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Review paper

PROCEEDINGS

Expansion of the Old Oil Field of Bunjani on the Basis of Geological Reinterpretation

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Key words: Reservoir development, Geological reinterpretation, Sava depression.

Ključne riječi: razrada ležišta, geološka reinterpretacija, Savska potolina.

Abstract

Due to the non-defined contouring of the Bunjani field and the positive exploration well Jo-2 at the southwest of the field outside the concession, a need for the geological reinterpretation of the area was discovered in order to solve the petroleum-geological relationships in the area, and determine field expansion and reservoir contouring in a more qualitative way. The recent geological reinterpretation was perfomed on the basis of a review of all available data from the existing wells, the results of field development to the present, the interpretation of new seismic profiles and the knowledge of the petroleum-geological relationships in the part of the basin previously acquired. The reinterpretation proved to be justified and it resulted in the determination of new well locations and their drilling in 1993 and 1994. In this way, the field expanded towards the southwest and the north. With the new reservoir geometry, better quality data of the reservoir characteristics, analyses obtained from the new wells, together with the reinterpretation of electric log analyses obtained from old wells, the reserves of oil have been increased by 31.4%.

Sažetak

Zbog nedefiniranog okonturenja polja Bunjani i pozitivne istražne bušotine Jo-2 na jugozapadu polja, izvan koncesije, ukazala se potreba za geološkom reinterpretacijom s ciljem kvalitetnijeg rješavanja naftnogeoloških odnosa ovog područja, proširenja polja i okonturenja ležišta. Najnovija geološka reinterpretacija izvršena je na temelju ponovnog pregleda svih raspoloživih podataka iz postojećih bušotina, rezultata dosadašnje razrade ležišta, rezultata interpretacije novosnimljenih seizmičkih profila, te dosadašnjih saznanja o naftnogeološkim odnosima tog dijela potoline. Reinterpretacija se pokazala opravdanom i rezultirala lociranjem i izradom novih bušotina u 1993. i 1994. godini. Time je polje prošireno prema jugozapadu i sjeveru.

S novom geometrijom ležišta i proširenjem polja, te kvalitetnijim podacima analiza i svojstava kolektora, s novih i starih bušotina, povećane su rezerve nafte za 31.4%.

1. INTRODUCTION

The objective of this paper is to explain how the geological reinterpretation (using the available data and with the minimum of investment) has enabled expansion of the old Bunjani oil field and secured the successful continuation of petroleum production.

In order to revitalise old oil fields with a low profitability margin, (of which the Bunjani is one sample), attempts have been made to renew development activities. The essential target was to make profitable use of the available data and to define the possible expansion of the oil field with the minimum cost and with the use of standard development practices. In view of the above criteria attention was directed to the possible expansion of undepleted parts of the reservoir, or the discovery of new hydrodynamic oil saturated bodies, as well as other development activities which would increase oil recovery from the old part of the oil field. The first step was the geological reinterpretation which resulted in drilling of the new productive wells, the oil field expansion and an increase in the petroleum reserves.

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2. REVIEW OF EXPLORATION OPERATIONS TO DATE

The Bunjani oil field belongs to the Pannonian region of the Sava depression (Fig. 1). The structural closure of "Križ", where the Bunjani oil field is located, was discovered by the regional gravimetric survey performed by the German group "Seismos" from Hannover between 1940-1942.

Since the whole area is covered by diluvial and alluvial deposits, it has been impossible to carry out surface geological mapping. Hence during 1941-1942, 20 shallow structural wells were drilled to confirm the geophysical results. Only one of these wells (Š-12) is located within the Bunjani oil field. Based on the gravimetric survey and structural wells, the first deep exploration well was drilled in 1948, which discovered oil at Šumećani. For the purpose of further expansion of the Šumećani oil field (Križ), the deep exploration well Bn-1 was drilled in Autumn 1951. This well penetrated beds confirming the presence of an oil reservoir in this area. This is how the Bunjani oil field was discovered, which produced oil of a different quality to that found in the Križ oil field.

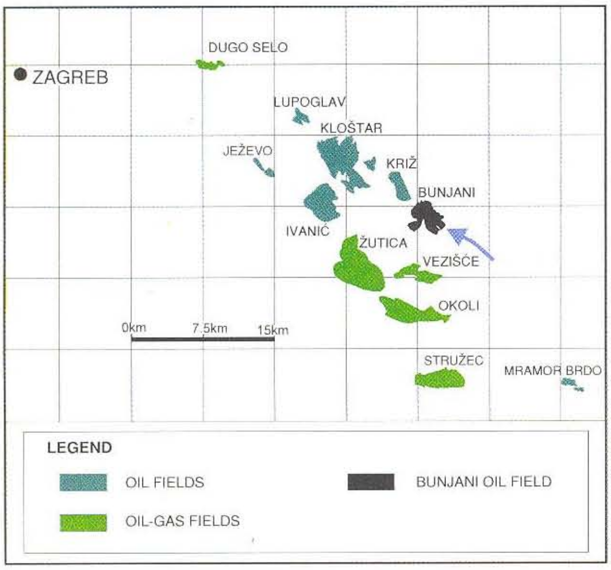

Fig. 1 Location map of the fields in the north-west area of the Sava depression.

By 1964, 61 wells were drilled through the field, without the field contours having been precisely defined. The field was put into production in 1952. Between 1964-1979, there were no exploration or development operations. In 1979, in the southwestern part of the field, (outside the concession), the Jo-2 exploration well was drilled, which was pronounced negative, but which later produced good results during subsequent testing. It offered new possibilites for field extension to the southwest beyond the boundaries of the production field. With this aim development activities were resumed in 1992.

