COMPARISON OF RECOVERY METHODS OF THE SEISMIC AMPLITUDE FROM EFFECTS CAUSED BY THE ATTENUATION AND DISPERSION OF THE MEDIA

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Abstract

The attenuation and dispersion phenomena imply difficulties in exploratory work, the consequences of these phenomena range from the improper processing of seismic data to the inaccurate calculation of the reservoir volume. The inverse Q filtering is a compensation technique to this effect, and its purpose is to restore the amplitude and the signal shape. Although the inverse filtering Q is an established technique, it is unstable in its basic form; thereby stabilizing this technique is need for the improvement of the inverse Q filtering effectiveness. This work deals with the evaluation of results of three inverse filtering techniques Q that are applied to a synthetic seismic data from a numerical simulation performed by finite difference, of wave propagation through a viscoelastic medium. It´s build planes parallel three-tier model, in which the intermediate layer has more dispersive properties over the other. In this way, we can apply the inverse filtering techniques Q and verify the effects of filtering at second from above and bellower reflector the dispersive interlayer. This work compared the effectiveness of the following inverse filtering techniques Q: Kolsky in basic form, Kolsky in stable and GLS (general linear solid).

Introduction

Carbonate rocks in Brazilian pre-salt reservoirs are still a technological challenge from the exploration point of view. Image methods are being improved overcoming difficulties. Effects of attenuation and dispersion are physical characteristics of the phenomenon of propagation of elastic waves in the substrate. The dispersion is the delay of the phase of the recording of the arrival of the wave without receiver, while the attenuation is an absolute decrease of the value of the amplitude of the temporal seismic record. The effects involve loss of information in exploratory seismic studies. The phase delay and deformation of the original wave shape are consequences of the dispersion effect which is related to a faster displacement of the high frequency signal components with respect to the attenuation of the low frequency components (WANG, 2009). Intrinsic attenuation in turn is a consequence of geometric scattering and the Joule effect, which is energy dissipation in heat by particle friction.

The recovery of the attenuation and dispersion effects is a process performed through a mathematical filter where in input is an attenuated signal and the output is the dispersion effect corrected signal. This technique is called in the geophysical literature as the inverse Q filtering, where Q is the quality factor and it´s physical meaning is a rate of energy loss per cycle. When Q is a function of the frequency, there are counts in the energy loss rates for the cycle for the different frequency components; the signal shape is characterized by dispersion of the high frequencies, phase delay, and deformation of the seismic record.

The inverse Q filter corrects the effect of the dispersion and results in a better fit between the seismic data and the synthetic data in inversion processes in which the observed seismic data had been corrected by the Q factor. The use of the inverse Q filter increases a frequency band and decrease deformation of wave shape. After application of the inverse Q filter, the target reservoir, the thin vertical thickness was clearly evident (WANG, 2008). The reverse filtering process demands two fundamental inputs: the attenuated signal and estimated average quality factor. The estimation of the quality factor also counts on several techniques. In the case of synthetic testicles, the average quality factor can be estimated by a simple time-weighted average of the Q factor (LUPINACCI, 2015).

In this work, three different Q-filtering techniques were tested and input data were plotted from finite difference seismic modeling (BOHLEN, 2002). These filters were tested for noise input and their error level so that they could be compared to each other. The seismic modeling employed generates two classes of outcomes: elastic data and viscoelastic data. Traces of three receivers closer to the source and from the viscoelastic modeling were filtered by three different methods and compared to the elastic simulation treatments, so that the relative efficiencies of the three filters were analyzed.

Method

Elastic modeling has been widely used to simulate the propagation of in a medium. This method takes into account the effects of spherical divergence, reflection, refraction, wave energy separation and diffraction. However, the elastic modeling does not take into account the dispersion effect (MOCZO, 2007) that is caused by a lag between the deformation of the solid rock and that of the fluid that saturates and the scattering of the elastic energy (ROMANELLI, 2010).

