Attenuating the ice flexural wave on arctic seismic data

David C. Henley

ABSTRACT

The frozen surface encountered in arctic seismic exploration, while providing consistent coupling for sources and receivers, also contributes to one of the strongest known source-generated coherent noises. This noise, the ice flexural wave, originates in uniform plates of ice floating on liquid water, a situation commonly associated with both river channels and offshore sea ice. The flexural wave is both strong and often highly dispersed, the high frequency energy travelling at much higher velocity than that at low frequency. Because of its strength and dispersion, the flexural wave is difficult to attenuate with standard coherent noise methods. We demonstrate attenuation of this noise in the radial trace (R-T) domain, which provides a convenient framework for separation of dispersed linear noise from reflections. Using a set of field seismic data from Hansen Harbour in the MacKenzie Delta, we show significant attenuation of the ice flexural wave, in spite of the fact that the noise is substantially spatially aliased.

INTRODUCTION: THE PROBLEM

Generating the ice wave

The arctic environment is one of the more challenging in which to conduct seismic exploration because of the difficult near-surface conditions encountered there. Much exploration activity is carried out in winter, when the surface is frozen and provides consistent coupling conditions for sources and receivers. Winter also leads to ice sheets of relatively uniform thickness covering river channels, ponds, and sheltered near-shore areas of sea. Because these ice sheets usually float on a layer of liquid water, seismic energy injected into the ice is not efficiently radiated from the ice through the water and into the firmer sediments beneath. Instead, much of the energy is trapped within the ice as flexural waves, consisting of combined P-SV modes internally reflecting from both the top and bottom of the ice sheet (Ewing et al., 1957). Since they are trapped in the ice layer, the ice wave modes attenuate with the reciprocal of the distance from the source, thus often overwhelming any reflection energy, which attenuates as the inverse square of the distance from the source. Furthermore, the ice flexural modes can be very highly dispersed, with high frequencies propagating at high velocities and low frequencies at low velocities, depending upon the source spectrum and the thickness of the ice relative to the source wavelengths.

The type and placement of the source greatly affects the generation of ice flexural waves. As might be expected, a source placed on the surface of the ice or inside the ice layer itself radiates most of its energy as coherent noise, while a source within the water beneath the ice, or better yet, buried beneath the water bottom, is much more efficient at radiating useful elastic energy downward into the earth layers to be imaged. In spite of this, logistics and other considerations sometimes dictate the use of a surface source. Because only near-vertical particle motion is transmitted through the ice layer and the water into the earth layers beneath, the surface source of choice is usually a vertical component vibrator. In this case, the ice flexural modes generated will be basically grazing-incidence P-SV modes whose velocity ranges from less than air blast velocity at the lowest frequencies to ice compressional wave velocity at the highest frequencies.

Attenuating the ice wave

Of all the coherent noise modes encountered in seismic data acquisition, the ice flexural modes are among the most difficult to attenuate adequately for several reasons: (1) The velocity contrast between floating ice and both the air above and the water beneath is so large that the ice flexural modes are very easily excited and quite large in amplitude. In many cases, the amplitudes of the ice modes are so great that they overwhelm any reflection signal, due to limited dynamic range in the acquisition system. This means that even if the coherent noise can be attenuated by some means, there may be no significant underlying reflection energy to be recovered. (2) Seismic acquisition parameters, including station spacing, are usually optimised for properly recording reflection energy; so coherent noises, like the flexural wave, are often badly aliased spatially. (3) The large dispersion often displayed by ice modes means that it is difficult, if not impossible, to construct an f-k filter that will attenuate noise while leaving reflection energy untouched. The range of velocities spanned by the various frequency components of the ice modes usually overlaps and includes much of the range occupied by various reflection events. The challenge for geophysicists is to determine strategies for both acquisition and processing that allow the ice wave to be properly recorded and subsequently removed from seismic records. The only choice that can affect condition number (1) above is to relocate the source, removing it from proximity to the ice layer; but conditions (2) and (3) can be addressed with less drastic solutions.

SOLUTIONS

An example

In 2001, experimental seismic data were acquired in the Hansen Harbour area of the MacKenzie Delta (Hall et al., 2001). As part of the experiment, CREWES positioned a short experimental line of 50 3-C geophones for which both dynamite and vibroseis were used as sources. The geophone line was positioned so that it crossed the shoreline of the Beaufort Sea, with roughly half of the phones planted on either floating or shore-fast ice, the other half on land. Station spacing was 15 m with single phones. The survey was conducted by initiating the source at regular intervals into the fixed 50 station geophone spread. The source positions began at a large positive source-receiver offset from the first geophone station, progressed toward the end of the spread, continued through it, and ended at a large negative offset from the last geophone station. We focus here only on the Vibroseis data, specifically on the vertical component recorded by the 3-C phones, since we expect these data to be most affected by the strong ice flexural wave.

As would be expected, when the source vibrator was positioned on the floating sea ice, it generated ice waves copiously. The geophones, which were also on the floating ice, recorded the ice wave almost exclusively. Those on land saw no ice wave, since the wave reflects from the impedance contrast at the shoreline and is not supported in the frozen near-surface land on which half the geophone spread is planted. Since most of the source energy is trapped in the ice, little or no reflection energy is seen on those shot gathers whose source position is on the floating ice, even at the receivers planted on land. When the source position is on land, however, the corresponding gathers show good reflection signal, not only on the landward geophones, but on those placed on the floating ice, as well. Figure 1 shows an example of a shot gather with the source on the floating ice near the beginning of the geophone spread. The traces are scaled such that relative trace amplitudes are preserved, showing that the ice wave on the left half of the spread is much stronger than anything recorded on the land-fast half of the spread. The same shot gather, with trace amplitudes normalized, is shown in Figure 2. A few reflection fragments can now be observed, but only on the land-fast half of the spread. Figure 3 is an example of a shot gather where the shot is positioned just off the landward end of the spread. On this gather, reflections can be seen not only on the landward traces, but also on those recorded on the sea ice, although there they are more obscured by noise. Furthermore, no ice wave is generated when the source is on land.

Another observation pertaining to the gather shown in Figures 1 and 2 is that the ice wave is aliased at most frequencies, due to the relatively coarse station spacing. The aliasing increases the difficulty for any multi-trace noise attenuation scheme and highlights the importance of choosing acquisition parameters not only to properly sample the desired reflections, but also the coherent noise wavefield. Because of the wide range of velocities and frequencies encompassed by typical ice wave noise, station spacing as small as 5 m might be required.

An attractive domain

Attenuation of coherent noise generally begins with separation of the noise from desired signal, using frequency, velocity, or some other discriminating physical characteristic. The flexural wavefronts overlap those of the reflections in the X-T domain, and its velocities overlap reflection velocities in the F-K domain, leading to difficulty in separating this noise in either the X-T or F-K domains. The radial trace (R-T) domain, however, because it samples energy along trajectories with specific origins and velocities, is an appropriate one for efficiently capturing the ice wave and hence separating it from other parts of the wavefield. Figure 4 shows the shot gather of Figure 1 overlaid with a set of R-T sample trajectories whose origin is the shot position. Note that because of the dispersion of the ice wave, each R-T trajectory overlies a single frequency component (or narrow frequency band) of the ice wave. Due to severe spatial aliasing, however, the apparent frequency is nearly the same for each radial trace component. Figure 5 shows the R-T transform of the gather in Figure 4; the narrow-band ice wave components on the radial traces are the most obvious feature on the gather. Figure 6 is the spectrum of a single radial trace whose position is flagged by a red line on Figure 5; the spectral peaks due to the ice wave noise are conspicuous. In the R-F domain (radial frequency), the ice wave is distinguished by its monochromatic frequencies. This means that attenuation of the ice wave can be accomplished by shaping the spectrum to attenuate the ice wave components in the R-F domain.

