Nonlinear seismology: the Priddis pulse-probe experiment revisited

Kris Innanen, Gary Margrave and Malcolm Bertram

ABSTRACT

One of the objectives of the 2012 Priddis pulse-probe experiment was to revisit the idea of measuring nonlinear seismic responses on the exploration/monitoring scale. In this initial study, we consider the difference between seismic responses from (1) the CREWES mini vibe as a lone source carrying out a linear sweep, (2) a standard (Geokinetics Mertz 22) vibe as a lone source vibrating at a fixed 25Hz, and (3) the two simultaneously. We show examples of the uncorrelated data for these sweeps, as well as compare the sizes of the data sets with and without the background signal. Early indications are that "something is going on", which we have not yet been able to falsify as nonlinear behaviour. Our main obstacle is to distinguish between true seismic nonlinearity and vibe feedback. We are unable at present to conclusively say what we have measured is one and not the other; pursuing these twin potential explanations for magnitude and phase differences is our near term plan.

INTRODUCTION

In 2008 CREWES undertook the "Priddis Pump Probe" experiment (Margrave et al., 2008), in which dynamite sources were shot into quiescent media and media being excited by a vibe sweep. The idea was, and is, that a medium being illuminated by a seismic wave has slightly different properties than when all is quiet, and that this might be detectable through a secondary seismic experiment. If detected, this would constitute evidence of a nonlinear seismic response on exploration/monitoring scales (see also Campman et al., 2012; Zhukov et al., 2007). This is not a simple experiment to configure, however, and the results were reported as being ambiguous.

In 2010 an acoustic theory was developed in order to provide a framework within which such signals (should they be detected) could be interpreted (Innanen, 2010). There are descriptions of nonlinear acoustics in the medical imaging literature, but this particular version, which treats the linear wave field as an inhomogeneous term in a further PDE for a secondary, nonlinear field, is derived from scratch in what we think is an intuitive manner (for instance, it can be seen as an extension of normal linear wave equation derivations familiar to seismologists such as that of De Santo, 1992).

More recently we have heard unofficial word of (as yet unpublished) laboratory experiments seeming to confirm nonlinear signal detection on scales that suggest that detection in a seismic experiment may not be that farfetched.

In July 2012 CREWES carried out the Priddis Pulse Probe experiment, to revisit the question of nonlinearity, using sources with a greater degree of repeatability, namely two vibrators, rather than one vibrator and dynamite. Further, we would configure this experiment to minimize the danger of what one listener to the presentation of Campman et al.

(2012) offered as the key obstacle to detection: the fact that the vibrators are adaptive, and therefore, in effect, could impose an apparent degree of nonlinearity on the signal. We want to measure the nonlinearity of the Earth, not the vibe, and so this potent source of error, which must be expected if the vibes are close together, is to be avoided if possible. We do so by maximally separating the vibes. Still, a key obstacle in interpreting our results is and will continue to be ensuring that vibe feedback and nonlinearity are not confused.

In this paper we will describe the basic configuration of the 2012 Priddis experiment, and present some early stage extractions of the data, including some early (though not yet conclusive) evidence of nonlinearity.

