IDENTIFICATION OF LOW-MAGNITUDE SEISMIC DISTURBANCES USING REGIONAL OBSERVATIONS IN THE KARA/BARENTS SEA REGION

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ABSTRACT

Earthquakes have been identified successfully by demonstrating that the *P*-seismograms, observed at long range (>3000 km), are consistent with the radiation pattern expected from a double-couple moment tensor. However, for small seismic disturbances, the only signals available will be those recorded at local and regional distances (<3000 km). Seismograms recorded at regional distances are generally difficult to interpret as the propagation path through the heterogeneous crust and upper mantle results in complex signals. Thus, the radiation pattern can rarely, if ever, be inferred from regional observations. We have calculated mean *P* and *S* amplitude spectra by stacking the spectra at each element of the array at SPITS (Spitsbergen, Norway, distance 1270 km) using signals from the 16 August 1997 seismic disturbance in the Kara Sea (OT 02:10:59.7 UTC, 3.2mb, PDE). The spectra show clear signal-above-noise in the frequency range 2 to above 15 Hz. Assuming an ω-2 source spectrum, the spectra show a slower fall-off with frequency than that predicted by "shield" regional attenuation models for *Pn,* such as those determined by Sereno *et al.* (1988) for Scandinavia [who assume frequency-independent geometrical spreading, with Q*Pn(f) = 325 f 0.48*], and by Chun *et al.* (1989) for the Canadian Shield [who assume both attenuation and geometrical spreading are frequency dependent, with *Pn* amplitude decaying as Δ *-n*, where *n = 2.17 + 0.022 f*]. Thus, attenuation across the Barents Sea is much lower than for these models. We obtain a reasonable fit to the observed spectra, using frequency-independent *Q* values of $Q\alpha$ = 9000, and $Q\beta$ = 4000. We have also examined the spectra of *P* and *S* recorded at KEV (Kevo, Finland) from the 16 August disturbance and find that attenuation is also low for this path. *Pn* and *Sn* on the vertical, radial, and transverse components at SPITS, KEV and AMD (Amderma) show weak cross-component scattering. Thus, *P* and *S* propagate efficiently in the Kara/Barents Sea region, suggesting that the radiation pattern may be inferred for the 16 August 1997 disturbance. We apply a grid-search method to identify moment tensors that are consistent with the observed three-component seismograms at SPITS, KEV and AMD, and with the *P*-seismograms observed at the array stations HFS (Hagfors, Sweden) and NORES (Norway). We conclude that the observed relative *S*-amplitudes (*SV/SH*) and *P* first-motions (positive at HFS and NORES) are consistent with a double-couple moment tensor.

Key Words: regional *Pn* and *Sn* attenuation, Kara/Barents Sea Region, focal mechanisms

OBJECTIVE

To develop a discriminant for the Kara/Barents Sea region, based on the differences in P and S radiation patterns from earthquakes and explosions, to determine whether the 16 August 1997 3.3 m_b OT 02:11 UTC seismic disturbance can be positively identified as an earthquake.

RESEARCH ACCOMPLISHED

Introduction

At around 02:11 UTC on 16 August 1997 there was a small seismic disturbance (3.3 m_b) in the vicinity of the northernmost test site at Novaya Zemlya (NNZ). The epicentre of the disturbance (e.g., Israelsson *et al.* 1997) is in the Kara Sea, about 100 km from NNZ (Fig. 1), thus the disturbance is likely to have been an earthquake. However, initial reports in the press (e.g., Washington Times, 28 August 1997) suggested that the disturbance has 'explosion-like characteristics' that may indicate a Russian low-yield nuclear test at NNZ. Such reports of possible low-yield tests at NNZ are not uncommon (e.g., van der Vink and Wallace, 1996; Ryall *et al.*, 1996). Thus, it seems that identification with high confidence of small ($M_L < 4.0$) seismic disturbances in the vicinity of known nuclear test sites is an important issue in the context of monitoring compliance with the Comprehensive Nuclear-Test-Ban Treaty (CTBT).

