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I certify that I have read this dissertation and that, in my opinion, it is fully adequate in scope and quality as a dissertation for the degree of Doctor of Philosophy.

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Approved for the University Committee on Graduate Studies

Abstract

In this thesis I present an extensive study of the potential to use microseism noise for reservoir-scale passive seismic interferometry. Microseism noise is excited by interfering ocean swells exerting pressure variations on the sea floor. In marine recordings, this noise is composed primarily of interface waves travelling along the sea floor. Previously, the belief was that the low-frequency noise in marine seismic recordings carried no useful information for imaging the subsurface. The theory of passive seismic interferometry predicts that crosscorrelating recordings made at two stations retrieves the seismic response measured at one station as if the other station were a seismic source. This theory retrieves an estimate for the Green's function but holds only under certain constraints on the character of the seismic noise. Most important is the constraint of energy equipartition and illumination by uncorrelated noise sources surrounding the station pair. I test whether these conditions are fulfilled for microseism noise recorded by ocean-bottom cables at two locations in the North Sea: Valhall and Ekofisk. Then, I study which properties of the near-surface lithology below the sea floor can be imaged using virtual seismic sources retrieved from crosscorrelating microseism noise.

Both recordings contain strong microseism noise below 2 Hz. The microseism noise grows stronger when weather conditions deteriorate. The waves composing the noise appear chaotic, and beam steering show that waves generally travel in all azimuths with equal strength. These characteristics match the constraints necessary for passive seismic interferometry to turn recording stations into virtual seismic sources. Bandpassing removes energy that does not fulfill the constraints, and isolates the

microseism energy. Crosscorrelations of all combinations of recordings of participle velocity at Valhall retrieves an estimate for the Green's matrix for Scholte and Love waves between frequencies 0.175 and 1.75 Hz. Crosscorrelation of pressure recordings at Ekofisk retrieves an estimate for the Green's function for Scholte waves between frequencies 0.4 and 1.2 Hz. These Scholte and Love waves are dispersive, i.e. their velocity is frequency dependent. The frequency-variable wavelength of interface waves implies a frequency-variable sensitivity to medium parameters away from the interface of propagation. The medium parameters vary strongly as a function of depth in the near surface immediately below the sea-floor, causing dispersion of the interface waves traveling along the sea-floor. Two properties commonly extracted from surface waves are their frequency-dependent group and phase velocities. These properties vary as a function of space and maps of the group and phase velocities image the subsurface lithology.

Measurements of group travel-time are inverted by straight-ray tomography into maps of group velocities. Scholte-waves at Valhall image buried paleochannels and other geology known (from controlled-source data) to be in the top 300 m below the sea floor. These images can be retrieved with high-repeatability from short recordings (six hours to a day), making continuous subsurface monitoring an achievable application. By comparing Scholte-wave velocities obtained from ambient-seismic recordings made in 2004 with Scholte-wave velocities from ambient-seismic recordings made in 2010, I find a time-lapse velocity change. The overall shape of the velocity change from ambient-seismic data compares very well with the overall shape of a velocity change obtained from controlled source data. The overall shape is interpreted to represent near-surface geomechanical effects of production-induced reservoir compaction. The Love-wave group-velocity images at Valhall are dominated by smoother shapes that may relate to the production-altered stress-state of the reservoir's overburden. Scholte-wave group-velocity maps at Ekofisk image a high-velocity anomaly in the center of the array surrounded by a lower-velocity region. The high-velocity anomaly coincides with the center of a production-induced sea-floor 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.

Phase velocity maps are found through a novel version of eikonal tomography. An eikonal equation is derived for an elliptically anisotropic wave-mode at a single frequency propagating in two dimensions. This eikonal equation relates the spatial derivatives of phase travel-time surfaces to the local elliptically anisotropic slowness. Measurements of the spatial derivatives of phase travel-time surfaces for virtual sources retrieved at all stations can be inverted into elliptical-anisotropic phase-velocity maps. The method is applied to Scholte and Love waves at Valhall and Scholte waves at Ekofisk. The isotropic component of phase velocities generally images the same features as the group velocities from straight-ray tomography. The fast direction of anisotropy of Scholte-wave phase velocities form a large circular pattern over the Valhall and Ekofisk fields. They are likely related to the production-induced sea floor subsidence bowl.

Preface

The electronic version of this report[1] makes the included programs and applications available to the reader. The markings **ER**, **CR**, and **NR** are promises by the author about the reproducibility of each figure result. Reproducibility is a way of organizing computational research that allows both the author and the reader of a publication to verify the reported results. Reproducibility facilitates the transfer of knowledge within SEP and between SEP and its sponsors.

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[1] http://sepwww.stanford.edu/public/docs/sep151/
[2] http://sepwww.stanford.edu/public/docs/sepdatalib/toc_html

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Our testing is currently limited to LINUX 2.6 (using the Intel Fortran90 compiler) and the SEPlib-6.4.6 distribution, but the code should be portable to other architectures. Reader's suggestions are welcome. For more information on reproducing SEP's electronic documents, please visit *http://sepwww.stanford.edu/research/redoc/*.

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To my grandfather,

thank you for inspiring me to seek scholarship.

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