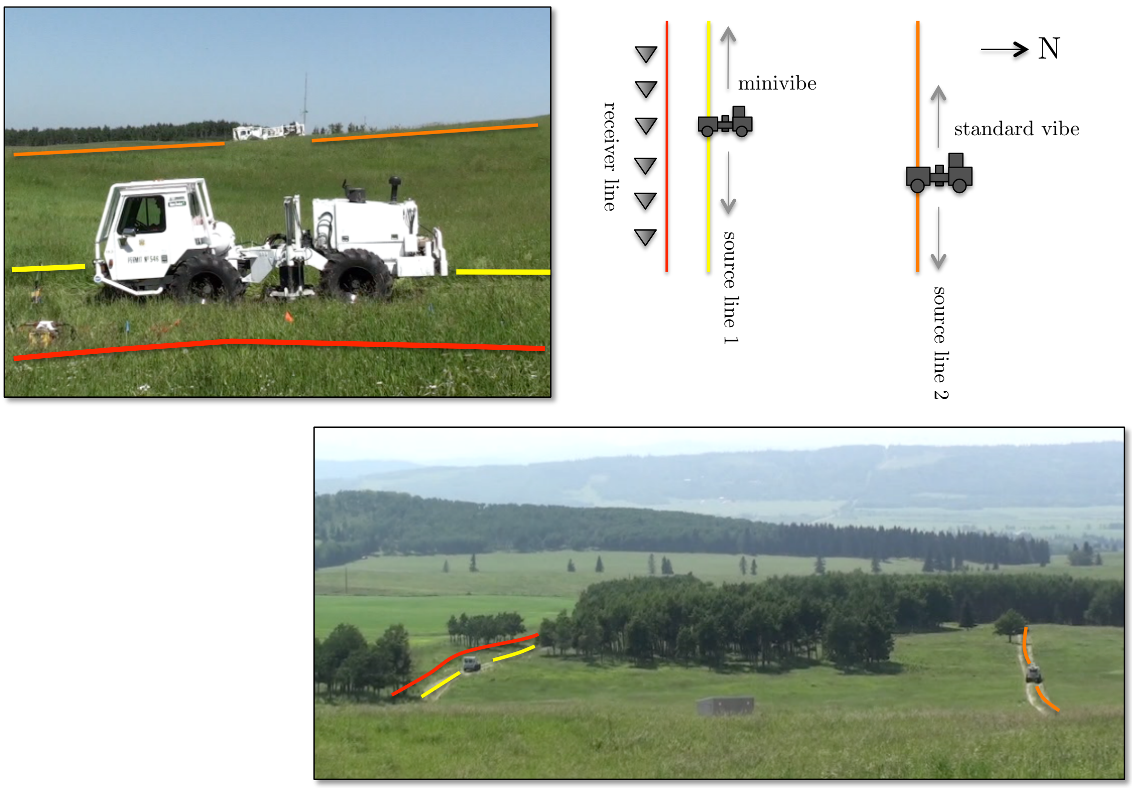

FIG. 1. Schematic illustration of the 2012 Priddis pulse-probe experiment. Two vibes are activated as sources on parallel source lines (yellow and orange); the CREWES Envirovibe on the receiver line and the Geokinetics vibrator on the 100m offset line. The offset vibe excites a fixed 25Hz wave in the Earth, and the Envirovibe carries out a standard sweep with and without this background wave field.

EXPERIMENTAL CONFIGURATION

In Figure 1 the basics of the pulse-probe experiment are laid out along with some photographs. The secondary source line (to the north, in orange) is occupied by the Geokinetics ("big") vibe. The primary source line (to the south, in yellow) is occupied by the CREWES ("mini") Envirovibe. The receiver line is in red. The data we will examine in this paper comes from the conventional multicomponent geophones which are laid out at 2m intervals.

The big vibe illuminates the subsurface with a fixed 25Hz signal, through which the mini vibe sends a standard linear 10-100Hz sweep. As baseline data, we also record the mini vibe at each flag point without the big vibe's signal, and we record the big vibe's signal alone.

The pulse probe experiment was carried out twice. Figures 2a-d illustrate the first of these, the "marching" configuration, in which the two vibes maintain a fixed zero inline offset, stepping together from west to east. Figures 3a-d illustrate the second of these, the "fixed" configuration, in which the big vibe remains at a fixed point roughly halfway along the secondary receiver line, and the mini vibe again steps from west to east, sweeping at each flag point.