3. GEOLOGICAL REINTERPRETATION

Undefined field contouring and the positive exploration well Jo-2 (1979) have prompted the resumption of development activities on the field. On first reviewing the available field data, it became evident that the geological reinterpretation was necessary in order to better define the petroleum-geological relationships of the area, delineate an area for field extension and to facilitate precise reservoir contouring.

The last available integrated geological presentation detailed 41 drilled wells (1955) in the archives of the Ina-Naftaplin trade and technical papers and records library, and in the published paper (GALOVIĆ, 1951-1953). In addition to the above mentioned geological data, there are also available anonymous maps prepared at the reservoir top but which contain insufficient information, based on 61 drilled wells. Three seismic lines (2D) of mediocre quality and standard processing were

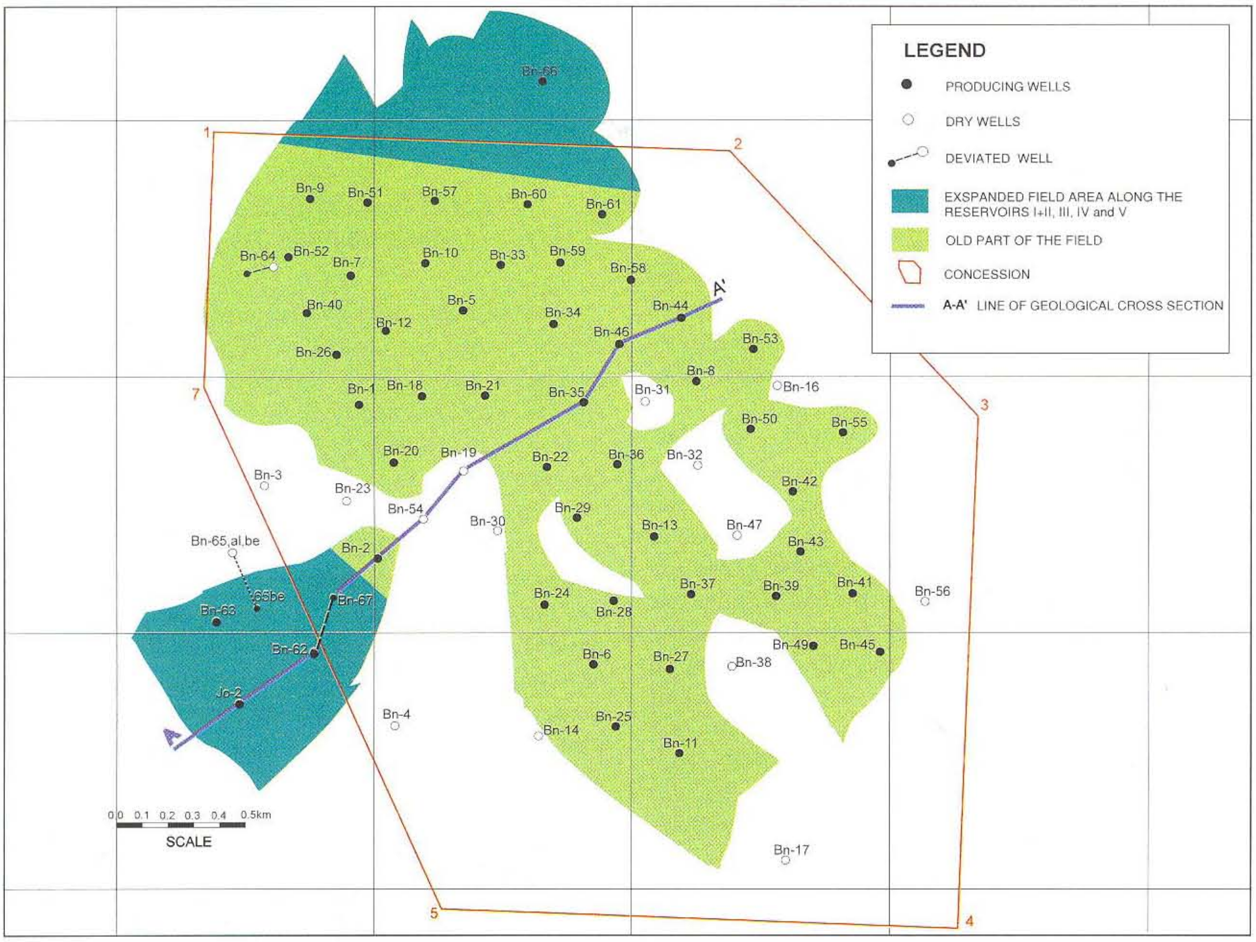

Fig. 2 Map of all the Bunjani field reservoirs with marked expansion.

