Applications of Seafloor Compliance Measurements in the Faroes-Shetland Basin

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Abstract

Seafloor compliance is a geophysical prospecting method that uses the seafloor motion under ocean waves to determine the shear modulus structure of the subsurface. Seafloor compliance measurements are of interest to petroleum exploration because they are sensitive to fluid-filled regions and because their source is always "on", which should permit continuous monitoring of regions of interest during exploitation. We review the seafloor compliance method and previous studies made using the method, and then calculate the sensitivity of seafloor compliance measurements to sub-surface features of interest in the Faroes-Shetland Basin, particularly to sub-basalt sediments. We find that seafloor compliance measurements will be sensitive to shear velocity structure from 50 meters to as much as 6 km beneath the seafloor. They will be sensitive to sub-basalt sediments almost everywhere where the water depth is greater than 0.9 km and in some shallower areas directly south of the Faroe Islands. Assuming sub-basalt sediments start 3.5 km beneath the seafloor, compliance measurements will constrain their depth and thickness to within 0.1-0.2 km if the water depth is 1 km or more. For the same water depths, if the depth limits of the sub-basalt sediments are already well constrained, seafloor compliance measurements will constrain their shear velocities to within approximately 0.1 km/s. For water depths greater than 0.05 km, seafloor compliance measurements should constrain the average shear wave velocity in sediments above the basalt flows to within 0.01 km/s.

Introduction

Fluid-rich zones are an important but often difficult to locate target in petroleum exploration. The Faroes region is a prime example, with potential petroleum reservoirs lying undetected in fluid-rich sediments beneath basalt flows or in trapped unconsolidated sediment layers (Mack, 1997). Fluids are defined by their inability to support shear without deformation, but most geophysical methods are insensitive or secondarily sensitive to low shear modulus/velocity regions and some are even hindered by them. The seismic method is one of the best tools for detecting and monitoring petroleum reservoirs, but it is mostly sensitive to compressional-wave velocities and the acoustic impedance. In addition, the well-known difficulties of seismic imaging beneath stratified basalt flows hinder seismic imaging of sub-basalt sediments in the Faroes region. Much work has been done to overcome these difficulties (Fruehn *et al.*, 1999; White *et al.*, 1999; Barzahi *et al.*, 2001; Fliedner and White, 2001; Fruehn *et al.*, 2001; Martini and Bean, 2001; Hobbs, 2002; Fliedner and White, 2003; White *et al.*, 2003; Ziolkowski *et al.*, 2003), but the problem remains difficult.

Seafloor compliance measurements should help to locate and study fluid-rich zones. Seafloor compliance is the displacement of the seafloor under pressure forcing from slowly propagating ocean surface waves. Seafloor compliance measurements are most sensitive to the sub-surface shear modulus and compliance values are largest over low shear modulus zones, making compliance measurements a perfect complement to seismic data. Seafloor compliance measurements have been used to study shallow sediment properties (Yamamoto and Torii, 1986; Trevorrow and Yamamoto, 1991), gas hydrates (Willoughby and Edwards, 1997; 2000) and the melt structure between mid-ocean ridges (Crawford *et al.*, 1994; Crawford *et al.*, 1999; Crawford and Webb, 2002), and have proven par-

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ticularly sensitive to fluid-rich targets at depth. Much progress has been made recently in modeling seafloor compliance and in understanding its properties (Crawford *et al.*, 1998; Latychev and Edwards, 2003; Hulme *et al.*, 2004). The method has its limitations, in particular a relatively low vertical resolution, but these can be overcome by combining with seismic data (Hulme *et al.*, 2004; Roberts, 2004).

In this paper, we review the state of the art in seafloorcompliance measurements, modeling, and data inversion, and investigate what compliance measurements can contribute to studies of the Faroes-Shetland Basin. We first review the seafloor compliance method describe what it is sensitive to and how it is modeled. We then present the data inversion technique we use to calculate subsurface structure from seafloor compliance data. We estimate the sensitivity of seafloor compliance measurements to subsurface features of interest in the Faroes region by applying our data inversion to synthetic Faroes-area compliance data. We calculate the depths to which compliance will be sensitive throughout the Faroes region and identify where compliance measurements can be used to study sub-basalt sediments.

Seafloor Compliance

Seafloor compliance is the transfer function between pressure forcing from linear ocean surface gravity (LOSG) waves and the seafloor displacement beneath them. It is measured using a seafloor broadband seismometer and pressure gauge (Figure 1). Both the seafloor compliance and seismic methods are based on elastic motions, but the compliance method uses the quasi-static subsurface deformation under shear stress rather than wave propagation, which gives it quite different properties than active seismic methods. The applied stress is mostly shear because the pressure highs and lows act normal to the seafloor and are separated horizontally.

We use LOSG waves because we can calculate their wavelength, $L(\omega)$, from the water depth, H, and the angular frequency, (ω), using the LOSG wave dispersion relation:

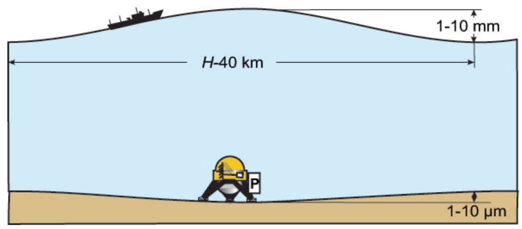

Figure 1. Cartoon representation of the compliance wave source and the compliance measurement using a broadband seismometer and differential pressure gauge (P) deployed to the seafloor. The typical ocean wave and the seafloor signal amplitudes are shown. *H* is the water depth.

$$\omega^2 = gk(\omega)\tanh(k(\omega)H) \quad (1)$$

where $k(\omega) \equiv 2\pi / L(\omega)$ is the wavenumber and g is the gravitational acceleration (Apel, 1987). In general, LOSG waves only generate a measurable seafloor pressure signal if $L > H$, because the pressure signal decays exponentially with depth (Apel, 1987). The upper frequency bound, f_{max}, for compliance measurements is the frequency where both the seafloor pressure signal and the seafloor motion underneath it are significantly above background noise levels, which corresponds approximately to $L = 1.1H$. Using this observation and equation (1), we can calculate f_{max} as a function of water depth: for example, $f_{max} \approx 0.119$ Hz for $H = 100$ meters and 0.038 Hz for $H = 1000$ meters. Ocean surface waves that are visible to the naked eye are generally less than 100 meters long, so most of the seafloor signal at water depths greater than 100 meters comes from very small (0.001-0.01 meter tall), low frequency LOSG waves known as *free infragravity* waves (Webb *et al.*, 1991).

