Geological mapping of the near seabed section on central Campos Basin through elastic attributes extracted from 3D reflection seismic data

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Abstract

A method of geological mapping of the near seabed section is presented in that such a characterization was performed through the interpretation of elastic attributes extracted from 3D reflection seismic data inversion and AVO (amplitude versus offset) analysis. The results regarded as the best ones were obtained from the ratio between Lamé's coefficients, λ/μ (for the former) and an AVO attribute related to the so-called parameter "B" from Aki-Richards equation (Aki and Richards, 1980) for the latter. Although seismic inversion is more commonly applied to relatively consolidated rocks in the hydrocarbon Exploration, we were able to discriminate less consolidated sediments from the near seabed section in terms of four different morpho-structural domains or compartments as well as a few faciological characteristics. In addition to the conventional seismic data, high resolution data (sub-bottom profile or SBP and multi-beam bathymetry) were used. Other sources of information include geotechnical *in situ* data (soil resistance to the penetration of piezocone device or PCPT and seismic piezocone device or SPCPT) and geological sampling through piston core.

Introduction

The area under investigation is located offshore central Campos Basin, in the continental slope province, 150 km southeast from the city of Macaé, Rio de Janeiro state. Slope here is 45 km wide on average, aligns NE-SW and has an average gradient of 2 to 3 degrees, which may reach up to 8 degrees towards lower slope. Higher values may be locally related to scarps or faults. Bathymetry ranges from 800 m (middle slope) to 2,100 m (lower slope, up to the São Paulo Plateau province). Physiography reflects shallow geology, represented by an Upper Miocene prograding wedge with seismostratigraphic sigmoidal pattern. This results in a convex shaped morphology with gradient increasing downslope and the shedding of upper strata by gravitational mass-transport. This process exposes older strata that progressively outcrop downslope.

The upper and middle slope is typified by slump or creep deposits, crumpled and folded, that leave behind scar-like features, described by Kowsmann and Viana, 1992, Castro *et al.,* 1995, Caddah *et al.,* 1998 and Silveira, 2006, Amaral *et al.,*2008.

Four different morpho-structural domains may be established after the interpretation of bathymetry and elastic attributes extracted from 3D seismic data. The interpretation of seismic inversion derived attributes (Sobreira *et al.,* 2010) was complemented with data such as high resolution multi-beam bathymetry, high resolution sub-bottom profile seismic data, *in situ* geotechnical tests (piezocone penetration test or PCPT and seismic piezocone or SPCPT) and piston core geological sampling (Kowsmann *et al*., 2004).

The output parameters of the seismic inversion are acoustic impedance, shear impedance and density, from which and through algebraic manipulation, elastic moduli such as (dynamic) shear modulus (μ) and Lamé's parameter (λ), jointly named Lamé's coefficients were derived A combination of these two, the λ/μ ratio, was found to be the attribute that provided the best morpho-structural discrimination throughout the area. One can characterize slump/ creep deposits on the upper and middle slope as well as older sediments' outcrops on the lower slope, and chaotic mass-transport deposits at the base of the slope. Besides, integrating seismic attributes and geotechnical data has allowed to characterize different geotechnical facies such as normally consolidated muds, over-consolidated muds, stiff muds, heterogeneous muds and carbonate formations.

Method

This paper aims to assess the relationship between elastic parameters derived from AVO (amplitude versus offset) analysis and from elastic seismic inversion in marine soils. To achieve this, one must bear in mind the behavior of marine unconsolidated sediments. Near seabed silty-muddy sediments act as a porous soil saturated with salty water, and may be composed by highly porous and permeable granular and bioclastic matrix. These behave rather viscoelastically, although upon dependence of deformation rate or history (burial or mass removal/ erosion processes). Viscoelastic materials may be mathematically represented by equations that consider the viscosity and stress duration in the models (Mavko *et al.,* 2009), although elastic wave propagation effect on marine soil (liquid-solid interface) be here analyzed in the context of AVO and seismic inversion. Lamé's parameter λ and shear modulus μ were obtained from acoustic impedance (Ip=Vp.ρ) and shear impedance (Is=Vs.ρ), which are respectively related to compressional or P-wave velocity (Vp) and shear or S-wave velocity (Vs), besides density (ρ):

$\lambda = \rho(Vp^2 - 2Vs^2)$ and $\mu = Vs^2\rho$.