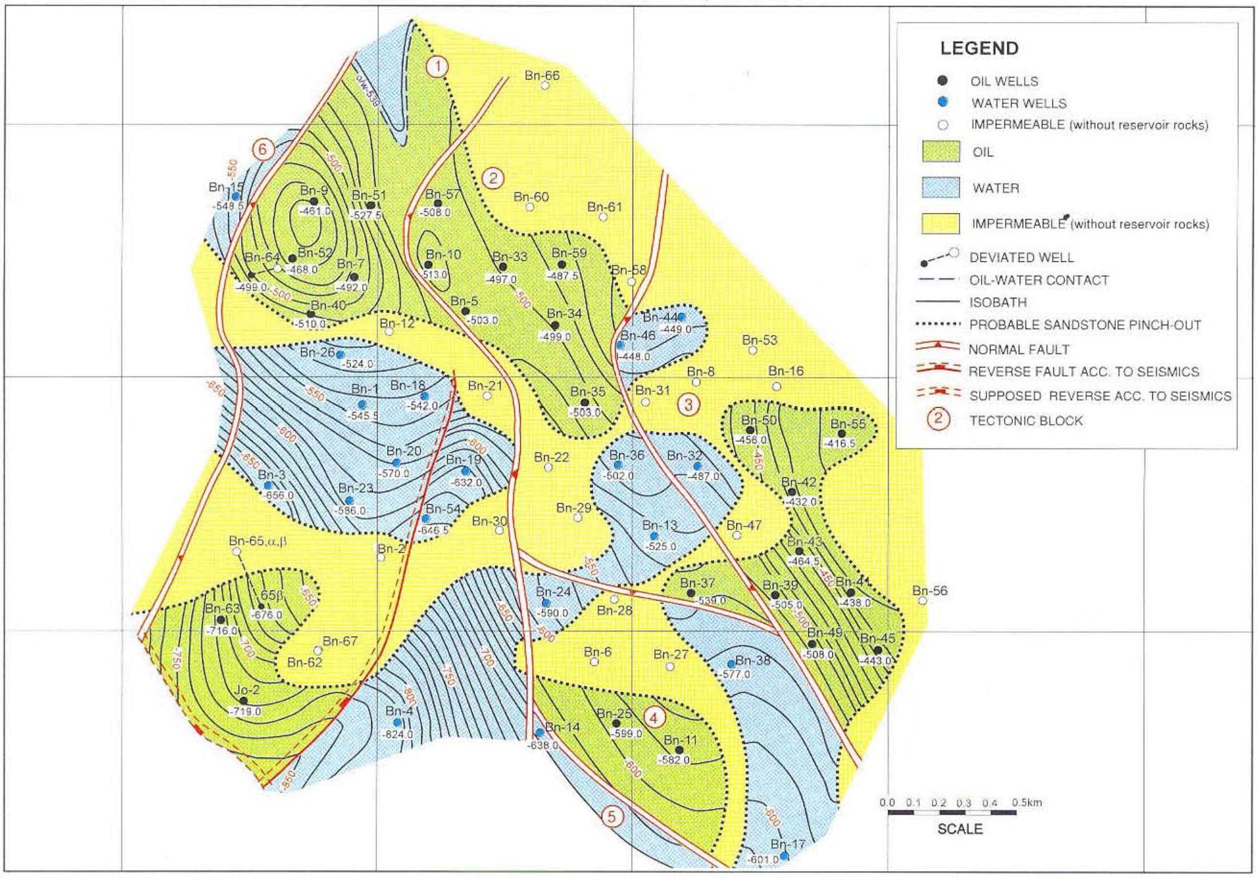

Fig. 3 Contour map of the top of the "III" reservoir.

shot on the field. Wireline logs (EL, ML) from 61 wells were also used, as well as the results of laboratory analysis and data on the field production history covering the years from 1952 to 1992.

After having defined the potential prospectivity of the field extension, the next question to discuss was the profitability of investment in further development operations, in respect of the field size and the oil reserves present within the old part and possible extension thereof. The objective was to define the field extension and to put new wells in production with the minimum financial investment, using the available data and standard practices usually applied in geological reservoir development. Exploration began with the shooting of 10 short seismic lines (2D) (total of ca. 40 km) across the field and marginal parts, covering principally the possible extension areas. The survey and interpretation proved to be justified. Based on the interpretation and synthesis of all geological data, including the Jo-2 well, the locations were proposed and the positive wells Bn-62, Bn-63, Bn-64, Bn-65β and Bn-67 were drilled, thereby extending the field to the southwest, and Bn-66 which initiated extension to the north (Fig. 2).

Geological reinterpretation was based on the renewed analysis and interpretation of all available well data (geological monitoring records, DST; physical and geochemical rock analyses; biostratigraphic, petrographic and sedimentologic assignments; oil and water analyses, well completion results, reservoir pressure and temperature measurements, as well as field production history), and in particular revised the renewed wireline log correlation.

Evaluation of the physical rock properties for the Bunjani field was performed using porosity and water saturation data obtained from wireline log analyses and laboratory analyses of rock samples from conventional cores. E-logs from recent wells (Bn-62, Bn-63, Bn-64, Bn-65, Bn-65α, Bn-65β and Bn-66) have been performed within an integrated programme. This included different resistivity measurements (ML, DIFL, DLL, EL), acoustic logs (ALBHC), natural radioactivity measurements of the rocks (GR), density and apparent porosity measurements (CDL/CNL) and formation dip measurements. This data combined with the laboratory core analyses and geological monitoring data, provided a good basis for evaluation of the physical parameters of the reservoir. For this purpose an "EPILOG-CRA" computer program set was used. Lithological assignment and porosity calculation were mainly defined from CDL/CNL/GR logs.

The new reservoir geometry was defined by reinterpretation, excluding some of the reservoir rock bodies originally believed to be oil saturated, but which in fact have been water saturated or which are not reservoirs.

Until now, the Bunjani field had three classified reservoirs ("M", "K" and "Tg"). During the geological

