ISSN 0043-8790

DECEMBER
1984

World Oil

EXPLORATION • DRILLING • PRODUCTION

Exploration '84: New Technology Is Emerging

Part II

Seismic stratigraphy moves towards interactive analysis

Stephen F. Simson, Seismic Services Manager, Hunting Geology and Geophysics Ltd., London, England; **H. Roice Nelson, Jr.,** Senior Vice-President, Landmark Graphics Corp., Houston

20-second summary

Seismic stratigraphy aids interpretation of complex geology, particularly by helping effectively identify the right geologic environment for potential hydrocarbon traps. This article, the second in a series of three, reviews three of the four key approaches to interpreting stratigraphy from seismic, namely, seismic sequence analysis, seismic facies analysis and reflection character analysis.

THERE ARE AT LEAST four different approaches to interpreting stratigraphy from seismic data.[1] In a primary approach, **seismic sequence analysis,** the observed seismic sequence is used to define the gross depositional packages, and then predict the stratigraphy within these units that have common characteristics. A second method, often overlooked, is direct interpretation of stratigraphic features on high-quality, high-frequency, broad-bandwidth seismic data. This is referred to as **seismic facies analysis.** A third, strictly geophysical approach, known as **reflection character analysis,** uses amplitude variations to directly predict stratigraphy or porosity from the seismic data. A fourth approach is **computer modeling,** which is used to evaluate the seismic reflections from different stratigraphic and fluid contact situations. Modeling begins by designing a depth model of the stratigraphic feature(s) of interest, inputting parameters such as velocity and density, and creating a synthetic seismogram, which can be compared to the field seismic data.

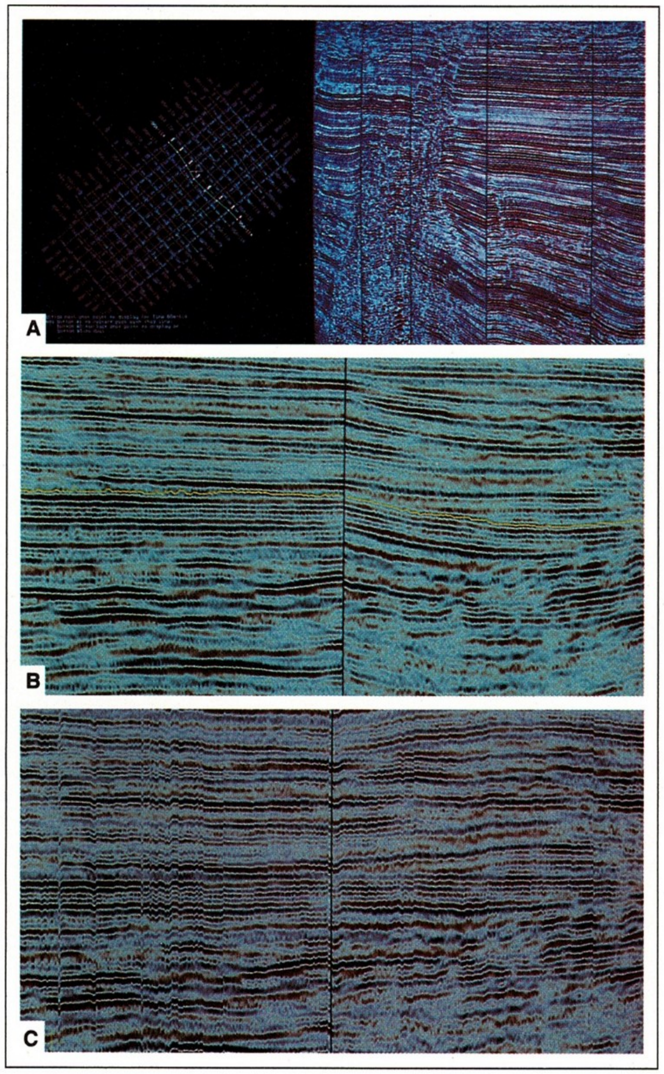


Fig. 1—Flattening a seismic section on a particular horizon removes the effects of subsequent tectonic movement, allowing an interpreter to understand the geologic configuration of the area at the time the chosen horizon was deposited. Such an exercise is illustrated in softcopy form. (A) Softcopy display of a 2-D seismic survey location map and the portion of five time-series sections picked from the map for display to close a loop. (Data courtesy Grant/Norpac). (B) Softcopy interpolated zoom on two orthogonal sections of interest. Note the yellow horizon. (C) Flattening of the time-series seismic data on the yellow horizon with the display of two orthogonal seismic sections. Note the thickening of sediments beneath the flattened horizon, and also the baselap of sediments in the right section above the flattened horizon.

