Relative Impedance Inversion of Seismic Traces by Means of Complex Trace Attributes (CTA Inversion) – 40 Years On!*

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Abstract

Complex trace attributes have been used by exploration geophysicists since they were made popular by a paper of Taner and Sheriff in the famous AAPG Memoir 26 (Seismic Stratigraphy, 1977). Envelope, instantaneous phase, and frequency commonly served to create alternative displays of seismic data. The results were of limited usefulness because their appearance was hard to interpret beyond some basic rules of thumb. To extend the utility of these complex attributes, we developed an algorithm to transform stacked seismic traces into reflectivity sequences in a recursive procedure. The transformation is accomplished by translating principle attribute sets (envelope amplitude, phase, and frequency picked at envelope peaks) into single layer elements. The resulting reflectivity traces are broad-band filtered, and finally integrated to form relative impedance traces. Panels of these traces resemble geologic cross-sections much more than the original seismic sections, albeit based on a time scale. Provided the input data is of good quality with a stable source wavelet the vertical resolution is drastically improved and thus allows the analysis of fine structural details, which were not recognisable on the original seismic sections. On the same provision the resulting relative impedance variations can be used to identify possible reservoirs. Isolated layers as thin as a few milliseconds two-way travel-time may be resolved, if the noise level of the data is low. Field examples will confirm the quality and accuracy of the described method.

Introduction

40 years ago, AAPG published their classic Memoir 26: Seismic Stratigraphy - Applications to Hydrocarbon Exploration (Payton, 1977), which launched modern exploration through seismic stratigraphic interpretation and other then advanced methods to evaluate seismic data. Amongst the contributions was a paper introducing complex attributes (instantaneous amplitude, phase, and frequency) as a means to gain more information out of seismic reflection traces (Taner and Sheriff, 1977). Robertson et al. investigated the complex reflection responses of a low impedance wedge (Widess, 1973) in a homogenous half-space by synthetic seismograms generated by convolution of reflection

coefficients with a zero-phase wavelet (Robertson and Nogami, 1984; Robertson and Fisher, 1988). They found a significant and unique change of instantaneous frequency around the tuning travel-time at half the dominant wavelet period T (Figure 1).

Updating the Model - Tuning Tables

In reality, the top and base of a layer rarely have the same reflectivity contrary to the model displayed above. Consequently, layer scenarios with different top and bottom half-spaces are considered additionally, represented by two reflection coefficients R1 and R2. R1 is the larger reflector in absolute sense. R2 is modelled smaller and of opposite sign, separated from R1 by a positive or negative travel-time ΔT. Modeling is done by convolution of this (asymmetric) 'reflector dipole' with a zero-phase wavelet. After computation of the complex trace instantaneous attributes are selected at the time of the maximum instantaneous amplitude, as only these 'principle or response attributes' are significant for layer characterization. Since changing the polarity of both reflectors simultaneously or flipping the reflector pair in time simply results in instantaneous phase rotation of 180 or 90 degrees, respectively, only R1 normalized to +1 and a positive ΔT need to be considered. The resulting tuning tables displayed as Figure 2 provide an update to Figure 1.

Some obvious anchor points are worth pointing out to help to understand the plots. When R2/R1 approaches zero, (left hand side of all plots) we have a single interface with a constant phase of zero (symmetric), a constant frequency (the central frequency of the wavelet), a constant envelope to amplitude ratio of 1 (no tuning effects) and an envelope lag of zero (spike in the centre of the envelope). When we have R2/R1 equal to 1, then we have the simple symmetric dipole case (right hand side of all plots) and the phase is +90 (symmetric peak over trough), a frequency that monotonically decreases with thickness, a variable envelope to amplitude ratio (which is the classic tuning curve) and an envelope lag of half the dipole separation (dipole symmetrically placed within the envelope).

CTA Inversion

To invert the attributes from a seismic response to layer values we need to know the wavelet, i.e. the seismic bandwidth and its phase characteristic. The input trace must processed to represent zero phase. After calculating the above tuning tables, reflection elements for picked events can be determined. For a good range of instantaneous phase and frequency values, unique values for the reflector quotient R2/R1 and layer travel time may be directly read from the tables. Finally, the absolute value of the reflectors and their position in time are calculated from the measured amplitude maximum size and its time, accounting for amplitude tuning and reflector lag ΔT.

