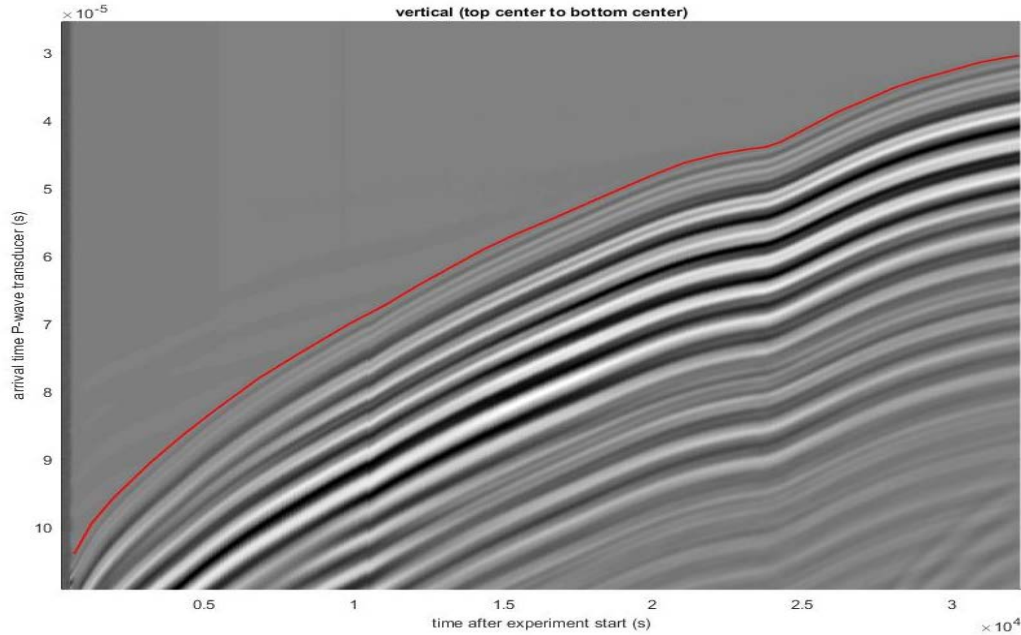


Figure 3: P-wave arrival time profile for a compaction experiment. Here is the immature sample, signal propagating vertically. The red line is the picked time for velocity computation.

P-wave velocity is computed from the travel time data. Figure 4 shows the evolution of the P-wave velocity (plain and dashed lines), and the unconfined velocities measured during the dielectric tests (triangles). At the start of the compaction, for all samples, vertical and horizontal velocities are all around 1500 m/s, the velocity of P-waves in water. During the first phase, the velocity increases very slowly when porosity decreases, until the sample enters the second phase. During the second phase, the velocity increases drastically and elastic anisotropy develops, with the horizontal velocity becoming progressively larger than the vertical velocity, as expected from a compacting clay-rich shale exhibiting a preferential orientation of clay platelets/particles orthogonal to the direction of compaction. Also expected is the fact that the unconfined velocity is lower than its confined counterpart. However, with this Figure, it is difficult to distinguish notable differences between samples.