Unfortunately, signals from small ($M_L < 4.0$) seismic disturbances are too weak to be detected at long range (teleseismic distances), so an alternative to common teleseismic discriminants, such as $m_b : M_s$, is required. This led to a major research effort, especially by the United States, directed at developing methods of identifying small seismic disturbances using seismograms recorded at regional distances where signals are typically detected from $M_L > 2.5$ disturbances at distances of up to 2000 km (see Blandford (1996) for a recent review).

Blandford (1996) concludes that S/P ratios at high frequencies ($f > 2$ Hz) are a promising discriminant (where S refers to the group of phases arriving at, and after, S_n). However, each regional phase needs to be corrected for path (distance Δ) and station effects before phase ratios can be applied as a discriminant. These corrections are usually a complicated function of frequency, predominantly due to heterogeneity in the crust and upper mantle. High-frequency signals are also desirable as decoupling factors (the muffling of an explosion by detonation in a large gas-filled cavity) are typically an order of magnitude lower at 20 Hz than at 1 Hz (e.g., Sykes, 1996).

Several authors have identified the 16 August 1997 disturbance as an earthquake using both the location and high-frequency S/P ratios measured from the vertical component (Richards and Kim, 1997, Hartse, 1998, Baumgardt, 1998). Bowers *et al.* (1998) also argue that the 16 August 1997 disturbance is an earthquake on the basis of high-frequency S/P ratios measured from three-component seismograms recorded at KEV (Kevo, Finland) and SPITS (Spitsbergen), and from a comparison of P_n waveforms recorded at NORSAR (southwest Norway) from an earthquake on 1 August 1986 in the Kara Sea (Marshall *et al.*, 1989), and a small explosion (4.2 m_b) on 26 August 1984 at NNZ. However, Ringdal and Kremenetskaya (1999) present evidence that the high-frequency S/P discriminant is unreliable in the Kara/Barents Sea region (although they only analyse S/P ratios from the vertical component) and thus claim that the 16 August 1997 disturbance cannot be identified using seismological observations.

Here, we take a different approach and show that, because P_n and S_n propagation is efficient within the Barents/Kara Sea region, the radiation pattern from the 16 August 1997 disturbance may be inferred. Thus, we can test if the seismograms observed at KEV, SPITS, HFS (Hagfors, Sweden) and NORES (Norway) are consistent with a double couple (earthquake) source.

Observations of P_n and S_n at SPITS and KEV

Fig. 2 shows the results of passing the seismogram recorded at SPA0, within the small-aperture SPITS array, from the 16 August 1997 disturbance, through a bank of bandpass filters. The signal-to-noise ratio remains reasonably constant with increasing frequency, suggesting that the spectral amplitude of the seismic noise at high frequencies is falling off at a similar rate to that of P_n. Also S_n is observed above the noise (P_n coda) at least up to frequencies of 14 Hz.

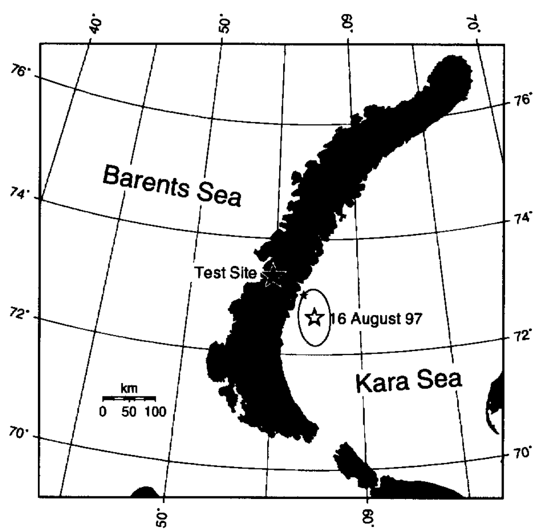

Figure 1: The preferred location of Israelsson *et al.* (1997) for the 16 August 1997 disturbance [72.645°N, 57.369°E]. This is about 50 km from a 4.3 m_b earthquake that occurred on 1 August 1986 (small star). The ellipse marks the 90% confidence interval, and suggests that the 16 August disturbance is located in the Kara Sea (water depth about 250 m), at least 60 km from the NNZ test site.

