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Potential of 3-D vertical seismic profiles to characterize seismogenic fault zones

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[1] The potential of a 3-D vertical seismic profile (VSP) to improve resolution of seismogenic plate interfaces was explored with synthetic modeling. The 3-D VSP modeled is at a proposed site for a 1 to 1.5 km deep open hole that provides background for riser drilling. Three-dimensional VSP images could resolve 30–60 m spaced reflective horizons in a Costa Rican subduction zone. It can record a great amount of high-fidelity S wave data to invert for physical properties, directions of strain, and pore pressure above and below the plate interface fault. A 6 km × 12 km grid of shots with a surface ship will illuminate a ~4 km × 7 km area of the plate interface fault zone with a high data density. Acquisition adds 5 to 9 days to drill ship time on site and a shooting ship. Seismic image resolution falls between that of borehole information and 3-D surface ship seismic images. A multiple-kilometer 3-D volume of high-fidelity S wave data is an exceptional addition not available with other techniques.

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Theme: Central American Subduction System
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1. Introduction

[2] Drilling several kilometers deep to penetrate the seismogenic segment of a subduction zone is a major IODP goal. The target areas for drilling represent diverse end-member environments that host the world's largest earthquakes and frequent tsunamis. Active seismogenic rupture along a plate interface can be reached with IODP deep riser drilling at the accretionary Nankai margin (NanTroSEIZE) and the erosional Costa Rica margin (CRISP). Anticipated are distinctly different interplate fault gouge zones

derived from subducted trench sediment at Nankai and debris from upper plate erosion at Costa Rica. The subducting lower plate igneous ocean crust at Nankai has moderate relief smoothed by trench sediment, whereas that of central and southern Costa Rica includes numerous seamounts and ridges covered by thin sediment. Subducted relief and the more rapid rate of plate convergence is associated with smaller more frequent earthquakes in southeastern Costa Rica than in Nankai. The planned IODP investigations involve two geologically different subduction zones characterized by diverse patterns of seismicity.

[3] Research on convergent margins that involves scientific drilling focuses on the behavior of rock, fluid, and sediment input to the seismogenic zone. The subducted materials are modified progressively along the plate interface by increasing temperature and pressure. Such progressive modification probably changes the fault rupture behavior from stable (aseismic) slip to unstable slip (stick slip) down a subduction zone. At accretionary margins, that change is likened to a conveyor belt. A sediment layer underthrust at the deformation front is modified as it subducts to conditions of increasing pressure and temperature. The input material and its initial modification can be investigated with a transect of non riser holes. Conversely, at the deformation front of erosional margins, trench sediment is sparse and igneous ocean crust is commonly rough with topographic highs covered only by thin sediment and thicker sediment in the lows. Relief projecting through the sediment off Costa Rica may become asperities for magnitude 6 to 7 earthquakes [*Bilek et al.*, 2003] or it may form barriers to slip propagation. Thus a patchwork of frictional behaviors appears to develop along the plate interface fault. This patchwork in space [*Sage et al.*, 2006] changes character in time during the seismogenic cycle [*Bilek and Lay*, 2002; *Wang and Hu*, 2006; *Kanamori*, 2008]. The frictional patchwork from material and rupture character is speculative because seismic resolution at the scale of the roughness and sampling of eroded upper plate debris on the lower plate requires riser drilling that has yet to be realized. Seismogenic zone structures are poorly resolved even in the best surface ship seismic images. Suspected fossil plate boundary faults on land have gouge zones 30 to 50 m thick and damaged zones 50 to 200 m thick [*Hickman et al.*, 2007; *Okamoto et al.*, 2007; *Li et al.*, 2007; *Rowe*, 2007]. Seismic images acquired by surface ships typically image only 150 to 400 m spaced reflections because high frequencies are attenuated and signals to and from plate interface reflectors are scattered. In the geologic environment explored by the oil industry significant gains in depth imaging and quantifying rock properties have been made with the 3-D VSP [i.e., *Paulsson et al.*, 2004]. Whether comparable gains might be realized in the convergent margin seismogenic zone environment is the focus of this report.

