UNLOCKING NEW RESOURCES IN COMPLEX TECTONIC SETTINGS AN INSIGHT INTO THE PROSPECTIVITY AND PETROLEUM SYSTEMS OF THE NANKAI ACCRETIONARY PRISM

CĂLIN CONSTANTIN NIȚĂ[1], IZABELA MARIȘ[1], IOAN MUNTEANU[1,2]

[1] *Faculty of Geology and Geophysics, University of Bucharest, Bucharest, Romania*
[2] *„Sabba S. Ștefănescu" Institute of Geodynamics of the Romanian Academy*

Recent advances in seismic acquisition and processing have allowed research centers and corporations all over the world to move the frontiers of hydrocarbon exploration in complex areas, such as subduction zones. Three dimensional seismic surveys, corroborated with log data, tops and biostratigraphic ages from wells, now permit geoscientists to define sedimentological models, and to characterize deformation mechanisms and visualize the extent of various thrust sheets structures in accretionary prisms. The focus of this study is to integrate 672 square km of seismic coverage with data from available wells in order to understand the petroleum systems from the Nankai region. In the final step, we would like to define multiple prospects along with the hydrocarbon products, estimating the recoverable resources that these host.

Key words: seismic, Nankai, gas, subduction, accretionary prism, petroleum systems, exploration.

1. INTRODUCTION

Accretionary prisms represent tectonic edifices that form at convergent plate margins. They are specific fold and thrust belts that grow in response to subduction of the lower plate and accretion of the sedimentary deposits at the upper plate (Beaumont, 1981; Uyeda, 1981). The continuous pursuit for new oil and gas fields marks the abandonment of depleted areas, such as passive margins or continental aulacogens and foreland basins, and the onset of exploration in such challenging compressional environments.

The Nankai accretionary complex is a young Miocene-Quaternary fold and thrust belt formed as a result of the migration of the Boso Triple Junction and the reactivation of the Philippine Sea Plate subduction underneath the Eurasian Plate around 6 Ma ago. It is located in southwest Japan and holds an amazing potential for hydrocarbon resources. In this study, using seismic and well data, we intend to reveal the biogenic gas system in this region and to define a couple of prospects in order to understand if the accretionary complex yields an economic profitability.

2. GEOLOGICAL SETTING

The study area is located along the southwestern margin of Japan, near the Kii Peninsula (Fig. 1). This region is characterized by a convergent tectonic setting which commenced around 6 Ma, when the Philippine Sea Plate subduction beneath the Eurasian Plate was resumed after a pause that lasted for almost 8 Ma (Kimura *et al*., 2014). The Philippine Sea Plate is moving to the north-west, following a 300º–315º azimuth, at a subduction rate of 4 to 6.5 cm per year (Miyazaki and Heki, 2001; Zang *et al*., 2002; Seno *et al*., 2013).

The Nankai system is represented by the accretion of a thick (over 1000 m), mostly terigenous, succession which is made up of the formations deposited in the oceanic trench and in the Shikoku Basin (Park *et al*., 2002), an Oligo-Miocene back-arc basin (Seno and Maruyama, 1984; Chamot-Rooke *et al*., 1987; Hibbard and Karig, 1990) that develops in the northern part of the Philippine Sea Plate (Shiraishi *et al*., 2019), close to the Izu-Bonin island arc (Okino *et al*., 1994). The Shikoku depocentre includes sedimentary deposits that consist mostly of turbidites and hemipelagic muds, along with pelagic shales and tephras in a reduced proportion (Shiraishi *et al*., 2019).

The Nankai fold and thrust belt can be tectonically divided in two major domains (Fig. 2), the inner accretionary prism and the outer accretionary prism, these two being separated by a transition zone which is marked through a major strike-slip megasplay fault, known as the Kumano Basin Edge Fault Zone (KBEFZ) (Kimura *et al*., 2007).

Fig. 1 – Location of the study area within the Japanese Archipelago (Google Earth Pro).

Fig. 2 – Regional TWT seismic cross section along the Nankai accretionary prism showing the main tectonic elements.

