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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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 $0.4 \mu\text{rad dbar}^{-1}$ ($0.04 \mu\text{rad kPa}^{-1}$) at 10° true (down under positive load) at the continental shelf site, to $0.6 \mu\text{rad dbar}^{-1}$ at 243° at the Cascadia prism, $0.4 \mu\text{rad dbar}^{-1}$ at 90° at the eastern Juan de Fuca Ridge flank, and $0.2 \mu\text{rad dbar}^{-1}$ 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 (VanArk 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).

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 Appendix 1, Fig. A1).

Ground motion is measured by the seismometers using the output of capacitors and coils that provide sensitivity to the position and velocity of three masses relative to their suspension frames. Each mass is supported on horizontal- or vertical-axis leaf springs (Fig. 2b). At long periods, electromagnetic coupling for each axis provides a restoring force that keeps the mass

centered in its suspension. In these instruments, the voltages supplied to maintain this force are digitized with the same resolution as the shorter-period velocity data (24 bits with sign) and reported via the NEPTUNE cable system at a sampling frequency of 1 Hz. The relationship between the restoring force (force-feedback voltage) and acceleration of the instrument (in the direction along the degree of freedom of mass motion) is linear, related simply to the coil constants and mass values, from DC to a period near 360s. At shorter periods (well outside the range considered in this paper), the sensitivity of the mass-position restoring voltage falls off at several dB per octave. Sensitivity of horizontal component acceleration to tilt, θ , is simply $-g \sin\theta$. The negative sign of the sensitivity derives from the sign convention of tilt itself; e.g., a tilt down in a given direction, defined as positive, results in a positive acceleration in the opposite direction. The vertical component has a gravity-compensation spring (Fig. 2b), and its sensitivity to tilt is $g \cos\theta - g$. Coefficients for converting mass-position values to acceleration and tilt are given in Table 1. Full mass-position histories showing drift, mass re-centering events, and responses to power cycling and temperature variations are provided in Appendix 1, Figure A2 and A3. Further details about the instruments and installations can be found at <http://guralp.com/products/instruments/cm-g-1> and <http://oceannetworks.ca>, and data can be accessed at <http://iris.edu>.

The inclination of these instruments is believed to be small, as they are leveled at the time of deployment and adjusted later if needed. A ball-and-socket mechanism used at the time of installation can react to inclination of the seismometer's sphere of up +/- 18 degrees with a leveling accuracy of 0.2 degrees. Finer subsequent adjustments are applied to each axis independently using the mass position values for electromechanical control. Horizontal axes are adjusted via their suspension frames, while the vertical axis is adjusted via a biasing

displacement of the gravity compensation spring, not via adjustment of the vertical component suspension frame itself. This “re-leveling”, referred to as mass re-centering, can accommodate an instrument inclination of up to ± 2.5 degrees. It is important to note that in this way the horizontal sensors will be maintained horizontal to a high degree of accuracy, while the vertical sensor can be off-plumb by up to 2.5 degrees with the mass properly centred. All instruments were deployed by remotely operated vehicles with careful attention to initial leveling, and no coarse re-leveling was required subsequent to installation. Mass re-centering was done only a small number of times when mass position values indicated accumulated changes greater than approximately $160 \mu\text{rad}$. Hence, we assume that the sensitivities to tilt of the horizontal components of mass-position-derived acceleration are constant over the range of tilts experienced, and that the vertical component is insensitive to tilt. If the instrument is inclined near the limits of re-centering accommodation, however, significant cross-talk between tilt and measured vertical acceleration can occur. This may be the case at NC89 (discussed in Section 4).