2. Vertical Seismic Profile

[4] A high-resolution seismic imaging technique employed in industry is the vertical seismic profile (VSP). It was used in scientific ocean drilling for 1-D and 2-D experiments [*Stephen et al.*, 2007] by lowering single or multiple geophones in a drill hole that receives signals from a surface source. Coverage is obtained by lowering the recording array to various depths in the hole. The VSP is used to measure velocity precisely, which indexes logged and seismically imaged layers to strata and faults in cores or logs. The 1-D measurement is extended to 2-D images with a ‘‘walkaway’’ line of surface ship shots fired at increasing ranges away from the hole (Figure 1) and recorded by a receiver array at a fixed depth in the drill hole. In a ‘‘three-dimensional offset VSP’’ a grid of shots above the drill hole are recorded. The topic of this study is the ‘‘three-dimensional offset VSP’’ and for convenience we refer simply to a 3-D VSP. The 3-D VSP provides high-resolution images and physical and elastic properties over kilometer distances around and below boreholes. It is possible to determine physical properties, because instead of the hydrophones in a surface receiver array the VSP array employs 3-axis geophones that are clamped to the walls of the borehole giving optimum coupling and direction to the reflector. These receivers give higher-fidelity records of ground motion than ocean bottom seismometers (OBS) deployed on seafloor sediment. Higher frequencies are acquired because the seismic signal travels through the water and the seafloor interface only once (Figure 1), whereas sea surface systems record signals that passed through the water and seafloor interfaces twice. These interfaces degrade signals and attenuate high frequencies. In addition, the shortened path reduces the Fresnel zone which is further reduced during 3-D depth processing. The much better signal-to-noise ratio in a quiet borehole environment enhances recording of low-amplitude signals. Available in IODP is the wireline type of instrument system in which up to 20 geophones may be deployed (conventional). However, a tubular

