Fractured carbonate reservoir characterization and modelling: a multidisciplinary case study from the Cavone oil field, Italy¹

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Introduction

The Cavone Field is an Agip-operated oil field located in the Po Valley of Italy. It produces from a Mesozoic carbonate reservoir lying at a moderate depth of approximately 2900 m. Original oil in place is estimated at $15 \times 10^6$ m³ (94.5 MMBBLS).

Field recovery rates are relatively low, and significant quantities of mobile oil could remain in place after primary and secondary recovery operations if trapping and production mechanisms in the reservoir are poorly understood. Reservoir heterogeneities exist which resulted from original depositional controls, diagenetic modification during subsequent burial, and fracture development during structural trap formation. The fracture systems provide a significant contribution to fluid flow.

This report presents the methodologies employed at Agip to define in detail the internal structure of the Cavone reservoir. The key aspects of the study include seismic reprocessing, structural modelling, detailed characterization of carbonate rock types and diagenetic history, the application of new fracture identification technology using well logs, the calibration of well-log data to core analysis data, and reservoir modelling.

Geological framework

The Cavone Field is located 25 km north of Modena, in the Po Valley subsurface (Fig. 1). It covers an area of 12 km (E–W) by 3 km (N–S) and is bounded to the east by the analogue S. Giacomo-Concordia structure (Fig. 2).

The Cavone structure is an asymmetric anticline with an Apennine trend of Upper Tertiary age, which is elongated in the E–W direction and cut by a series of reverse faults (Fig. 2). The reactivation of these N–S trending, Jurassic-aged faults during the compressive Apennine phase led to the subdivision of the structure into various blocks, but did not prevent hydraulic communication between the blocks themselves.

The reservoir rocks are predominantly carbonates belonging to the Veneto Series shown in Fig. 4. The Breccia di Cavone Formation and the Nor A unit of the Calcari Grigi di Noriglio Formation, in particular the oolitic horizon at the top, are the most productive reservoirs. Production is from good primary (intergranular) porosity and locally from secondary (vuggy) porosity. In the Nor A and B units and the Rosso Ammonitico and Maiolica horizons, natural fracturing contributes to the matrix porosity and affects permeabilities to an even greater extent.

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Sedimentation type and geometry, diagenetic history and, above all, the effect of fracturing give the reservoir considerable heterogeneity. As a consequence, a multidisciplinary study integrating geological data with engineering aspects was necessary in order to evaluate fluid-flow mechanisms and optimize recovery of the original oil in place.

The Cavone Field was discovered in 1973 and the reservoir has been producing since 1979. The cumulative oil production to date amounts to $1.5 \times 10^6$ m$^3$ (9.45

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<td>CURRENT PRODUCTION RATE</td>
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Fig. 3. Summary of technical data on the reservoir.

Fig. 4. Lithostratigraphic column of reservoir and cap rocks.
Current production is 500 m$^3$/d (3150 BBLS/d) of oil. The average density value is 23° API (Fig. 3).

After seven years of production (1979–1986) with fourteen wells drilled, knowledge of the field has reached considerable detail. A dynamic model of the field was produced using this database plus an additional seven wells.

**Seismic and structural interpretation**

The first interpretations of the structure of the Cavone Field, dating back to 1974–1975, were based on a wide-mesh seismic grid. A new 2D survey consisting of 12 lines, 101 km in total length, was subsequently shot in 1983–1984. Conventional processing of these lines to produce time-migrated seismic sections showed only a modest improvement with respect to the earlier data, although better definition of the overall structure was achieved with further drilling data. In 1989, reprocessing of selected lines from the 1983–1984 survey was carried out in order to obtain better detail of the structure. Sophisticated depth-migration techniques were adopted in the reprocessing.

Conventional seismic processing, which provides time-migrated sections, is only considered acceptable where there are only weak lateral variations in seismic velocities. In more complex conditions, where the reconstruction of subsurface geometries becomes even more important, conventional seismic data migration techniques break down for two main reasons:

- the occurrence of conflicting dips generated by faults; and
- the presence of steep dips associated with strong lateral velocity variations.