Figure 2 shows seafloor acceleration and pressure spectra measured at 345, 900, and 2600 meter water depths. The free infragravity waves are the high energy in the pressure signal between 0.001 and 0.1 Hz (Figure 2a). At the shallowest site, wind waves generate a small pressure peak at 0.05 Hz ($L \approx 500$ meters) (these waves are also LOSG waves, and so their signal and effects can be used for compliance studies). The compliance motion under free infragravity waves generates a broad peak in the acceleration signal between 0.0035 and 0.1 Hz (Figure 2c). By plotting the spectra as a function of the wavelength calculated using

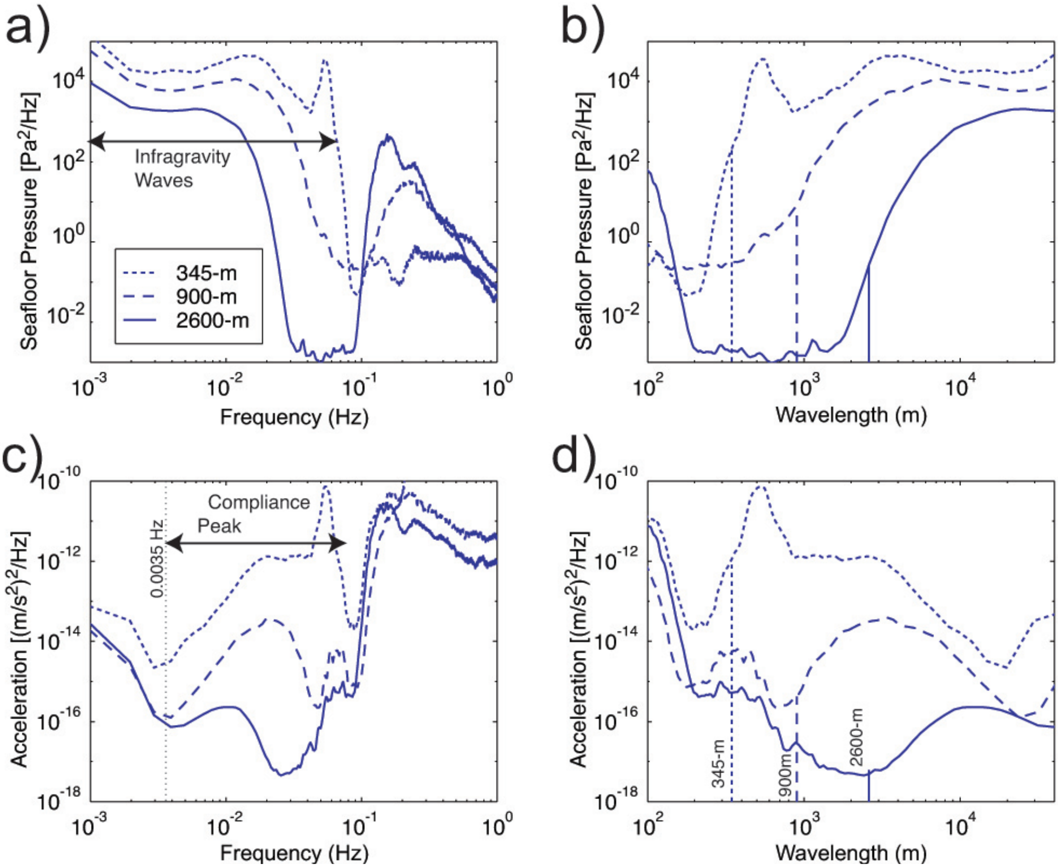

Figure 2. Seafloor pressure and acceleration power spectral densities (PSD) in the compliance frequency-wavelength band, measured at 345-m, 900-m and 2600-m water depths. In the right column, a vertical line marks the wavelength equal to the water depth for each measurement. (**a**) Pressure PSD as a function of frequency. (**b**) Pressure PSD as a function of wavelength. (**c**) Acceleration PSD as a function of frequency. (**d**) Acceleration PSD as a function of wavelength.

equation (1), it is clear that most of the compliance signal is at wavelengths longer than the ocean depth (Figure 2b, d). The seafloor compliance is the transfer function between the acceleration and pressure in this band.

Compliance is governed by the same equations of motion that describe elastic wave motion:

$$\rho(\mathbf{x})\ddot{u}_i(\omega,\mathbf{x}) = \tau_{ij,j}(\omega,\mathbf{x}) \tag{2}$$

where ρ is the material density, u_i is the motion in the ith direction and τ_{ij} is the stress acting in the jth direction across the plane normal to the i-axis (i,j=1,2,3). We define seafloor compliance as

$$\eta(\omega) = k(\omega)\left.\frac{\mathbf{u}(\omega)}{\tau_{zz}(\omega)}\right|_{z=0}. \tag{3}$$

The seafloor compliance has been calculated for an isotropic uniform half-space and slow wave forcing:

$$\eta(\omega) = \frac{-1}{2(\lambda+\mu)}\, i\hat{x} + \frac{(\lambda+2\mu)}{2\mu(\lambda+\mu)}\hat{z}\,, \tag{4}$$

where λ is the dilatation modulus, μ is the shear modulus and $\hat{x}$ and $\hat{z}$ are unit vectors (Crawford, 2004). The horizontal compliance motion is very hard to measure at the seafloor, so we concentrate here on the vertical compliance motion ($\hat{z}$ term). This motion is at least 5 times more sensitive to μ than to λ and is inversely proportional to μ if $\mu = \lambda$. It is this sensitivity to μ, especially where μ is small, that makes compliance useful for studying fluid-rich regions within the sub-surface. A fluid-rich region within the subsurface generates a peak in the compliance (Figure 3) whose center frequency depends on the region's depth: the deeper

