Reservoir Seismic Characterization of Brazilian Offshore and Pre-Salt Fields

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Abstract

This paper focuses on the strong impact that seismic technology has had on the production development of the Brazilian marine hydrocarbon fields starting from the first oil discovery in 1968 (Guaricema field) to 2006, when the pre-salt new province was revealed in Santos basin. The evolution of three main knowledge areas of seismic technology will be detailed, namely: acquisition, processing and interpretation. Seismic acquisition technology has experienced an increase in "information density" (seismic traces per square kilometer) which grew by one order of magnitude (from less than 100,000 to 1,024,000), from 1978 (first 3D in Brazil) to 2010. In the seismic processing domain, the improvement of seismic algorithms and methodologies has allowed for better seismic data quality, resolution and imaging. In particular, the algorithms/techniques of 3D multiple suppression and 3D depth migration have significantly evolved in recent years. In the seismic interpretation area, geological context-oriented seismic attributes algorithms/methodologies have made possible better reservoir characterization and monitoring in the deep and ultra deep-water Brazilian offshore basins.

Introduction

This work will not limit the concept of Advanced Seismic Imaging-related technologies to the classic development of seismic migration–oriented methodologies and algorithms as traditionally perceived by the seismic processing area. It seems to us that the advanced seismic imaging technology capable of correctly impacting the development of oil reservoirs would be better understood if viewed as an integrated complex to include acquisition, processing and interpretation technologies.

This will provide us with a more adequate and systemic view of the real impact of the evolution of these technologies on the development of Brazil's offshore oil fields.

A brief historical evolution will be outlined below together with the identification of significant technological milestones in each of the respective seismic activity areas in the Brazilian coast. Greater emphasis will be placed on results of the last 10 years when Petrobras decided to invest in high-density data (>1,000,000 traces/km^2) for characterization and monitoring of turbidite reservoirs and also decided to invest in multicomponent seismic technology with a sizeable initial portfolio of 3C and 4C projects. We will also mention the company's initial efforts to improve the seismic imaging of the recently (2006) discovered reservoirs of the new pre-salt hydrocarbon province. Huge efforts in seismic data acquisition and processing have been put forth both by Petrobras and service companies in this new oil province to enhance the seismic imaging. The Brazilian pre-salt reservoirs have their own specific geological and geophysical characteristics (range of velocities, salt stratification, complex imaging, etc.) which differ from those displayed by the sub-salt reservoirs of GOM and other sedimentary basins of the world. In view of this, new seismic technologies encompassing the three general knowledge areas namely, acquisition, processing and interpretation, will have to be rapidly developed to cope with the challenges posed by the massive dimensions of the energy resources discovered, and still to be discovered, in that new province.

Advanced Seismic Imaging Impacting a Field in Development Phase - Caratinga Field Case

The first oil discovery off Brazil's coast using 3-D seismic was Caratinga Field, in Campos Basin. Those 3-D seismic data, which were acquired in 1989, have been considered practically all throughout the 90's decade as the best data set for that basin with respect to seismic data quality, resolution and imaging. In 1999, the need to define if a geological fault separated or not a turbidite lobe between a production well and the drilling of a bi-lateral water injector well showed the necessity to improve the spatial resolution to allow the proper characterization of these small geological faults and to define if they separated or not the reservoirs between the production well and the future injectors (Fig. 1).

After performing value of information studies, it became clear that the needed investment for a new seismic effort for the Caratinga project was economically attractive in view of this bi-lateral water injector case. Motivated by this demand for high spatial resolution, the first high-density seismic project for a Brazilian marine sedimentary basin was tendered by Petrobras. The service company PGS won the tender and was awarded

the contract. At that time, there were doubts if the processing algorithms would be capable of extracting the full potential of these high-density data. However, the lessons learned through the past experience of Petrobras in the Brazilian offshore scenario since the 60's decade could assure that once the best acquisition efforts were made, the processing algorithms would either cope with the task, or would rapidly evolve to respond to the needs for better resolution and improved seismic imaging of these denser data sets. The processing and interpretation of these higher density data sets, starting in the 2000's decade, revealed amazing positive results in terms of impact on the production development of the field. The new seismic interpretation not only revealed that the bi-lateral water injector well was not in an adequate position nor was it correctly oriented, but also allowed the project interpreters to characterize that the interior of the turbidite lobes presented evident geological channels with a great potential to preferentially orient the flow of fluids inside the field's reservoirs.

