Nig. J. of Pure & Appl. Physics. Vol. 4. pages 75-81, 2005

THE STRUCTURAL SIGNIFICANCE OF SEISMIC VELOCITY REVERSALS - AN OVERVIEW.

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Abstract: The basic property under investigation is the change of seismic velocity from one layer to the other. This paper looks into problems of velocity reversal, locations of low velocity zones, delineation methods, and presents case studies in the Niger Delta. This study therefore aims at delineating from the surface the subsurface distribution of velocity changes in the area of study. It has been recognised in the study area that seismic velocity contains important geological information. To be most effective determining these, however, it is necessary to have a thorough understanding of the rock properties under investigation. In areas with absence of structural uplift and lateral variation of lithology, iso-velocity surfaces are nearly horizontal planes. However, where structural uplift occurs, iso-velocity surfaces tend to follow structure but less relief than the structure. The study showed that seismic velocity increases with depth and age in some of the areas and deviation from this was observed within the geopressured shales. These low velocity zones constitute anomalies that are not only geophysically significant but have structural definition.

Keywords: seismic velocity reversals, Niger delta

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1. INTRODUCTION

The basic measurement in seismic reflection method is time. In order to transform this into depth, there is a need for knowledge of the seismic velocities. It is for this reason, estimation of seismic velocities has been one of the most important tasks in seismic exploration methods..

The velocity variability and the stratal characteristics in terms of seismic velocity were examined with a view to delineate the velocity anomaly zones. Seismic modelling allows a prescription of subsurface condition in terms of geometric and acoustic parameters including velocity, density and attenuation factors. The geometric distribution of certain physical properties in the subsurface can be determined via geophysical surveys. Generally, this delineation conforms to the distribution of different rock types and associated structures and thus, provides geophysical information. There must be contrast between the physical properties of the target or its associated structures and those of the surroundings in order that delineation is possible.

Seismically derived velocities are used in three separate ways to aid in depth conversion, stratigraphic and lithologic differentiation. First, they are used to augment well velocity data when determining the constants for mathematical formulas. Second, they are assumed to be an estimate for the spatial distribution of average velocity for depth conversion. Third, they are used to map the interval stacking velocities as an estimate of the spatial distribution of the interval stacking velocities. The third use is very important in lithologic and stratigraphic interpretation.

[1] has dealt in detail with the problem of velocity measurement by shooting in holes. He is known as one of the first to study velocity in relation to seismic reflection method. Since that time several different theoretical studies have been made on effects of lateral variation in velocities on seismic response.

The content of fines in the strata (clays, muds, or shales) contributes to scatter about empirical fits to velocity data [2] and [3]. Since clay content also affects porosity [4] and [5], neither exerts an independent effect on seismic velocity. [4] have shown this using a model for the packing of clay and sand that appears to account for the non-linear behaviour of compressional velocity with increasing clay content.

The term "Seismic Stratigraphic" has become a house word for geophysicists and geologists alike [6]. The determination of sand/shale ratios [7]) and in particular the "bright spot" technique are still manifestations of the new trend to regard seismic velocity as a source of geological information. Low velocity zones constitute anomalies that are not only geophysicallly significant but has also structural

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Nig. J. Pure Appl. Phys. (2005) Vol. 4 pp 75-81. Printed in Nigeria, ISSN 1596-0862. E-mail: njpapjuta@yahoo.com. For rights of reproduction and web access, contact African Journals Online, UK, www.inasp.ajol/journals/njpap

geophysicallly significant but has also structural information.

Low velocity zones in the subsurface constitute anomalous conditions. This low velocity results from velocity reversals. It is the contention that

diapir mother-beds.

Diapiric type of trap will always be extremely difficult to locate since seismic reflections beneath any diapir are always distorted due to the lateral velocity changes (Figs 1 and 2).

The structural styles of thrust faulting, growth faulting and diapirism have in common the presence of such zones not only exhibit abnormally low seismic velocities but are mechanically weak and of lower than normal density. For this reason, such zones are prime candidates for detachment horizons and/or

detachment planes and/or diapir mother-beds. In both detachment planes (decollements) and unconformities structural deformation above and below are totally independent. Therefore, geophysical explanation under such conditions is an important tool for any viable interpretation and assistance to the geoscientist.