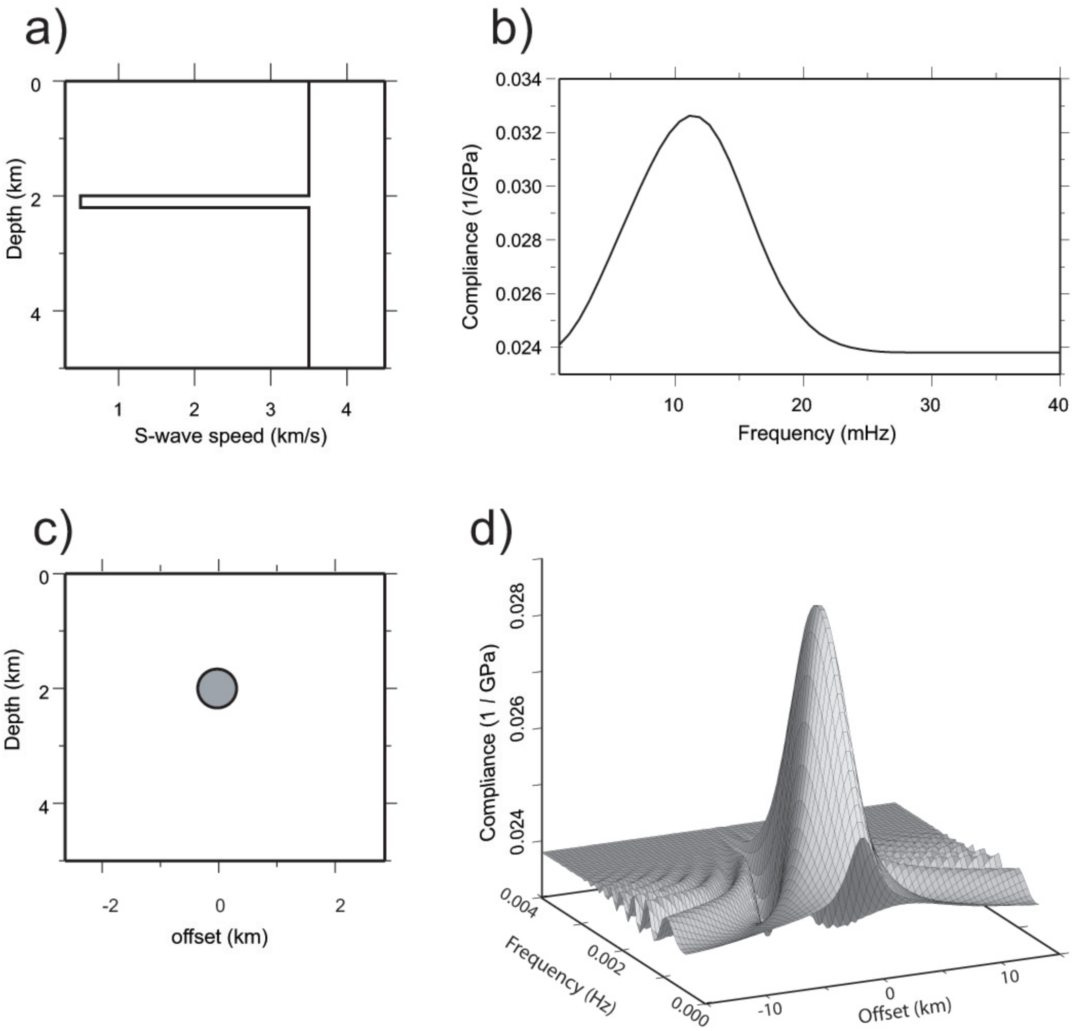

Figure 3. The effect of a low velocity zone on seafloor compliance, calculated using 1D and 2D models. In both cases the LVZ is 2 km beneath the seafloor. (**a**) 1D shear velocity model. (**b**) 1D compliance. (**c**) 2D velocity model, the low velocity zone is modeled as a cylinder (Hulme *et al.*, 2004). (**d**) Compliance of the 2D model as a function of frequency and offset.

the region is, the lower is the peak frequency. If the fluid-rich region is bounded horizontally, the peak is largest directly over the region and decays to one-half its maximum height at a distance away from the region equal to 1.7 times the region's depth (Crawford *et al.*, 1998; Latychev and Edwards, 2003; Hulme *et al*., 2004). A large number of compliance measurements can be made with a few instruments because each instrument can be deployed multiple times and there is no need to make the measurements concurrently. Typically, we recover and redeploy each compliance instrument every two days.

The depth, D_{sens}, beneath the surface to which compliance is sensitive is between $L(\omega)/6$ and $L(\omega)/4$ (Crawford *et al.*, 1991; Crawford *et al.*, 1998). The shortest wavelength is approximately $1.1H$ and the longest, from equation (1), is $\sqrt{gH}\,/\,f_{\min}$, where $f_{\min}$ is the minimum measured frequency (typically 0.0035 to 0.004 Hz). If we assume $D_{sens} = L/5$ and $f_{\min} = 0.0035$ Hz, the minimum sensitive depth is approximately $H/5.5$ and the maximum sensitive depth, $D_{\max}$, is approximately $180\sqrt{H}$ (Figure 4). Compliance measurements can be used to calculate the average velocity above and just below these bounds, but they can only distinguish velocity structure within these bounds.

The sensitivity of compliance to a given feature depends on the feature's size and shear modulus: small but very low shear modulus features can generate a stronger signal than larger features with more subtle shear modulus variations (e.g. Crawford *et al.*, 1991; Crawford *et al.*, 1999; Latychev and Edwards, 2003; Hulme *et al.*, 2004). To date, compliance measurements have been used to study shallow sediment shear moduli at shallow water sites (Yamamoto and Torii, 1986; Trevorrow and Yamamoto, 1991), magma chambers beneath volcanic seamounts (Crawford *et al.*, 1991), gas hydrates (Willoughby and Edwards, 2000) and lower crustal partial melting beneath oceanic ridges (Crawford *et al.*, 1994; Crawford *et al.*, 1999; Crawford and Webb, 2002). In November 2004, seafloor compliance was measured in the Faroe-Shetland Basin to study sub-basalt sediments.

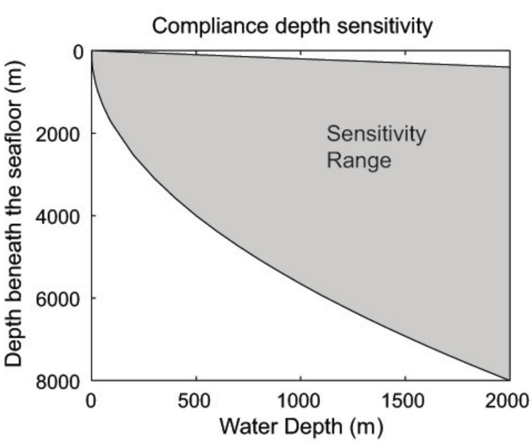

Figure 4. Depth sensitivity of compliance. For a given water depth (x-axis), compliance is sensitive to structure at the shaded sub-surface depths. The calculations assume a minimum sensitive frequency of 0.0035 Hz.

