Journal of Geotechnology and Energy | vol. 40 | no. 4 | 2023 | pp. 15–21

https://doi.org/10.7494/jge.2023.40.4.5837

Marek Leszek Solecki

AGH University of Krakow, Faculty of Drilling, Oil & Gas
ORCID: 0000-0001-8637-8300
e-mail: marek.solecki@agh.edu.pl

DEFORMATION BANDS – MIGRATION PATHWAYS OR BARRIERS FOR HYDROCARBONS IN SEDIMENTARY ROCKS – MINI REVIEW

Date of submission:
20.08.2023

Date of acceptance:
7.09.2023

Date of publication:
29.09.2023

Abstract: A mini review of the topic of deformation bands is presented in the paper. The concept of deformation bands is defined and their impact on the flow of fluids in porous sedimentary rocks is determined. Deformation bands are mm-thick low-displacement deformation zones which have intensified cohesion and lower permeability compared with ordinary fractures. This term was introduced in 1968 in material science, ten years later it appeared in the geological context. This microstructures can occur as barriers or migration pathways for hydrocarbons. Their role depends mainly on microstructural features, and they are also considered in reservoir modeling. The occurrence of deformation bands in Poland is also outlined and discussed - they have been described in Western Outer Carpathians (Magura and Silesia nappes).

Keywords: deformation bands, hydrocarbons, permeability, migration, fluid flow

1. Introduction

Deformation bands are mm-thick low-displacement deformation zones that tend to have intensified cohesion and lower permeability compared with ordinary fractures [1]. They mostly occur in porous sandstones [2] but have also been observed in chalk [3] and carbonates [4, 5]. These structures should be considered when looking into cores from clastic reservoirs due to their potential role as barriers or pathways to fluid flow [6–25]. In this paper, the author discusses the term deformation band and the influence of this specific kind of microstructure on petroleum engineering.

2. Deformation bands – characteristics and classification

The term "deformation bands" was introduced in 1968 by [26] in material science; in the geological context, it was first applied in 1978 [27, 28]. Since then, some researchers have studied the occurrence of this microscructure in many regions of the world, e.g. United States of America, Norway, Italy [29–33]. They also occur in Poland, especially in the Carpathians [34–36].

Below are the key features of deformation bands within the context of sediment deformation and porous rock, as outlined in [1].

I. Deformation bands are predominantly found in clastic rocks, particularly in porous sandstones. The development and progression of these bands are connected to the rotation and translation of grains, necessitating a specific level of porosity. Insufficient porosity will favor the formation of tension fractures, stylolites, and slip or shear surfaces instead (refer to Fig. 1).
II. A deformation band is distinct from a slip surface.
III. Deformation bands typically manifest as individual bands, band zones, or faulted bands.
IV. Even in instances where these bands extend for hundreds of meters, single bands seldom exhibit offsets exceeding a few centimeters.

There are also some differences between deformation bands and ordinary fractures. At first, they are thicker and present smaller offsets than slip surfaces of comparable length. Also, deformation bands increase cohesion, whilst cohesion decreases across ordinary fractures. What is more, they also show a reduction in porosity and permeability, whereas tension fractures and slip surface exhibit an increase of these parameters. The differences between deformation bands and "classical" fractures may influence fluid flow and have an impact on hydrocarbon and groundwater reservoirs, where deformation bands are likely to occur.

In terms of kinematics, deformation bands can be categorized into three types: dilation bands, shear bands, and compaction bands (refer to Fig. 1). The majority of deformation bands documented in the literature are identified as shear bands which are often characterized by compaction, commonly referred to as compaction shear bands.