Seismic sequence analysis

Seismic sequence analysis is the process of grouping seismic events into sedimentary segments. The breaks between segments are often periods of uplift or sea level abatement and resulting erosion, which are represented in the geologic column and on seismic data by unconformities.

Recognition of seismic sequences begins with an identification of changes in reflection character. For example, parallel strong reflections may represent alternating sands and shales; whereas, zones with few strong reflections probably relate to a single massive lithology, like a reef or a diapir.

The steps of seismic sequence analysis have been summa-

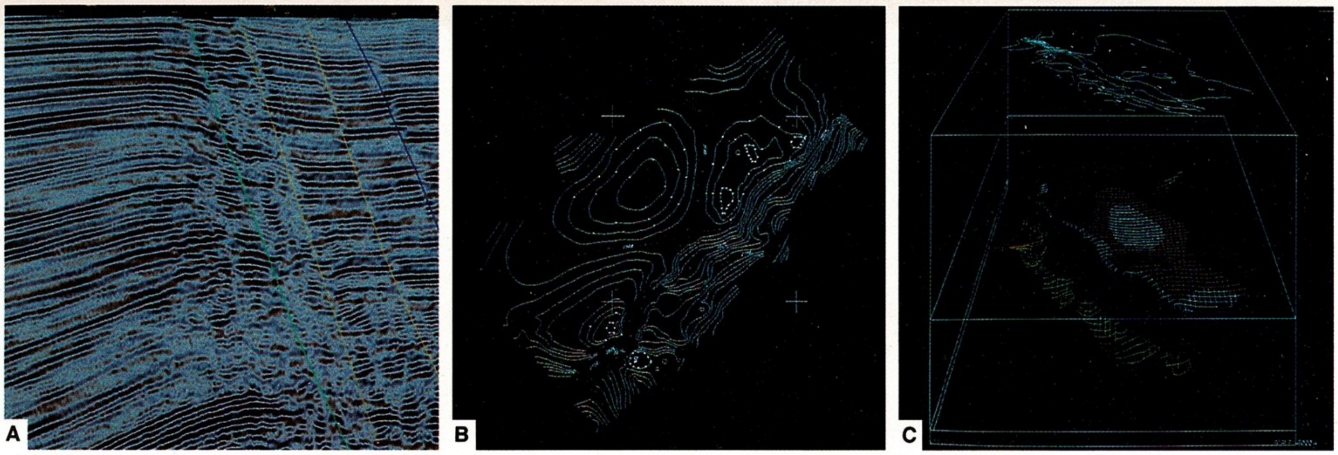


Fig.2—Seismic facies interpretation requires an understanding of the relationship between geology and different reflection configurations. Different reflection configurations are illustrated as well as how seismic sequence boundaries can be displayed in softcopy form. (A) A seismic section from the Gulf of Mexico showing areas of continuous reflections and of no reflections (Data courtesy Grant/Norpac). The continuous reflectors could be due to alternating shales and sands, while the no-reflection areas could be areas of a consistent lithology, like massive sands. (B) Softcopy map display of a seismic sequence boundary. (C) Perspective display of a sequence boundary with a contour map projected on the surface of the volume.

rized by Sheriff as described below[2]:

1. Recognize unconformities based on their angularity and regard these as unit boundaries.

2. Extrapolate these boundaries where the reflections are conformable, so as to define the sequence units completely.

3. Characterize portions of the units by evidences at the upper and lower boundaries and by seismic facies characteristics within the units.

4. Map the units so as to see their shapes, orientations, etc.

5. See how the units relate to neighboring units, known geological information, velocity information, etc.

6. Synthesize these evidences into an interpretation based on stratigraphic concepts.

Unconformities. The key to recognizing seismic sequences is to recognize unconformities. Table 1 summarizes the major types of unconformities and how they relate to reflection form.[3]

It is interesting that one of the most important parts of the geological record is that which is missing. Looking at worldwide basins that are actively growing at present, it becomes obvious that the geologic record is mostly one of nondeposition, or of unconformities. Table 2 summarizes this by listing modern and ancient sedimentation rates.[4] When sequence boundaries are identified, an easy evaluation of the sequence can be made by creating an isopach map to show areas of thinning and thickening.

