# Transmission effects of localized variations of Earth's visco-acoustic parameters

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## ABSTRACT

In an effort to understand the transmission effects of localized heterogenities in the subsurface, we present the travel-time and amplitude distortions caused by localized variations in velocity and absorption. To examine the relative impact of velocity and absorption heterogeneities on seismic events, we conducted numerical experiments using visco-acoustic finite-difference modeling of the linearized wave-equation for Newtonian fluids. We analyzed the distortions in the midpoint-offset domain. We find that the distortion caused by an anomaly that is both slow and absorptive is different from that an anomaly that is either slow or absorptive, but not both. Our results also indicate that amplitude distortion of highly absorptive anomalies ($Q < 50$) can be comparable to that of small velocity variation (less than 4%), and therefore absorption must be considered in seismic amplitude inversion and AVO analysis.

## INTRODUCTION

Localized heterogeneities in the subsurface cause amplitude and travel-time distortions of seismic reflections from underlying reflectors. These distortions are problematic to imaging and AVO analysis. The distortions come in almost regular patterns and usually are recognizable by V-shaped trajectories in the midpoint-offset domain (X-shapes for split-spread acquisition geometry). These distortions can be used to find the locations of the anomalies, which can reveal valuable information for interpreters such as fault locations (Hatchell, 2000). Moreover, they can be used to invert for velocity and absorption anomalies. The analyses of several authors Vlad (2005), Hatchell (2000) and Harlan (1994) have considered mostly velocity anomalies, which cause focusing and defocusing effects.

In this report, we stress that absorption must be considered in the analysis of these distortions. A seismic amplitude inversion that disregards absorption is likly to be biased, especially if velocity perturbations of interest are less than 4%. We examine the relative impact of localized velocity anomalies versus absorption anomalies on seismic amplitude.

# BACKGROUND

For a constant background velocity with non-dipping reflector, the distortion trajectory (i.e. the location in prestack data space) caused by a single anomaly can be described by

$$h = \frac{t}{t - t_a} \mid m - m_a \mid \quad , \tag{1}$$

where $h$ is the half offset, $t$ is travel-time, $m$ is the midpoint, and $m_a$ and $t_a$ are the midpoint and traveltime location of the anomaly (Vlad, 2005). The trajectory of the distortion is controlled by the background velocity and the geometry of the reflectors (Vlad, 2005). Besides the trajectory, the distortion has a time-signature (i.e. changes in travel time caused by the presence of the anomaly) and an amplitude-signature (i.e. changes in amplitude). Hatchell (2000) showed real data examples of different amplitude signatures caused by faulting. He also showed that the asymmetry of a velocity anomaly causes different focusing effects depending on whether it is encountered in the receiver leg or source leg, which means the signature can be asymmetric. The signature of an anomaly depends on it's size, shape, type (i.e. velocity, absorption, or both), and the strength (departure from the background velocity and/or absorption).

Considering only type of the anomaly for this study, we use a constant-background velocity and constant-background Q-factor with non dipping-reflectors. Although simple, this geologic model of non-dipping reflectors exists in many geologic provinces, which justifies using it here.

# VISCO-ACOUSTIC MODELING

For this study, several seismic experiments were simulated using many different geologic visco-acoustic models. The models are parametrized by three fields for velocity, density, and Q-factor (i.e. the Q-factor for the peak frequency in the source wavelet used). Direct wave-equation modeling was conducted using time-domain finite differencing of the linearized wave equation for Newtonian fluids (Mavko et al., 2003). Finite differencing was explicit in time, and the spatial derivatives were computed in the Fourier domain to attain better accuracy.

A problem with using the linearized wave equation for Newtonian fluids is the acausality, which was observed as negative time shifts in some of our test cases (see Figure 1). Those time shifts, however, are extremely small and can be observed only after dense resampling, which is unreasonable considering the accuracy of our numerical modeling. For this study, only the time shifts of the maximum absolute amplitude are considered.