The pressure monitoring instrumentation employed was initially developed to study hydrologic phenomena in sub-seafloor formations drilled by the Ocean Drilling Program, and has been adopted for use in simple absolute ocean-bottom pressure recorders (BPRs). The instruments use depth sensors built by Paroscientific Inc. (model 8B4000-1) in which a quartz crystal oscillator is loaded by water pressure via a Bourdon tube. The output frequency is compared to that of a temperature-compensated reference crystal with a precise (c. 1 ppb) fractional-period counting system (PPC), developed with J. Bennest of Bennest Enterprises Ltd.. These instruments resolve pressure variations with a precision of 0.4 Pa ($4 \times 10^{-5} \text{ dbar}$, or $.04 \text{ mm}$ equivalent water depth), and transmit 1 sample-per-second data to shore also via the NEPTUNE

cable system. Values are recorded in units of dbar ($= 10 \text{ kPa} \approx 1 \text{ m water depth}$), and these units are used here. The combination of high precision and sampling rate, and the use of absolute sensors yields a response to oceanographic, hydrologic, geodynamic, and seismic signals that is constant from nearly steady-state (limited by sensor drift $\sim 0.01 - 0.1 \text{ dbar yr}^{-1}$) to the 0.5 Hz Nyquist frequency. Further details can be found and data accessed at <http://oceannetworks.ca>.

One other source of data discussed in this paper is a new accelerometer that employs a quartz tri-axial acceleration sensor also built by Paroscientific, Inc., and a new version of the Bennest frequency counter now being built by RBR, Ltd. The instrument (acceleration, pressure, temperature, or “APT”) is housed in a 1-m-long 7-cm-diameter pressure case pushed vertically into and flush with the seafloor (Davis et al., 2015). The tool was deployed in September 2015 at NC89, 140 m northeast of the buried seismometer. During the first few months of operation, data were recorded at 1 s.p.s.; in March 2016 the sampling rate was increased to 6 s.p.s. The sensor measures over a dynamic range of 3 g with a resolution of $0.3 \mu\text{m s}^{-2}$. Data from this deployment can be accessed at <http://oceannetworks.ca>. Prior to construction of this instrument, the acceleration sensor was tested in an instrumentation vault at the Pacific Geoscience Centre, along with a prototype tilt sensor provided by Paroscientific, Inc., and a Guralp CMG-1T seismometer. Data from this comparative test are discussed in Appendix 1.

3. Overview of observations

Five-day segments of pressure and seismometer mass-position data are shown in Figure 3. Pressure variations include relatively high-frequency signals from microseisms, infragravity waves, and earthquakes (e.g., Davis and Heesemann, 2014), but are dominated by ocean tides. Some infragravity wave energy is likely to be present in the mass-position data as well, but as in

the case of pressure, tidal period signals are dominant. For the purposes of this study, signals with periods of less than 1 minute have been reduced by averaging. Variations having periods longer than several days are also common in the mass-position data, including drift, which ranges up to the equivalent of 40 $\mu\text{rad}/\text{year}$, and variations up to several μrad in amplitude that appear to be associated with temperature variations (see Appendix 1, Fig. A3). For the purpose of examining tidal signals, these have been removed by subtracting a running 3-day linear trend. As discussed in the previous section, the vertical mass-position values should be insensitive to tilt, whereas at long periods the opposite is true for the horizontal components. Hence, in Figure 3 and subsequent plots, vertical component values are shown as acceleration, and horizontal component values as tilt.

Observed pressure variations are similar at all of the sites. Small inter-site differences in phase and amplitude are present, but these are consistent with what is expected according to the local modeled ocean tides, and the match between observed and predicted pressure at each of the sites is excellent (Fig. 3).

Tidal variations in acceleration and tilt on the ocean bottom arise from solar and lunar gravitational attraction and tidal deformation of the solid Earth (referred to herein as body tides), and from ocean tidal mass movement and associated gravitational attraction and loading (referred to as ocean-tide attraction and loading). For the purpose of comparison to the observations, these components have been computed for the locations of the four sites (NCBC, NC89, NC27, and ENWF) using the SPOTL ocean tide loading software package (Agnew, 2012). SPOTL provides a means of integrating point load response functions for gravity and tilt (Green's functions) for an appropriate elastic Earth structure using local and global ocean tide models for eight major tidal constituents. The responses at the frequencies of the major