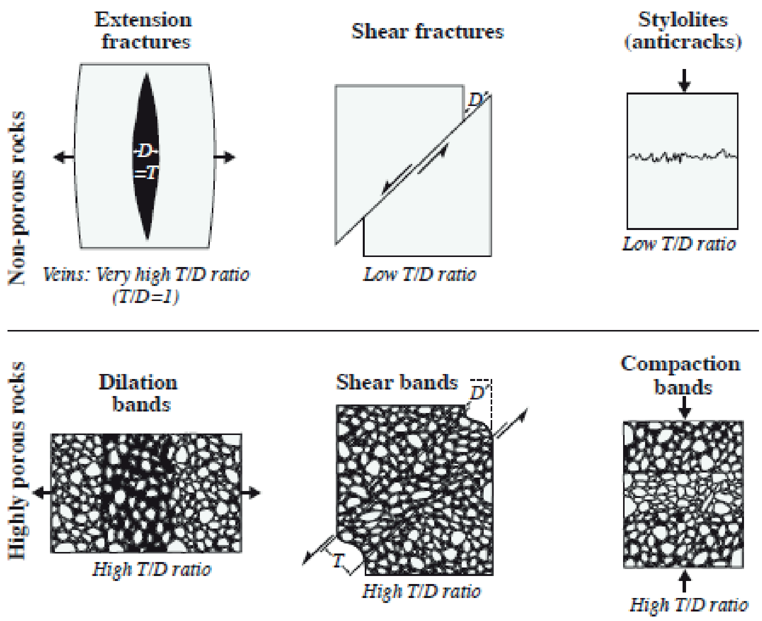

Fig. 1. Kinematic classification of deformation bands and their relationship to fractures in porous and non-porous rocks. *T*–thickness, *D*–displacement [2]

3. The influence of deformation bands on fluid flow

A visible reduction in permeability can be observed in most deformation bands, even by several orders of magnitude. However, the impact of these bands on fluid flow remains uncertain.

In the case of single-phase flow, such as oil moving through oil-saturated rock or water flowing in water-saturated rock, the key factors influencing Darcy flow are the permeability and thickness of deformation bands. Matthäi et al. [37] made numerical analyses in their paper of the impact of deformation bands on the reduction of permeability and fluid flow. The authors concluded that the influence of the bands on the reduction of these parameters is very small. Walsh et al. [38] considered that deformation bands only have significant effects on effective permeability when the ratio P^{DB}/P^{M} (deformation band permeability to matrix permeability) is less than 10^{-3}. Fossen and Bale [10] suggested the ratio as 10^{-4} and less. Nonetheless, Harper and Moftah [39] believed that zones of deformation bands were responsible for the reduction of productivity in some wells (the reduction of permeability in some fractures was even about 10%). Sample et al. [21] described the relationship between deformation bands and petroleum migration in the Monterey Formation. Sternlof et al. [40] in turn discussed the anisotropy of permeability – deformation bands parallel to the strike of a fault show higher values than those with a perpendicular strike, where fluids are more likely to encounter bands. The occurrence of deformation bands contributes to changes in the reservoir parameters of rocks; hence they are taken into account in reservoir modeling [41]. The influence of deformation bands on the flow of fluids through rock is illustrated in Figures 2 and 3.

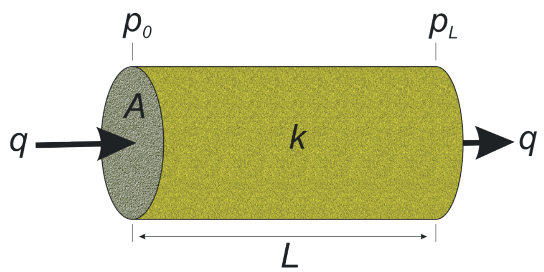

Fig. 2. Linear flow through a porous and homogeneous rock medium (sandstone) with permeability (k) (after [10])

Figure 2 depicts a linear flow system characterized by a consistent cross-sectional area (A) and a finite length (L). The medium possesses uniform permeability (k) and is saturated with an incompressible fluid of constant viscosity (m). Due to the incompressibility of the fluid, the flow rate (q) remains constant at all points within the system.