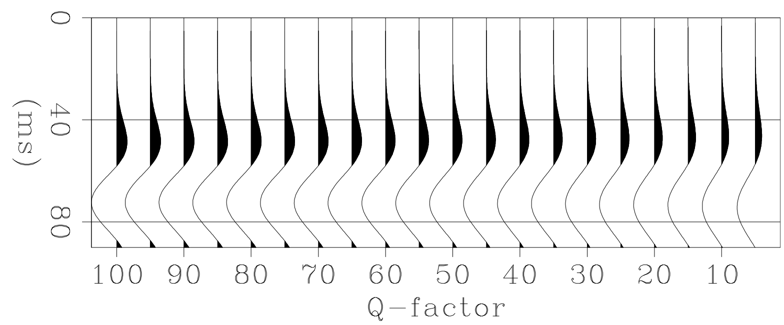


Figure 1: Distortions of a wavelet after passing an absorption anomaly. The amplitude drop as a function of Q-factor is accompanied by a wavelet stretch and a shift of the zero crossing. **[CR]**

## EFFECT ON REFLECTED WAVES

The models used to analyze transmission effects on reflection data have four reflections caused by density contrasts in a constant-background velocity and constant background absorption medium. Four different possible models are considered, two of which are shown Figure 2. In the first model (left), there are three slowness anomalies with a velocity that is 2% less than the background velocity (3000 $m/s$). In the second model (right), the three anomalies are replaced by absorption anomalies with same shape and size. These absorption anomalies have a Q-factor 50% less than the background Q-factor ($Q = 100$). The third model has the both the velocity and absorption anomalies. In the fourth model, a similar model, but without the anomalies, was used as a reference model for the subsequent analysis.

To measure the effect of the anomalies, we applied NMO correction to the seismic events coming from the reference model. Then, the maximum amplitude $A_{ref}$ of each reflection event and its arrival time $t_{ref}$ were picked (trace by trace). The same procedure was applied to the resulting data from the models with anomalies to obtain $A_{max}$ and $t_{max}$. Time delays are then computed by taking the difference of the arrival times,

$$\delta t = t_{max} - t_{ref}. \tag{2}$$

Figure 3 shows the travel-time delays $\delta t$ of the maximum amplitude (caused by the presence of the anomalies) sorted into the midpoint-offset domain. The maximum amplitude differences normalized with the amplitude of reference reflections (i.e. reflections if the model had no anomalies) were computed using

$$\delta A = \frac{A_{max} - A_{ref}}{A_{ref}}, \tag{3}$$

and are shown in Figure 4.

Each row of the Figures 3 and 4 corresponds to one of the four reflectors; the top rows are for the shallowest reflector and the bottom ones are for the deepest. The left