Nevertheless, a close inspection of the tuning tables in Figure 2 reveals that some areas of the tables lines of constant phase and frequency both run parallel or sub-parallel to the axes, and the resolution for layer parameters is nil or poor. This occurs predominantly for very small R2 or short travel times but also for thick layers where frequency is not significant (see lower, upper, and left edges of displays). In these areas of weak significance an approximation of reflectivity by a single a spike is a good remedy.

In order to invert a complex seismic trace, we can assume the geological column as a sequence of relatively discreet impedance changes with depth. An iterative procedure starting with the largest amplitude will then unravel step by step a model reflectivity trace, which is then converted to a relative impedance trace.

Figure 3 shows schematically this iteration procedure. The left hand trace in the top plot (*a*) is a synthetic input trace. After the largest event has been identified (see black triangle), attribute look up tables based on the principles explained in Figure 2 are used to determine the dipole that fits that event. The left hand trace in *b* displays its seismic manifestation; *c* shows the implied impedance layer. The trace in *b* is taken from the input trace in *a* to create the second input trace in *a*. The procedure iterates until a predefined level of remnant noise is achieved. The result is the last trace in plot *d*, which when converted to reflectivity and convolved with the wavelet, matches the left hand trace in *a*, the original input trace, apart from the said remnant noise.

Synthetic Example

Since CTA inversion calculates a "dipole" sequence of the input which is then integrated for relative acoustic impedance, it can also be seen as a form of spectral broadening technique. Figure 4 shows how a narrow band input (red trace top plot) can be converted into a broadband trace (red trace bottom plot.)

Field Examples

The first example is Figure 5 and shows how a fairly “tramline” seismic character conceals considerable detail. The right hand plot is displaying the dipole reflector sequence as lines with a background color of the relative impedance. CTA Inversion is a trace by trace process iteratively picking dipoles to decipher and yet the continuity in the result is quite remarkable.

The second example (Figure 6 below) provides a blind test at 5 wells on relatively noisy data. The impedance overlays at the well positions compare very favorably with the inversion to a considerable level of detail. For example, there a two high impedance kicks at (a) that can be chased up-dip and down-dip. Up-dip from (a) there is a hard unit that is considerably below tuning showing thickness and amplitude variations since CTA makes a decision of whether a unit is very hard and thin or thicker and less hard.

Summary

Sometimes it is good to remember what has gone before and to think afresh on how it can be used. In this case we took an old observation, used new programming technology to map the phase and frequency of all dipole scenarios and found that there was generally a good set of the model space providing a one to one relationship between observed complex trace parameters and the underlying reflector "dipole" of a layer. This was then developed into CTA Inversion which is a trace by trace inversion scheme that only relies on the stationarity of the seismic input trace and its phase. The inversion is fast, deterministic, and remarkably accurate.

