Evaluation of the impact of rock fracturing on the reservoir properties on the example of the hydrocarbon-bearing sandstones in the Polish part of the Western Carpathians - a case study

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Abstract. So far, the largest documented reserves of oil in the Skole unit are found in the Wańkowa-Łodyna-Brzegi fold, where the reservoir rock is composed of the sandstones belonging to layers of the menilite series. The oil inflow from Inoceramian, Hieroglyphic and Krosno layers was also obtained from this fold. These layers characterized by a low level of reservoir parameters, are associated with the presence of a system of fractures. The impact of fracturing on the permeability of these sandstones is of interest to the oil industry. The aim of the research was to carry out measurements of the basic geometric parameters of fractures, i.e: the length of the fracture trace, the assessment of the degree of mineral fill, the openness and the determination of the angle and azimuth of fracture dip. Then, linear densities, surface coefficients of fracture and the fracture permeability coefficient were calculated for each measuring field. Obtained research results in the form of diagrams, tables and diagrams showed that inoceramian sandstones belong to rocks of low-class reservoir capacity. The analyzed sandstones are characterized by low permeability and have a low effective porosity. The results of the analyzes carried out simultaneously confirmed the effect of the fracturing of inoceramian sandstones on their potential permeability.

1 Introduction

Fractures in reservoir rocks plays an important role as often the only routes of reservoir fluids transport and an element ensuring hydrodynamic communication of the profile. Correct determination of porosity and fracture permeability is of fundamental importance for a reliable estimation of reservoir and filtration parameters of reservoir rocks [1].

The term fractures is understood to mean the occurrence of cracks breaking the continuity of rocks, without a macroscopically perceptible displacement along their surface. Cracks with a macroscopically measurable dilatation are called fractures [2]. The genesis of fracturing is most often associated with tectonics of the rock medium, and sometimes also with the processes of lithification of sediments, especially when they are characterized by varying intensity [3].

In petroleum geology, the classification taking into account the fracture opening is used. On this basis, we split the fractures into [4]:

- *macro-fractures,* with the aperture greater than 0.1 mm, these fractures are visible to the naked eye, which makes it possible to measure them in exposures; an arbitrary 20 mm aperture was assumed arbitrarily for the upper limit of aperture the macro-fractures;
- *mikro- fractures*, with the aperture below 0.1 mm, hardly visible or invisible to the naked eye, i.e. possible to be tested only with laboratory techniques.

The parameters of the spatial orientation of fractures are called the quantities characterizing the location of cracks in space in relation to the parts of the world. This location determines the dip angle α [°] and the azimuth of the dip angle β_u. The dip angle α is the dihedral angle contained between the fractures plane and the horizontal plane. On the other hand, the azimuth of the dip angle β_u [°] is the angle between the north and the direction of fractures measured in a clockwise direction. Linear length and aperture were qualified for linear parameters. The fractures length is the length of the fracture trace on the measuring plane measured along the track line. Distinct fractures are distinguished.

a) actual - measured as distance between two surfaces of fracturesalong normal to these surfaces at the measurement point;

b) and apparent - distance between two surfaces of fracture measured alongnormal to the fracture mark on the measuring level.

The physical features of fractures can also include the surface of fractures, this is the surface of rock separation, resulting from the cracking of the layer. This surface can be smooth or have a relief. Fracturing parameters include the linear density of fractures, i.e. the ratio of the number

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of fractures to the length of the measurement sections, which were assigned to the sides of the measurement fields and the lines in the middle. The degree of mineral filling (scarring) is determined by using a magnifying glass, the enlargement of which allows a more accurate estimation of the scarred trace scarred to the total surface. The assessment of the degree of filling the fractures should be completed with a lithological description of the filling material [5].

Reservoir rocks for oil and natural gas, in which fractures occur, can be characterized, as in the case of intergranular pores, with two parameters - porosity and fractures permeability. Fractures porosity is a characteristic characterizing the share of the volume of free spaces in the fractures in the volume of rock available for fluids. In contrast, the fractures permeability is a parameter that is conditioned by the effective aperture of fractures (i.e., not filled with mineral substances), their density and spatial orientation. As a unit of slit permeability, darcy [D] or millidarcy [mD] is assumed.