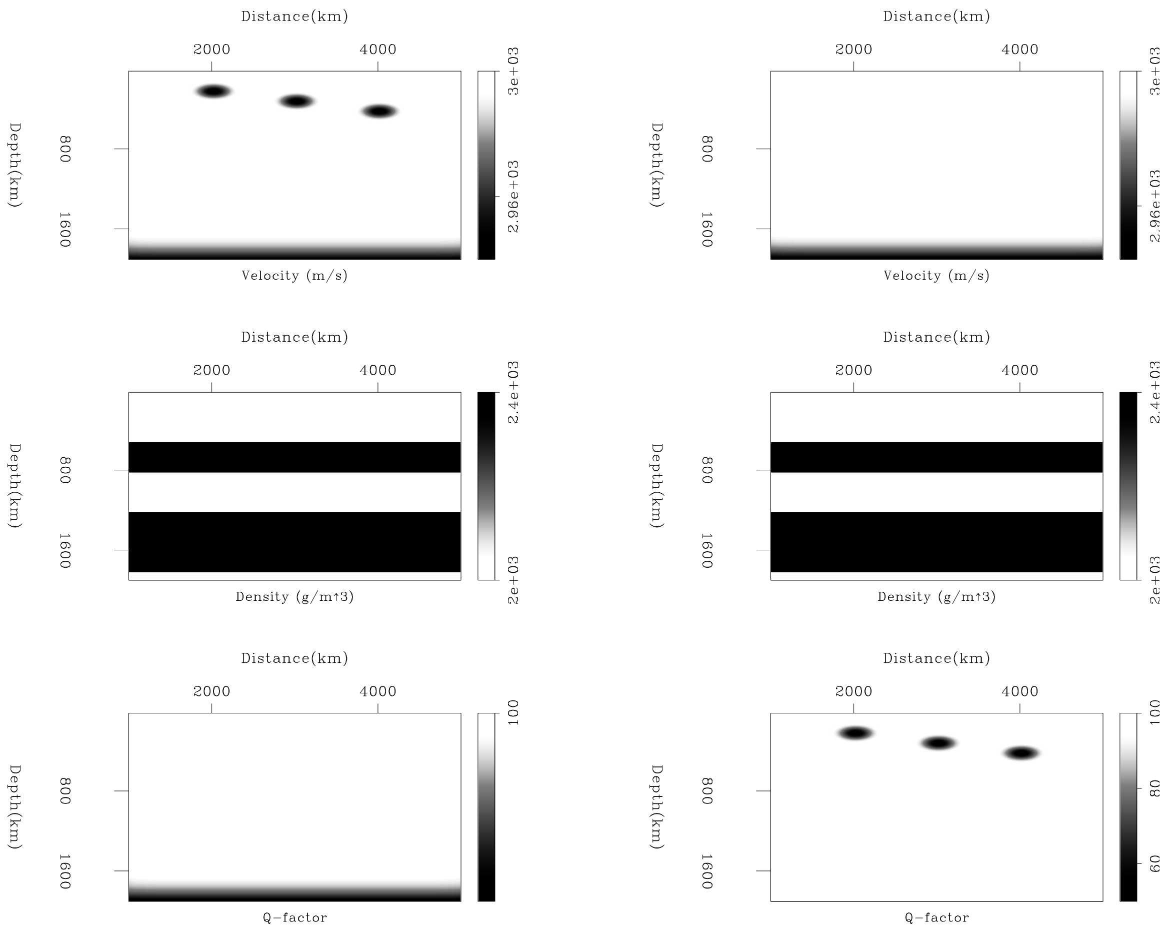


Figure 2: Visco-acoustic models with a constant background velocity (top) and Q-factor (bottom), with four density (middle) reflectors, and three anomalies at depths of 100 m, 200 m and 400 m. Left: the anomalies are velocity variations of 2% from the background velocity. Right: the anomalies are absorption variations with Q-factor 50% less than the background.[**ER**]

columns of the two figures are for the data resulting from the left model in Figure 2, and the right columns are for the right model in Figure 2.

Each anomaly in the model causes an X-shaped signature centered at the midpoint location of the anomaly. The arms of the shape generally spread further apart and each becomes broader with increasing offsets. The trajectory angle (i.e. the angle between the arms of the X-shape) is generally narrower for the deepest anomaly, especially for the first reflector, with which the anomaly coincides. This distinction, however, is gradually lost with increasing depth of reflectors, as shown in the fourth reflector, where the trajectory angles are almost the same for all three anomalies.

As expected, the slow anomalies cause time delays (positive shifts) as shown in the left side of Figure 3. The magnitudes of the time shifts are smaller for deeper reflectors, and span a larger range of offsets, which results in fatter patterns. Absorption anomalies cause almost no time shifts. The width of the signature is less dependent on increasing offset. Instead, it depends on the depth of the anomaly.

Amplitude distortions in Figure 4 show trajectories similar to time shifts in the midpoint-offset domain. The magnitude of the distortion generally decreases with depth, and becomes less focused with increasing offsets. The arms of signatures narrow with depth. Because of tilting of the upcoming waves, the energy is confined closer to the source and stretches with increasing offset. This causes the asymmetry of the signatures about the axes of the arms. Velocity anomalies cause focusing. Therefore, we have higher amplitudes paired with two shadow zones (drops in amplitude), as shown in the left side of Figure 4. The absorption signature, on the other hand, shows only a drop in amplitude. The width of the absorption signature is generally smaller than that of velocity because of the absence of focusing.