constituents are interpolated to provide a complete response at all frequencies across the tidal band. The ocean tide loading computations for the sites utilize the Green's functions of Farrell (1972). Green's functions for the Gutenberg-Bullen-A Earth model, with the top 1000 km replaced by an oceanic structure, was chosen for integration over the local ocean tidal model for our study area. The local ocean tide model is `osu.usawest.2010` provided by Oregon State University (Egbert et al., 1994; Egbert and Erofeeva; 2002). The unmodified Gutenberg-Bullen-A structure was chosen for integration over the remaining global ocean tides, modeled by GOT4.7, the 2004 version of the Goddard Ocean Tide Model (Ray, 1999). Body tide predictions for the three sites were generated by SPOTL program `ertid` (Agnew, 2012) based on studies by Munk and Cartwright (1966), Berger (1969) Appendix C, and Harrison (1971). Resulting predictions are included with the observed signals in Figure 3.

Observed horizontal components of tidal tilt vary substantially from site to site, and the variations are generally much larger than model predictions (Fig. 3). Signals are weak in the east-west direction at NCBC and in the north-south direction at NC27, but all other components display clear tidal variations with amplitudes ranging to over $\pm 1 \mu\text{rad}$, and the observed tilt waveforms are reasonably well matched to pressure in character and phase.

Directionality of tilt is well defined at each of the sites, as is indicated by x-y tilt cross plots (Fig. 4). Here and in subsequent figures, predicted values arising from the standard-earth models have been subtracted from the observations to yield local tilt and acceleration anomalies. The sense of this residual tilt as a function of pressure at each site is apparent in Figure 5, where the principal components of tilt are calculated in the directions defined in Figure 4. Under increased load, tilt increases (positive down) at 130° true at ENWF, at 243° true at NC89, at 90° true at NC27, and at 10° true at NCBC. Senses of tilt under increased load are also shown by the

arrows in Figure 4. The amplitude response of tilt to ocean loading varies from roughly $0.2 \mu\text{rad dbar}^{-1}$ at ENWF, to $0.4 \mu\text{rad dbar}^{-1}$ at NCBC and NC27, and $0.6 \mu\text{rad dbar}^{-1}$ at NC89. Principal tilt waveforms are well matched to pressure, with the exception of ENWF where the semidiurnal component of tilt leads pressure by roughly 1 hour.

Variations in vertical acceleration defined by the seismometer mass position data match model-predicted variations very well (Figs. 3a, c, d), with the exception of NC89 where observed variations are roughly 20% smaller than predicted and shifted slightly in phase (Fig. 3b). The mismatch in both amplitude and phase can be rectified by adding to the predicted acceleration a component that is proportional to the local ocean tidal pressure (Fig. 6a). Alternatively, since tilt and pressure are well correlated (Fig. 5), an equally good match between observed and predicted vertical acceleration can be gained by adding to the observed acceleration a component that is proportional to tilt (cf. Fig. 6b). A discussion of the logic of these adjustments, and of which is more likely to be the operative one, is included in Section 4.

A more comprehensive view of the tilt and vertical acceleration data has been gained by computing the x-y tilt covariance matrix and the vertical acceleration - ocean gravity covariance matrix for 3-day windows after removing the long-term background variation that is present in all mass-position records (see Appendix 1 Figs. A2, A3). In the case of tilt, the direction was established by the matrix diagonal (much like the cross plots in Fig. 4), then the maxima and minima of resolved components were calculated. The relationship between the vertical-component data and pressure were calculated following the scheme shown in Figure 6. This has been done systematically through 3.5-year-long records from each of the sites. Tidal tilt signals are nearly eliminated from the minimum-component values, the maximum-component values are consistently in phase with seafloor pressure (with the exception of ENWF), and no long-term

variations in the tilt response (amplitude or directionality) or in the relationship between vertical acceleration and pressure were found. Hence, the results shown in Figures 4-6 can be considered representative of deformation response to loading over a period of years.