Strong lateral velocity variations exist above the Cavone Field due to the carbonate anticline being overlain by a silico-clastic sequence. A prestack depth migration technique was therefore used. This was achieved by alternate downward continuation of common shot and common receiver gathers in discrete depth steps (providing a depth focusing analysis for quality control of the migration process).

This kinematic approach is based on the fact that when both sources and receivers are continued downward to the exact depth of the reflector, then if the correct propagation velocity has been used, the reflected energy is perfectly focused and the imaging gives the highest amplitude in the zero-offset plane. Therefore, at each step of the downward continuation process, the seismic data above and below the migrated depth point are analysed in order to identify the depth at which the energy is best focused.

Differences between the migrated depth and the focusing depth provide valuable information regarding the accuracy of the migration velocity field. In particular, for small velocity errors the real depth of the reflector is located midway between the migrated depth and focusing depth (Faye and Jeannot 1986).

Thus from this analysis it is possible to determine
Fig. 6. Seismic section from line MO 377/873 after processing with time migration in 1983 (top) and with depth migration in 1990 (bottom). The wells shown are Cavone 11 (left) and Cavone 2 (right).
depth error values that may be used to revise the migration velocity field for a new prestack migration. This is, therefore, an iterative process where the velocity model, adopted as primary input to the depth migration, can be modified after each iteration. The final seismic section is the best subsurface image possible.

In this instance, the depth focusing analysis was not treated as a stand-alone procedure in defining the velocity-depth model. The results were integrated with additional information from regional well data and geology. Integration of geological and geophysical data is the key to better constraining the velocity-depth model result. In contrast to conventional migration, the geological information was brought in at the processing phase. Reconstruction of a model consistent with both the geophysical and geological data was therefore possible, giving a complete and synergetic interpretation, not merely obtained from processing of the seismic data alone.

Figure 6 shows the results obtained from application of this method to sample line MO 377/83 (location shown in Fig. 2). The seismic section is depth-migrated rather than time-migrated as in the 1983 processing, and shows improved definition of the structural framework, especially in the central part where certain significant horizons are more clearly delineated than before. Although the result is not outstanding, it can nevertheless be considered satisfactory considering the low signal-to-noise ratio of the raw field data.

Using well data and lines processed with this technique, a structural interpretation of the field was made in order to reconstruct its dynamic evolution and explain the complex geometry of the structure. Magnetic and gravimetric data published in previous reports (Pieri and Groppi 1981; Cassano et al. 1986) were also used.

A section of the interpretation thus obtained is shown in Fig. 7. The Cavone anticline, shown here, belongs to the most external structural element of the Northern Apennine trend, known as the Ferrara Folds. Here the sediments of the northeastern sector of the Po Valley overlap the Veneta pre-Alpine monoclinal sediments.

We believe that the major thrust cutting the basement developed at an early stage during the Neogene compressional phase, probably during the Messinian. The Cavone structure may be interpreted as a ramp anticline above a second major thrust whose detachment plane can be identified at the base of the Mesozoic series. Thrusting on this plane occurred in several phases.
from Lower Pliocene to Early Pleistocene, giving rise to all the Neogene compressional features.

According to our hypothesis, the basal detachment surface for this second major thrust was reactivated, having previously formed the deeper shallow-dipping portion of a listric fault developed during Jurassic extensional tectonics. However, this only applied to the kinematically feasible portion of the originally listric fault, i.e. its deeper shallow-dipping portion. At shallower levels the Jurassic extension may have been preserved, while the thrusting cut through beneath on the same shallow-dipping trend. This type of structure has been called a footwall short-cut (Knipe 1985).

Interestingly, the Tertiary clastics deformed independently with respect to the underlying layer, involving detachment planes located at the top of the Cretaceous series and at the base of the Messinian series. This leads to passive backthrusting which compensated for the shortening of the Mesozoic carbonates.

