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Modeling Seismic Signature of Small Faults from Outcrop Analogues

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The application of outcrop analogues to seismic modeling of fractured reservoirs has been limited to fracture orientation for seismic anisotropy. This study presents a method to translate fracture spacing data into relative values of Hudson's crack-density parameter (Hudson, 1981); and a method to evaluate the effect of stress and fracture orientation on crack density distribution.

Roughness of fracture surfaces impedes immediate fracture closure under any confining stress. We can represent fractures, and specifically joints with rough surfaces, as a by a population of aligned cracks with given crack density and aspect ratio density distribution. For fractures of similar origin, it is reasonable to assume that one of these distributions describe the average roughness of the fracture set. Based on that assumption, we can translate fracture spacing into the crack-density parameter.

In order to evaluate the effect of confining stress, we applied Mavko's solution for closure of nonelliptical cracks (Mavko and Nur, 1978; Mavko et al, 1998). We have generated a random gamma density distribution to describe a population of cracks with a specified crack-densities and aspect ratios. Mavko's solution determines the aspect ratios that will be closed under the applied stress. Closure of cracks with those aspect ratios reduces the crack density, allowing us to evaluate the effect of stress and fracture orientation on crack density distribution.

These two methods allow us to generate synthetic seismograms using outcrop data, to model the seismic signature of small faults. The results help to explain the signature of subseismic faults in gas-filled fractured limestones in the Lower Cretaceous of Texas.

Fracture Frequency Distribution and Crack Density

Traditionally, fracture frequency distribution has been thought as controlled by the radius of curvature in bending layers, however other factors like shearing along either fault planes or bedding planes play a significant role on fracture clustering and localization. As an example we present two scan-lines parallel to bedding strike, which show the variability of fracture frequency associated to fault offset (Fig. 1). Fracture spacing within the fault damage zone (Fig.2) can be less than 1 cm, and there can be different sets and hierarchies of fractures. We have assumed a fracture frequency of 100/m as an acceptable estimate of the maximum fracture spacing within the damage zone.

Fracture intensity can be described in terms of the fracture-spacing index (*I*) defined by Narr (1991) as the ratio of bed thickness (*T*) to fracture spacing (*S*). In brittle rocks, most of the fractures are joints and sheared joints, which are formed by two well-defined surfaces. If these surfaces were completely smooth, then these joints would be closed even under low confining stresses. But since these surfaces have roughness, they can preserve open areas even under high confining stresses (Bandis et al, 1983). The ratio of the contact area to the total area of the joint surface provides a first order estimate of the degree of joint closure.

The area of the joint that is still open can be represented by a series of aligned cracks. If we assume that all the joints have similar roughness, then a good estimate of the maximum crack density for a given sedimentary layer of thickness (*T*), can be obtained under the assumption that the diameter of these circular cracks equals the layer thickness. In this case the crack density parameter (Hudson, 1981; Mavko et al, 1998) can be approximated by the expression

$$\varepsilon \approx \frac{I}{8} \qquad (1)$$

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where *I* is the fracture index. However, since the crack density depends on the area of contact, it will change as this area decreases or increases according to the applied confining stress.

Crack Density and Confining Pressure for Nonelliptical Cracks

In order to estimate the effect of confining stress on crack density, we have used the solution for closure of nonelliptical cracks (Mavko and Nur, 1978). These cracks have blunted ends and shorten as well as thin under applied pressure (Mavko et al, 1998). We have also assumed that the entire population is composed by cracks with different initial aspect ratios and characterized by a gamma probability density function (Fig. 3). The closure criteria is determined by the applied stress (*Sn*) and the rock elastic properties, in terms of the initial aspect ratio (α_0), as follows:

$$\alpha_0 = \frac{4(1-\nu^2)Sn}{E} \qquad (2)$$

where *E* is Young modulus and ν is Poisson's ratio. As the confining stress increases, cracks with α_0 below the specified threshold will close, decreasing the initial crack density.

Modeling Seismic Signatures from Fracture Spacing Data

Fracture index can be determined from fracture spacing measured directly from outcrops. The maximum crack density occurs at surface, where confining pressure is negligible, and can be estimated from fracture index (Eqn. 1). Starting from that estimate, we applied the method outlined in the previous section to incorporate the effect of confining stress on crack density. As a result, crack density values decrease dramatically at subsurface (Fig. 3, upper left). Once we have obtained these crack density values, we applied Hudson's model (Hudson, 1981; Mavko et al, 1998) to estimate the effect of fractures on normal-incidence reflectivity. Hudson's model requires crack density values to be normalized to a maximum of 0.1.