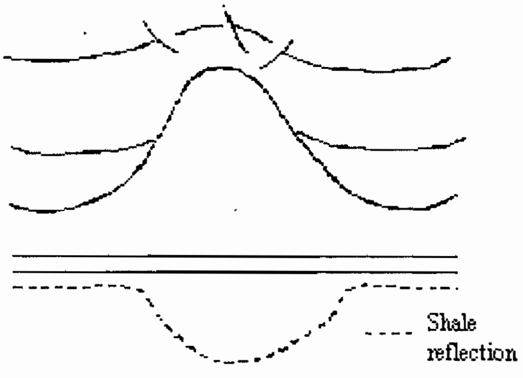

Fig. 1: Effect of shale masses on deep reflections

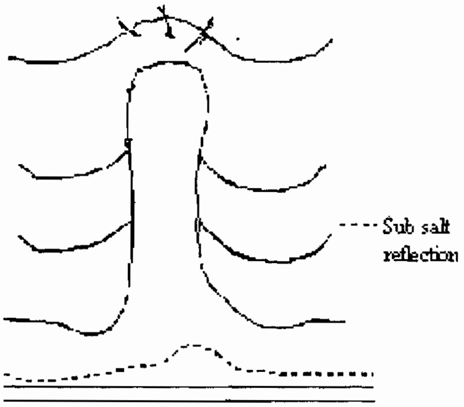

Fig. 2.: **Effect of salt diapir on deep reflections**

2. REVIEW OF FACTORS AFFECTING SEISMIC VELOCITY AND IT'S DETERMINATION

It is worthwhile reviewing the various factors affecting seismic velocity and methods of its determination.

Velocity and Diapirism:

The importance of diapiric structures for the geoscientists needs no further elaboration. The literature on the subject is vast.

A density reversal - a low density material covered by a high density material; high mobility of the low density material; and uneven loading of the low density material are necessary requirements for diapirism.

Diapiric materials are mechanically weak and tend to be of low density because of their abnormally high porosity and low effective overburden stress. The common diapiric prospects in the Niger Delta are the overpressured shales. Indeed today, shale diapirism is a well-accepted feature of all continental margins as shown by [8] and [9].

In Table 1 some of the physical properties of overpressure shales are compared to those of salt. It can be seen that both have low density and low strength, they differ in other respect. The velocity of salt is high while one of shale is low. In view of the velocity contrast between salt and shale, it is possible to predict that sub-salt or sub-shale reflections should be characterised by velocity pull-ups or velocity says as shown in figures 4 and 5. The work of [10] has shown that this is indeed one way of outlining shale diapirs. Shale is usually perceived to be a high velocity material. Just on what observation is this notion really based? The geophysical refraction surveys from this work located shale diapiric structures by fan shooting and recognised their presence by negative time anomalies.

Table 1: Some physical properties of salt and overpressure shale.

Physical Properties	**Salt**	**Geopressure Shale**
Thermal conductivity	high	low
Electrical resistivity	very high	very low
Strength	low	low
Density	low	low
Velocity	high	low

Generally, the water under little overburden remains non-compatible, which gives it a density invariant with depth (Fig. 6,) and also a velocity which is not a function of depth, a highly anomalous situation.

3. PROCEDURES FOR VELOCITY DETERMINATION:

3.1. The t^2-x^2 method:

The t^2-x^2 method has been shown for a long time but its application was limited due to less than perfect record quality and the fact that before about 1962 a special field effort in the form of the velocity profile was required in order to produce proper data.