4. Possible causes of anomalous signals

As evident from the presentation in Section 3, a good match between observed signals and signals predicted by standard tidal body and ocean loading and attraction models is found in the case of vertical acceleration at three of the sites, a significant anomaly in vertical acceleration is seen at NC89, large anomalies are seen in tilt at all sites, and all anomalies are correlated with local ocean tide (Figs. 3, 5, 6). Effects of topography and elastic properties heterogeneity have been shown to be significant as a percentage of solid-earth deformation signals (e.g., Meertens and Wahr, 1986; Beaumont and Berger, 1974), but such effects are normally small relative to the anomalies observed here, and not of the same phase as ocean tide. Where large anomalies have been observed on land, they are often linked to open sub-surface voids (e.g., mines, tunnels), or to local coastal loading near shorelines (e.g., Marthelot et al., 1980; Dragert et al., 2000; see Appendix 1 Fig. A4), but these are not significant factors in deep-ocean far-offshore settings. In this section we consider a few means by which ocean tidal loading might generate tilt and vertical deformation signals beyond those predicted by standard gravity and earth deformation models. First we consider the possibility of instrumental origins for the anomalies.

4.1. Instrumental sources. Calibrations have been carried out on the velocity output of the seismometers, and cross-checks have been done between seismometer velocity output and signals from co-located accelerometers using natural signals (e.g., Appendix 1 Fig. A1). In the case of the long period mass position data, the characteristics of the electronic and physical

components involved are very well known, and high confidence can be given to the sensitivity of mass position values to acceleration. A check on this supposition has been provided by results of tests carried out in the seismic vault at the Pacific Geoscience Centre, with a fully-assembled seismometer in its pressure vessel operating beside a quartz tilt sensor. Tidal signals are well matched (see Appendix 1 Fig. A4), and the amplitude and relationship with local ocean tidal loading agree with data recorded many years earlier with a mercury tilt meter (Dragert, 1982). A further check is provided by a comparison between observations made with the seismometer at NC89 and simultaneous observations made with the nearby accelerometer described in Section 2 (Fig. 7). While there is a phase shift in the observed tilts and the signals are not far above the resolution of the accelerometer, tidal amplitudes recorded by the independent instruments are well matched. These results add confidence in the conversion of the mass position data to acceleration and tilt, and they also help to demonstrate that the tilt signals are not some artifact of external pressure variations acting to deform the instrument mounting frame via the pressure case which, with its equatorial and longitudinal reinforcing ribs, is not a simple sphere. Because of the small baseline of the instrument (c. 0.3 m), a very small deflection ($0.3\ \mu\text{m}$) would be required to produce the $1\ \mu\text{rad}$ tilt signals observed. This possibility is discounted by the comparison shown in Figure 7. It is also discounted by the fact that the tilt signals were the same before and after replacements of the seismometer at NC27 (Table 1).

The existence of the vertical acceleration anomaly at NC89 and its relationship with pressure (Fig. 3b) could reflect mass changes beneath the instrument or vertical deformation of the seafloor, but such explanations are unlikely. Free gas in the formation and gas vents at the seafloor are known to be present beneath and in the vicinity of this location (e.g., Riedel et al., 2006), and if the formation were connected to the seafloor via high-permeability pathways, then

gas-bearing fluid ventilation could be modulated by tidal loading to produce a variation in interstitial mass. Under high tidal pressure, fluid venting would be slowed both by the compression of the free-gas component and by the associated reduction in buoyancy, and the opposite would be the case under low tidal pressure. A crude upper limit on the magnitude of the effect on seafloor acceleration is provided by the Bouger (infinite slab) term of replacing gas with water, i.e., roughly $0.42 \mu\text{m s}^{-2} \text{m}^{-1}$. An exchange of an equivalent of a 2-m-thick layer of water would be required to produce the observed acceleration anomaly. Even if distributed over a thick sedimentary section, accommodation of this amount of mass exchange driven at tidal periods by gas compression and decompression is unrealistic.