The inner prism is a double-vergent accretionary complex that is comprised of highly deformed nappes and the overlying sediments of the Kumano Forearc Basin (Fig. 2). The age of the inner prism thrust sheets varies from 5.9 to 8.1 Ma, in accordance with the ages obtained from the cores that were collected in the Integrated Ocean Drilling Program, indicating that the subduction process was initiated circa 6 Ma (Saffer *et al*., 2009; Gulick *et al*., 2010; Moore *et al*., 2015; Boston *et al*., 2016). The growth of the Kumano Basin triggered a sedimentary loading subsidence mechanism that gradually stabilized the inner prism from a mechanical point of view. This marked the onset of a new compressional cycle which led to the formation of the outer prism, a unit that has been tectonically active in the last couple Ma. Deformation is mainly concentrated in the frontal zone of the fold and thrust belt (Screaton *et al*., 2009; Moore *et al*., 2015). The outer accretionary complex presents an imbricate structure (Fig. 2) that allowed the development of slope basins above the nappes (Strasser *et al*., 2009; Kimura *et al*., 2011).

3. DATASET AND METHODOLOGY

The dataset for this project consisted of a TWT (PSTM) seismic cube that covers almost 672 square km and seven wells (only borehole COOO6 data was used in this study) with the associated geological and geophysical information (tops, logs, cores, reports) (Fig. 3). Another seismic volume, in depth (PSDM), was also available, but it was not selected for interpretation due to the fact that it had a considerably smaller coverage area. The JAMSTEC Agency from Japan acquired and processed the seismic survey in 2006 for scientific research regarding the origin of tsunami generating earthquakes in the region.

Fig. 3 – The dataset that was made available by the JAMSTEC Agency in Japan (seismic) and the IODP Program (wells). In this study we focused on the petroleum systems from the outer prism (red polygon) using the seismic survey and well COOO6. The pseudo-well used for the depth conversion is referenced with the red arrow.

The Kingdom 2017 software was used to manipulate the data in the project. A classic seismic interpretation was carried at a 10 line increment using the principles of seismic sequence stratigraphy. Key surfaces, such as the Bottom Simulating Reflector (BSR) and the tops of the reservoirs, and major thrust faults were mapped in order to understand the geometry and architecture of the thrust sheets in the outer accretionary prism. At the same time, the V_{shale} curve was defined in well COOO6 using the gamma ray log (Fig. 4), with the purpose of creating a depositional model and estimating the lithology variations along the succession (different cut-off values were used to delineate the types of sedimentary rocks: 0–25 for sands/sandstones, 25–35 for silty sands/silty sandstones, 35–55 for silts, 55–60 for silty shales, 60–100 for shales; Fig. 4).

Fig. 4 – V_{sh} curve obtained by processing the gamma ray log (A) and the associated lithology that was delineated using multiple cut-off values (0–25 for sands/sandstones, 25–35 for silty sands/silty sandstones, 35–55 for silts, 55–60 for silty shales, 60–100 for shales).

The following stage was represented by the depth conversion of the TWT maps, in which the *Depth Map by Shared T-D Chart* function was applied. In order to avoid consistent errors that reached more than 600 m for the charts in the existent wells, due to low drilling depths, one pseudo-well was built using both the TWT and depth seismic surveys (Fig. 3). This approach presumed that each stratigraphic element (sea bottom, BSR, the top of the reservoir, Benioff zone etc.) from the time volume was assigned to the exact same element in the depth seismic.

The final approach in the methodology marked the integration of the results from the previous phases in order to define the petroleum systems and to establish a couple of prospects with their associated volumetric calculations.

4. HYDROCARBON POTENTIAL AND PETROLEUM SYSTEMS – RESULTS AND DISCUSSIONS

Two, fully imaged, elongated anticline structures (that are named in this paper Tokugawa and Toranaga) (Fig. 5), that have not been drilled yet, were selected for the evaluation of the hydrocarbon potential in the area. The biogenic gas system in the Nankai region was defined using core and log data from the COOO6 well and the interpretation from the seismic survey. The system includes the following elements:

- Source rocks: plant fragment-bearing silty and shaly turbidite levels. Hydrocarbons are definitely of microbial origin, due to the low heat flux values and temperatures in the area that make the thermogenic origin impossible. The existence of biogenic gas is demonstrated by the BSR reflector (Fig. 2), which is a consequence of the presence of gas hydrates (a cryogenized mixture of water and methane). Another indicator is represented by the high RMS Amplitude values obtained bellow the BSR map, suggesting the existence of free gases in the reservoirs under the gas hydrates;
- Traps: mostly structural (anticline folds with 3 way dip closure or 4 way dip closure);
- Seal: fine grained sedimentary intervals or the BSR level.
- Reservoir rocks: porous and permeable, high quality turbidite sandstones/sands;
- Migration pathways: the most important hydrocarbon migration occurs *in situ* in the basin floor fan sequences; another scenario is for the gas to circulate along thrust faults, but this process comes with a question mark, for two reasons (a, b): gas hydrates are present in the area, so they could act as a seal unit, decreasing the possibility of gas molecules to migrate along faults and fractures (a); there are no gas seepages that could indicate hydrocarbon leakages at the bottom of the ocean (b);

The results for the volumetric section were obtained in a special module of the Kingdom Program which runs the calculations. The main input consisted of the P90 and P10 statistic values for: the areal extent of the last closing contour, Net/Gross Ratio, porosity, water saturation, gas volume factor, gas recovery factor (Table 1).