Dvorkin *et al.* (1999) proposes estimating seismic velocities for unconsolidated sediments by taking into account effective pressure, porosity and mineral composition of the sediment, in which elastic moduli such as *k* (incompressibility or bulk modulus) and µ may be adjusted to such elevated saturation percentages even beyond correspondent critical porosity, what is not uncommon by the mudline. Critical porosity may be related (Nur *et al.,* 1998) to the transition between suspension and a continuous matrix and has strong impact on the elastic velocities of near seabed sediments. Generally, at percentages over 50%, sediments behave as non-connected solid particles immersed and suspended in fluid (water) whose global acoustic velocity may be even smaller than that of water itself. This may be empirically thought as being caused by adding to the compressibility (*Co=1/k)* of fluid the effect of the suspended particles (Raymer and Gardner, 1980). As bulk modulus $\kappa = 1/Co$ decreases, so it does compressional velocity Vp.

$Vp = \sqrt{\dfrac{k + (4/3)\mu}{\rho}}$, where $Co = \dfrac{1}{k} = \dfrac{\phi}{k_f} + \dfrac{1-\phi}{k_a}$.

Or, similarly, $k + (4/3)\mu = \lambda + 2\mu$. ø is the porosity and k_f and K_a are bulk modulus of fluid and sediment's matrix respectively.

Shear wave doesn't propagate on sea water, since µ=0. However, one could argue that its propagation through very unconsolidated marine sediments may be caused by the increase of density variation related to the presence of suspended particles with no need to substantially increase µ values (Dvorkin *et al*. 1999).

Although density may be regarded as a critical quantity to enable a more complete analysis of elastic parameters, there could be some related ambiguities, since at some intermediate incidence angles *θ* (required to properly extract it) the reflection coefficient r(*θ*) no longer behaves linearly. Besides, the steep and irregular gradient of the seabed also contributes to some instability on the results. On the Richards, Frasier and Aki approximation based seismic inversion approach (Rosa, 2010) density (or its relative variation) could be obtained indirectly through the amplitude versus offset (AVO) variation, by subtracting the third term from the first one (A-C):

$$r(\theta) = A + (B + C\tan^2\theta)sen^2\theta ,$$

$A - C = \left[\dfrac{1}{2}\left(\dfrac{\Delta Vp}{\overline{Vp}} + \dfrac{\Delta\rho}{\overline{\rho}}\right)\right] - \left[\dfrac{\Delta Vp}{2\overline{Vp}}\right] = \dfrac{1}{2}\dfrac{\Delta\rho}{\overline{\rho}}$ and

$B = -\gamma A + \left(\dfrac{1-\gamma}{2}\right)\dfrac{\Delta Vp}{\overline{Vp}} + \dfrac{\Delta\upsilon}{(1-\overline{\upsilon})^2}$, where $\gamma = 4\dfrac{\overline{Vs}^2}{\overline{Vp}^2}$

and υ is the Poisson ratio. The symbol " ¯ " stands for average values.

However, one may wish not to consider C and still obtain a linear approximation useable for the purpose of quality control of seismic inversion results, so that parameters A and B (first and second terms, respectively) now represent intercept and gradient (Rosa, 2010), respectively $\overline{A}$ and $\overline{B}$:

$$r(\theta) \cong \overline{A} + \overline{B}\,sen^2\overline{\theta} .$$

Intersection and gradient are related to elastic properties as $\overline{A} \cong A = r(0)$ and $\overline{B} = B$. A good approximation for parameter B is the normalized F-N ("Far trace" seismic amplitude minus "Near trace" seismic amplitude). Numerical simulations were done by considering Aki-Richards AVO approximation (Aki and Richards, 1980) and using S-wave velocities from *in situ* geotechnical measurements, that could predict the corresponding F-N behavior. This enabled comparisons between preliminary AVO results and λ/µ, a ratio that doesn't strictly consider density:

$$\frac{\lambda}{\mu} = \left(\frac{Ip}{Is}\right)^2 - 2 \cdot$$

Lamé's coefficient (λ) depends upon incompressibility (or bulk modulus) *k* and shear modulus µ. The former is a function of two components, the incompressibility of non-saturated matrix (k_a) and the incompressibility of the pore content or fluid (k_f),

$\lambda = \kappa - \dfrac{2\mu}{3}$ where $\kappa = \kappa_a + \kappa_f$.