Attenuation techniques

There are several possibilities for attenuating ice wave energy that has been concentrated into spectral peaks in the R-F domain. One of these is to apply spectral whitening deconvolution to raise the level of the broad signal spectrum relative to the ice wave spectral peaks. Another approach is to apply a narrow bandpass filter centred on each ice wave spectral peak, in order to isolate and model each component of the ice wave for subtraction from the original gather. Yet another approach is embodied in the non-linear procedure called “spectral clipping” (Henley, 2000). In this operation, a smooth median spectrum is computed from each raw trace spectrum. For each raw spectral amplitude that differs from the median by more than a threshold amount, the value itself and a symmetric window of neighbouring spectral amplitudes are set to the median spectral value, thus “clipping” off the spectral peak (or valley) representing the ice wave component. In what follows, we illustrate the whitening deconvolution technique as well as the spectral clipping method.

RESULTS

Spectral clipping

The spectral clipping technique was developed to attenuate noise on seismic traces that is characterised by very narrow bandwidth (monochromatic). While techniques such as notch filtering can be effective against this type of noise, they are often accompanied by undesirable filter artefacts; and the frequency characteristics of the noise must be known very precisely in order to specify the filter. Spectral clipping, on the other hand, requires no prior knowledge of the noise, except that it is monochromatic and of high amplitude. In general, the stronger the noise, the more reliably spectral clipping operates, since it attempts to detect abnormal spectral amplitudes against the background of a “normal” spectrum. Figures 7-10 show schematically how spectral clipping works. In Figure 7, a signal with very strong additive monochromatic noise is transformed to the frequency domain. Next, in Figure 8, a moving median window is used to smooth the raw input spectrum to provide a baseline. Then, raw spectral amplitude values which lie more than a specified amount above or below the median spectrum baseline are flagged. Finally, in Figure 9, the flagged spectral values as well as a few neighbouring values (in the “wings” of the spectral peak or notch) are replaced with the corresponding median spectral values, thus “clipping” off any deep notches or large peaks in the spectrum. The phase of the spectrum is unaltered by the clipping operation. The edited trace spectrum is transformed back to the time domain in Figure 10. Only three parameters are involved in spectral clipping: the length of the median smoothing window in spectral samples; the threshold value in dB for allowed deviations from the spectral median; and the width in spectral samples of peaks or valleys to be clipped. Of these parameters, the most critical is the threshold level for clipping. In general, a value of 12 dB leaves the essential spectral features of the seismic reflection information unaltered, so monochromatic noise that is more than 12 dB above the rms signal level is easily attenuated. Lower levels of noise are more difficult to attenuate with this method, because the threshold parameter and median smoothing length have to be carefully adjusted to preserve seismic character while still allowing clipping of the noise. If the threshold needs to be as small as 6 dB, some degradation of the seismic reflection character is inevitable.

The spectrally clipped radial trace spectrum of Figure 6 is displayed in Figure 11, while the filtered R-T transform from which it was extracted is shown in Figure 12. The resulting filtered X-T domain shot gather appears in Figure 13. While some ice wave energy is still visible, it has been greatly attenuated relative to Figure 1. Weak fragments of reflections can now be found in some parts of the gather.

The deconvolution approach

While spectral clipping works very well on very strong monochromatic noise, it may be less effective on noise characterised by less spectral purity (broader band) or lower amplitude relative to the background energy. A fruitful way to approach this type of noise is to use a spectral whitening deconvolution approach, wherein we apply an operator which attempts to whiten or equalize the spectrum, damping out large spectral amplitude deviations. A type of deconvolution particularly suited for this is one which uses spectral division as a means of applying the whitening. We have chosen Gabor deconvolution (Margrave et al., 2001) to test this concept, since it uses spectral division and is also time-varying. The latter characteristic may be useful, since the amplitude of the ice wave, a surface noise, increases relative to underlying reflection amplitudes as a function of time.

As before, we first transformed the shot gather into the R-T domain, in order to collapse the dispersed ice wave energy into narrow frequency bands on each radial trace. The current Gabor deconvolution algorithm includes several options which can be helpful for the present application. One of the more obvious is to use the Burg spectrum rather than the Fourier spectrum for estimating the “wavelet” to be removed from the data. The reason for this is that the Burg algorithm is a better estimator than the Fourier algorithm for spectra which contain monochromatic components or spikes. Hence, if the Burg wavelet spectrum includes the ice wave components, they will be effectively removed from the data. Indeed, Figure 14 shows the result of applying Gabor whitening deconvolution, using the Burg algorithm, in the R-T domain before transforming back to the X-T domain. Once again, as in Figure 13, the ice wave noise has been significantly attenuated, leaving fragmentary reflection-like events.

Gabor deconvolution was applied to the raw X-T domain shot gather to see whether simply whitening the shot in a conventional way would provide enough noise attenuation. The results in Figure 15 indicate, in spite of the AGC “shadow” above the residual ice noise, that deconvolution in the X-T domain is somewhat more effective for ice wave attenuation in this domain than in the R-T domain. Applying Gabor decon in both the R-T and X-T domains, however, is more effective than either operation separately, as illustrated in Figure 16. Most effective of all, however, judging from Figure 17, is spectral clipping in the R-T domain followed by Gabor decon in the X-T domain.

In order to show the effectiveness of this ice wave attenuation procedure, Figure 18 shows the entire Hansen Harbour vertical component vibroseis line stacked, with no pre-stack noise attenuation or statics. The presence of the ice wave is obvious, as is the paucity of recognizable reflection events on the left half of the line (under the floating ice). Figure 19, however, shows the stack of shot gathers which have been filtered in the R-T domain using spectral clipping, followed by X-T domain Gabor deconvolution. While the left half of the image is poorer than the right half, the obvious interference of the noise has been removed, and several reflections are now visible.

CONCLUSIONS

One of the more troublesome coherent noises generated by a seismic source is the group of modes known collectively as the ice wave or ice flexural wave. Many attempts have been made to attenuate the noise or to prevent its generation or propagation even including sawing slots in the ice perpendicular to the seismic line to break up the continuity of the waveguide (Proubasta, 1985). The most successful attenuation methods take advantage of the well-known characteristics of the wave, particularly its large dispersion. No matter what method is applied, success is likely to be most assured when the acquisition parameters ensure that the wave is recorded with no spatial aliasing. This generally means single phones, spaced no further than 5 metres apart on the surface.

The radial trace (R-T) transform is useful when attenuating the ice wave, because it captures the dispersion, allowing an efficient representation of the noise in the R-F domain. Since each trajectory of the R-T transform tends to capture a single frequency component of the ice wave, the corresponding representation in the R-F domain consists of narrow, large amplitude peaks superimposed upon the broadband spectrum of the underlying seismic reflection events. We have illustrated two frequency domain techniques which are effective in attenuating the ice wave, based on its R-F representation. While spectral clipping is the simplest technique and can handle the highest amplitude noise, spectral whitening deconvolution, as embodied in the Gabor deconvolution algorithm, can be similarly effective for lower levels of noise or noise which is spatially aliased or not as monochromatic in the R-F domain.

No matter how effective the attenuation of the ice wave, however, if the noise is large enough in amplitude, the dynamic range of the acquisition system will be insufficient to successfully record reflections. Hence, in the example shown here, strong reflections can be recovered from beneath the ice wave noise, but smaller reflections are overwhelmed by the noise during acquisition and cannot therefore be recovered.

