The sensitivity of seafloor compliance measurements to sub-basalt reservoirs

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Abstract — We investigate the sensitivity of seafloor compliance measurements to the existence and size of a sub-basalt sediment layer, using a model based on the expected structure of the Faeroes basin region. We calculate "measured" compliance for a model — taking into account the height of the waves that force seafloor motion, the seafloor noise levels, the water depth and the measurement time — and then invert these "data" to calculate the shear modulus/velocity profile. Prior structural information from seismic studies (such as the velocity in the surface sediments and the depth to the top of the basalts) improves the sensitivity of compliance measurements to sub-basalt sediment properties. For an ocean 1.7 km thick, a sub-basalt layer more than 0.75 km thick with shear velocity ≤ 1.7 km/s can be detected by a compliance measurement under weak ($10^{3.5}$ Pa^2/Hz) long-period ocean waves. Under the same conditions, a compliance measurement can constrain the depths to the top and bottom of a 2-km-thick sub-basalt reservoir to within 0.25 km. These constraints improve if the ocean surface waves are stronger and degrade if the sub-basalt sediment shear velocity is faster (which will be the case, for example, if the sediments are fluid-depleted).

Introduction

Basalt flows that cut through sedimentary basins are of interest to petroleum geologists because of their potential for trapping and storing hydrocarbons. One of the most promising places to find such sub-basalt reservoirs is in the Faeroe Basin, located off the northwest coast of Scotland between the Faeroe and Shetland Islands. There, basaltic flows from the Faeroe Islands intrude into a 5-9 km thick sedimentary sequence at approximately 1.5 km beneath the seafloor (kmbsf) [Hughes *et al.*, 1997; Fliedner and White, 2001]. The thickness of these basalts and the thickness and fluid content of the underlying sediments have proven difficult to determine. The very existence of sediments under the basalt flows is difficult to directly image, because active seismic imaging methods have difficulty penetrating the many reflective layers in the basalts. Recently, progress has been made in imaging beneath the basalt region using active seismics with streamer offsets out to 38 km [White *et al.*, 1999], but this technique is expensive and the shear properties of these sediments remain poorly constrained. In addition, there is as yet no way to ground proof the results.

Seafloor compliance measurements promise a simple and relatively inexpensive way to verify the existence of sub-basalt sediments and to determine their fluid content. Compliance – the motion of the seafloor under low-frequency (0.003-0.03 Hz) ocean wave forcing – is sensitive to the shear modulus structure of the subsurface to approximately four times the ocean depth [Crawford *et al.*, 1991]. Compliance data can be inverted to determine the shear velocity/modulus structure of the subsurface, which is very sensitive to the existence and distribution of fluids. The measurements are even more useful when combined with compressional velocity constraints from seismic data, since the ratio of shear to compressional velocity depends strongly on the amount of fluids in a region, decreasing in the presence of fluids from a maximum of approximately 0.58 in dry rock.

In this paper, we investigate the sensitivity of seafloor compliance measurements to the type of sub-basalt sediment basin expected in Faeroe-Shetland Basin. We investigate how small a sediment layer can be detected by compliance measurements, how accurately the size and depth of