The fact that the field was still in its initial development stage made it possible to reposition most of the injectors and producers wells of the field, thus significantly changing the drainage conception of its reservoirs. The strategy of imaging with high-density seismic data has clearly had a significant and positive economic impact on this project.

Advanced Seismic Imaging Impacting a Field in Mature Phase - Marlim Field Case

Marlim Field, in Campos Basin, was discovered in 1985 with the use of 2-D seismic. The characterization of its reservoirs for field development purposes was based on 2-D seismic (1985) and on 3-D seismic acquired in 1997, after its discovery and start of the production phase (1991). The first Marlim high-density seismic was shot in 2005 with the objective of enhancing the seismic characterization of the reservoirs and also to make possible the first try at using seismic to monitor water injection fronts in the field's reservoirs (Fig. 2). The impact of the high-density seismic imaging far exceeded expectations and estimated results of value of information studies (Johann et al, 2006). Several wells were drilled to form a denser drilling pattern using the new seismic imaging achieving highly significant results in terms of recovery factor enhancement: RF evolved from 35% to 50%. Among the most significant results related to the monitoring technology of this project we could mention the revealing fact disclosed by the 4-D seismic imaging related to the interpretation of the 4-D seismic anomalies between 2005 and 1997 data, which allowed the injection water preferential flow paths to be characterized as trends in the basal reservoirs of the field (Fig. 2). This made possible to build permeability distribution maps using geostatistics algorithms based on wells information and on this trend defined by the 4-D seismic interpretation. The new permeability model has impacted the change of the conceptual geologic model of the field (Fig. 3). The introduction of this new geologic model in the flow modeling provided a more effective and coherent 15-year history match for the field's reservoirs (Johann et al, 2009). Thus, this high-density seismic imaging strategy together with the seismic monitoring vision have greatly impacted the production and the economics of this mature field, being this the pioneer 4-D seismic technology project in the Brazilian offshore area.

Advanced Seismic Imaging Impacting a Pre-Development Area - Pre-Salt New Province Case

Seismic imaging has impacted the Santos Basin pre-salt area from the mapping of its structural framework to the support to the facies distributions in reservoirs which are now in production phase through a pilot system, in Lula Field (ex-Tupi lead).

In spite of all the advances made between the 60's and the 90's decades in the seismic imaging of Campos Basin, the same reality was not shared by Santos Basin, especially since the seismic available for that basin was only 2-D having to cope with a much more complex geological area with the presence of very thick salt layers. Consequently, the reality was that the 2-D based seismic imaging of Santos Basin, specially, that of the rift section, where Africa and South America separate, and also of its pre-salt reservoirs, was rather deficient as compared to the excellent seismic data sets available, at the time, for Campos Basin (Fig. 4).

Several re-processing efforts were put forth to improve these 2-D data sets so as to ameliorate the conditions for the identification of

exploratory leads in the post and pre-salt reservoirs of this basin (Fig. 4). These were very important improvements which have motivated the implementation of a large 3-D seismic campaign still for exploratory ends. Thus, in 2001, the first phase of a 3-D seismic acquisition campaign aimed at the imaging of the new pre-salt province was performed (Fig. 4c). This large scale (>20,000 km^2) survey, shot by Veritas (presently CGGVeritas), was parameterized for the post-salt section and still had exploratory objectives. These seismic data, time and depth-migrated, are serving now as the basis for the findings and initial development of fields of the new Santos Basin pre-salt province. In 2010, Petrobras and its partners in this new pre-salt province, have started a second phase of the seismic acquisition effort, comprised now by high-density seismic imaging projects (>1,000,000 traces/km^2) in the Santos pre-salt area, which were now focused on the recently discovered oil fields. This tender was won by PGS who was awarded the job. The initial processing and interpretation results of these data already show the striking importance of high-density data for the characterization of these pre-salt reservoirs in the new oil province (Fig. 5).

The improved seismic characterization of these reservoirs using high-density data guarantees a strong positive impact on the development, production and economics of these projects.

Conclusions

Petrobras has allocated sizeable investments and efforts in marine seismic since 1968. The evolution of marine seismic technologies started with 2-D seismic followed by one-streamer 3-D seismic, multi-streamer 3-D seismic, solid streamers, radio-positioned navigation, GPS navigation, steerable source arrays and streamers, single receivers, multicomponent seismic, full-azimuth seismic, permanent seismic monitoring system with the use of conventional or optical sensors.