From Figures 3 and 4, we can observe that the time delay of the velocity signature is strictly positive, and the amplitude signature has a doublet of positive and negative amplitude changes. The absorption amplitude signature is strictly negative, with no time shifts. It should be noticed, however, that that the magnitude of the absorption amplitude distortions matches those of the velocity distortions. This is shown in the two cases presented. Figure 6 shows amplitude changes to the zero-offset reflection that passes twice through an anomaly (left). The changes in amplitude are shown as functions of percentile change of velocity (middle) relative to the background velocity ($v = 3000\ m/s$), and Q-factor (right) relative to the background Q-factor ($Q = 100$). The range of amplitude drop due to absorption is generally similar to that caused by the velocity changes of interest ($< 5\%$).

Figure 5 shows the time signature (left) and the amplitude signature (right) for the third model, i.e. the model with both velocity and absorption anomalies coinciding. The time signature looks similar to that of slowness-only anomalies. The amplitude signature is more complex than the two velocity-only and absorption-only cases. For the near offsets, the focusing effect and the absorption effect cancel each other leaving only two parallel shadow zones. The focusing effect dominates the amplitude signature at the far offsets and we see the dim-bright-dim signature again. From this, we

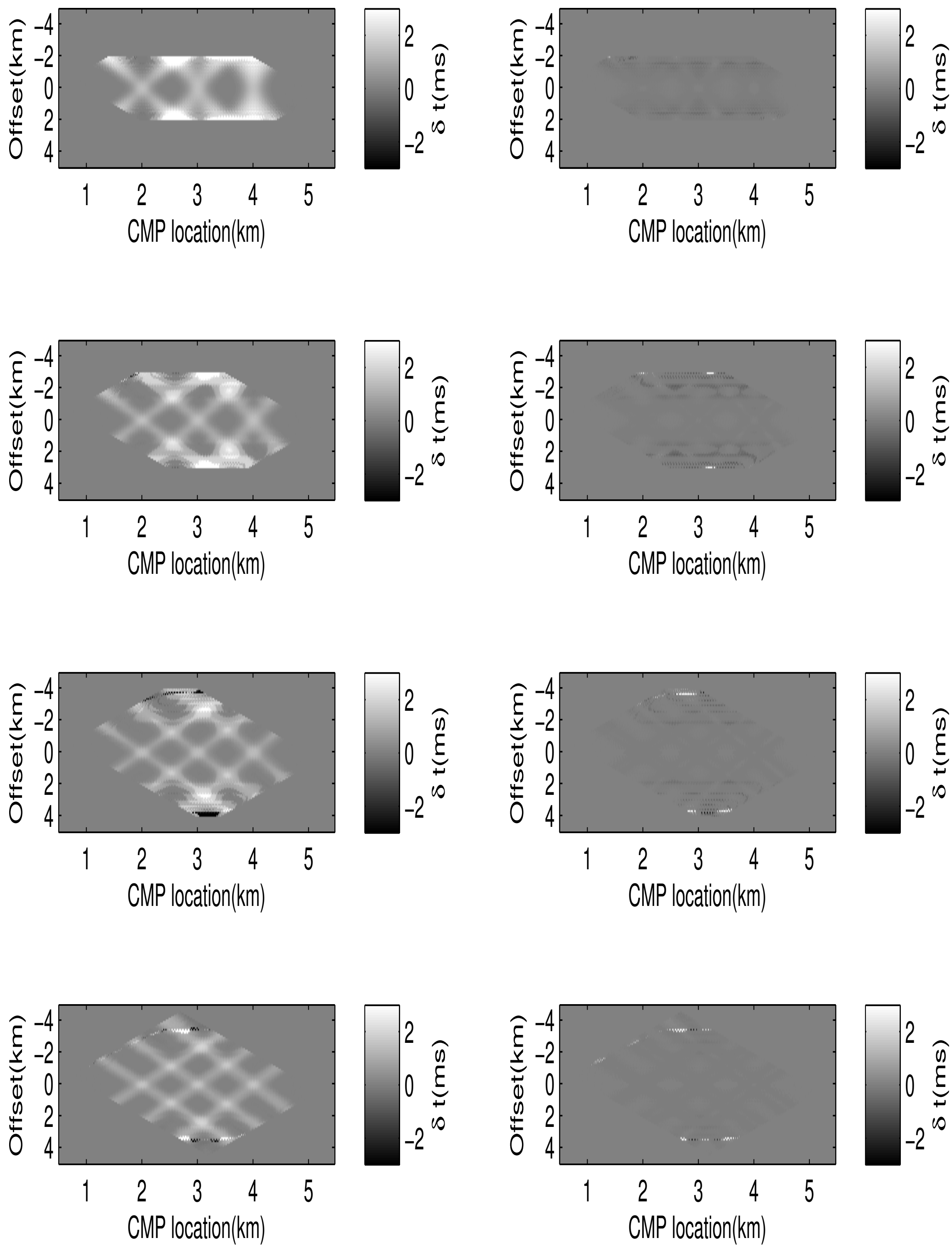


Figure 3: Time delays caused by the velocity anomalies (left) and absorption anomalies (right) on on the four primary reflections, the shallowest (top) to the deepest (bottom) in the midpoint-offset domain. **[CR]**