It is possible to find several approaches for the direct modeling of wave propagation and its application can answer several questions in seismic data processing. Direct modeling can be applied, for example, as quality control in inverse problems due to the lack of theorems to demonstrate the effectiveness and reliability of in data inversion. Thus, direct modeling is an approach for verifying the applicability of data inversion rebuilding the model from it´s synthetic. Several techniques of modeling have been developed throughout history, such methods include wave number integration, eg: Reflectivity Method (MULLER, 1985), Ray Tracing (CEVERNY et al., 1977), Finite Elements (CHEN, 1984) , Pseudo Spectral Method (KOSLOFF and BAYSAL, 1982), and Finite Differences (ALTERMAN and KARAL, 1968). Among the methods mentioned, the one employed in this work is the Finite Differences approach because it simulates the propagation of seismic waves along an arbitrary heterogeneous environment (BOHLEN, 2002).

For this study a three-layer parallel plane digital geological model was constructed. Viscoelastic properties for wave propagation along a highly dispersive environment Q = 60 between two relatively low dispersion layers Q = 100 were employed in to build a model for the simulation. Thus, the simulation contemplates properties: Vp, Vs, density, thickness and Q. Carbonate reservoirs, due to anisotropy, can also be well represented as dispersive material. Two simulations were carried out on this model, one taking into account only elastic properties, while the other one also took in account the dispersive properties. The elastic register was used as a matching reference comparing the result of the corrections on viscoelastic data. The Kolsky and SLG models are applied separately on the resulting record of a viscoelastic simulation.

Table 1: Parameters set in elastic and viscoelastic model (i.e. plus Q_p and Q_s)

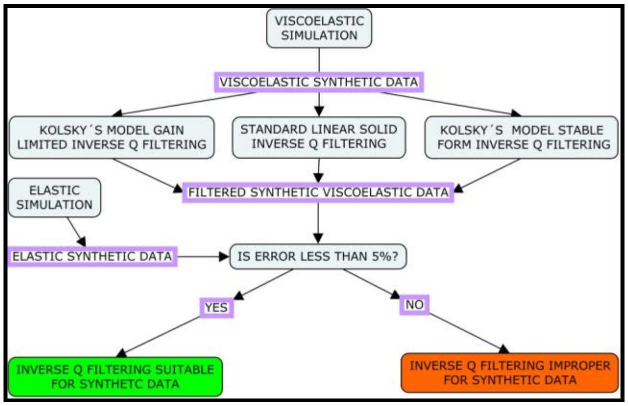
	Vp(m/s)	Vs(m/s)	rho(kg/m³)	h(m)	Qp	Qs
Bed 1	2000	1200	2000	800	100	60
Bed 2	2500	1500	2300	1600	60	40
Bed 3	3000	1800	2600	-	100	60

Note: layer 1: consolidated sediments, layer 2: unconsolidated sediments (reservoir), layer 3: consolidated sediments.

There are three filters implemented in this work: based on the Kolsky model, frequency stabilization of the Kolsky model and the inverse filter Q based on the general linear solid theory. Gain limited Kolsky and stabilized Kolsky had their implementation from models of attenuation coefficients and phase velocities. The stabilization for the Kolsky filter comes from a reformulation of the basic Kolsky model. This stabilization allows a wider set of spectrum frequencies to be included in the filtering without any divergence (WANG, 2008).

In the General Linear Solid model, its physical principle, described in its name and discussed in the bibliographic review, is the same as the principle used in the SOFI3D modeling implementation. Thus, it is expected that Kolsky's inverse Q filter in both its basic gain limited and stabilized form and the inverse filter of the general linear solid would have different effects on the correction of the attenuation and dispersion effects when applied in traces from the viscoelastic simulation. Likewise, it´s possible to validate which model fits better to finite difference viscoelastic wave simulation.

Figure 1: Workflow illustrating the approach employed.



The implementation of inverse Q filtering algorithm based on Kolsky gain limited is based on Equation 1 and follows the following script:

Equation 1:

$$U(\tau+\Delta\tau,\omega)=U(\tau,\omega)\exp\left(\left(\frac{\omega}{\omega_h}\right)^{\frac{-1}{\pi Q}}\frac{\omega\Delta\tau}{2Q(\omega)}\right)\exp\left(i\left(\frac{\omega}{\omega_h}\right)^{\frac{-1}{\pi Q}}\omega\Delta\tau\right)$$

(1) The Fourier transform is applied to the trace.

(2) The amplitude spectrum is taken respecting the stability limit of frequencies smaller than | 2Q / dt | <0,125 rad.

(3) Equation 1 is applied to the limited amplitude spectrum in step 2.