Depending on the degree of fracture participation in the volume of reservoir rock, which wasclassifiedon the types of oil and natural gas collectors as: fracture, fracture-pore or pore-fracture [1].

2 Methodology

Fieldwork included studies of the outcrops of the inoceramian sandstones of Łodyna-Kopalnia and Chwaniów folds in the Strwiąż basin below Brzegi Dolne. The research was located mainly in the streams of streams and watercourses, with exposed outcrops of inoceramian sandstones (Fig. 1).

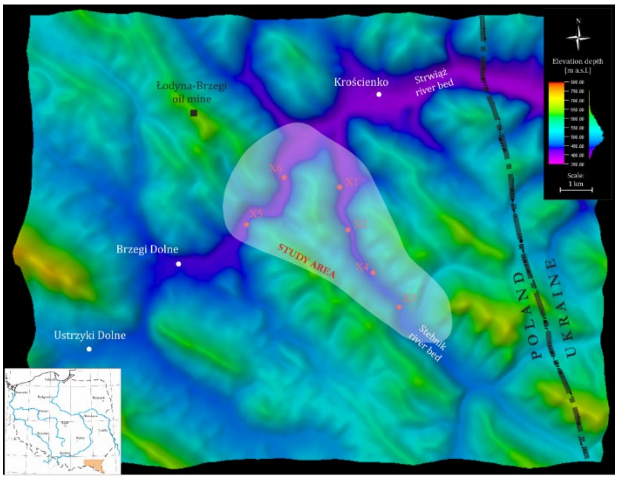

Fig. 1. Location of the measuring fields.

Six measuring fields with different spatial orientation within the outcrops of sandstone packages were selected and accurately located for measurements and observations. The preparation of the field for measurement consisted in removing the debris and determining the boundaries in the shape of a rectangle with the center line. The 10 rock samples for porosimetric tests [6] were collected from each measurement field and to determine their effective porosity and fracture permeability.

In each designated field measurements were performed:

a) sides of the field (height and width) and thickness of sandstone packets
b) parameters of spatial orientation of layers and measurement field;
c) parameters of fracture orientation, i.e. the exact determination of the angle (α) and the azimuth of the dip (β);
d) length of individual traces of fractures (l) and their maximum ($R1$) and minimum ($R2$) aperture;
e) the average degree of filling of the surface fracture mark (S_s);
f) linear density of fractures ($gl1$, $gl2$, $gl3$), ie. the ratio of the number of gaps to the length of the measurement sections which were assigned to the sides of the measurement fields and to the center lines;
g) the total area of fractures (P_c), and the effective - open surface of fractures $P_e = P_c\,(1 - S_s)$.

The average filling levels of the fractures were assessed by means of a magnifying glass or macroscopically in case of their significant opening. Angle and azimuth measurements of fracture fall were made with a geological compass. The length of the fractures was measured with a metal measuring tape with an accuracy of 1 cm. They were measured by a technical feeler gauge with an accuracy of 0.05 mm to obtain values as close as possible to the real ones.

Values of the indicators of the fracturing were averaged for the entire measurement fields and calculated on the basis of the following formulas:

$$G_l\left(\frac{n}{mb}\right) = \left(\frac{g_{l1} + g_{l2} + g_{l3}}{3}\right)\cdot 100\,\left[mb^{-1}\right] \quad (1)$$

where:
$gl1$, $gl2$, $gl3$– measured linear density on the sides and in the middle of the measuring field,
n – quantity of fractures.

The surface density is the ratio of the sum of the length of the traces of all the fractures on the measuring surface to the area of the measuring surface:

$$G_p = {\Sigma l(n)}/{P_p}\;\left[cm^{-1}\right] \quad (2)$$

where:
l – lenght of fracture trace,
Pp – area of the measuring surface.

The degree of filling, calculated as the sum of the average degrees of filling in the fractures to their number, expressed in a fraction:

$$S_u = {\Sigma S_s(n)}/{n}\;[-] \quad (3)$$

where:
S_s – average rate of fracture filling,

n – quantity of fracture.