If shear velocities are available from seismic data, these values can be combined with compliance-estimated shear velocities to calculate the shear wave attenuation. The compliance frequency band is several orders of magnitude lower than the active seismic frequency range and the shear wave velocity may be significantly lower in the compliance frequency band if attenuation is important between the two bands (Figure 5). This was the case at a site on the East Pacific Rise, where converted S-wave phases recorded using a shot-streamer configuration indicated much higher upper crustal shear velocities than did seafloor compliance data. Hulme *et al.* (2003) found that transverse anisotropy could explain up to a 5% variation between shear wave velocities measured by seismic and compliance methods and that anelasticity could cause up to a 40% decrease in seismic velocities between the seismic and seafloor compliance frequency bands (Figure 5). If there is significant anelasticity, compliance-derived shear velocities should better indicate a region's permeability to fluid flow, since this flow generally occurs over time scales closer to seafloor compliance frequencies than to seismic frequencies.

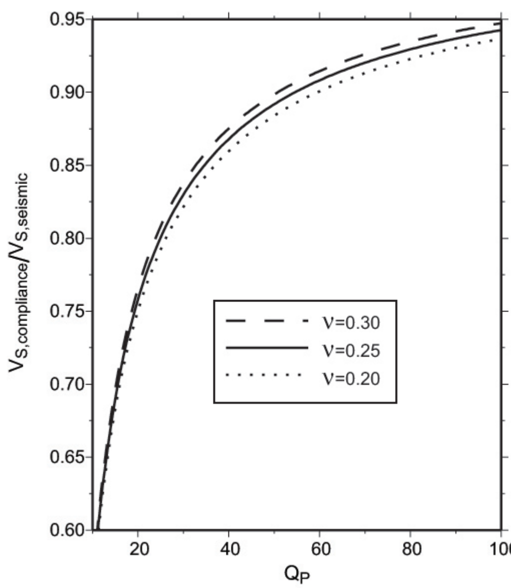

Figure 5. The ratio of shear wave speed values measured by compliance versus active seismic data as a function of quality factor Q_P. The different curves show values for different Poisson's ratios (0.2 to 0.3) (from Hulme *et al.*, 2003).

Compliance measurements, modeling and data inversion

Compliance is measured using a seafloor seismometer and pressure gauge (Figure 1). If the water is more than 100 meters deep, these instruments should be sensitive out to at least 300 seconds period. We use a broadband seismometer (Streckeisen STS-2 or Guralp CMG3-T) and a differential pressure gauge (Cox *et al.*, 1984). To reduce uncertainty, we stack 100 or more data windows during which there are no extraneous signals from instrument settling, earthquakes, ships, and etcetera. We generally deploy each seafloor compliance sensor every two days to obtain one hundred or more good 1024-second windows (28.5 hours), while allowing for the time required to recover and redeploy the instruments (6-8 hours), for them to thermally and mechanically settle at the seafloor (5-10 hours) and for events such as earthquakes that mask the compliance signal (0-5 hours).

We calculate the subsurface shear modulus from the compliance data using geophysical inversions in which the model constraint is either minimum structure or *a priori* values (Crawford, 2004). Using the minimum structure constraint, the results are independent of the starting model, but we cannot use prior data and a large model parameter space is required, making the inversion slow for all but 1-D models. Using an *a priori* constraint takes advantage of prior data and gives quicker inversions for 2D and 3D models.

Some compliance applications in the Faroes region

We begin our investigation of compliance applications in the Faroes region by calculating the depth range of compliance sensitivity around the islands (Figure 6), and comparing these ranges to the estimated depths of sub-surface features of interest. We focus on the area where most of the seismic lines have been shot in Faroes waters (blue polygon, Figure 6a) and a sub-region of this area in which seismic coverage is particularly dense (red polygon). We refer to these areas as the “exploration area” and the “densest seismic area”, respectively. Within the exploration area, water depths are concentrated at 200 and 900 meters (Figure 6b), corresponding to maximum sensitive depths of 2500 and 5500 meters beneath the seafloor, respectively (Figure 6d). Within the densest seismic area the depths are clustered at 300 and 1100 meters, corresponding to maximum sensitive depths of 3000 and 6000 meters. Compliance measurements are sensitive to subsurface structures starting about 50 meters beneath the seafloor in the shallower zones and about 200 meters beneath the seafloor in the deeper waters (Figure 6c).

To determine the sensitivity of compliance to sub-basalt sediments and surface sediments, we ran geophysical inversions on synthetic compliance data calculated for the range of water depths and subsurface structures expected in the Faroes region. The synthetic compliance data includes uncertainties calculated using typical seafloor noise levels and assuming 28.5 hours of good data (Crawford, 2004).

Shallow sediment properties

Compliance is very sensitive to shallow sediments, especially if they have low shear moduli (unconsolidated sediments, for example). Crawford *et al.* (2004) ran inversions on synthetic data for a model with a 50 meters thick, 200 m/s shear velocity sediments overlying 1500 meters thick sediments with 700 m/s shear velocity layer, for a water depth of 1300 meters. They recovered the surface sediment layer thickness to within 10 meters and its shear velocity to within 30 m/s, and the underlying layer thickness to within 10 meters and its shear velocity to within 1 m/s. Inversion uncertainties will be greater for real data because of lateral inhomogeneities and depth variations in velocity within each layer, but the results underline the sensitivity of compliance measurements to low shear velocity regions. When compliance measurements are combined with active seismic data that provide accurate information about horizon depths and lateral variations, one may obtain inversion accuracies approaching these ideal values.

