Two roads diverged in a wood, and I–
I took the one less traveled by,
And that has made all the difference.

The Road Not Taken
Robert Frost (AD 1874-1963)

Chapter 8

Conclusions

In this thesis I presented an extensive study of the potential to use microseism noise for passive seismic interferometry at a reservoir scale. Until this study, the common belief was that the low-frequency noise in marine recordings carried no useful information. However, as predicted by seismic interferometry, crosscorrelations extract virtual-seismic sources from this random wavefield. I show that an abundance of subsurface properties and information, especially related to the near surface, can be imaged using these virtual-seismic sources. Moreover, the reliability and repeatability of this method is sufficiently high to extract time-lapse responses. Thus, a system can be designed to continuously monitor the subsurface using recordings of microseism noise and crosscorrelations.

In Chapter 2 I characterize the microseism noise in four recordings, made in 2004, 2005, 2008 and 2010, from Valhall's LoFS array. All four recordings document strong microseism energy between 0.175 and 1.75 Hz. The microseism energy is characterized by studying its spectral amplitude as a function of time and space. The images of spectra versus time show that the strength of the microseism noise depends on weather conditions in the North Sea. Mapping the spectral amplitudes of the microseism noise reveals low-amplitude anomalies that match buried paleochannels in the top 200 m. The spectral amplitude maps also reveal high-amplitude anomalies that match a set of low-velocity anomalies south and east of the main oil platform. The propagation directions of the microseism noise are further characterized by beam steering. Because the propagation directions of the microseism noise are generally uniformly distributed over azimuth, microseism noise is a promising seismic energy source for application of passive-seismic interferometry.

In Chapter 3 I presented crosscorrelations of microseism noise in the 2004, 2005 and 2010 recordings made at Valhall. The microseism energy at Valhall is successfully isolated by bandpass filtering and proves sufficiently omnidirectional to be employed for passive seismic interferometry. These virtual seismic sources emit wave modes at frequencies not usually excited by controlled sources. The vertical-to-vertical and radial-to-radial elements are dominated by fundamental-mode Scholte waves, while the tangential-to-tangential element is dominated by fundamental-mode Love waves. A first overtone Scholte-wave mode is clearly retrieved. A first overtone Love-wave mode is also retrieved, but is fainter. The retrieved Scholte and Love waves are dispersive, and lower frequencies travel faster than higher frequencies. The fundamental-mode Scholte-waves become aliased in the cross-line direction above 0.9 Hz and the fundamental-mode Love waves above 0.95 Hz. The fundamental-mode Scholte waves are faster than the fundamental-mode Love waves below 0.6 Hz, while the Love waves travel faster than the fundamental Scholte waves above 0.6 Hz. The fundamental-mode Love waves are not well retrieved above 1.0 Hz. Vertical-to-vertical crosscorrelations converge to a long-term average more rapidly for short interstation offsets and low frequencies than for long interstation offsets and high frequencies. As little as one day of recording time may be sufficient to retrieve fundamental-mode Scholte waves at frequencies below 1 Hz at offsets smaller than 6 km. Background correlation fluctuations diminish when stacking more crosscorrelations, and a coherent signal emerges. A convergence analysis shows that for frequencies below 1 Hz and offsets smaller than 6 km, stacking as little as two days of crosscorrelations converges to within 5% of a 5-day long recording. It is inconclusive whether the crosscorrelations at higher frequencies have converged to their long-term average. The ability to systematically construct virtual sources from noise provides the opportunity to survey the subsurface continuously using noise recordings.

In Chapter 4 I showed how crosscorrelations of microseism noise recorded by Valhall's LoFS array can be inverted into credible velocity models. The virtual-seismic sources computed in Chapter 3 are imaged by group-velocity tomography. Traveltimes picked on vertical-to-vertical crosscorrelations are inverted for Scholte-wave group-velocity images. Traveltimes picked on transverse-to-transverse crosscorrelations are inverted for Love-wave group-velocity images. The Scholte-wave velocity correlates well with the subsurface lithology in the top 250 m below the sea floor known from full-waveform inversion of controlled-source P-wave seismic data. The Love-wave group-velocity images are dominated by smoother shapes that may relate to the production-altered stress state of the reservoir's overburden. The regularization strength is normalized for all inversions of traveltime picks from crosscorrelations of a particular stack length. This allows for one-on-one comparisons between images. Quantification of the expected variance between tomography images from consecutively recorded periods provides a temporal resolution. The expected variance in Scholte-wave velocity images decreases with lower frequency and for longer crosscorrelation stack lengths.