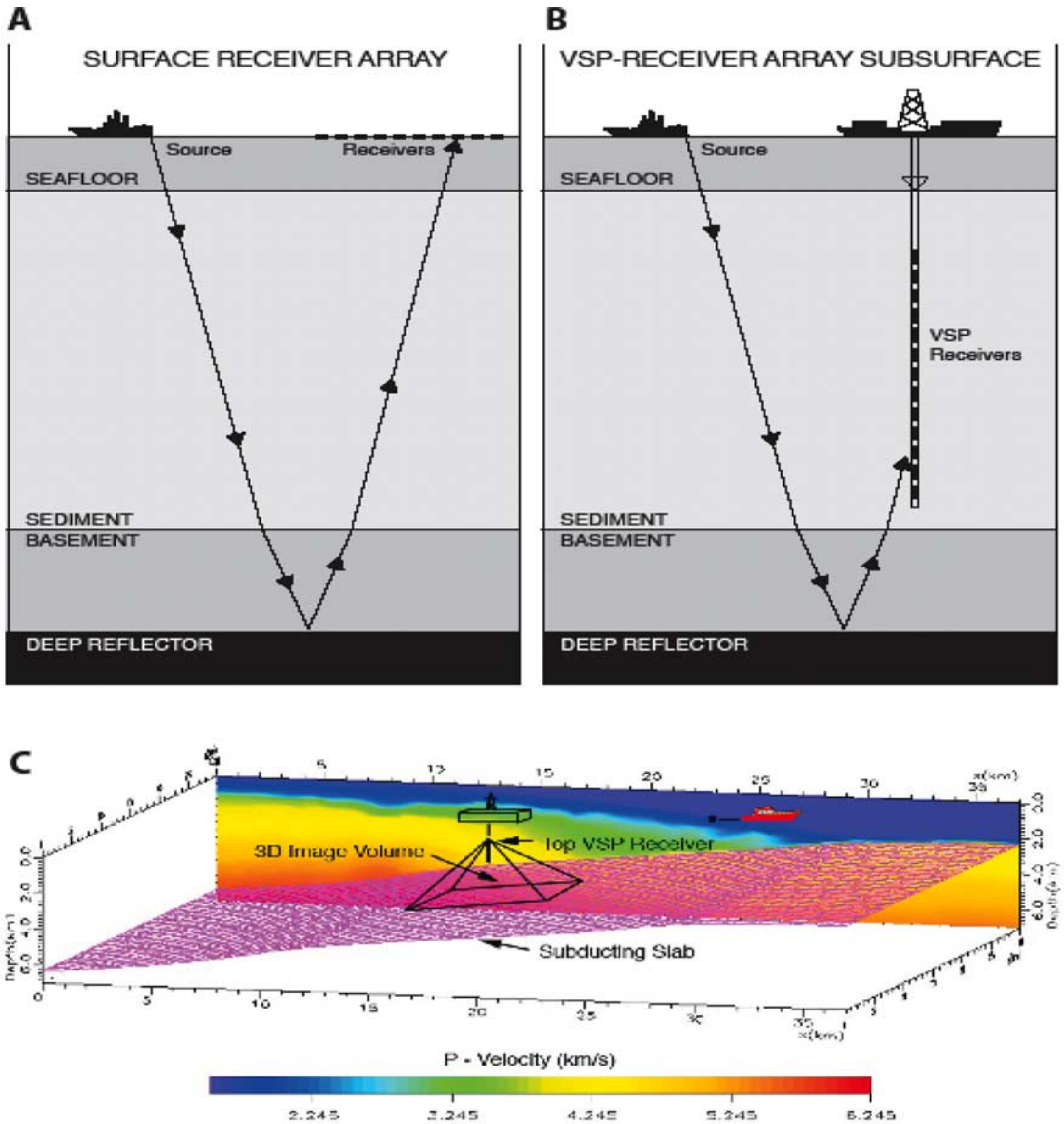

Figure 1. (a) Surface receiver acquisition where reflections pass twice through the seafloor and sea surface. (b) VSP array in a borehole below the seafloor. (c) Vertical backdrop is a seismic velocity section from Costa Rica. The pyramid on the subducting slab represents the 3-D volume of seismic data acquired, and its base is the plate interface area imaged. Reflections from a grid of surface signals are received by the vertical geophone array beneath the drill ship.

array system can support 240 three-axis geophones (massive) that allow resolution of greater detail than other techniques.

[5] VSP arrays are commonly lowered into cased holes but an open IODP drill hole can be instrumented with an array deployed and clamped in the drill pipe. Coupling of the pipe to the surrounding rock is enhanced by the heavy mud or gels filling an open drill hole during arrested circulation. Although conventional 2-D experiments have been conducted in scientific ocean drilling [*Stephen et al.*, 2007] the greatest gain in data for seismogenic zone applications will come from the massive 3-D VSP. A massive VSP array can record from ~4 to ~10 times more S waves than the conventional arrays from a given grid of shots as shown by our modeling. That increases resolution of seismic attribute inversions for physical properties. The fidelity of shear wave records allows observation of shear wave splitting, which indicates fracture directions.

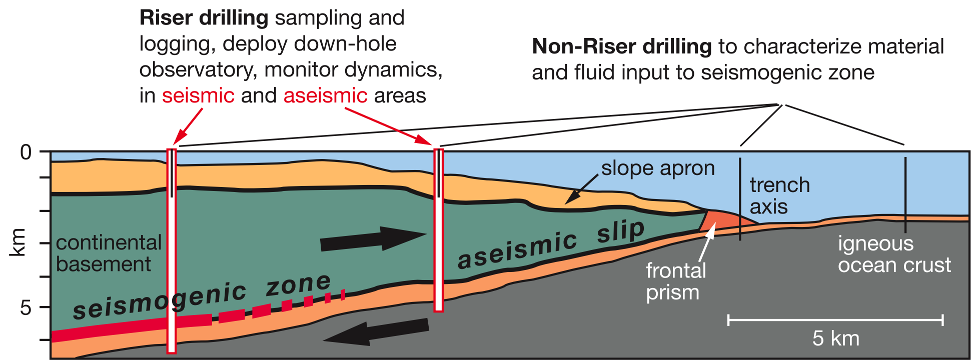

Figure 2. The proposed CRISP transect of drill holes showing site 3A in the aseismic zone. Heavy lines indicate target velocity discontinuities entered into the model.

[6] Site survey information sufficient for past open hole scientific drilling is insufficient for deep riser drilling. Although proposals to IODP for seismogenic zone riser drilling are reviewed with 2-D seismic information, once a proposal is accepted the proponents must supply 3-D seismic data for final site selection and engineering. The 3-D surface ship survey records similar acoustic frequencies as 2-D seismic acquisition. Seismic images from the plate boundary commonly lack resolution because they display only low-frequency surface ship seismic information. At the depths of seismogenic zones, drilling operations become the most difficult [*Prevedel*, 2007]. Recorded frequencies are seen in a 3-D survey near the IODP Costa Rica drill transect to compare with industry VSPs. The 3-D prestack depth migrated seismic images above the plate interface peak between 10 and 30 Hz [*Hinz et al.*, 1999; *Berhorst*, 1999]. A massive 3-D VSP can record up to an order of magnitude higher frequencies (100–150-Hz) at similar depths although such examples are from a different geologic environment [*Paulsson et al.*, 2004]. In industry examples, VSPs reveal faults not imaged in surface seismic images and accurately position subsurface structure as verified with drilling [*Arroyo et al.*, 2003]. A 3-D VSP will illuminate very steep to vertical faults not imaged by surface sensor 3-D data. The VSP at the SAFOD site imaged the near vertical San Andreas fault and positioned it accurately [*Chavarria et al.*, 2007]. At the KTB deep drill hole, unexpected near vertical faults were not imaged with a 3-D seismic survey but could have been displayed in a look-ahead 3-D VSP deployed in pilot holes around the drill site. The fault precluded achieving target depth.