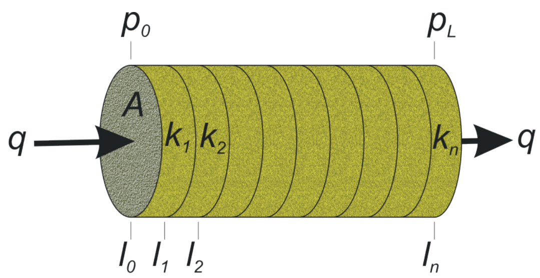

Fig. 3. Linear flow through a porous and heterogeneous rock medium (sandstone) composed of segments (deformation bands and surrounding rock) with distinct permeabilities (k_n) (after [10])

At Figure 3 a linear flow system comprising uniform segments arranged sequentially is illustrated. Each segment is characterized by a permeability that may vary from others, and the points where permeability changes occur are identified as (l_0, l_1, l_2, ..., l_n). The average permeability, denoted as (k_A), for a series of linear segments with distinct permeabilities is determined by dividing the length of each homogeneous segment by its permeability and summing these values for all segments. Subsequently, this sum is divided by the total length of the system (L).

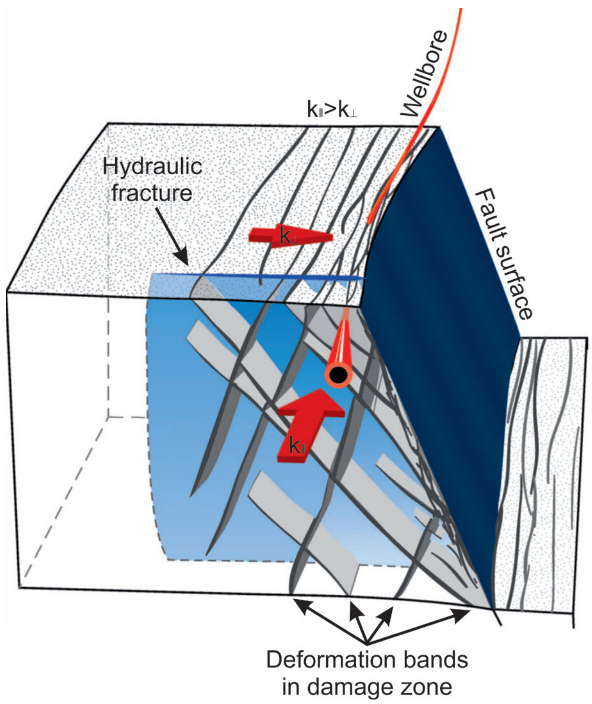

Fig. 4. A scheme showing the typical collocation of deformation bands in the destruction zone around the fault (after [10])

Figure 4 shows the collocation of deformation bands in the immediate vicinity of the damage zone surrounding the fault. The permeability measured parallel to the fault, denoted as ($k\parallel$), is higher than the permeability measured perpendicular to the fault, denoted as ($k\perp$), owing to the orientation of the deformation bands in relation to the fault.

4. The occurrence of deformation bands in Poland

To date, several places where deformation bands occur in Poland have been described. First, Aleksandrowski [42] described deformation bands in the Magura nappe near the Babia Góra Mountain region. Świerczewska and Tokarski [34, 43] and Tokarski et al. [44] described deformation bands in the Eocene strata of the Magura nappe in the Western Outer Carpathians near Tylmanowa and Gruszowiec. Nescieruk et al. [45] described structures called "step lineation" after [42] in the Krakowiec clays of the Sarmatian strata of the Carpathian Foredeep in the Sieniawa area. The occurrence of deformation bands in the Otryt facies of the Krosno sandstones of the Silesian nappe (Eastern Outer Carpathians) was reported by [35], as well as in the High Bieszczady part of the same tectonic unit (Figs. 5 and 6), in the valleys of Wołosaty, Dwernik and Solinka streams and in Połonina Wetlińska, Połonina Caryńska and Tarnica ranges [36, 46–50]. The Krosno sandstones constitute a regional layer of hydrocarbon reservoir rocks here.