The results obtained with these technological achievements in acquisition and seismic processing has had a strong impact on the quality of the seismic imaging. This has made possible the drilling of wells with much improved exploratory success rates and the more precise and correct positioning of delimitation and production development wells for the characterized reservoirs, all this contributing to increase the recovery factor of the reservoirs off the Brazilian coast.

Along these last 40 years, the strategy of being always at the forefront of innovation introducing new seismic technologies, from data acquisition to processing and interpretation, has proved to be correct. Moreover, the strong qualification of the Brazilian professional geophysicists, geologists and reservoir engineers attained through a massive investment in career-oriented training has been one of the outstanding features of this strategy. The resulting competence achieved by these professionals in the understanding of the essentials of the seismic method and in the in-house seismic processing practice has guaranteed Petrobras the capacity to critically analyze the data to be interpreted during the decision process involving substancial financial investments such as the ones made in Brazilian offshore areas, especially in deep and ultra-deep waters.

The resulting increase of reserves and production experienced during recent years clearly confirms that the followed path has been correct.

Some remaining challenges should be listed: the constant pursuit for better seismic data quality, resolution and imaging, especially for studying thin turbidite reservoirs with less than 10m thickness; for the understanding of the Albian carbonate reservoirs, their facies distribution and permo-porous properties; for the seismic characterization of facies and permo-porous properties of microbial and carbonate reservoirs of the new pre-salt province.

The need still remains for the seismic technologies to increase their capacity to discern fluid presence and type within the reservoir. Furthermore, detection of both, fluid

and pressure changes that occur along the production phase on carbonate reservoirs has a high impact on E&P business. Consequently, it is crucial to focus on time-lapse seismic studies using dense and repeatable surveys on these highly heterogeneous and incompressible rocks. The multicomponent seismic approach has yet to prove that the added investments needed for these specific acquisitions will provide significantly better seismic imaging results than those obtainable by more traditional high-density acquisition methods. The permanent monitoring systems segment will undergo an initial evaluation when the results of the first pilot project being implemented in Jubarte Field, Campos Basin become available. The value of that strategy for reservoir management ends will then be assessable.

The foreseen role for the seismic technology in the realm of E&P shall be its effective use as a reservoir management tool, besides its indispensable contribution to the improvement of the exploratory success rate and to the enhancement of the recovery factors of fields during the production development phase and of mature fields alike. Its effective use as a reservoir management tool will guarantee that the seismic imaging will increasingly bring a positive impact to the economics of the E&P projects.

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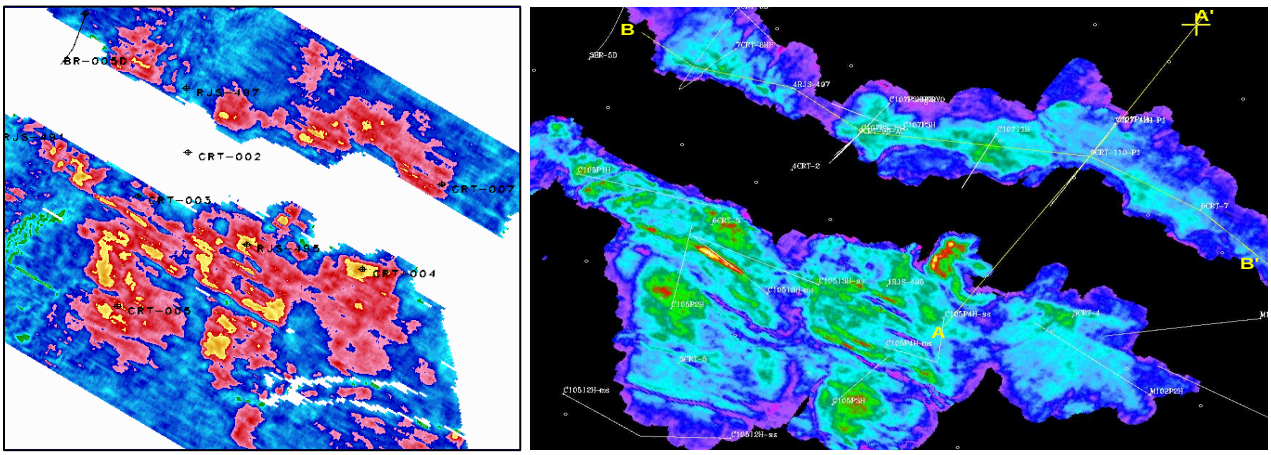


Fig. 1 - New seismic interpretation that not only revealed that the bi-lateral water injector well was not in an adequate position nor was it correctly oriented, but also allowed the project interpreters to characterize that the interior of the turbidite lobes presented evident geological channels with a great potential to preferentially orient the flow of fluids inside the field's reservoirs.