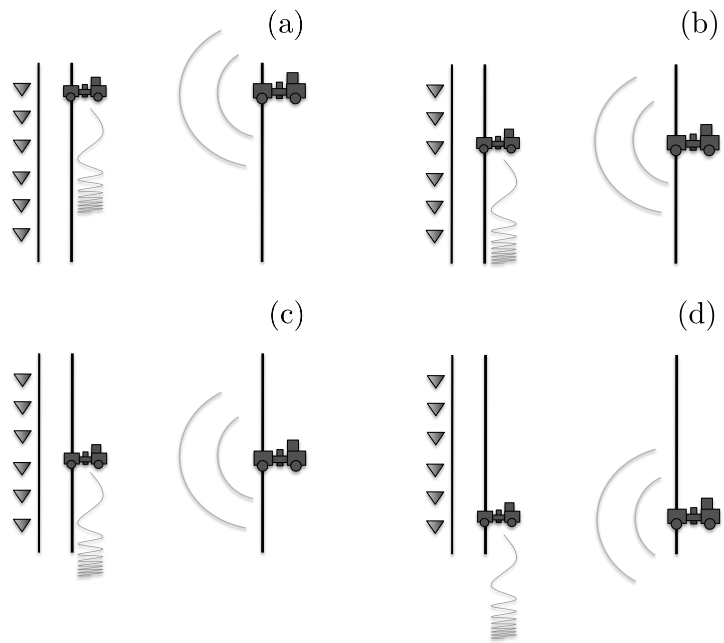

FIG. 2. "Marching configuration". The receiver line and the principal source line are illustrated on the left sides of the panels, and the secondary source line (100m offset) is illustrated on the right. (a)–(d) The CREWES Envirovibe and the Geokinetics vibe maintain a zero inline offset from one another, marching together from the west to the east.

AN APPROACH FOR DETECTION OF NONLINEAR BEHAVIOUR

In this paper we will not review or develop additional theory regarding the character of the nonlinear signatures, should they be found. Rather, we will establish some simple calculations and quantitative behaviours, which should be zero (or at least as small as some reasonably chosen baseline field noise/repeatability quantities) unless nonlinearity is present in some form.

In the marching configuration, we have access to data from the big vibe and mini vibe together (Figure 4a), the big vibe alone (Figure 4b), and the mini vibe alone (Figure 4c).

In linear seismology, wave fields add, in accordance with the principle of superposition. A characteristic of nonlinear behaviour—in a sense, the definition of nonlinear behaviour—would be the violation of this principle. So, let us frame our first look for nonlinear behaviour in terms of a hunt for violations of superposition.

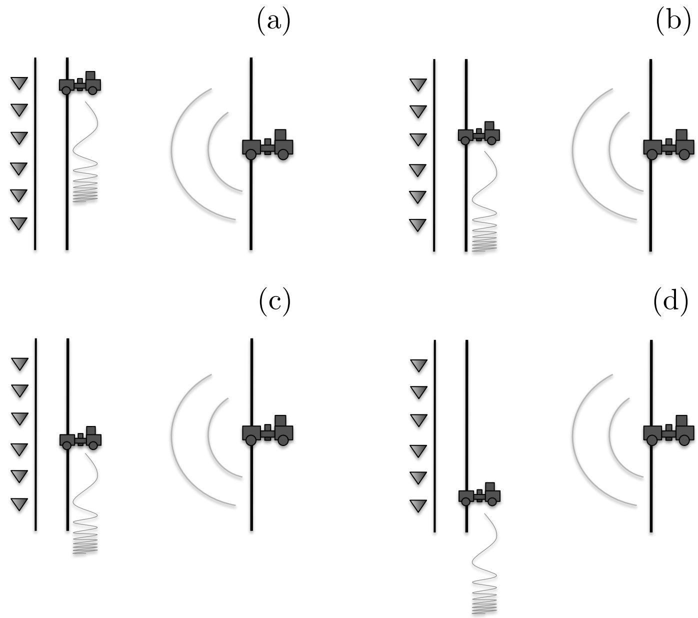

FIG. 3. "Fixed configuration". The CREWES Envirovibe occupies each flag location from west (a) to east (d), with the Geokinetics vibe maintaining a fixed location near the centre of the offset secondary source line. This configuration is the focus of the current paper.