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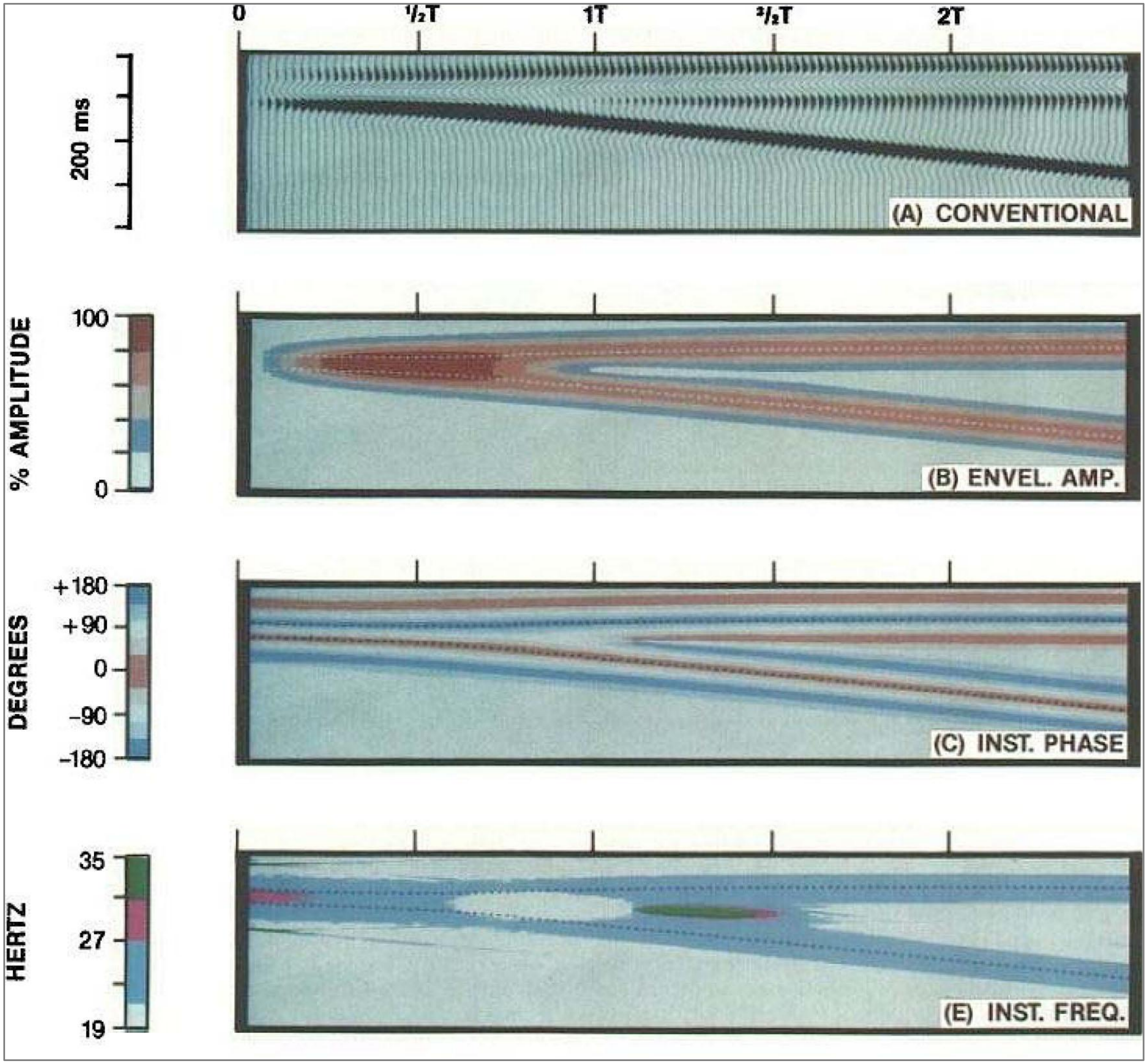
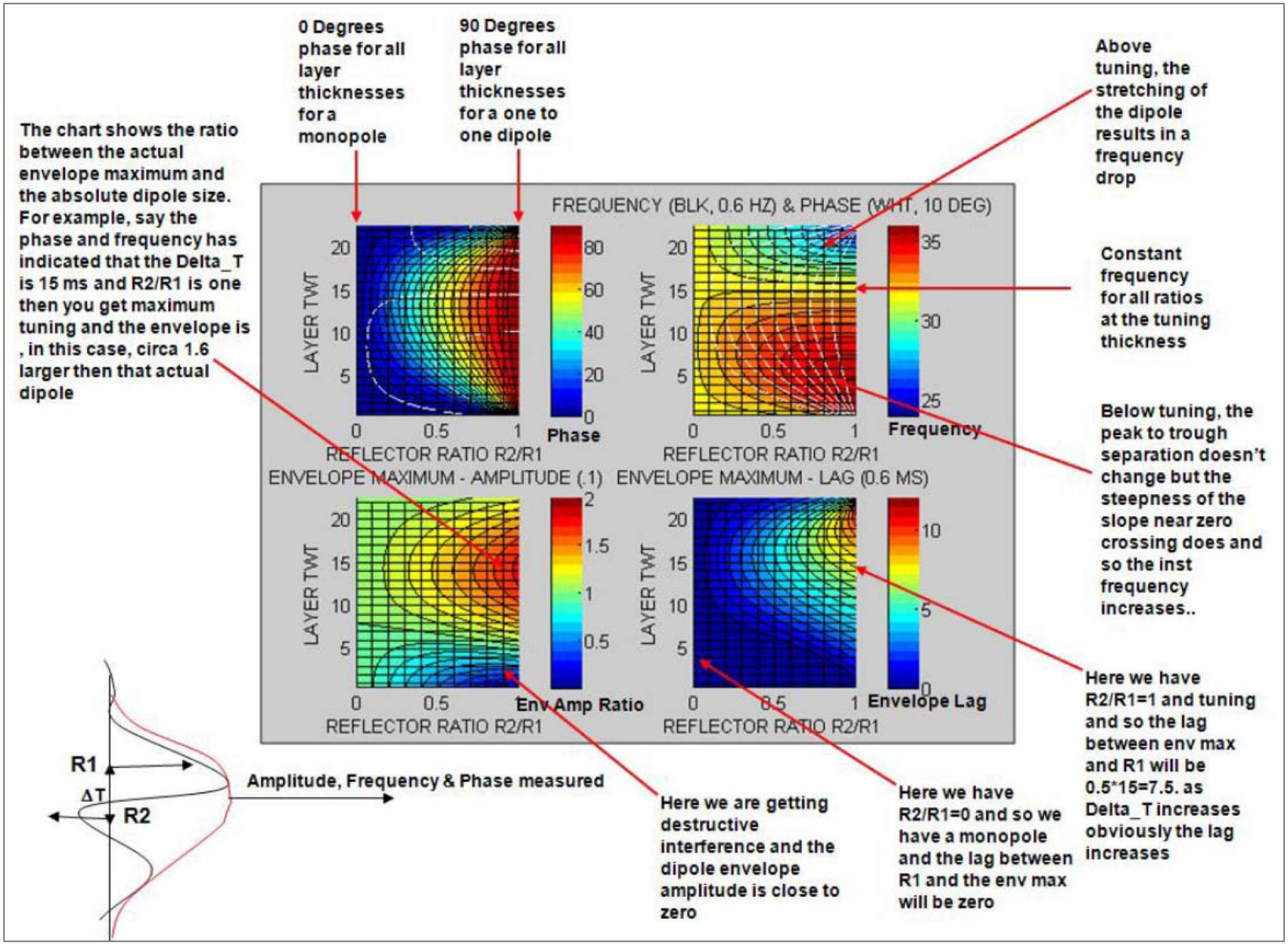