Morpho-structural domains

Seafloor morphology may be characterized by four different morpho-structural domains: (figure 1). These were initially based on the interpretation of sea bottom rugosity through terrain digital model (TDM) visualization plus the above-mentioned normalized F-N attribute, later correlated with the λ/µ ratio.

Domain I occurs on the middle slope, whose relief is rather undulated, due to the slump or creep--related folding and crumpling of thick deposits, thus giving rise to linear structures known as "pressure ridges", which tend to parallelize the isobaths ranging from 800 to 1,200 m. Average sea bottom gradient here is around 2.4 degrees.

Domain II occurs on the middle to lower slope transition zone, and has a typically rugose relief as a consequence of gravitational slump or creep deposits triggered by cracks or listric faults or locally (on the smoother seafloor to the southwest) due to younger sediments being partially or totally removed, thus allowing older (Lower Pleistocene) and stiffer hemipelagic sediments to outcrop. Water depth here ranges from 1,100 to 1,400 m and average sea bottom gradient is around 3.7 degrees.

Domain III occurs on the lower slope, being characterized by linear erosional features (*scours* or large-scale *slickensides*) formed through removal of Pleistocene sediments downslope (thus allowing even older and stiffer marly Upper Miocene sediments to outcrop) and further by faults that may extend up to the seafloor. Water depth ranges from 1,200 to 2,000 m, and average seafloor gradient is around 8 degrees.

Domain IV occurs on the base of the slope (São Paulo Plateau), in a typically rugose relief formed by matrix-supported muddy conglomerates, genetically related to *debris-flows*. These are usually termed “diamictites” (or DMT), actually originating from sediments removed from the middle and lower slope. Water depth ranges from 2,000 to 2,100 m, and average seafloor gradient is around 1.7 degrees.

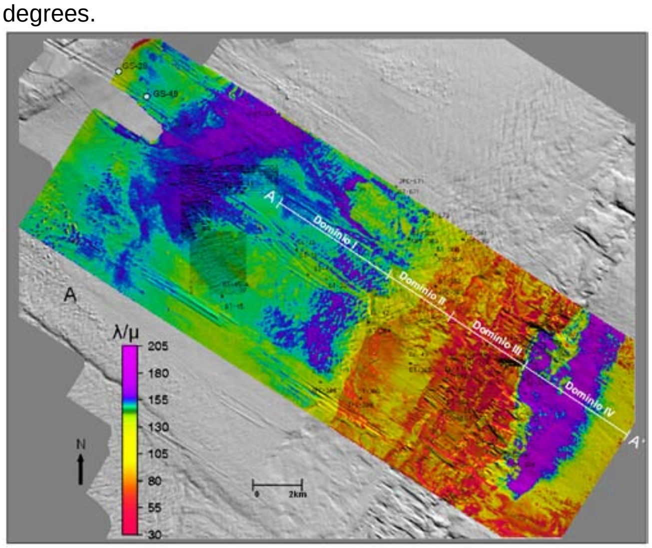

Figure 1 - Seismic inversion derived attribute λ/μ superimposed by shadowed sea bottom relief. A-A’ transect crosses through the several morpho-structural domains (corresponding geological section shown in figure 2). Important features are carbonate mounds occurring on Domain I, smooth to undulated, transitional relief, on Domain II, sliding-related scar features on Domain III, and rugose features, related to conglomeratic debris flow deposits, on Domain IV.

Sedimentary facies

Sea bottom relief is strongly controlled by the geometry of shallow strata, over which a hemipelagic drape has settled. This drape, Pleistocene to Holocene in age, occurs everywhere in the area (Kowsmann *et al.*, 2004), covering mass transport-related deposits and over-consolidated sediments from Domains I to IV. These are mainly muddy to silty sediments, with occasional fine sand, whose thickness may range from 0.5 to 5 meters.

Mass transport-related deposits caused by sliding are made up of muddy hemipelagic sediments, internally deformed (folded and crumpled), while those related to debris flow (DMT) are made up of stiff clasts and muddy blocks dispersed within a less stiff muddy matrix with internal chaotic structure. These sediments tend to occur on Domain IV while slide-related deposits tend to occur on Domain II.

Stiff, over-consolidated mud is made up of marl (mud with $CaCO_3$ content over 30%) and occurs in depths ranging from a few to tens of meters below the seafloor. It tends to occur on Domain III.