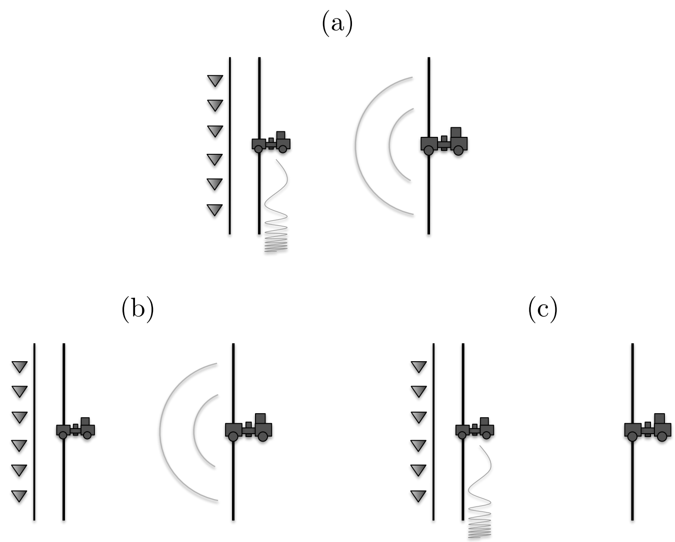

FIG. 4. The fixed configuration experiment allows us to compare (a) the two vibes together, (b), the "big" (Geokinetics) vibe data alone, and (c) the "mini" Envirovibe data alone, across the whole receiver line.

If we measure a data set $D_{\text{both}}(x_g,t)$ with both vibes active, a second data set $D_{\text{mini}}(x_g,t)$ with the mini vibe only active, and a third data set $D_{\text{big}}(x_g,t)$ with the big vibe only active, then superposition dictates

$$D_{\text{both}}(x_g,t) = D_{\text{mini}}(x_g,t) + D_{\text{big}}(x_g,t), \tag{1}$$

or

$$\delta D = D_{\text{both}}(x_g, t) - D_{\text{mini}}(x_g, t) - D_{\text{big}}(x_g, t) = 0. \tag{2}$$

Our initial approach will be to inspect the quantity δD for deviations from zero. Of course, in practice, data noise, repeatability, and innumerable other factors will cause the calculation of δD to deviate regularly from zero, and would do in the presence and the absence of nonlinearity. Therefore, we will have instead to compare the calculated δD quantities not to zero precisely, but rather to some baseline measure of repeatability and noise.

Since the "mini-vibe alone" data involved two stacked sweeps:

$$D_{\text{mini}}(x_g, t) = \frac{1}{2}\left(D_{\text{mini1}}(x_g, t) + D_{\text{mini2}}(x_g, t)\right), \tag{3}$$

and those two sweeps were kept individually, we propose using the difference between the two mini-vibe sweeps,

$$\delta D_{\text{baseline}} = D_{\text{mini1}}(x_g, t) - D_{\text{mini2}}(x_g, t), \tag{4}$$

as a baseline measure. If $|\delta D|$ is significantly larger than some scalar multiple of$|\delta D_{\text{baseline}}|$ (whose size is still a matter of study), then we will take this as preliminary evidence for the presence of nonlinear processes being measured.

THE UNCORRELATED DATA

In Figures 5a-c an example set of three uncorrelated shot records is illustrated (from mini vibe flag 179). They are arranged to match the scheme illustrated in Figure 4: (a) contains the mini vibe sweep alone, (b) the big vibe sweep alone, and (c) the two sweeps simultaneously active.

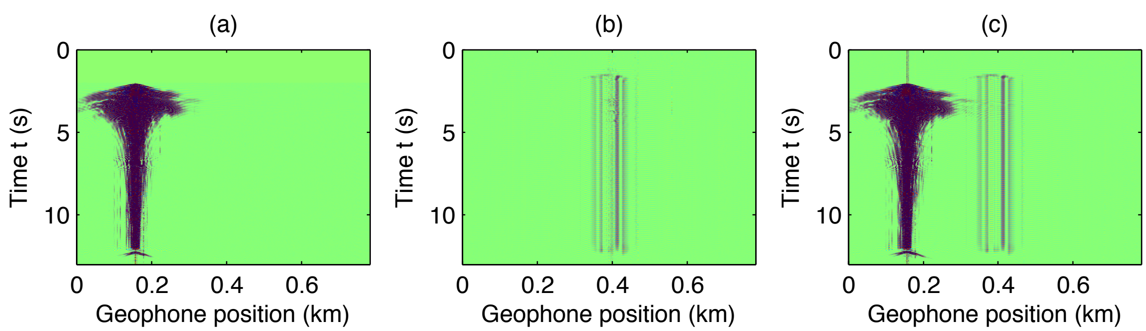

FIG. 5. An example of the uncorrelated data. (a) Mini vibe alone sweep from vibe point 179 (of roughly 450 shot points); (b) big vibe signal alone; (c) mini and big vibes active simultaneously.