THE FUTURE

In all likelihood, exploration will continue and even increase in the arctic. When surface sources are used on floating ice, as is often the case, it is inevitable that copious amounts of ice wave noise will be generated. Hopefully, those designing exploration programs of the future will note that the most effective attenuation of the ice wave requires adequate spatial sampling of it and will adjust station spacing to accommodate sampling issues, at least when receivers themselves are on the floating ice.

REFERENCES

Ewing, W.M., Jardetzky, W.W., and Press, F., 1957, Elastic waves in layered media, McGraw-Hill, pp281-327.

Hall, K.W., Nieto, C.E., Gallant, E.V., and Stewart, R.R., 2001, Multicomponent seismic survey over ground-fast and floating ice, MacKenzie Delta, N.W.T., CREWES 2001 Research Report Volume 13, pp 29-45.

Henley, D.C., 2001, Spectral clipping: a ProMAX module for attenuating strong monochromatic noise, CREWES 2001 Research Report Volume 13, pp 311-320.

Margrave, G.F. and Lamoureux, M.P., 2001, Gabor deconvolution, CREWES 2001 Research Report Volume 13, pp 241-276.

Proubasta, D., 1985, Ice Saw—an incisive solution to seismic noise, The Leading Edge, Volume 4, Number 10, Oct. 1985, pp 18-82.

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FIGURES

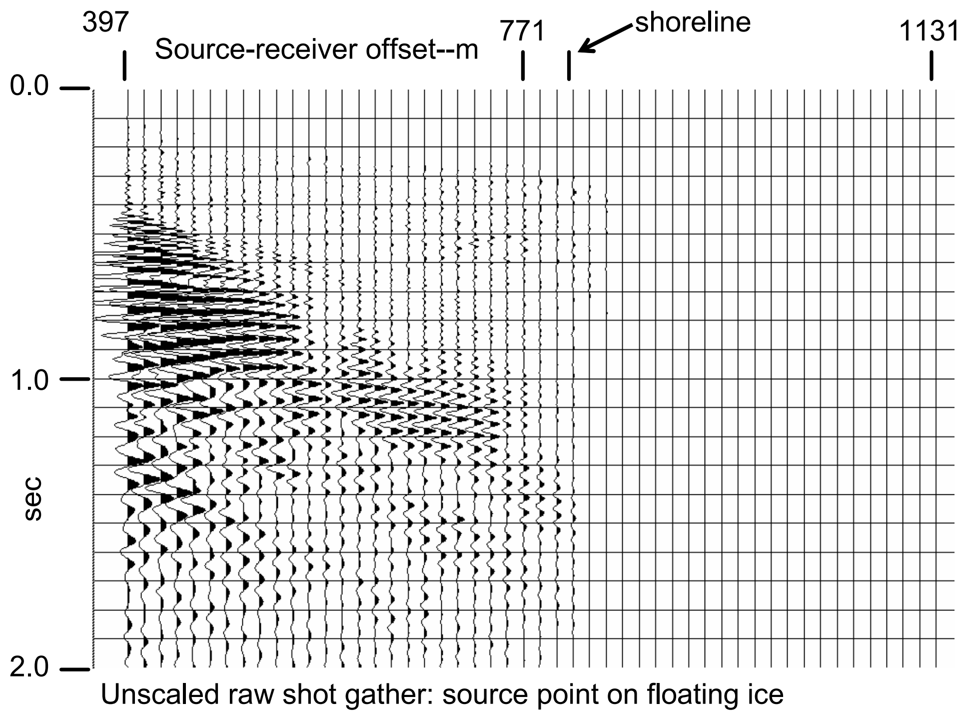


FIG. 1. Typical ice flexural noise generated by a surface source positioned on floating ice. The strength of the noise is evident, since no legitimate reflection energy can be seen on this unscaled shot gather.

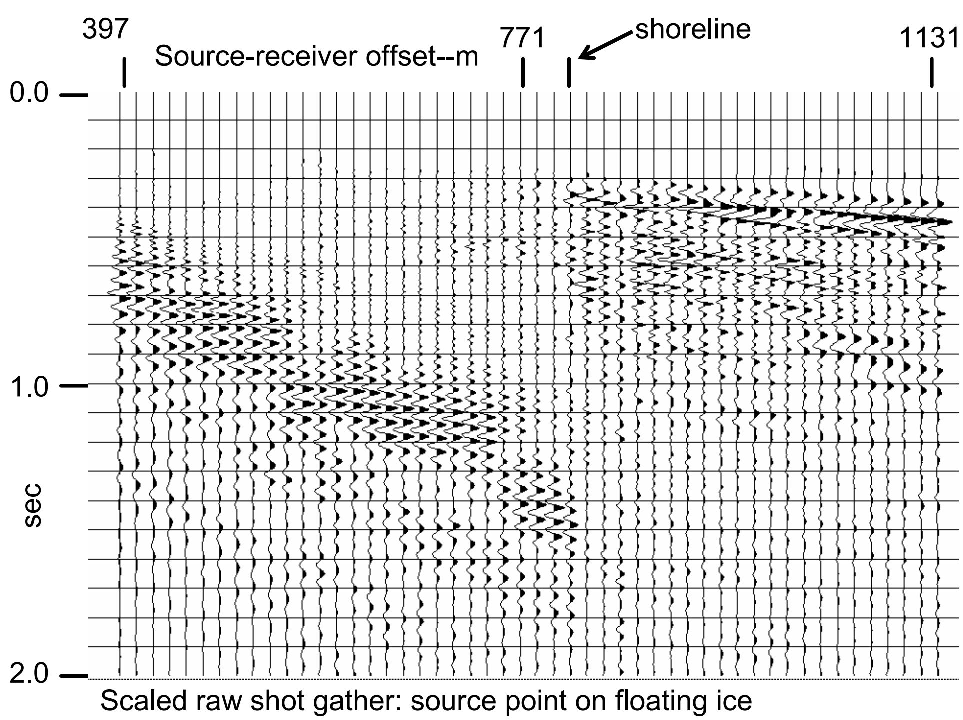


FIG. 2. Shot gather of Figure 1 after normalizing the traces. Legitimate seismic events can now be seen on those stations positioned on solid land. Stations positioned on floating ice are still dominated by the flexural noise.

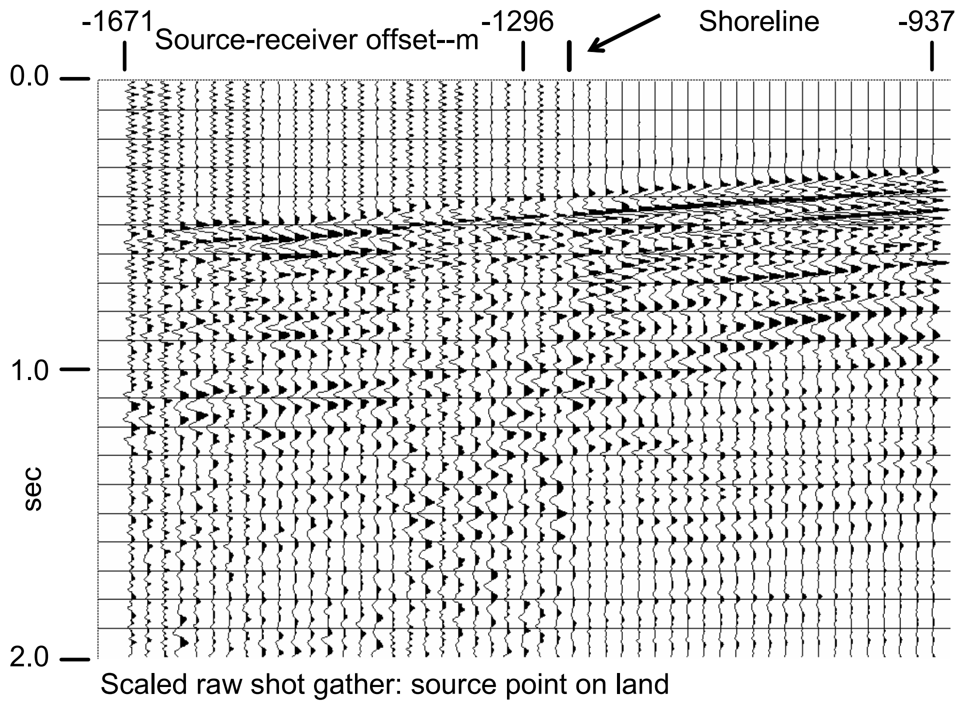


FIG. 3. Shot gather for shot positioned off the shoreward end of the receiver line. Legitimate seismic events can be seen on all stations, including those on the floating ice.