Fig. 2 also shows time windows containing P_n, S_n and noise samples. Since the amplitudes of P_n and S_n do not appear to vary significantly within each time window we follow Chael (1987) and assume that P_n and S_n are approximately stationary, and that at a distance of 1280 km P_g and S_g do not contribute significantly to P_n and S_n in the defined windows. We then calculate power spectra using a 5% Hanning tapered window of 1024 points (25.6 sec. duration) for each element of the array. We then follow Bache *et al.* (1985) and estimate the average normalised amplitude spectrum, by smoothing each power spectrum with a three-point moving average, calculating the mean of the power spectra, and taking the square-root. The resulting normalised amplitude spectra for P_n, S_n and noise samples are shown in Fig. 3.

The large signal-to-noise ratio of P_n above 5 Hz in Fig. 3 suggests that, (1) SPITS is a low noise site at high frequencies (this is consistent with noise spectra calculated by Anonymous (1995) for SPA0), and (2) there appears to be little attenuation of P_n from the Kara Sea to SPITS. We show the second point quantitatively in Fig. 3 by comparing the observed spectra with theoretical spectra calculated assuming the w-square earthquake source model and published estimates of P_n attenuation.

Fig. 3 shows the spectral decay above the corner frequency (assumed to be 4 Hz) predicted by the w-square source model, along with the spectral decay due to the source model and three attenuation models: (1) a constant Q_{P_n} (frequency-independent attenuation operator) of 9000 (Evernden *et al.*, 1986), (2) the frequency-dependent attenuation operator $Q_{P_n}(f) = 325f^{0.48}$ obtained by inversion of P_n spectra recorded in Scandinavia by Sereno *et al.* (1988), and (3) the spectral decay of P_n due to the combined effects of frequency-dependent attenuation and geometrical spreading ($\Delta^{-(2.17+0.022f)}$) determined by Chun *et al.* (1989) for the Canadian shield.

The spectra in Fig. 3 suggest that P_n attenuation along the path from the 16 August 1997 epicentre in the Kara Sea to SPITS is effectively negligible – a remarkable observation given the epicentral distance of 1280 km. Fig. 3 shows the observed S_n spectral decay along with the w-square model, and a constant Q_{S_n} of 4000. Baumgardt (1998) claims that there is strong S_n attenuation along the path from the Kara