Paleosections. Sedimentary deposits are typically laid down on sea beds at some distance from land in flat layers. These layers are bent and broken over geologic time by tectonics. Flattening a seismic section on a particular horizon removes the effects of subsequent folding and faulting, and shows the configuration of deeper layers at the time the chosen horizon was deposited. This is similar to referencing well logs to a particular formation. Flattened sections can be made for several geologic times, allowing study of the structural history of the area. The data above a flattened horizon are not part of this particular paleogeological picture, since they had not been deposited at the time of the layer that was flattened. Flattening helps to understand tectonic forces in an area and leads to new prospects. Interactive interpretation systems facilitate such flattening studies, which are otherwise extremely time consuming. Fig. 1 illustrates softcopy display and horizon flattening.

TABLE 1—Types of unconformities[3]

Hiatus—A break or interruption in the continuity of the geologic record

Disconformity—Any interruption in sedimentation whatsoever its cause or length, usually a manifestation of nondeposition and accompanying erosion

Erosional unconformity—An unconformity made manifest by erosion, a surface separating older rocks that have been subjected to erosion from younger sediments covering them

Paraconformity—An obscure or uncertain unconformity in which no erosion surface is discernable, or in which the contact is a simple bedding plane, and in which the beds above and below the break are parallel

Angular unconformity—An unconformity between two groups of rocks whose bedding planes are not parallel, or in which the older underlying rocks dip at a different angle (usually steeper) than the younger overlying strata

Nonconformity—An unconformity developed between sedimentary rocks and older rocks (plutonic igneous or massive metamorphic rocks) that had been exposed to erosion before the overlying sediments covered them

Onlap unconformity—A surface of nondeposition that is progressively onlapped by successively younger stratigraphic units.

Reefs are an example of a stratigraphic sequence easier to see after flattening. In areas with severe weathering problems, flattening allows statics correction by hanging the data on a shallow reflector. If there is a lot of folding in an area, it may be easier to pick layers if the best reflector is flattened. Another softcopy stratigraphic interpretation technique is to horizontally compress a section in order to enhance subtle thickness changes. Subtle folds become anticlines; faults become more vertical and easier to see.

Seismic facies analysis

Seismic facies* interpretation is the process of interpreting depositional environment directly from the form of seismic

* **facies**—a group of rocks that have a unique appearance compared to surrounding units.
seismic facies—indicators of a depositional environment as distinguished by different reflection characteristics.

TABLE 2—Sedimentation rates[4]

MODERN RATES

Location	μmm/year
Lake Vierwaldstätter[1]	3,500–5,000 freshwater
Lake Lunz[1]	1,800
Rhone Delta	700 delta
Nile Delta	660
Clyde Sea[2] (shallow)	5,000 largely terrigenous
Norwegian fjord[2]	1,500
Gulf of California[2]	1,000
Moluccas[2] (volcanic ash)	700
Tyrrhenian Sea[2]	100–500 inland seas
Black Sea	200
Bahamas[3]	33.8 carbonate environments
Florida Keys[3]	80
Florida inner reef tract[3] (contaminated by terrigenous material)	220
Globigerina ooze[2]	8–14 deep sea
Red clay[2]	7–13

ANCIENT RATES

		μmm/year			
Location	Duration (m.y.)	Maximal America	Maximal Europe	Effective maximal	Shelf
Cambrian	100	86	55	40	15
Ordovician	60	147	77	66	25
Silurian	40	49	154	113	30
Devonian	50	78	314*	160	32
Lower Carboniferous	40	51	88	50	13
Upper Carboniferous	40	188	210	150	13
Permian	45	62	224*	100	23
Triassic	45	178	140	67	43
Jurassic	45	152	111	67	33
Cretaceous	65	354	230*	230	43
Paleogene	45	236	224	133	31
Neogene	23	533	533*	226	47
Weighted average		160.9	171.5	108.9	27.7

[1] Quoted after Schwärzacher (1946).
[2] Quoted after Kuenen (1950).
[3] Stockmann et al. (1967).
* Caledonian, Variscian, and Alpine orogenic periods.

reflectors. In order to be effective, the process requires a seismic record of high-frequency, broad-bandwidth and good signal-to-noise ratio. It also requires an understanding of the relationship between geology and different reflection configurations. Fig. 2 illustrates different configurations, and horizon sequence boundaries can be displayed in softcopy.