Fig. 5. Krosno sandstone with deformation bands – outcrop near Dwernik village, deformation bands visible as "steps" on the rock

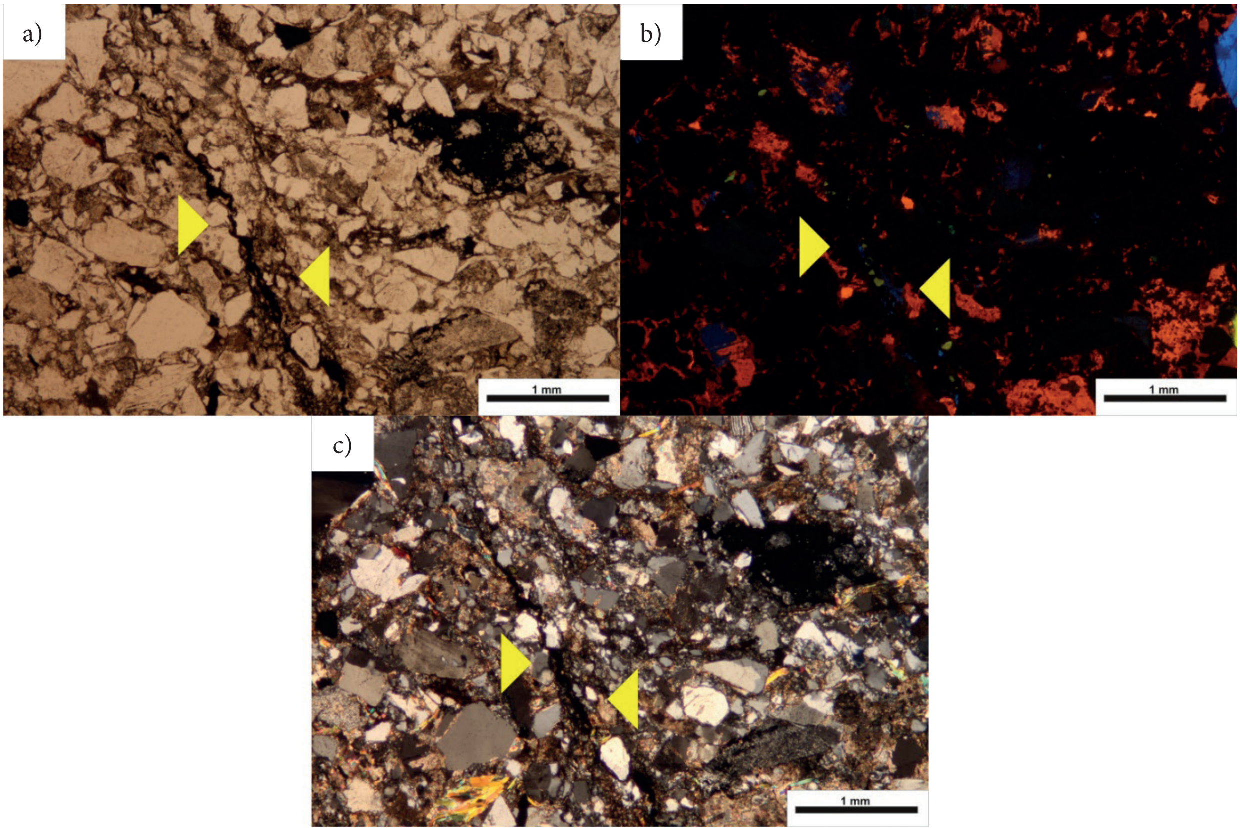

Fig. 6. Microphotographs showing the deformation bands (yellow arrows) in Krosno sandstone in a polarizing microscope: a) – parallel nicols; b) – cathodoluminescence (orange – calcite, blue – feldspar); c) – crossed nicols

5. Conclusions

Deformation bands are microstructures commonly found in sedimentary rocks (mainly sandstones, but also chalk and carbonates). They may act as barriers or privileged migration routes for fluids (e.g. hydrocarbons, water) in rocks. However, to significantly influence the petrophysical parameters of the rock, the ratio of their permeability to the permeability of the host rock should be at least 1:1000. This does not mean that deformation bands have no effect on the flow of fluids in rocks. Instead, their role mainly depends on microstructural features, and they are also considered in reservoir modeling.

Funding: This research was funded by the AGH University of Krakow subsidy No. 16.16.190.779 (Faculty of Drilling, Oil and Gas, Department of Petroleum Engineering).