Based on our field observations of the relationship between fault offset and damage-zone width, we created a simple earth model with a shale interval overlying tight sandstone with a fault damage zone about 100 m wide, limited by two faults. This damage zone may correspond to faults of about 10 to 20 m vertical offset. To incorporate the distribution of fracture intensity, we took the fracture spacing data as measured in a low-density fracture region (Fig. 1), and the high fracture density observed within the damage zone between two relatively small faults with offset less than 10 m (Fig. 2). We assigned a maximum fracture frequency of 100 fractures/m to the breccia zones.

To evaluate the effect of offset and seismic frequency, we created synthetic seismograms for different fault offsets and seismic frequencies. Our results indicate that the ability to resolve fault offset from flexure is limited to offsets larger than $\lambda/8$, where λ is the seismic wavelength. However, the effect of the faults can be observed as a flexure even for offsets about $\lambda/16$. In any case, the higher fracture frequency at the fault zone decreases the acoustic impedance, generating an amplitude anomaly within the fault zone. These results correspond to normal incidence on a single interface, for vertical fractures. We did not incorporate the effect of fluids or angular incidence (AVO). The effect of uncompressible fluids, like water, will decrease the impact of fractures on impedance. Nevertheless, an analysis of elastic impedance may enhance the visualization of the lower bulk and shear modulus within the damage zone.

References

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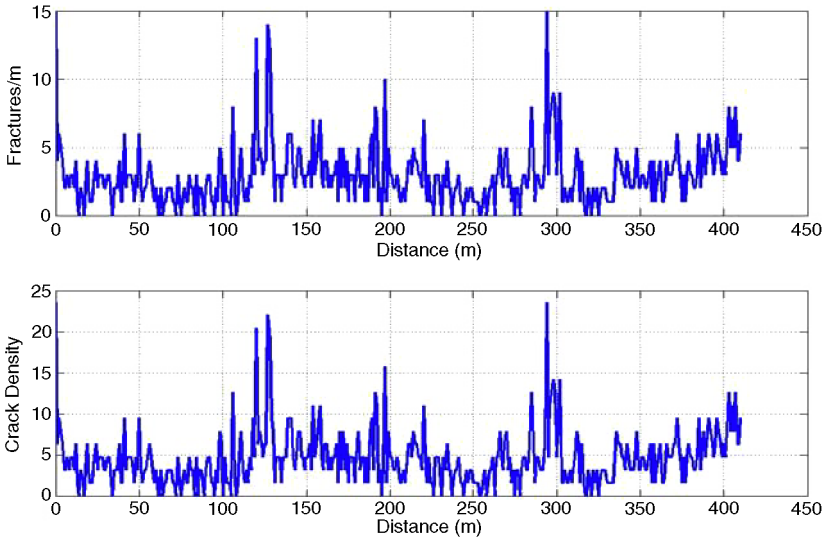

Figure 1: Fracture frequency (above) and the corresponding crack density (below) estimated for a 12 m-thick layer, in a region with low fracture intensity.

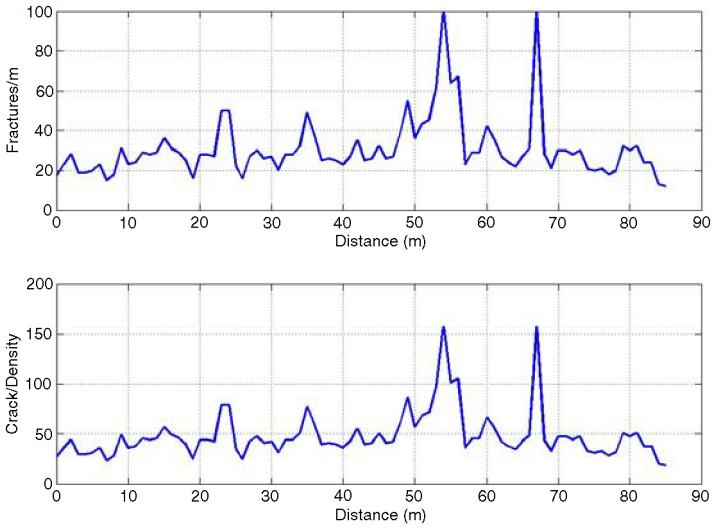

Figure 2: Fracture frequency (above) and the corresponding crack density (below) estimated for a 12-m thick layer, within the damage zone between two faults with offset less than 10 m.

