

An expert system for Seismic data interpretation using visual and analytical tools

Neelu Jyothi Ahuja* and Parag Diwan

Abstract--Seismic images are extensively used by petroleum geologists to delineate subsurface geological structures. This interpretation is dependent on interpreter's individual skills, and expertise causing a complex seismic image to be interpreted differently by different seismologists. To overcome this uncertainty a prototype expert system SeisExpert, has been developed in which the experience and heuristic knowledge of the experts have been incorporated in the form of a set of rules. Over 120 rules have been built into a commercially available expert system shell, 'Flex' (from Logic Programming Associates, UK). Information received from the user is chained through these rules to interpret the seismic images. Additionally, analytical procedures have been provided to refine the interpretation in case of complex subsurface structures. These include statistical cross-correlation across the seismic traces and secondary attributes such as instantaneous phase and reflection strength. Using this system, several horizons were successfully tracked across seismic traces in four different seismic images containing field data from existing oil fields. Discontinuities such as faults, wherever present, were also correctly identified.

Keywords: Expert System, Seismic Data Interpretation, Rule-Base, Knowledge-Base, Seismic Attributes, Expert System Shell, Flex

1 INTRODUCTION

1.1 Petroleum Exploration

In an early twentieth century, the exploration for petroleum was carried out by petroleum geologists, whose prime concern was to locate geological structures suitable for hydrocarbon accumulation. Commercially valuable accumulations of hydrocarbons are usually found at depths of at least a few thousand meters below the ground surface. Although exact knowledge of geology at such depths can come only from drilling a bore hole, such drilling is very expensive. The deeper the structures, less is the resolution that gravity or magnetic surveys can give. Under such conditions, seismic reflection methods become useful, and play a prominent role in the search for suitable geological structures.

1.1.1 Seismic Survey: Two dimensional (2D) seismic survey is generally carried out in virgin/new areas to delineate and map the structures on a regional scale and propose locations for 3D and 4D surveys and also for exploratory drilling. An area of operation is covered with seismic profiles at regular intervals both in dip and strike directions depending upon

the orientation of the sub-surface structure inferred from the surface geological mapping. The 2D seismic survey provides an image of a geological cross-section only whereas 3D and time-lapsed 3D (4D) surveys are carried out to fill-in more details of the geological structures with greater precision. However, 2D surveys provide the basic data and hence are of utmost importance. The present study concerns only with 2D seismic data interpretation.

A typical seismic survey involves creating seismic waves by explosion in a hole in the ground. These waves travel in all directions and get reflected from certain subsurface formations and are received by a number of geophones located on the earth's surface in the vicinity of the explosion. This process is called Seismic Data Acquisition, in which amplitude of the reflected wave of a fixed frequency is recorded as a function of time which is essentially a two-way travel time from explosion source to the reflecting horizon and back to the geophones.

The data recorded at the geophones are amplitudes of reflected waves at sampling time instants (usually 2 or 4 milliseconds). These data undergo extensive processing with a view to improve signal-to-noise ratio and resolution. The processed data are finally presented in a universally accepted SEG-Y^{†1} format for interpretation. The next most significant step is the interpretation of the processed seismic

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[†] Glossary of terms in Appendix A

data. This involves obtaining accurate and meaningful inference from reflectors[†] which can be tied to subsurface geology in terms of structural lithology of possible hydrocarbon bearing elements. Some of the geological structures encountered are folds, faults, salt domes, pinch-outs, stratigraphic traps etc. The problem of seismic data interpretation is to track horizons reliably and delineate geological structures correctly.

There are recognized human experts who routinely interpret seismic images manually, using their expertise. However, in this process of interpretation, there is fair amount of uncertainty in terms of geological structure. A given set of seismic images are likely to be interpreted in two different ways by two different seismologists with widely varying conclusions, and these often deviate from the actual structures found. This uncertainty is partly because of extreme geological complexities and partly because there are no formal rules, and each expert uses his individualistic knowledge-base of unwritten thumb rules, that he or she has developed over the years.

The development of computer technology, with increased sophistication in recording, processing and displaying techniques, created a perfect environment for the growth of seismic technology. The availability of multitude of color coding and printing facilities further added to increased clarity in the interpretation process. Digital displays are preferred because of their superior color rendering and depth effect. But paper displays are still used for practically understanding the seismic section and interpreting it [1].

1.2 Artificial Intelligence

AI can handle complex, non-numeric problem-solving tasks where there are uncertainties or when the available information is incomplete. Its application in petroleum engineering is gaining currency and has the potential to dominate other analytical tools used in the Exploration and Production industry. The uncertainty in interpretation of seismic data has motivated us to apply artificial intelligence to this significant part of petroleum exploration. The present study is aimed at developing an expert system for seismic data interpretation. This will minimize dependence on human experts.

A WinProlog based expert system shell 'FLEX' (Logic Programming Associates, UK) has been used to develop the expert system that has been christened as SeisExpert, in which individualistic interpretation knowledge, solicited from experts, has been incorporated to form its knowledge-base. The formulated rules mimic expert's way of thinking, reasoning and decision making to generate an acceptable inference about the geological structures in a particular region. The input to SeisExpert is the seismic image and amplitude of the reflected wave as a function of two-way travel-time. The output provides information about the geological structures present in that area.

2 LITERATURE REVIEW

Analytical tools were developed for interpretation once computer processed data became available. The most elementary but very powerful technique was statistical cross-correlation of amplitude from one trace[†] with the adjoining trace. This allowed the user to move across the traces but along the same reflecting horizon[†] [2]. What appears as reflecting horizons on seismic maps could be confirmed with this technique. This allowed tracking all significant horizons in an area with high level of confidence as long as there were no discontinuities. Similar results were obtained using auto-trackers based on image-processing tools [3,4].