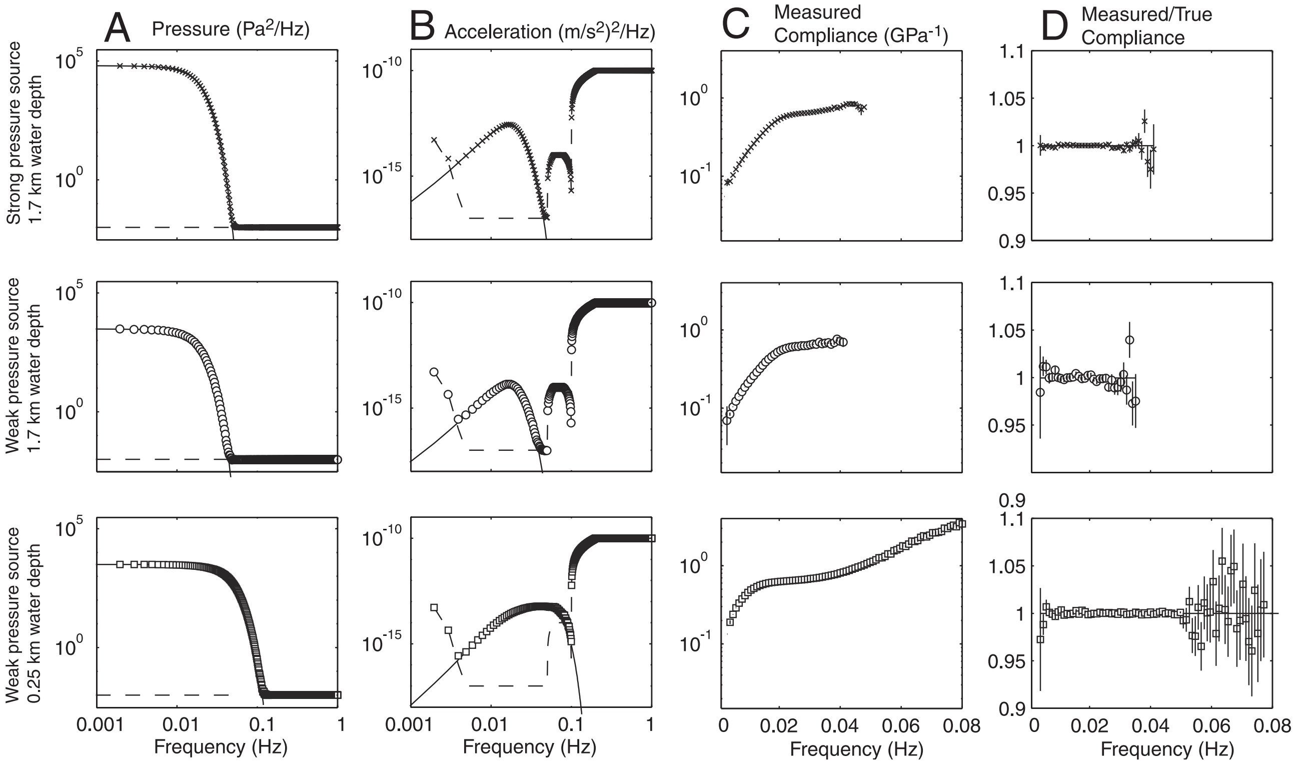


Figure 1. The effect of changes in the source wave strength and the water depth on the compliance signal. **A)** seafloor pressure signal. Solid line = pressure signal from a constant sea surface pressure source, dashed line= instrument noise, symbols = measured signal. **B)** Seafloor acceleration signal. Solid line= signal due to compliance under the pressure signal, dashed line= earth noise, symbols = measured signal. **C)** measured compliance, in the frequency band where the true pressure and compliance signals dominate. **D)** Measured compliances divided by the theoretical compliance value. Top row: Strong pressure source ($10^{4.8}$ Pa^2/Hz) and deep water (1.7 km). Middle row: Weak pressure source ($10^{3.5}$ Pa^2/Hz) and deep water (1.7 km). Bottom row: Weak pressure source ($10^{3.5}$ Pa^2/Hz) and shallow water (0.25 km)

the layer can be estimated using compliance measurements, and how the existence of fluids in the reservoir affects this sensitivity.

Seafloor Compliance

Seafloor compliance is the transfer function between the seafloor pressure and acceleration in the frequency band from 0.003 to approximately 0.03 Hz. In this frequency band, the pressure signal comes from linear ocean surface gravity waves and the acceleration signal depends on this pressure and on the elastic structure of the underlying sediments and crust. The upper frequency limit for compliance measurements depends on the water depth, because the seafloor pressure signal from the ocean waves drops off rapidly at wavelengths shorter than the ocean depth. The lower frequency limit is created by the intersection of the seafloor acceleration signal with the seafloor noise levels at ~0.003 Hz. For a constant pressure signal with respect to frequency, the acceleration signal from compliance decreases with frequency because the velocity is approximately constant with frequency, and the seafloor noise level is flat or increases with decreasing frequency in the compliance band (**Figure 1**, **B**).

The principle properties of seafloor compliance are that 1) the compliance value is principally sensitive to the shear modulus of the underlying crust, 2) the compliance increases as the shear modulus decreases, and 3) the compliance at different frequencies is sensitive to structure at different depths, with low frequencies sensitive to deep structure and high frequencies sensitive to shallow structure. In 0.25 km of water, compliance is most sensitive to structure from 0.04 to 0.9 km beneath the seafloor (kmbsf). In 2 km of water, compliance is most sensitive to structure from 0.4 to 7 km. Compliance measurements are especially sensitive to fluids trapped within the crust and sediments because these fluids create a low shear modulus zone that generates a peak in the compliance function at the frequency corresponding to the zone's depth. The behaviour of the compliance function is described in more detail in the *2000 LITHOS Report* [Crawford, 2000] and in Crawford *et al.* [1991; 1998].

Compliance is measured by deploying a sensor containing a broadband seismometer and a differential pressure gauge to the seafloor for 2 or more days. A 2-day deployment allows the pressure-acceleration transfer function to be calculated with a 0.001 Hz frequency step and good statistical confidence. Multiple deployments of the compliance sensor (or sensors) can be used to create a two- or three-dimensional map of the subsurface shear modulus structure.