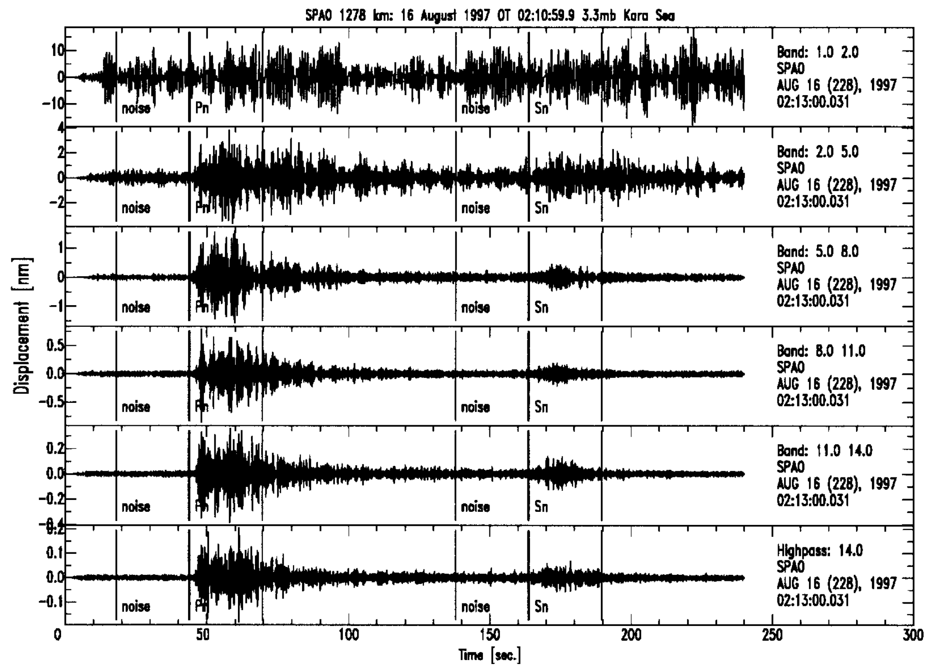

Figure 2: Bandpass filtered seismograms recorded at SPA0 from the 16 August 1997 disturbance. The response of the Guralp CMG3ES seismograph has been deconvolved to give estimates of the vertical component of ground displacement (within the passband of each 5-pole Butterworth filter)

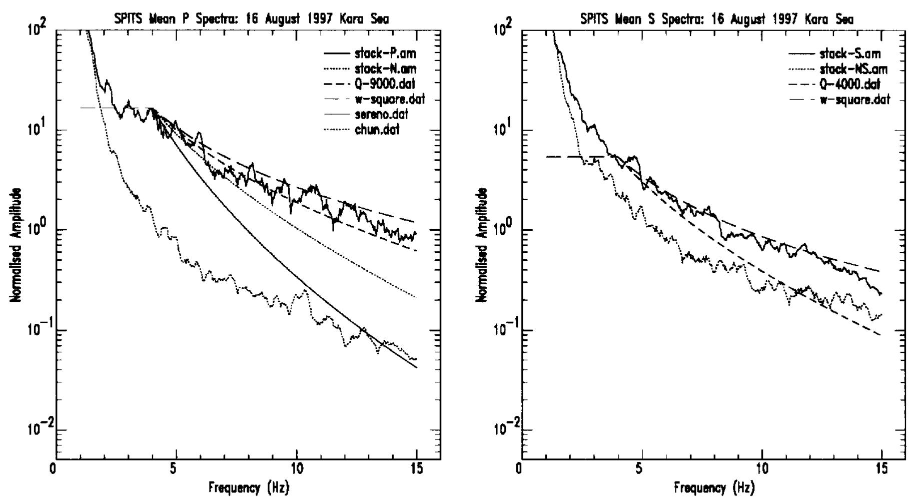

Figure 3: P_n, S_n and noise spectra calculated for the SPITS array, compared with attenuation models discussed in the text.