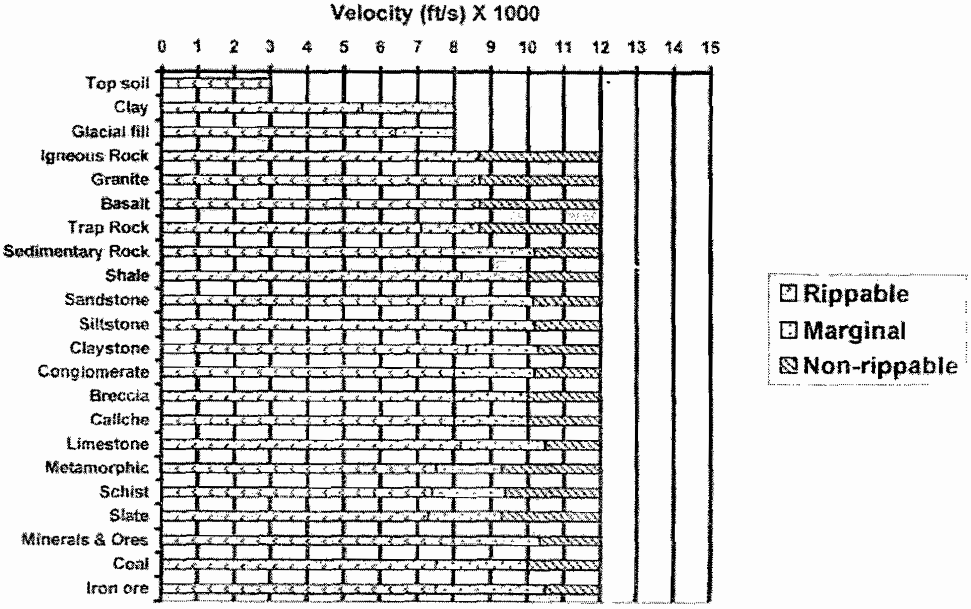

Fig. 3: A rippability chart as found in most catalogues advertising small seismic equipment for engineering purposes.

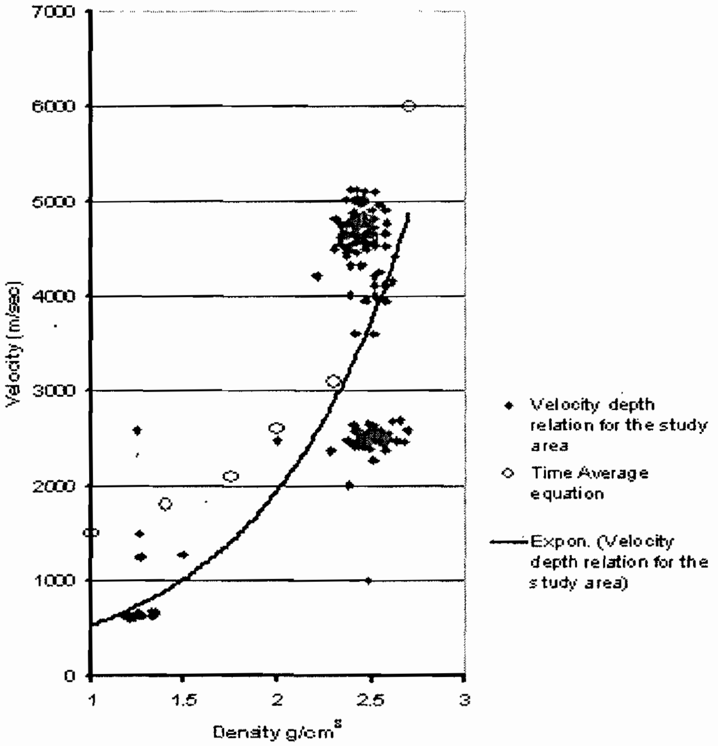

Fig.4: Crossplot of Seismic velocity vs.Density. Superimposing velocity from the time average equation for the parameters as shown.

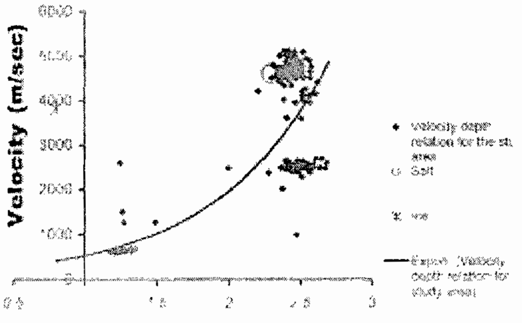

Fig. 5 Figure 4 with salt and ice. These materials do not fit this graph at all (Modified after [11])

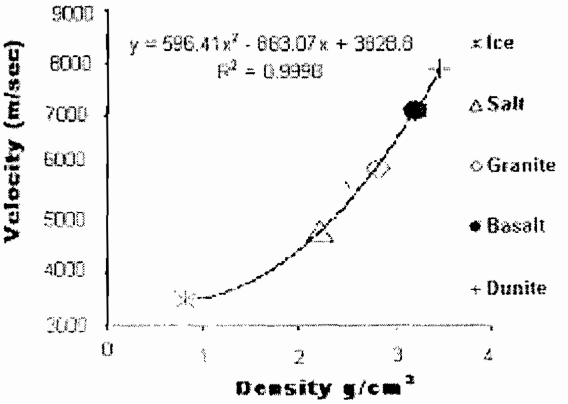

Fig. 6: Crossplot of Seismic velocity Versus Density for non-porous materials. *Velocity shows a significant positive correlation with density.* (Modified after [11])

Seismic velocities were determined using normal movement (NMO) with high accuracy on regular and continuous basis with normal field equipment and procedures. The seismic velocities were plotted against station depth on linear graph paper. The trend lines of the velocity curves show the points of velocity reversal.