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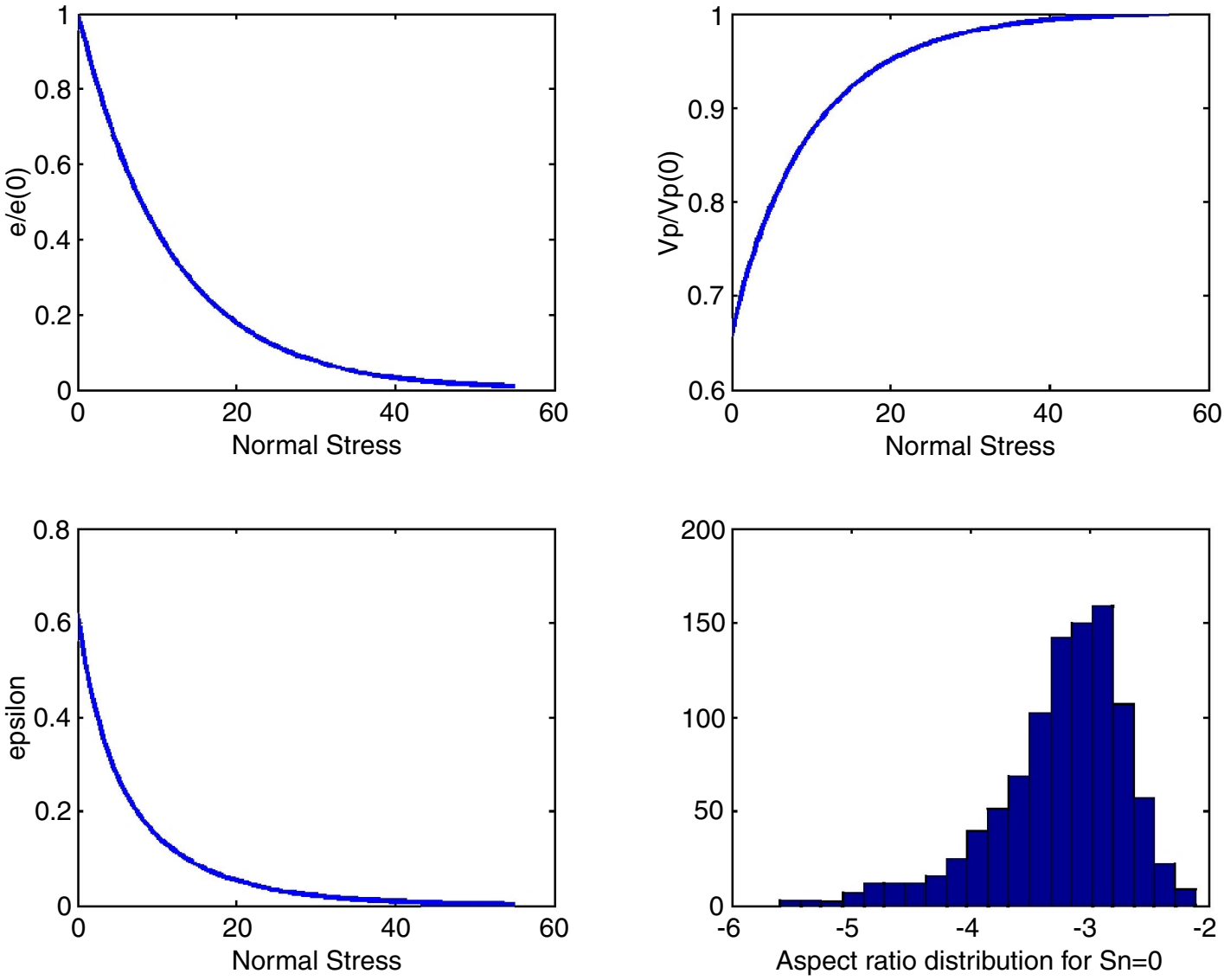

Figure 3: Results from the algorithm used to estimate the effect of confining stress on crack density. Units of the applied normal stress (Sn) are MPa. The ratio e/e(0) corresponds to the ratio between the initial and the final crack densities. Similarly, Vp/Vp(0) indicates the ratio between the initial and the final P-wave velocities. Epsilon is Thomsen's parameter (Thomsen, 1986) for weak anisotropy. The histogram shows the probability density function assumed for the logarithm of the aspect ratios of the initial crack population.