Sub-basalt sediments

Compliance should be sensitive to sub-basalt sediments if D_{max} is more than 1000 meters beneath the bottom of the basalts. A typical case for Faroes Basin is H=1000 meters and the bottom of the basalts is 3500 meters beneath the seafloor (White *et al.*, 2003). For this case, a minimum structure inversion detects the sub-basalt sediments (Figure 7a) and a Bayesian inversion constrains the depth to their top to within 200 meters. If the sediments

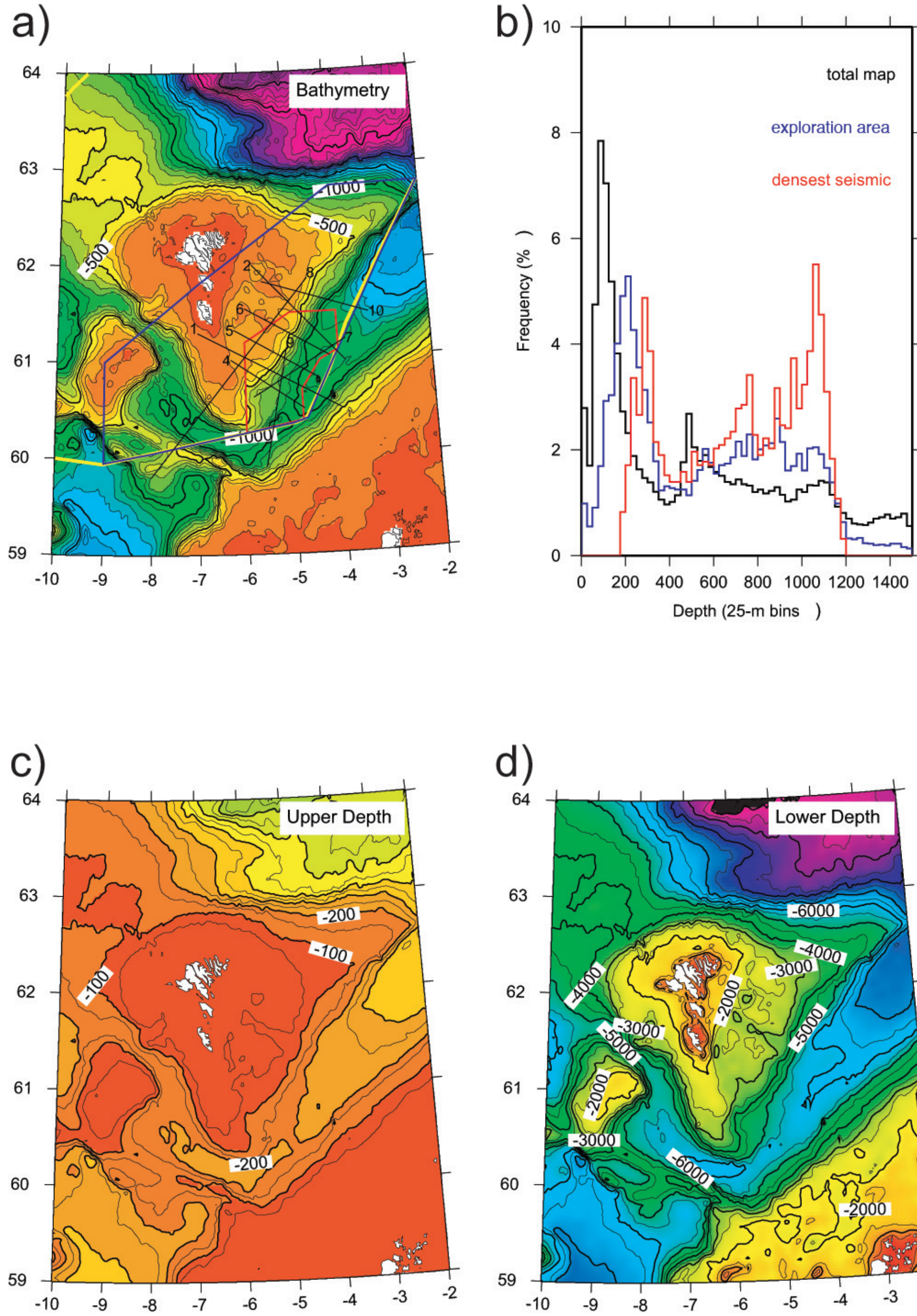

Figure 6. Bathymetry and compliance depth sensitivity around the Faroe Islands. (**a**) Bathymetry. The blue polygon contains the region of principal seismic exploration within the Faroes economic zone. The red polygon contains the densest region of seismic studies (from the SINDRI web site: http://www.sindri.fo/data/surveys/geophys_data.html). The numbered black lines mark wide-angle seismic lines from the FLARE experiment (Fruehn *et al.*, 1999; White *et al.*, 1999; Fruehn *et al.*, 2001; Fliedner and White, 2003). The yellow line marks the boundary between Faroes and United Kingdom waters. (**b**) The distribution of water depths within the entire map (black line) and the two polygons. (**c**) The upper (shallow) limit of compliance sensitivity to structural variations in the subsurface. (**d**) The lower (deep) limit of compliance sensitivity to structural variations in the subsurface.

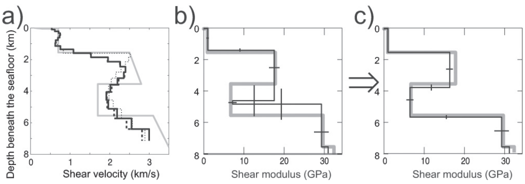

Figure 7. Minimum structure and Bayesian inversion results for a model with sub-basalt sediments starting 3500 meters beneath the seafloor. (**a**) Minimum structure inversion (the starting model contains no low-velocity zone). Grey line = true model. Thick black lines: inversion results with no *a priori* information. Thin dashed line: inversion results if the depth to the top of the basalts is known. (**b**) One *a priori* model (black line) and uncertainties. Grey line = true model. (**c**) Bayesian inversion result (black line) and uncertainty calculated from the *a priori* model and synthetic compliance data as discussed in the text.

are 2000 meters thick, the depth to their bottom is also constrained to within 200 meters. Without *a priori* constraints, a sub-basalt sediment layer more than 600 meters thick should be detected by compliance data (Crawford, 2004).

To determine where in the Faroes region seafloor compliance measurements will be sensitive to sub-basalt sediments, we subtracted the depth to the bottom of the basalts (White *et al*., 2003) from D_{max} in the Faroes area (Figure 8). North of ~61°N, this region is limited to water depths greater than 900 meters, whereas south of 61°N, where the sub-basalt sediments are shallower, the region spans most of the Faroes waters. The region of sensitivity includes about 75% of the densest seismic area.