Each polygon`s area was measured directly by the software (Fig. 6) and the Net-to-Gross Ration was obtained from the V_{sh} curve by using two endmembers from the COOO6 well (which is positioned close to the oceanic trench): the second and fourth tectono-stratigraphic units. The second unit in the borehole is characterized by a low NTG value, the sequence being dominated by thick shale intervals. Sandstone bodies are thin and non-amalgamated. This scenario corresponds to mud-rich submarine fan systems or to the overlap of distal areas of lobes in regular turbidites. On the other hand, the fourth unit is dominated almost exclusively by massive arenite deposits, suggesting a sand rich basin floor fan or multiple median lobe zones that are super imposed (Fig. 7).

Porosity values were available in the well final completion report. The rest of the parameters, such as the water saturation, gas volume factor and gas recovery factor, were evaluated with respect to the fluid type and the depth of the structure (related to pressure and temperature).

The recoverable resources (Table 2), as expressed by the P_{mean} values (the median between P99 and P1), are 600 BCF (billion cubic feet) for the Tokugawa Prospect and 291 BCF for the Toranaga Prospect. These results suggest that the area could pe economically profitable. A new exploration well can decipher the oil and gas potential in the imbricate nappes of the outer prism.

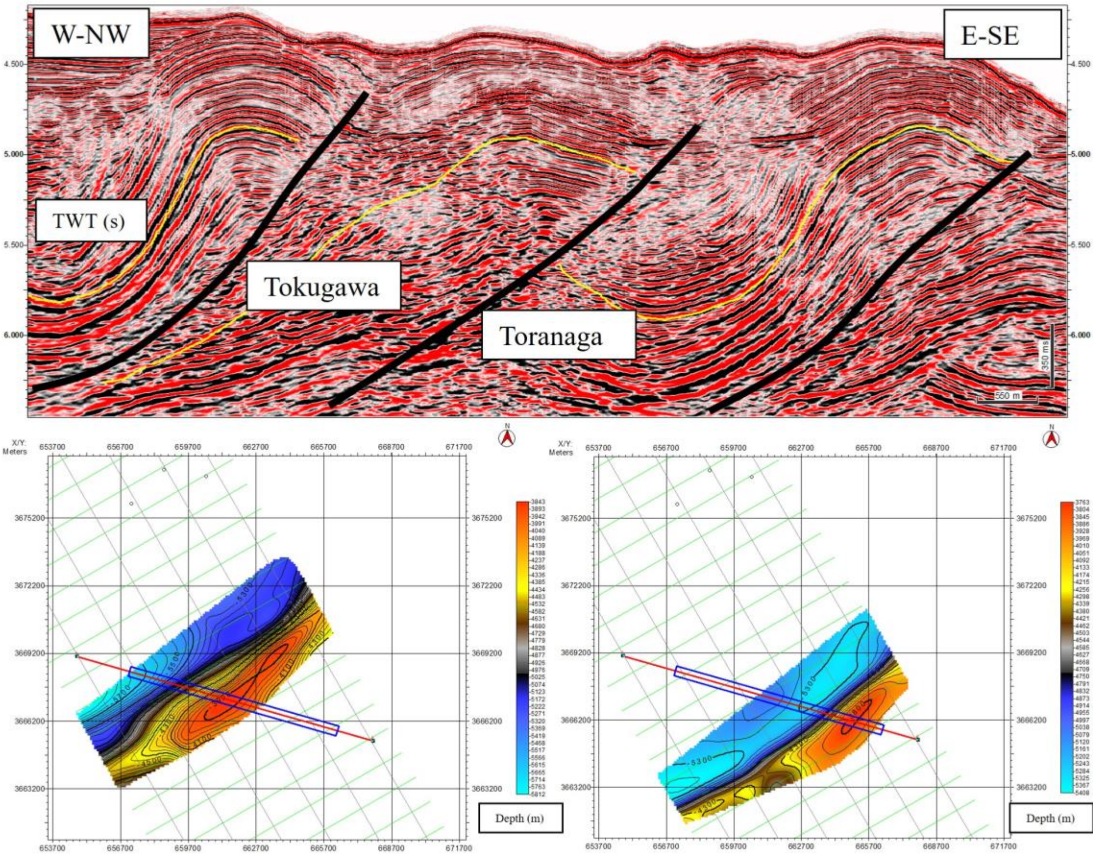

Fig. 5 – The two elongated anticline structures (Tokugawa on the left; Toranaga on the right) that have been evaluated for the biogenic gas potential, as seen from a seismic line and from the structural maps in depth.

