

Robust surface-consistent residual statics and phase correction – part 1

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Summary

In land AVO processing, near-surface heterogeneity issues are resolved by surface-consistent processing. It is presumed that the amplitude and phase corrections are taken care of by surface-consistent deconvolution, and the statics solution is applied assuming that no wavelet phase errors exist. In this paper, we show that phase errors may remain in the data after deconvolution and therefore that statics and phase corrections need to be simultaneously estimated and corrected. Thus, we recommend that simultaneous statics and phase correction become routine. Specifically, we show that if phase errors in the data are ignored, they are compensated for by the statics algorithms as if they were statics errors. This biases the static solution and the phase errors remain in the data.

We introduce a robust surface-consistent method to resolve residual statics and phase simultaneously by maximizing the stack power. The method is evaluated on several synthetic data models using both flat reflectors and a pinchout model. The method is demonstrated on real data showing the improvement expected from simultaneous statics and phase correction. Further, we show evidence that the phase errors exist after surface-consistent deconvolution.

Introduction

The issue of near-surface heterogeneity influencing the sub-surface data in land processing is routinely resolved by surface-consistent (SC) algorithms. While SC statics algorithms resolve the statics errors, the purpose of SC deconvolution (Cary et al. 1993) is to attempt to whiten the amplitude spectrum and zero the phase. Due to noise and other factors, we expect that phase errors exist in the data after SC deconvolution. Other reasons for near-surface phase variations in the near surface include a varying Q in the over-burden and different source types.

In processing, most methods to correct static errors use cross-correlation of trace pairs in a surface-consistent framework (Taner *et al.* (1974, 1981), Disher *et al.* (1970), Ronen *et al.* (1985) and others). Simultaneous SC statics and phase correction is necessary to address statics errors properly. The analytic trace of the averaged cross-correlation is used in Downie *et al.* (1988) to solve for statics and phase, simultaneously. In their approach, each shot or receiver trace is cross-correlated with a model trace. Taner *et al.* (1991) use a conjugate gradient approach to solve for the unknown static and phase for each shot and receiver component. Downie *et al.* (1988) and Taner *et al.* (1991) compute a constant phase rotation for all frequencies. In Cambois *et al.* (1990), SC amplitude and phase correction in the log/Fourier domain is presented, where a partial phase unwrapping scheme is used to address phase discontinuity. Guo *et al.* (2001) proposed a method which appears to solve for statics and phase separately.

In this paper, we extend the stack power optimization method (Ronen and Claerbout (1985)), to simultaneously solve for residual statics and residual phase in a surface-consistent approach. We show that phase errors can exist after SC deconvolution, discuss why statics and phase corrections need to be solved simultaneously and show real data results.

Theory and/or Method

In land data, the need for phase correction arises due to spatially varying noise, source types with different phase responses, etc. To see the effect of noise on phase, consider data in the frequency domain. At a given frequency f ,

$$D(f) = S(f) + N(f)$$

where, D is data, S is signal and N is noise that includes source noise, random noise that is spatially varying and white noise.

Surface-consistent deconvolution assumes that the wavelet spectrum is equal to the smoothed, windowed trace spectrum and computes the amplitude $G(f)_{rsc} = [D^2(f)]^{0.5}$ for each frequency. The subscripts r,s,c and o indicate receiver, shot, cdp and offset components respectively. The scalar $G(f)$ is decomposed into various components and deconvolution operators are designed for shot and receiver terms. Recognizing that data is the sum of signal and noise, we can expand the spectral amplitude as

$$G(f)_{rsc} = [S^2(f) + N^2(f) + 2 S(f) N(f)]^{0.5} \geq [S(f)] \quad (1)$$

From the inequality in Equation (1) we can see that the wavelet spectrum is biased when the cross-term between signal and noise does not cancel or when noise is spatially varying. For example, coherent noise and signal are often correlated, and spatially varying noise is not uncommon in seismic data. For example, in marshy areas signal-to-noise differs from other areas and likewise the ground roll can vary spatially. From (1) we can see that if the amplitude spectrum is biased then the phase spectrum will be incorrect. One can reduce the bias by noise attenuation. However, deconvolution is commonly applied at a stage where residual noise remains in the data. As a result, phase errors in the data persist after deconvolution.

