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Seafloor compliance measurements: applications for hydrocarbon exploration

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Abstract — Seafloor compliance, the seafloor deformation under ocean wave forcing, is sensitive to the shear modulus structure of the underlying basement, in particular to low shear modulus regions such as melt bodies or hydrocarbon reservoirs. Compliance is calculated from data measured during 2-3 day deployments of an autonomous seafloor sensor containing a broadband seismometer and a differential pressure gauge. The calculated compliance can be inverted to determine basement shear moduli. We use a simple model of a petroleum reservoir under basaltic cap rocks to demonstrate the properties of seafloor compliance and its sensitivity to changes in various elastic parameters. Compliance measurements using existing broad-band OBSs and differential pressure gauges should be sensitive to the modeled reservoir, but the reservoir shear modulus/velocity would much better constrained if we input structural constraints from seismic reflection data. Compliance measurements compliment active seismic measurements because the strength of the compliance technique (high sensitivity to low shear moduli/velocities) is the principal weakness of seismic methods, and the weakness of the compliance technique (low vertical resolution) is one of the strengths of seismic methods.

Introduction

The defining property of fluids is their inability to support shear strain. Therefore, the principal effect of concentrating hydrocarbons in a subsurface reservoir to decrease the local shear modulus/velocity, and measurements of the basement shear structure should constrain the existence and amount of hydrocarbons beneath the seafloor. Unfortunately, active marine seismic methods have problems determining reservoir shear velocities, because 1) marine seismic sources are inefficient at exciting shear waves in the basement, and 2) low velocity regions tend to attenuate and diffract seismic waves (Wilcock *et al.*, 1993).

We describe a method for calculating the shear modulus structure of the seafloor from measurements of the seafloor deformation under ocean waves. The transfer function between the pressure from the waves and the seafloor deformation, known as the seafloor compliance, is sensitive to the shear modulus in the crust, and becomes more sensitive as this modulus decreases. I will describe seafloor compliance, show how it is measured, and demonstrate how the compliance function can be inverted to determine crustal structure, revealing in particular low shear modulus zones such as hydrocarbon reservoirs.

What is compliance?

Seafloor compliance is the deformation of the seafloor under a pressure signal. Specifically, it is the transfer function between the seafloor displacement $u_z(\omega)$ and pressure $\tau_{zz}(\omega)$, multiplied by the forcing wavenumber $k(\omega)$:

$$\eta(\omega) = k(\omega)\left.\frac{u_z(\omega)}{\tau_{zz}(\omega)}\right|_{z=0} . \qquad (1)$$

The amplitude of this compliance depends primarily on the shear modulus, μ, of the basement beneath the measurement site. The seafloor motion is largest over low shear modulus regions such as melt bodies or gas-filled reservoirs. The dependence of compliance on the shear modulus is easily seen in the equation for compliance over a uniform half space:

$$\eta(\omega) = \frac{\lambda + 2\mu}{2\mu(\lambda + \mu)} \qquad (2)$$

where λ is the other Lamé parameter (*Crawford et al.*, 1998). To a first order, compliance varies as $1/\mu$, and so is especially sensitive to changes in μ (or to the shear velocity, $V_S \equiv \sqrt{\mu/\rho}$) where $\mu << \lambda$ (equivalently, where Poisson's ratio, $\sigma \equiv \lambda/\left(2(\lambda+\mu)\right)$, approaches 0.5).

We measure seafloor compliance in the "infragravity" wave frequency band, where the seafloor pressure field comes from linear ocean surface gravity waves with the dispersion relation $\omega^2 = gk\tanh(kH)$, where g is the local gravity and H is the water depth. The depth to which compliance is most sensitive to is about 1/5 of the wavelength of the forcing waves (Crawford *et al.*, 1998). Because the wavelength of infragravity waves increases with decreasing frequency, compliance is sensitive to deeper structure at low frequencies and to shallower structure at high frequencies.