References

[1] Fossen H., Schultz R.A., Shipton Z. K., Mair K.: *Deformation bands in sandstone: A review*. Journal of the Geological Society, vol. 164, 2007, pp. 755–769. https://doi.org/10.1144/0016-76492006-036

[2] Fossen H.: *Structural Geology*. Cambridge University Press, Cambridge, United Kingdom, 2016.

[3] Wennberg P.O., Casini G., Jahanpanah A., Lapponi F., Ineson J., Graham Wall B., Gillespie P.: *Deformation bands in chalk, examples from the Shetland Group of the Oseberg Field, North Sea, Norway*. Journal of Structural Geology, vol. 56, 2013, pp. 103–117. https://doi.org/10.1016/j.jsg.2013.09.005

[4] Cilona A., Baud P., Tondi E., Agosta F., Vinciguerra S., Rustichelli A., Spiers C.J.: *Deformation bands in porous carbonate grainstones: Field and laboratory observations*. Journal of Structural Geology, vol. 45, 2012, pp. 137–157. https://doi.org/10.1016/j.jsg.2012.04.012

[5] Rotevatn A., Thorsheim E., Bastesen E., Fossmark H.S.S., Torabi A., Sælen G.: *Sequential growth of deformation bands in carbonate grainstones in the hanging wall of an active growth fault: Implications for deformation mechanisms in different tectonic regimes*. Journal of Structural Geology, vol. 90, 2016, pp. 27–47. https://doi.org/10.1016/j.jsg.2016.07.003

[6] Antonellini M., Aydin A.: *Effect of faulting on fluid flow in porous sandstones: Geometry and spatial distribution*. AAPG Bulletin, vol. 79, 1995, pp. 642–671. https://doi.org/10.1306/8D2B1B60-171E-11D7-8645000102C1865D

[7] Antonellini M., Aydin A.: *Effect of faulting on fluid flow in porous sandstones: petrophysical properties*. AAPG Bulletin, vol. 78, 1994, pp. 355–377. https://doi.org/10.1306/BDFF90AA-1718-11D7-8645000102C1865D

[8] Antonellini M., Aydin A., Orr L.: *Outcrop-Aided Characterization of a Faulted Hydrocarbon Reservoir: Arroyo Grande Oil Field, California, USA*. In: Haneberg W.C., Mozley P.S., Moore C.J., Goodwin L.B. (eds), *Faults and Subsurface Fluid Flow in the Shallow Crust.* Geophysical Monograph Series, vol. 113, American Geophysical Union, Washington 1999, pp. 7–26. https://doi.org/10.1029/GM113p0007

[9] Beach A., Brown J.L., Welbon A.I., Mccallum J.E., Brockbank P., Knott S.: *Characteristics of fault zones in sandstones from NW England: application to fault transmissibility*. In: Meadows N.S., Trueblood S.P., Hardman M., Cowan G. (eds), *Petroleum Geology of the Irish Sea and Adjacent Areas*. Geological Society, Special Publications, vol. 124, The Geological Society, London 1997, pp. 315–324. https://doi.org/10.1144/GSL.SP.1997.124.01.19

[10] Fossen H., Bale A.: *Deformation bands and their influence on fluid flow*. AAPG Bulletin, vol. 91, no. 12, 2007, pp. 1685–1700. https://doi.org/10.1306/07300706146

[11] Gabrielsen R.H., Koestler A.G.: *Description and structural implications of fractures in late Jurassic sandstones of the Troll Field, northern North Sea*. Norsk Geologisk Tidsskrift, vol. 67, 1987, pp. 371–381.

[12] Gibson R.G.: *Physical character and fluid-flow properties of sandstone derived fault zones*. In: Coward M.P., Johnson H., Daltaban T.S. (eds), *Structural Geology in Reservoir Characterization*. Geological Society, Special Publications, vol. 127, The Geological Society, London 1998, pp. 83–97.

[13] Hesthammer J., Fossen H.: *Uncertainties associated with fault sealing analysis*. Petroleum Geoscience, vol. 6, 2000, pp. 37–45. https://doi.org/10.1144/petgeo.6.1.37

[14] Heynekamp M.R., Goodwin L.B., Mozley P.S, Haneberg W.C.: *Controls on fault zone architecture in poorly lithified sediments, Rio Grande Rift, New Mexico: Implications for fault zone permeability and fluid flow*. In: Haneberg W.C., Mozley P.S., Moore C.J., Goodwin L.B. (eds), *Faults and Subsurface Fluid Flow in the Shallow Crust*. Geophysical Monograph Series, vol. 113, American Geophysical Union, vol. 113, Washington 1999, pp. 27–49. https://doi.org/10.1029/GM113p0027.