Carbonate mounds are prominent, circular and elongated features, which impose themselves over the undulated relief of the seafloor, containing about 30 to 60% skeletal fragments of cold water corals mixed in with muds. These mounds occur on Domain I, where normally consolidated muds prevail.

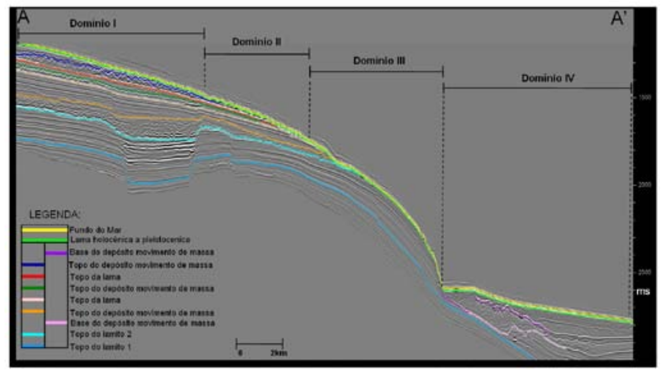

Figure 2 – Interpreted seismic section with key horizons and the several morpho-structural domains shown

The relations between sedimentary facies and elastic parameters are shown in figure 3. These must be taken as general geological models, and variations such as the thickness of drape sediments, matrix structure and composition of over-consolidated sediments may occur. The acceptable threshold for vertical resolution is normally considered a quarter of dominant seismic wavelength, which, in the case, is about 4-5 metes. In order to obtain Gassmann`s calculated values of compressional velocities for highly-porous near seabed sediments, it’s necessary to input an average shear modulus at the depth of investigation. The very shallow resolution relates to very low Vs values, and as it becomes deeper, the average Vs increases enough to be correlated with Vs inverted seismic data. It has been verified that calculated elastic parameters refer to seismic resolutions of approximately T/2, or 8-10 meters.

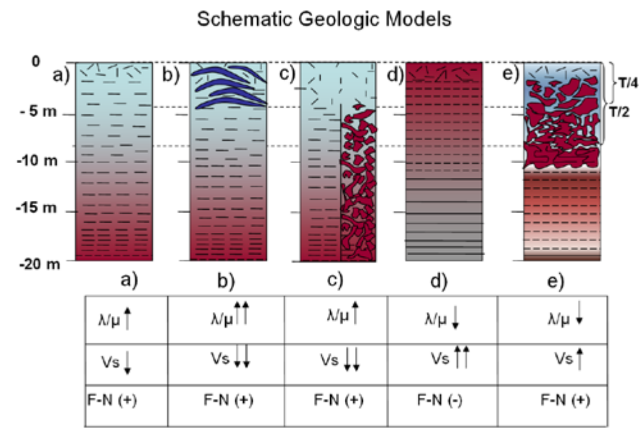

Figure 3 – Several geological scenarios for the shallow section, from domain I (left) to IV (right)**:** a) a thin ooze layer covers normal consolidated sediments; b) carbonate mound formations enveloped by normal consolidated sediments; c) A thick ooze layer covers normal consolidated sediments and mass transport-related deposits; d) A thin ooze covers over-consolidated sediments; e) A thin ooze covers mass transport-related deposits. The arrows mean relative variations between elastic parameters and T/4 is the thickness equivalent to minimum seismic resolution.

Results

By numerically simulating the reflectivity through Aki-Richards approximation (1980) it becomes clear that shear wave velocity (Vs) is higher (and shallow sediments are more rigid) where the positive seismic amplitudes decrease with increasing incidence angle (figure 4). When the opposite happens, that is, amplitudes increase with increasing incidence angle, Vs is lower (and shallow sediments are less rigid). Similarly, the λ/μ ratio is lower where more rigid (or consolidated) sediments occur such as in Domain III.