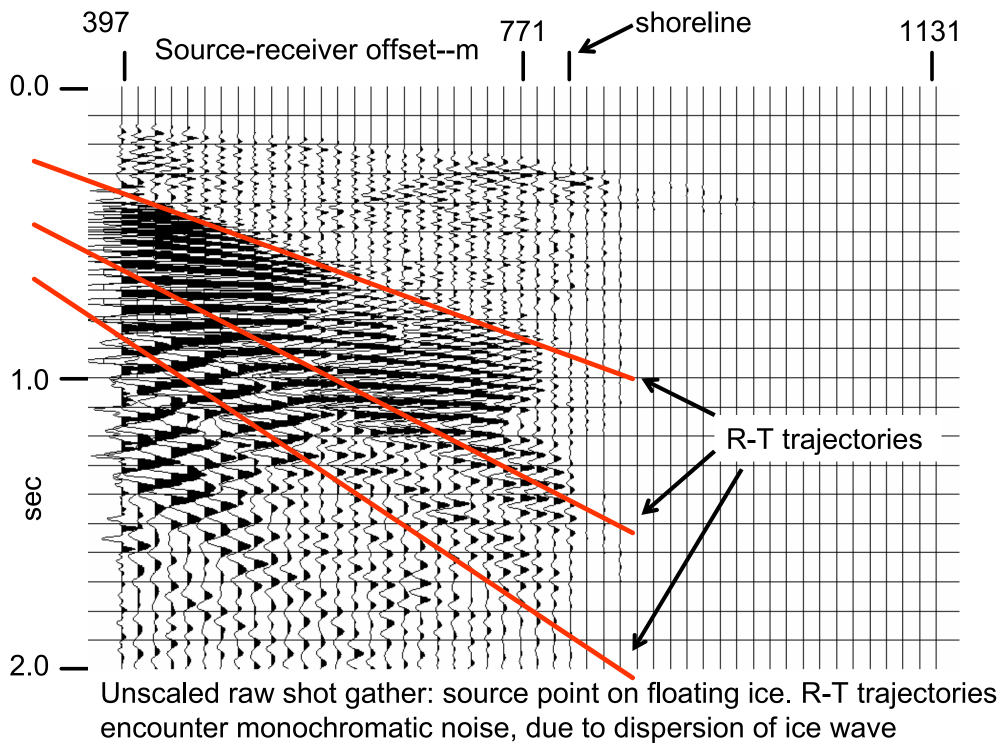


FIG. 4. Illustration showing why the radial trace (R-T) domain is an attractive one in which to attack the ice flexural wave. R-T trajectories sample the noise along paths of constant frequency, due to dispersion.

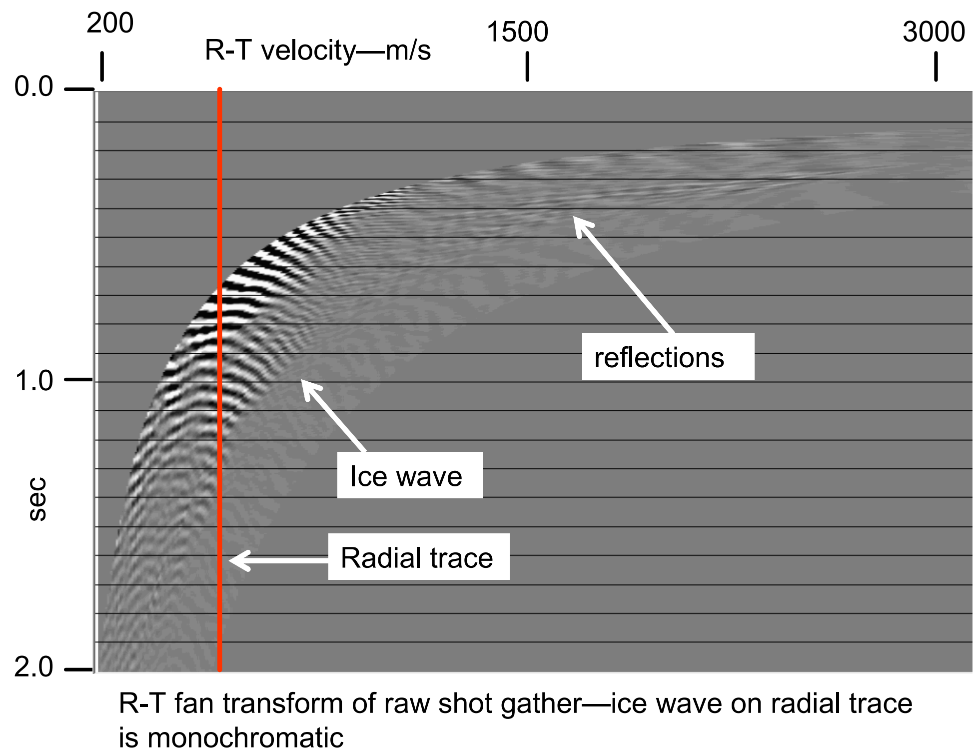


FIG. 5. Shot gather in the R-T domain. The ice wave noise is the strongest energy in the gather. Note the constant frequency of the noise along the radial trace axis (red).

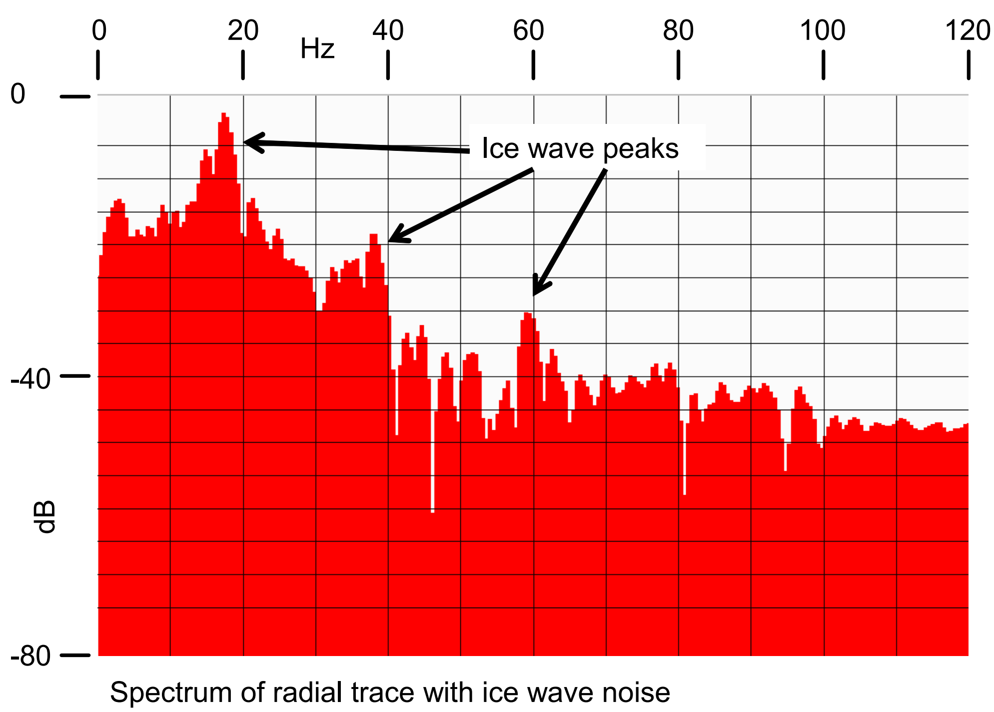


FIG. 6. The power spectrum of a radial trace at the position shown in Figure 5. Note the prominent spectral spikes just below 20, 40, and 60 Hz, all manifestations of the ice flexural wave.