[7] VSP velocities index most accurately the deep seismic image with cored and logged features. During deep drilling accurately located fault zones are important for efficient operations. Precise velocities are important for pore pressure prediction and engineering casing programs. The precision provided by massive VSPs is optimal and even with expanded shooting patterns into multiple sensor wireline VSP arrays, a much lower data density is recorded. Information acquired with a massive VSP was investigated with the modeling procedures of a geophysical services company used in planning programs for industry clients. Estimation of reflection frequencies was modeled at IFM-GEOMAR.

3. Modeling of a Massive VSP at CRISP Site 3A

[8] CRISP 3A is a proposed site for IODP drilling to sample the plate interface just before seismogenic behavior begins (Figure 2). The target is 3 km deep in 1 km deep water, and the seismic image is shown by *Kinoshita et al.* [2006] and *Ranero et al.* [2007]. Modeling was done by Paulsson Geophysical Services (P/GSI) under contract to JOI USSSP. The objective was to estimate the area on the plate interface illuminated with a massive look-ahead 3-D VSP and an optimum area of surface ship shooting. Two target horizons, the plate interface and the sediment basement contact at the top of the margin wedge, were selected. These geologic interfaces are prominent within the velocity section interpreted from OBS wide-angle records and those derived prestack depth migration [*Ranero et al.*, 2007]. Dip and strike velocity sections through the proposed drill site were provided by C. Ranero (Figures 1 and 3). P/GSI uses a multi step workflow to determine the optimum acquisition parameters for the survey. The full P wave modeling procedure and results (on file at the IODP data bank) are summarized here.

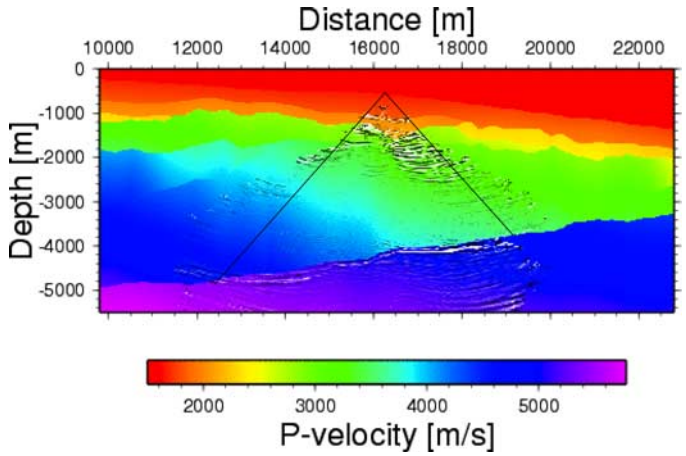

Figure 3. Migrated image of target horizons superimposed on the velocity section through the drill site. Seventy receivers at 15.24 m are located between 800 and 2019 m depth for modeling, but a closer spacing and shallower deployment are anticipated in the field. Lines indicate volume imaged inside of diffraction tails.

[9] The 2-D dip and strike velocity sections through the proposed drill site were extended laterally to construct a "3-D volume" that was used to ray-trace an optimized specular fold coverage. Various acquisition scenarios were simulated such as maximum source offset and selection of a shooting geometry. The modeled receiver array settings began at 800 m depth consisting of 70 levels at 15.24 m spacing. P/GSI's prestack depth migration was used in dry-run mode to estimate the hit count obtained at the target depth. With the optimum acquisition parameters for modeling, ProMAX FD, a 2-D finite difference migration software system, was used to output synthetic VSP shots along a 2-D line through the drill hole. Several wavelets were used to simulate various recoverable frequency bands. Limitations on modeling time made it necessary to work at 40 HZ and below with a Ricker wavelet. Basic processing was applied to isolate the raw upgoing compressional wavefield. Kirchhoff PSDM was applied to create final 2-D images using various shot and receiver geometries previously identified.

[10] Modeling indicates that a geophone array in the upper 1.5 km of a drill hole will illuminate a 7.5 ×