To demonstrate the relationship between compliance and the seafloor elastic properties, and to compare compliance sensitive to μ vs the compressional velocity ($V_P \equiv \sqrt{(\lambda+2\mu)/\rho}$) and density ($\rho$), I calculate the seafloor compliance above a simple one-dimensional model of a petroleum reservoir (**Table 1**) beneath sediments, then vary each of these parameters in the reservoir layer while holding the other two constant (**Figure 1**). Compliance is always much more sensitive to the shear modulus than to the density. For a reservoir Poisson's ratio of 0.38, compliance is twice as sensitive to shear velocity than to compressional velocity, but for a reservoir Poisson's ratio of 0.49, compliance is five times more sensitive to the shear modulus.

While compliance measurements are sensitive to small low velocity zones, it is often difficult to discriminate between these and larger features in the vertical (**Figure 2**). Therefore, some other constraint or bias is usually necessary to estimate the thickness of a low-velocity region.

Thickness (m)	ρ (g/cc)	V_P (km/s)	V_S (km/s)	μ (GPa)	Comments
200	2.0	1.6	0.6	0.72	sediments
1000	2.3	2.5	1.5	5.2	basalts
500	2.2	2.4	0.9	1.8	reservoir
infinite	2.5	3.5	2.2	12.1	basement

Table 1. Elastic parameters of a one-dimensional hydrocarbon reservoir model.

We can also calculate compliance for 2- and 3-dimensional models. Compliance behaves the same for these models as for the one-dimensional cases shown above. A series of measurements over a low velocity zone will reveal a peak in compliance centered over the zone. The rate at which this peak decays away from this zone indicates the size of the zone (Crawford *et al.*, 1998; Latychev, 1999).

Measuring seafloor compliance

To measure compliance, we deploy an autonomous package containing a broad-band ocean-bottom seismometer and a long-period differential pressure gauge to the seafloor for 2-3 days (**Figure 3**). The seismometer and pressure gauge must be sensitive enough to measure the small, low-frequency pressure and acceleration signals in the infragravity wave band. Infragravity waves are usually detectable at the seafloor at frequencies between 0.003 and 0.12 Hz, depending on the water depth, and have an