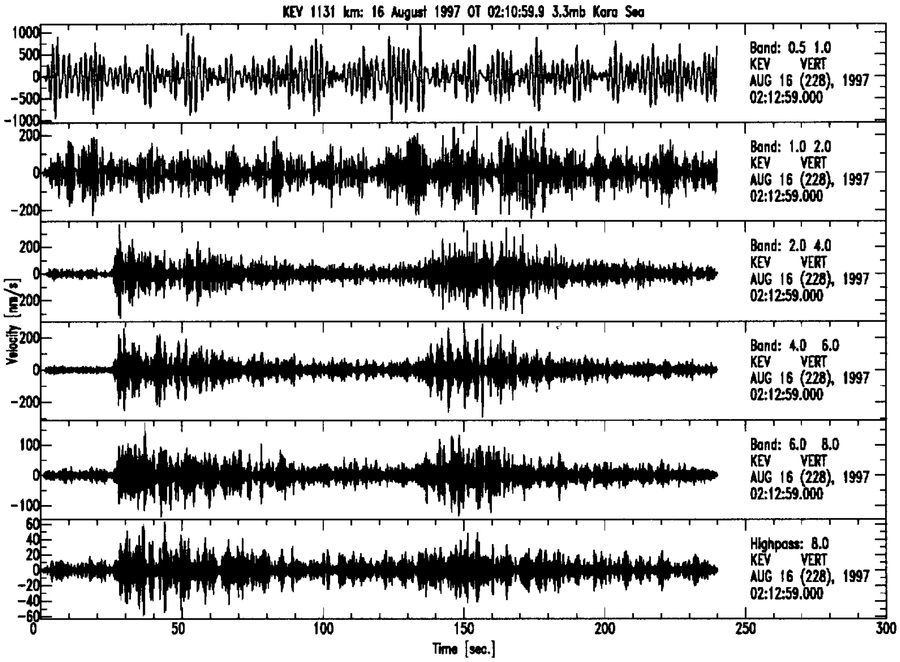

Figure 4: Bandpass filtered seismograms recorded at KEV from the 16 August 1997 disturbance.

Sea to SPITS. However, the spectra in Fig. 3 suggest weak attenuation of S_n with $Q_{S_n} > 4000$.

Fig. 4 shows the results of passing the vertical-component seismogram recorded at KEV (Δ = 1130 km) through a bank of bandpass filters. While the Nyquist frequency is at 10 Hz, there is still significant P_n and S_n energy in the above 8 Hz passband, indicating weak P_n and S_n attenuation along the path from the Kara Sea to KEV.

Free-Surface Corrected Three-Component Seismograms at SPITS and KEV

We correct the three-component seismograms recorded at KEV and SPB4 (within the SPITS array) for the effect of the free surface in order to recover estimates of P, SV and SH at the receiver. Kim *et al.* (1997) give expressions to derive P, SV and SH from the vertical, radial and transverse components. These require the P and S angles of emergence and the ratio of the S and P wave speeds (β/α).

The frequency-wavenumber spectra for P_n and S_n at the SPITS array (between 2.5 and 3.5 Hz), calculated using the high resolution method of Capon (1969), suggest a P_n slowness of 0.13 s km^{-1}, and an S_n slowness of 0.18 s km^{-1}. The amplitude of S_n at SPB4 is weak on the vertical component compared with the radial, implying a small S_n angle of emergence. Thus, S/P ratios measured from the vertical component at SPITS will be much lower than S/P from the free-surface corrected three-component seismograms at SPB4. The relative amplitude of S_n on the vertical and radial components at SPB4, and the observed S_n slowness at SPITS, suggest low wave-speeds within the surface layer. We assume $\alpha = 2.5$ km s^{-1} and $\beta = 1.2$ km s^{-1}; this gives estimates of the P_n and S_n emergent angles of 19° and 12° respectively.

At KEV we cannot measure the P_n and S_n slownesses directly, so we apply the approximate free-surface corrections for P_n and S_n derived by Kennett (1991). We use the P_n-slowness to calculate the free-surface corrections for the portion of the seismograms with group velocities greater than 5.0 km s^{-1}, and the S_n-slowness for the corrections to the remaining portion of the seismograms.

Figures 5 and 6 show the complex envelopes of the resulting free-surface corrected seismograms. At