Interpretation flow would typically be to define seismic sequence packages and follow by interpreting the depositional environment of each sequence unit. Table 3 summarizes these relationships in outline form,[5] while Fig. 3 illustrates the relation of reflections within a sequence unit** to the unit boundaries.[6]

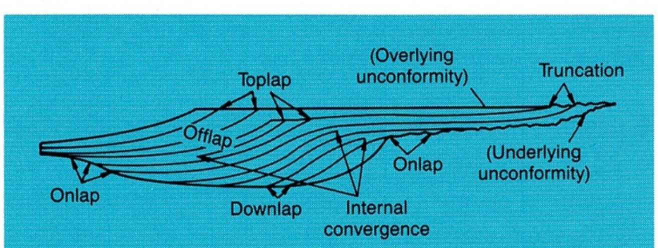


Fig. 3—This schematic illustrates how seismic sequence units can relate to the unit boundaries.[6]

With good seismic data and an understanding of the type of reflections expected from different geology, the next step is to tie in well log data (like density or sonic) and identify seismic facies units.*** These units are then integrated spatially and chronologically in order to define the depositional systems that fill the basin being studied.

Seismic facies interpretation starts by picking events on a single seismic section. It is useful to pick a representative section in some detail, indicating obvious features, coloring several reflections, and following up with more detailed analysis of the section. This provides an idea of horizons to pick on all the lines, as well as identifying problems to expect in the interpretation project. However, in interpreting a single line

** **seismic sequence**—a depositional sequence identified on a seismic section by mapping the bounding unconformities.

seismic sequence unit—a package of reflections that results from the sediments within a time-stratigraphic, depositional unit.

*** **seismic facies unit**—a mappable, three-dimensional unit of reflections whose characteristics differ from that of the adjacent facies. Seismic facies units are used in conjunction with unconformities to separate seismic sequence units.

TABLE 3—Outline summary of reflection configurations as they relate to geologic significance[5]

A. Simple
- Parallel
- Subparallel
- Divergent

B. Unit boundaries
- Onlap—thinning because not much room for deposition
- Downlap—thinning because not much sediment
- Parallelism to boundary (concordance)
- Erosional truncation—sedimentary unit formally extended beyond present limits, possibly exposed
- Toplap—deposition near wave base, implying sorting of grain size by wave energy

C. Complex

• hummocky	• shingled
• contorted	• wavy
• lenticular	• disrupted
• chaotic	• irregular
• variable	• reflection-free

D. Complex internal (indicating progradation—outbuilding)
- Oblique—near wave base, angularity, grain size sorting
- Sigmoid—quiet deep water, S-shaped, poor sorting, fine grain sediments

there are no loop ties to expose errors. It is useful to work with a single line to get general impressions, but a thorough interpretation to find a drilling location requires interpretation of a group of lines, or a volume of data. The more complete the data volume, the more detail can be brought out in the interpretation. One should consider local and regional geological considerations; the quantity and quality of data; known and accepted geological, geophysical and petrophysical principles and practices, and the interpreter's background, professional experience and prejudices.[1] The goal is to determine the sedimentary process that best fits the observed seismic facies, the resulting implications on the geologic evolution of the area and the economic consequences of the interpretation.

Reflection character analysis

Reflection character analysis is basically the study of lateral changes along a reflection, like variations in amplitude, waveshape, frequency, velocity or thickness between reflection events. Determining these parameters from seismic implies information about lithology and pore fluids content. There are new algorithms being tested that provide more accurate discrimination of reflection variations and better synthetic modeling of lithology composition.

Seismic inversion modeling. Inverse modeling assumes that the amplitude of a seismic trace is proportional to the reflection coefficient, and solves the reflectivity equation for the acoustic impedances. The reflection strength is proportional to the reflectivity of the rock interfaces and to velocities. The reflection coefficient series is derived and an estimate made for the velocity at some point in the series. With this start, it is possible to calculate the next deeper layer velocity, and from that velocity the next deeper velocity, etc.[7] Velocities are constrained using the stacking velocity as a guide. The results are plotted as a synthetic sonic log, or inverted seismic trace. These traces are hard to interpret as plotted. However, by contouring these synthetic logs, horizontal alignments highlight the layers and lenses of different sediments. Assigning colors to the different velocities highlight anomalous zones, which may be due to variations in porosity or fluid content.