In Chapter 5 I presented a time-lapse analysis using ambient seismic noise. Almost seven years passed between the recordings in 2004 and 2010. From repetitive controlled-source surveying it is known that production and development of Valhall's reservoir affected velocities in the shallow subsurface. A time-lapse Scholte-wave velocity image is obtained from ambient noise by differentiating tomographic Scholte-wave velocity images from recordings made years apart. Analysis confirms that this response is statistically significant. The shape of the time-lapse response matches very well with that obtained from controlled-source data and is interpreted to represent near-surface geomechanical effects of production-induced reservoir compaction.

In Chapter 6 I presented the results of a study of almost 40-hours of pressure-sensor recordings made by Ekofisk's LoFS array. I find that the microseism noise in the ambient seismic field between 0.4 and 1.2 Hz is suitable for retrieval of Scholte-wave virtual seismic sources. The microseism energy at Ekofisk field in this recording is uniformly distributed over azimuth, and thus is ideal for seismic interferometry. Dispersive virtual seismic sources emitting Scholte-waves between 0.4 and 1.2 Hz are retrieved by passive seismic interferometry. The interface waves exhibit an approximate peak sensitivity between 160 and 730 m below the seafloor. Scholte-wave group-velocity tomography locates a high-velocity anomaly in the center of the array. This high-velocity anomaly is surrounded by a lower-velocity region. The high-velocity anomaly coincides with the center of the seafloor subsidence bowl. The ring of lower velocities corresponds with high magnitudes of the bathymetry gradient. I find higher velocities again under the southern end of the array. This behavior may reflect overburden stress states caused by decades of production and reservoir depletion.

In Chapter 7 I presented a new method for anisotropic eikonal tomography inversion for elliptically anisotropic phase velocities. The parameters of the ellipse are inverted from two perpendicular spatial derivatives of traveltime surfaces. The novelty of this anistropic formulation is that it is based on an elliptically anisotropic wave equation instead of an anisotropically interpreted isotropic wave equation. Another major advantage is that the inverted anisotropic phase velocities can be regularized straightforwardly over space and frequency. The method is applied to Scholte and Love waves at Valhall and Scholte waves at Ekofisk. At Valhall, Scholte-wave and Love-wave phase velocities match well with the group velocities of Chapter 4. Phase velocities are generally higher than group velocities. I conclude that the Scholte-wave velocity correlates well with the subsurface lithology known from full-waveform inversion of controlled-source P-wave seismic data. The Love-wave group-velocity images are dominated by smoother shapes that may relate to the production-altered stress state of the reservoir overburden. At Ekofisk, Scholte-wave phase-velocity tomography locates a high-velocity anomaly in the center of the array that is surrounded by a lower-velocity region. The high-velocity anomaly coincides with the center of the seafloor subsidence bowl. Higher velocities occur under the southern end of the array. Azimuthally anisotropic Scholte-wave velocities form a large circular pattern over the Ekofisk field, and they are likely to be related to the overburden stress state induced by decades of hydrocarbon extraction. These results are significant because they show that noise recordings made by Ekofisks LoFS array can be used to monitor azimuthal anisotropy in the near surface of Ekofisk.

This thesis presents an extensive analysis of microseism noise, and I made many choices with respect to preprocessing, crosscorrelation and imaging. A significant effort was made to achieve the best possible result by exploring many avenues and alternative choices. However, there is always room for improvement. Improved crosscorrelation and stacking techniques may increase temporal resolution of Green's function retrieval by passive-seismic interferometry at Valhall. There are many more imaging and inversion strategies for virtual-seismic source wavefields than the ones presented in this thesis, and some may improve the spatial resolution. A depth inversion will map the velocities with depth. Ideally, one would apply an anisotropic, anelastic nonlinear waveform-fitting strategy to the estimated Green's functions, to fully extract all medium information carried by the crosscorrelations.