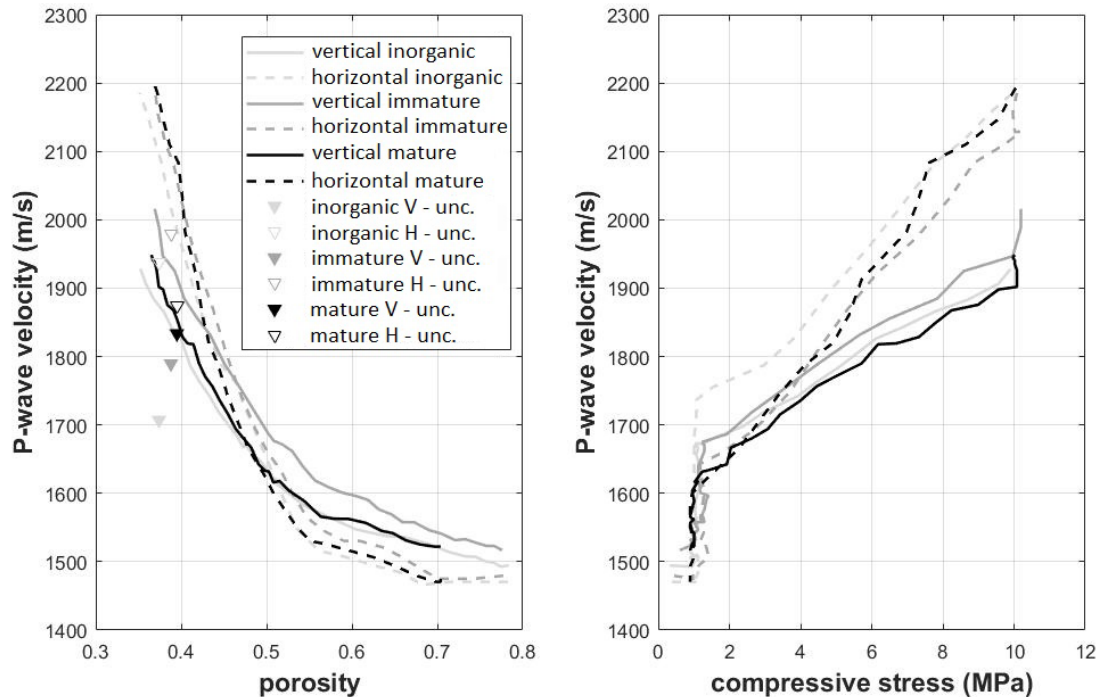


Figure 4: P-wave velocity as a function of Porosity (left) and compressive stress (right). The unconfined data (unc. in the legend) was acquired during the dielectric tests and the rest of the data was acquired during the compaction experiments.

In an attempt to clarify this data, we compute Thomsen's P-wave anisotropy parameter ϵ (Thomsen, 1986) equal to $[V_p(\pi/2)^2 - V_p(0)^2]/2 * V_p(0)^2$ with 0 indicating vertical propagation (slower) and $\pi/2$ indicating horizontal propagation (faster). Although the general trends in the evolution of anisotropy are similar to those of the previous figures, a few new elements are worth noting. First of all, we can note a negative initial anisotropy where we would expect a null anisotropy because the samples are in a liquid state at the beginning of the compaction. This is due to the error on the vertical velocity early in the experiment. Indeed the top and bottom transducers are far from each other at that moment (the piston is in the highest position) and the liquid sample dissipates most of the P-wave energy and weakens the first P-wave arrival amplitude. The arrival time is thus over-estimated and the vertical velocity underestimated. However the signal strengthens throughout the compaction and the error on the vertical velocity becomes similar to the error on the horizontal velocity (at 50% porosity approximately). we see both on the porosity and stress plots that the immature sample develops less anisotropy ($\epsilon \approx 0.07$) than the other samples whereas the inorganic and mature samples reach the same anisotropy by the end of the compaction ($\epsilon \approx 0.14$). This suggests that the immature OM impedes the development of anisotropy whereas the mature OM had a minor effect. We also note that the unconfined anisotropy of the inorganic and the immature samples is within the