Generation of the acceleration anomaly by vertical seafloor displacement is equally implausible. To create the observed relationship between gravity residual and pressure of $0.21 \mu\text{m s}^{-2} \text{dbar}^{-1}$ (the correction factor required to match predicted to observed acceleration; Fig. 6a), motion of the seafloor through the free-air gravity gradient ($3.086 \mu\text{m s}^{-2} \text{m}^{-1}$, or $2.67 \mu\text{m s}^{-2} \text{m}^{-1}$ after accounting for ocean water mass displacement) would suggest vertical displacement with a sensitivity to loading of 0.08 m dbar^{-1} (0.008 m kPa^{-1}). It is well known that vertical deformation is a fundamental consequence of seafloor loading, whether caused by shear in the case of short-wavelength loading (e.g., infragravity waves; e.g., Crawford et al., 1991; Willoughby et al., 2008) or compressive deformation, as in the case of the response to large-wavelength loads such as tides. Volumetric elastic compression is the product of the load, formation thickness, and compressibility which depends on the compressibility of the solid and fluid constituents, their proportions, and the compressibility of the solid matrix. To produce 0.08 m of vertical displacement under a load of 1 dbar imposed on the c. 4.5 km sediment section at site NC89 would require a bulk formation compressibility of roughly $2 \times 10^{-9} \text{ Pa}^{-1}$, an order of magnitude

greater than the value that is likely to characterize the sediments (Appendix 1 Fig. A5). Enhanced compressibility could result from free interstitial gas, but not to the degree required, and this would run counter to observations made by Willoughby et al. (2008) who found decreased shear compliance in the vicinity of NC89 which was interpreted to be the consequence of interstitial gas hydrates. Large vertical displacement of the seafloor is also contradicted by the close agreement between observed and predicted pressure seen in Figure 3b. Vertical deformation of a magnitude suggested by this interpretation of the observations would be observed readily as an anomalous tidal pressure signal, but no anomaly is seen. Thus we are left to conclude that the vertical acceleration anomaly seen at NC89 must be instrumental in origin.

As noted in Section 3, because of the tight correlation between seafloor pressure and tilt (Fig. 5), a match that is equally good to that achieved in Figure 6a (using an adjustment proportional to pressure) can be achieved by adjusting the observed acceleration by a term proportional to tilt (Fig. 6b). This raises a question about whether there may be cross-coupling between tilt and the measured vertical acceleration. Generation of a tilt sensitivity of $0.4 \mu\text{m s}^{-2}/\mu\text{rad}$ (Fig. 6b) would require the vertical axis of the instrument to be off-plumb by little more than 2 degrees. While this amount of inclination may seem large, it is possible and could go undetected: The individual component adjustments can accommodate up to 2.5 degrees of inclination, and the absolute amounts of corrective adjustment are not recorded. Thus, while on the basis of the observations alone the anomalous vertical acceleration at NC89 is explained equally well by an origin in tilt or pressure, an origin in tilt via vertical axis inclination (i.e., the logic behind Fig. 6b) is more likely.

4.2. Compliance variations leading to tilt. Where lateral variations in vertically integrated compressibility are present, tilt will result. One simple instance of this is a tapering

wedge of compliant material (e.g., sediment) lying on a more ridged base (e.g., igneous crust) as illustrated in Figure 8a. Such a wedge will behave as a “bellows”, with vertical seafloor deformation increasing in proportion to the increasing sediment section thickness and producing tilt as a by-product. A compressibility appropriate for semi-consolidated sediment of $2 \times 10^{-10} \text{ Pa}^{-1}$ (Appendix 1 Fig. A5) yields a sensitivity of tilt to taper of $0.035 \text{ } \mu\text{rad/degree/dbar}$ of load. Beneath site NC89, the outer prism tapers at an average of roughly 8 degrees, which would allow tidal loading to produce a tilt of roughly $0.3 \text{ } \mu\text{rad dbar}^{-1}$. To match the magnitude of tilt observed (c. $0.6 \text{ } \mu\text{rad dbar}^{-1}$ at NC89) would require a compressibility twice that assumed, a value reached only with an unreasonable amount of free gas (Appendix 1 Fig. 5). Furthermore, the sense of tilt is opposite to that observed, so this simple mechanism appears inapplicable at NC89. The simple calculation does show, however, that significant tilt can result from geologically reasonable lithologic gradients. Near NC27 sediment thickness increases from 250 m to 600 m over a distance of roughly 2 km (a dip of 10 degrees; see Fig. 1c), and locally steeper gradients can exist where sediments bury rugged faulted igneous oceanic crust. ENWF is situated near a seismically imaged magma chamber (Van Ark et al., 2007; Fig. 1d), an obvious source of compliance, in this case residing locally beneath a more rigid upper-crustal lid. This could easily give rise to loading-induced tilt in the direction from ENWF towards the ridge axis as observed.