In this paper, low velocity layers are of particular concern. Now that seismologists no longer just record time but also monitor the size and the polarity of the reflection amplitudes, the top of the low velocity layer was recognised by a polarity reversal.

3.2. Relationship between Seismic Velocity, Mechanical Strength and Density.

In the "Statement of the Problem" it has been suggested that:

High Velocity = Low
Strength = High Density
Low Velocity = Low
Strength = Low Density

All those who have experience in petrophysics may regard such a generalisation with some reservations, and not without cause. It is a well-known fact that all physical properties of rocks are controlled by many variables. It is, therefore, naive to expect the above postulate to hold exceptions, or shall we say, "seeming exceptions".

A simplistic view sees rocks as two-phase systems: holes or pore spaces within a rigid framework, which in itself may be complex. In those rocks where porosity is high and greatly variable, porosity is undoubtedly the controlling factor for all physical properties. Thus for sedimentary rocks one expects porosity to be the most important single variable. For those rocks where porosity is low, such most igneous and metamorphic rocks, the composition and texture of the rigid framework (matrix properties) will be the most important aspect (let us not forget that even very low porosities {mocrocracks} can have rather drastic effects.

The fact that velocity and mechanical strength correlate well has been known to engineers for some time. Charts as in figure 3 are found in all catalogues of firms manufacturing small scales seismic equipment for engineering purposes. The rippability of the rocks in question is again primarily related to the existing pore space. It has been found that ordinarily strong rocks may become rippable when sufficiently weathered (opened). Seismic velocity seems to be one of the most sensitive parameters to record such a change.

It is also well known that basalt is stronger than granite that correlates well with the respective velocities. This, however, may be more of a lucky coincidence than real proof for our statement. The lower strength of the granite must be ascribed to its coarse grain size and the toughness of the basalt to its aphonic texture. Velocity is, however, more a function of mineral composition rather than texture. Be it as it may it seems not unreasonable to say that at least a tentative positive correlation between strength and velocity can be established.

Let us now investigate the relationship between velocity and density. [11] have published the data shown in figure 4. If one superimposes on it the velocity-density relationship as given by the time average equation (equation 1) using the numerical values as shown in figure 4 one notices a good fit for zero porosity and porosities less than about 25%, just as one would expect for data of sediments of decreasing porosity.

$$\Delta t = (1\text{-}n).\Delta t_m + \Delta t_w \;............1$$

where n is the fractional porosity; Δt_m the transit time of the matrix, and Δt_w the transit time for the pore filler [12].

If one plots salt and ice, two non-porous materials, on the same graph as in figure 5 one finds that these do not fit the plot at all. Just as I have said before in the presence of appreciable porosity this becomes the overriding factor. It therefore, becomes important to find whether a correlation between velocity and density exists in the absence of porosity. In figure 6 a velocity-density graph is plotted for rocks with negligible porosities. It can be seen that under these conditions, where the properties of the framework are the decisive factor again a positive correlation seems to exist between velocity and density.

Salt is no doubt the best known diapiric material. It is mechanically weak, in fact a geological liquid, and of low density. Yet salt is usually perceived to be high velocity material. Just on what observation is this notion really based? The early geophysical refraction surveys located shallow salt domes in the Gulf Coast by fan shooting [13]. At shallow depth, intruded into young, semi-consolidated coastal sediments, salt is indeed a high velocity material. The situation is that depicted in figure 5. The Salt has risen several kilometres from its mother-bed and now sits as a non-porous material in a high porosity environment. [14] cites porosity values for freshly deposited salt of 30% (Russian literature). From the computation it showed that such salt has a density of about $1.9.10^3$ kg/m^3 and a velocity of about 2,800 m/s (9,00 ft/s), which by any standard is a low velocity-low density material. In fact, considering that the time-average equation begins to fail at these high porosities, the above numerical values provide not a bad fit on the graph drawn after [11] shown in figures 4 and 5. Generally, salt under deep-waters and under little overburden remains non-compactable which gives it a density invariant with depth (Fig. 7, [15]) and also a velocity which is not a function of depth, a highly anomalous situation. At its depth of origin in the Gulf Coast, salt is not only a low density but also a low velocity material [16]. It seems that the anomalous situation of salt can be resolved in two ways:

Either by accepting salt itself as the anomalous earth material as really is or else,

by recognizing that diapiric salt is "out of its depth" and resides in an anomalous environment.