(4) The inverse transform is applied on the filtered spectrum in step 3. The filtered trace is obtained.

Following up the inverse Q filtering based on Kolsky stable form (WANG, 2002) are grounded on Equations 2 and 3. Both equations refer respectively to stabilizer and to the frequency/time domain stable filter. The ratio of amplitude spectrum to the square of the same characterizes the stabilizer implementation, thereby intelligently eliminating frequency domain anomalies. Considering that the square of the amplitude diverges more rapidly in the limit to infinity of frequencies than the amplitude itself, and then the ratio of the spectrum to its square would tend to be null. Therefore, the absolute ratio of the spectrum to its square is always less than 1. This process allows a larger set of frequencies to be used in the reverse filtering Q without divergence.

Equation 2:

$$\Lambda(\tau,\omega)=\frac{\beta(\tau,\omega)+\gamma^2}{\beta^2(\tau,\omega)+\gamma^2},$$

Equation 3:

$$U(\tau,\omega)=U(0,\omega)\Lambda(\tau,\omega)\exp\left[i\int_0^\tau\left(\frac{\omega}{\omega_h}\right)^{-\gamma(\tau)}\omega d\tau'\right],$$

where β stands for the exponential of Equation 1 that contains only real numbers and γ summon a constant number.

The implementation algorithm of the stabilized form of filtering follows the following script:

(1) The Fourier transform is applied to the trace.

(2) The spectrum of amplitudes is taken over any set of frequencies.

(3) Equation 3 is applied to the limited spectrum in step 2.

(4) The inverse transform is applied on the filtered spectrum in step 3. The filtered trace is obtained.

In this way, the stabilizer allows us to extend the set of frequencies of the input signal for filtering. Thus, for a same set of frequencies and a same time record the basic Kolsky filtering presents a relative amplitude correction climb when compared to Kolsky's filtering in stable form.

The simulation propagation of the wave field that produced the synthetic data for this test is based on the principle of the general linear solid. This model is composed of a sum of standard linear solids. To correct the dispersion and attenuation in the synthetic data produced by the modeling process, the inverse Q filter was implemented and it´s principles are the same as the general linear solid. The GLS filter was built replacing Equations 4 and 5 at plane wave equation (AKI-RICHARDS, 1980). The implementation script is the same of the stable form in exception of the equation at step 3.

Equation 4

$$\alpha(\omega) \approx \frac{1}{v_\infty}\left[\frac{a}{2}\left(1+\frac{1}{2}\omega^2\tau^2\right)+b\right]\frac{\omega^2\tau}{1+\omega^2\tau^2},$$

Equation 5:

$$\frac{1}{v(\omega)} \approx \frac{1}{v_\infty}\left\{1+\left[a\left(1+\frac{5}{8}\omega^2\tau^2\right)+b\right]\frac{1}{1+\omega^2\tau^2}\right\},$$

Where a and b are given by Equation 6:

$$v_\infty = v_r, a = \frac{-8}{7Q_r}, b = \frac{13}{7Q_r}.$$

Examples

For the simulation analysis purposes, as well as the analysis of propagation effects of the elastic and viscoelastic wave fields, instantaneous pictures of the propagation were generated. Snapshots from simulation performed at Sofi3D (BOHLEN, 2002) (Figures 2, 3 and 4). On Figure 2 we remark the fact of the wave front presenting almost the same level of energy for both frames (left and right) at time=0.4s, it is because of the relatively higher Q value assigned to the first bed makes it behave like an pure elastic media in right frame. Successively, on Figure 3 it´s visible a slightly loss of energy at first reflection event wave front (t=0.6s) due significant lower Q value assigned. At second reflection event (t=1s) we observe clearly a meaningful loss of energy due the accentuated bed´s viscoelastic sort.

Figure 2: None relevant energy differences between the frames, t=0.4s.