Especially in the big vibe alone illustration, there is some image aliasing due to the length of the records being plotted. To get a better sense of the big vibe 25Hz signal, in Figure 6 the same plot zoomed in on the source location and early times is shown.

The detection calculation we have advocated, in equation (2), will in practice amount to computing the sum of Figures 4a and b, and subtracting the result from Figure 4c.

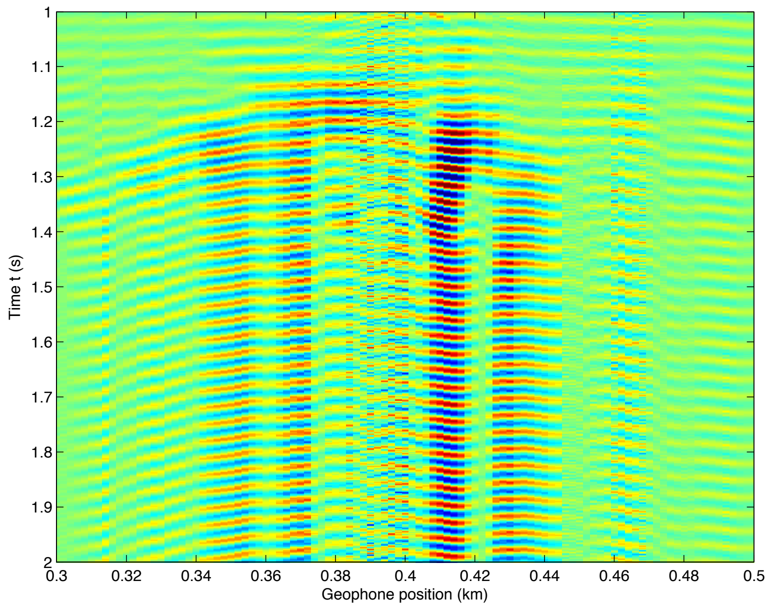

FIG. 6. Big vibe alone, shot record from Figure 5b zoomed in to near the source location and early times.

EARLY EVIDENCE FOR A NONLINEAR SIGNAL

Our early indications are that "something is going on", behaviour which we have not yet been able to falsify as nonlinear. Our findings are summarized here.

We will be forming the differences in equations (2) and (4), and seeing if the former is larger than the latter in a persistent manner. First let us have a detailed look at the data that will be going into these calculations, at the trace level. In Figure 7 four traces are examined. In Figure 7a, the difference between both and the big vibe is plotted in black, and overlain on top of this is the mini vibe trace in red. These will be differenced in order to establish a pattern of potential nonlinear behaviour. Clearly, at least at certain times, there are some significant differences between these traces. As a comparison, in Figure 7b the two collocated mini vibe sweeps are plotted over top of one another. While they are not identical, they are close. Indeed, we expect some differences at earlier times, which we see, but for these to settle down after 1-2s, which is also visible in b.

However, at the scale of Figure 7 we cannot be particularly detailed in our comments. In Figure 8a-b, the same plots are zoomed in on, near the first breaks. We notice some significant differences between the "both minus big" trace (black) and the "mini alone" trace (red); but, then, at this early time we also detect some differences between the nominally identical mini vibe sweep traces in green and blue. However, we note that at this early time the phases of the red vs. black and the green vs. blue traces show little difference.

A second zoom in on Figure 7 is illustrated in Figures 9a-b, further along in the sweep. Here, we notice that the two mini vibe repeated sweeps, while exhibiting some variability in amplitudes, are again well aligned in phase. But, the "both minus big" trace and the "mini vibe alone" traces (black and red respectively) have taken on a very noticeable relative phase shift.