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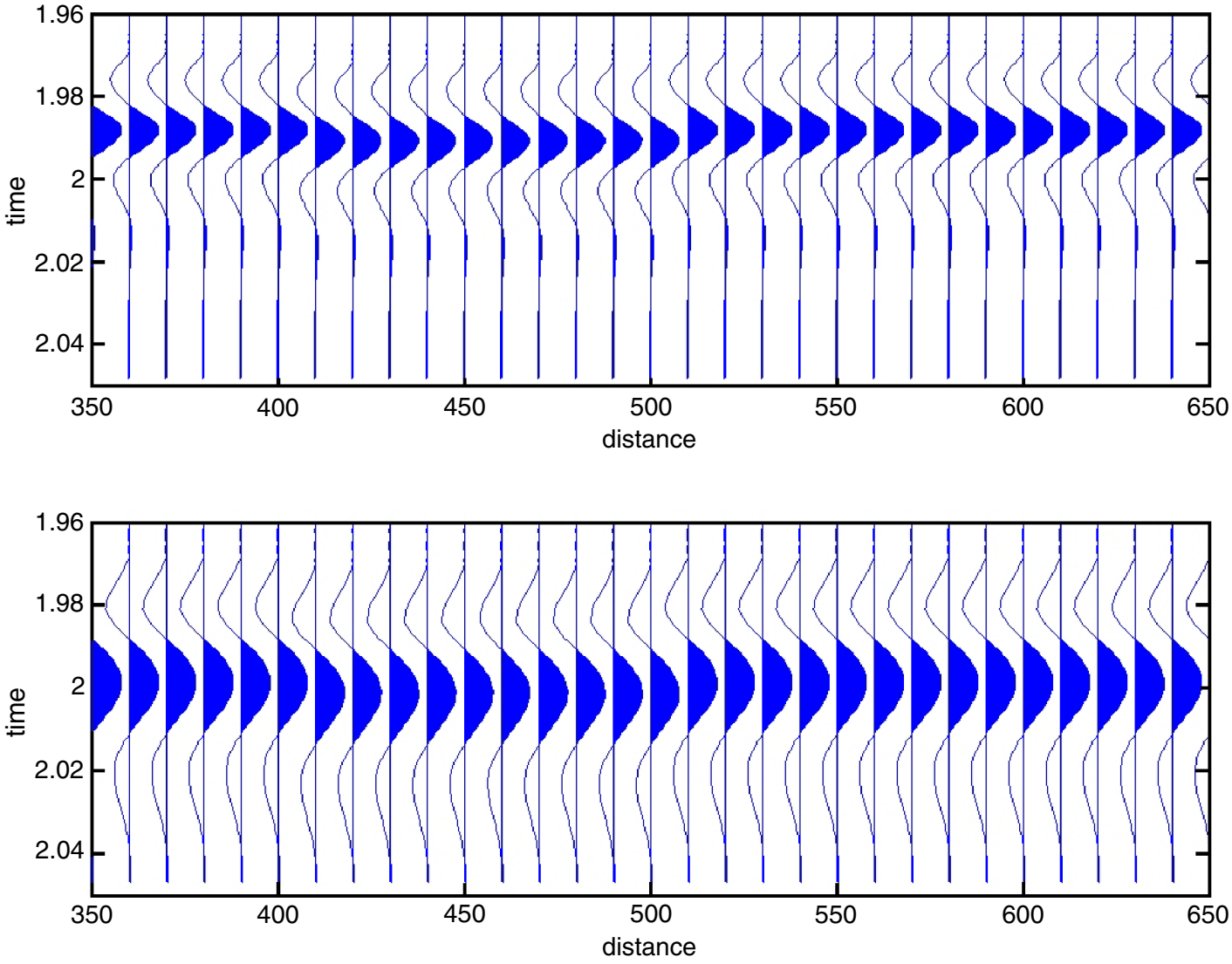

Figure 4: Synthetic seismic section for interface with 10 m offset. For the high frequency section (25 Hz), the offset is about $\lambda/8$. For the lower frequency section (50 Hz) the offset is about $\lambda/16$.