The episodic nature of compression and the variety of structures characterizing the propagation of the Apennine front imply that different palaeogeographic structural domains conditioned the type and distribution of deformation in this part of the Po Valley. The geometric constraints, such as basement depth and thicknesses of the series involved, suggest that the Cavone structure originated at a Mesozoic transition zone between a northern Alpine domain (the Veneta platform) and a southern Apenninic domain (the Umbria-Marche basinial series).

This regional interpretation formed the basis for constructing a new series of geological cross-sections on a reservoir scale. These were constructed parallel to the direction of tectonic movement, in order to describe in more detail the deformation of the individual blocks into which the reservoir is divided.

The cross-sections were balanced with the aid of the LOCACE software package, jointly developed by IFP, AGIP, ELF and TOTAL. This is an interactive system for verifying the geometric coherence of geological sections in their pre-deformed state through the application of simple balancing principles (Moretti and Larrère 1989).

An example of a cross-section balanced using this software is shown in Fig. 8. The reverse faults which displace the northern side of the anticline (interpretable as the splay of a deeper sole thrust) and the associated backthrusts are considered to have developed after the
folding phase. Consequently the restoration method adopted included firstly removal of the effects of the shearing phase (utilizing the shear-along-fault method, an option in the software), and subsequently removing the effects of deformation by flexural slip associated with the folding (kink method).

The simplest interpretation is that the Cavone structure formed as a result of fault-propagation folding, in which the anticline forming the termination of a deeper thrust in an earlier phase subsequently undergoes translation caused by up-section propagation of the thrusting. Currently, the LOCACE software is being used for a structural study of the individual blocks of the Cavone reservoir in order to define its structural evolution in the axial direction. The results of this study will establish the role of Jurassic-aged lineaments during compressive stages of deformation of the Cavone structure. This is considered to be important, as these lineaments controlled the structural developments of the field.

Sedimentology and diagenesis
A sedimentology study of the Cavone Field was conducted in order to identify petrophysical heterogeneities in the reservoir, defining their geometry, porosity and permeability, and to understand their diagenetic evolution. The study focused on the Calcari Grigi di Noriglio Formation in the eastern part of the field (in particular the oolitic horizons) and the Brecce di Cavone Formation in the western part of the field.

Based upon detailed facies analyses, the Calcari Grigi Formation was divided into two main units; Nor A and Nor B (Fig. 4). Nor B is a carbonate sequence which was deposited under tidal flat conditions. Periodic drops in sea level resulted in subaerial exposure and development of secondary (moldic and vuggy) porosity and palaeosol horizons. The Nor B unit is separated from the overlying Nor A unit by a marker bed characterized by high radioactivity associated with organic material.

Unit Nor A is represented by shallow water, open platform carbonates with considerable vertical and lateral facies variation. These facies consist of shallowing-upward parasequences with an overall transgressive trend. The top of the Nor A unit in the eastern part of the Cavone Field is comprised of oolitic shoal deposits of well-sorted grainstone approximately ten metres thick. These deposits have good lateral continuity and are con-

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**Fig. 9.** W–E cross-section flattened at the top of the Marne del Cerro formation (upper diagram) and at the top of the Calcari Grigi di Noriglio Formation (lower diagram).
considered to be the most prospective facies in the field, especially in the crestal portion of the structure where they are less well cemented.

The sedimentological analysis was then complemented by a sequence stratigraphy study of the Mesozoic carbonate series in order to delineate the facies architecture at reservoir scale. Figure 9 is a W–E oriented cross-section illustrating the two depositional sequences in the Mesozoic. The datum planes adopted are the top of the Liassic platform sequence (i.e. the top of the Calcari Grigi Formation) and the top of the Marne del Cerro Formation. The tidal flat facies of the Nor B unit are several hundreds of metres thick, which suggests a period of relative tectonic stability and constant subsidence, a low stand systems tract (LSST). The Nor A unit, separated from Nor B by the increasing subsidence surface (ISS) of the radioactive marker, constitutes a transgressive systems tract (TST) which culminated with sedimentation of an oolitic layer at the top.