Figure 1. Modeled responses and instantaneous attributes for a simple wedge. T denotes dominant period of a zero-phase wavelet (Ricker 20Hz). (Altered from: Robertson and Fisher, 1988)



The chart shows the ratio between the actual envelope maximum and the absolute dipole size. For example, say the phase and frequency has indicated that the Delta_T is 15 ms and R2/R1 is one then you get maximum tuning and the envelope is , in this case, circa 1.6 larger then that actual dipole

0 Degrees phase for all layer thicknesses for a monopole

90 Degrees phase for all layer thicknesses for a one to one dipole

Above tuning, the stretching of the dipole results in a frequency drop

Constant frequency for all ratios at the tuning thickness

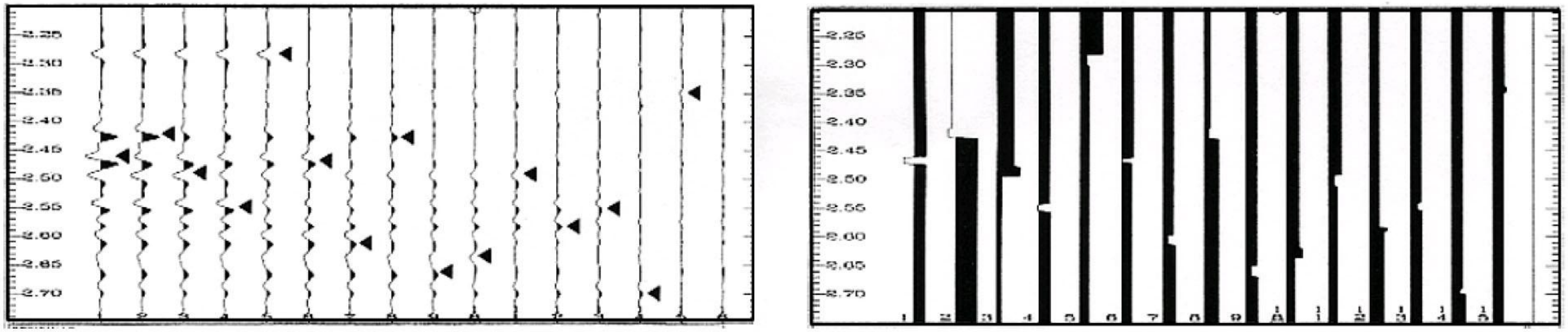
Below tuning, the peak to trough separation doesn't change but the steepness of the slope near zero crossing does and so the inst frequency increases..