4.3. Influence of low shear modulus faults. A second case considers the deformation induced by uniform seafloor loading of a layer penetrated by a fault having a low shear modulus (Figure 8b). Using the same elastic properties as the previous case (compressibility, $\beta = 2 \times 10^{-10} \text{ Pa}^{-1}$, Poisson’s ratio, $\nu = 0.33$, used for all models), and a layer thickness equivalent to that of the accretionary prism at NC89 (4.5 km), a finite difference numerical model yields tilt that varies with distance and includes a region characterized by negative tilt in the direction of fault

dip (Fig. 8c), opposite that for a simple wedge but consistent with the direction observed at NC89, where thrust faults dip predominantly landward. In a case where the basal layer boundary is defined to have a low shear modulus, the tilt anomaly is broad and the response to loading ranges up to $-0.8 \mu\text{rad dbar}^{-1}$, spanning the value observed (Fig. 5b).

A third scenario considers the possible role of anisotropic elastic structure in causing load-induced tilt (Fig. 8d). On the ridge flank, the oceanic crust carries the structural history of seafloor spreading, including normal faults and fractures that typically dip towards the ridge axis; within the accretionary prism, thrust faults and fractures dip predominantly landward. Such structure could behave like a deck of cards, with “cards” possessing normal properties bounded by dipping faults that are anomalously compliant in shear (as in Fig. 8b). Under a load of ΔP , vertical displacement at the seafloor will be $\Delta h = \beta \Delta P h$, where h is the thickness of the section. For the optimal case of 45° dipping faults (that which produces the greatest response of tilt to loading), and assuming that all shear deformation is concentrated in the bounding faults, the resulting rotation of the volumes (“cards”) between faults will be simply $\text{atan}(\Delta h/h) = \text{atan}(\beta \Delta P)$. For the same compressibility assumed above, $\beta = 2 \times 10^{-10} \text{ Pa}^{-1}$, this yields sensitivity of tilt to loading of $2 \mu\text{rad dbar}^{-1}$, and a direction of tilt opposite structural dip.

A slightly different description of the influence of dipping structure is illustrated in Figure 8e, where compressible material is bounded by low shear modulus faults, in this case of circular section. Under uniform load, displacement will be guided by the faults, resulting in rotation that is defined by the radius of the faults. The magnitude of the resulting tilt will depend on the fault segment length and the integrated compressibility of the fault-bounded volume. For the case of listric faults having a 45° surface dip, the effective compressibility integration length (including the taper of the volume between listric faults sharing a common decollement) will be

1/16 of a circle segment. With the same properties as above, the response of tilt to seafloor load will be $\text{asin}(2\pi r\beta/16r) = 0.8 \mu\text{rad dbar}^{-1}$.

In reality, the amplitude of the response to loading will depend on the actual dip and details of structure and on the actual elastic properties, and the pattern of dip at the seafloor will be locally complex, yet the general consistency of the sign and magnitude produced by such mechanisms with those observed at NC89, NC27, and ENWF is compelling. Thus such mechanisms cannot be ignored as a means of generating tilt from spatially uniform ocean loading.

5. Discussion and Summary

Long-period acceleration data have been obtained using mass-position values from four buried broad-band seismometers deployed at the edge of the continental shelf off Vancouver Island, Canada (NCBC), on the nearby outer accretionary prism of the Cascadia subduction zone (NC89), on the eastern flank of the Juan de Fuca Ridge (NC27), and on the Juan de Fuca Ridge 2 km west of the ridge axis (ENWF). Seafloor pressures have been observed at each of these sites with closely co-located instruments. All the instruments are part of the NEPTUNE Canada cabled observatory array and have been in nearly continuous operation for periods of up to seven years. Observed tidal-period variations in acceleration are of the order of $\pm 1.5 \mu\text{m s}^{-2}$ in the vertical direction, and of the order of $\pm 10 \mu\text{m s}^{-2}$ in the horizontal direction equivalent to 1 μrad tilt. Temporal stability of the tilt magnitudes and directions, and of the magnitudes of vertical acceleration observed by the seismometers, has been confirmed by examination of more than three years of the history of recording at these sites. At NC89, confirmation of the direction and amplitude of these values has been gained with observations made with an independent tri-

axial accelerometer during its operation that began in late 2015, and with a seismometer replacement at NC27 in 2014.