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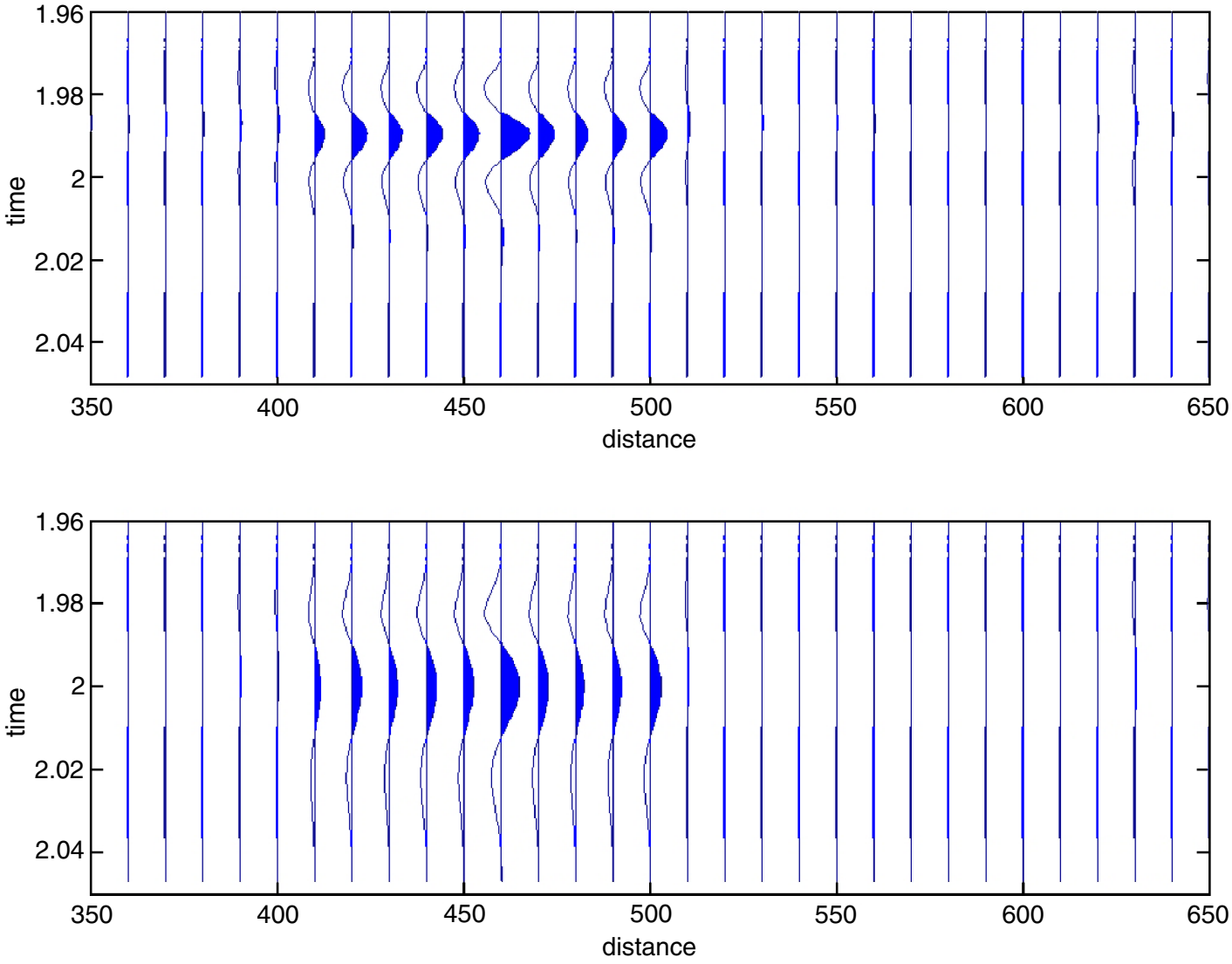

Figure 5: Amplitude anomaly for normal incidence reflectivity, as calculated from the higher fracture intensity within the damage zone.

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