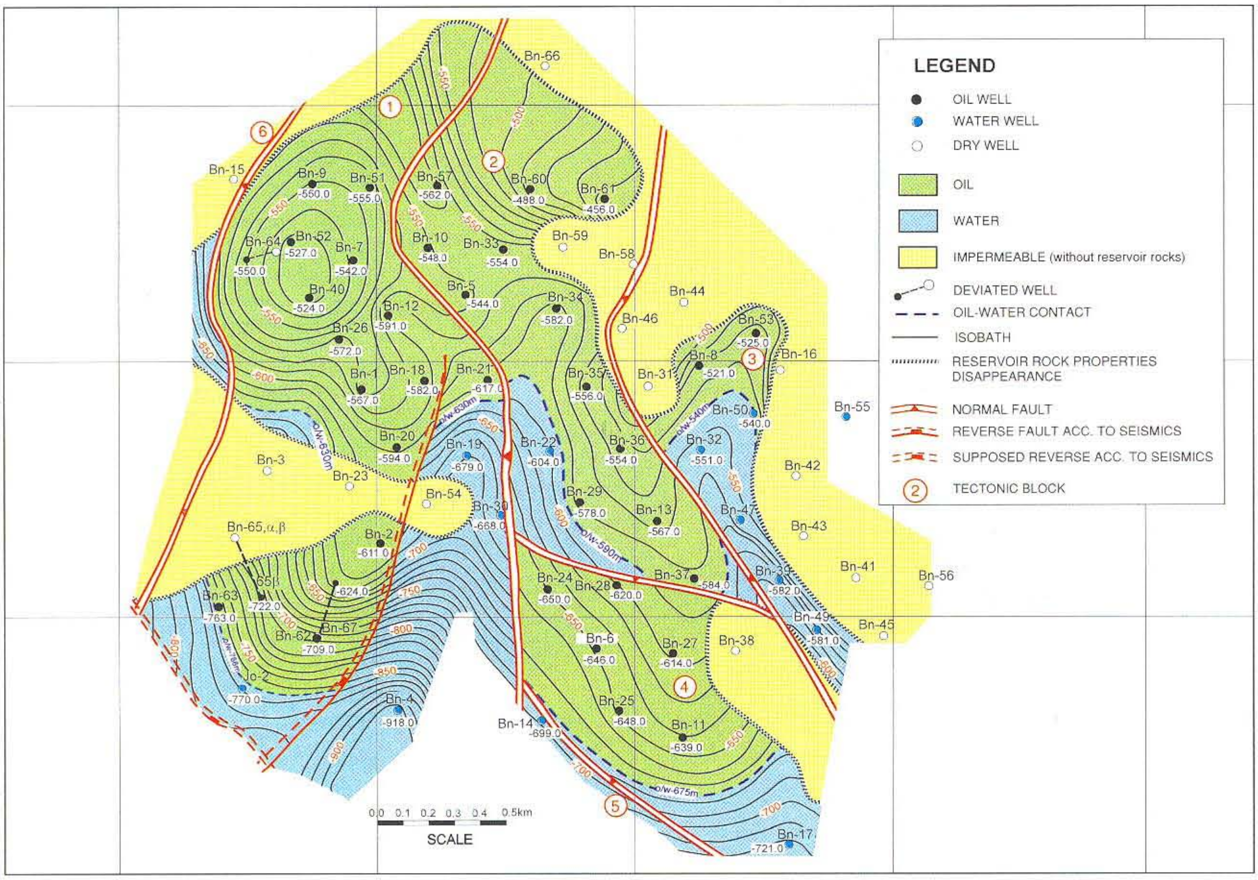

Fig. 4 Contour map of the top of the "V" reservoir.

reinterpretation and after drilling the new wells, four reservoirs were identified (I+II, III, IV and V). The reservoir classification was based on data synthesis, revised correlation of wireline logs, results of analyses of open interval tests in the wells, well pressure measurement data and the production history.

A synthesis of the utilised data, with interpretation of the newly shot seismic lines, together with the absence of preconcived ideas and the aim of extending the field resulted in a new picture of the structural and tectonic relationships, reservoir division and contours involved. By including the better quality data for each new drilled well, a new geological scenario was prepared for the Bunjani field and the extensions to the southwest and north were defined (Fig. 2).

With the field extension to the southwest over the reservoir III (Fig. 3) and the reservoir V (Fig. 4), the presence of separate hydrodynamic units has been identified. These units have higher reservoir pressures (nearly hydrostatic), which are independent in respect of the old part of the field (excepting the Bn-2 well area), with the trial production of the new completed wells. The Bn-62 well (20 m^3/day of water free oil), Bn-63 well (15 m^3/day of oil), Bn-65β (25 m^3/day of water free oil) and Bn-67 (35 m^3/day of water free oil) produce yields well above the average of the old wells. The contouring/bounding of the well to the southwest at reservoir III is not final. In this geological scenario, the reverse fault is anticipated as a boundary only on the basis of 2D seismic lines which are characterized in this area by extremely dispersed seismic reflections, which implies that the seismic interpretation is also unsafe.

The extension to the north with the new well Bn-66, is based upon contouring of all four wells from the old field area (Fig. 2), and that of reservoirs I+II (Fig. 5) in particular.

Based on the results of the reinterpretation, it was proposed that the hydraulic fracturing method for reservoir rocks should be used in order to enhance the productivity of 12 wells. Three fracturings were performed (Bn-40, Bn-57 and Jo-2) and good results were obtained.

The production history to date indicates that the gas-oil energy and the water environment elastic energy are used in reservoir exploitation. An overview of the oil production to date and future predictions as the result of the geological reinterpretation, are shown in Fig. 8.

The proven results of the geological reinterpretation have opened the possibility for yet another extension of the field to the southwest (across reservoir III), where the fault boundary is also uncertain to the north across reservoir I+II. There is a shallow depth of soil to the north, and it is necessary to establish with more precision the pinchout boundary of the oil-bearing sandstone. It is absolutely necessary for the final definition of the reservoir boundaries to carry out the seismic sur-