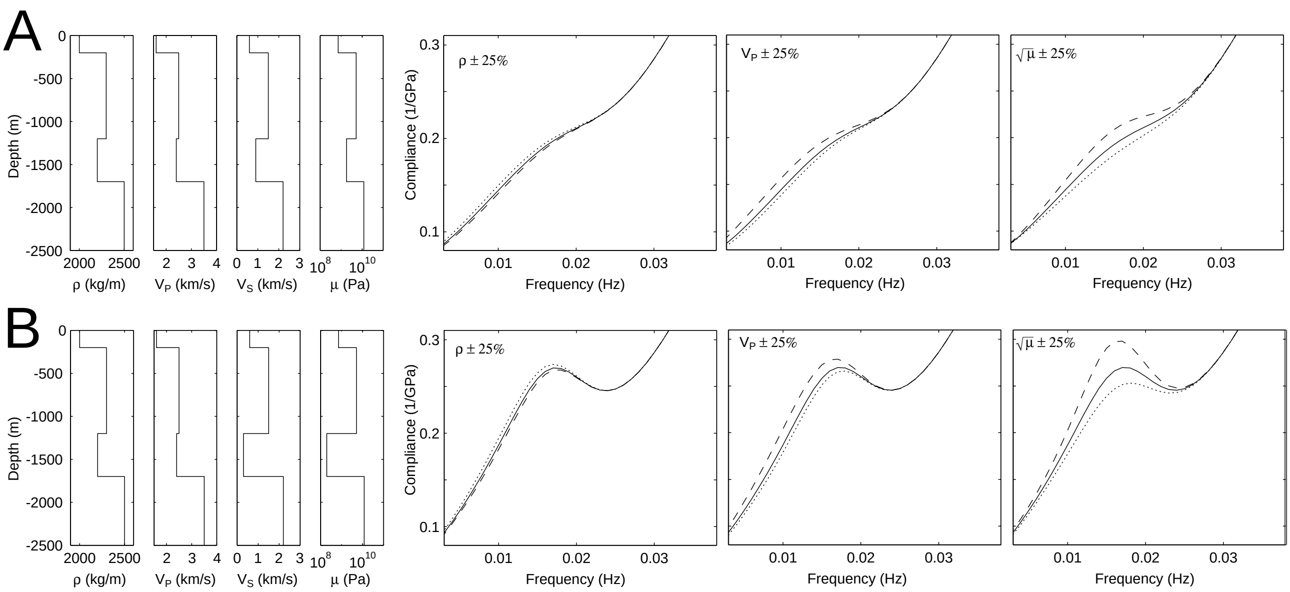

Figure 1. Changes in seafloor compliance for changes in each of the three basic properties of an elastic medium: density, compressional velocity, and shear modulus. The solid lines show the seafloor compliance function over the starting model (left). The dashed and dotted lines show compliance for a 25% increase (dotted line) and 25% increase (dashed line) in each parameter within the reservoir. A: The starting model as in Table 1. B: Same as A, except starting reservoir shear modulus = 0.2 GPa (V_S=0.3 km/s).

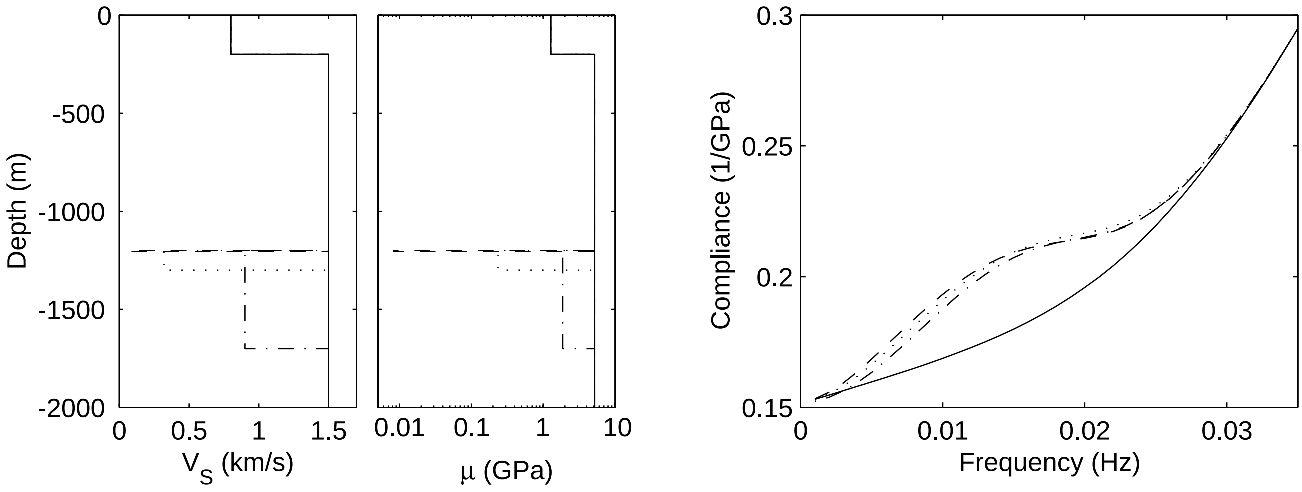

Figure 2. Compliance (at right) over low shear velocity zones of different thicknesses, with shear moduli selected to give the most similar compliances possible.

power spectral density of 10^2-10^5 Pa^2/Hz. The seismometer generally measures acceleration rather than displacement, and the seafloor acceleration under the pressure forcing depends on the wave amplitude and on the seafloor compliance. This acceleration is generally between 10^{-16} and 10^{-12} $(m/s^2)^2$/Hz (Webb, 1998), with the smaller values found on unsedimented seafloor in the deep ocean and the larger values found on soft sediments on the continental shelf.