A seismic attribute is a quantitative measure of a seismic characteristic of interest. These attributes are calculated from the primary attribute which is the amplitude of the reflected wave. This amplitude can be viewed as the real component of a complex trace which can be uniquely calculated under usual conditions. The complex trace permits the calculation of instantaneous phase and reflection strength of the seismic signal at any instant of time. These terms will be defined later in the 'Expert System Architecture' section. These and other quantities can be displayed in a color-encoded manner which help an interpreter see their interrelationship and spatial changes [5]. Additionally, the instantaneous phase and reflection strength could also be used to track the horizons even across faults. There are a number of other attributes that have been identified but not all are useful [6-8].

Semi-automatic fault interpretation was introduced by Landmark Graphics Corporation in 1997 [9] with 'seeding' technique which allowed 'seeding' one or more fault segments on a vertical seismic section, and the automatic operation would perform a cross-correlation on a series of slanted traces derived parallel to the seeded fault segment [10]. A 'seedless' approach to fault segment extraction was presented by Bemmell and Pepper [11], where the gaps and sharp gradients from a horizon interpretation were subjected to a connected body analysis followed by feature testing to deduce likely fault candidates. Aurnhammer and Tonnie [12] described a model-based approach which reduces uncertainties in horizon correlation across faults by introducing global features based on geological constraints.

In seismic data interpretation, horizon picking is important for structural analysis, feature recognition and site appraisal. These were commonly done by hand, and are error-prone and time-consuming. A new method was devised by Harrigan et al., [13] which combined the traditional approach with a new technique using a trained artificial neural network (ANN). This method is more robust and facilitates tracking through conventionally difficult regions containing faulting and other geophysical anomalies.

Some researchers in the field claim that inherent seismic information is lost in the attribute extraction process and advocate the use of raw data instead. Benbernou and

Warwik [14] investigated the performance of ANN using both characterization methods (seismic attributes and raw amplitude data), and demonstrated how the complementarity of both can be exploited in conjunction with other geological information in a fuzzy inference system (FIS) to achieve an enhanced auto-tracking performance. Li [15] described a new classification technique to recognize and predict reservoirs from seismic data using Support Vector Machine (SVM) pattern recognition. It was demonstrated that this method is less subject to overtraining difficulties unlike ANN and can be used to distinguish between oil and gas reservoirs.

Computer assisted geo-interpretation explores the logic of human interpreters and applies it in designing expert systems. Expert Systems are early commercial successes of Artificial Intelligence. Main objective of these systems is to gather expert knowledge, represent it in appropriate format and use it like a human expert to take decisions. The system is also made capable of providing justifications and explanations for the decisions taken [16]. A system named "PROSPECTOR" [17] was developed to provide consultation services for mineral exploration. Cairn's Petrophysical Handbook [18] has described, in detail, several systems including PROSPECTOR, FACIOLOG, MUDMAN etc. A well-log interpretation system was developed at this time using artificial intelligence techniques to show what a computerized stratigraphic interpretation system can do [19]. Pitas and Venetsanopoulos [20] developed an automated knowledge-based system AGIS (Automated Geophysical Interpretation of Seismic Images), for geophysical interpretation of seismic data that can recognize various patterns working interactively with the interpreter for improved performance.

A new conceptual approach was presented by Whitney to show use of expert systems to assist in decision making process [21]. A second era of expert systems began with the developments in the field of health and medicine [22].

The user's confidence in the derived conclusion can be significantly increased by revealing internal rules that led to it. [23]. There are a few formats that have been popular for knowledge representation. Rattanaprateep and Chittayasothorn [24] presented design and implementation of a frame-based object-relational database with a tight coupling between the expert system and the external knowledge-base.

Expert systems have been developed with application in diverse fields [25-27]. Some examples are: tourist advisor system [28], as education tool [29-30], in fault diagnostics and control of power system equipment [31], testing and equipment trouble-shooting [32,33], and disaster management [34].

Many expert systems were developed in subsequent years for variety of geological and mineral exploration tasks such as Dipmeter Advisor [35,36], Laser Drilling System Optimizer [37-40].

Traditional expert systems were constructed using a single monolithic software program for a specific application which required coding the structural framework every time a system was developed. Bache et al., [41] discussed construction of an expert system shell which provided a framework for constructing application specific systems. These workers developed, an automated and interactive tool called Intelligent Monitoring System, to detect and locate seismic events. It is programmed to provide the knowledge representation framework and inference mechanisms for complex and knowledge-rich rule-based reasoning. Pan and coworkers [42] presented a general network with fuzzy logic in a large scale expert system shell which was particularly suited to deal with uncertainty in information. A fuzzy expert system called Smart-Drill, was developed to solve lost circulation problems [43], another one was for screening wells for drilling and preliminary drilling fluid selection based on different well-bore and reservoir conditions [44]. Kumar and coworkers [45] developed a shell-based expert system for the design of airborne equipment.

McCormach [46] combined ANN modeling for pattern recognition, with expert system to increase its interpretation capability. Quah and Tan [47] presented architecture of a hybrid neural network expert system shell aimed at preserving semantic structure of the system rules whilst incorporating learning capability of neural networks into the inference mechanism.

'Flex' (from Logic Programming Associates, UK) is a versatile expert system shell, which offers an open-ended knowledge-based solution to business problems. It is implemented in Prolog, which is a high-level logic-based language suited for rule-based decision making. It employs a natural language style approach to define knowledge through the provision of a dedicated Knowledge Specification Language, KSL [48].

