METHANE CLATHRATE EFFECTS ON SEISMIC PROPAGATION WITHIN TITAN.

A. G. Marusiak[1], S. D. Vance[1], M. P. Panning[1], A. S. Bryant[2], M. A. Hesse[3,4], E. Carnahan[3,4] and B. Journaux[5]. [1]Jet Propulsion Laboratory, California Institute of Technology, 8200 Oak Grove Drive, Pasadena CA 91109. marusiak@jpl.nasa.gov, [2] Department of Physics, University of Chicago, Chicago IL. [3]Department of Geological Sciences, The University of Texas at Austin, Austin TX. [4]Oden Institute of Computational Engineering and Science, The University of Texas at Austin, Austin TX. [5]Department of Earth and Space Science, University of Washington, Seattle WA.

Introduction: Titan's surface icy shell is likely composed of water ice and methane clathrate [*1, 2]*. Methane clathrate may play a role in Titan's methane cycle [3–5], which would affect Titan's thermal profile [6] and possibly the habitability of Titan's ocean. Although the density and seismic velocities of clathrates are close to those of pure water ice Ih, the thermal conductivity of methane clathrate is about 20% the value for pure water ice [7, 8]. The lower thermal conductivity acts to insulate Titan's icy shell. As seismic wave speeds [9, 10] and attenuation [11] depend on temperature, any changes to the thermal profile will result in changes to recorded seismic waveforms, including those recorded by the upcoming Dragonfly mission [12] . Here, we compare the seismic waveforms of Titan models with a 100 km thick pure water ice shell, versus a model with a 10 km clathrate lid over 90 km of pure water ice.

Methods: We use PlanetProfile [13, 14] to create interior structures models of a pure water ice shell and a model with a pure water ice shell with a 10 km clathrate lid. The interior structure models are used as inputs with AxiSEM [15] and Instaseis [16] to generate seismic waveforms. We interpret the results to quantify the differences in seismic velocities, arrival times of seismic phases, and amplitudes of seismic waveforms at the surface of Titan.

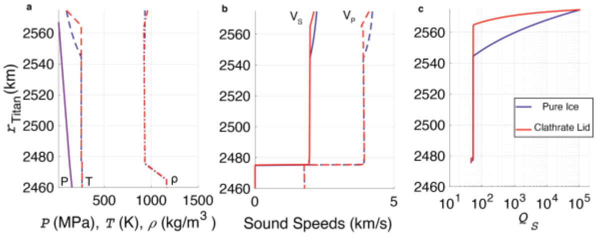

Figure 1. Results from PlanetProfile for a pure water ice (blue) model and a model with a clathrate lid (red). a) Pressure (solid), temperature (dashed), and density (dotted) profiles for the surface icy shell. b) Shear (solid) and compressive (dashed) wave speeds for both models in the icy shell. c) Seismic quality factor at 1 Hz.

Results: The interior structure models show that a clathrate lid will reduce the conductive lid thickness by ~ 2/3 compared to the pure water ice shell model. Thus, the clathrate lid model reaches higher temperatures at shallower depths (Figure 1a). The temperature profile affects the seismic velocity (Figure 1b) and the seismic quality factor (*Q*, Figure 1c) profiles. A clathrate lid creates a steeper negative gradient in seismic velocities and *Q*. The greatest difference in seismic velocities occurs at the base of the clathrate lid (Figure 2).

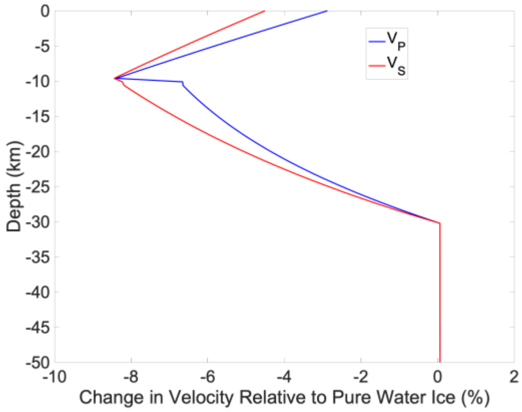

Figure 2. Percent difference between clathrate lid seismic velocities compared to pure water ice velocities for shear (blue) and compressive (red) velocities. A value of 0% indicates both models have the same velocity. Both velocities maximize around 8.5% decrease.

Because of the change in seismic velocities, the arrival times and observable distances of seismic phases will be different between the two models. Using TauP [*17*], we calculate the differences for several seismic phases. We find that the change in seismic velocity profile results in a difference of a few seconds at most in arrival times. The range of observable distances will also vary by a few degrees. The small changes might be noticeable on waveforms, but such detection would require high signal-to-noise ratios and precise determinations of the location and depth of the event.