Vertical accelerations seen at NCBC, NC27, and ENWF match predicted gravity variations very well. An anomaly at NC89 is seen that most likely is operatively related to tilt, with cross-coupling caused by inclination of the instrument vertical axis. At all sites, the c. 1 μrad tilts observed are much larger than those predicted by standard earth models, and larger than those typically observed on land, commonly in the range of a few tens of nrad (e.g., Kohl and Levine, 1995). Instrumental sources for the tidal tilts have been ruled out. Among possible natural causes, it seems most reasonable to ascribe the signals to seafloor-load-induced deformation in the presence of structural or lithologic heterogeneity or anisotropy. In the case of ENWF, positive tilt under positive load is oriented towards the ridge axis, possibly the consequence of a compliant axial magma chamber located nominally 2 km away. A difference in phase between pressure and tilt is observed; this may be a consequence of visco-elastic deformation of the magma body. At NC27 and NC89, where tilt is oriented in directions opposite to structural dip, rotational deformation (about a strike-parallel axis) and associated tilt may result from the anisotropic properties that could arise from normal and thrust faults, respectively. Amplitudes of load-induced tilt are large, ranging from 0.2 $\mu\text{rad dbar}^{-1}$ at NC27, to 0.6 $\mu\text{rad dbar}^{-1}$ at NC89. Simple models show that tilts of this magnitude can be generated if faults are characterized by high shear compliance.

A check on the consistency in direction and amplitude of tilt signals will soon be possible at the Cascadia accretionary prism site NC89 by comparing the data obtained with the instruments used in this analysis with those of a borehole tilt meter that has been installed in IODP Hole 1364A roughly 3.5 km along strike (J. McGuire, WHOI, pers. comm.). Further in

the future, a simple test of the hypothesis that fault structure exerts an influence over formation response to ocean loading could be carried out with similar observations of tilt and pressure at a location dominated by seaward dipping faults. Such seaward-dipping faults and landward-verging structures are ubiquitous not far to the south off the coast of Washington as well as to the north of the location of NC89. A recent expansion in the number of seismometers deployed as part of the DONET observatory at the Nankai subduction zone may also shed further light on whether there is any consistent link between the orientation of structure and direction of tilt.

At this point, these explanations are reasonable, although speculative. The primary conclusion of this paper is robust, however: Seismometers like those deployed are capable of resolving small amplitudes of tilt and vertical acceleration at periods much longer than normally spanned by seismology. Measurement sensitivities range down to a fraction of $1 \mu\text{rad}$ in tilt and a fraction of $1 \mu\text{m s}^{-2}$ in vertical acceleration. Noise that appears to be of thermal origin is present in observations at periods longer than a few days, but amplitudes of these perturbations are modest, of the order of $1 \mu\text{rad}$ in tilt. Thus it should be possible with instruments like these to observe transient tilt signals associated with seismic and aseismic deformation events in a variety of tectonically or volcanically active settings, including mid-ocean ridges and subduction zones. Mass-position data are normally used only as a state-of-health indicator for engineering purposes and are not recorded at high fidelity; where they are not, they should be.

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Figure captions

Figure 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.

Figure 2. Seismometer installation photos at Site NC27 before and after burial (a). Simplified schematic of the Guralp CMG-1T seismometer (b).

Figure 3. Representative records of observed tidal-period seafloor pressure (blue), and observed vertical acceleration and tilt derived from horizontal mass position data (dark red), at each of the three NEPTUNE broadband seismometer sites (NCBC in a, NC89 in b, and NC27 in c, and ENWF in d; see Fig. 1 and Table 1 for instrument locations and for coefficients used for converting mass-position to acceleration and tilt). Modeled pressure, acceleration, and tilt are shown as dashed lines (nearly indistinguishable from the observations in the case of pressure). Pressures here and in other figures are plotted in units of dbar ($10 \text{ kPa} \approx 1 \text{ m water load}$).