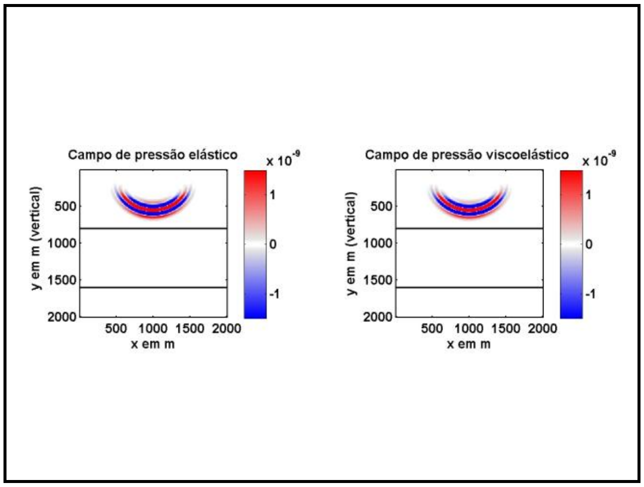


Figure 3: First reflection below t=0,6s, less energy reflected at rigth frame due de viscoelastic properties of inner bed.

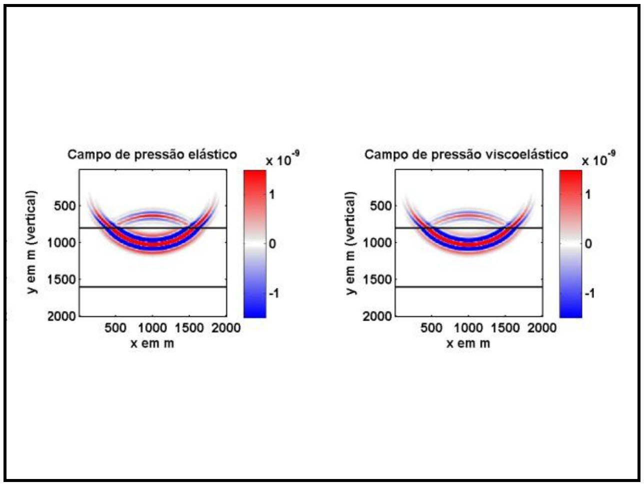
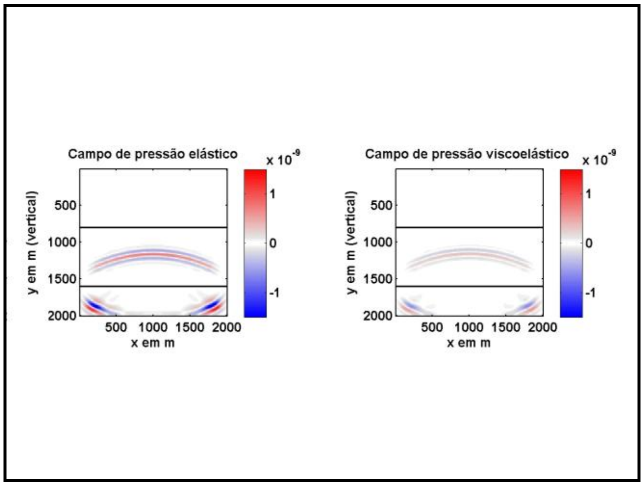


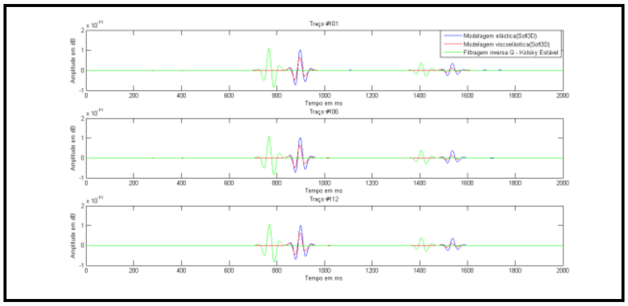
Figure 4: Relevant loss of energy at right frame implies less energy at second reflection due the dispersive bed (t=1s).



Results

It was found by inspection that the inverse Q filtering in stable form works better for the same frequency range of the prior experiment as the base form based filter. Amplitude recovery was effective, with an error of less than 5%. But the correction of the phase was not satisfactory, due to the filtering: the position of the reflectors did not correspond to the position of the model interfaces.

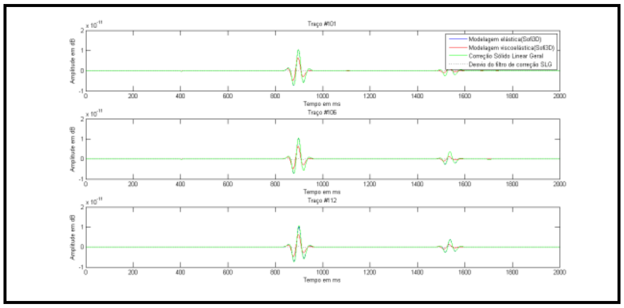
Figure 5: Inverse Q filtering (Stable Form) on viscoelastic simulated trace (red). The filtering outcomes are showed by trace green and the error is the difference between trace two and green.