In this paper, we interchange the terms "shear modulus" (μ) and "shear velocity" (Vs), which are related by the equation $\mu = \rho V_S^2$, where ρ is the material density. Compliance is principally sensitive to the shear modulus, while seismic data are principally sensitive to compressional velocity. Density variations are generally much smaller than velocity or shear modulus variations, so we can express the results of compliance inversions (which are always shear moduli) as shear velocities by assuming a standard density.

The sensitivity of compliance measurements to small differences in the true compliance depends on the uncertainty of the compliance measurements, which depends primarily on the strength of the pressure signal, the background seismic noise level, and the water depth. For a well-installed sensor, the background seismic noise level is well below the noise floor of the "passive-sensor" ocean bottom seismometers (OBS) typically used for active seismic studies. Therefore, a "passive-sensor" OBS cannot be used for compliance measurements under most conditions. For our modelling, we assume that the measurements are made using a broadband seismometer whose noise floor is below the seafloor noise levels shown in **Figure 1, B**. **Figure 1** shows compliance calculated for different values of the pressure signal and water depth. The "weak" pressure model corresponds to the weakest pressure signal recorded in the open ocean ($10^{3.5}$ Pa^2/Hz, from the North Atlantic Ocean in summer) and the "strong" pressure model corresponds to the average Pacific ocean spectral levels ($10^{4.8}$ Pa^2/Hz). The stronger the pressure signal, the smaller is the data uncertainty. In shallow water, compliance can be measured out to higher frequency, which gives better information about shallow structure. The source wavelengths are shorter at all frequencies in shallow water and they can in fact be too short to detect/constrain a sub-basalt reservoir several km beneath the seafloor.

The Sub-basalt Reservoir Model

To study the sensitivity of compliance measurements to sub-basalt reservoirs, we use a one-dimensional model based on the estimated subsurface structure of Faeroe Basin where basalt flows appear to intrude into the sedimentary sequence. Our principle sources for this model are the models of Faeroe Basin structure by [Hughes *et al.*, 1997] and [White *et al.*, 1999] and sediment shear velocity models from [Dorman, 1997]. Shallow (<100 m) sediment shear velocities can be very slow (as slow as 100 m/s). Since these low velocities could potentially create a large compliance signal, which could in turn mask the effect of sub-basalt reservoirs, we included such a layer in all of our models.

The base model we use (**Figure 2a**) consists of a thin low velocity sediment layer (50 m thick, 0.1-0.3 km/s velocity) overlying a thick sedimentary section (1.5 km thick, 0.7 km/s), over a variable thickness basalt layer (2.5-2.8 km/s), over a variable thickness

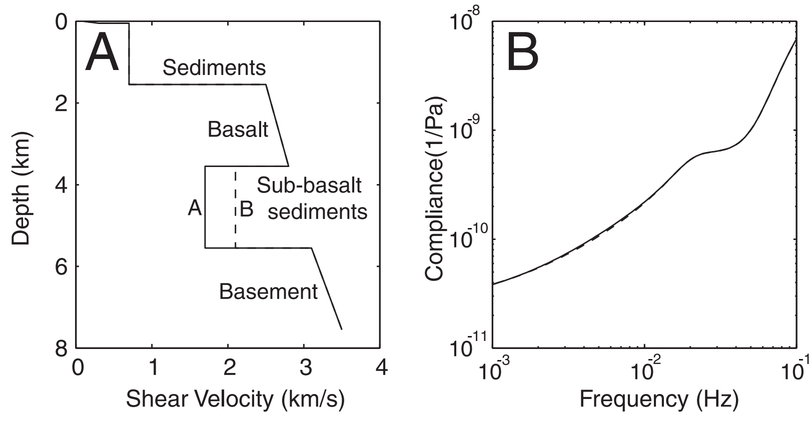


Figure 2. Sub-basalt reservoir models and corresponding compliance functions. A) Shear velocity models. Solid line = model A, dashed line = model B. B) Compliance functions. The Model B compliance (dashed line) is almost imperceptibly lower between 0.002 and 0.01 Hz.

sub-basalt sediment layer (1.7 or 2.1 km/s), all over a rock basement (Vs=3.1-3.5 km/s). We use two different models for the velocity in the sub-basalt reservoir: in Model A, the layer shear velocity is 1.7 km/s and in Model B the layer velocity is 2.1 km/s. Models A and B assume a compressional velocity of 3.6 km/s in the sub-basalt reservoir, based on the results of the FLARE experiment [White *et al.*, 1999]. The Model A shear velocity of 1.7 km/s a shear to compressional velocity ratio of 0.47 (Poisson ratio 0.36), typical for fluid-bearing sediments. The Model B velocity comes from [White *et al.*, 1999] and corresponds to a velocity ratio of 0.58 (Poisson ratio 0.24), indicating no significant fluids in the sediments. Although the difference in the effect on the compliance of the two Models is barely visible to the naked eye (**Figure 2b**), we will see below that the compliance method is much more sensitive to the fluid-bearing model A than to model B.