Another pitfall in current processing is that static corrections are performed assuming either that phase errors do not exist or that they can be ignored. Phase errors will cause incorrect estimation of statics, even though the coherence of the stack is improved. Figure 1 shows a group of traces after statics correction, ignoring the phase errors. The peaks of the event are lined up by the statics correction algorithm, however the wavelet phase is not consistent across the event. On the other hand, correcting for phase errors while ignoring static errors will result in increased coherence of the stack but static errors will still persist. In essence, when static and phase errors exist in the data, correcting for one of them results in a more coherent stack but there will still be inconsistency in wavelet phase and statics. When statics and phase corrections are resolved simultaneously, then the wavelet inconsistency in static and phase can be resolved at the same time.

Ronen and Claerbout (1985) proposed a stack power optimization method to solve for statics in a surface-consistent manner. They showed that maximizing the stack power is equivalent to maximizing cross-correlation of a shot gather with its relevant stack or a receiver gather with its relevant stack traces. In this paper, we extend that method to solve for statics and phase simultaneously, whose objective function is given below;

$$\text{Power}(t_d, p_d) = \sum_t [F(t-t_d, p_d) + G(t)]^2 \quad (2)$$

$$J_{\max} = \text{maximum of Power}(t_d, p_d) \quad (3)$$

In Equation (2), t_d is static, p_d is phase for a given shot or receiver, t is time and Σ is summation. F is a super trace of a shot or receiver gather with static and phase errors and G is a super trace of corresponding stack traces. Equation (3) signifies that the objective function J is maximum when static and phase errors are corrected. We expect the 2D objective function to be an ellipse whose local maxima exist along a sloped line as shown in Figure 2 (right panel). To reduce computation, we use the analytical trace of the cross-correlation to find statics and phase. Specifically, the static value is given by the lag time at the envelope maximum, and the phase value is given by the instantaneous phase at the lag time. It is important to note that in this algorithm, we are correcting for short-to-medium wavelength relative phase errors, and long-wavelength phase variations may persist afterward for the same reasons that long wavelength static errors may exist after residual statics. After simultaneous correction, we expect to get consistent short-to-medium wavelength statics and phase among shots

and receivers. The proposed method can converge to a local maximum. To avoid this, it is necessary to have good NMO velocities and have a starting model close to the true solution i.e., one or two passes of residual statics.

We estimate source and receiver phase corrections that are constant for all frequencies in order to increase the robustness of the algorithm. In addition robustness is improved in the presence of noise by the use of the stack-power approach since the phase is essentially being estimated after CDP stack.

The effect of ignoring the phase errors and solving for static alone can be understood from the contour map of a representative source or receiver in Figure 2. Static and phase errors are present as indicated by the green dot in the left panel. If statics alone is solved (ignoring the phase), a local maximum along the grey arrow is chosen (see middle figure) as the statics solution. Thus, the static is over-compensated in this case. Depending on the magnitude and sign of the static error, solving for statics-only can over or under-compensate the error. In other words, a phase error will be compensated as if it were a static error. This results in inconsistent wavelet phase; yet, the coherence of the stack is improved because a local maximum solution is sought as seen in Figure 1. After applying the statics-only solution, applying the simultaneous statics and phase solution corrects the over-compensated static and the phase correction (right panel). As seen in the right panel, we expect there to be an anti-correlation between the static and phase corrections (statics and phase are opposite in sign). It is important to recognize that the stack-power could be increased by solving for phase alone, while ignoring the static. However, the wavelet static and phase will be inconsistent. We will now show that the simultaneous solution of statics and phase may have a subtle effect on the stack, but can provide important details for AVO analysis or structural interpretation that are otherwise skewed by a statics only solution.