The changes in seismic velocities and *Q*, however, affect the observed ground motion amplitude much more strongly. Using AxiSEM and InstaSEIS, we create a database of seismic waveforms spaced 1 degree in epicentral distance. We compare the same event magnitude and distance between source and seismometer for the two models. For each waveform we calculate the root mean square (RMS) using ground acceleration. In Figure 3 we show the ratio of the RMS for the ice model to the RMS for the clathrate lid model. At small distances, the clathrate lid model tends to produce stronger ground motion. However, as distance increases, the pure water ice model produces much stronger ground motions (up to ~175 x stronger).

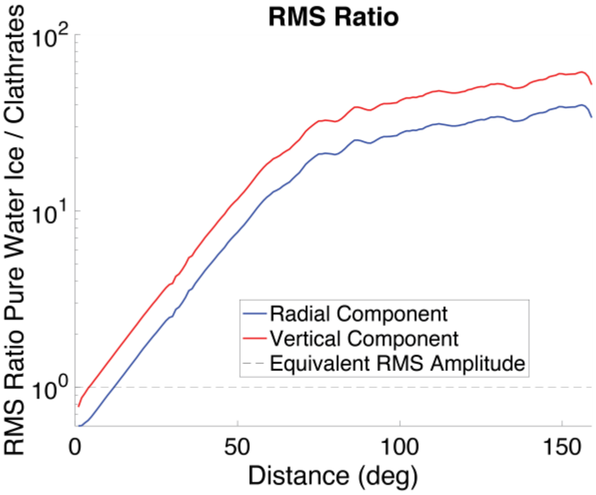

Figure 3. RMS ratio of pure water model to clathrate lid model. A value of 1 (dotted black line) indicates the waveforms have approximately the same amplitudes.

In Figure 4, we show a small sample of individual waveforms to highlight the cause of the differences between RMS values. We show that the body waves tend to have similar amplitudes, with clathrates often having stronger ground motion. However, the surface waves (shaded gray regions) show great variations between the models. Because the pure water ice model can retain higher *Q* for a greater depth, the surface waves do not attenuate significant energy with increases in distance. However, the clathrate lid model shows that attenuation (inverse of *Q)* becomes strong at shallower depths. The lower *Q* causes the surface waves to attenuate more energy with increased distance compared to pure water ice models. The relative suppression of surface waves causes the large RMS ratios seen in Figure 3.

Summary and Conclusions: Our analysis shows a clathrate lid will alter Titan's thermal profile compared to a pure water ice shell. The change in thermal profile will result in changes to the seismic profile of Titan. The changes in arrival time and observable distances are small and may not be conclusive of a clathrate lid. There are other factors such as topography, porosity, and heterogeneities in the ice shell that can likewise cause changes in arrival time and observable distances. However, the relative amplitudes of the waveforms may indicate the presence of a clathrate lid. If a seismometer records strong surface wave energies for distant events, then the ice shell is likely cold and brittle, indicating a thicker conductive lid thickness and likely a lack of clathrates. Constraints on the conductive lid thickness would thus also constrain the presence of a clathrate lid.

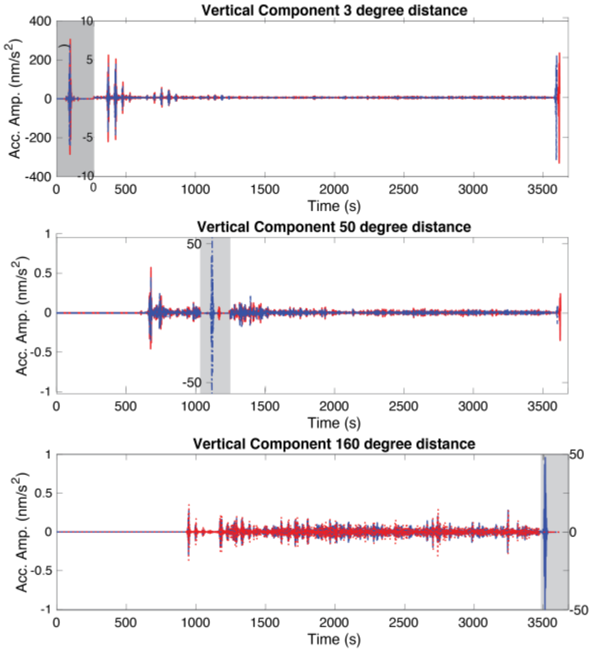

Figure 4. Example of waveforms at 3 degrees (top), 50 degrees (middle), 160 degrees (bottom). The clathrate lid model (red) and pure water ice (blue) models are plotted. Due to the large differences in surface and body waves, the scale bars are adjusted in the gray shaded region so that the surface waves can be seen without dominating over the smaller amplitude body waves.

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