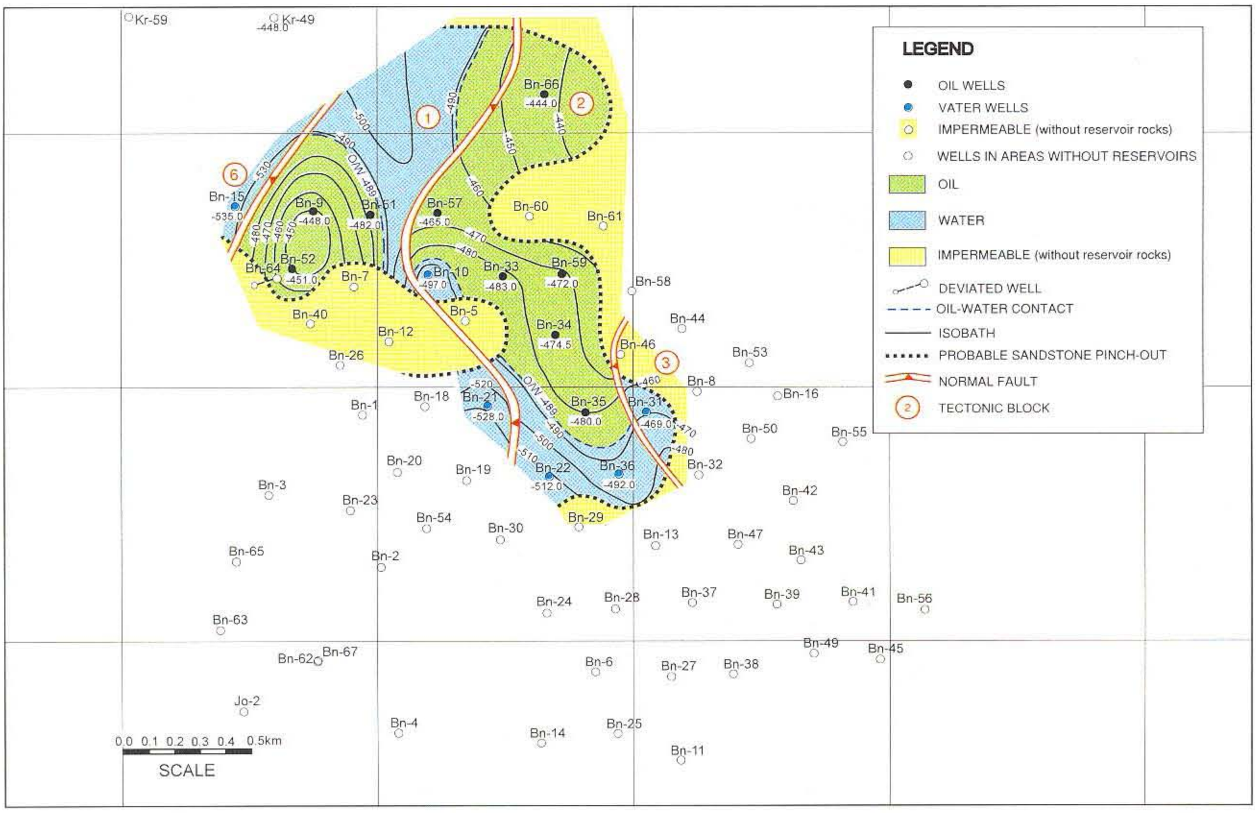

Fig. 5 Contour map of the top of the "I+II" reservoir.

vey and 3D seismic interpretation together with a realistic evaluation of further development operations in terms of cost-effective feasibility.

4. GEOLOGICAL STRUCTURE OF THE FIELD

The description of the geological structure of the field has been prepared on the basis of known data obtained during exploration and development operations to date with special reference to the results of the geological reinterpretation.

4.1. STRATIGRAPHIC RELATIONS

The stratigraphic age of separate beds of the Bunjani field has been established on the basis of palaeontological analysis, superposition, lithological characteristics as well as the wireline log correlation, and also the results of the regional correlation of lithostratigraphic units (ŠIMON, 1973).

Based on the available data, the following stratigraphic units can be distinguished (Figs. 6 and 7) in the Bunjani field area:

Quaternary: Represented by diluvial beds within the yellow clay facies, with loess in places in the base.

Pliocene (Romanian and Dacian): Pliocene beds developed within the facies composed of variegated clays, coarse grained sands and argillaceous sands. No cores have been recovered from these beds, hence there is no palaeontological data available.

Upper Pontian: The Upper Pontian beds are characterized by the alternation of gray and brown argillaceous marls, marly sands and sands. The fauna has not been specifically defined, but *Limnocardides* with large shells and *Congeriae* with *C. rhomboidea* and *C. zagrabienses* species have been observed. There was no hydrocarbon present. The Upper Pontian beds were deposited in a concordant relationship with the Lower Pontian beds within the facies of grey marls and local clayey marls.

Lower Pontian: Palaeontological macrofossil determination has been performed only during geological monitoring of wells where specific specimens of the genus *Paradacna* with *P. abichi* species were identified. No hydrocarbon presence was found within these beds.

Upper Pannonian: The lithological composition of this stratigraphic member is characterised by greyish marls with slightly arenaceous marls with calcareous marl intercalations in places. This member exhibits strong uniformity across the study area. The fauna has not been specifically determined. However, *Congeria* spp. fragments and limnocardids debris have been determined in the field. There is no hydrocarbon reservoir within these beds.

Lower Pannonian: This stratigraphic member represents a facies composed of hard, white to grey calcareous marls and argillaceous limestones. These are frequently interlayered with thin sandstone beds. Usually, marls are fractured. There is a freshwater fauna