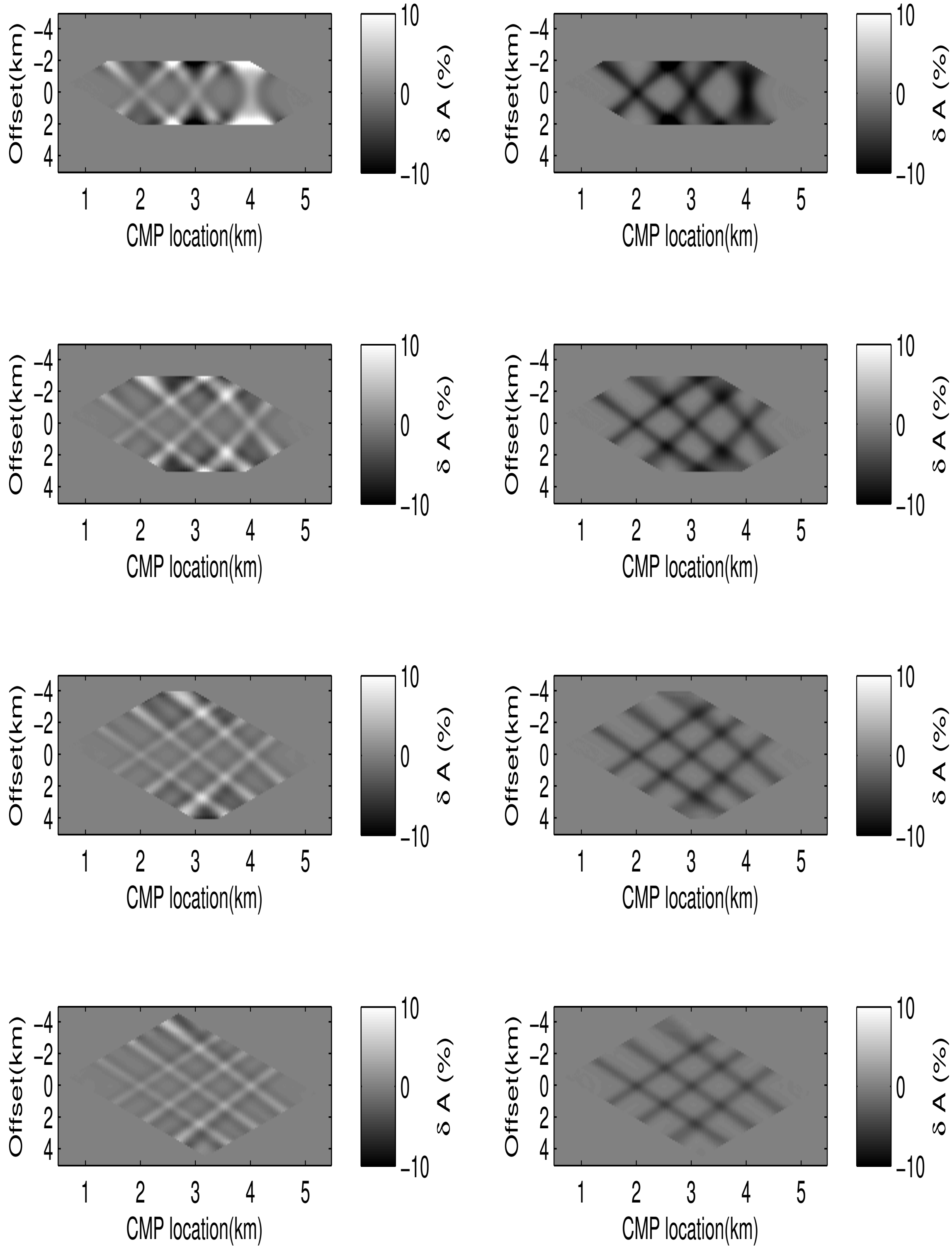


Figure 4: Amplitude changes caused by the velocity anomalies (left) and absorption anomalies (right) on the four primary reflections, the shallowest (top) to the deepest (bottom) in the midpoint-offset domain. **[CR]**