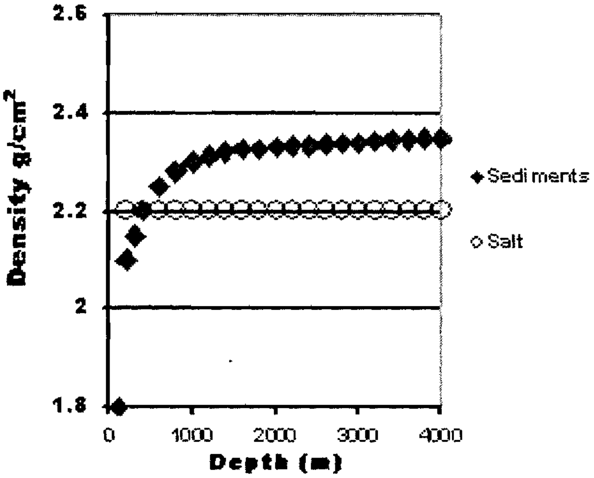

Fig. 7: Crossplot of Sediment (Niger Delta)and salt (US Gulf Coast) densities versus depth. Data for US Gulf Coast from [19]

4. DISCUSSION OF VARIOUS LOW VELOCITY LAYERS.

The more prominent sedimentary low velocity layers are discussed here. Their geological and geophysical importance is assessed.

Geopressured Shales:

Geopressured shales have recently become recognised as a major structural material. Because of the restriction of fluid escape such shales are under-compacted and usually of abnormally low density and velocity [17]. At the same time they are weak and mobile and, therefore, not only act as detachment planes for growth faults but themselves form major diapirs [9]. The presence of gas is often observed [18] and it will further enhance the diapiric nature of these shales and lower velocity and density.

The combination of shale diapirs and growth faults has been described from many continental margins where oil exploration has been carried ou, such as: the U.S Gulf Coast, the Niger delta, the Mackenzie delta and others ([19] and [20]). As pointed out earlier it is the listric nature of the growth faults that produces the rollover. This combined with the regional dip accounts for the structural traps, many of which carry major hydrocarbon accumulation. It should not be forgotten, however, that shale flowage and diapirism are a form of decollement tectonics and deeper structures. So-far this aspect has been of little interest since the sub-shale structures are mostly beyond current "commercial depth" and geopressured shales even today are hazardous to drill.

Since geopressured shales present a drilling problem special precautions must be taken. Formation properties must be continuously monitored and casing must be set at the appropriate depth in the transition zone. It is, therefore highly important to know the "top geopressures" in advance. For years every self-respecting geophysicists had to predict the depth to the overpressured shales on the basis of seismic velocity analysis [21]. The geophysicists make use of the velocity reversal in order to send the early warning.

Salt:

Salt is the clastic diapiric material. As a sedimentary rock it is unusual insofar as it is not subject to compaction (or another way to say it: it' gets compacted instantaneously under as little as 30 m of overburden according to [22]. It is for this reason that salt does not show the usual trend of increasing velocity and density with depth (Fig. 7). Due to its extreme mobility - being a geological liquid - salt is often encountered many kilometres above its mother-bed. In this unusual environment of only semi-consolidated, near-surface coastal sediments salt is no longer a low velocity nor low-density material.

5. CONCLUSIONS

Seismic velocity has structural significance. Low velocity layers are weak layers and, therefore. potential detachment planes, which tend to be activated during structural deformation. The low velocity layer is the diapiric shale structure, which in the Akata

Formation has been recognised as a preferred decollement. In addition, thick low velocity layers because of the associated density inversion can act as mother-beds for diapirs.

Acknowledgements

The author wishes to express her appreciation to Department of Petroleum Resources and Elf Nigeria Limited both in Lagos, for the data used and for their permission to publish this material. Their assistance is gratefully.acknowledged.

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