As discussed in this section, we can see that expert systems and even rule-based expert systems have been developed in several areas but little has appeared in published literature on seismic data interpretation. Although auto horizon picking programs, fault recognition programs and several other pieces of software have been developed to deal with specific problems, there appears to be no attempt in the recent past to develop an overall system to interpret the entire seismic image. This served as motivation to undertake the present study to develop a rule-based expert system using the shell 'Flex'.

3 EXPERT SYSTEM ARCHITECTURE

The system has been designed with the following components:

1. Front-end/ User Interface
2. Expert System Shell
3. Intelligence Server

4. Analytical Application Programs

The following section presents in detail, the design and working of each of these components and elaborates their role in the operation of the system.

3.1 Front-end

The front-end serves as a user interface for the rest of the system. The product presents itself in the form of a user-friendly package that facilitates rule-based interpretation of 2D seismic sections. It displays the seismic section and queries the user to gather responses. It also invokes programs that apply analytical techniques on seismic data. The product assimilates results obtained from analytical tools to further reconfirm and fine tune the interpretation. Finally, the interpretation of the given horizon or the seismic section is displayed to the user. This part of the system has been developed in Visual Basic 6.0.

The interpretation process of the expert system can be put forth in the form of two main components of the system. These are: manual interpretation and the analytical interpretation. The manual interpretation requires only the seismic image as input and conclusions are based on the visual observations alone. On the other hand, analytical interpretation additionally requires the amplitude of the reflected seismic wave as a function of two-way-time as input, and makes use of some calculated seismic attributes to support interpretation. More details of both follow.

3.1.1 Manual interpretation

Manual Interpretation works on the principle of visual inspection of the image of a seismic section, coupled with questioning by the system. The reflecting horizons seen on a reasonably clear seismic map are in many ways comparable to the subsurface geology of the region. Therefore, close observation of the reflectors can reveal the presence of reasonable number of features of interest on the seismic map. The user can call any seismic section from the database for interpretation in the form of an image on the screen. The user can navigate between the sections available in the database and choose the desired section for display in the image box on the screen. The system then begins with the questioning process where the user is presented with questions and the responses given by him are recorded. Based on the responses, more questions are put forward. The expert system provides clues and explanations, as and when desired, to assist the user in answering questions and also provides justifications for the line of reasoning followed and conclusions obtained. The questions are presented in three

major styles: edit box[†], list box[†] and multi-box[†]. In all of these questioning styles, a button labeled 'Explain' is available with each question. This button when clicked provides the rationale behind the question being asked to the user. In the form of responses to the questions, the information is gathered and provided to rules which fire in the background. In the present case, the rules have been chained in a data-driven or forward chaining manner. In forward-chaining strategy, the system continues to collect data at each step, and builds the final results. After the question bank is exhausted and all relevant rules have fired, the expert system builds an interpretation from gathered information and displays it to the user.

3.1.2 Analytical Interpretation

Analytical interpretation process for seismic sections is invoked only when the user chooses 'seismic images with data' option. The amplitude vs. two-way travel time (TWT) data in the form of an 'excel sheet' is loaded and displayed to the user.

For analytical interpretation, certain seismic attributes are computed and used in a procedure to track a reflecting horizon across seismic traces. The most important attribute is the measured amplitude of the reflected wave which forms the basis for computation of other desired attributes such as 'instantaneous phase' and 'reflection strength'. The measured amplitude of the reflected wave depends on the nature of interface between two adjacent rock types. A statistical technique called 'Cross correlation' employs this attribute to track a reflection horizon across the seismic traces and clearly shows, slopes, slope reversals etc in the subsurface formations. This technique has been described later in the 'Implementation Notes' (Appendix B).

In order to compute the secondary attributes, the seismic trace is considered as a complex quantity with the amplitude of the reflected wave forming the real component. The imaginary component can be found, by taking Hilbert transform of the real part [5]. Some of the attributes that can be computed through this complex trace analysis are: instantaneous phase, reflection strength (envelope), apparent polarity, instantaneous frequency, weighted average frequency etc [7].

The real seismic trace $f(t)$ can be expressed in terms of time dependent amplitude $A(t)$ and phase $\theta(t)$ as

$$f(t) = A(t) \cos \theta(t) \quad (1)$$

The imaginary part, $f^*(t)$ can be expressed as

$$f^*(t) = A(t) \sin \theta(t) \quad (2)$$

Combining equations (1) and (2), the complex $F(t)$ is represented as:

$$\mathbf{F}(t) = \mathbf{f}(t) + \mathbf{f}^*(t) = \mathbf{A}(t) e^{j\theta(t)} \quad (3)$$

Instantaneous phase $\theta(t)$ can be calculated as:

$$\theta(t) = \tan^{-1} [\mathbf{f}^*(t)/\mathbf{f}(t)] \quad (4)$$

The term phase (or phase angle or phase shift) used in control literature is a function of frequency but independent of time. On the other hand, the instantaneous phase is defined for a fixed frequency but varies as function of time which is being used here. Instantaneous phase is effective in demarcating discontinuities, faults, pinch-outs and angularities clearly.

Reflection strength $A(t)$ can be calculated as:

$$\mathbf{A}(t) = [\mathbf{f}^2(t) + \mathbf{f}^{*2}(t)]^{1/2} = |\mathbf{F}(t)| \quad (5)$$

The reflection strength, also called the "amplitude of the envelope", can be calculated at each time instant in a similar manner as instantaneous phase, but is independent of it. Maximum reflection strength need not coincide with maximum phase or amplitude of the largest real trace peak. Major lithological changes between adjacent rock layers usually result in high reflection strength which facilitates tracking reflecting horizons, discontinuities etc.