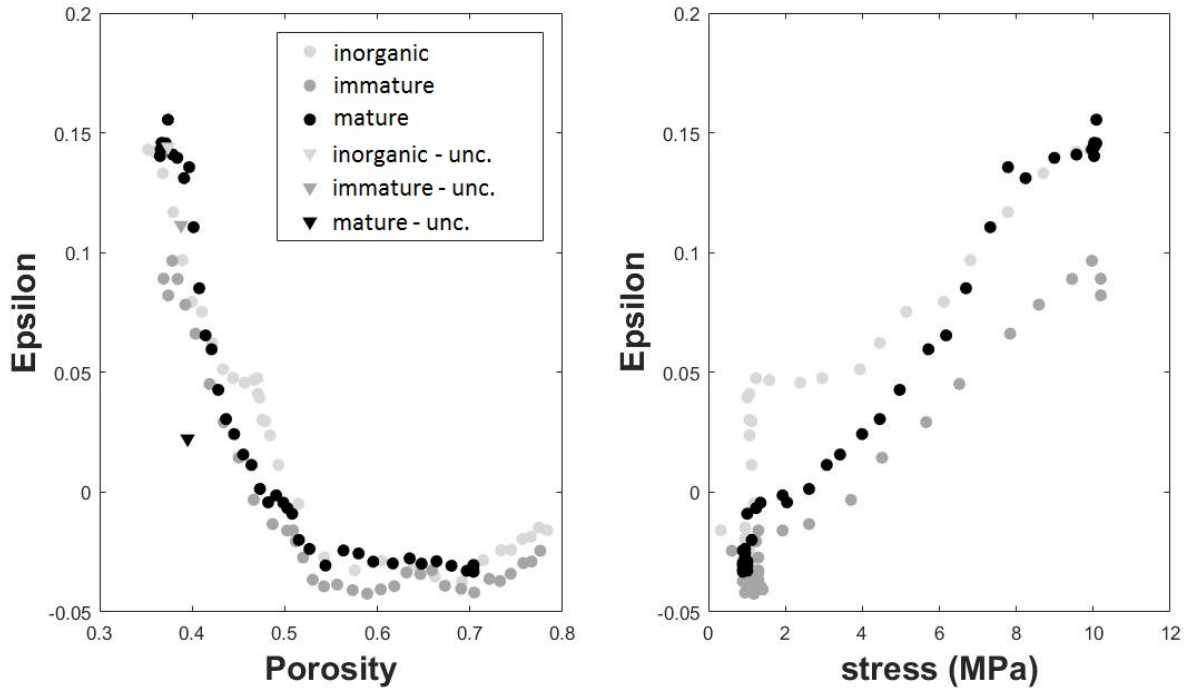


Figure 5: Porosity (left) and compressive stress (right) as a function of Thomsen's anisotropy parameter ϵ . Unconfined data (unc. in the legend) is in agreement with compaction data for the inorganic and immature samples, but not for the mature one. The cluster of point on the right graph corresponds to the compaction phase 1, where stress is constant and anisotropy do not vary much.