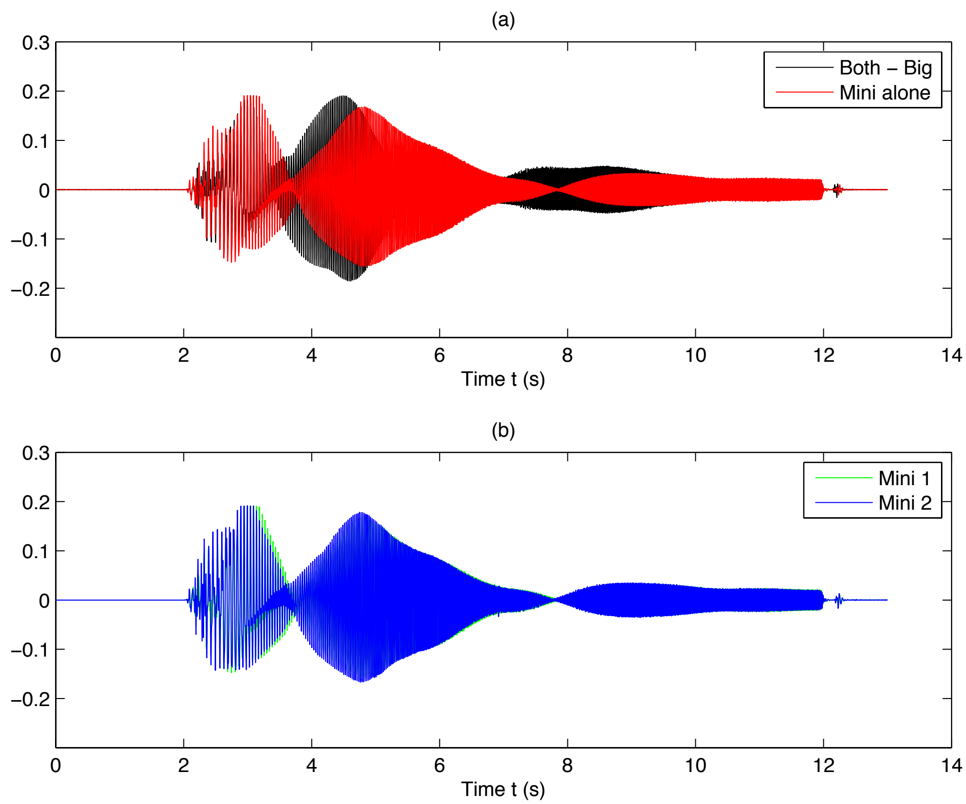

FIG. 7. Trace comparisons prior to differencing. (a) The big vibe signal is subtracted from the simultaneous vibes, and plotted in black opposite the corresponding mini vibe trace. (b) The two collocated mini vibe traces are similarly compared (blue and green). We point to some very significant phase differences occurring between 3 and 6s.