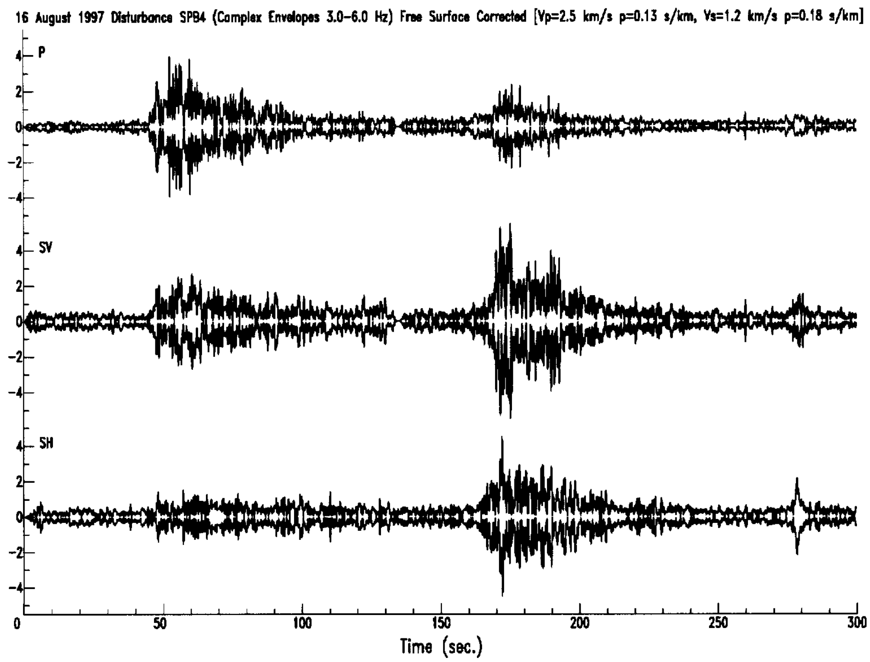

Figure 5: Complex envelopes of free-surface corrected three-component seismograms recorded at SPB4

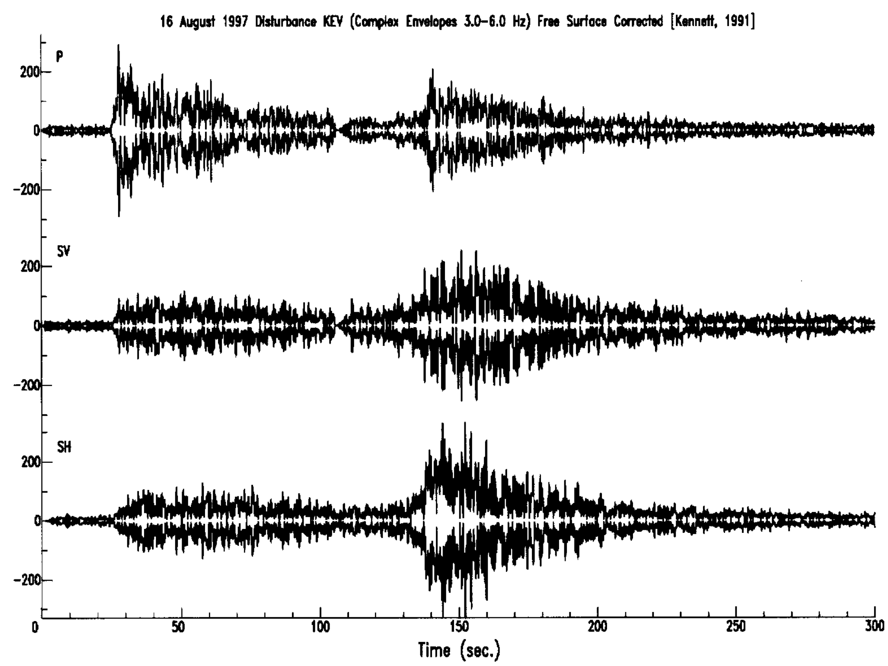

Figure 6: Complex envelopes of free-surface corrected three-component seismograms recorded at KEV.

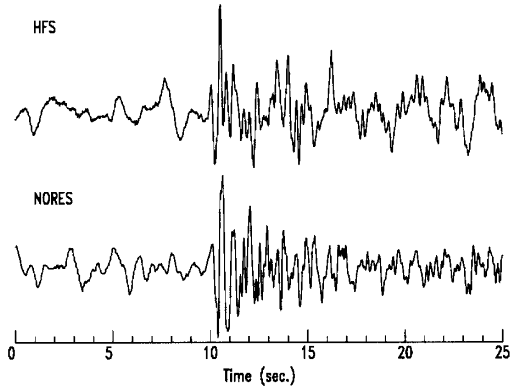

Figure 7: Beamformed P-seismograms recorded at HFS and NORES showing clear positive first-motion (P-onset is at 10 sec.).

about the P_n arrival time there is little P-energy on the SV and SH components. This indicates that cross-component scattering along the paths to SPB4 and KEV is weak, which combined with the weak attenuation demonstrated above, shows that P_n and S_n propagation is efficient in the Kara/Barents Sea region. Thus, we conclude that the relative amplitudes of the SV and SH complex envelopes relate to S-radiated by the 16 August 1997 disturbance, and so can be used to infer the source radiation pattern.