To calculate compliance from the collected data, we first calculate seafloor pressure and acceleration power spectral densities (PSDs) $\hat{S}_p(\omega)$ and $\hat{S}_a(\omega)$ using 1024-second windows. Good estimates generally require a high number of good data windows, so we leave the instruments down for 2-3 days at each site. We calculate compliance from the PSDs using the equation

$$\eta(\omega) = \frac{k(\omega)}{\omega^2}\left|\gamma_{ap}(\omega)\right|\sqrt{\frac{\hat{S}_a(\omega)}{\hat{S}_p(\omega)}}\ , \tag{3}$$

where the coherence $\gamma_{ap}(\omega)$ between the acceleration and pressure signals accounts for any non-pressure noise sources that might contaminate the acceleration signal.

Two factors control the compliance estimate uncertainty: the sensitivity of the acceleration sensor and the size of the forcing ocean waves. In general,

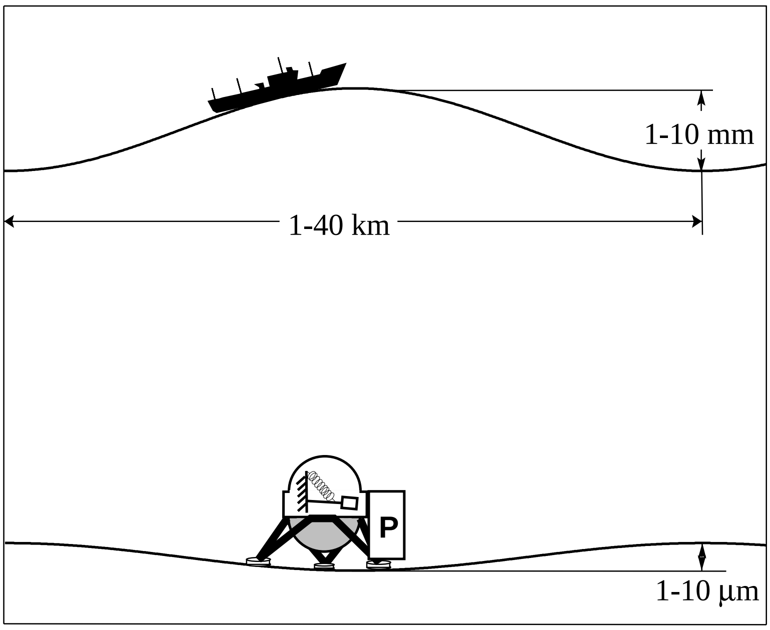

Figure 3. Schematic of a compliance measurement. Small-amplitude linear ocean surface gravity waves excite even smaller amplitude seafloor displacements. An autonomous seafloor sensor containing a broad-band OBS and a differential pressure gauge measures the seafloor motion and the pressure from the forcing waves.

infragravity waves are refractively trapped on continental shelves, so they are much larger there than in the deep ocean. In the deep ocean, the infragravity wave energy is strongest in the Pacfic ocean (10^4-10^5 Pa^2/Hz), weaker in the Atlantic ocean (10^3-10^4 Pa^2/Hz), and weakest in the Arctic (10^2-10^3 Pa^2/Hz) (Webb, 1998). Infragravity waves are created where large wave groups strike coastlines; Webb (1998) postulates that the energy level is related to how "open" the ocean is, that is, how much coastline is within line-of-site of the measurement site.

We have measured compliance in a range of different environments, ranging from relatively shallow, heavily sedimented coastal sites to unsedimented mid-ocean ridges. These measurements give an idea of the frequency range that can be measured at different water depths, from which we can calculate the approximate subseafloor depths to which compliance should be sensitive (**Table 2**). The frequency (depth) range may be broader at sites with exceptionally strong infragravity waves, and narrower at sites with weak wave energy.

Water Depth (m)	Frequencies (mHz)	Depth Range (m)	Data uncertainty (%)
100 m*	10-120	20-620	
250 m	10-75	50-1000	0.5-1.0
500 m	10-55	100-1400	0.5-2
1000 m	6-38	200-3200	1-3
2500 m	4-22	500-7500	1-5

Table 2: Estimated depth range of seafloor compliance sensitivity to basement structure. The 100 m depth parameters are extrapolated; we have never measured compliance at water depths shallower than 250 m.