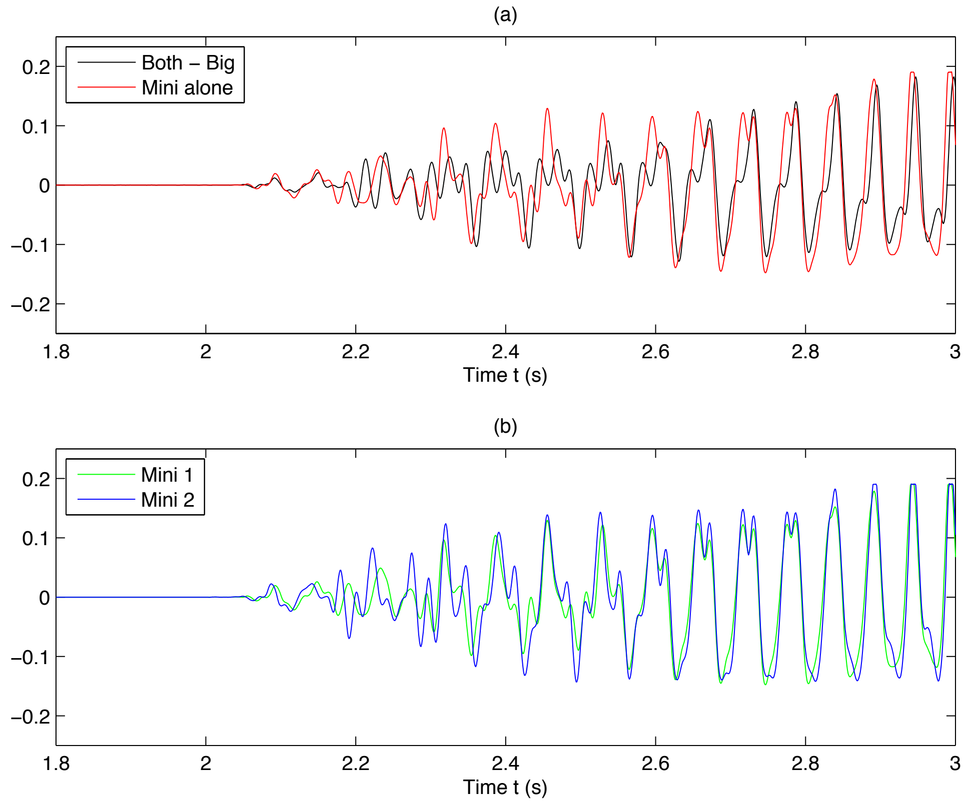

FIG. 8. Zoom in on Figure 7 near the first break.

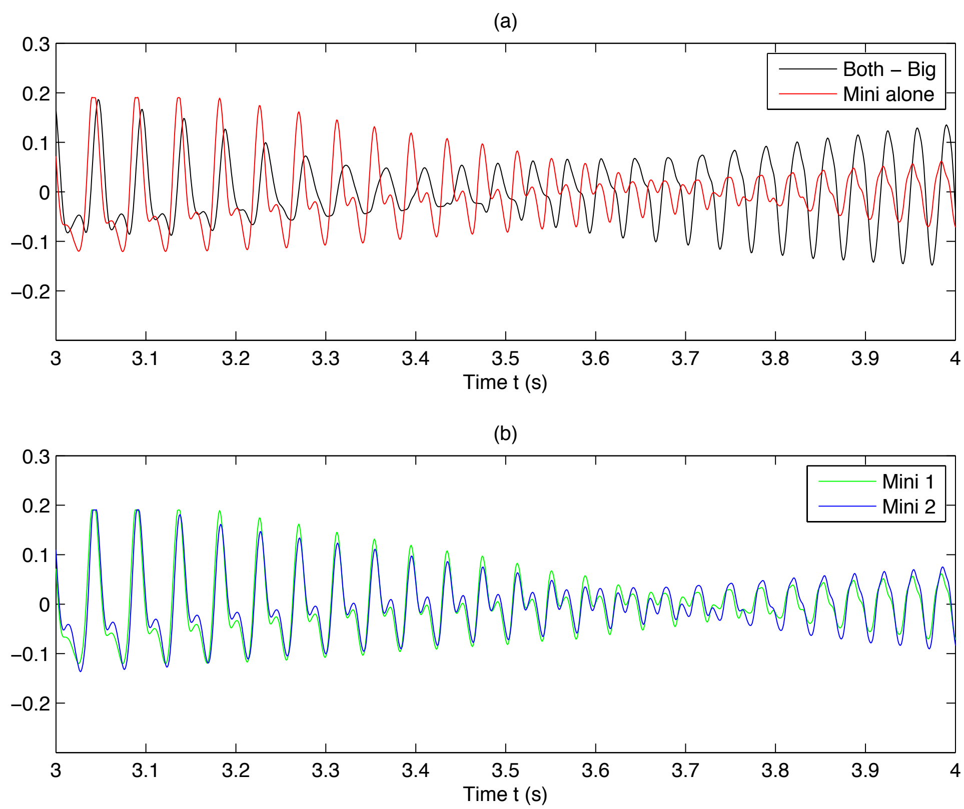

FIG. 9. Zoom in on Figure 7 further into the sweep.

A difference between the red and black traces ($|\delta D|$) in the above plots that is larger than the difference between the green and blue traces ($|\delta D_{\text{baseline}}|$) will be an early indication of nonlinearity. To the extent that the single trace we have examined is representative, it seems we should expect some differences. What remains for our initial examination is to ascertain whether differences of this type are common and persistent or rare throughout the data set. In Figure 10 we calculate the norms of these difference shot records for each vibe point along the primary source line. The norm $|\delta D|$ is in red and the norm $|\delta D_{\text{baseline}}|$ is in blue.

