Earth and Planetary Science Letters 463 (2017) 243–252

Contents lists available at ScienceDirect

Earth and Planetary Science Letters

www.elsevier.com/locate/epsl

Seafloor tilt induced by ocean tidal loading inferred from broadband seismometer data from the Cascadia subduction zone and Juan de Fuca Ridge

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ARTICLE INFO

Article history:
Received 8 July 2016
Received in revised form 26 January 2017
Accepted 28 January 2017
Editor: P. Shearer

Keywords:
seafloor tidal acceleration
seafloor tidal tilt
seafloor tidal loading
seismometer mass positions

ABSTRACT

Mass-balancing voltages from four buried broadband seismometers connected to the NEPTUNE Canada seafloor cable are being recorded at 24-bit resolution. Sites are located on the Vancouver Island continental shelf, the nearby Cascadia accretionary prism, the eastern flank of the Juan de Fuca Ridge, and the western flank close to the Juan de Fuca Ridge axis. Tidal variations are present throughout the records. Variations in vertical acceleration at three of the sites match predicted gravitational attraction variations very well; those at the fourth site show a small residual that is probably caused by sensitivity to tilt resulting from sensor inclination. Horizontal accelerations, which at tidal periods are sensitive primarily to tilt, are anomalously large relative to standard-earth model results. After removal of predicted tidal body and ocean attraction and loading terms, the residuals are seen to follow ocean pressure variations. Responses range from 0.4 μrad dbar^{-1} (0.04 μrad kPa^{-1}) at 10° true (down under positive load) at the continental shelf site, to 0.6 μrad dbar^{-1} at 243° at the Cascadia prism, 0.4 μrad dbar^{-1} at 90° at the eastern Juan de Fuca Ridge flank, and 0.2 μrad dbar^{-1} at 116° true on the western ridge flank. Except at the continental shelf site, tilts are roughly perpendicular to structural strike. The tilt observations can be explained by loading-induced deformation in the presence of local lithologic gradients or by the influence of faults or structurally controlled anisotropic elastic properties. The observations highlight the utility of using mass position data from force-feedback broadband seismometers for geodynamic studies.

1. Introduction

Oceanographic loading at the seafloor is both a troublesome source of noise and a useful source of geophysical signals. Currents can stimulate unwanted ground motion when instruments have a significant hydrodynamic profile in the water column. Pressure variations generated by wind-waves and swell at the ocean surface generate ground motion in their own wave bands (typical periods of 10–30 s), in the microseismic (double-frequency) band (5–15 s periods), and in the infragravity wave band (100–500 s) (Webb, 1998). The last can be used to infer shear moduli and seismic velocities of sub-seafloor formations (Crawford et al., 1991). Tidal loading induces volumetric strain and pore-fluid pressure variations that are tied to solid and fluid compressional moduli and to large scale permeability (Wang and Davis, 1996; Davis et al., 2000). In this paper we explore observations made with ocean bottom seismometers and bottom pressure recorders connected to the NEPTUNE Canada/ONC (Ocean Networks Canada) offshore cable system that demonstrate a link between ocean tidal loading and seafloor deformation. The study was stimulated by discussions with Eiichiro Araki, who pointed out to us tidal-period ground-velocity signals observed by several DONET (Dense Ocean Network) seismometers at the Nankai subduction zone that are free from the influences of ocean currents. The NEPTUNE/ONC sites are representative of four contrasting structural/lithologic settings: Site ENWF is situated 2 km west of the axial rift of the Juan de Fuca Ridge where a magma chamber has been imaged in seismic reflection data (Van Ark et al., 2007). Site NC27 is located on the eastern ridge flank 110 km from the axis over 3.5 Ma igneous crust that is buried locally by 250 m of turbidite sediment. Site NC89 is situated on the thick actively accreting sedimentary prism of the Cascadia subduction zone. Site NCBC lies near the edge of the adjacent continental shelf and is underlain by older accreted crustal rocks of the subduction forearc (Fig. 1; Table 1).

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http://dx.doi.org/10.1016/j.epsl.2017.01.042