Examples

We first show three synthetic datasets that illustrate the method: (a) a flat reflector with no noise (b) a flat reflector with noise and (c) a pinch-out model with no noise. In all three cases, random statics and phase errors were introduced in a shot and receiver-consistent manner. Then the proposed algorithm was used to resolve the statics and phase errors, simultaneously. The modeled and estimated values were compared. In synthetic (a) static and phase errors in the magnitude of -5 to 5 ms and -90° to 90° , respectively, were introduced. In synthetic (b) they were -15 to 15 ms and -90° to 90° , and in synthetic (c), they were -5 to 5 ms and -90° to 90° . Cross-plots of estimated versus modeled statics and phase values are shown in Figure 3 for synthetic dataset (a) and (b). A clear linear trend is seen between modelled and estimated values of statics and phase in both cases suggesting that the algorithm is able to reliably predict the statics and phase errors. In Figure 4, CDP gathers are shown for noise-free synthetics (a) before and after correction. After correction, the wavelet statics and phase are consistent. In contrast applying a statics-only correction resulted in the inconsistent wavelet phase in Figure 1. In Figure 5, a stacked line of a pinch-out model is shown. In Figure 5(a) the stack power is reduced due to statics and phase errors. The inset figure in Figure 5(a) shows statics and phase errors on a gather in the data. When SC statics and phase are applied to the data, the stack-power increases as shown in Figure 5(b). This compares well to an ideal data stack shown in Figure 5(c) that has no static or phase errors. The inset figure in Figure 5(b) shows that the statics and phase errors are resolved on the gather.

In Figure 6, we show a stacked line from a 3D dataset (a heavy oil play in Alberta) that this method was applied to. Final NMO, several passes of residual statics, and mute were applied before stack. Compared to Figure 6a, the stack-power in Figure 5(c) increases after applying SC statics correction. The stack-power increases further in Figure 6(c) after applying SC statics and phase correction. The coherence of events are preserved or enhanced (reflections pointed by arrows) compared to statics-only stack. After statics and phase correction, the phase variation of wavelet is consistent over neighboring CDPs. On the analysis of CDP gathers, we also note that with statics-only correction, the phase varied significantly between neighboring CDPs. Gathers after simultaneous statics and phase estimation had consistent phase and thus reliable AVO and velocity analysis can be performed.

To see if phase errors persist after deconvolution, we performed statics and phase estimation at various stages of AVO processing. We then computed histogram plots of estimated receiver phase before and after SC deconvolution as shown in Figure 7. Before deconvolution, relative phase corrections in the range of -180° to 180° were found. After deconvolution, shot and receiver phase corrections were in the range of -90° to 90° . This shows that the SC deconvolution operators are likely being biased by noise so that wavelet phase is not resolved perfectly.

Conclusions

Surface-consistent noise biases the standard SC deconvolution operators and thus phase errors persist in data after SC deconvolution. We have shown that simultaneous statics and phase correction is necessary when data has statics and phase errors. Solving for statics alone will result in over or underestimation of statics when phase errors are ignored. Although the stack-power increases after static correction, the wavelet phase is inconsistent.

We have introduced a method to resolve surface-consistent statics and phase simultaneously using stack power maximization as a 2D objective function. The analytic trace of the cross-correlation is used to determine statics and phase. Phase un-wrapping is not required. The method is robust because of the stack-power approach is used. The stack-power increased after statics correction alone, however the power increases even more after simultaneous statics and phase correction. More detail is observed after statics and phase correction and the reflections are more coherent. Statics and phase correction results in consistent wavelet phase, thereby showing potential for improved AVO analysis. We also can see that velocity analysis and 4D processing can be improved by having a consistent phase.

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References

- Cambois, G. and Stoffa, P. (1993), Surface-consistent phase decomposition in the log/Fourier domain, *Geophysics* 58:8, 1099-1111
- Cary, P. and Lorentz, G., (1993), Four-component surface-consistent deconvolution, *Geophysics* 58:3, 383-392
- Disher, D. and Naquin, P. (1970), Statistical automatic statics analysis, *Geophysics* 35:4, 574-585
- Downie, A. L., (1988), Near-surface corrections, *SEG Expanded Abstracts*
- Guo, J. and Zhou, X. (2001), Surface-consistent phase correction, *SEG Expanded Abstracts*
- Ronen, J. and Claerbout, J. (1985), Surface-consistent residual statics estimation by stack-power maximization, *Geophysics* 50:12, 2759-2767
- Taner, M., Koehler, F., and Alhilali, K. (1974), Estimation and correction of near-surface time anomalies, *Geophysics* 39:4, 441-463
- Taner, M. and Koehler, F. (1981), Surface consistent corrections, *Geophysics* 46:1, 17-22
- Taner, M., Lu, L., and Baysal, E. (1991) Static corrections: Time amplitude, and phase. *SEG Expanded Abstracts*