Above the TST a condensed sequence (maximum increasing subsidence surface) is recognizable from the deposition of strongly bioturbated phosphate and iron-oxide-rich wackestone and packstone, at the interface with the Rosso Ammonitico Formation. The influence of Upper Liassic tectonic activity, which resulted in the western portion of the Cavone Field area subsiding at a more rapid rate than the eastern portion, is demonstrated by the occurrence of thick lagoonal deposits in the western area. The separation between the domains was established during the deposition of the Rosso Ammonitico Inferiore, Rosso Ammonitico Superiore and the Maiolica Formations, which form a high stand systems tract (HSST). In the eastern sector the Rosso Ammonitico and Maiolica Formations are represented by a condensed deep water marine sequence.

The top of the Maiolica Formation can be interpreted as a sequence boundary conformable with the overlying Marne del Cerro Formation. The latter constitutes the basin floor facies of a turbidite system at the base of a low stand systems tract deposited during the Aptian–Cenomanian Alpine compressive phase.

For the purpose of developing the reservoir model, the Cavone Field reservoir was divided into the following four main facies using petrophysical and lithological data:

- An oolitic facies with primary intergranular porosity (grainstone/packstone) typical of the oolitic layer at the top of the Calcari Grigi Formation (average porosity 10%, permeability around 100 mD).
- A leached carbonate limestone facies with secondary vuggy porosity development. This occurs with grainstone/packstone/wackestone present in the Nor A unit, but predominantly occurs within the Nor B unit (average porosity 10%, permeability < 10 mD).
- A grainstone/packstone facies with connected intra-granular porosity, forming the clasts of the Brecce di Cavone Formation (porosity approximately 10%, permeability 10 mD).
- A brittle limestone facies with secondary fracture porosity development. This division includes all limestones, tight or not, whose very low porosity is combined with high fracture permeability.

Well-log analysis

During the first development phase of the Cavone Field, lithological and petrophysical analyses were carried out using density, neutron, gamma-ray, resistivity (DLL) and sonic (BHC and full-waveform) logs. Log analysis quantified pay thicknesses by eliminating the marly horizons present in the Calcari Grigi carbonate facies. Moreover, the reservoir intervals with matrix porosity were discriminated from those with fracture porosity by means of the sonic log analysis. Since the fracture porosity is of extreme interest in a fractured reservoir, high vertical resolution geophysical logs recorded in more recently drilled wells (Cavone 19, 20 and 21) were employed in the second study phase.

Two of the state-of-the-art tools used to recognize and study the fractured intervals in the field are the sonic array tool, which defines intervals of different fracture density along the vertical well profile, and the formation microscanner (FMS) which, through orientated images of the borehole walls, allows calculation of both the location and attitude of structural features such as bedding planes, joints and faults.

The sonic array tool is a multiple system of two acoustic wave transmitters and eight receivers with down-hole digitization of the data. In a well filled with drilling mud, body waves and guided (Stoneley) waves are recorded.

The Stoneley waves appear to be the more diagnostic in evaluating the degree of fracturing in reservoir rocks. Since these waves propagate along the borehole wall, when an open fracture is encountered they dissipate energy through the action of pumping drilling mud in and out of the fracture. This results in anomalies in transit time and attenuation of the energy of the wave itself.

Figure 10 graphically displays the main results obtained from the Cavone 19 well. The track on the left shows the waveforms of the three types of wave (compressional, shear and Stoneley) at receiver 1. Compressional and shear waves are characterized by high frequencies, low amplitudes and transit times of 900–1700 μs, while the clearly defined, continuous black band at 1700 μs represents the arrival of the compressional wave propagated through the mud. This separates the body waves from the Stoneley waves, which have longer transit times.

The track on the right shows the results of the waveform analysis. The transit times of the shear waves (DT shear), compressional waves (DT comp) and the ratio of the two (RSC) are included, as well as the
Fig. 10. Full waveform sonic log data and energy analysis for the depth interval 2829–2900 m in the Cavone 19 well.