[15] Jamison W.R., Stearns D.W.: *Tectonic deformation of Wingate Sandstone, Colorado National Monument*. AAPG Bulletin, vol. 66, 1982, pp. 2584–2608. https://doi.org/10.1306/03B5AC7D-16D1-11D7-8645000102C1865D

[16] Knipe R.J., Fisher Q.J., Clennell M.R. et al.: *Fault seal analysis: successful methodologies, application and future directions*. In: Møller Pedersen P., Koestler A.G. (eds), *Hydrocarbon Seals: Importance for Exploration and Production*. Norwegian Petroleum Society Special Publication, vol. 7, Elsevier, Amsterdam 1997, pp. 15–40. https://doi.org/10.1016/S0928-8937(97)80004-5.
[17] Lothe A.E., Gabrielsen R.H., Bjørnevoll Hagen N., Larsen B.T.: *An experimental study of the texture of deformation bands: effects on the porosity and permeability of sandstones*. Petroleum Geoscience, vol. 8, 2002, pp. 195–207. https://doi.org/10.1144/petgeo.8.3.195.
[18] Parnell J., Watt G.R., Middleton D., Kelly J., Baron M.: *Deformation band control on hydrocarbon migration*. Journal of Sedimentary Research, vol. 74, no. 4, 2004, pp. 552–560. https://doi.org/10.1306/121703740552.
[19] Pittman E.D.: *Effect of Fault-Related Granulation on Porosity and Permeability of Quartz Sandstones, Simpson Group (Ordovician), Oklahoma*. AAPG Bulletin, vol. 65, no. 11, 1981, pp. 238–2387. https://doi.org/10.1306/03B5999F-16D1-11D7-8645000102C1865D.
[20] Rotevatn A., Sandve T.H., Keilegavlen E., Kolyukhin D., Fossen H.: *Deformation bands and their impact on fluid flow in sandstone reservoirs: the role of natural thickness variations*. Geofluids, vol. 13, iss. 3, 2013, pp. 359–371. https://doi.org/10.1111/gfl.12030.
[21] Sample J.C., Woods S., Bender E., Loveall M.: *Relationship between deformation bands and petroleum migration in an exhumed reservoir rock, Los Angeles Basin, California, USA*. Geofluids, vol. 6, iss. 2, 2006, pp. 105–112. https://doi.org/10.1111/j.1468-8123.2005.00131.x.
[22] Shipton Z.K., Evans J.P., Robeson K., Forster C.B., Snelgrove S.: *Structural heterogeneity and permeability in faulted eolian sandstone: implications for subsurface modelling of faults*. AAPG Bulletin, vol. 86, no. 5, 2002, pp. 863–883. https://doi.org/10.1306/61EEDBC0-173E-11D7-8645000102C1865D.
[23] Shipton Z.K., Evans J.P., Thompson L.B.: *The geometry and thickness of deformation-band fault core and its influence on sealing characteristics of deformation-band fault zones*. In: Sorkhabi R., Tusuji Y. (eds), *Faults, Fluid Flow, And Petroleum Traps*. AAPG Memoir, vol. 85, American Association of Petroleum Geologists, Tulsa, Oklahoma 2005, pp. 181–195.