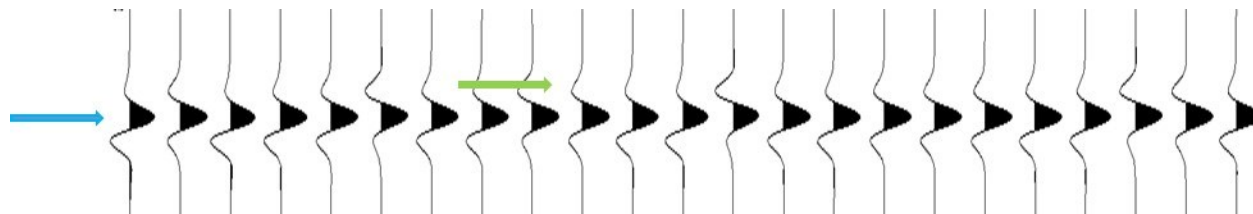


Figure 1 A gather showing statics correction that have been applied while ignoring the phase errors. The blue arrow shows that the peaks of the event are lined up and the green arrow shows that the wavelet phase is not consistent across the event.

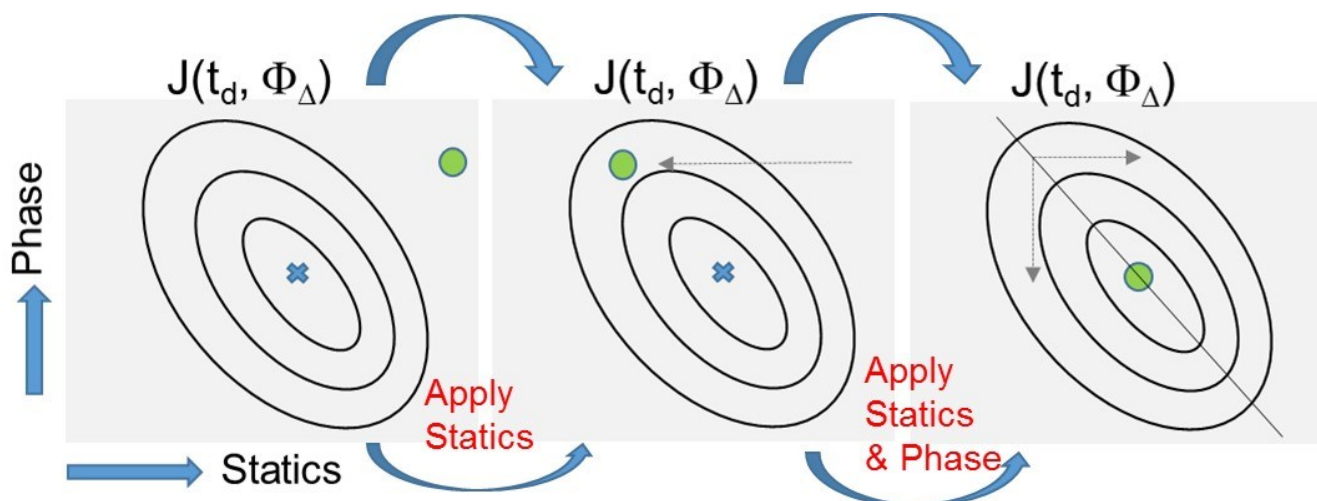


Figure 2 Effect of ignoring phase error is illustrated on this contour plot of the stack-power as a function of statics and phase for a single source or receiver. When static and phase errors are present (green dot) in the left picture, applying a static correction will over-estimate the static correction (the green dot moves to local maximum in the middle figure). The objective function's largest maximum is identified by the cross-mark in the left and middle panels. When statics and phase are resolved simultaneously as in the right panel, appropriate static and phase corrections are estimated. The local maxima exists along a sloped line of the contour plot (right panel).