The analysis of energy behaviour for the three types. A comparison between the shear and Stoneley wave energy curves shows a zone of higher permeability due to macrofractures between 2868 and 2871 m. This zone is also visible on the left-hand track, due to the pronounced attenuation of all wavetrain components. The maximum energy values for the Stoneley curves are constant over long sections, indicating impermeable zones. The slightly accentuated activity of the individual Stoneley energy traces over the interval 2835–2860 m can be explained by microfractures, evident in the core.

Following the analysis of the sonic array tool data, the most prospective reservoir zones were further investigated by FMS analysis, in order to define individual structural features. The FMS data allow recognition of very thin features, such as fractures, stylolites, bedding planes and vugs, when the conductivity contrast between them and the host rock is sufficiently high. The
The borehole wall images were calibrated with cores, where available, allowing recognition and spatial orientation of structural and sedimentological features in the uncored zones of the reservoir. Figure 11 illustrates FMS images of a productive interval in the Cavone 19 well recognized using sonic array data (cf. Fig. 10). The attitude of events is expressed here as true dip and true dip direction, already corrected for well deviation from the vertical. Fracture planes (F sinusoids) orientated northwards are here clearly discordant with bedding planes (B sinusoids) orientated southwestwards.

Using the colour contrast technique in reprocessing the same images, evaluation of secondary porosity was attempted in terms of both fracture and vuggy porosity. The results (Fig. 12) show better definition of conductive events, due to the enhanced black/white contrast. Fractures and vugs (small circular-shaped events) can be identified. The corrected fraction of conductive events on the total image surface (matrix) was calculated at 6.5% for this interval. This method, however, has limitations mainly due to hole conditions, vertical resolution of the tool and the essentially qualitative nature of the interpretation. The results of this interactive analysis of the oriented images were displayed as a function of depth. Together with direct core analysis they allow the evaluation of vertical distribution and orientation of the fractures, bedding planes and stylolites.

**Petrophysical reservoir characterization**

All core and log data were then subsequently processed with cluster analysis statistical algorithms, in order to interpret the reservoir layering. Each layer represents a statistically homogeneous unit with consistent values of
petrophysical variables and uniform modes of fluid transport.

Cluster analysis (for a detailed description see specialist works on statistical data processing: e.g. Davis 1973; Descalzi et al. 1988) involves repeated data grouping processes to determine facies type. This technique, previously developed for cored wells, was also used for the statistical evaluation of petrophysical parameters in uncored wells. In the Cavone Field the compressional and shear wave travel transit times and waveform energies were subjected to cluster analysis with the particular aim of determining fracture distribution in the reservoir.

In order to isolate the contribution of the acoustic signal from lithological and textural parameters, similar processing was applied to the lithological logs (gamma-ray, density and neutron). This allowed log facies to be defined only by fracture density values.

Six log facies resulted from this processing in the Cavone Field: they are considered sufficiently descriptive of the fracturing variations, and their vertical distribution is shown in graphic symbol form in Fig. 13. An average fracture density value taken from data obtained from cored wells was then assigned to each log facies. This allowed the extrapolation of average fracture density values even for uncored wells, where those same log facies were identified.

Using this system, the potential contribution of each log facies to reservoir flow was defined. The characteristics of each log facies thus acquired a unique objective value, since they represent averages from the simultaneous interpretation of numerous wells. The best potential pay intervals could be found from the log facies distribution.

**Reservoir simulation study**

The data obtained from the previously described studies were then utilized to construct a high resolution model of the reservoir. The reservoir itself was vertically zoned into layers; from bottom to top: aquifer, Nor B Unit, Nor A Unit excluding the oolitic layer, oolitic layer (top Nor A Unit), tight Maiolica and Rossi Ammonitici layers, Brecce di Cavone. The static geological model, representing the distribution of all the reservoir heterogeneities, formed the basis for the subsequent dynamic numerical model. The latter is aimed at forecasting fluid saturation and pressure trends with time at each point in the reservoir, as well as oil, gas and water production rates for each well.