Inversion for the Focal Mechanism

We test if there is an orientation of the double-couple (earthquake) source that is consistent with the observations, and thus determine if the data from the 16 August disturbance are consistent with an earthquake given reasonable assumptions about the source structure.

We measure the maximum amplitude of the complex envelopes in Figures 5 and 6 to estimate the relative amplitudes of SV/SH at SPB4 and KEV (Schwartz, 1995). We also measure the amplitude of P at HFS and NORES (Fig. 7), and note that there are no arrivals with amplitude greater than P, thus we conclude that the pP and sP amplitude at the station is smaller than P. The first-motion of P at HFS and NORES is positive (compressional).

Table 1 gives the amplitude bounds we have placed on our measured amplitudes to account for uncertainties in our measurements (Pearce, 1977). We calculate frequency-wavenumber spectra for P_n at HFS and NORES, and estimate the slownesses as 0.09 s km^{-1} and 0.08 s km^{-1} respectively. We calculate the take-off angles of P and S, using our estimated slownesses, assuming a Poisson source layer with

	Slowness (s km^{-1})		Pol.	Min.	Max.	Pol.	Min.	Max.	Pol.	Min.	Max.
	P_n	S_n		P			pP			sP	
HFS	0.09		+	8.0	10.0	U	0.0	8.0	U	0.0	8.0
NORES	0.08		+	8.0	10.0	U	0.0	8.0	U	0.0	8.0
				SV			SH				
SPB4	0.13	0.18	U	4.4	5.2	U	3.5	4.3			
KEV	0.11	0.22	U	3.2	4.0	U	4.4	5.2			

Table 1: The relative amplitude bounds of the SV, SH, P, pP, and sP phases. The polarity of each phase is: + compression, U unknown. The take-off angle is calculated using the slowness assuming a Poisson source layer with a P-wave speed of 6.5 km s^{-1}.

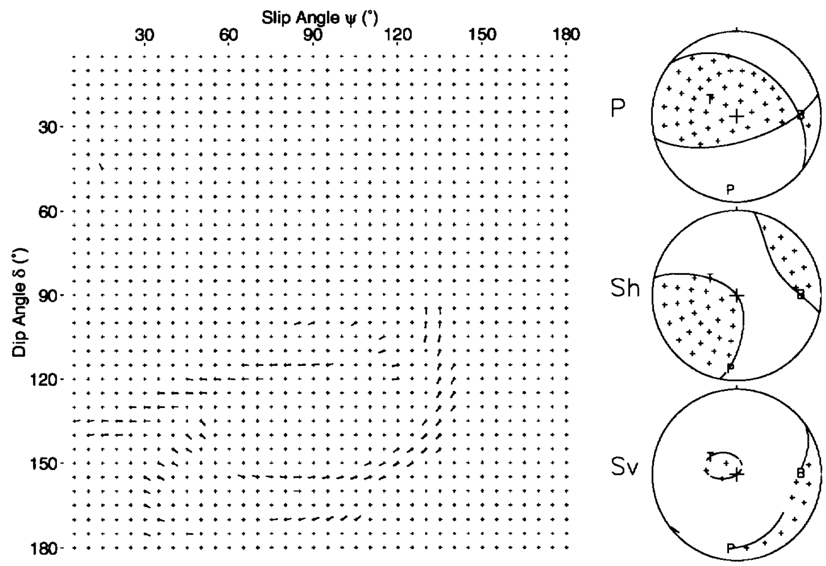

Figure 8: [left] Vectorplot of Pearce (1977) showing the orientation (σ strike measured clockwise from north, δ dip angle, ψ slip angle) of double couples that are consistent with the SV, SH, P, pP and sP bounds in Table 1. [right] Lower hemisphere focal plots showing the P, SV and SH nodal planes of our preferred focal mechanism ($\sigma = 255°$, $\delta = 115°$, $\psi = 120°$).