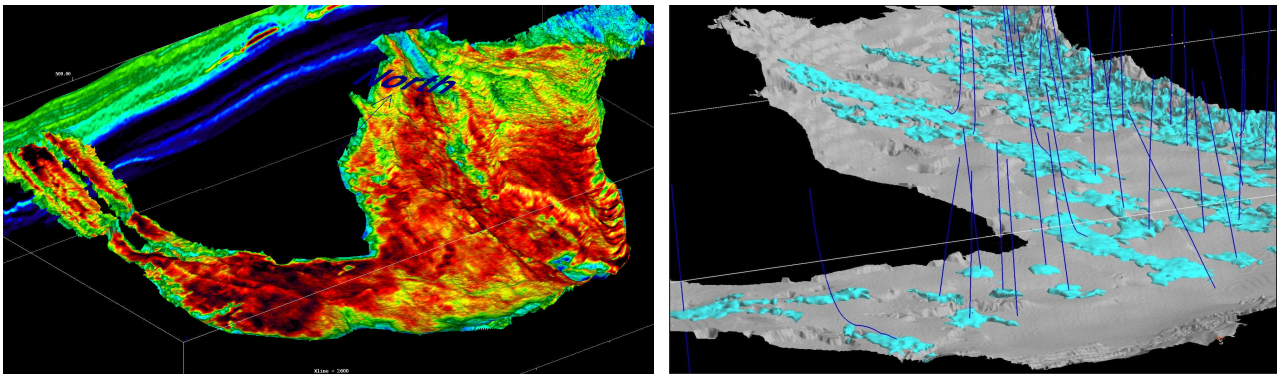
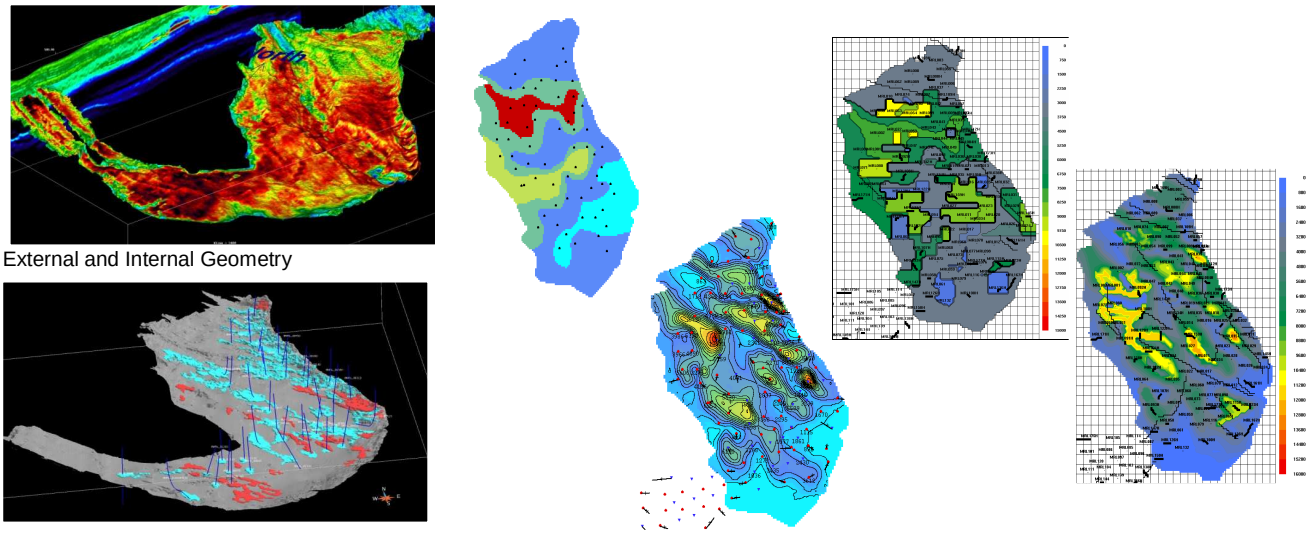


Fig. 2 - 3-D amplitude map and a 4-D seismic interpretation (water replacing oil) from Marlim field. Note: data quality, resolution and seismic imaging evolution at Marlim field.