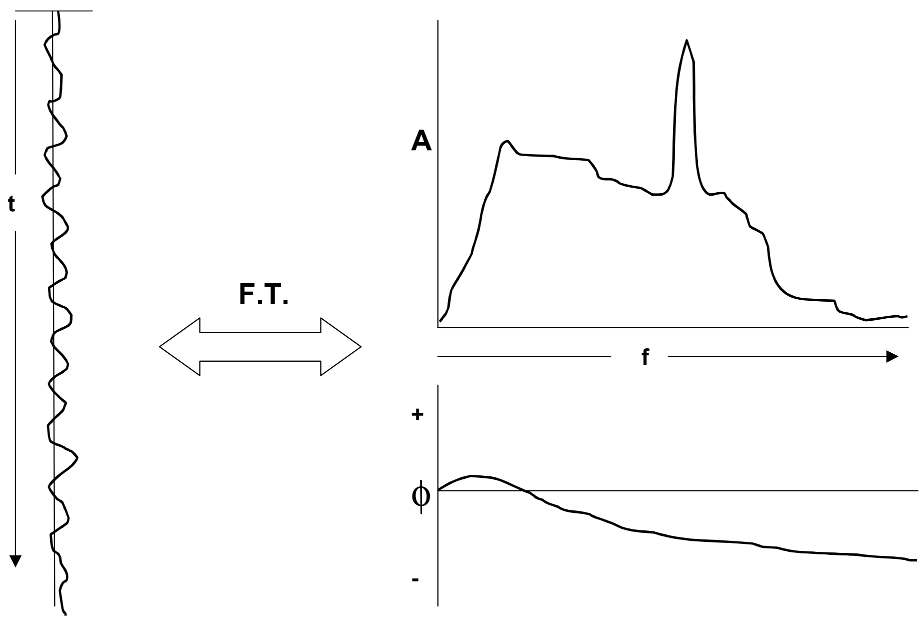


FIG. 7. Schematic showing the relation between a seismic trace contaminated with a strong monochromatic noise (left) and its amplitude and phase via the Fourier Transform.

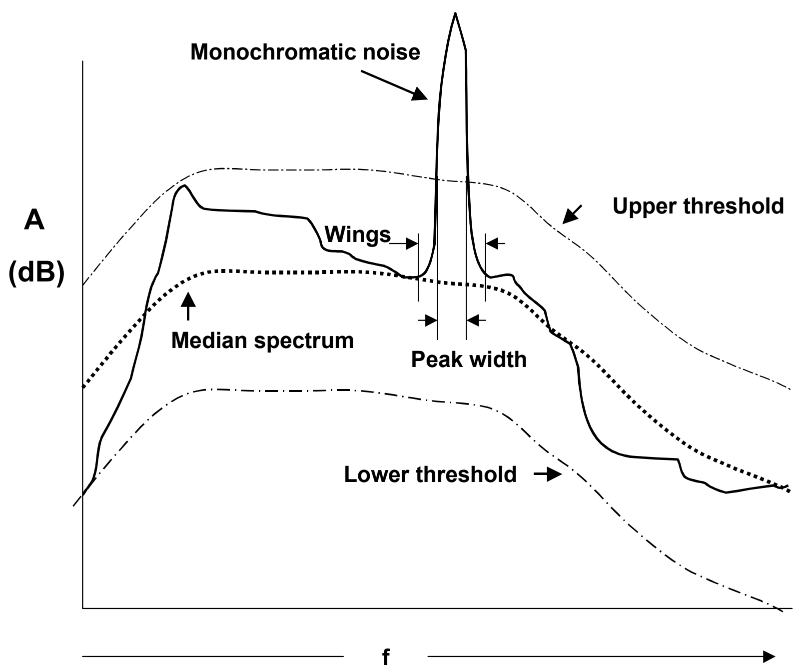


FIG. 8. Schematic illustrating the principle behind the "spectral clipping" algorithm. First, a running median of the amplitude spectrum is computed. Next, "threshold" curves are placed parallel (in dB space) above and below the median. Then, any frequencies for which the raw input amplitudes fall above or below the threshold curves are flagged, as are a few adjacent "wing" values. Finally, amplitudes for the flagged frequencies are set to their corresponding median values.

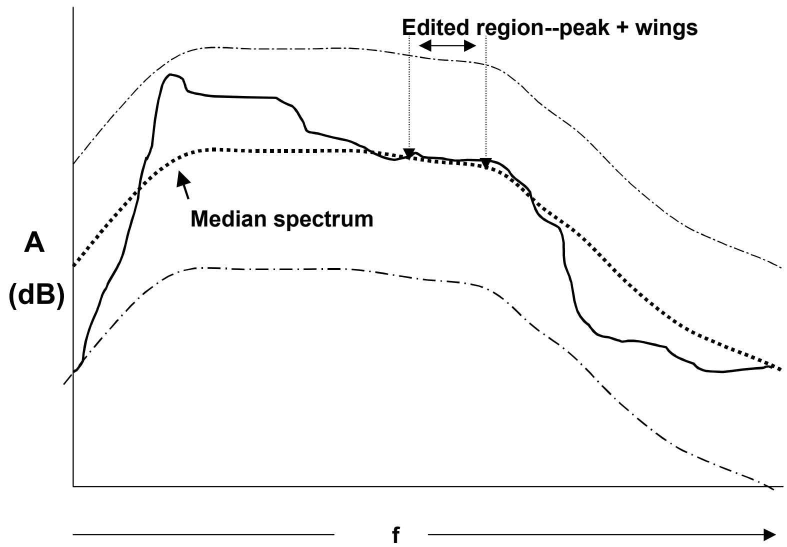


FIG. 9. The result of applying spectral clipping…the raw amplitudes are untouched, except for those frequencies which fell outside the thresholds. Phase is completely unaltered.

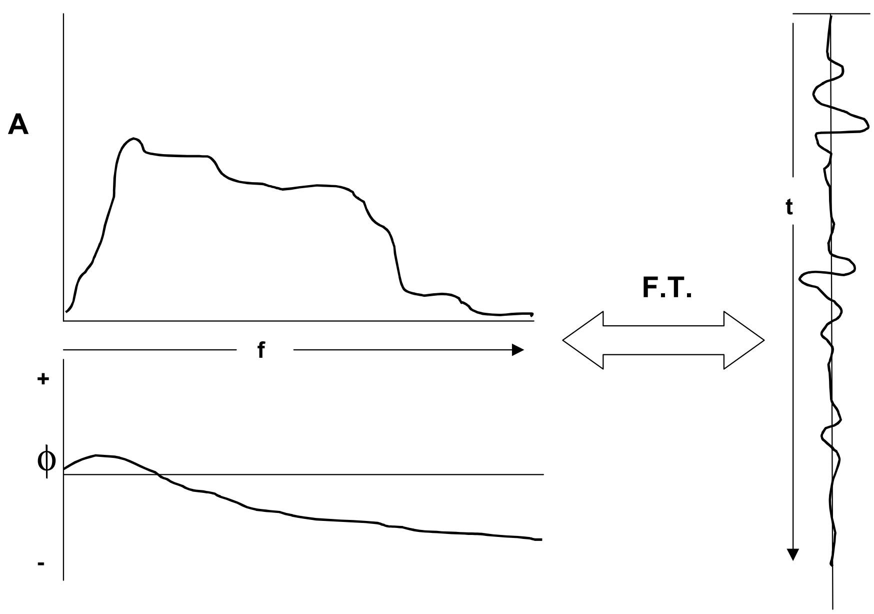


FIG. 10. After spectral clipping, amplitude and phase spectra are transformed back to a seismic trace, now with no monochromatic noise contamination.