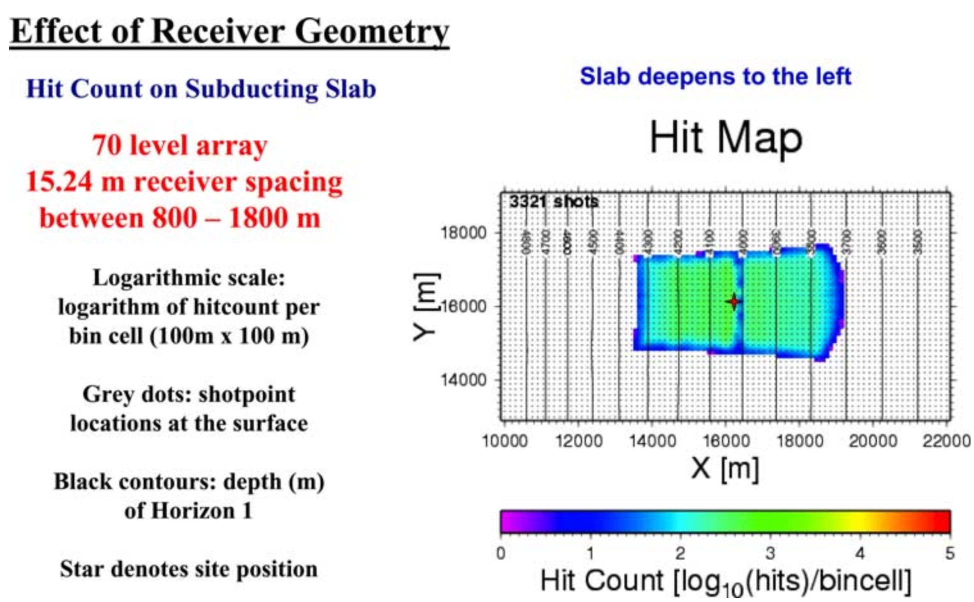

Figure 4. Data density shown as a hit map indicating number of seismic source signals received in 100 m bins on the plate boundary or top of the slab. The model assumes a featureless planar plate interface fault at the top of the subduction channel.

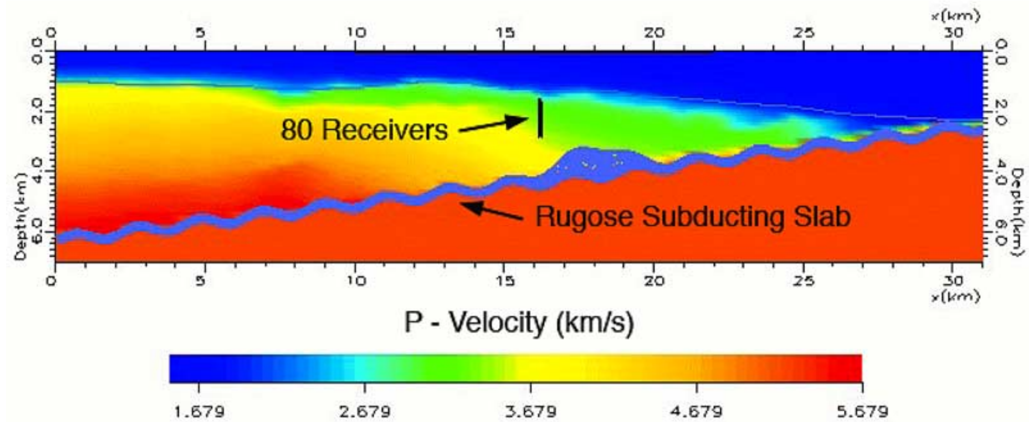

Figure 5. Synthetic rugose plate boundary modeled. Larger feature at center represents a 1.5 km high subducted seamount.

4 km area of the plate interface when receiving shots from a 6 × 12 km shooting grid (Figures 3 and 4). In its central portion the illuminated area receives more than 2000 hits in a 100 m^3 bin and the outer cutoff shown is 1000 hits per bin (Figure 4). A rectangular shooting grid rather than a spiral was selected for operational and processing simplicity (Figure 1) although the latter is more efficient. Within the imaged 3-D pyramid each 100 m^3 bin receives more than 1000 hits to the outer cutoff. Since a 5 s long recording interval will image the plate interface, the number of shots in actual operations at 6 kts can be doubled, thereby doubling the number of hits. Modeling shows that with the same shooting grid, a conventional 5 sensor array at any position in the drill hole yields fewer than half the hits of the modeled massive array and an aperture of only 0° to 5° rather than 25° to 30°. Aperture enhances the success of AVO analysis to obtain physical properties and recording more hits improves resolution. Reflections from below the plate interface are expected since basement shows strong reflective layering. Only P waves were modeled and S wave data modeling is expected to show a slightly smaller illuminated area.

[11] Defining a frictional patchwork requires imaging of the plate interface at the scale of subducted relief. Seaward of the CRISP transect the ocean plate input to the subduction zone shows considerable relief in multibeam bathymetry [cf. *Ranero et al.*, 2007] that is hardly apparent in surface seismic images of the subduction zone.