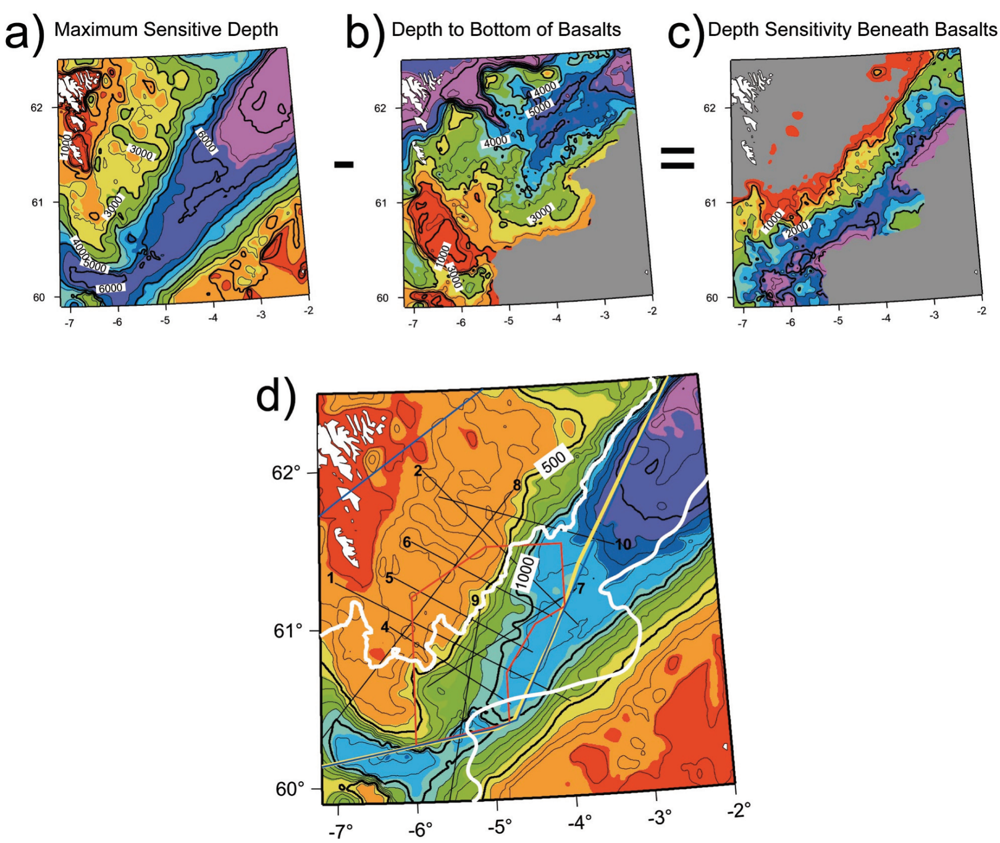

Figure 8. Estimates of where compliance measurements can be used to study sub-basalt sediments in the Faroes region (white colour, subplot (**d**)). (**a**) Maximum sensitive depth of compliance. (**b**) Depth to the bottom of the basalt layer (calculated using a compilation of seismic lines in the region and first published in White *et al*., 2003). (**c**) Compliance depth sensitivity beneath the basalts, obtained by subtracting (b) from (a). (**d**) Faroes bathymetry, with the "good compliance" zone (wherever compliance is sensitive to more than 1000 meters beneath the basalts) within the white outline. The eastern bound of this zone is the limit of the basalt flows. Depth contours and lines indicating other boundaries are the same as in Figure 6a.

Figure 9 compares the compliance depth sensitivity to subsurface cross-sections from the two-ship active seismic FLARE experiment (White *et al*., 1999; Fliedner and White, 2003; White *et al*., 2003).

We identified two end member structures, a "Faroes Deep" (FD) profile with sub-basalt sediments starting 3500 meters beneath the seafloor and a "Faroes Shallow" (FS) profile with sub-basalt sediments starting 2500 meters beneath the seafloor. We used these models as references to calculate the seafloor compliance sensitivity to surface and sub-basalt sediments. We assumed the basalt layer was 1000 meters thick in the FS model and 2000 meters thick in the FD model. The FD model is the same as that used by (Crawford, 2004) to investigate sub-basalt compliance sensitivity, except we decreased the water depth from 1300 to 1000 meters to more accurately represent the Faroes region. We use realistic infragravity wave