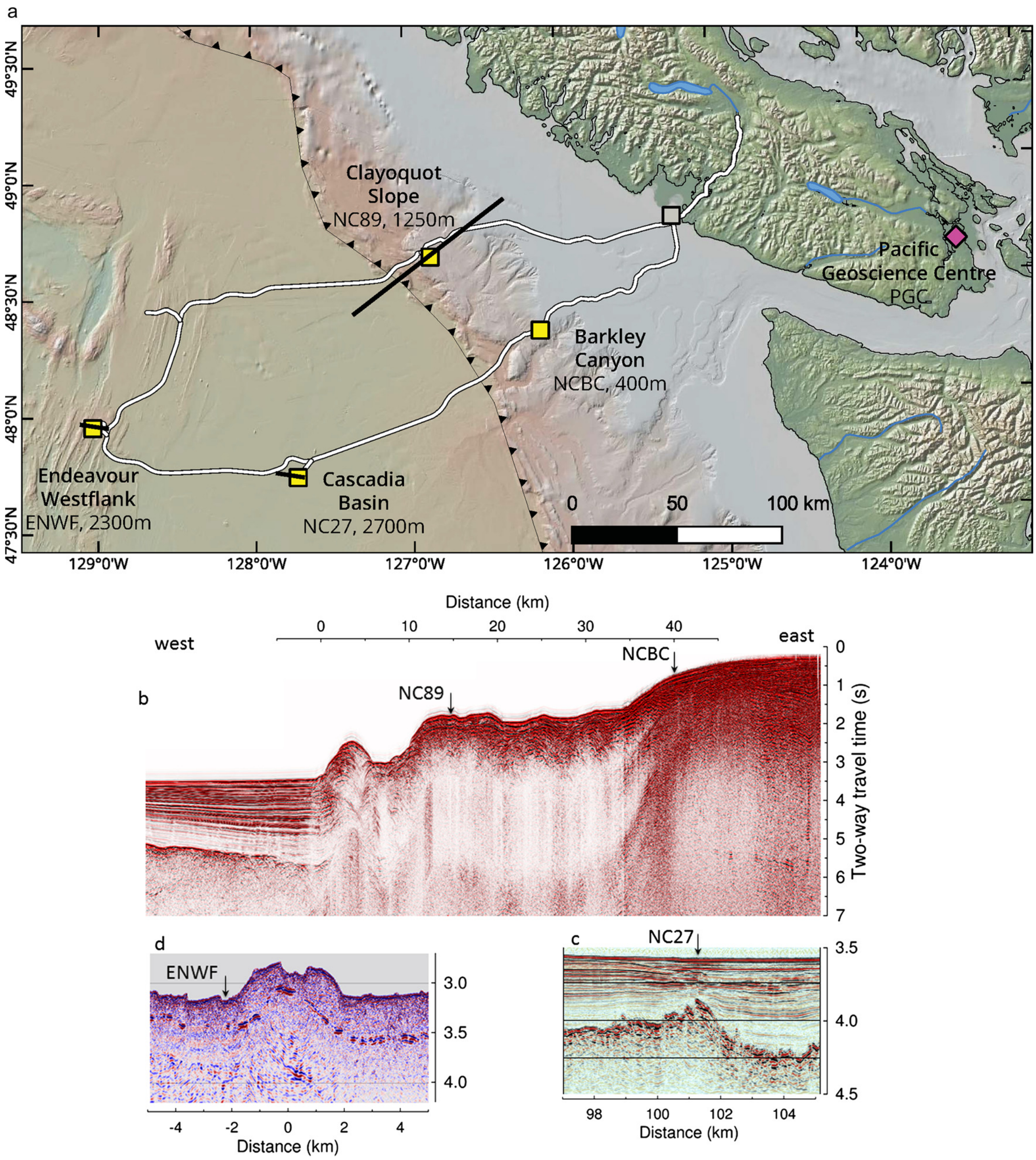

Fig. 1. Regional site map (a) and seismic sections crossing observatory sites (b, c, d). The ONC/NEPTUNE cable route is shown on the regional map as a white line, and locations of seismic lines are shown black. Location of NCBC is projected onto the seismic line in b in a direction parallel to margin structure. Primary reflection horizons include the seafloor and the top of the igneous oceanic crust. Sediment cover is not resolved at ENWF; secondary reflections in the line crossing that site can be seen from the extrusive/intrusive igneous boundary roughly 0.4 s (a few hundred m) below the seafloor, and from an axial magma chamber roughly 1 s ($\approx$2 km) below the seafloor.

The data from each of the four seismometers are unusual in that mass-balancing feedback voltages have been digitized and recorded at high precision. The observations serve to demonstrate the utility of using the "mass-position" data from the type of broad-band seismometers deployed—which at long periods are sensitive to vertical acceleration and horizontal tilt—for geodynamic studies. Results from all sites show clear tidal signals, and surprisingly large tilts that appear to be induced by ocean tidal loading.

2. Instrumentation

The seismometers used in this study were built by Guralp, Ltd. (series CMG-1T). Their response to ground velocity is flat from 40 Hz to 360 s period, and they include strong-motion accelerometers which extend the dynamic range of the instruments for characterizing large-amplitude signals that exceed the range of the velocity sensors. The seismometers are contained in cast titanium spheres that are installed in 80 cm deep, 80 cm diameter caissons driven into the surficial sediment and evacuated of sediment. The spheres and cabling are then buried with silica beads to a level flush with the surrounding seafloor to avoid noise generated by ocean-bottom currents and temperature variations (Fig. 2a). The combined mass of the instrument and bead backfill is reasonably well matched to that of the displaced sediment, so anomalous dynamic response of the installation to ground motion should not be present. This has been demonstrated to be the case on the basis of the excellent match between seismic waveforms observed with one of these instruments and those observed with a high-fidelity tri-axis accelerometer deployed recently nearby (see supplementary Appendix 1, Fig. A1).