[24] Taylor W.L., Pollard D.D.: *Estimation of in situ permeability of deformation bands in porous sandstone, Valley of Fire, Nevada*. Water Resources Research, vol. 36, no. 9, 2000, pp. 2595–2606. https://doi.org/10.1029/2000WR900120.
[25] Zhang H.: *Fluid flow through deformation band*. Master Theses, no. 7577, 2016. https://scholarsmine.mst.edu/masters_theses/7577.
[26] Brown N., Duckett R.A., Ward I.M.: *Deformation bands in polyethylene terephtalate*. Journal of Physics D: Applied Physics, vol. 1, no. 10, 1968, pp. 1369–1379. https://doi.org/10.1088/0022-3727/1/10/317.
[27] Aydin A.: *Small faults formed as deformation bands in sandstone*. Pure and Applied Geophysics, vol. 116, 1978, pp. 913–930. https://doi.org/10.1007/BF00876546.
[28] Aydin A., Johnson A.M.: *Development of faults as zones of deformation bands and as slip surfaces in sandstones*. Pure and Applied Geophysics, vol. 116, 1978, pp. 913–930. https://doi.org/10.1007/BF00876547.
[29] Antonellini M.A., Aydin A., Pollard D.D.: *Microstructure of deformation bands in porous sandstones at Arches National Park, Utah*. Journal of Structural Geology, vol. 16, iss. 7, 1994, pp. 941–959. https://doi.org/10.1016/0191-8141(94)90077-9.
[30] Ballas G., Fossen H., Soliva R.: *Factors controlling permeability of cataclastic deformation bands and faults in porous sandstone reservoirs*. Journal of Structural Geology, vol. 76, 2015, pp. 1–21. https://doi.org/10.1016/j.jsg.2015.03.013.
[31] Exner U., Kaiser J., Gier S.: *Deformation bands evolving from dilation to cementation bands in a hydrocarbon reservoir (Vienna Basin, Austria)*. Marine and Petroleum Geology, vol. 43, 2013, pp. 504–515. https://doi.org/10.1016/j.marpetgeo.2012.10.001.
[32] Del Sole L., Antonellini M., Soliva R., Ballas G., Balsamo F., Viola G.: *Structural control on fluid flow and shallow diagenesis: insights from calcite cementation along deformation bands in porous sandstones*. Solid Earth, vol. 11, 2020, pp. 2169–2195, https://doi.org/10.5194/se-11-2169-2020.
[33] Parnell J., Watt G.R., Middleton D., Kelly J., Baron M.: *Deformation band control on hydrocarbon migration*. Journal of Sedimentary Research, vol. 74, 2004, pp. 552–560.
[34] Tondi E., Antonellini M., Aydin A., Marchegiani L., Cello G.: *The role of deformation bands, stylolites and sheared stylolites in fault development in carbonate grainstones of Majella Mountain, Italy*. Journal of Structural Geology, vol. 28, iss. 3, 2006, pp. 376–391. https://doi.org/10.1016/j.jsg.2005.12.001.
[35] Świerczewska A., Tokarski A.K.: *Deformation bands and the history of folding in the Magura nappe, Western Outer Carpathians (Poland)*. Tectonophysics, vol. 297, iss. 1–4, 1998, pp. 73–90. https://doi.org/10.1016/S0040-1951(98)00164-4.