In order to build the dynamic numerical model, the reservoir volume was firstly divided into a representative number of cells (Fig. 14). They were obtained by superimposing a grid system on the structural isopach and isonet/gross plots of each of the six layers. Each model cell was assigned the initial petrophysical, thermodynamic and fluid dynamic parameter values.

For the Cavone Field, the reservoir volume was divided into basic cells of 100 x 100 m$^2$ in the horizontal plane, and thicknesses equal to the layer considered on the vertical axis. Where greater detail was required, the basic cells containing single wells were split into four cells of 50 x 50 m$^2$ and the Nor A layer was split into two sub-layers. The total number of active cells came to 6018.

Before constructing the final model of the whole field, some smaller preliminary models were set up, and simulations run in order to reconstruct the behaviour of certain key wells. These models were run using finer and coarser grids in order to integrate the effects of individual wells in the full field model. Sensitivity tests were tried with these models in order to examine the influence of less well-known parameters on reservoir behaviour.

The sensitivity cases were run using the FRAGOR software package released by FRANLAB. This is a three-phase (oil, gas, water), 3D simulator with a dual porosity/dual permeability option (matrix-related porosity and permeability, fracture-related porosity and permeability). In order to verify the validity both of the geological model used and the dynamic numerical modelling, comparisons were made between the pressure, water cut and oil flow rates obtained from field produc-
Fig. 14. Grid system for reservoir modelling in the oolitic layer with two examples of distributions of initial oil saturation.

In order to obtain an optimal history match the differences between the calculated history and the real one were reduced by adjusting the individual model parameters until satisfactory results were obtained. The adjustments required were:

- An increase in the matrix permeability value from core tests in the most oil-productive zones (the oolitic and breccia layers), implying the presence of fractures.
- A reduction in permeability values for the aquifer, implying the presence of cementation in the fractures.
- A reduction in flow rate exchange between matrix and fracture.
- Changes in representation of the effects of workover in some wells, since simulation results were sometimes not as expected, probably due to casing cementation problems.

Validation of the history match for Cavane Field covered the period from 1 March 1980 (the start of the exploitation) to 30 September 1988. Cumulative production at the latter date was 1 195 350 m³ of oil.

Figure 14 shows two examples of oil saturation calculation for the oolitic layer. For the lower example it was assumed that only the intergranular porosity is oil saturated; in the upper example it was assumed that the fracture system is also oil-saturated. The saturated volume in the first case is therefore limited to the easternmost third of the field, amounting to 1 291 000 m³ of oil. In the second case this volume increases to 2 776 000 m³ of oil.

The full field model was subsequently used for a dynamic simulation study in order to define new development strategies for future reservoir performance. Two of the predicted cases are particularly significant and interesting:

Case (a): Natural reservoir depletion without workovers and additional drilling.
Case (b): Natural reservoir depletion assuming successful workovers in some wells and four new wells producing from the oolitic and Nor A layers.

In case (a), for a simulation period of 30 June 1988 to 31 December 2009, total cumulative oil production has been forecast at approximately 3 800 000 m³ of oil (obtaining 25% primary recovery of the original oil in place), at an abandonment pressure of 24.5 MPa.

In case (b), for the same simulation period, total cumulative oil production was forecast at approximately 5 000 000 m³ (obtaining a 34% primary recovery factor) at an abandonment pressure of 23 MPa.

Conclusions
The Cavane Field reservoir study is an example of a synergetic approach for identifying the trapping and production mechanisms of a fractured carbonate reser-
The main results of this work to date are: the successful application of updated seismic processing and structural interpretation tools; the use of wireline data for fracture identification; and the development of cluster analysis techniques for lithofacies characterization in fractured reservoirs. The 3D numerical model covering the whole field area is used in order to achieve maximum primary oil recovery. This target will be met by optimizing the future number and location of wells. The model will be updated after the drilling of each development well. This will allow the optimization of further well locations, drastically reducing the possibility of drilling dry or low-producing wells.

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References