Here we have R2/R1=1 and tuning and so the lag between env max and R1 will be 0.5*15=7.5. as Delta_T increases obviously the lag increases

Here we are getting destructive interference and the dipole envelope amplitude is close to zero

Here we have R2/R1=0 and so we have a monopole and the lag between R1 and the env max will be zero

Figure 2. Complex attribute values as a function of dipole reflector ratio and layer travel time (thickness). Top left: instantaneous phase, top right: inst. frequency, bottom left: amplitude tuning, bottom right: lag of envelope maximum with regard to time of R1.



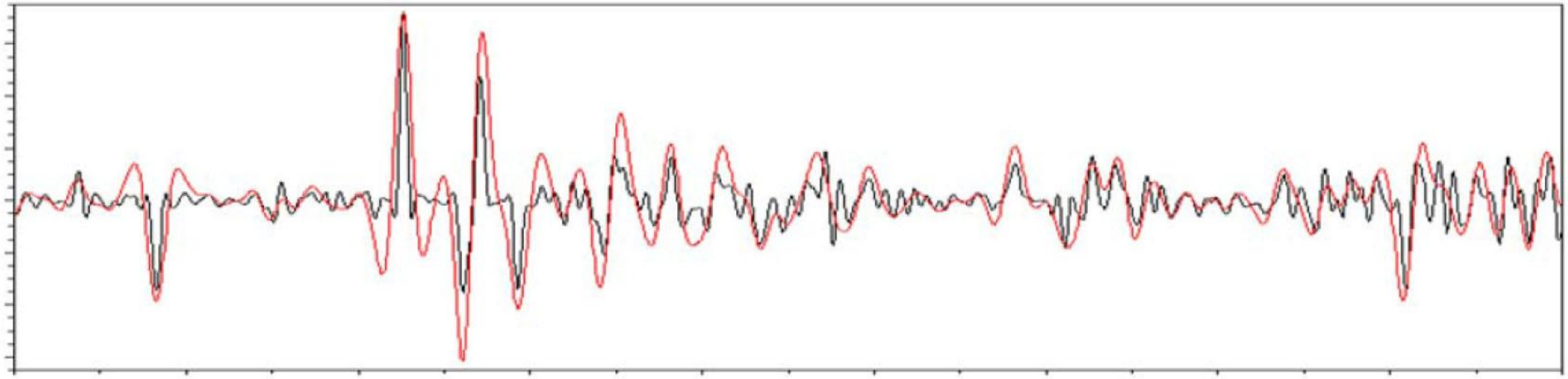
a) Input trace

c) Dipole modelled as an impedance change

b) Dipole modelled as a synthetic trace

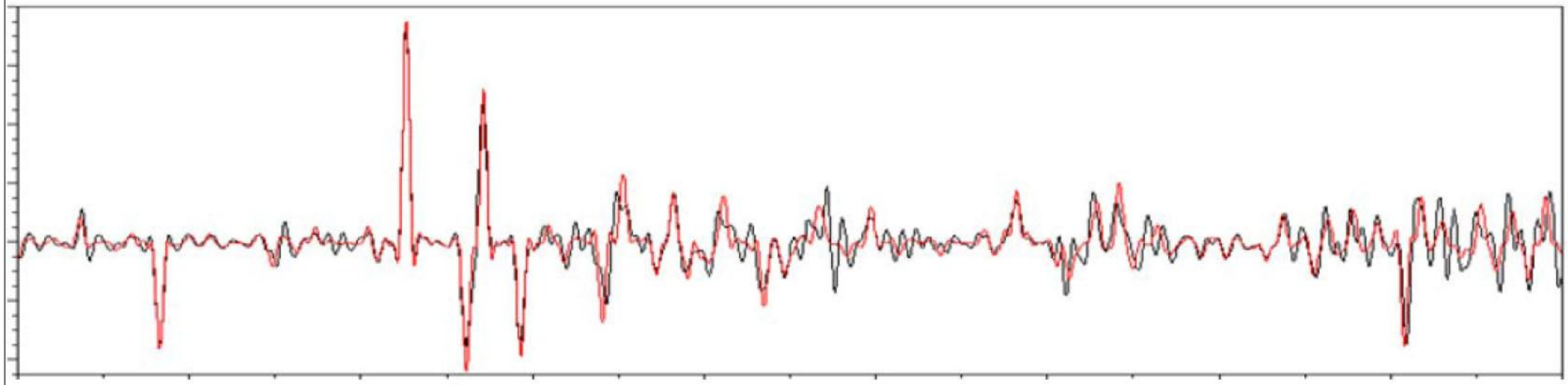
d) Incrementally added impedance changes