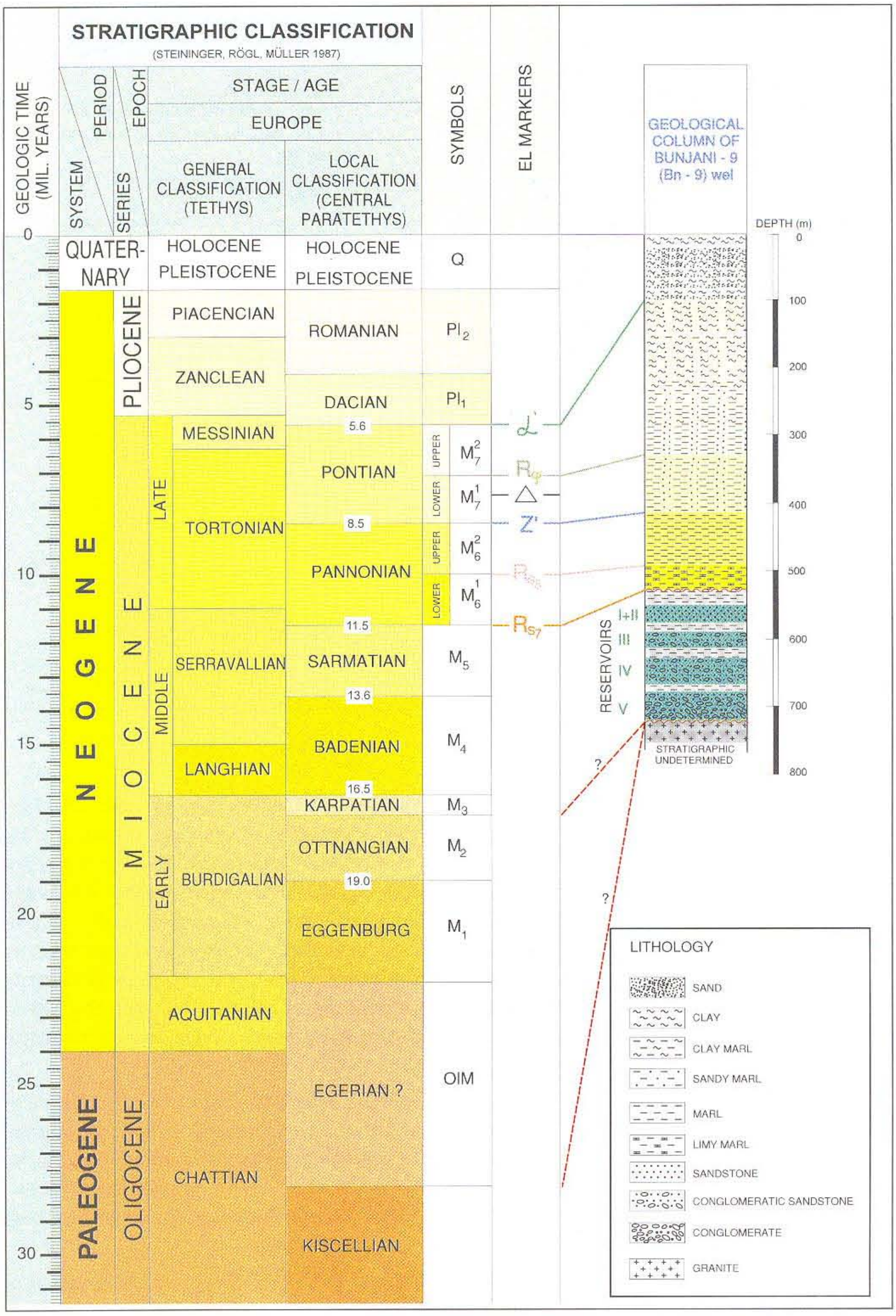

Fig. 6 Correlation of stratigraphic units of the Bunjani field with the geological column of the Bn-9 well.

composed of limneids, planorbids and ostracods. No hydrocarbon presence has been identified in these beds.

Sarmatian?, Badenian, Karpathian, Oligo-Miocene?: The lithological composition of this group of stratigraphic members is characterized by an extremely varied sequence of clastic sediments, beginning with coarse deposits directly overlying the basement (breccias, granitic debris, breccio-conglomerates and conglomerates), followed by conglomeratic sandstones, marly sandstones and marls. In the overlying layers there is also a calcareous component represented by calcareous marls and sandstones. It has been impossible to subdivide the stratigraphic members within this sedimentary sequence due to the high degree of lithological heterogeneity and considerable lateral changes, as well as due to their poor fossil content. No fossil remains were found in the breccias and conglomerates. The age was determined on the basis of a fauna which was found in the marl, and less frequently in the sandstone layers.

Within these sediments 4 oil reservoirs have been identified (I+II, III, IV and V), whereby the reservoir V also includes a part of the "basement".