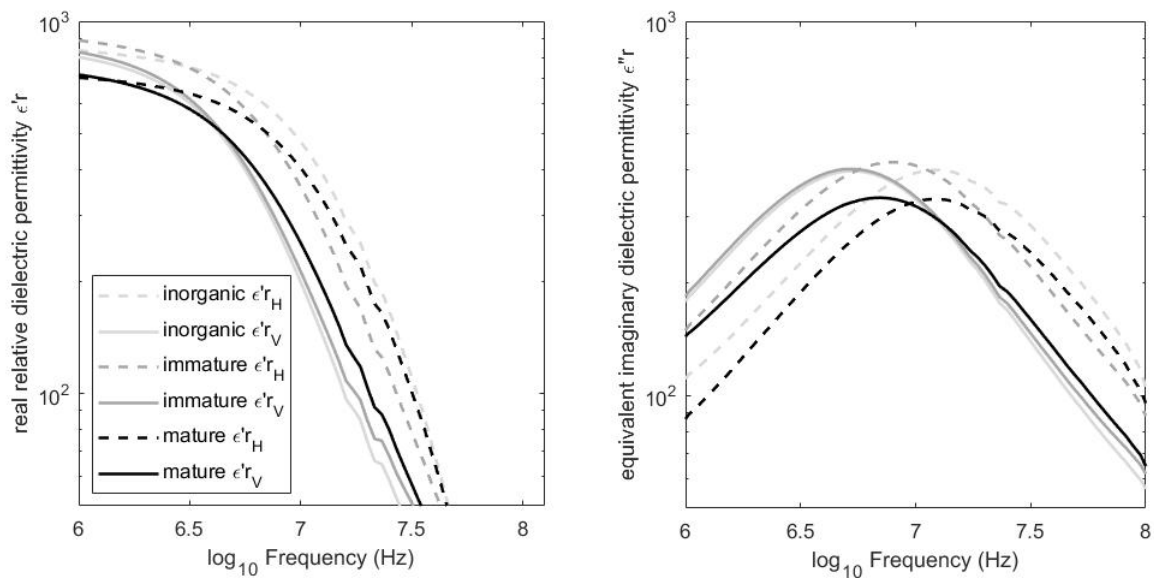


Figure 6: Real (left) and Imaginary (right) dielectric permittivity as a function of the electrical field frequency in the horizontal direction (dashed line) and vertical direction (plain line). Data obtained with a plastic film at the sample/electrode interface to prevent conduction processes from disturbing the permittivity measurements.

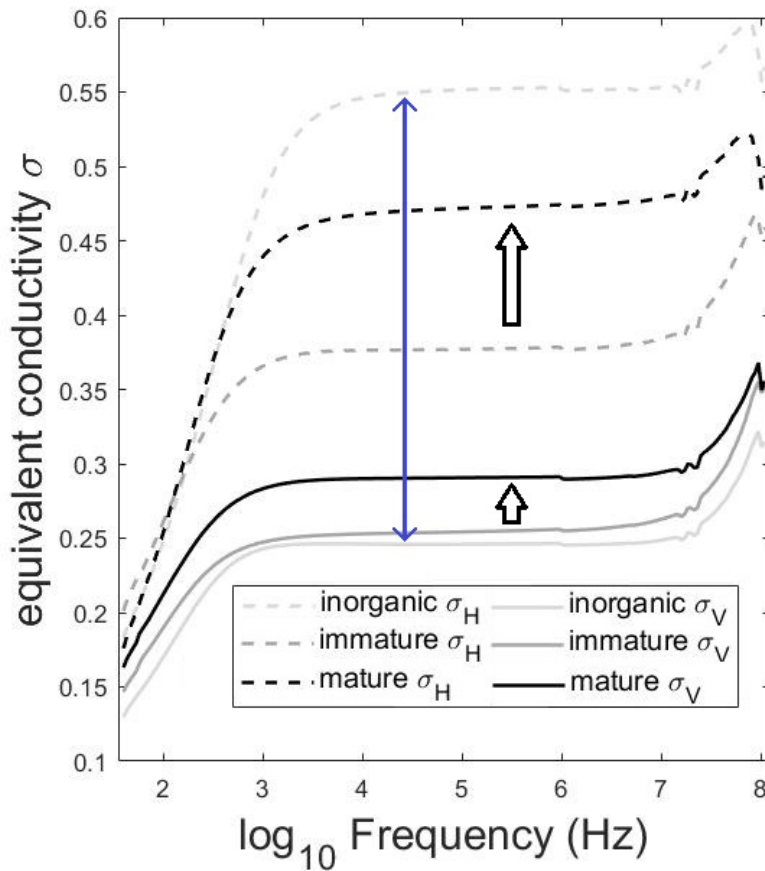


Figure 7: equivalent conductivity as a function of the electrical field frequency in the horizontal direction (dashed line) and the vertical direction (plain line). Data obtained with the sample in direct contact with the electrode. Inorganic sample has both the lowest and highest conductivity (blue double arrow). Mature sample is shifted towards higher values compared to immature sample (black arrows).

the samples, the inorganic sample has a more important clay total volume fraction than its organic counterparts. That may explain the difference in anisotropy, with more reoriented clay platelets in the inorganic sample.

We can see an increase in the real dielectric anisotropy for the organic samples around 10^7 Hz on Figure 8a. This was also observed in another study (Josh et. al., 2016). Yet, unlike our results, the inorganic sample in that study had a lower anisotropy at that frequency. Similarly, the imaginary dielectric anisotropy (Figure 8b) is similar for the two organic samples but the inorganic sample value rises above the organic samples at high frequency (above 10 MHz).