A different type of inverse modeling is called differential interformational velocity analysis.[8] This process starts with data that has been amplitude and wavelet processed. Next the velocities are picked on a shot-by-shot basis as accurately as possible. From this velocity data two curves are generated. One shows the stacking velocity for a deeper reflector, and the other a prediction of this velocity from the previous reflector. The results are displayed similar to a porosity log turned sideways, where the cross-overs represent low velocity zones. When applying this process in the Austin Chalk, velocity drops of more than 400 feet per second imply a gas field.

Topics covered

This second article in the series reviewed three of the four key approaches to interpreting stratigraphy from seismic, namely, seismic sequence analysis, seismic facies analysis, and reflection character analysis. The first article introduced key concepts behind seismic stratigraphy, including phase effects, resolution and how color softcopy interpretation is expected to affect the science. The third article will review advanced geophysical techniques, including direct hydrocarbon indicators, shear waves and seismic modeling (the fourth key seismic stratigraphy approach).

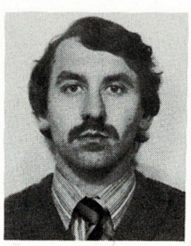
ACKNOWLEDGMENTS

Hunting Geology and Geophysics, Ltd. and Landmark Graphics Corp. for permission to publish this information.

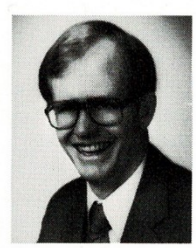
LITERATURE CITED

1 Andrew, J. A., "The art and science of interpreting stratigraphy from seismic data," SEG/CPS Joint Seminar on Seismic Interpretation, Zhouxian, China, May 8–12, 1984.
2 Sheriff, R. E., "Chapter 4—Seismic sequence analysis: The implementation," *Seismic Stratigraphy,* pp. 69–83, 1980.
3 Visher, G. T., *Exploration Stratigraphy,* p. 19, 1984.
4 Visher, G. T., *Exploration Stratigraphy,* p. 20–21, 1984.
5 Sheriff, R. E., "Chapter 5—Seismic facies analysis and reef patterns," *Seismic Stratigraphy,* pp. 85–116, 1980.
6 Mitchum, R. M., Jr., Vail, P. R., and Thompson, S., III, "Seismic stratigraphy and global changes of sea level, Part 2: The depositional sequence as a basic unit for stratigraphic analysis," *AAPG Memoir 26: Seismic Stratigraphy—Applications to Hydrocarbon Exploration,* Charles E. Payton, Ed., pp. 53–62, 1977.
7 Mummery, R. C., "Use of Seislogs for basin evaluation and field development," SEG/CPS Joint Seminar on Seismic Interpretation, Zhouxian, China, May 8–12, 1984.
8 Neidell, N. S., Cook, E. E., Beard, J. H., and Franz, W. L., "Improve prospect picks with moveout velocity analysis," *World Oil,* pp. 129–142, Jan., 1984.

The authors



Stephen F. Simson *is currently seismic services manager for Hunting Geology and Geophysics Ltd., London, England, and is responsible for all aspects of seismic exploration for hydrocarbons, including an interactive seismic interpretation service. He was employed from 1970 to 1983 by Geophysical Service International Ltd., Croydon, Surrey, England. He received a BS in geology and an MS in applied geophysics from Birmingham University. He is a member of the SEG, EAEG and the Petroleum Exploration Society of Great Britain.*



H. Roice Nelson, Jr., *senior vice president of resource development, is a founding partner of Landmark Graphics Corp. He earned a BS in geophysics from the University of Utah and an MBA from Southern Methodist University and worked as a seismic interpreter for Amoco Production Co. and Mobil Exploration and Production Services, Inc. He also was senior research scientist at the Seismic Acoustics Laboratory and general manager of the Allied Geophysical Laboratories at the University of Houston. Mr. Nelson has accumulated several years of experience with interactive interpretation and has coauthored more than 60 papers in that time. He is a member of EAEG, HGS and SEG and has been named in annual editions of* Who's Who in the South and Southwest *since 1979.*