The difference between the violation of superposition measure and the baseline repeatability measure is suggestive that the behaviour seen in Figures 7–9 persists along the whole line. The vertical component is illustrated in (a) and one of the horizontal components in (b). The means of the blue and red curves differ by factors of roughly 3. We are currently evaluating these differences to determine their significance.

We consider a sensible question to be is there a dependence in the red curve (in comparison to the blue curve) on the radial distance between the two vibes? This does not seem to be decidable based on our current calculations, which display a large variability.

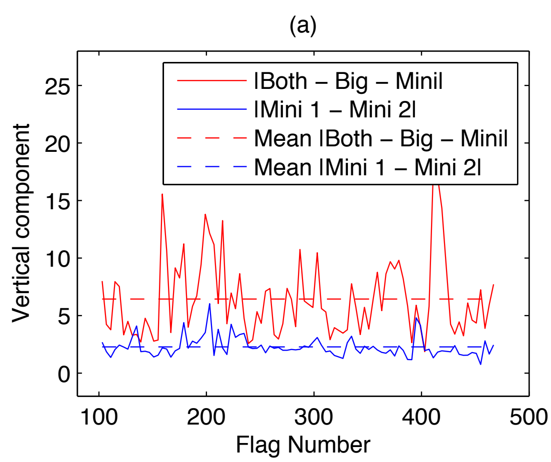

FIG. 10. Comparison of the norms $|\delta D|$ (red) and $|\delta D_{\text{baseline}}|$ (blue). (a) Vertical component; (b) One of two horizontal components. The means of these norms are plotted as dashed lines.

CONCLUSIONS

One of the objectives of the 2012 Priddis pulse-probe experiment was to revisit the idea of measuring nonlinear seismic responses on the exploration/monitoring scale. In this initial study, we consider the difference between seismic responses from (1) the CREWES mini vibe as a lone source carrying out a linear sweep, (2) a standard (Geokinetics Mertz 22) vibe as a lone source vibrating at a fixed 25Hz, and (3) the two simultaneously.

We have established a maximally controlled experiment in which violations of superposition of waves can be sought as evidence of seismic nonlinearity.

Magnitudes of quantities designed such that they are nil if superposition holds are, in fact, seen to be nonzero. We are evaluating their sizes relative to a control to establish whether or not they are significant.

Phase differences between the control and the experimental sweeps are noted, and may be the best near term "trail" to follow, possibly indicating altered travel times through the 25Hz-illuminated Earth volume.

The key issue going forward will be to distinguish between vibe feedback and "true" seismic nonlinearity.

ACKNOWLEDGMENTS

This work was funded by the sponsors of CREWES, whose support we gratefully acknowledge. We would like to express our gratitude to our partners in the Priddis pulse-probe experiment, Global Geophysical, Geokinetics, and Outsource, whose provision of equipment and expertise were mission critical. Kevin Hall, Kevin Bertram, Peter Manning, Laura Baird, and a large number of CREWES students and staff were major contributors to the success of the experiment.

REFERENCES

Campman, X. H., Kuvshinov, B. N., and Smit, T. H. J., 2012, Combined-harmonic analysis of seismic data acquired with two vibrators driven at different frequencies, *in* Proceedings of the 74th EAGE conference & exhibition, Copenhagen, Denmark, EAGE.

De Santo, J. A., 1992, Scalar Wave Theory: Green's Functions and Applications: Springer-Verlag.

Innanen, K. A., 2010, An acoustic description of nonlinearity in seismic exploration: CREWES Annual Report, **22**.

Margrave, G. F., Henley, D. C., Lu, H. X., Hall, K. W., Bonham, K., Bertram, M. B., Gallant, E. V., and Wong, J., 2008, Priddis pump-probe experiment: CREWES Annual Report, **20**.

Zhukov, A. P., Loginov, K., Shneerson, M. B., Shulakova, V. E., Kharisov, R., and Ekimenko, V. A., 2007, Nonlinear properties of vibrator-generated wavefields and their application to hydrocarbon detection: The Leading Edge, **26**, No. 11, 1395–1402.