Fracture aperture, the value of the fractures reduced by the degree of filled fractures, used to calculate the open surface of fractures:

$$R_o = \frac{\Sigma R_s(n)}{n} \cdot (1 - S_u)\,[mm] \qquad (4)$$

where:
R_s – average of fracture opening,
n – quantity of fracture,
S_u – level of fracture filling.

Total fracture porosity, defined as the sum of the total area of all fractures to the surface of the measurement field:

$$WP_c = \left(\frac{\Sigma P_c(n)}{P_p}\right) \cdot 100\ [\%] \qquad (5)$$

where:
P_c – total surface of fractures,
P_p – surface of the measuring field.

Effective fracture porosity, defined as the sum of the effective area of all fractures to the surface of the measurement field:

$$WP_e = \left(\frac{\Sigma P_e(n)}{P_p}\right) \cdot 100\ [\%] \qquad (6)$$

where:
P_e – effective area of fractures,
P_p – surface of the measuring field.

Averaged angle of fracture dip:

$$\alpha_S = \Sigma\alpha(n)/n[^\circ] \qquad (7)$$

where:
α – angle of fracture dip,
n – quantity of fracture.

Indexable fracture permeability coefficient [7]:

$$K_{sc} = 85000 \cdot R_o^2 \cdot WP_e\ [mD] \qquad (8)$$

where:
R_o – open fracture width,
WP_e – effective fracture surface coefficient, expressed in a fraction.

3 Results and discussion

Fracture parameters were measured in outcrops of four measurement fields in the Stebnik stream profile and in two fields in the Strwiąż river profile above the outlet of the Stebnik stream. Table 1 presents the parameters of selected measuring fields, linear density measurements, layer deposition parameters and their thickness.

The average fracture parameters for the six measuring fields of the research area are shown in Table 2. The average effective porosity for the entire zone is 0.33% and varies from 0.15 to 1.15%. The average fracture permeability (geometric) is 7.24mD for the entire zone, and analogically, as in the case of porosity, its elevated values occur along the X4 measuring field. In principle, all fractures are partially filled with calcite, only in the X1 measuring field, no fracture filling is noticed. The degree of fracture filling ranges from 0 to 0.609, the average value of the analyzed zone is 0.39. The average effective fracture aperture is 0.17mm for all measurement fields. The surface density of fractures varies in the studied zone from 0.124 to 0.372 cm^{-1} and is 0.23 cm^{-1} on average. The average fracture dip angle decreases in the range from 56.7° to 80° for the whole area with an average value of 69.11°.

Table 1. Parameters of individual measuring fields.

Measuring field	Location	Dimensions of the meausring field	Linear density measurements	Layer deposition parameters	Field deposition parameters	Layer thickness
		width [cm]; height [cm]; surface [cm^2]	g_{l1}, g_{l2}, g_{l3} (n/cm)	[°]	[°]	[cm]
X1	I	80; 30; 2400	2/30; 3/30; 4/30	40/82	40/82	11
X2	I	80; 50; 4000	1/50; 1/50; 1/50	2/85	2/85	25
X3	I	95; 35; 3325	4/35; 4/35; 4/35	35/54	30/60	9
X4	I	65; 25; 1625	3/25; 3/25; 3/25	33/62	32/35	6
X5	II	100; 30; 3000	2/30; 1/30; 2/30	192/70	120/65	15
X6	II	80; 50; 4000	2/50; 2/50; 1/50	50/230	40/360	13

Table 2. Average values of fracture parameters for measuring fields.

Measuring field	Linear density [mb^{-1}]	Surface density [cm^{-1}]	The degree of fracture filling [-]	Fracture aperture [mm]	Total fracture porosity [%]	Effective fracture porosity [%]	Averaged fracture dip angle [°]	Fracture permeability [mD]
X1	10.000	0.292	0.000	0.053	0.153	0.153	80.0	0.360
X2	2.000	0.128	0.433	0.214	0.459	0.215	79.5	8.395
X3	11.429	0.262	0.363	0.162	0.656	0.311	56.7	6.981
X4	10.667	0.372	0.493	0.331	2.463	1.152	59.6	17.381
X5	5.556	0.247	0.609	0.165	1.029	0.340	60.8	7.913
X6	3.330	0.124	0.488	0.133	0.320	0.164	78.1	2.451