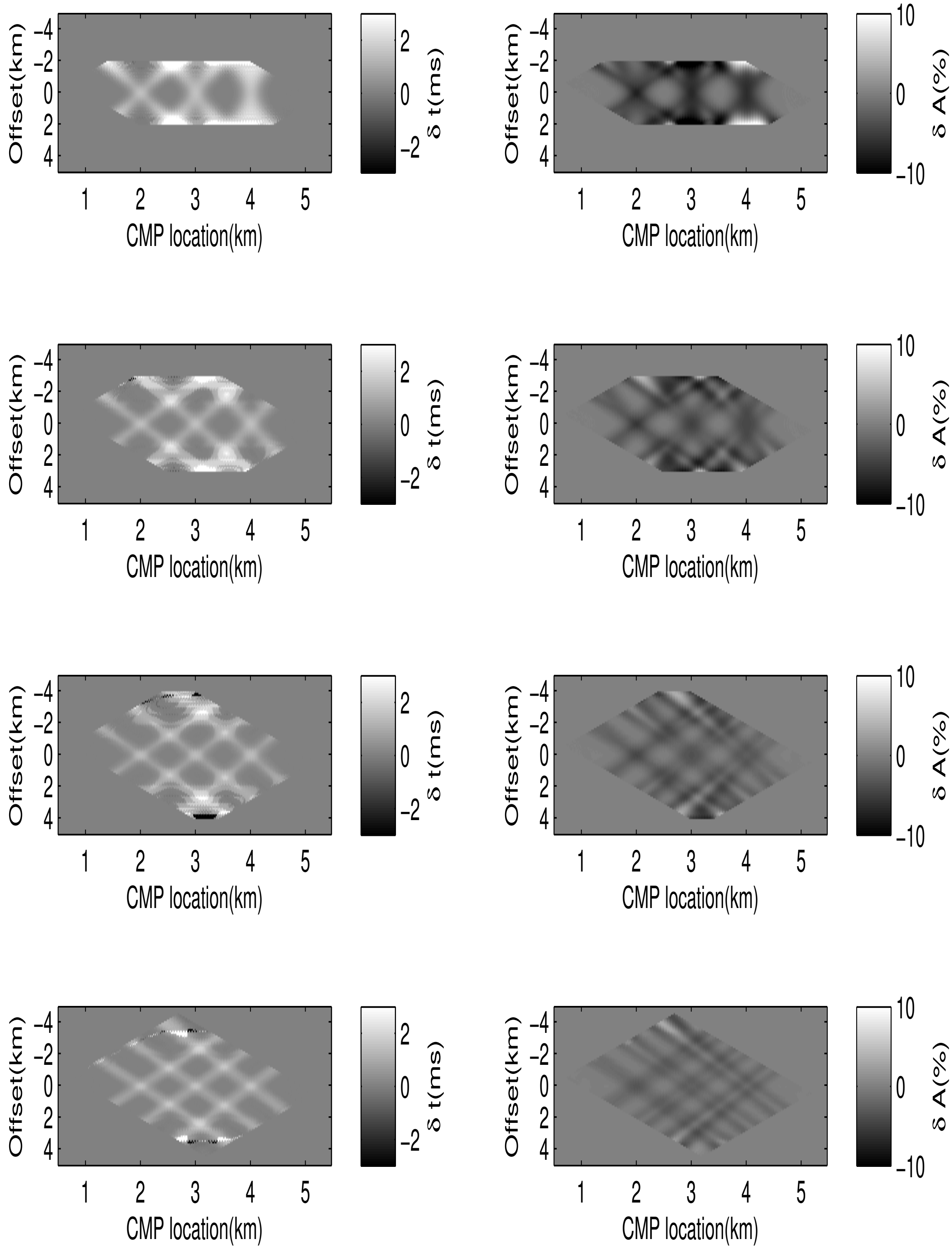


Figure 5: The time (left) and amplitude (right) changes to reflections from the shallowest (top) to deepest (bottom) caused by anomalies that are both slow and absorptive. [**CR**]

can see that the near offsets play a significant role in determining the presence of absoroption. Missing or noisy near offsets can potentially cause the velocity-absorption effect to be mistaken for velocity-only effect.

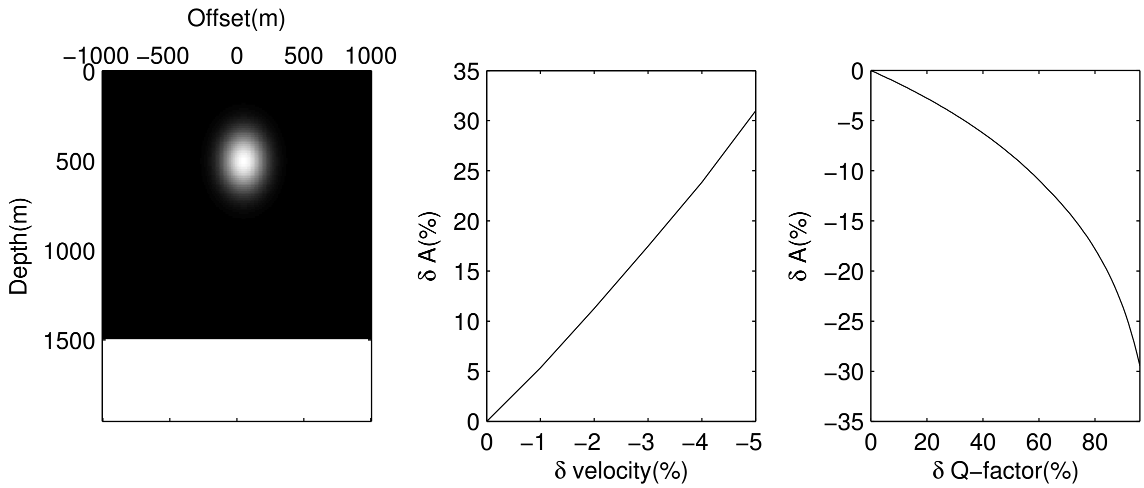


Figure 6: Left: a geologic model of a single reflector and an anomaly that will perturb the primary reflection. The changes of the zero offset reflection are normalized with respect to unperturbed reflection. The amplitude changes as a function of percent change in velocity (middle) or Q-factor (right). [**CR**]

## CONCLUSION

In this report, we showed that localized variations in velocities and absorption have smooth effect on seismic amplitude with increasing offset and can hinder AVO analysis. We also showed that the effect of highly absorptive anomalies on seismic amplitude can be of the same magnitude as the effect of small velocity perturbation. Consequently, a possible cancellation of concurrent effects of velocity and absorption can cause different amplitude signatures, which could be confused with the signature of smaller absorption or velocity anomalies.

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