Forward modelling tests

We start our investigation of the sensitivity of compliance measurements by calculating how much compliance changes for different thickness basalt layers and sub-basalt reservoirs (**Figure 3**). To detect the difference between two models, this difference should be within the range of measurement values and larger than the data uncertainty (grey forms, **Figure 3**). For a sub-basalt reservoir, an ~0.5 km change in the sub-basalt reservoir thickness will create a significant change in the measured compliance under a weak pressure source, while a change of ≤0.1 km create a significant change in measured compliance under a strong pressure source.

The peaks and troughs seen in **Figure 3** are much less visible on real compliance measurements, especially if the sediments are thick. The amplitude of these variations is on the order of 1–2x10^{-11} Pa^{-1} (**Figure 3**), while the compliance signal may be as high as 1–2x10-10 Pa^{-10} in the same frequency band because of surface sediments (thin line, **Figure 4A**). The peak due to the sub-basalt reservoir would appear much larger if we could replace the surface sediments with basalts (thick line, **Figure 4B**), but in fact the sub-basalt layer is just as visible to inversions in both cases. It is the difference between the models that matters (**Figure 4B**), because the form versus frequency of this peak cannot be duplicated by any surface sediment model.

Minimum structure inversions

To determine how well a sub-basalt reservoir can be resolved with little or no prior knowledge of the sub-seafloor structure, we performed minimum structure inversions on compliance calculated from model A under strong and weak forcing waves (**Figure 5**). These inversions require *a priori* compressional velocity and density models, but the effect of these models is relatively insignificant:

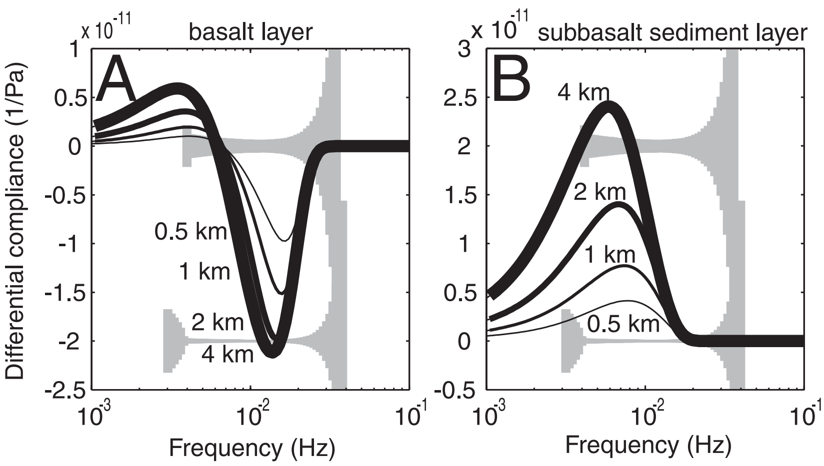


Figure 3. Sensitivity of compliance to different thickness basalt and sub-basalt reservoir layers. The curves show the "differential compliance", that is, the compliance for a model with the indicated layer thickness minus the compliance for a model without such a layer. Grey forms indicate the data range and uncertainty in deep (1.7 km) water for a weak source (10$^{3.5}$ Pa^2/Hz, top) and strong waves (10$^{4.8}$ Pa^2/Hz, bottom). (A) Differential compliance for different thickness basalt layers. In each model, the top of the basalt layer is 1.5 km beneath the seafloor (kmbsf) (B) Differential compliance for different thickness sub-basalt reservoirs. In each model, the top of the sub-basalt reservoir is 3.5 kmbsf.