Calculating basement shear moduli

To calculate the basement shear moduli from compliance data, we first create a crustal model of μ, V_P and ρ. We then vary the model until its compliance fits the data, using some constraint on the model structure. In general, we hold V_P and ρ constant and vary only μ. The calculated μ is well constrained in regions where $\mu << \lambda$ or where V_P is well-constrained by some other data (usually seismic data). The assumed ρ has little affect on the calculated μ.

The parameter we solve for can change the apparent compliance sensitivity enormously. Since compliance is more sensitive to μ than to V_P or ρ, and since V_P can be well-constrained from seismic methods, μ is the clear choice between these three parameters. But why not solve for shear velocity ($V_S \equiv \sqrt{\mu / \rho}$)? We can, but the result depends heavily on the density model. Since compliance is insensitive to density, increasing the assumed density will decrease the modeled shear velocity. The effect is usually minor because density generally varies much less than the shear velocity, but solving directly for μ avoids this hidden bias. We can then calculate the shear velocity from the μ values, making explicit the dependence of the these velocities on the assumed density.

To calculate μ we use either a minimum-structure geophysical inversion or we vary a pre-existing block model. Which method we choose depends on how well the crustal structure is constrained. If the crustal structure is poorly constrained, we use a linearized geophysical inversion to find the smoothest μ(x,z) model fitting the compliance data with an RMS misfit of 1 (Constable *et al.*, 1987; deGroot-Hedlin *et al.*, 1990; Crawford *et al.*, 1991). If the crustal structure is awell-constrained (from, for example, seismic reflection studies), we create a block model, allowing μ to jump across every change in structure, and then calculate the μ (or a linear μ gradient) in each block that best fits the compliance data (Crawford *et al.*, 1999).

We estimate how well compliance discriminates features of interest using the simple 1-D petroleum model (**Table 1**). We assume a 1000-m deep seafloor and compliance measurements every 0.001 Hz with a 2% measurement uncertainty. If we have little information about the compressional velocities, we construct the smoothest μ model possible fitting the data within an RMS misfit of 1 (**Figure 4a**). The resulting model has all of the features of the true structure, but it is much smoother, and it underestimates the amplitude of the shear velocity anomaly in the "petroleum reservoir" layer. If we have structural information from reflection studies, we can solve for the shear modulus in each layer (**Figure 4b**), and the resulting model is much closer to the original.