Figure 3. An illustration of the iterative inversion scheme.



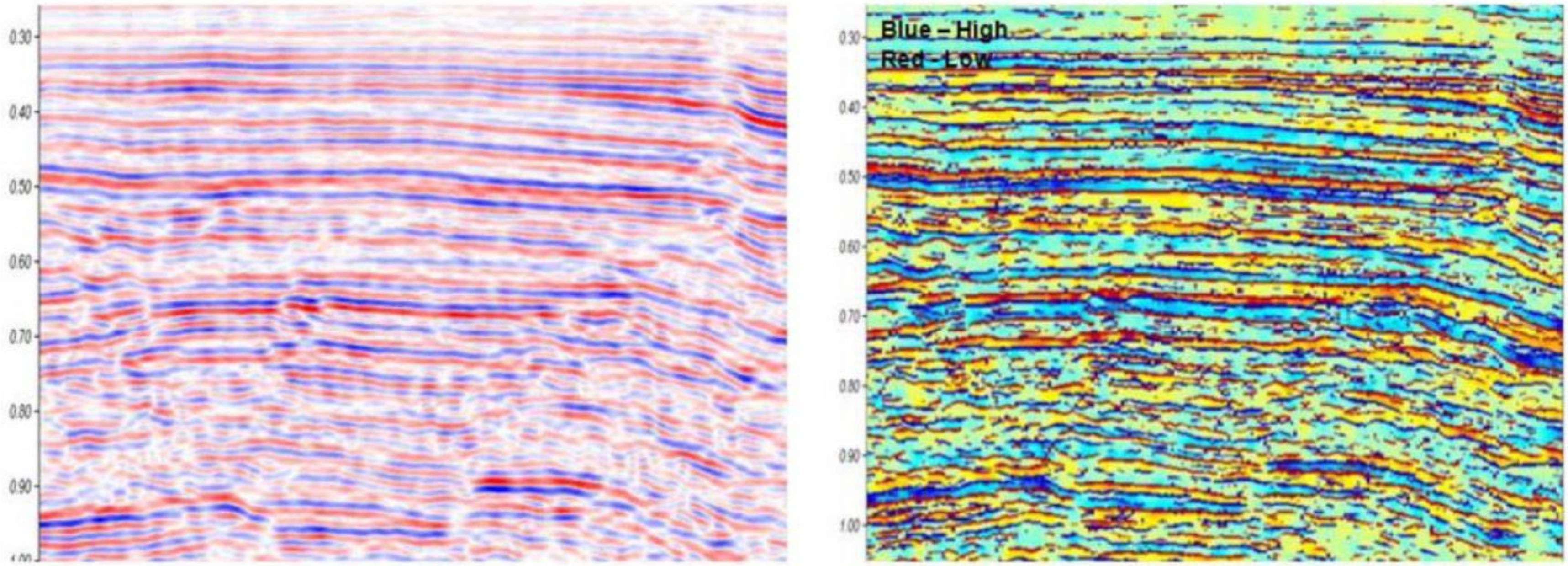
Starting point: Synthetic seismic trace (red) generated by filtering the original broad-band reflectivity (1/2 - 80/200 Hz - black) with a Ricker wavelet of 36 Hz central frequency.

Rosetta uses only the red trace above as the "seismic" input trace for attribute matching to define a "Layers and Boundaries " reflectivity model which can then be compared to the original broad-band reflectivity ("The Truth").



Resulting Rosetta "Layers and boundaries" model (red) overlain with original reflectivity model ("The Truth" - black, same as above).