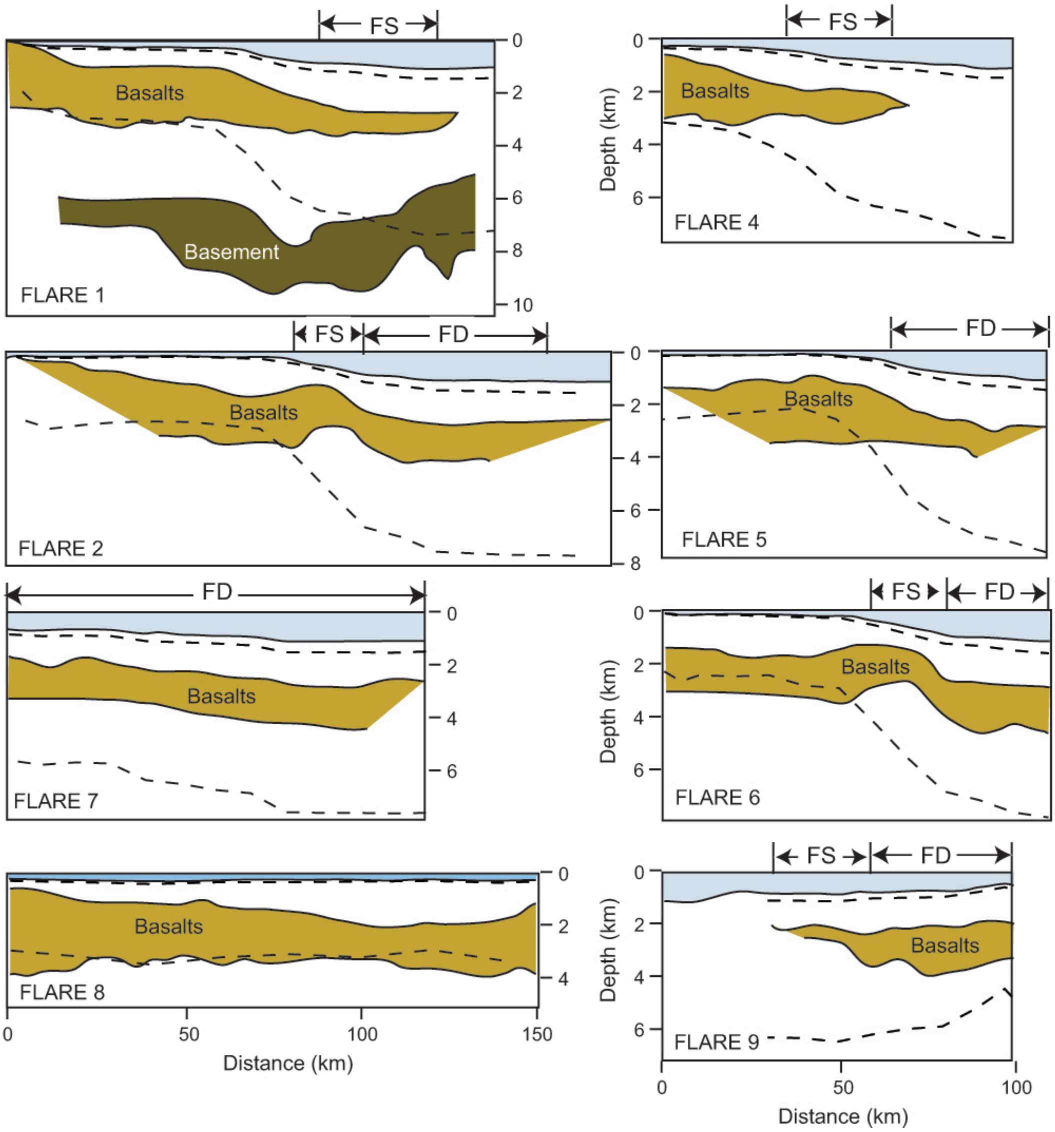

Figure 9. Cross-sections of sub-surface structure obtained from the FLARE experiment (Fliedner and White, 2003; White *et al*., 2003), compared to the compliance depth sensitivity limits (dashed lines). The top shaded area is water. The sections "FS" and "FD" indicate the models we ran that are most similar to these sections (Figures 7 and 10).

Parameter	FS model			FD model		
	Value	Uncertainty		Value	Uncertainty	
		a priori	After inversion		*a priori*	After inversion
Depth to top of middle sediments (meters)	50	20	3	50	20	3
Depth to top of basalts (meters)	1500	100	5	1500	100	4
Depth to top of sub-basalt seds (meters)	2500	1000	100	3500	1000	200
Depth to bottom of sub-basalt seds (meters)	5500	1000	200	5500	1000	200
Shear velocity of top sediments (m/s)	200	50	3	200	50	3
Shear velocity of middle sediments (m/s)	700	100	1	700	100	1

Table 1: Compliance sensitivity to features of two Faroes Basin sub-surface models.

source levels and random seismic noise based on observed seafloor noise levels to calculate hundreds of synthetic seafloor compliance data for each model. We ran inversions on all the data and statistically analyzed the results to determine the compliance sensitivity to each model layer (Crawford, 2004). Table 1 lists the *a priori* and final parameter uncertainties for both models and Figure 10 shows the uncertainties for the FS model.

The only significant difference in the compliance sensitivity to the FS and FD models is to the depth of the top of the sub-basalt sediments. Compliance measurements constrain this depth to within 100 meters in the FS model and to within 200 meters in the FD model. Both are significant improvements over the *a priori* uncertainty of 1000 meters. The depth of the sub-basalt sediments controls the compliance sensitivity, not the thickness of the overlying basalts (Crawford, 2004).

Discussion and Conclusions

Seafloor compliance measurements may be used to detect and study low shear modulus zones associated with unconsolidated sediments and sub-basalt sediments. They should be sensitive to unconsolidated sediments up to several km beneath the seafloor throughout the Faroes region and useful for studying sub-basalt sediments in the deeper waters (greater than 500 meters water depth to the south of the Faroe Islands and greater than 900 meters water depth to the east). The shallower the sub-basalt sediments are, the more sensitive the compliance measurements will be to them.

The greatest uncertainty in this analysis is the pressure levels of the source infragravity waves. We assumed that the pressure level was 10^4 Pa^2/Hz, which is a typical value worldwide, but the levels in the Faroes region could be higher or lower because of local effects. The only way to know these levels are to measure them directly at the seafloor over a period long enough to cover any seasonal

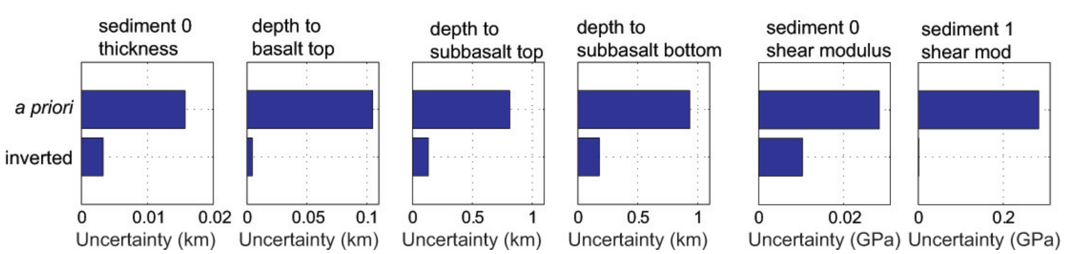

Figure 10. Uncertainties in Faroes FS model parameters before and after inversions using synthetic compliance data. The data are generated assuming a 1000 meters water depth, infragravity wave power spectral density of 10^4 Pa^2/Hz and 100 data windows of 1024 seconds each (see Crawford (2004) for details).

variations. The ideal solution would be year-long pressure measurements at a site in shallow water near the Faroe Islands and at a second site at 1000 meters water depth in the Faroes Basin.

Compliance inversions can be considerably improved by using *a priori* data, and the structure should be even better constrained using joint inversions with seismic and electromagnetic data. An experiment is scheduled to measure compliance over the FLARE-1 and FLARE-10 seismic lines in the Faroes Basin. The FLARE 10 line was the site of recent electromagnetic measurements (Jegen-Kulcsar and Hobbs, this issue): compliance measurements on this line should provide a good opportunity to investigate the relative strengths of active seismics, EM and compliance for studying unconsolidated and sub-basalt sediments and will provide a test bed to study the usefulness of joint seismic-compliance-EM inversions.