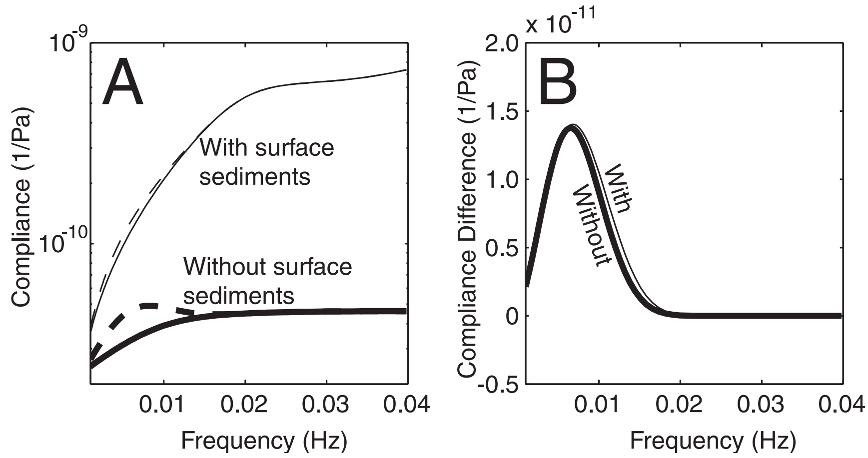
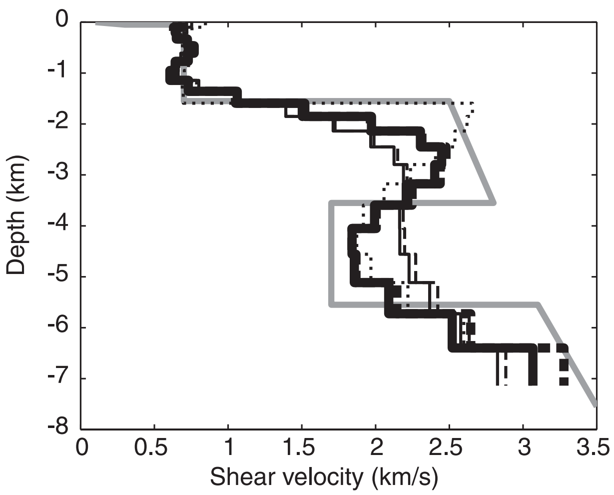


Figure 4. The effect of surface sediments on the "visibility" and on the true effect of a sub-basalt reservoir in compliance data. The "with surface sediments model" is our standard Model A, the "without surface sediments" model is Model A with the sediment velocities replaced by basaltic velocities. Left: The compliance function for each model. Dashed lines show compliance of the model with the sub-basalt reservoir, solid lines show compliance for the same model with the sub-basalt reservoir removed. Right: The differences between the dashed and solid lines in the left figure.

variations from the true values either give similar inversion results or (if the assumptions are too far from reality) the inversion does not converge. For example, inversions using compressional velocity and density models without sub-basalt sediments (dashed lines, **Figure 5**) give the same results as inversions starting with the correct values (solid lines, **Figure 5**).

The inversion results improve if the source waves are stronger because of the corresponding decrease in data uncertainty (compare the thick lines for the strong pressure source with the thin lines for the weak pressure source). The inversion results also improve greatly if we have some pre-existing knowledge of the shallow structure. To simulate *a priori* knowledge of the depth to the sediment-basement interface, we allowed a jump at that depth in an inversion for compliance measured under weak waves. The resulting inversion (dotted line, **Figure 5**) fits the original model better than inversions of data under strong waves.



Bayesian inversions

To further investigate the role of prior information on the detection and description of sub-basalt reservoirs, we performed a series of Bayesian inversions on simulated data, using block models with *a priori* interface depths, shear moduli and uncertainties consistent with the results expected from seismic data. We use a Bayesian inversion based on [Jackson and Matsu'ura, 1985]. We use a simplified version of Models A and B in which the velocity/moduli are constant in each layer.

Figure 5. Results of minimum structure inversions to determine shear velocity structure. Grey line shows the true values, thick lines show the inversion results for strong wave forcing and thin lines show inversion results for weak wave forcing. Solid lines: the starting model used in the inversion includes a sub-basalt reservoir, dashed line = the starting model contains no sub-basalt reservoir. Dotted line = weak wave forcing, but allow velocity to jump at the sediment/basalt interface.

This simplifies the model parameterisation for the inversion and does not alter the results since compliance is not very sensitive to the small gradients in our models. In the inversions, we assume that the following parameters are unknown but with some prior constraint

Table 1. *A priori* values and uncertainties assumed in Bayesian inversions to fit compliance data.

	Parameter	Value	
Depth to top of:	Normal surface sediments	0.05±0.02 km	
	Basalts	1.5±0.1 km	
	Sub-basalt sediments	3.5±1.0 km	
	Basement	5.5±1.0 km	
Shear modulus in:	Squishy surface sediments	0.06±0.03 GPa	(0.2±0.05 km/s)
	Normal surface sediments	0.98±0.28 GPa	(0.7±0.1 km/s)
	Basalts	17.9±1.3 GPa	(2.7±0.1 km/s)
	Sub-basalt sediments	6.8 or 10.4±1.0 GPa	(1.7 or 2.1±0.15 km/s)
	Top basement layer	29.7±1.8 GPa	(3.35±0.1 km/s)
	Bottom basement layer	32.5±0.9 GPa	(3.5±0.05 km/s)

We include a value for the top and bottom of the sub-basalt reservoir, even though in practice we have no idea such a reservoir exists. We simply put in a large enough data uncertainty to allow all feasible ranges of the sub-basalt reservoir and then observe the inversion results. **Figures 6** and **7** shows the *a priori* uncertainties and the uncertainties obtained by the inversion code using the compliance data. These inversions are by definition biased by the starting model, so we ran inversions for 100 randomly generated *a priori* models that fall within the defined parameter uncertainty. We calculate the uncertainty in the inverted data as the standard deviation in the parameters resulting from independent inversions of data with random noise and the *a priori* models.