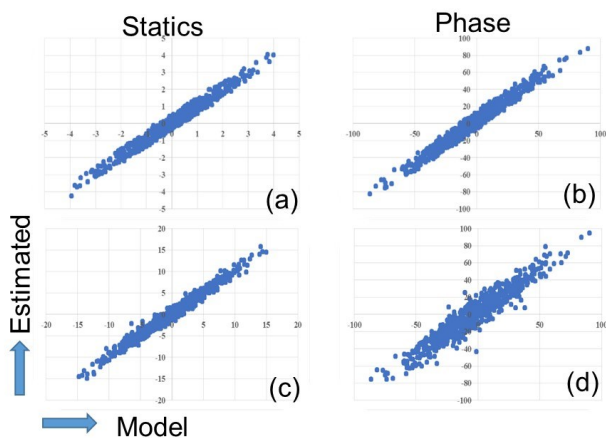


Figure 3 Cross-plots of modeled vs estimated static and phase values for all receivers are shown. (a) and (b) for noise-free, (c) and (d) for noisy cases.

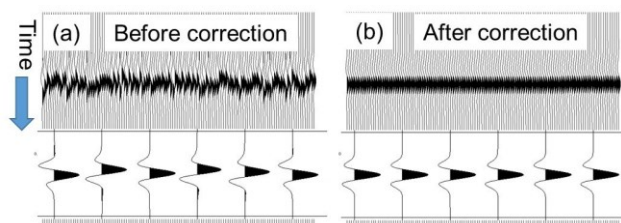


Figure 4 Noise-free gathers are shown. The inset panels in the top row show the static and phase errors in more detail. Gathers before correction are on the left and gathers after correction are on the right.

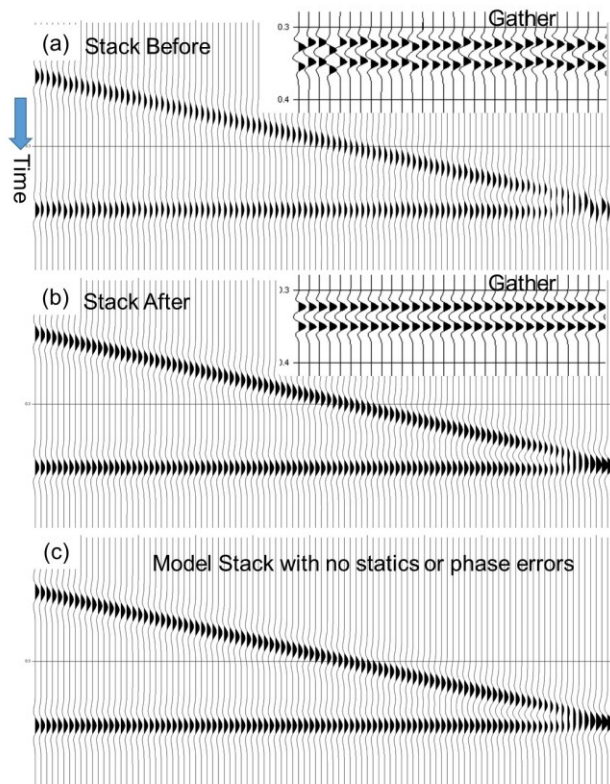


Figure 5 A pinch-out model. Stacks and gathers (inset) (a) before statics and phase correction, (b) after statics and phase correction and (c) ideal stack are shown.