Figure 4. Application of CTA Inversion as a spectral broadening technique to a single synthetic trace.



Input- Colour

Rosetta Relative Impedance & Automatic Detailed Stratigraphy

Figure 5. CTA Inversion applied to narrow band data.

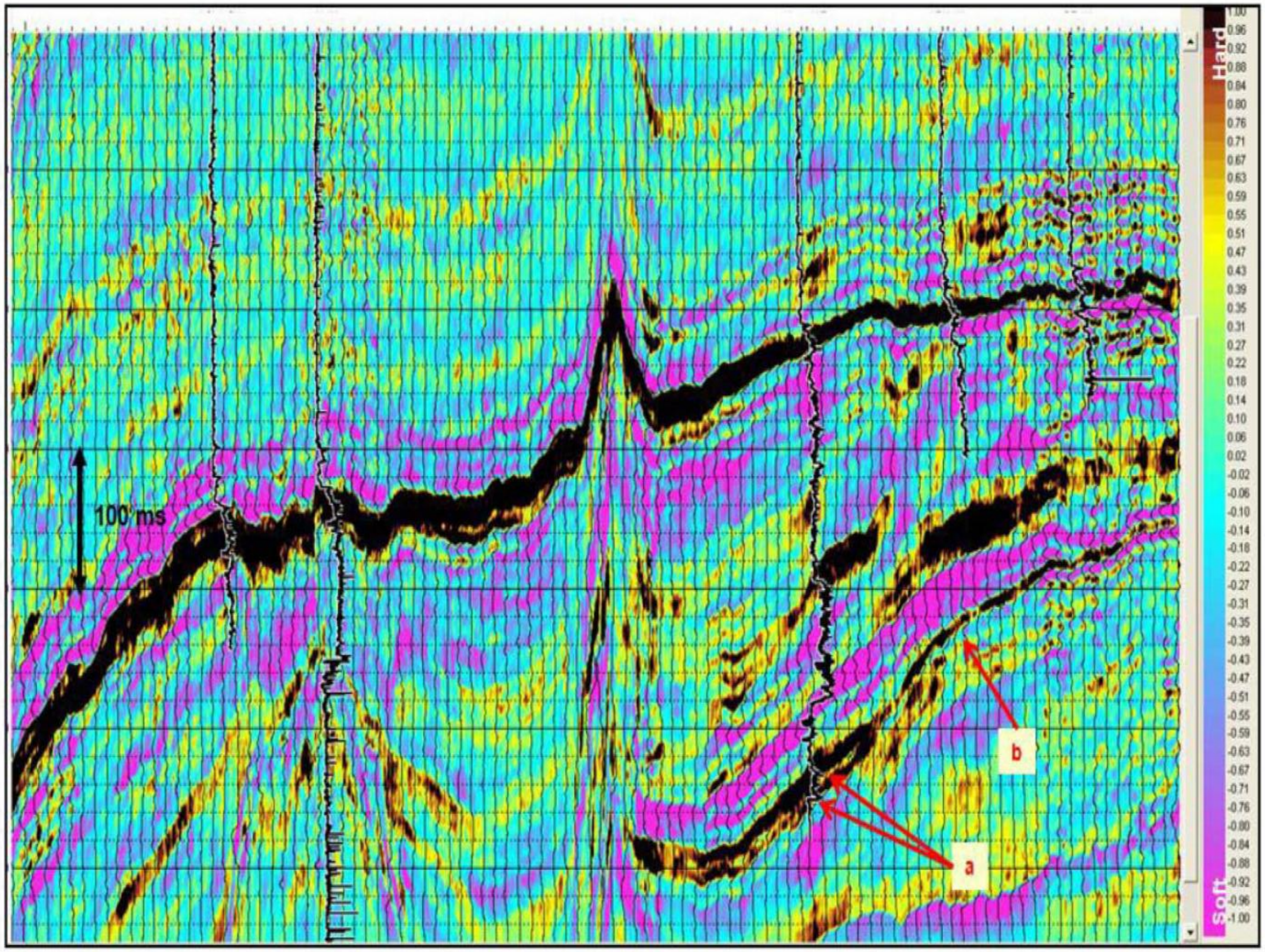


Figure 6. CTA Inversion applied to noisy data with 5 blind well tests.