The inversions significantly improve the resolution of the depth to the top and bottom of the sub-basalt reservoir if the overlying water is deep (1.7 km). The depth to the top and the bottom of the sub-basalt sediments is constrained to within 0.15-0.5 km depending on the strength of the waves overhead and the sediment shear modulus. The shear modulus in the surface sediments is also well constrained by the inversions, but the inversion does not improve constraints on the shear modulus in the basalts, the sub-basalt sediments, or the basement. Weak shear modulus constraints are expected for the basalts and the basement, because their high shear modulus has little effect on the compliance signal. The weak sub-basalt sediment shear modulus constraints probably arise from the much tighter *a priori* constraints on the layer shear modulus than on its thickness. To first order, the strength of the compliance signal generated by this region is proportional to its thickness divided by its shear modulus, so that varying the thickness can accommodate much of the effect of shear modulus variations. To a second order, the shape of the compliance peak as a function of frequency depends on the layer thickness, allowing the layer thickness and shear modulus to be de-coupled if the data uncertainty is very small. We need to run more tests with higher variability in the *a priori* sub-basalt sediment shear modulus to determine exactly how independently the layer thickness and shear modulus can be constrained.

In shallow (0.25 km) water depth, the upper sediment shear moduli are very well constrained but the sub-basalt sediment layer parameters are generally unconstrained. The compliance data improves constraints only on the depth to the top of the fluid-rich sub-basalt sediments (Model A). The lack of constraints on this layer arises because the source wavelengths are much shorter in shallow water, so that not much energy penetrates to the 3.5+ km depth of the sub-basalt layer.