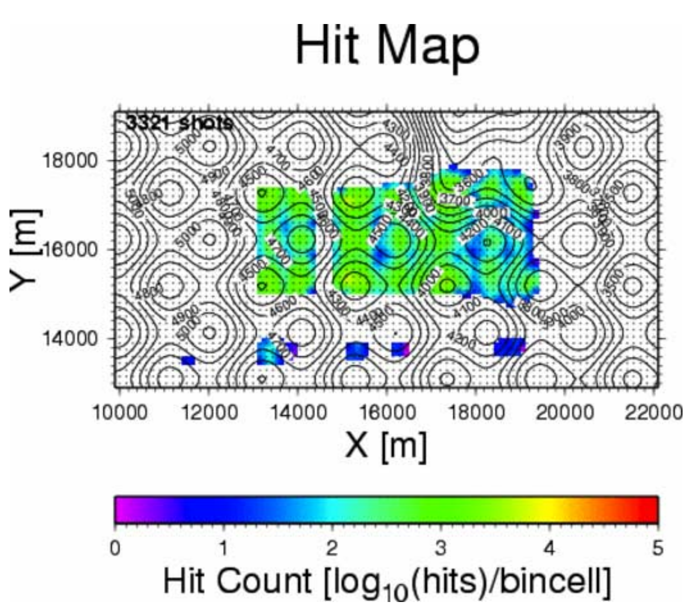

Figure 6. Hit map from modeling of a rugose plate interface.

The plate interface 2-D image near the area of proposed penetration has coherent reflective segments 2–3 km long and a vertical rise and fall of 200–300 m. A synthetic rugose plate boundary surface was modeled to examine its effect on imaging and hit count recorded in the upper 1.5 km of the drill hole (Figure 5). The modeled illumination of the smooth and rugose plate interface compare well despite the affects of relief on illumination. The hit count (Figure 6), the maximum and minimum incidence angles and angular aperture are similar in scale and cover the same area as in the smooth plate interface model. The flanks of large features will have a decreased coverage where the slopes are steepest. Thus the subducting plate relief along and below the plate interface fault can be imaged. Aperture broadens from between 5° and 30° so illumination is heterogeneous although the imaged area remains the same. In summary, the VSP images an area sufficiently large to include the variable topography of subducted basement that might occur beneath CRISP site 3A. A 3-D VSP at site 3A can map patchiness [*Bilek and Lay*, 2002] and variable physical conditions that could affect friction and the dominant directions of fracturing.

4. Modeled Resolution at the Plate Interface of a Look-Ahead VSP

[12] The 3-D VSP experience in industry shows that maximum frequencies of reflections in the shallow subsurface or near the VSP sensors can be in the range of 100–150 Hz [cf. *Paulsson et al.*, 2004]. There are no industry examples of looking ahead from a shallow drill hole to the plate interface thrust zone. In the absence of a field experiment, one of the few options to estimate the temporal resolution at the plate interface of a look-ahead VSP compared to a surface streamer is with modeling. A first step was to estimate attenuation due to high-frequency loss with a value for Q, a term that relates to the efficiency of energy dissipation through the rock volume [*Futterman*, 1962]. Q was estimated by forward modeling using the relations between the near seafloor reflections in a single good shot gather from BGR99 line 15, the sediment basement interface, and the targeted subducting plate interface reflection in the depth migrated image. In Figure 7a the frequency of the seafloor reflection and the plate boundary target reflections in observed data show a reduction from 45 Hz to 17 Hz. With forward modeling, this reduction could be simulated with Q values in the range of 130–150 for both the sediment and the basement layer. These values of Q are in the same range as estimates derived for planning of a surface ship survey in the area (N. Bangs, written communication, 2008).

[13] To estimate the response of a VSP compared to a surface streamer geometry three different source input frequency ranges were analyzed. In Figure 7b the amplitude spectra of the actual seismic trace (black) is displayed together with three different synthetic modeled spectra where the red-curve correspond to a modern 12 G-gun cluster used with good results to shoot many reflection lines during surveys of the German Geological Survey (BGR).

[14] We used instantaneous frequency to demonstrate the effect of attenuation and survey geometry in detail. Instantaneous frequency is the time derivative of the instantaneous phase [*Taner and Sheriff*, 1977]. The advantage of the instantaneous frequencies compared to the frequency spectra is that its value is appropriate to a point rather than being an average over some time interval (wavelet length). In this way the instantaneous frequency can vary abruptly, which allows analysis of the reflecting wavelet response at a specific interface and abrupt changes are not lost by averaging.