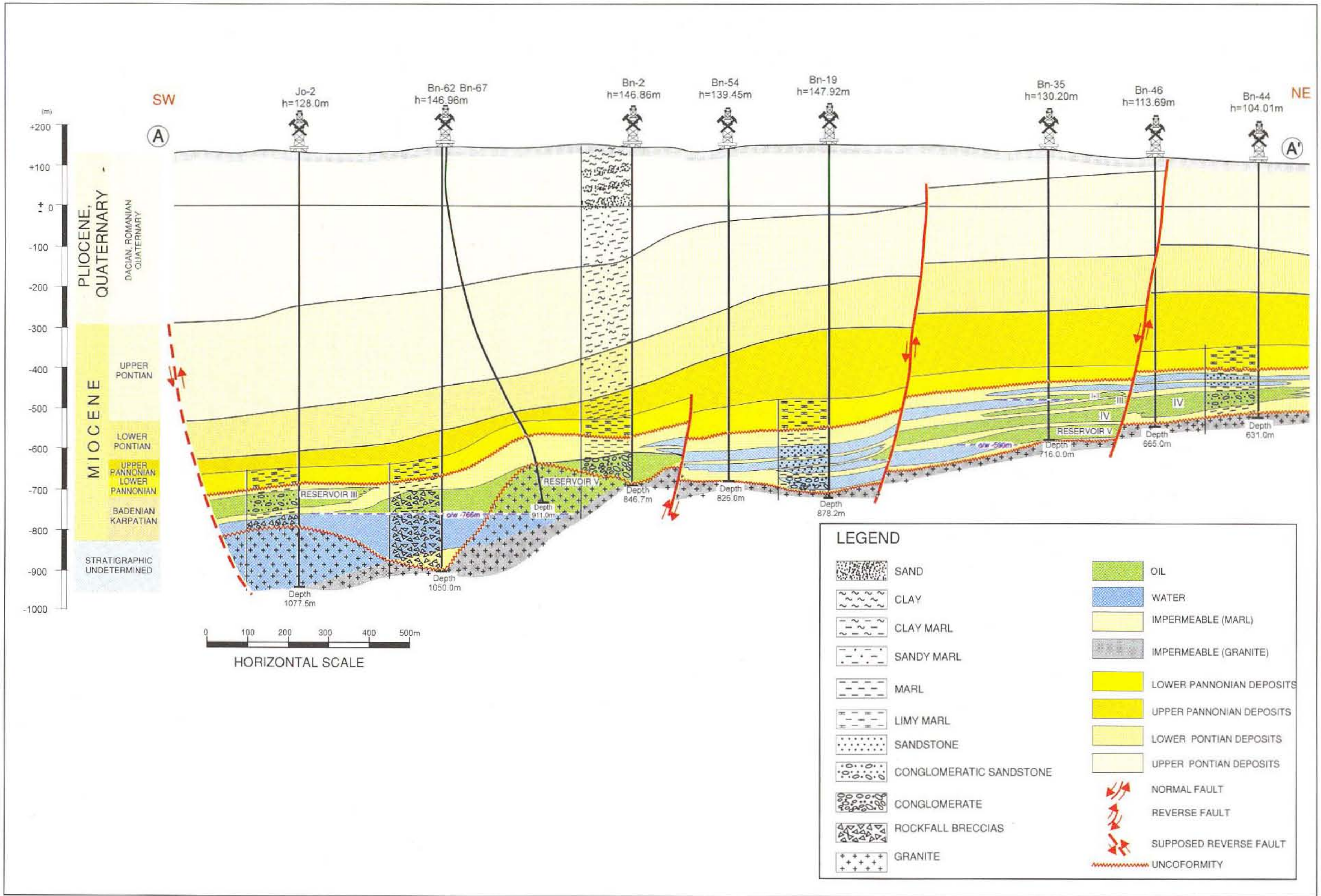

Fig. 7 Geological cross section (A-A') of the Bunjani field.

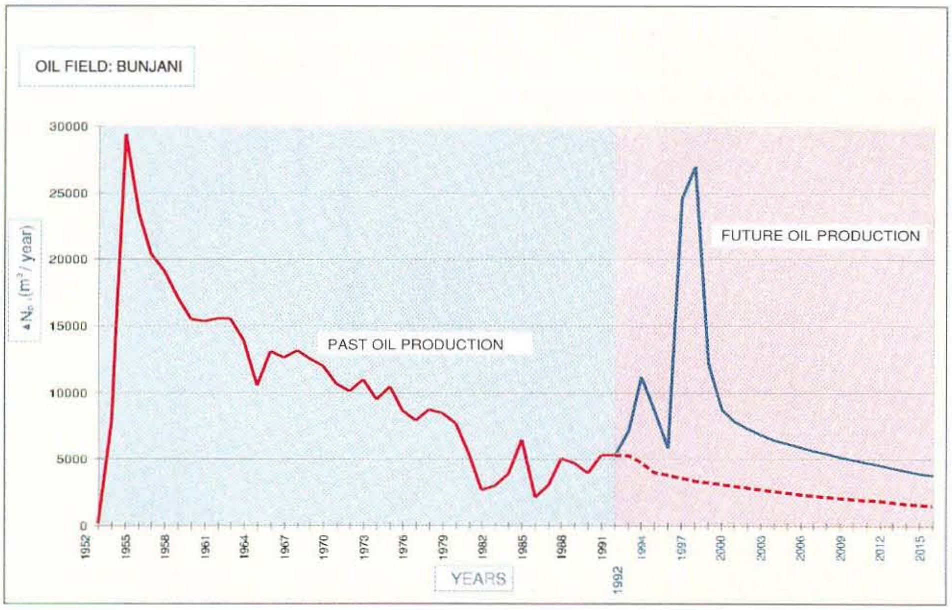

Fig. 8 Oil production of the Bunjani field past, present and future (based on predictions from this study).

The "Basement" (stratigraphically undetermined): Composed of weathered and fractured - cataclasticized, hydrothermally altered granite and gneiss. Granites occur within the overlying beds of the productive area, while gneisses occur in the peripheral parts in depth. Calcite may usually be found deposited in fissures. In those areas where the fractured "basement" lies in a structurally favourable position, an oil reservoir was formed.

4.2 LOCAL TECTONIC AND STRUCTURAL RELATIONSHIPS

In the most recent geological reinterpretation of the field, the solutions involved with the structural and tectonic relationships were based on the interpretation of new seismic lines and correlation of well data. Generally, the Bunjani oil field is separated from the southwest deep area by a fault zone, where tectonic blocks subsided in a "staircase slope" for over 1000 m. Structurally, the field is represented by a faulted monocline trending NW-SE. The monocline plunges to the SW at an angle of 10°. Some of the faults have been identified through the absence of some of the layers in wireline records and from the results of seismic line interpretation, and others have been anticipated. The Bunjani field has been divided in 6 tectonic units. The faults were important for the reservoir oil accumulations, representing barriers in places, as a result of which different hydrodynamic conditions were formed, hence the water-oil contact is at various levels within separate blocks.

4.3. GEOLOGICAL DESCRIPTION OF THE RESERVOIRS

In terms of their stratigraphic assignment and lithological characteristics, the reservoir rocks of the Bunjani field are represented by two different reservoir types: a) "the basement" consisting of cataclasticized and hydrothermally altered granite and gneiss, b) conglomerates, breccio-conglomerates, breccias of granitic debris, and Miocene sandstones (probably also Oligo-Miocene). The caprocks are marly sediments. The petroleum-geological relationships, in respect of their occurrence, distribution and lithological characteristics, are moderately complex within the individual stratigraphic members. The reservoir data summary of the Bunjani oil field is shown in Table 1.