Figure 4. North- and east-component tilt cross-plots for each of the broadband seismometer sites. Values are shown as residuals after removal of modeled tilts (see Fig. 3). Arrows show directions of tilt (positive down) under increasing pressure loading.

Figure 5. Pressure (blue), and tilt resolved in the principal direction (with modeled values removed; dark red) at each of the NEPTUNE observatory sites. Sensitivity and directionality (see Fig. 4) of the response of tilt to pressure are given for each site.

Figure 6. Comparisons of observed (dark red) and modeled vertical acceleration (red) at NC89. Mismatch of the observed and modeled waveforms can be accounted for either by applying a correction term to the modeled acceleration that is proportional to pressure, e.g., as if pressure loading caused vertical seafloor deformation (blue in a), or by applying a correction term to the observed acceleration that is proportional to tilt, as if there were cross-talk between tilt and vertical acceleration via a lack of verticality of the vertical sensor axis (green in b).

Figure 7. Vertical acceleration and tilt derived from site NC89 broadband seismometer mass position data (dark red) compared to values observed with an “APT” accelerometer located 140 m to the east-northeast (grey; described briefly in section 2; see Table 1 for locations). High-frequency components superimposed on the APT tidal signals are in part associated with ocean-wave loading, and in part a result of the limit of resolution of the tool (c. 10 ppb of 3g full scale, shown by vertical bars). The cause of the difference in phase of the signals is unknown.

Figure 8. Four simplistic ways in which tilt might be produced by spatially uniform seafloor loading, including deformation of a section with a spatial gradient in compliance, produced either by a tapering compressible layer thickness or a lateral gradient in compressibility (a); deformation of a compressible layer separated from a rigid base by a highly compliant fault (b, c); deformation of a layer having an anisotropic shear modulus (d), and deformation within a volume bounded by low shear modulus faults, in this instance having circular profiles (e). Results shown in (c) were calculated with a finite element model with properties and dimensions given in the text, with layer boundary conditions as shown, and with a right-hand boundary placed sufficiently far away (50 km) to have no effect.

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Figure 1a

Figure 1bcd

Figure 2a

Figure 2b

Figure 3a

Figure 3b

Figure 3c

Figure 3d

Figure 4

Figure 5

Figure 6

Figure 7

Figure 8

Table 1

Table 1. Instrument locations, operational histories, orientations, and sensitivities

Site	Setting	Station	Latitude	Longitude	Water Depth
Barkley Canyon	outer cont. shelf	NCBC	48.4275	-126.1752	396 m
Clayoquot Slope	accretionary prism	NC89	48.6705	-126.8488	1256 m
Clayoquot Slope	(accelerometer)	NC89	48.6710	-126.8470	1255 m
Cascadia Basin	ridge flank	NC27	47.7627	-127.7579	2654 m
Eneadeavour	ridge axis	ENWF	49.9598	-129.1245	2361 m

Station	Sensor	Time from	Orientation	E	N	Z	E	N
Code	Serial #	UTC	°true	nm s ⁻² /bit			nrad/bit	
NCBC	T1064	2009-09-08 11:04	0.7	1.61	1.59	1.07	-0.164	-0.162
NC89	T1063	2009-09-17 13:18	12.0	1.58	1.58	1.08	-0.161	-0.161
NC89	NA	2015-09-15 03:19	210.0	NA (Accelerometer)				
NC27	T1067	2009-09-11 10:03	4.2	1.58	1.57	1.05	-0.161	-0.160
NC27	T1065	2010-10-06 10:03	359.8	1.57	1.60	1.07	-0.160	-0.163
NC27	T1067	2014-05-22 23:16	357.0	1.58	1.57	1.05	-0.161	-0.160
ENWF	T1065	2016-06-21 17:35	0.0	1.57	1.60	1.07	-0.160	-0.163