[15] Figure 7c shows the instantaneous frequency from the target reflector centered at 0.025 s (relative time) for a surface geometry. The VSP geometry for the input spectra of 50, 80, and 120 Hz assuming no attenuation is superimposed. As no attenuation was assumed, the respond at the target reflection is the same for surface and VSP configuration. Only a temporal increase of resolution with higher frequency can been seen (wavelet compression). If a Q value of 150 is now assumed, the instantaneous frequency change depends on one or the other sensor geometry. In Figure 7d the continuous lines (red, green, and blue) correspond to a surface geometry, whereas the dashed lines are the recorded instantaneous frequencies from the targeted reflection recorded by the VSP. For the surface streamer geometry the upper frequency limit is 20 Hz which is nearly independent of the input frequency range. Thus input frequency in the range tested has little effect. An increase of the temporal resolution can only be achieved by changing the sensor geometry to a VSP configuration. In the configuration modeled, an upper limit of 30 Hz is recorded assuming the attenuation of 150.

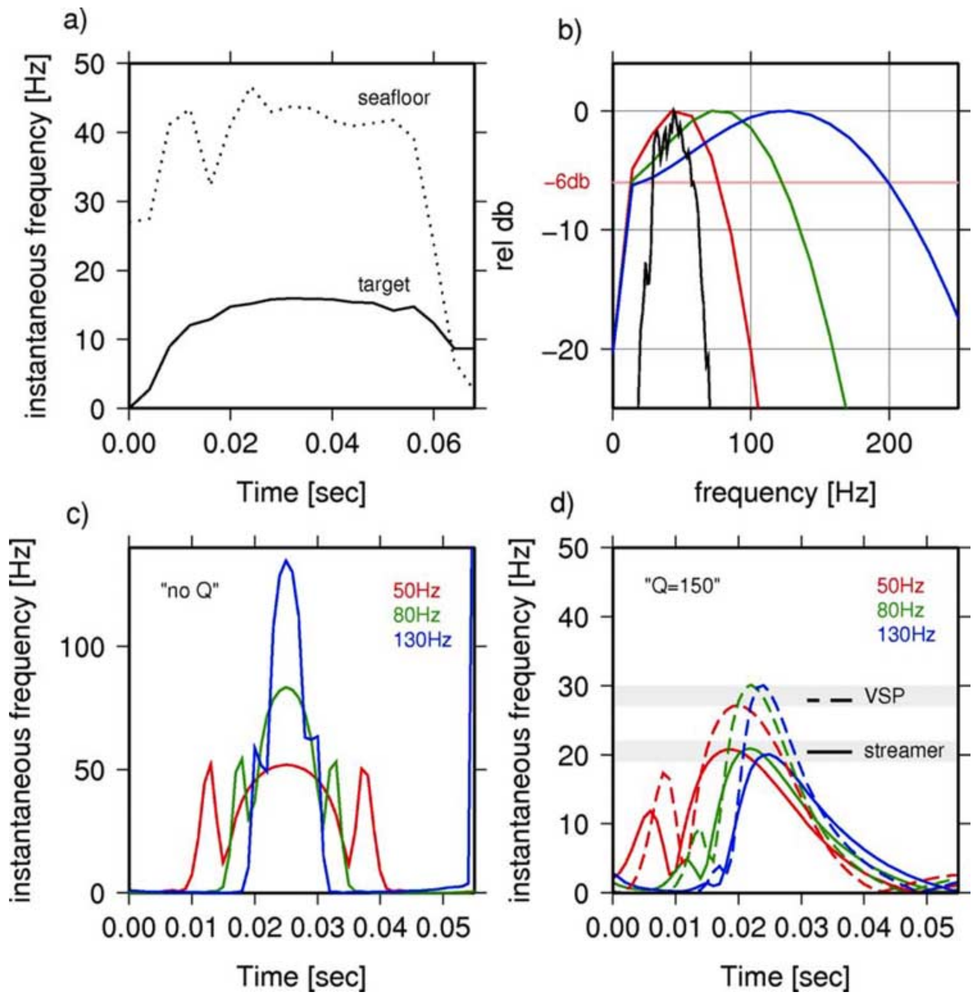

Figure 7. Temporal resolution of a VSP compared to a surface ship recording. (a) The instantaneous frequency reduction of observed data for the plate interface reflection was estimated to be ~150 (Q) with forward modeling. (b) Synthetic input frequency ranges were analyzed with main frequencies of 50 Hz (red), 80 Hz (green), and 130 Hz (blue). The input frequency spectra of the observed data are shown in black. (c) Instantaneous frequency response assuming no attenuation is sensor configuration independent. (d) Instantaneous frequency assuming an attenuation of 150 for surface ship (continuous lines) and VSP recording (dashed lines) shows 50% frequency increase of VSP.

[16] It is not possible to quantify with modeling the gains in resolution from reduction of the Fresnel zone and the greatly improved signal-to-noise ratio in a borehole. Further Fresnel zone reduction and fidelity are gained during 3-D data processing. Since those gains will be added to the 30 Hz, the increased frequency modeled is a minimum and improvement in resolution at the plate interface can be significantly increased depending on survey design and conditions at a site [*Arroyo et al.*, 2003].