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References

Apel, J.R. 1987. Principles of ocean physics, Academic Press, London.

Barzahi, I., Calacagni, D., Passolunghi, M. and Sandroni, S. 2001. Faeroe Sub-basalt seismic imaging - a new iterative time processing approach. *EAGE 63rd Conference and Technical Exhibition*: O-20.

Cox, C.S., Deaton, T. and Webb, S.C. 1984. A deep sea differential pressure gauge. *J. Atmos. Oceanic Technol*. 1: 237-246.

Crawford, W.C. 2004. The sensitivity of seafloor compliance measurements to sub-basalt sediments, *Geophys. J. Int*. 157: 1130-1145.

Crawford, W.C. and Webb, S.C. 2002. Variations in the distribution of magma in the lower crust and at the Moho beneath the East Pacific Rise at 9–10°N. *Earth Plan. Sci. Lett*. 203(1): 117-130.

Crawford, W.C., Webb, S.C. and Hildebrand, J.A. 1991. Seafloor compliance observed by long-period pressure and displacement measurements. *J. Geophys. Res*. 96(10): 16151-16160.

Crawford, W.C., Webb, S.C. and Hildebrand, J.A. 1998. Estimating shear velocities in the oceanic crust from compliance measurements by two-dimensional finite difference modeling. *J. Geophys. Res*. 103(5): 9895-9916.

Crawford, W.C., Webb, S.C. and Hildebrand, J.A. 1999. Constraints on melt in the lower crust and Moho at the East Pacific Rise, 9°48'N, using seafloor compliance measurements. *J. Geophys. Res*. 104(2): 2923-2939.

Crawford, W.C., Webb, S.C. and Hildebrand, J.A. 1994. The Coaxial segment crustal magma source. *EOS, Transactions, Amer. Geophys. Union* 75(44): 617.

Fliedner, M.M. and White, R.S. 2001. Sub-basalt imaging in the Faeroe-Shetland Basin with large-offset data. *First Break* 19: 247-252.

Fliedner, M.M. and White, R.S. 2003. Depth imaging of basalt flows in the Faeroe-Shetland Basin. *Geophys. J. Int*. 152: 353-371.

Fruehn, J., Fliedner, M.M. and White, R.S. 2001. Integrated wide-angle and near-vertical subbasalt study using large-aperature seismic data from the Faeroe-Shetland region. *Geophysics* 66(5): 1340-1348.

Fruehn, J., White, R.S., Fliedner, M.M., Richardson, K.R., Cullen, E., Latkiewicz, C., Kirk, W. and Smallwood, J.R. 1999. Large-aperture seismic: Imaging beneath high-velocity strata. *World Oil*: 109-112.

Hobbs, R. 2002. Sub-basalt imaging using low frequencies. *Journal of Conference Abstracts* 7(2): 152-153.

Hulme, T., Crawford, W.C. and Singh, S.C. 2004. Calculation and inversion of two-dimensional compliance data. *Geophys. J. Int*., submitted.

Hulme, T., Ricolleau, A., Bazin, S., Crawford, W.C. and Singh, S.C. 2003. Shear wave structure from joint analysis of seismic and seafloor compliance data. *Geophys. J. Int*. 155: 514-520.

Jegen-Kulcsar, M. and Hobbs, R. this volume. Outline of a joint inversion of Gravity, MT and Seismic Data. *In*: Ziska, H., Varming, T. and Bloch, D. (eds.) *Faroe Islands Exploration Conference: Proceedings of the 1st Conference*, *Annales Societatis Scientiarum Færoensis*, Supplementum 43, Tórshavn.

Latychev, K. and Edwards, R.N. 2003. On the compliance method and the assessment of three dimensional sea floor gas hydrate deposits. *Geophys. J. Int*. 155(3): 923-952.

Mack, H. 1997. Seismic response of Tertiary basalt flows in Northeast Atlantic – a modelling study. *In*: EAGE 59th Conference and Technical Exhibition, Paper B017, *EAGE*, Geneva, Switzerland.

Martini, F. and Bean, C.J. 2001. Application of pre-stack wave equation datuming to remove interface scattering in sub-basalt imaging. *EAGE 63rd Conference and Technical Exhibition*: O-17.

Roberts, M. 2004. Joint inversion of seismic and compliance data. *Lithos Science Report* 6, in press.

Trevorrow, M.V. and Yamamoto, T. 1991. Summary of marine sedimentary shear modulus and acoustic speed profile results using a gravity wave inversion technique. *J. Acoust. Soc. Am*. 90 (1): 441-456.

Webb, S.C., Zhang, X. and Crawford, W.C. 1991. Infragravity waves in the deep ocean. *Journ. Geophys. Res*. 96(C2): 2723-2736.

White, R.S., Fruehn, J., Richardson, K.R., Cullen, E., Kirk, W., Smallwood, J.R. and Latkiewicz, C. 1999. Faeroes large aperture research experiment (FLARE): imaging through basalt. *In*: Fleet, A.J. and Boldy, S.A.R. (eds.) *Petroleum Geology of Northwest Europe: Proceedings of the 5th Conference*. Geological Society, London: 1243-1252.

White, R.S., Smallwood, J.R., Fliedner, M.M., Boslaugh, B., Maresh, J. and Fruehn, J. 2003. Imaging and regional distribution of basalt flows in the Faeroe-Shetland Basin. *Geophysical Prospecting* 51: 215-231.

Willoughby, E.C. and Edwards, R.N. 1997. On the resource evaluation of marine gas-hydrate deposits using seafloor compliance methods. *Geophys. J. Int*. 131(3): 751-766.

Willoughby, E.C. and Edwards, R.N. 2000. Shear velocities in Cascadia from seafloor compliance measurements. *Geophys. Res. Lett*. 27(7): 1021-1024.

Yamamoto, T. and Torii, T. 1986. Seabed shear modulus profile inversion using surface gravity (water) wave-induced bottom motion. *Geophys. J. R. Astr. Soc*. 85: 413-431.

Ziolkowski, A., Hanssen, P., Gatliff, R., Jakubowicz, H., Dobson, A., Hampson, G., Li, X.-Y. and Liu, E. 2003. Use of low frequencies for sub-basalt imaging. *Geophysical Prospecting* 51: 169-182.