3.2 Expert System Shell

The expert system shell used in the current context is available with the framework comprising of all essential components of a typical expert system namely, the knowledge-base, inference engine and working memory. Flex is an expressive and powerful expert system toolkit which supports frame-based reasoning with inheritance, rule-based programming and data-driven procedures fully integrated within a logic programming environment, and contains its own English-like Knowledge Specification Language (KSL). Sample coding has been included in the "implementation notes" (Appendix B).

3.3 Intelligence Server²

The Intelligence Server acts like a glue connecting the front-end Visual Basic interface with the expert system shell and facilitates communication between these two components. The files *edtbox.frm*, *lstbox.frm* and *mltbox.frm* are to be specifically added into the front-end to facilitate interconnection. The questions, which have been written in 'Flex' are displayed through Intelligence Server and the gathered responses follow the same route to 'Flex'.

3.4 Analytical Application Programs

This component constitutes analytical programs that use amplitude data for seismic interpretation. The starting point of the analysis is the SEG-Y file. This file can be viewed using packages like 'Sei-See' (from DMNG Ltd). The file header holds various details such as location of the survey, sampling rate, distance between geophones, date and time etc.

Using the amplitude data, cross-correlation is carried out as detailed in "implementation notes" (Appendix B). The output in the form of a plot of the specific horizon traced is displayed on the screen which is then compared with the same horizon on the seismic image by superimposition or juxtapositioning. If there is a good match it confirms earlier manual interpretation and no further study is required. This is accomplished through a question-answer session and gathered responses are used to build the interpretation in the system. However, if only first part of the horizon matches with the later part deviating significantly, further investigation is required, as this may be due to an anomaly in the geological formation such as fault. Other attributes mentioned above have been used to confirm the presence of a fault.

As discussed earlier, the amplitude data are transformed into complexes containing both real and imaginary components (using Hilbert function, MATLAB, from Mathworks Inc.). Equations (4) and (5) were used to compute instantaneous phase and reflection strength. The resultant plots are displayed and compared as in case of cross-correlation. The findings are passed on to the system to further refine interpretation. All the above algorithms have been developed in C++ language.

The cross correlation technique is particularly useful in tracking continuous horizons, which may be inclined or flat, or folded. However, cross-correlation does not always give desired results in identifying discontinuities such as faults. This shortcoming can be overcome by using instantaneous phase and reflection strength which are characteristic of the reflecting horizon and therefore, capable of tracking horizons even across faults.

4 SYSTEM EVALUATION

The expert system described in the previous section was tested extensively using real seismic data collected from existing oil fields. The results of evaluation are discussed in this section. All geological sections selected for this study had already been interpreted and confirmed for the structural details. The different geological sections were examined using SeisExpert. Each horizon was studied by visual inspection and information was input through the question-answer sessions. Subsequently analytical tools were applied to confirm or refine the manual interpretation.

4.1 Horizon tracking using cross-correlation technique:

² Proprietary component of Logic Programming Associates, UK

The process started with picking up a marker, from the first trace of the reflected wave, in this case, maximum amplitude value in that trace, along with its corresponding time. Then a time window, of 5 sampling instants was selected, with marker in the center of the window. This was cross-correlated with the adjoining trace, as demonstrated by an example described below.

Example 1: Cross-Correlation

Sample data given in the table below shows amplitudes for first two traces with marker at 2520 ms in Trace#1. The first window comprises of 5 rows with marker at the center. For the ease of handling, the original data was scaled by multiplying with 10e-3 and truncated to 2 decimal places.

Time (in ms)	Amplitude value	
	Trace #1	Trace #2
2512	-9.19	-9.16
2514	-7.20	-6.68
2516	2.56	3.39
2518	16.17	16.85
2520	25.04	24.87
2522	21.84	20.24
2524	6.49	3.73
2526	-12.73	-15.25
2528	-24.78	-25.23

Labeling data in the columns under Trace#1 and Trace#2 as x_i and y_i respectively and substituting the values in the equations, given in Appendix B, we obtain the 5 cross-correlation coefficients, a1 to a5 as follows:

- (1). 274.02 (2). 229.42 (3). 99.93 (4). 204.95 (5). 94.43

Note that the first window of five sampling instants (x_1 to x_5 and y_1 to y_5) corresponds to time interval 2516 to 2524 ms. In order to eliminate noise, the trace corresponding to the maximum of the cross-correlation coefficients less than a threshold value was discarded. The choice of the threshold value is somewhat arbitrary and has been taken to be 0.2 in the present case. In the above example, the value at (1).274.02 is found to be maximum which is greater than the threshold value 0.2, and hence the trace#2 is retained. If the maximum value of cross-correlation coefficients had been less than 0.2, say 0.15, then we would have simply discarded trace#2 from further consideration.

Then the maximum amplitude from the window, on trace #2 was picked as the marker and the same process repeated between traces #2 and #3. This process was continued until all the traces were examined in a given section. Figure 1 shows the correlated reflection horizon using 2001 traces from a data sample. (These 2001 traces cover a distance of 50,025 meters adjoining the explosion).

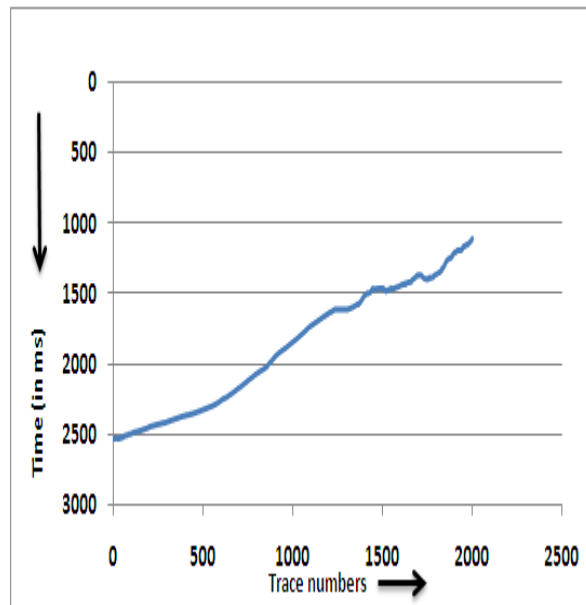


Figure 1: Correlated reflection horizon using 2001 traces.