In the outcrop zone (Stebnik stream profile) fracture parameters were measured in 4 measuring fields X1-X4. Against the other results, there are clearly higher fracture rates. The average porosity of macro-fractures is 0.37%, the average permeability is 8.27mD (Table 2). The highest fracture permeability occurs in the X4 measuring field profile, reaching the value of 17.38mD. Increased values of fracture parameters are probably related to the nature of the pore space of sandstones in this zone dominated by micropores and fractures. Research of fractures on outcrops in this zone, despite the small number of trials, showed the presence of macro-fracture networks with significant capacity and constituting the possible active paths of hydrocarbon flow in the Łodyna-Brzegi oil reservoir.

In the outcrop zone (profile of the Strwiąż river above the outlet of the Stebnik stream), the parameters of fractures were measured in the X5 and X6 measuring fields. Outcrop zone X5 and X6 is located on the south-western edge of the research area and shows low fracture rates. The average effective porosity is 0.25%, while the average permeability is 5.18mD (Table 2).

Almost twice the difference between the total and effective porosity in most of the measuring fields is associated with a moderately high degree of filling fractures, often in 60% filled with calcite, for the entire reservoir zone of X5 and X6 measuring fields ranges from 0.49 to 0.61% (Table 2). Such a high degree of fracture filling also results in their low effective aperture of 0.14 mm on average.

The average degree of fracture filling of the X1-X4 measuring fields is 0.27 and is about 50% lower than in the X5 and X6 measuring fields, which causes higher effective fracture porosity. Analyzing the histogram of the fracture length distribution of the X1-X4 measuring fields, higher values of the fracture length (67.5 cm) are observed compared to the area of the Strwiąż river profile above the outlet of the Stebnik stream, where the value of the fracture length is 61.8 cm (Fig. 2).The fractures length also affects the surface density of the fractures, the average value of which varies from 0.128 cm/cm^2 in the measuring field X2 to 0.372 cm/cm^2 in the measuring field X4. The average value of fracture density for the whole zone is 0.26 cm/cm^2.

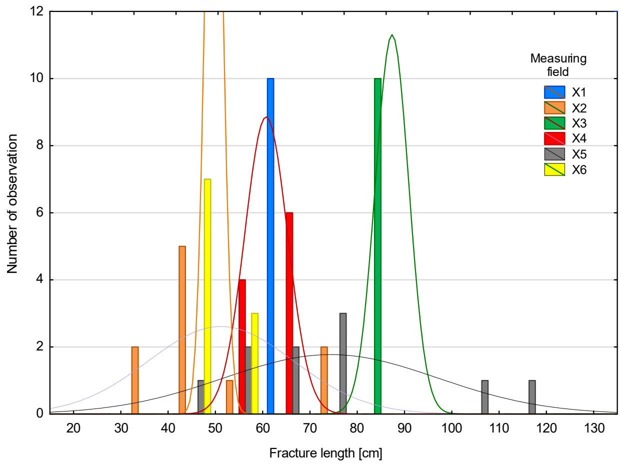

Fig. 2. Distribution of the fracture length for the research measurement fields.

Figure 3 presents a histogram of the fracture aperture distribution for all measurement fields. Analyzing the distribution of the average fracture apertures, it is noted that the biggest contribution of apertures close to 0.1 mm is present in the X1 measuring field (Fig. 3). The highest mean values of fracture apertures occur in the measuring field X3 and X4 and are respectively 0.67mm and 0.65mm. The size of these fracture apertures is undoubtedly affected by the state of stresses in the rock medium and in particular the differences between overburden pressure and the pressure of submerged fluids, which may have a limited effect on the permeability increase. The smallest fracture aperture value was observed in the X6 measuring field. It is related to the content of calcite binder at the level of 60%. In the case of fractures, the histograms of the aperture distribution fit well in the Gaussian curve (normal distribution).