External and Internal Geometry

4-D Seismic anomalies showing anisotropic trends Permeability maps: before and after 4D Flow maps: before and after 4D integration.

Fig. 3 - Impact of 4-D seismic interpretation at Marlim field in terms of geological and flow models. Note that the permeability and simulation flow maps obtained only from well log information (DST) and interpolation algoritms show complete different reservoir properties than after 4-D seismic interpretation was integrated . Moreover, these new maps are more coherent with the conceptual sedimentological model for Marlim field with NW-SE sands distribution.

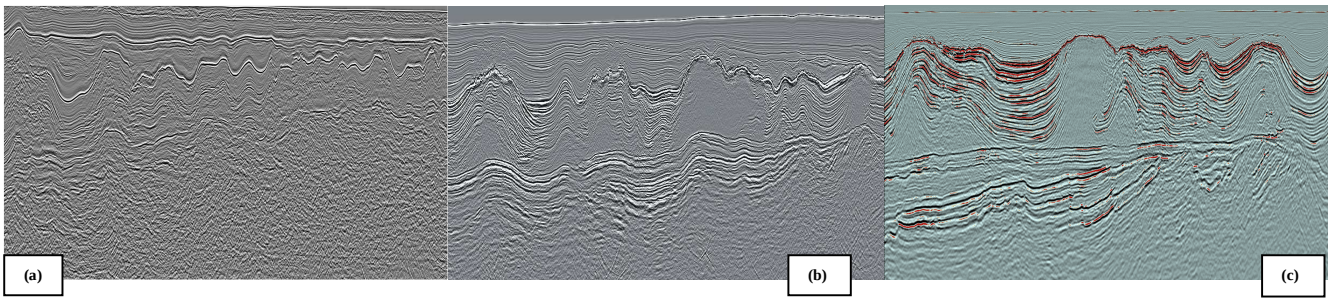


Fig. 4. Pre-salt province 2-D seismic section: (a) seismic image of the 90's; (b) seismic image after Petrobras' in-house re-processing effort - early 2000's; (c) seismic image extracted from 3-D data acquired at Santos basin (cluster acquired in 2001 by CGGVeritas).

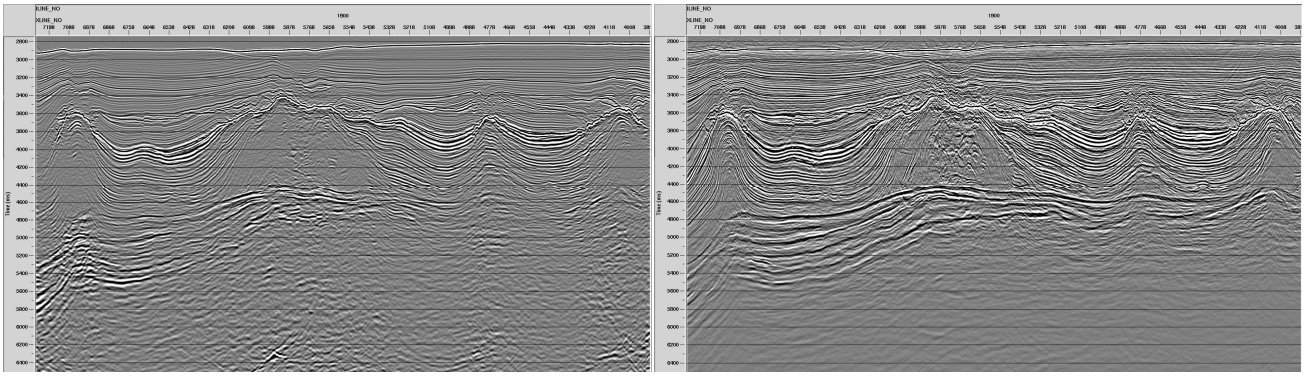


Fig. 5. Pre-salt province 3-D seismic data: (a) 2001 data; (b) after Petrobras' in-house processing of the high density data (preliminary results).