The stable form inverse Q filter corrects better the elastic trace when compared to the basic Klosky's model. Regarding the frequency content of the correction, it is observed the efficient recovery of high frequencies; however. Regarding the phase, the displacement of the event due to the filtering did not match the position of the reflectors layers in the model.

Even though the stable form was more satisfactory with respect to amplitude correction, it was less satisfactory with respect to the phase correction due to the distance between the events and positions of the reflectors in the case of the viscoelastic simulation.

Figure 6: Trace recovery after Inverse Q filtering GLS



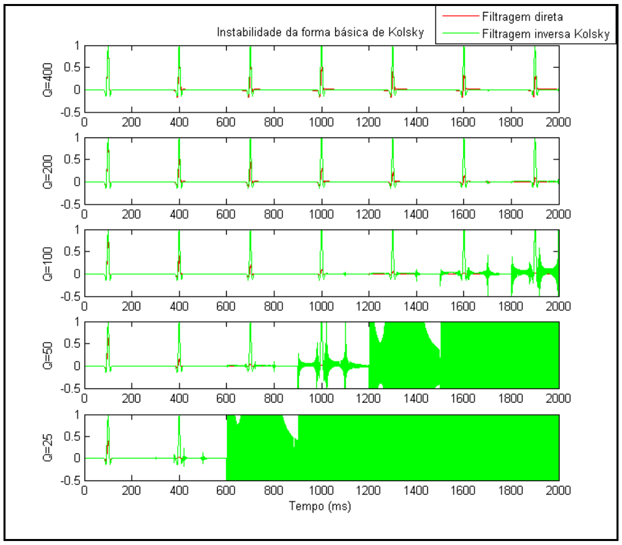
It is observed that the filtering (green line) fits well to the trace of the elastic modeling, from the point of view of the phase; there is no modification of the position of the event in relation to the reflector. SLG filtering corrected the phase and also corrected the amplitude with a maximum error of less than 2.5%.

The choice of the most suitable reverse filter depends on the signal noise level and also depends on the signal source, the literature suggests that the Kolsky model is the best option for the correction of real seismic data. However, in the case of the synthetic seismic record, this depends on the choice of the attenuation and dispersion model used in the modeling. This explains the best adjustment of the SLG reverse filter to the synthetic elastic data of the SOFI3D. Therefore, for the data generated by the SOFI3D the Inverse Q filtering SLG is labeled as the most suitable.

A realistic way to construct a seismic trait is by convolving a minimum phase wavelet with a series of reflectivity. The Ricker wavelet was used so that the phase change was conveniently verified by simple observation of the wavelet shape, as in Wang (2002), the symmetry of the wavelet shape is deformed by the dispersion effect. For this stability test, a signal consisting of a Ricker wavelet sequence with a center frequency corresponding to 60 Hz at t = 100, 400, ..., 1900 ms (300 ms increment) was used. The stability test employs five synthetic traits without addition of noise, each with one of the following values of Q = 400, 200, 100, 50 and 25 constant in depth.

Figure 7 shows the application of direct filtering that has an unconditionally stable behavior; however the reverse filtering has proved unstable for parameterizations where the transit time is long and the Q values are low. The phenomenon demonstrated by this test characterizes a limitation of applicability to the conventional form of reverse filtration. As it is observed, for a value of Q = 100, common of sedimentary rocks, appearance of instability artifacts occurs from 1 s. Most rocks have values of Q between 50 and 300 (Duarte, 1993), so this instability presents a limitation to the inverse filtering technique Q implemented on the principles.

Figure 7: Vertical axis of amplitude, the red dashes show the effects of direct filtering on earth for values of Q = 400, 200, 100, 50 and 25. In green the reverse filtering Q (compensating phase and amplitude) based on the basic form of Kolsky In which the traces clearly indicate the phenomenon of instability.