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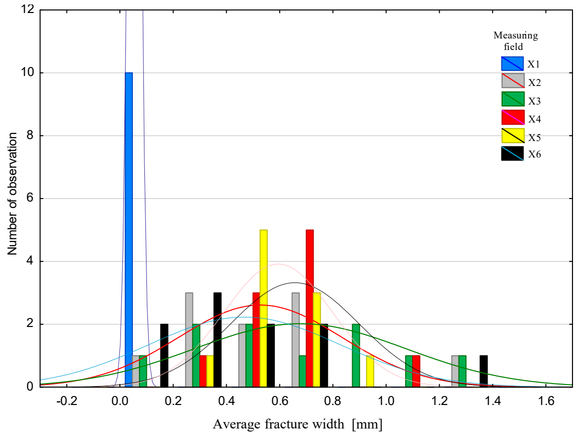

Fig. 3. Histogram of the average fracture width distribution in the measuring fields.

Among all the measurement fields, the X4 measuring field is particularly distinguished, where all measurements of effective porosity and fracture permeability have a higher value compared to other measuring areas. Measurements of porosity exceed 0.1% and their average value is 0.12%. The value of the fracture permeability within the measuring field differs from 0.16mD (log K = -0.79) to 86.85mD (log K = 1.94) with an average value for the entire tested zone equal to 17.38mD. High values of porosity and permeability results in this zone are associated with highly effective fracture aperture, which in turn is the result of the average degree of their filling with mineral substances.

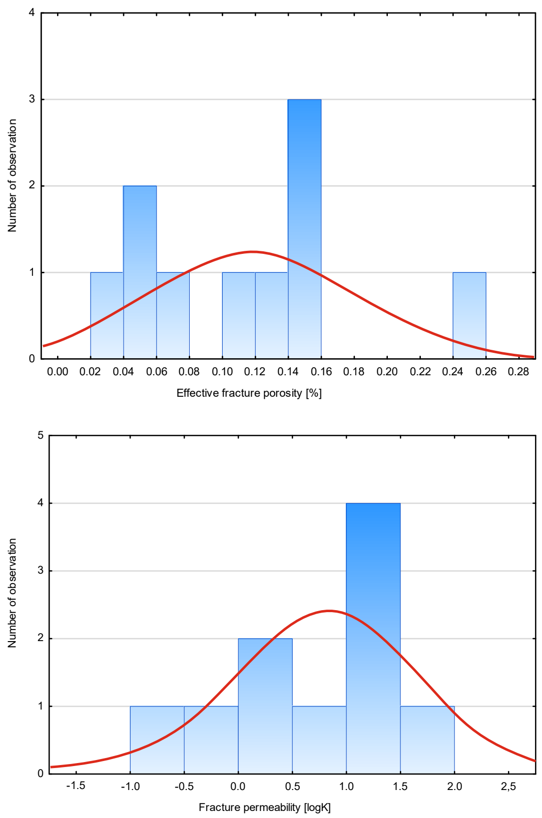

Fig. 4. Distribution of the effective porosity and fracture permeability for the X4 measuring field.

The analysis of average fracture deposition parameters for the entire measuring zone indicates that steep apertures predominate here (the average dip angle is 70°) (Fig. 5), with NE-SW direction (the average strike angle is 59°), i.e. perpendicular to the major fold structures (Fig. 6).

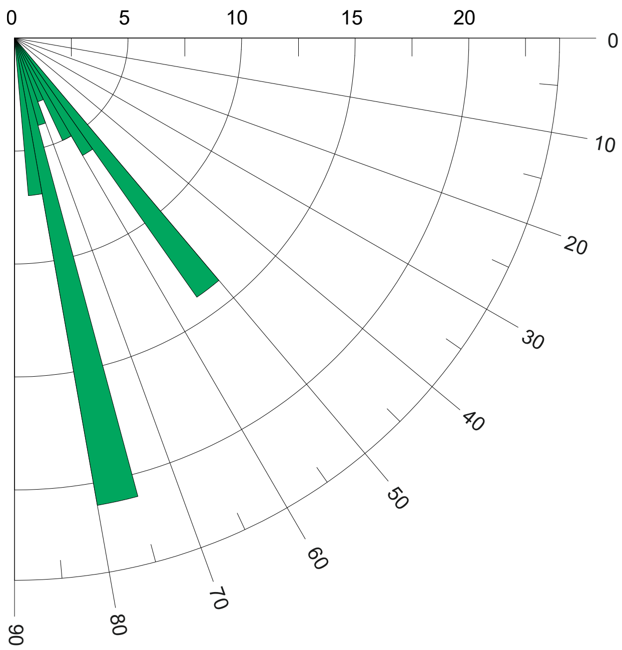

Fig. 5. Distribution of fracture dip angle.