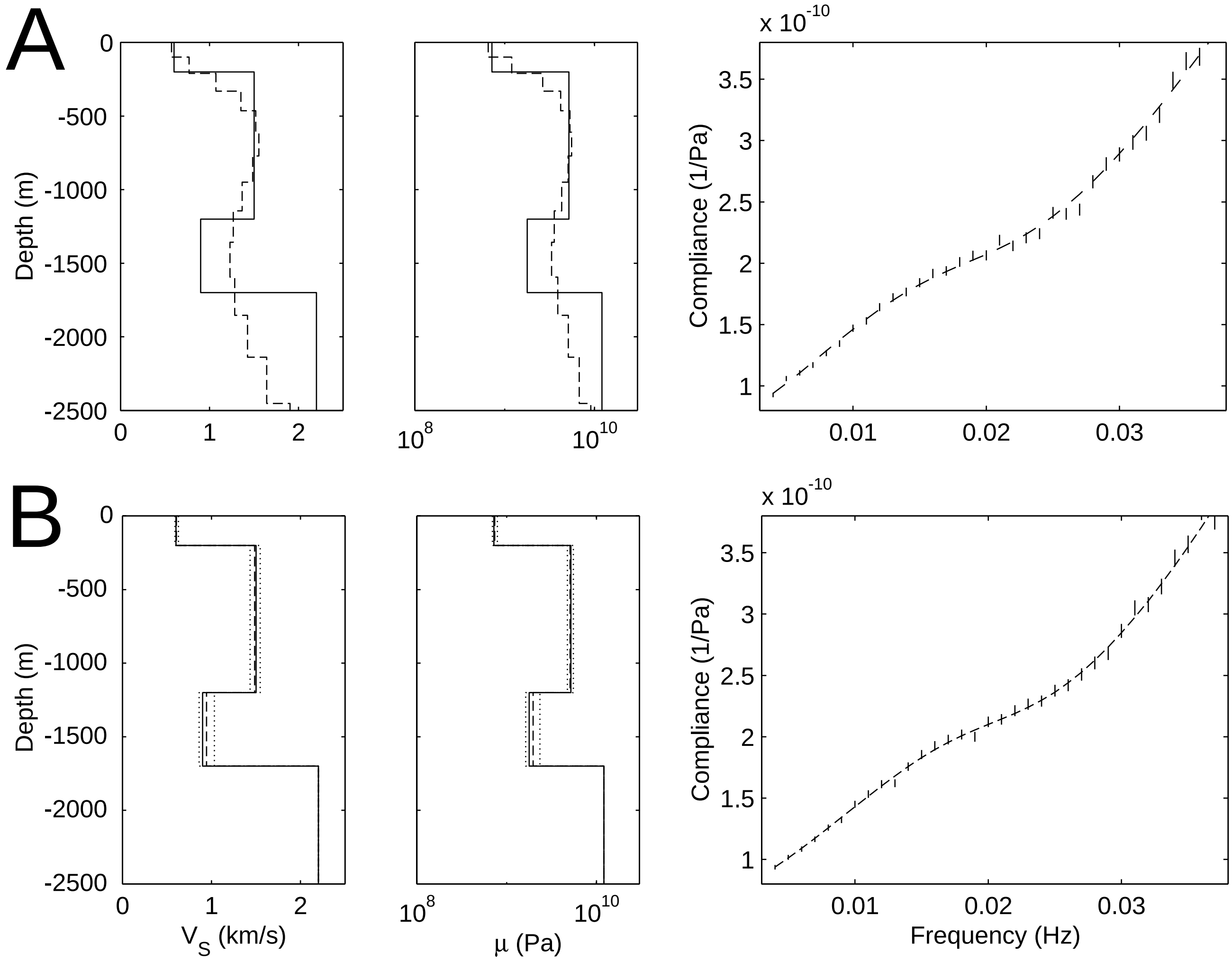

Figure 4. Original (solid line) and inverted (dashed line) models and compliance, assuming 2% data uncertainty. Left: shear velocities, middle: shear moduli, right: resulting compliance. A: Minimum structure model (C_2L_2-norm minimizing) fitting data with and RMS misfit of 1. B: "Block inversion", obtained by varying shear moduli independently in each of thet three top layers, assuming that the layer boundary depths are known.

Discussion and Conclusions

Compliance measurements should be useful for studying petroleum reservoirs because compliance is most sensitive to variations in the shear modulus beneath the seafloor. They avoid the problems of wave diffraction and attenuation that hinder seismic studies of fluid reservoirs because they don't use seismic waves but rather the seafloor deformation under much slower wave forcing. On the other hand, compliance measurements have relatively low vertical resolution.

The precision of basement shear modulus constraints improves significantly when the compliance data inversions are constrained by compressional velocity and layer boundary information from seismic data. Similarly, compressional velocity and boundary information from seismic data might also be improved by constraints from compliance measurements. We have not yet attempted a joint inversion of seismic and compliance data, but such an inversion should be possible

Compliance measurements are generally less expensive than seismic surveys, because they require fewer instruments and less ship time. Each compliance measurement can be made independently, so a compliance study can be made with as little as one compliance sensor. However, since each measurements take 2-3 days, it is more efficient to use multiple compliance sensors or to alternate compliance sensor deployments with other experiments during an expedition.

Compliance measurements should be sensitive to the simple petroleum reservoir modeled here. Compliance over 1-D models can be calculated in a matter of seconds to determine whether compliance measurements could detect/constrain other reservoir shapes/velocities. These 1D models are applicable in any case where the reservoir properties don't change significantly over distances as long as the reservoir is deep. Otherwise, accurate compliance calculations require 2-D or 3-D models. Compliance calculations for these models (which take from several minutes to several hours to run) can be used to determine whether compliance measurements/inversion can constrain the amount of hydrocarbons in any hypothetical reservoir.

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