Reservoir I+II: Composed of fine to coarse-grained, poorly cemented, quartz-micaceous sandstones and conglomeratic sandstones. The reservoir is of stratigraphic type, delineated by a lithological boundary - marlification and pinchout, and by a tectonic boundary (Fig. 5).

Reservoir III: In general, reservoir rocks of reservoir III are fine to coarse grained, poorly to medium cemented quartz-micaceous sandstones and conglomerate sandstones. Reservoir beds are as a rule thin and discontinuous and intercalated with marls. The reservoir is stratigraphic in type, delineated by a lithological and tectonic boundary. It is characterized by zonal marlification and pinchouts in combination with tectonic boundaries - faults, with separate water saturated zones (Fig. 3).

Reservoir IV: Also represented by zonal evolution. The reservoir rocks are composed of somewhat larger coarse-grained clasts, consisting of coarse-grained sandstones, conglomeratic sandstones, and sandstones with fragments of large granite pebbles. They were deposited in thin discontinuous layers and laminates. The reservoir is stratigraphic in type, delineated by a lithological and tectonic boundary. The reservoir boundaries have similar characteristics to those of reservoir III, since the reservoir rocks were deposited within the same sedimentary cycle.

Reservoir V: This is formed of two reservoir types: a) conglomerates, breccio-conglomerates, breccias of

Discovery Date:	1951			
Discovery Well:	Bn-1			
Productive Formation:	Prečec			
Depth of Formation:	700 m (average)			
Reservoir Type:	I+II, III and IV - stratigraphic with the lithologic and tectonic boundaries V - stratigraphic-massive type bounded by the impermeable zones			
Reservoir Age:	Karpathian, Badenian, (Oligo-Miocene?)			
Depositional Environment:	marine and fresh-water			
Drive Mechanism:	depletion drive and water drive			
Source Rock:	Miocene and Pliocene marly sediments in the Sava depression			
Cap Rock:	marly sediments			
Pre-Reservoir:	granite and gneiss			
Original Res. Pressure:	67.2 bar (9.7 bar/100m) (reduced to the weight level of -579.0 m)			
Present Res. Pressure:	different along the reservoirs			
Orig. Oil/Water Contact:	different in the reservoirs and tectonic blocks or without contact			
Rock Properties:				
Average Porosity:	I+II	III	IV	V
(parts of unit)	0.139	0.130	0.122	0.111
Initial Water Saturation:	I+II	III	IV	V
(parts of unit)	0.405	0.409	0.409	0.424
Average Permeability:	insufficient data			
Reservoir Temperature:	55.2°C (4.55 °C/100m)			
Average Oil Properties:				
Volume Mass of Oil (20°C):	875 kg/m^3			
Volume Ratio of Oil (B_{oi}):	1.074 m^3/m^3			
Viscosity (20°C):	21.6 mPas			
Parafin Content:	8.00%			
Consolidation Point:	11°C			

Table 1 Reservoir data summary of the Bunjani oil field.

granitic debris, conglomerate sandstones and b) weathered, fractured - cataclasticized and hydrothermally altered granite and gneiss ("basement"). Most of the wells penetrated the "basement" whereas in several of the wells the drilling terminated in the basal Miocene sediments and therefore the reservoir V was not completely uncovered. The basal sediments as the integral reservoir parts, are transgressively overlying the "basement". They have variable thickness, and in some places they are completely absent, depending on the palaeorelief. These sediments are composed of pebbles and granite fragments, and to a lesser extent gneiss. The pebbles vary in size. Roundness and sorting are poor. Large pebbles are frequently incorporated into coarse-grained sandstones. The matrix is argillaceous.

In the southwest, newly extended part of the Bunjani field, these reservoir rocks consist of granite debris breccias, unevenly cataclasticized with a dense mineral compound matrix consisting of sericite, chlorite, feldspar and quartz. Rare sedimentary bodies composed of silty-grained fossiliferous marl, with traces of coal, can be found within these brecias.

The reservoir V (Fig. 4) is of mixed type (massive and stratigraphic), bounded by zones with no reservoir properties and by faults which are probably barriers considering the different oil-water contacts within the separate tectonic blocks.

5. CONCLUSION

Based on the geological reinterpretation carried out on the old Bunjani oil field, the following conclusions may be drawn:

1. The geological reinterpretation was justified and performed with the minimum financial investment (the cost of approximately 40 km of seismic lines and the work of the geological project manager).
2. Standard reservoir development practices were used with the available data during the reinterpretation.
3. Instead of the three reservoirs discovered to date, four reservoirs were identified.
4. The evaluation of the reservoir parameters for the old field area was more realistic, since it was based on the reservoir rock analyses from new well data from which the oil reserves were recalculated.
5. The determination of the structural and tectonic relationships through interpretation of the new seismic

lines resulted in the better evaluation of reservoir contouring/boundaries.

6. The field was extended to the southwest and north, which increased the recoverable oil reserves by 31.4%, and facilitates the successful continuation of oil production between 1995-2014.
7. The field extension to southwest identified reservoirs with higher formation pressures which are independent of the old part of the field and the eruptive well production. The extension to the north is based on the reservoir contouring from the old field.
8. The reinterpretation also proved the suitability of hydraulic fracturing of reservoir rocks as a means of increasing productivity of the wells Bn-40, Bn-57 and Jo-2.
9. The possibility has been opened for further extension of the field by application of 3D seismics assuming a detailed study proves the cost effective feasibility of such a project.

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