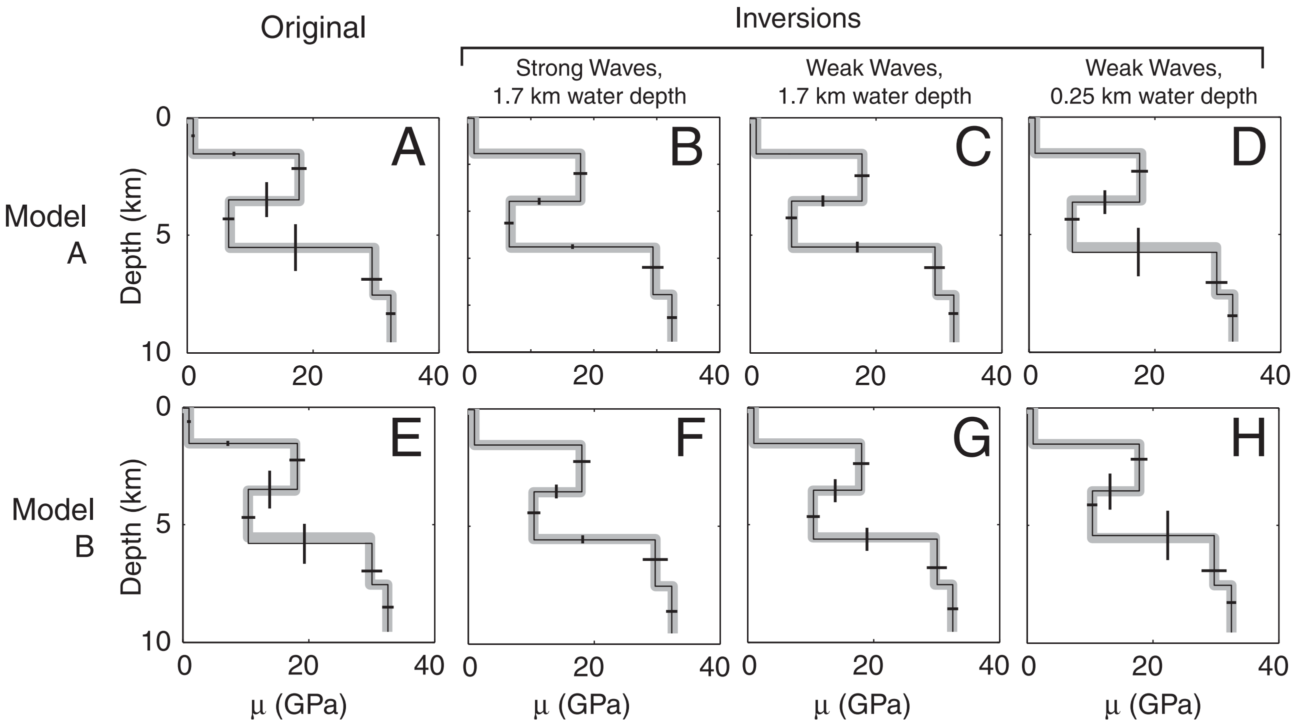


Figure 6. Sensitivity of Bayesian inversions to model properties. Thick grey lines show the true model, thin black lines and error bars show the average fit and standard deviation of the a priori model (A,E) and the inversions. Plots A and E show the starting model, B and F show inversion results in deep water with a strong wave source, C and G show results for deep water and weak wave forcing, D and H show results in shallow water for weak wave forcing. Plots A-D are for a model with low shear velocities consistent with fluid-rich sediments. Plots E-H are for a model with high shear velocities consistent with dry sediments.

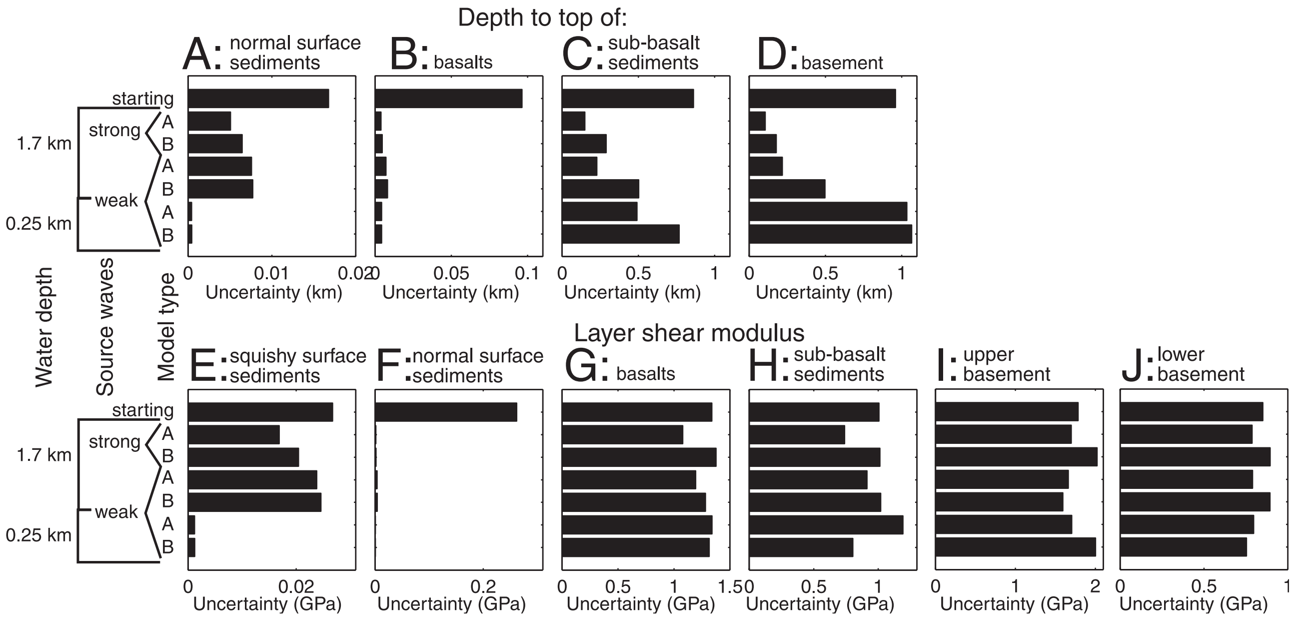


Figure 7. Parameter uncertainty for the starting and inverted models in Figure 6. In each plot, the top bar shows the starting uncertainty and the other bars show uncertainties obtained for inversions in different water depths, forcing wave strengths, and sub-basalt sediment shear velocities. Each plot shows the uncertainty for one property: plots A-D for boundary depths and plots E-J for layer shear modulus.

What is the smallest reservoir that can be detected by compliance measurements? We calculated the RMS misfit to models with varying sub-basalt reservoir thicknesses using an inversion that assumes there is no sub-basalt reservoir (**Figure** 8). For each thickness, we created a model and then calculated and inverted compliance 100 times, each time with random noise added to the data and *a priori* model. The data random noise is distributed consistent with a weak pressure source and 1.7 km water depth. We then calculated the mean and standard deviation of the resulting RMS values. **Figure 7** shows the misfit as a function of the reservoir size for Model A. The sub-basalt reservoir is "detectable" if the average misfit to the non-reservoir model is greater than 1 plus 1 standard deviation (equivalently, more than 84% of the inversions give a RMS misfit greater than 1). **Figure 8** shows that sub-basalt sediments with shear velocity ≤ 1.7 km/s are detectable under weak waves and in deep water if they are more than 0.8 km thick.