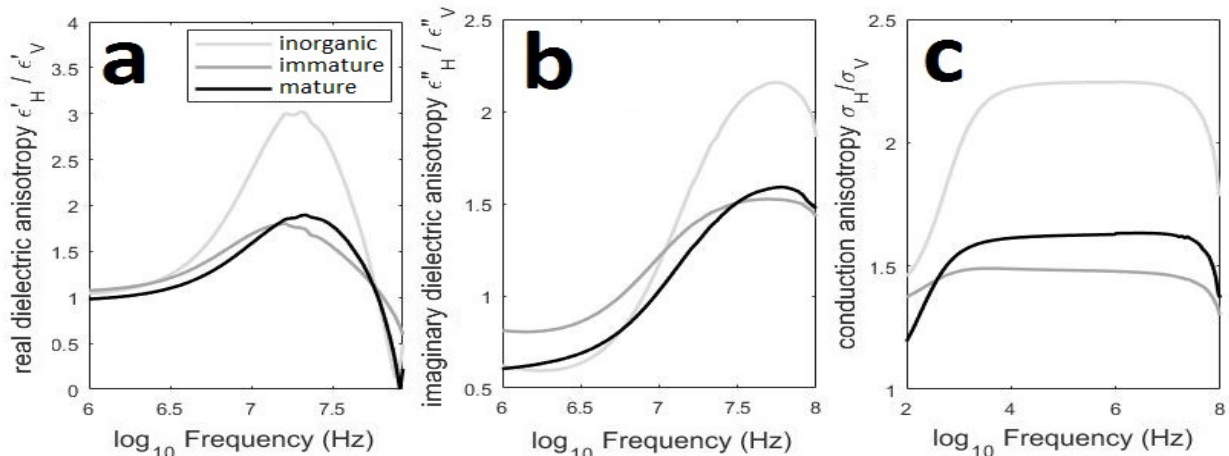


Figure 8: Anisotropy of the real permittivity, imaginary permittivity and the equivalent conductivity for each sample.

trend of the confined values. On the other hand the unconfined anisotropy of the mature sample is much lower than the confined one, at equivalent porosity. Therefore the more mature organic sample may be more affected by the stress release than the immature and inorganic samples. Nevertheless the small number of unconfined data points doesn't allow us to draw any definitive conclusion on this aspect.

The dielectric permittivity data do not allow for discriminating among the three sample types. For all three, the horizontal permittivity becomes higher than the vertical permittivity in the higher frequencies: at $10^{6.5}$ Hz for the real permittivity and 10^7 Hz for the imaginary permittivity. (Figure 6). However, the equivalent conductivity displays an interesting pattern (Figure 7). The immature sample is less conductive than the mature one, both in the horizontal and vertical directions. It may be that the more carbon rich mature OM is overall a better electrical conductor than fresh immature organic matter. However the maturation time and temperature necessary to make OM more conductive are greater than what was achieved in these tests. An alternative explanation would be the presence of air trapped in the immature organic particles, reducing its ability to conduct current. Otherwise the horizontal inorganic sample has a lower conductivity than any of the other samples whereas the vertical inorganic sample has the greatest conductivity of all. This feature is also visible in Figure 8c, with a conduction anisotropy much higher for the inorganic sample. Alike what we saw with the P-wave anisotropy of the immature sample, organic matter appears to reduce the anisotropy of electrical conductivity, Even though the inorganic minerals are present in the same proportions in all

CONCLUSION

Our results suggest that the OM, regardless of the maturity, affects the rate of primary consolidation and the onset of secondary consolidation of compacting sediments. Besides, highly immature peat when compacted in a shale mineral matrix seems to lessen the development of elastic anisotropy, whereas matured peat doesn't. Also, organic-rich samples decrease the electrical conductivity anisotropy, and the more mature sample is more conductive than its immature counterpart. Finally, the organic matter, in our sample set, lessened both the real and imaginary part of the dielectric permittivity.