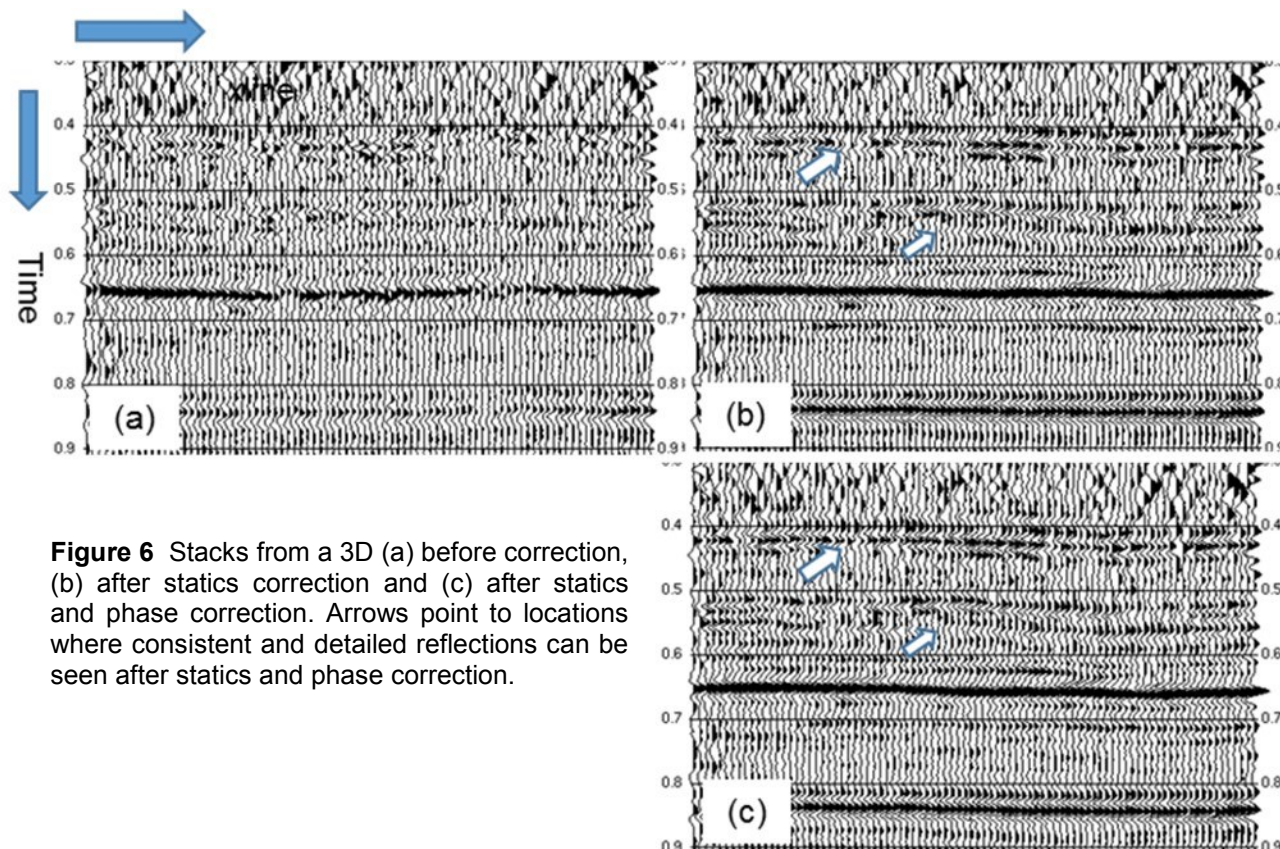


Figure 6 Stacks from a 3D (a) before correction, (b) after statics correction and (c) after statics and phase correction. Arrows point to locations where consistent and detailed reflections can be seen after statics and phase correction.

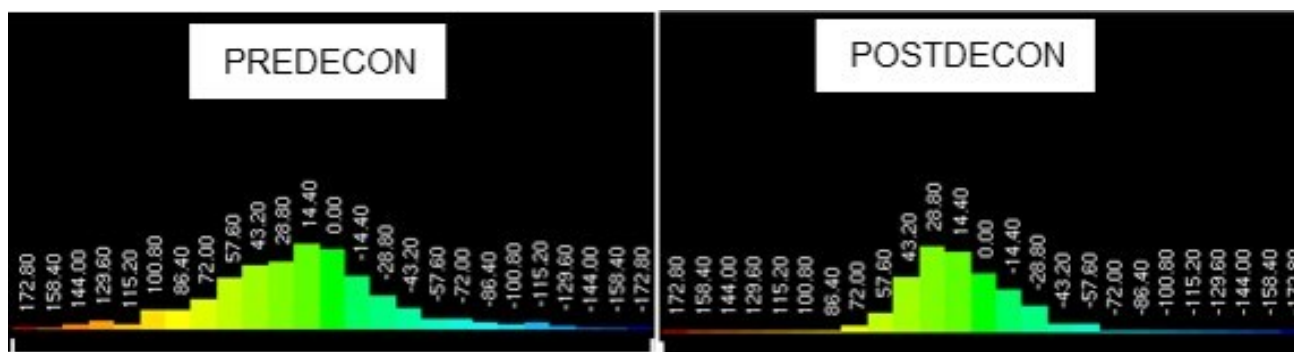


Figure 7 Histogram of estimated receiver phase correction before (left panel) and after SC decon (right). Post-deconvolution errors range from -90° to 90° . The values in the histogram indicate the bin centres and the height of each bin is proportional to the number of receivers that belong to a bin.