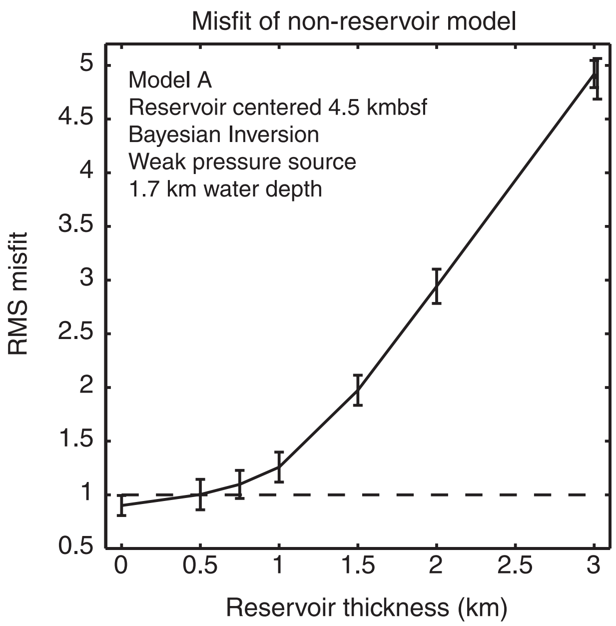


Figure 8. Sensitivity of compliance measurements to the existence of a sub-basalt reservoir centred 4.5 km beneath the seafloor under a 1.7 km water layer with a weak ($10^{3.5}$ Pa^2/Hz) pressure source. Compliance is calculated for a starting model containing a sub-basalt reservoir from 0-3 km thick, then Bayesian inversions are run assuming that there is no sub-basalt reservoir. The average RMS misfit and standard deviation is shown for 50-100 inversions at each reservoir thickness. Dashed line marks a RMS misfit of 1.

Discussion and Conclusions

Our tests indicate that compliance can detect sub-basalt sediments of the size and properties expected beneath Faeroe Basin, even under relatively unfavourable conditions (a weak pressure signal), as long as the ocean is relatively deep (>1 km). We do not know the strength of the seafloor pressure signal in the Faeroe region, so I have concentrated on the case equivalent to weakest pressure source measured in open oceans (from 20-35° in the Atlantic Ocean). The pressure signal in the Faeroe region (~60°) may be stronger because of the stronger winds at high latitude [Webb *et al.*, 1991]. Even under weak waves, compliance measurements can detect and constrain the depth and size of sub-basalt sediments. It is important to note that compliance becomes the most sensitive to the properties of the sub-basalt layer in the case that they are heavily fluid-saturated, which is the case of most interest for petroleum exploration.

Compliance measurements also provide very precise information about the shear properties and thickness of the sediments above the basalt layer. In this case, shallow sites (<=0.25 km) do an even better job than deep sites (>1 km), but the improvement is significant in either case. The tightest apparent constraints (less than 10 meters in some cases!) are unrealistic, however, because other variables not considered in our inversions (two-dimensionality, variations in velocity within the sediments) will play a role at these precision extremes. A thin layer of very low-velocity sediments (~0.05 km thick, 0.1-0.3 km/s shear velocity) is only detected and constrained by compliance measurements in shallow water.

Here is a summary of the results:

- Under weak waves ($10^{3.5}$ Pa^2/Hz) and in deep water (~1.7 km), compliance measurements can detect a relatively low shear velocity (1.7 km/s) sub-basalt sediment layer more than 0.75 km thick.
- In deep water, under weak waves and for Vs(sub-basalt)=1.7km/s, compliance measurements constrain the depth to the top and bottom of 2 km thick sub-basalt sediments to within 0.25 km.

- In deep water, under strong waves and for Vs(sub-basalt)=2.1km/s, compliance measurements constrain the depth to the top and bottom of 2 km thick sub-basalt sediments to within 0.25 km.
- In deep water, under weak waves and for Vs(sub-basalt)=1.7km/s, compliance measurements constrain the depth to the top and bottom of 2 km thick sub-basalt sediments to within 0.5 km.
- In shallow water (0.25 km) and under weak waves, compliance measurements do not constrain the depth to the bottom of a 2-km thick sub-basalt sediment layer.
- In shallow water (0.25 km) and under weak waves, compliance measurements constrain the depth to the top of a 2-km thick sub-basalt sediment layer to within 0.5 km if the sediment shear modulus is ≤ 1.7 km/s.

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