Nevertheless the results presented in this study have to be interpreted carefully. It is worth highlighting the maturation of the organic phase was done prior to the compaction experiment and was incorporated after drying. Hence the observed behaviour reflects the intrinsic influence of the OM only and in water-saturated conditions. The effects the microcracks produced upon hydrocarbon generation and the hydrocarbon itself aren't present here. Also the slow deposition of the minerals and the OM in natural sediment occurs far differently from the mixing method we used for our sample and must have an impact on elastic anisotropy notably. These additional mechanisms are not accounted for here.

Further analysis such as optical microscopy of thin sections and petrological analysis of the OM is yet to be carried out on these samples. It will help determine the role of OM in the observed dielectric and elastic responses. The computation of Thomsen's anisotropy parameter δ for this dataset is also underway (a parameter that controls the geometry of the wavefront in the transversely isotropic shale). In the continuity of this study, plans for other artificial samples with maturation performed post-compaction, different organic matter types and the presence hydrocarbon-wet OM will help evaluate the importance of OM on petrophysical and geomechanical properties.

ACKNOWLEDGMENTS

I (MC) was supported by Curtin International Postgraduate Research Scholarship and Australian Government Research Training Program Scholarship. This work was partially funded through the CSIRO Shale Rock Physics and Petrophysics (SHARPP) project sponsored by Total. I would also like to thank Sam Battah for his contribution to the design of the cell and Ausama Giwelli for introducing me to compaction experiments.

REFERENCES

- Barth, T. (1999). Similarities and differences in hydrous pyrolysis of biomass and source rocks. *Organic Geochemistry*, 30(12), 1495-1507.
- Delle Piane, C., J. Bourdet, M. Josh, M. B. Clennell, W. D. A. Rickard, M. Saunders, N. Sherwood, Z. Li, D. N. Dewhurst, M. D. Raven, 2017, Organic matter network in post mature Marcellus Shale: effects on petrophysical Properties, AAPG Bulletin, In Press.
- Delicato, D. (1996). *Physical-chemical properties and sorption characteristics of peat* (Doctoral dissertation, Dublin City University).
- Emmanuel, S., Eliyahu, M., Day-Stirrat, R. J., Hofmann, R., & Macaulay, C. I. (2016). Impact of thermal maturation on nano-scale elastic properties of organic matter in shales. *Marine and Petroleum Geology*, 70, 175-184.
- Ewy, R. T. (2015). Shale/claystone response to air and liquid exposure, and implications for handling, sampling and testing. *International Journal of Rock Mechanics and Mining Sciences*, 80, 388-401.
- Hillier, S., 2006, Appendix A. Mineralogical and chemical data, in GM Reeves, I Sims, and JC Cripps eds., Clay materials used in construction: London, Geological Society, *Engineering Geology Special Publications Volume 21*, p. 449-459.
- Josh, M., Clennell, B., Cauchefert, M. & Han, T. (2016). Dielectric permittivity and anisotropy of intact multi-saturated organic shales.
- Rahman, H. M., Kennedy, M., Löhr, S., & Dewhurst, D. N. (2017). Clay-organic association as a control on hydrocarbon generation in shale. *Organic Geochemistry*, 105, 42-55.
- Stanek, W., & Silc, T. (1977). Comparisons of four methods for determination of degree of peat humification (decomposition) with emphasis on the von Post method. *Canadian Journal of Soil Science*, 57(2), 109-117.
- Thomsen, L. (1986). Weak elastic anisotropy. *Geophysics*, 51(10), 1954-1966.
- Sayers, C. M. (2013). The effect of kerogen on the elastic anisotropy of organic-rich shales. *Geophysics*, 78(2), D65-D74.
- Vernik, L., & Nur, A. (1992). Ultrasonic velocity and anisotropy of hydrocarbon source rocks. *Geophysics*, 57(5), 727-735.
- Wu, L. M., Zhou, C. H., Keeling, J., Tong, D. S., & Yu, W. H. (2012). Towards an understanding of the role of clay minerals in crude oil formation, migration and accumulation. *Earth-Science Reviews*, 115(4), 373-386.