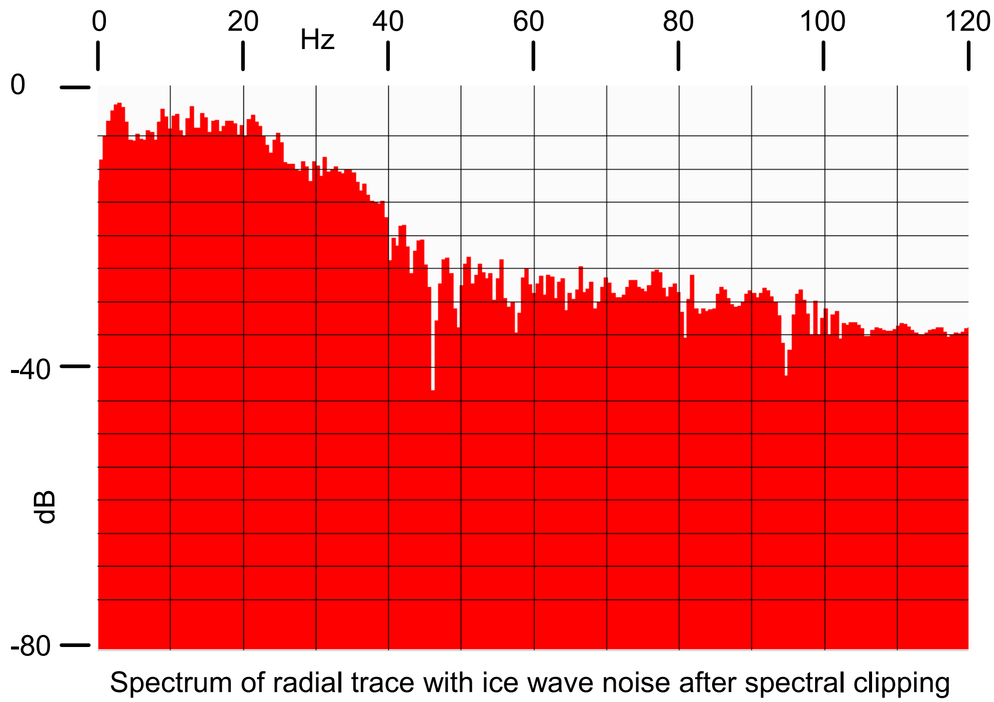


FIG. 11. Spectral clipping applied to the spectrum of Figure 6. There are now no spikes, but local spectral detail remains.

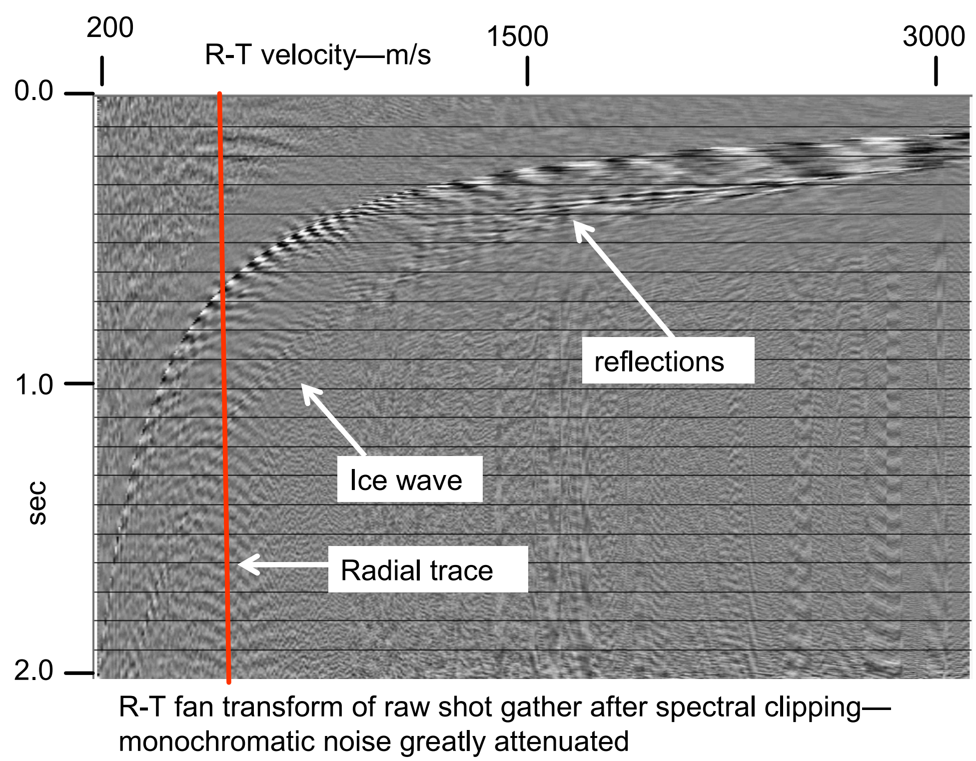


FIG. 12. R-T transform of shot gather after application of spectral clipping to the radial traces. The portion of the transform dominated by reflections is now much stronger than that dominated by the ice wave.

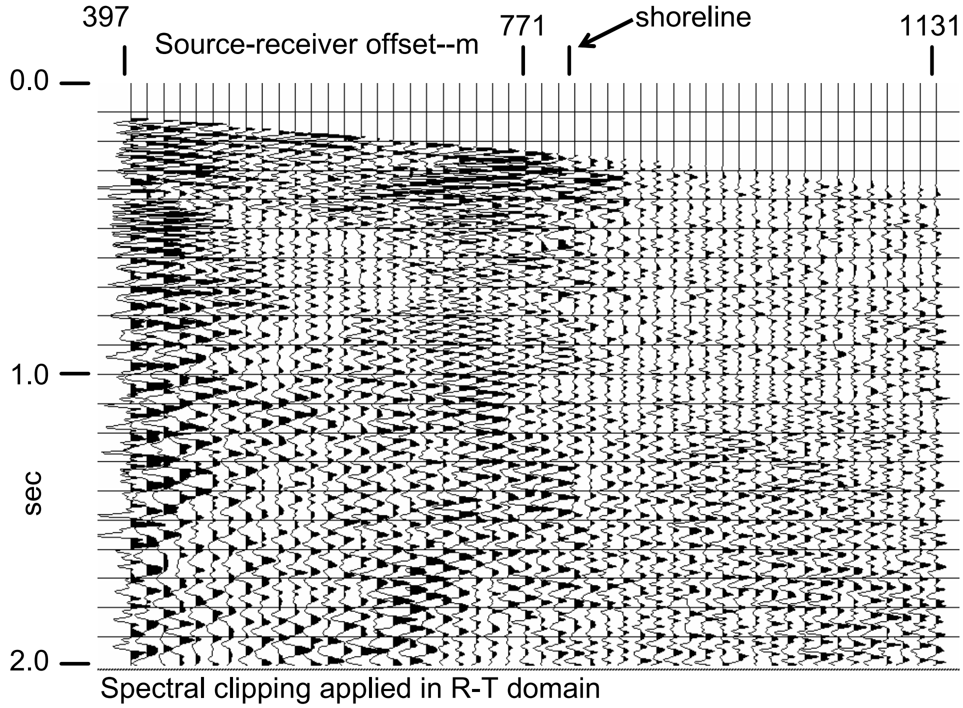


FIG. 13 Shot gather after spectral clipping in the R-T domain. The ice wave, though still present, is greatly diminished compared to Figure 4.