[36] Haczewski G., Kukulak J., Bąk K.: *Budowa geologiczna i rzeźba Bieszczadzkiego Parku Narodowego*. Wydawnictwo Naukowe Akademii Pedagogicznej, Kraków 2007.
[37] Solecki M.: *Rola mikrostruktur tektonicznych w zapisie migracji węglowodorów w skałach płaszczowiny śląskiej w dolinie potoku Wołosatego (Bieszczady)*. Master thesis, KSE WGGiOŚ AGH Archive, Kraków 2012.
[38] Matthäi S.K., Aydin A., Pollard D.D., Roberts S.G.: *Numerical simulation of departures from radial drawdown in a faulted sandstone reservoir with joints and formation bands*. In: Jones G., Fisher Q.J., Knipe R.J. (eds), *Faulting, Fault Sealing and Fluid Flow in Hydrocarbon Reservoirs*. Geological Society, Special Publications, vol. 147, The Geological Society, London 1998, pp. 157–191. https://doi.org/10.1144/GSL.SP.1998.147.01.11.
[39] Walsh J.J., Watterson J., Health A.E., Childs C.: *Representation and scaling of faults in fluid flow models*. Petroleum Geoscience, vol. 4, 1998, pp. 241–251. https://doi.org/10.1144/petgeo.4.3.241.
[40] Harper T.R., Moftah I.: *Skin Effect and Completion Options in the Ras Budran Reservoir*. In: *Middle East Oil Technical Conference and Exhibition: March 11–14, 1985, Bahrain*, SPE-13708-MS, Society of Petroleum Engineers, 1985, pp. 211–226.
[41] Sternlof K.R., Chapin J.R, Pollard D.D., Durlofsky L.J.: *Permeability effects of deformation bands arrays in sandstone*. AAPG Bulletin, vol. 88, no. 9, 2004, pp. 1315–1329.
[42] Qu D., Tveranger J.: *Incorporation of deformation band fault damage zones in reservoir models*. AAPG Bulletin, vol. 100, no. 3, 2016, pp. 423–443. https://doi.org/10.1306/12111514166.
[43] Aleksandrowski P.: *Step-like tectonic lineation in the Magura flysch (Western Outer Carpathians)*. Annales Societatis Geologorum Poloniae, vol. 50, no. 3–4, 1980, pp. 329–339.
[44] Świerczewska A., Tokarski A.K.: *Deformation development of a flysch sandstone, Outer Carpathians (Poland): from water escape structures to brittle faults*. In: *Abstracts: 30th International Geological Congress, Beijing, China, 4–14 August 1996. Vol. 2*, 1996, p. 269.
[45] Tokarski A.K., Świerczewska A., Banaś M.: *Deformation bands and early folding in Lower Eocene flysch sandstone, Outer Carpathians, Poland*. In: Rossmanith H.-P. (ed.), *Mechanics of Jointed and Faulted Rock*. Balkema, Rotterdam 1995, pp. 323–327.
[46] Nescieruk P., Wójcik A., Malata T., Aleksandrowski P.: *Tektoniczne struktury deformacyjne w iłach krakowieckich sarmatu w Wylewie k. Sieniawy (zapadlisko przedkarpackie): świadectwo młodej przesuwczej aktywności podłoża miocenu*. Przegląd Geologiczny, vol. 55, no. 8, 2007, pp. 690–698.
[47] Strzelecki P.J., Solecki M.L.: *Wpływ mikrotekstury i procesu kwasowania skały na jej parametry zbiornikowe: studium przypadku piaskowców krośnieńskich z rejonu Dwernika, Bieszczady* [*The influence of rock microtexture and acidizing on reservoir properties: a case study of the Krosno Sandstones from Dwernik, Bieszczady Mts.*]. Przegląd Geologiczny, vol. 69, nr 7, 2021, pp. 454–457. https://doi.org/10.7306/2021.30.
[48] Strzelecki P.J., Świerczewska A.: *Wpływ więźby skały na mechanizm deformacji: studium przypadku wstęg deformacyjnych w piaskowcach otryckich (Bieszczady)* [*The impact of rock fabric on deformation: a case study of deformation bands in the Otryt sandstone (Bieszczady Mountains, SE Poland)*]. Przegląd Geologiczny, vol. 71, 2023, pp. 231–234. https://doi.org/10.7306/2023.20
[49] Strzelecki P., Świerczewska A.: *Pure compaction bands in the naturally deformed flysch sandstones of the Silesian Nappe (SE Poland): early markers of tectonic shortening*. EGU General Assembly, 2023, EGU23-14083, https://doi.org/10.5194/egusphere-egu23-14083
[50] Strzelecki P.J., Świerczewska A., Tokarski A.K.: *Structural Evolution of the Eastern Part of the Silesian Nappe Recorded in Deformation Bands, Polish Segment of the Outer Carpathians*. Geology, Geophysics & Environment, vol. 44, no. 1, 2018, p. 196.
[51] Strzelecki P.J., Świerczewska A., Tokarski A.K.: *Do Deformation Bands Record the Early Onset of Backthrusting?: Insights from the Inner Part of the Silesian Nappe (outer Western Carpathians, Poland)*. In: Hrdličková K., Daňková L. (eds), *CETEG 2019: 17th Meeting of the Central European Tectonic Groups: Rozdrojovice, 24–27 April, 2019: Abstract Volume*. Czech Geological Survey, Prague 2019, pp. 79–80.