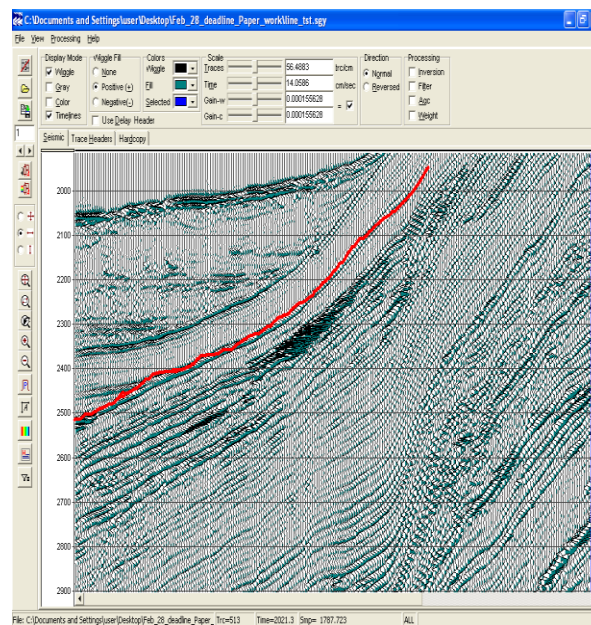


Figure 2: SEG-Y section corresponding to correlated horizon shown in Fig 1

The slope of the line in Figure 1 corresponds to the slope of the reflecting horizon A in Figure 2. The correlated horizon attains a steep upward slope. This corresponds to an interface between two types of rocks. A close similarity between the computed horizon and the one seen in SEG-Y image, establishes the correctness of the approach. In the case shown above, the maximum amplitude along with its time was chosen, after inspecting the entire trace, in order to proceed with cross-correlation. The user can also give a random time interval range, between which the trace of reflected wave is examined and maximum amplitude along

with its time is taken as its starting point to begin cross-correlation. Alternatively, the user is free to specify time on the first trace and use it to apply cross-correlation to the adjacent traces.

The cross-correlation technique was applied on several reflecting horizons from three seismic sections of anonymous geological areas. Figure 3 shows 14 horizons that have been tracked using this technique. These have been compared with the corresponding SEG-Y image shown in Figure 4. Similar results were obtained with the other two sections (not shown).

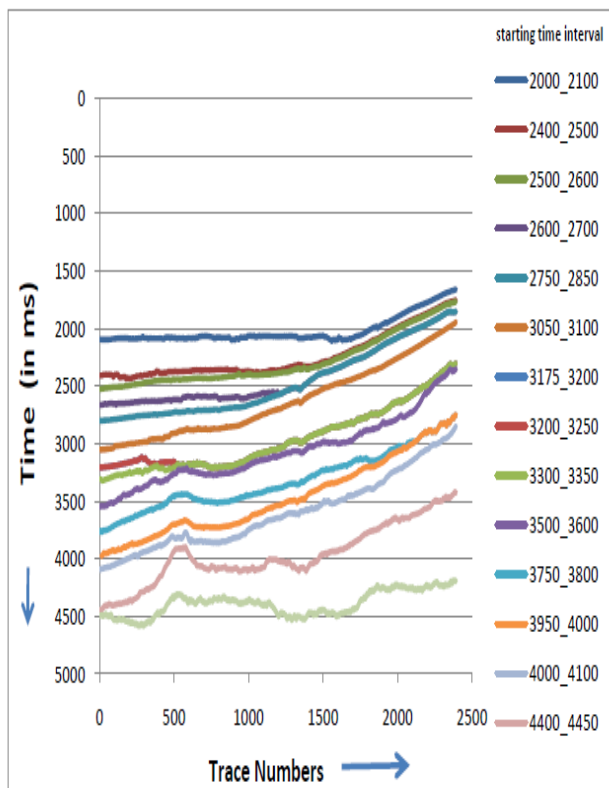


Figure 3 Reflecting horizons tracked using cross-correlation technique corresponding to horizons seen in Figure 4

Comparing the reflected horizons tracked using cross-correlation with their corresponding SEG-Y images, it was observed that technique worked well for continuous horizons. On close observation, it can be seen that while all the correlated horizons were found to be identical with those in the seismic image except the one starting between 4000 and 4100 ms which drifted away after traversing some distance. This is because of a discontinuity encountered in that horizon. This aspect has been described in greater detail in the following subsection.

4.2 Horizon tracking using secondary attributes

As mentioned earlier, MATLAB has been used to generate complexes corresponding to amplitude data. As an example consider a measured amplitude value of -0.37. Hilbert function transforms this into a complex, $-0.37-1.82j$ with $f(t) = -0.37$ and $f^*(t)=-1.82$. Use of equations (4) and (5) will yield corresponding values of instantaneous phase and reflection strength respectively.

Consider a SEG-Y section shown in Figure 4 where a fault is known to be present between trace numbers 3450 and 3650 (encircled). Let us try tracking a horizon across this interval starting at time instant 4092 ms where a strong reflection exists. We first used cross-correlation and the resultant horizon is shown in Figure 5 by curve 1. Starting with the same time instant we next tracked the instantaneous phase across the traces and the resultant horizon is also shown in the same figure by curve 2.