Table 1

Input parameters for the volumetric calculations: last closing contours areas, NTG, porosity, water saturation, gas volume factor and gas recovery factor.

PARAMETER	LOWER LIMIT (P90)	UPPER LIMIT (P10)
Last closing contour for the Toranaga Prospect (square m)	619037	6599967
Last closing contour for the Tokugawa Prospect (square m)	627526	11198021
NTG	0.11	0.92
Porosity (ϕ)	0.3	0.38
Water saturation (Sw)	0.2	0.3
Gas volume factor (Bg) (SCF/ cu ft)	300	350
Gas recovery factor	0.75	0.8

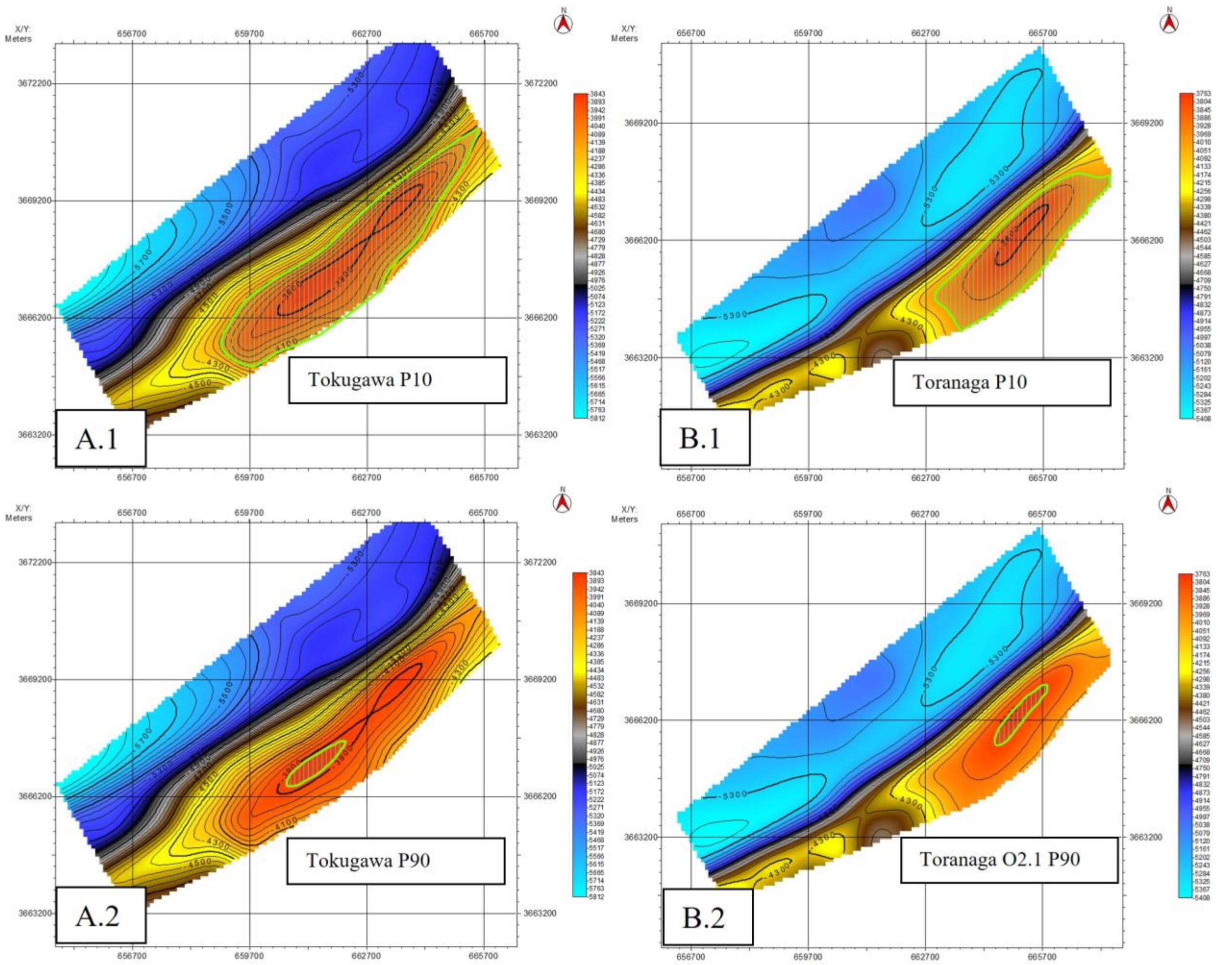

Fig. 6 – The last closing contours for the two structures in the statistic scenarios: P10 (A.1; B.1) and P90 (A.2; B.2).

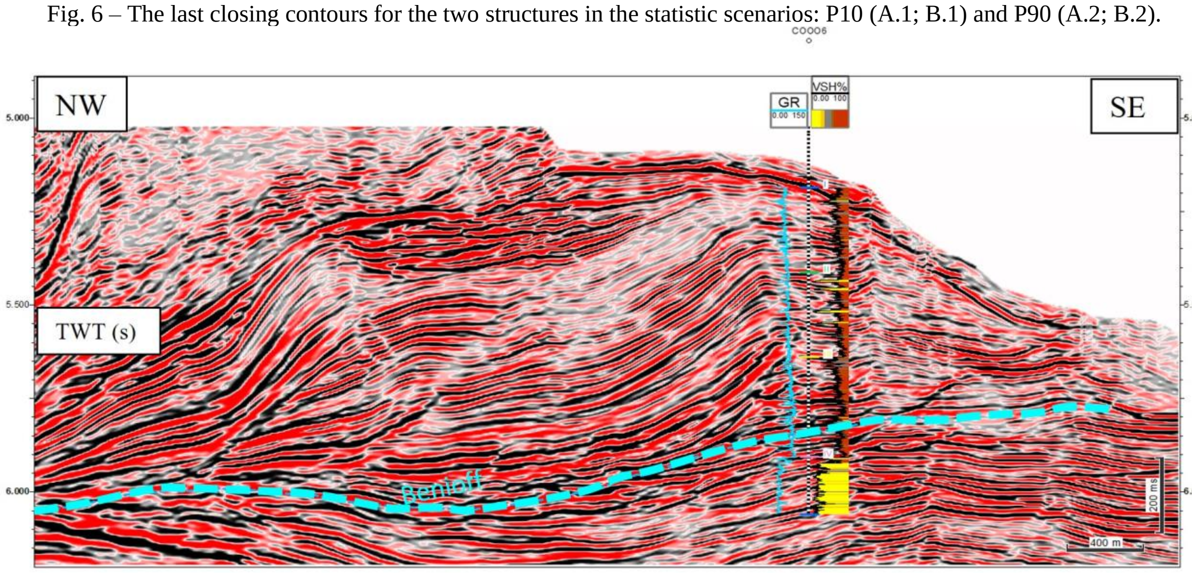

Fig. 7 – Seismic section and V_{sh} curve from the location of the COOO6 well.
The two endmembers for the NTG, units II and IV, can be observed.

Table 2

Recoverable resources from the two prospects in terms of statistic variations

Statistic variations	Tokugawa resources (BCF)	Toranaga resources (BCF)
P1	2581	1060
P10	1396	610
P50	436	222
P90	108	75
P99	32	20
Mean	617	291

5. CONCLUDING REMARKS

In this study we were able to define the petroleum system of the Nankai accretionary complex in the offshore area of southwest Japan using petrophysical, sedimentological and structural inferences from the seismic and well dataset. Every single element of the biogenic gas system was delineated over the course of the project: source rocks (shales and silts rich in organic matter), reservoirs (turbidite sandstones), migration (mostly in situ, but also possibly along thrusts), traps (structural) and seal (hemipelagic or turbidite shales).

The hydrocarbon volumes, as reffered from the P*mean* values of the statistical calculations, indicate that the Nankai subduction zone can be economically subject to exploration and production activities. The Tokugawa structure yields over 600 BCF of methane and Toranaga hosts almost 300 BCF of gas. For example, the premiere gas fields in the Western Black Sea Shelf, Ana and Doina, from the MGD Project operated by Black Sea Oil&Gas S.A., include a volume of 300 BCF (P50 value), smaller than the 436 BCF (P50 value) recoverable resources that were assumed for the Tokugawa Prospect.

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