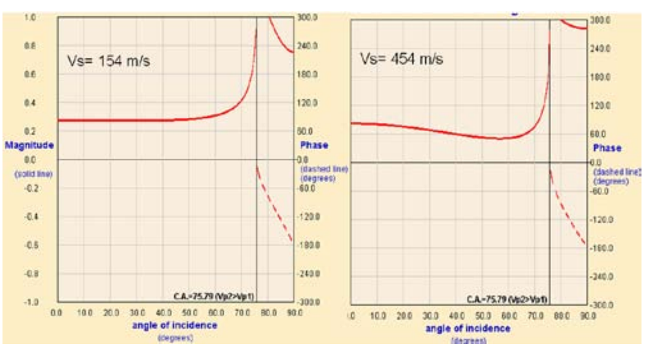

Figure 4 – Numerical simulation based on Aki-Richards approximation (Aki and Richards, 1980), comparing less consolidated shallow sediments (Vs=154 m/s) and more consolidated shallow sediments (Vs=454 m/s) and the corresponding differentiated behavior of the reflection coefficient with incidence angle.

Joint analysis of elastic attributes and F-N was used by Sobreira *et al.* (2010) to obtain some insight into their qualitative relationship with degree of consolidation or rigidity of marine sediments, especially in siliciclastics. While for these rocks a consistent relationship was found (for both elastic attributes and F-N), the same doesn't hold true for the carbonate mound facies that occur in Domain I, for which very low Vs (even lower than surrounding normally consolidated muds – figure 5 -) opposes highly consolidated matrix (or high shear strength). This would happen in the case of a rigid, but highly porous sediment's framework, which seems to be a more plausible explanation for these carbonate mound formations. Figure 6 depicts the topographic expression of these features.

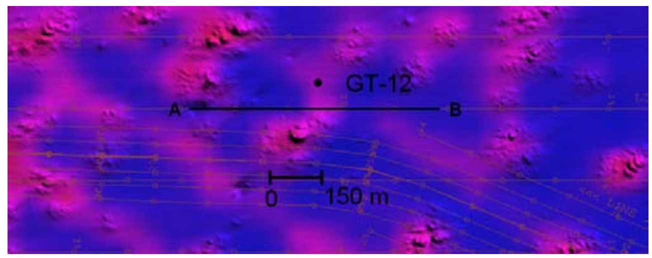

Figure 5 – Detail of Domain I: carbonate mound facies that occur as circular features (in reddish colors) are related to very low shear modulus (and thus, Vs) values with respect to the surrounding muddy sediments (in blue). Section corresponding to A-B transect is shown in figure 6

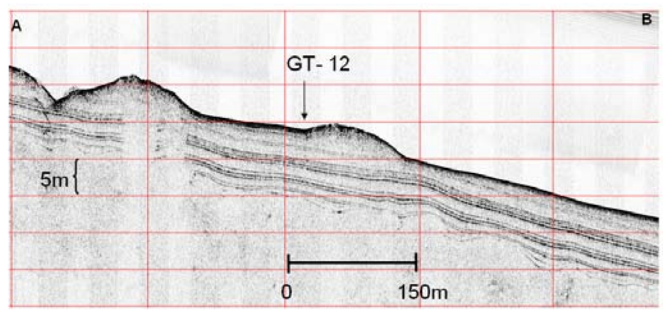

Figure 6 – SBP (sub-bottom profile) section along transect from figure 1 (3.5 KHz emission frequency). High-relief carbonate mounds are surrounded by normally consolidated muds.

Considering the variation in Vp, the sediments may present velocities lower than seawater of up to 3%(Hamilton, 1970). This is probably due to the presence of solid particles in suspension. In the study area, compressional velocities in seawater were observed to be higher (mean: 1495 m/s) near the seabed interface in deep waters (1700-2000m isobaths) and to be lower (mean: 1485 m/s) in shallower waters (600-1300m isobaths). When the velocity of seawater near the seabed is greater than that of the surficial sediments, a reduction in the reflection coefficient occurs with the increase in the angle of incidence. An increase in the reflection coefficient can also occur due to the decrease in Vs in the presence of a thick package of unconsolidated mud. Thus, according to the latter, the seabed sediments tend to be less consolidated than in shallower waters.

Conclusions

Joint analysis of the elastic attribute λ/μ and AVO made it possible to characterize four different morpho-structural domains, each one with its own faciological features. While for the siliciclastic facies a positive relationship was found between elastic attributes and degree of consolidation (or shear strength), the same doesn't hold true for the carbonate mound facies, whose framework is highly rigid however porous enough to affect shear modulus and Vs significantly (causing them both to decrease). The shear impedances for the carbonate mound facies tend to be smaller than for the surrounding normally consolidated muds.

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