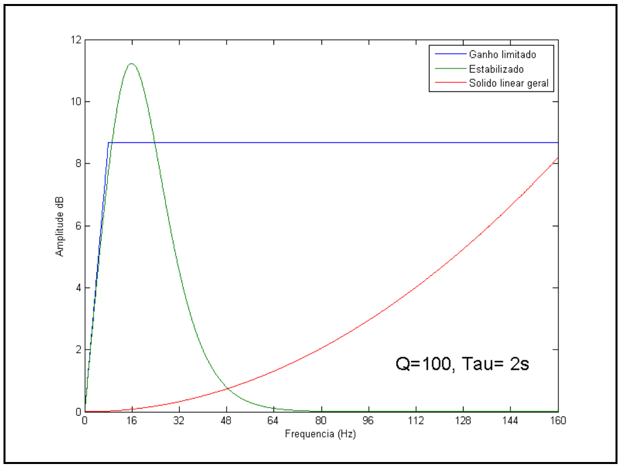


The reverse filtering test that compensates only the phase to demonstrates numerically the univocal stability of this filter component, so it was possible to isolate the instability characteristic for the amplitude correction component of the filter from the basic form of Kolsky (i.e., the first exponential factor of Equation 1). To show the performance enhancement of the limited gain form, when compared to the basic form of Kolsky, a test was made with the same configuration of five strokes each with a constant Q value, however the amplitude component was modified from such (WANG, 2002), if the filtered frequency component is greater than the frequency limit, then the amplitude is assumed to be the unit value. The results for the limited gain test showed insufficient amplitude recovery mainly for low Q values.

The limited gain technique did not show adequate signal compensation. In order to circumvent the deficiency of the limited gain technique, the stable form of reverse filtration was implemented. This method allows all the constituent frequencies of the signal to be contemplated in the reverse filtering, thus allowing the higher frequencies to be contemplated throughout the filtering process and contained in the filtered signal. Therefore, the inverse filtering based on the stable form was more effective.

Comparison of the three amplitude operators (GLS, Kolsky and Kolsky Stable) employed in this work is shown in Figure 8. The amplitude compensation operator is a window filtering the amplitude component of the signal in the frequency domain. The inverse filtering Q has its applicability conditioned to the interval of the trace on which the filtering will be executed, that is: it is up to the operator of the seismic data processing flow to understand by means of tests what would be the best parameterization for the filtering to be carried out.

Figure 8: Comparison between frequency operators



The GLS operator preserves higher frequencies, while the stabilized operator preserves frequencies closer to those contained in the wavelet signal. In this context, the limited gain operator does not override any frequency component.

Conclusions

The viscoelastic modeling was employed in the construction of a dispersive synthetic data, while the elastic modeling was used to validate the three inverse filters applied on the trace from the viscoelastic simulation, thus the filtered viscoelastic data that is closest to the elastic data Error) points to the most effective filtering method. It was clear that parameterization is the fundamental requirement for the success of this technique. In this work, the synthetic data from the elastic and viscoelastic simulations were stable and well represented the attenuated reflection phenomenon that is the object of analysis on which the filtering techniques were tested. The input parameters for the elastic and viscoelastic modeling processes are products of parameterization tests. Reverse filtering techniques based on Kolsky models (basic and stable forms) were implemented and tested. Its stability was verified in relation to frequency and noise level limitations. The techniques were validated for an additive noise level of 5% of the maximum amplitude value and for a range of frequencies below the limit deduced from the filters. In the case of the basic form of the filter there was an overcompensation of amplitudes in relation to the compensation of amplitudes of the stable form for a same frequency limit. Thus, the inverse filter based on the stable form proved to be more effective than the inverse filter in the basic form when applied in viscoelastic data from finite difference modeling. When compared to the methods based on the Kolsky model, the inverse filtering based on the general linear solid model showed a maximum error of 2.5%. This filtering showed an adjustment in the shape of the trace in both amplitude and phase and, therefore, characterized the best efficiency among the filtering techniques presented in this study.

Post-stacked seismic data of carbonate reservoirs located beneath salt formations are ideal for testing these filters. In addition, a systematic analysis of the methods of estimation of the quality factor on these data together with the sonic profile of wells should enable the tests with the inverse filter, thus characterizing which filter model would better correct the effects of dispersion attenuation in a situation regarding Brazilian oil fields.

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