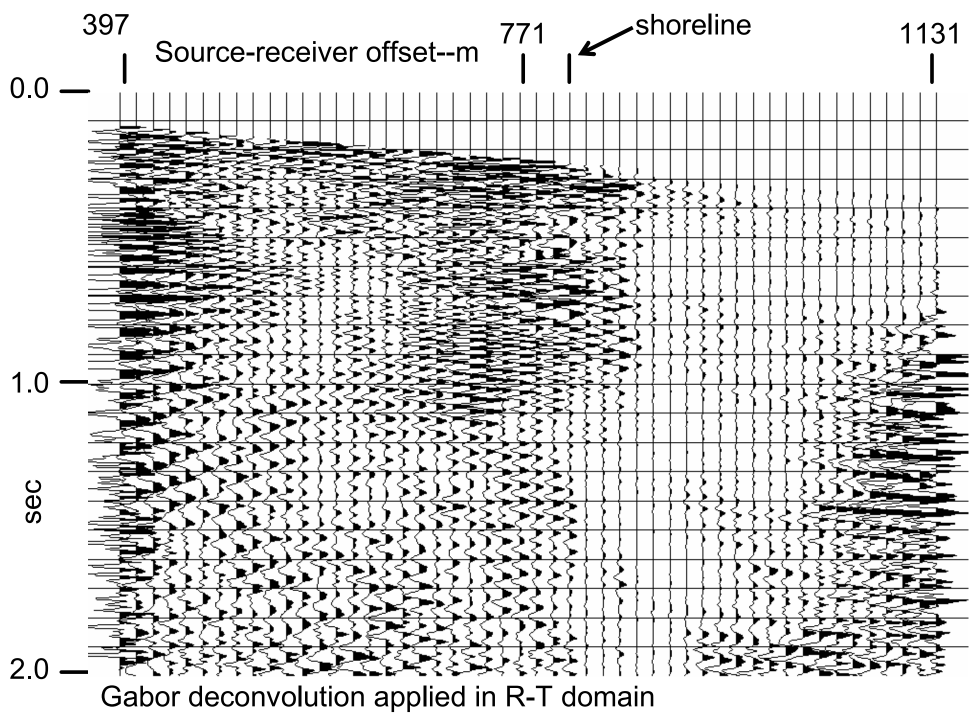


FIG. 14. Instead of spectral clipping, Gabor deconvolution has been applied in the R-T domain to attempt to reduce monochromatic spectral spikes by whitening. This result is not as good as that shown in Figure 13.

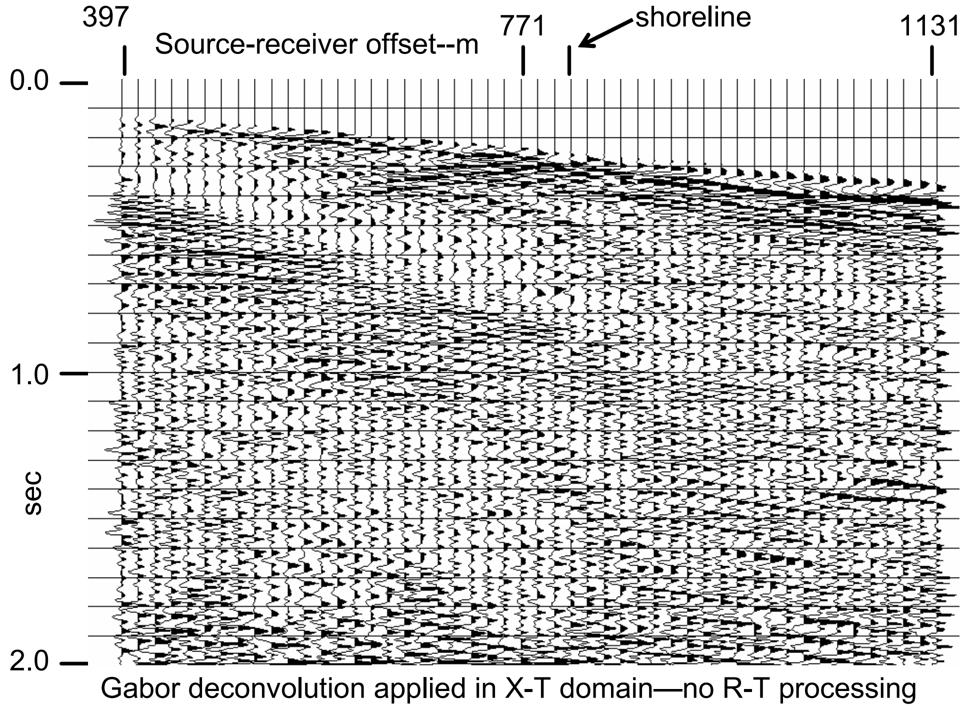


FIG. 15. Gabor deconvolution has been applied in the X-T domain to attempt to remove the ice wave noise by whitening. While an improvement over Figure 14, the imprint of the noise is still prominent.

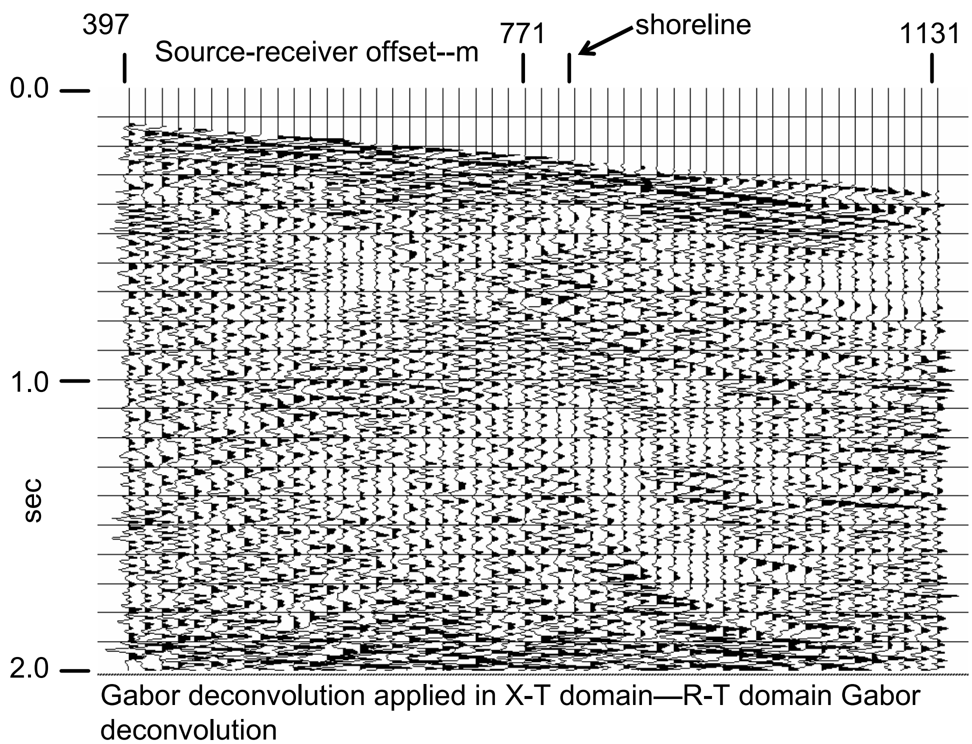


FIG. 16. Gabor deconvolution has been applied in both the R-T and X-T domains. This is the best result yet.