A comparison of the two curves with the SEG-Y section (Figure 4) clearly shows that while cross-correlation failed to track the horizon across the fault plane, the instantaneous phase identified the horizon correctly all the way. A closer look shows that the cross-correlation, as it progressed across the fault plane, picked another strong reflection horizon and moved along this horizon which was actually, a horizon above the one we started to track. But because of the rock movement downwards, after the fault it juxtaposed with the upper horizon before the 'fault'. Since, cross-correlation only correlates the strongest signal in the adjacent trace it makes no difference which horizon it picks next. However, instantaneous phase essentially remains constant for a given horizon and hence tries to identify the same horizon across the fault plane.

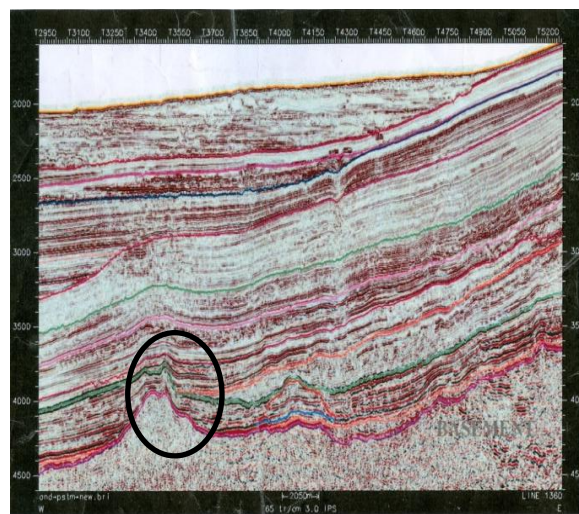


Figure 4: SEG-Y section showing a fault at bottom left

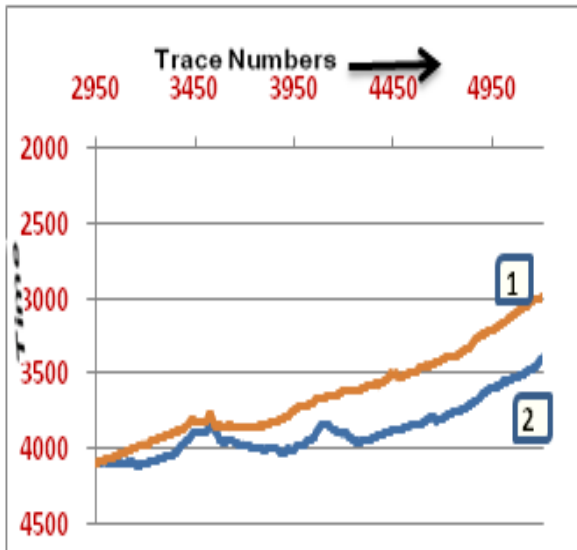


Figure 5: Tracking across a fault plane using: cross-correlation curve 1, instantaneous phase curve 2.

Reflection strength attribute was used to track the same horizon. The procedure used was similar to the one used with instantaneous phase. The starting time was same as that in case of cross-correlation (See Figure 6). As seen, in the figure, the horizon picked across the fault plane is correct one but resolution of the structure is not as good as in Figure 5.

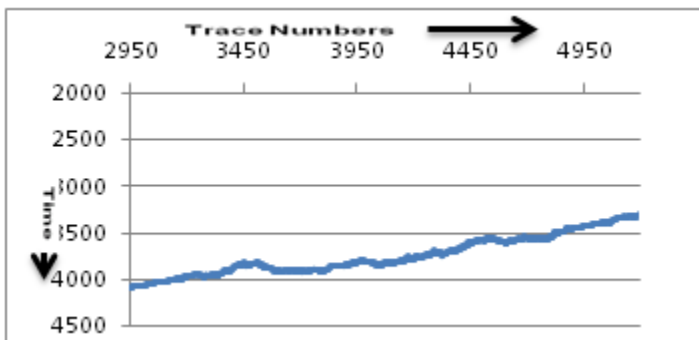


Figure 6: Tracking across a fault plane using 'reflection strength'.

4.3 Tracking fault by traversing in reverse direction (backwards)

In the close vicinity of the fault plane, there is intense heat generated because of rock shearing and this leads to changes in the rock texture and composition. Because of this change, instantaneous phase and reflection strength may also change making it difficult to delineate the precise location of the fault plane [5]. To be able to locate the fault plane more accurately, the horizon was tracked from left to right until a small distance from the fault plane on the left. The same horizon was tracked in the reverse direction, from right to

left, starting from the other end of the traces until a short distance from the fault plane on the right. The fault plane can be located more precisely in this interval.

To summarize, a total of three already interpreted seismic sections were used for validation of the present system. 14 horizons were tracked in first section and 5 and 4 respectively in the second and third sections. The system tracked all the horizons successfully. In the first section (Figure 4) there are some horizons which are monotonic, others are folded and one is faulted. All the continuous horizons were correctly tracked by cross-correlation alone and instantaneous phase and reflection strength reconfirmed their nature. However, horizons with faults, one in first section (starting at 4092 ms and shown in Figure 5) another in second section (not shown) could not be tracked correctly by cross-correlation beyond the fault planes. But when the other seismic attributes were used, complete horizons were correctly identified.