5. Discussion

[17] High-resolution geophysics and drill hole information are complimentary. They both advance knowledge toward the goal of a more unified understanding of subduction zone fault mechanics each in its own way. Cores indicate geologic and petrophysical conditions of the rock that are extended some meters around the borehole with LWD and wireline logs. These data provide precise information in a small volume. The potential to extend this information into a much larger volume of the crust and across an extensive area of the plate interface is offered by 3-D VSPs. VSP information will illuminate larger features in a physically heterogeneous fault zone environment. Borehole fractures are mapped as larger patterns with S wave splitting data. Velocity and amplitude anomaly maps indicate material and fluid distribution. Physical properties are precise in a relative

sense and can be calibrated with the borehole information. Although similar information can be derived from surface ship 3-D surveys the resolution and fidelity are less.

[18] The IODP objectives of recovering samples across a seismogenic fault and a downhole observatory require long and expensive drill time. The VSP could optimize a drill path and precisely locate potential trouble spots. High-resolution 3-D geophysical images that illuminate 30 km^2 of the plate interface will clearly advance scientific understanding of subduction zone fault structure. With the great expense of the drill program it seems prudent to insure against unfavorable conditions in the unknown geology surrounding an active interplate thrust fault.

[19] A great gain in information with a VSP is in the amount and quality of shear wave data recorded. Shear wave information converted from P waves are recorded with surface streamers. Sensing with geophones in a drill hole eliminates one of the two conversion at the seafloor and records actual shear waves with improved continuity and amplitude. This record quality greatly increases the precision and resolution of physical properties from inversion. It also allows inversion where reflectors depart from near-horizontally thereby increasing the volume as well as the resolution of physical property information around the drill hole. Additionally, shear wave splitting can be derived from the data because of record fidelity and wave forms may be available or may be reconstructed.

[20] Another gain in direct recording of 3 axis geophone data is directivity of the reflected rays. If the direction from which a reflection came is included in seismic data processing it improves the positioning of reflectors significantly at the scale of a drill hole. Knowing where strata and faults are with such precision is important when setting casing and operating at the limits of drill rig capability, where each meter of hole is far more expensive than at shallower depths and where dealing with unexpected problems can be exceptionally difficult.

[21] The variable character of plate interface surfaces and the complex distribution of barriers and asperities along the Costa Rican margin can be resolved in more detail with a 3-D VSP than with surface hydrophone recording. The VSP resolution relates the meaning of drill samples at a spot through the seismogenic zone to the temporal and spatial diversity of seismic slip. One measure of that diversity is shown by the spatial rupture pattern of the Landers earthquake. The patches with large and small slip are 5 km to 8 km across, which is within the coverage indicated by our modeling. The best available resolution is desired to relate a single series of samples across the subduction zone to physical properties and stress that is fundamental to studies of rupture physics. On the other hand, to precisely calibrate the physical properties information from inversion requires values from the drill hole. Calibration at shallower levels can help constrain accuracy before reaching target depths.

6. Summary

[22] The risks attending deep sampling across fault zones are known from deep fault zone drilling experience on land [*Prevedel*, 2007]. Active interplate thrust fault drilling will probably share similar operational obstacles. Drilling costs increase logarithmically with depth but can be minimize with a 3-D VSP. Costs of a few days of deep drilling saved are in the range of costs for a massive 3-D VSP. Value added information will be maximum seismic resolution and resolution of active plate boundary structure approaching the scale of fossil plate boundary gouge zones examined on land. Gouge character, an inferred control of seismogenic behavior, is related to physical properties and fracturing that are acquired with the 3-D VSP.

[23] Modeling a proposed site off Costa Rica helps constrain rough costs/benefits analysis. It shows an optimum surface ship shooting grid and the plate boundary area it will illuminate with high-density data. In scientific ocean drilling, logging illuminates the volume of rock surrounding a core at decimeter scale. That local information is interpreted in the approximately kilometer-scale framework of plate boundary surface ship seismic images. Information from a 3-D VSP bridges this gap in scale with a 3–4 times improvement in resolution. The VSP does not eliminate a need for 3-D surface ship seismic surveys but compliments it with a narrower focus and greater resolution. At the modeled erosional Costa Rican margin site, coring the sediment apron would uncover a geologic history and show the underlying upper plate geology. That geology can be extended to the plate interface with 3-D VSP physical properties mapping and structural images. In addition to a map-scale geology, optimization of the drilling pathway

increases chances for success in reaching deep targets.

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