$\alpha = 6.5$ km s^{-1} (Table 1). While these take-off angles are reasonable for a source located in the middle of a continental-type crust, we acknowledge there is probably large uncertainty in these values. We then grid-search for orientations of the double couple that are consistent with the amplitude bounds in Table 1, using increments of 5° in strike (σ), dip (δ) and slip (ψ), calculating SV/SH, pP/P and sP/P amplitude ratios at each grid-point. This procedure is a modification of the relative amplitude method of Pearce (1977, 1980).

Fig. 8 shows the orientations of a double couple that are consistent with the amplitude bounds in Table 1 plotted on a vectorplot (Pearce, 1977) ($\delta > 90°$ indicates reverse-type faulting). The vectorplot allows the whole range of consistent solutions to be displayed, and shows both the fault and auxiliary planes of the double couple (the two are indistinguishable as we assumed a point source when calculating the P, SV and SH radiation patterns).

Consideration of the P, SV and SH radiation coefficients of the solutions in Fig. 8 suggests that a reasonable fit to the observed relative amplitudes is obtained with $\sigma = 255°$, $\delta = 115°$, $\psi = 120°$ (Fig. 8). This solution is similar to that determined by Marshall *et al.* (1989) for the 1 August 1986 Kara Sea earthquake (their model II solution is $\sigma = 253°$, $\delta = 130°$, $\psi = 147°$). Also, the P-radiation coefficient for our preferred focal mechanism is 0.04 to NRI (Norilsk, Russia, $\Delta = 1180$ km, Az. = 95°), suggesting that the emergent P_n, with poor signal-to-noise ratio, reported for this station (Baumgardt, 1998) can be explained by weak P-radiation, rather than by poor P_n propagation across the Kara Sea. The P-radiation coefficients to HFS and NORES are 0.65 and 0.74 respectively, perhaps explaining why clear P_n signals are observed at these far-regional stations from the 16 August 1997 disturbance.

CONCLUSIONS AND RECOMMENDATIONS

Our analysis of high-frequency three-component P_n and S_n at SPITS and KEV, from the 16 August 1997 disturbance, shows that P_n and S_n propagation across the Kara/Barents Sea is efficient. A comparison of S_n amplitudes on the vertical and radial components at SPB4, suggests that the S_n emergent angle is small. Thus, S/P ratios measured from the vertical component at SPITS will be smaller (more explosion-like) than S/P measured from free-surface corrected three-component seismograms. We have calculated the complex envelopes of free-surface corrected three-component seismograms at SPB4 and KEV to estimate P, SV and SH at each station. We use the maximum amplitude of the complex envelopes of SV and SH at SPB4 and KEV, along with P_n at HFS and NORES, to determine a range of focal mechanisms (double couples) that are consistent with the observed relative amplitudes of SV/SH, pP/P and sP/P. After consideration of the radiation coefficients of P, SV and SH our preferred solution ($\sigma = 255°$, $\delta = 115°$, $\psi = 120°$) is similar to that determined by Marshall *et al.* (1989) for the 1 August 1986 Kara Sea earthquake. The P-radiation coefficient to NRI is 0.04, suggesting that the reported emergent nature of P_n at NRI from the 16 August 1997 disturbance can be explained by weak P-radiation to this station, rather than by poor P_n propagation across the Kara Sea.

Digital three-component data exists for AMD (e.g., Ringdal and Kremenetskaya, 1999), but has yet to be released. We eagerly await the release of these data, in order to refine the focal mechanism determined above, and to verify that the corner frequency of 4 Hz, assumed to determine the attenuation at SPITS, is reasonable.

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