5 CONCLUSIONS

A rule-based expert system (SeisExpert) has been developed with capability to track horizons and identify faults. A graphical user interface has been provided in Visual Basic language, through which the system seeks information from the user. A lot of information can be provided from visual inspection of the seismic images which leads to a tentative interpretation of the geological structures. Analytical tools built into the 'Applications' part of the shell such as cross-correlation, instantaneous phase and reflection strength further aid in refining the interpretation. Continuous structures could be manually interpreted and reconfirmed when invoking cross-correlation program. However, discontinuities such as faults which are likely to be missed, by cross-correlation were correctly identified by the secondary attributes namely instantaneous phase and reflection strength, which are characteristic of a reflection horizon.

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APPENDIX A: GLOSSARY OF TERMS

SEG-Y format: The SEG Y file format is one of several standards developed by the Society of Exploration Geophysicists for storing geophysical data. It is an open standard, and is controlled by the SEG Technical Standards Committee, a non-profit organization.

Reflectors/ Reflecting horizons: It is the sub-surface rock interface from where the seismic wave reflects back due to density changes of the layers.

Trace: The seismic data recorded for one channel is referred to as a seismic trace. It represents the response of the elastic wavefield to velocity and density contrasts across interfaces of layers of rock or sediments as energy travels from a source through the subsurface to a receiver or receiver array.

Edit box style: This style is useful when the user is expected to enter some text or an integer in response to the question being asked. This style presents the question along with the

text box, so that the user can enter the response to the question.

List box style: This style is used when the user is given a question and the options available to him are presented in the form of a list box and he is expected to choose any one option from the listed items

Multi-list-box style: This style of questioning is similar to the list-box style, except that the user is allowed to choose more than one items in the list box

APPENDIX B: IMPLEMENTATION NOTES

Data Storage and Retrieval

The seismic images and their corresponding amplitude data are stored in a database in MS Access and these can be accessed through the front-end using *ActiveX Data Objects (ADO)*. ADO objects help in establishing connection with database and at the same time facilitate requesting the data as record-set from database through query statements sent from the front-end. These also facilitate adding of new records by passing them from the front-end to the database for the purpose of storage and later recall.

Manual Interpretation: The seismic image, to be interpreted, is displayed on the screen, as shown in Figure B1. The questions are displayed, one at a time, on the same screen and responses are gathered from the user.

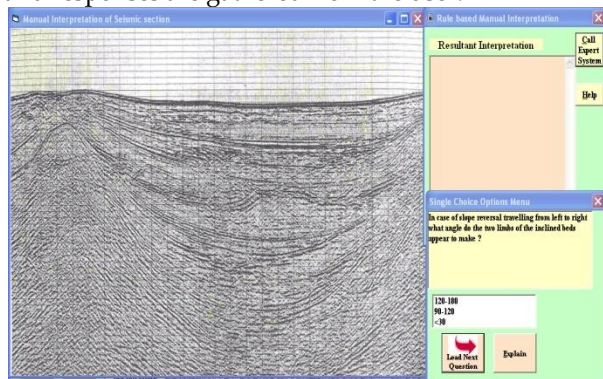


Fig B1 Seismic section (left), interpretation window (top right), questioning interface (bottom right)

The questions range from simple ones concerning the appearance of the section like: 'Where do you find the y-coordinate of the section beginning from?' ('From zero', or 'At a numeric value'), to questions which are concerning a particular reflector as it moves from left to the right of the section.

The questions then begin to enquire about 'continuity of horizons', and further about 'existence of slope changes in horizons'. Further, based on the answers, other set of relevant questions are asked such as 'Is there a slope reversal present?'

Slope reversal can be indicative of presence of anti-cline/syncline/salt-dome structure. The system asks detailed questions regarding direction of slope reversal etc, to narrow down to decision regarding presence or absence of a particular structure.

Having tracked a particular horizon as one moves horizontally across the traces, the questions then concentrate on the section vertically, depth-wise, to ascertain shifts in the horizon. Questions such as 'Do you find a sudden vertical shift in the horizon' ascertain the presence of discontinuity which could be to a 'fault'. Once, a fault structure is confirmed, the questions try to ascertain the type of fault, whether normal or thrust fault, depending upon the direction of slip of the hanging block and foot wall of the proposed fault plane.

Analytical Interpretation: In order to undertake analytical interpretation, the amplitude vs time data (corresponding to the seismic image) are also called on the screen.

Cross-correlation Technique

The process starts with picking up a user-defined marker, from the first trace of the reflected wave (such as maximum amplitude value in that trace or in a specified time interval which is akin to depth interval), along with its corresponding time. Then a time window, of user-specified size (e.g. 5, 7, 9 or 11 time instants) is selected, with marker in the center of the window. This is cross correlated with the adjoining trace. These two adjacent traces within the time window represent a matrix with 2 columns and (2n-1) rows where n is the size of the window. The computations are done and the values of cross-correlation coefficients calculated. Shown below are the equations for cross-correlation coefficients for a window of five time instants.

$$a_1 = (x_1y_1 + x_2y_2 + x_3y_3 + x_4y_4 + x_5y_5) / 5 \quad (a)$$

$$a_2 = (x_1y_0 + x_2y_1 + x_3y_2 + x_4y_3 + x_5y_4) / 5 \quad (b)$$

$$a_3 = (x_1y_{-1} + x_2y_0 + x_3y_1 + x_4y_2 + x_5y_3) / 5 \quad (c)$$

$$a_4 = (x_1y_2 + x_2y_3 + x_3y_4 + x_4y_5 + x_5y_6) / 5 \quad (d)$$

$$a_5 = (x_1y_3 + x_2y_4 + x_3y_5 + x_4y_6 + x_5y_7) / 5 \quad (e)$$

In order to eliminate noise from signal, the cross-correlation coefficients lower than a certain threshold value, are discarded. The time corresponding to maximum amplitude of the adjacent trace in the matrix is taken as the centre for the next window. Each time after cross-correlation coefficient computation is done and centre for the time window is chosen, the trace from the left of matrix is removed and the adjacent trace from the right is included and the window slides ahead. This process continues till all the traces within a seismic section have been examined. Typically, a seismic

section may contain any number of traces depending upon the length of area for which the recording has been done. The time instants at the centre of the window for each seismic trace are given as output. These when plotted depict the reflecting horizon. Similar analysis is carried out to track all reflecting horizons within a given section.