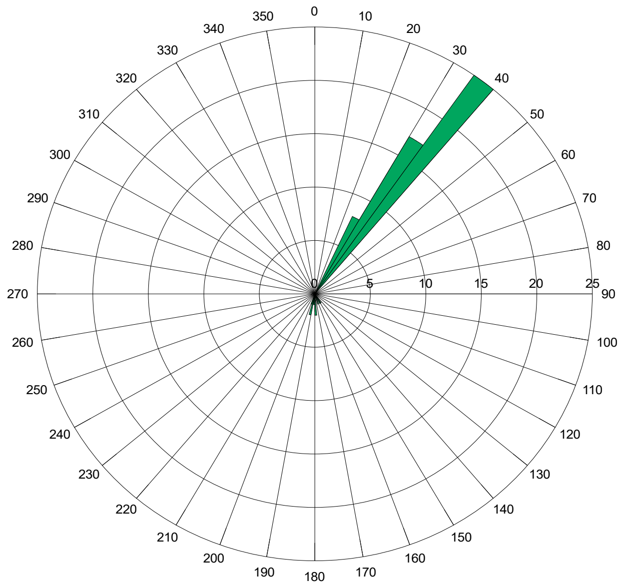

Fig. 6. Fracture strike distribution.

Due to the specificity of field measurements on outcrops, the calculated fracture parameters (porosity, permeability) can be subject to some errors. The biggest mistake can be the parameter of the degree of filling the fracture with mineral substances. It is estimated macroscopically or using a magnifying glass and is a subjective measurement. Substances filling fractures, under surface conditions, may be partially removed due to erosion, which further influences the subsequently calculated parameters of fractures (effective aperture, effective porosity and permeability).

The potentially smaller error can be attributed to the measurements of fracture aperture, in this case for objective reasons. The fracture aperture was measured with a technical feeler gauge or with a millimeter scale magnifier. It changes depending on the angle of its inclination in relation to the measuring field. If the fracture is perpendicular to the surface of the measuring field, then the real fracture aperture is measured, in any other case the fracture orientation is measured as an apparent aperture on the surface of the measuring field. It should also be mentioned that the adopted calculation method also has an impact on the obtained results of the fracture parameters.

4 Conclusions

The aim of the authors' work was to investigate the impact of fractures of inoceramian sandstones on their reservoir properties. The article analyzes the methodology for measuring effective porosity and permeability for the fractures of samples of the Polish part of the Western Carpathians.

Based on the conducted analyzes, it was found that the dominating factor affecting the reservoir properties of inoceramian sandstones is porosity and permeability. The nature and type of pore space should also be taken into account, as presented in the previous work of the authors. In addition to the factors listed above, the mineral composition of the rock should be mentioned. All these parameters affect both the formation of the pore space, as well as the stiffness of the skeleton, the arrangement of rock grains and their structure and texture.

The area of the Stebnik stream profile, where most of the tested measuring fields were located, showed higher values of fracture parameters. The highest values of fracture porosity exceeding 1.1% (with the average for the entire area - 0.45%) occur in the X4 measuring field. In these zones, the highest values are also assumed for the fracture permeability, exceeding 17mD (with the average for the region - 8.28mD). The high porosity and permeability results in this zone are associated with the highest (in the whole area) effective fracture aperture, which is, in turn, the effect of medium and low degree of their filling. In the remaining measuring fields, the fracture parameters decrease.

In the outcrop zone (profile of the Strwiąż river above the outlet of the Stebnik stream), high values of effective porosity (0.34%) and permeability (7.91mD) were obtained from fracture measurements (0.6 mm) in the X5 measuring field. In this case, the high values of fracture parameters were influenced by the probable relaxation of the rock mass in the area of the measuring field located in the studied area.

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