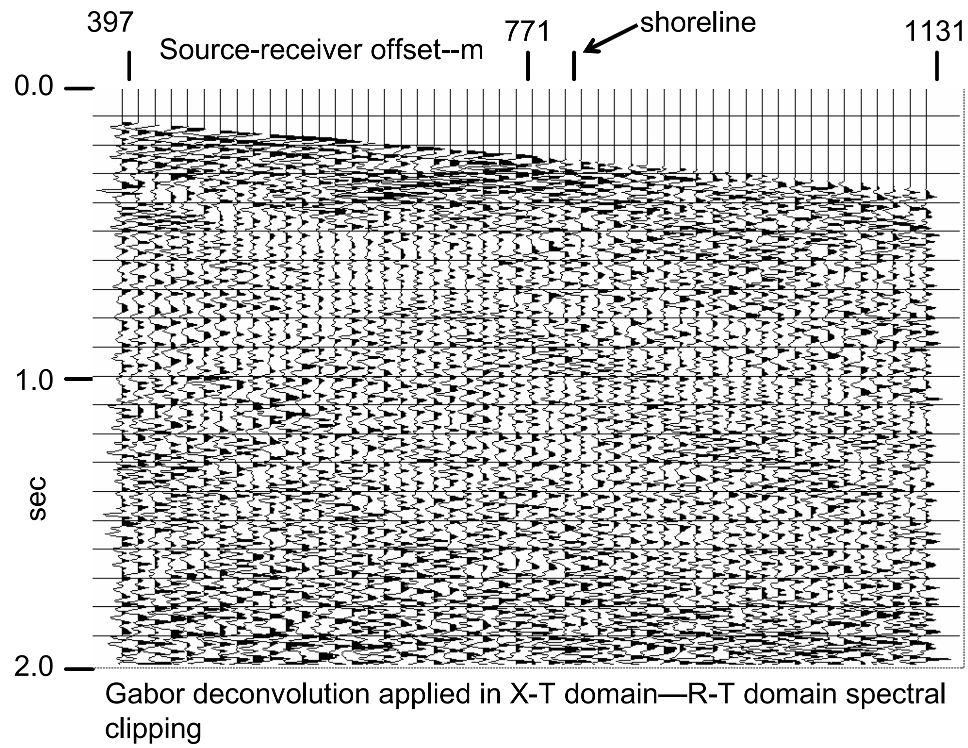


FIG. 17. Gabor deconvolution applied in X-T domain after spectral clipping in the R-T domain. This is the best result obtained yet, particularly for reflections deeper than 1.0 sec.

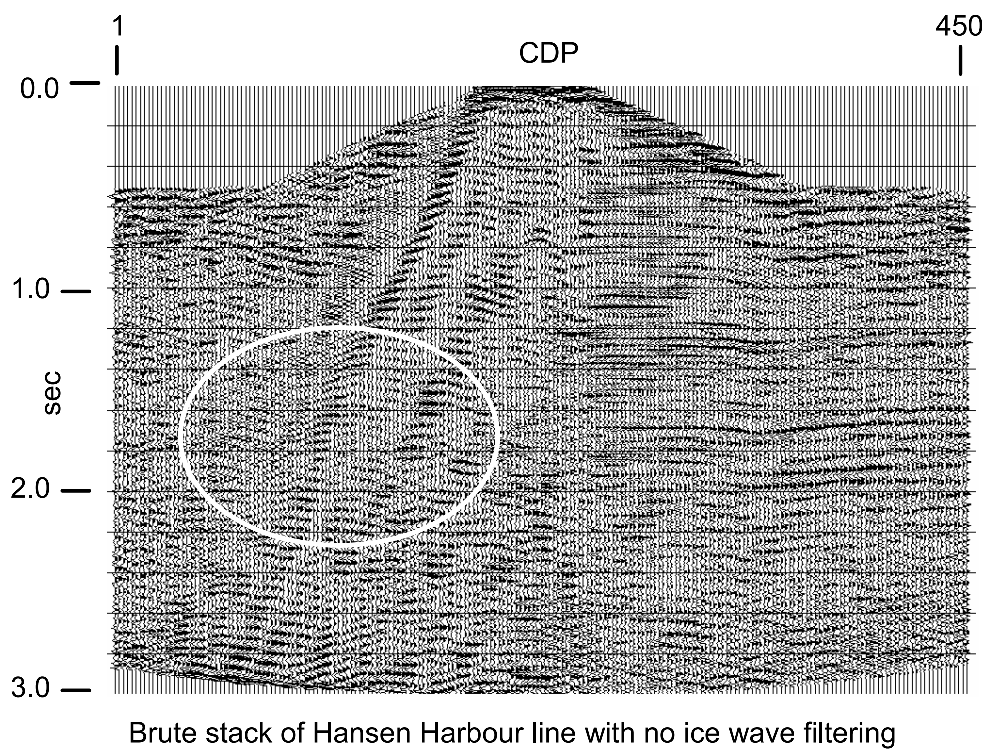
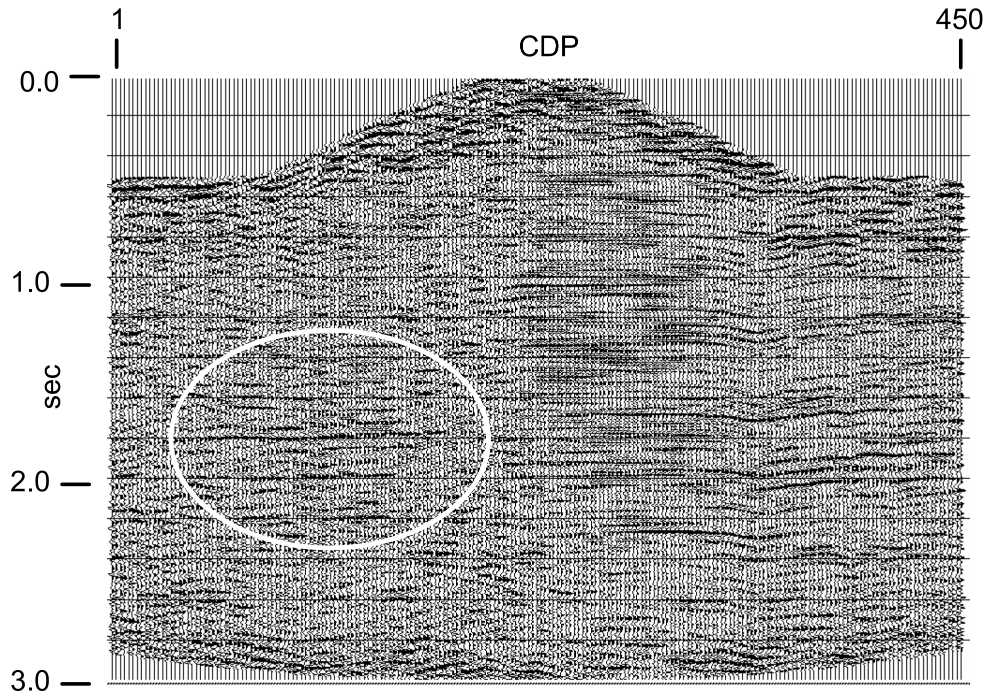


FIG. 18. Hansen Harbour stack—no ice wave filtering applied to shot gathers. Ice flexural noise dominates much of the left half of the section.



Brute stack of Hansen Harbour line after ice wave filtering

FIG. 19. Hansen Harbour stack after shots filtered to remove ice wave. Note the clear reflection energy to the left of the centre of this section.