Once these plots are available, questioning starts once again based on this new information. The user is asked to compare the obtained plot with the corresponding horizon from the seismic image and the responses are recorded. A close match between the obtained plot and the picked horizon indicates confirmation of observations made earlier. There is a possibility that the horizon in the image may indicate a break, which may be missing in the plot. The absence of the break in the plot may be due to the fact that, the cross-correlation technique failed to track horizons across discontinuities. In such a situation, the user is prompted through a question to use the seismic attributes, instantaneous phase and/or reflection strength to track the same horizon.

Instantaneous Phase and Reflection Strength

Starting with the amplitude vs time data, Hilbert transform generates the complex which when used with Equation (4) gives instantaneous phase as a function of time. The initiation of the process of tracking reflecting horizon using instantaneous phase takes place, with the user picking up a reasonably large value of instantaneous phase in the time window in which that particular horizon originates. Then the instantaneous phase nearest to this phase value in the adjoining trace is chosen and its corresponding time is considered as centre for the next time window. This process continues till all the traces are examined in the given section. Same procedure is used to track the reflecting horizon with the reflection strength attribute. Appropriate application programs are invited by the expert system to track the horizon and plots thus generated are displayed. The user is prompted to compare the plot with the corresponding horizon in the seismic image. A match between the two confirms the interpretation. The user is then prompted to choose the next horizon for interpretation and the same procedure is followed. Thus, the user may choose to interpret a set of horizons in a given seismic section and finally display the overall interpretation.

Help Module

The system provides context-sensitive help that can be accessed from the menu bar, help button or by pressing 'F1' key.

Expert System Shell

One sample each of a question, rule, group, rule-set and an action has been shown below. The expert system gathers information from the user through responses to the questions. Questions have been designed and added to 'Flex'

user interface, using the key word 'question', an example of which is given below.

```
question q3
On visual inspection of the section, How do
you find the reflections?
Choose one of grp_ref_type
because The dark reflections indicate density
of the strata/layer is more and if the light
reflections are found the density of the layer
is less.
```

The name of the question is **q3** and it holds the body of the question which is 'On visual inspection of the section, How do you find the reflections?'

The user is allowed to choose from a group **grp_ref_type** which provides two options 'Dark' and 'Light' that are displayed with question through a list box. The 'because' clause is used to provide question-specific instruction and explanation along with the question, to assist the user to understand and answer it appropriately.

Creating of group **grp_ref_type** with the options is shown below:

```
group grp_ref_type
'Dark', 'Light'.
```

Based on the responses to the questions appropriate rules are invoked. The response to the question is held in the name of the question, **q3** in this case.

Flex provides a very simple procedure to add rules using keyword 'rule'.

```
rule r1_q3
If ref_density is q3 and
q3='Dark'
Then
Write( 'Dark reflections indicate Density of
layers is more').
```

In the above rule, **r1_q3** is the name given to the rule. The name of the question being asked to capture data for the rule is **q3** and the statement within the **write ()** function is displayed only if the response to the given question is 'Dark'. The response to **q3** would be 'Dark' if user had chosen to answer 'Dark' from the given choices. Full-stop (.) is the command terminator.

The 'Flex' interface provides the feature to group the rules into various categories by designing specific sets using keyword 'ruleset'. Then rule sets can be appropriately chained and invoked by designing actions using 'action' keyword. For example, the ruleset **set_set1** has been designed which is made to contain three rules, **r1_q1**,

r2_q1, r3_q1. It is supposed to fire each of these rules in the first come first served manner and remove the rules fired once. The last statement indicates that when a rule misfires (invoked when the condition was not true), the process stops and exits.

```
Ruleset set_set1  
Contains r1_q1, r2_q1, r3_q1;  
Update ruleset by removing each selected rule;  
When a rule misfires do true.
```

The action **run_a1** is used to invoke the ruleset and run next action **run_a2**.

```
action run_a1;  
do restart  
and invoke ruleset set_set1 and run_a2.
```

About seventy rules have been incorporated for manual interpretation and another fifty rules for analytical interpretation.

The following code takes care of invoking Flex, from visual basic front-end. The object 'flx' of class Flex is created as follows.

Dim flx As New flex

Using this object, the functions, namely, LoadFlex(), InitGoal(), CallGoal(), ExitGoal() are called. The LoadFlex() function loads flex, and InitGoal() loads the flex file (.ksl file) holding the rules, questions, rulesets and actions. '.ksl' is the extension for the flex files. It stands for 'Knowledge Specification Language'. It is very close to natural language in its syntax and semantics. This makes it very easy to understand and code.

```
flx.InitGoal ("reconsult_rules ( '<flex code>' ) . ")
```

Then RunGoal() can be called with the main action name to be invoked.

```
flx.RunGoal ("<action_name>. ")
```

The CallGoal() function starts the execution of the expert system by putting forth the questions, firing rules, using responses to move towards the goal. ExitGoal() is a very important function to stop execution, once the rules for the current session have been fired. HaltFlex() is

used to unload the previously loaded instance of 'Flex' from memory.

Deployment of Expert System

The expert system has been packaged, using 'Package and Deployment wizard', into installable software. This wizard determines which files need to be distributed with the software, compresses them all into a cabinet file (.cab file), that acts like a setup file. This setup file can be used to install the software.