Beyond fractures: the role of bedding planes in fluid flow pathways within a well-bedded carbonate sequence

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Key Points:

- Bedding planes can significantly contribute to horizontal fluid flow
- Fracture networks alone might be insufficient for predicting subsurface fluid behavior
- Integrating both fractures and bedding planes can improve fluid flow models, enhancing reservoir management and waste disposal strategies

Abstract

Conventionally, subsurface fluid flow modelling studies have concentrated on the characterization of fracture networks and their capacity to facilitate vertical and lateral fluid movements. This study utilizes unique field observations of oxidation halos in a well-bedded carbonate sequence in the Paris Basin, France, offering new perspectives on fluid flow pathways. It demonstrates that, in addition to fractures, bedding planes also serve as critical conduits for horizontal fluid flow. This research highlights the importance of integrating both fractures and bedding planes to assess connectivity and therefore improve fluid flow models, especially in sedimentary basins. This approach is vital for geoscience and engineering applications, including reservoir management and waste disposal strategies.

1 Introduction

In tightly cemented sedimentary rocks, fractures are widely recognized as the primary conduits for fluid flow, especially in environments where matrix permeability is low (Nelson, 1985). Consequently, common approaches to predicting subsurface fluid migration have predominantly focused on characterizing fracture networks (Bourbiaux, 2010; De Dreuzy et al., 2012; Lei et al., 2017). Conventionally, outcrop-scale data is utilized to inform larger-scale subsurface flow models by assessing the geometric and topological properties of these fracture networks (Odling et al., 1999; Agosta et al., 2010; Sanderson and Nixon, 2015; Wennberg et al., 2016; Lei et al., 2017). These properties, typically measured directly at the outcrop scale, help estimate the extent and scaling of these networks in the subsurface, thereby constraining flow properties (Wilson et al., 2011; Zhu et al., 2021).

However, this well-established approach assumes that subsurface fluid flow is primarily accommodated by fracture networks, which predominantly facilitate vertical and lateral fluid movements. Consequently, it often neglects the potential for horizontal fluid movements that could be facilitated, for example, by bedding planes—stratigraphic layers and/or interfaces between layers. This neglect is largely due to the challenges associated with identifying these horizontal fluid flow pathways, leading to an exclusive focus on fractures as the main conduits for fluid flow.

The primary goal of this study is to highlight the often-overlooked importance of bedding planes in fluid flow. Field observations from an exceptional exposure of oxidation halos within a well-bedded carbonate sequence in the Paris Basin, France, provide critical insights into past fluid flow pathways. Results suggest that bedding planes also play a crucial role as pathways, and their interaction with sub-vertical fractures enhance the overall connectivity of fluid systems. This finding highlights the necessity of integrating both fractures and bedding planes into subsurface fluid flow models, especially in well-bedded sedimentary sequences. Incorporation of bedding planes into flow models can therefore improve our understanding of subsurface fluid dynamics, which is essential for various geoscientific and engineering applications, including efficient reservoir management and waste disposal strategies (e.g., Bear et al., 2012).

2 Data and Methodology

The study is based on an outcrop exposure within the Sommerécourt quarry at the eastern Paris Basin, France. The Paris Basin is an intracratonic basin that experienced multiple episodes of subsidence and sedimentation during the Mesozoic (Pomerol, 1978; Mégnien, 1980). This study focuses on the Dogger Formation, primarily composed of limestone and marl, deposited during the Middle Jurassic and marking a transition from marine transgression to more restricted lagoonal conditions (e.g., Brigaud et al., 2009). The formation is extensively studied for its petroleum potential and geothermal resources in the Paris Basin (e.g., Lopez et al., 2010) and its western continuation in the Upper Rhine Graben (e.g., Böcker et al., 2017).

On a more regional scale, the outcrop is located approximately 200 meters north of the E-W striking Vittel fault, which forms part of the extensive Variscan Wight-Bray-Vittel megastructure, extending over 700 km from the Bristol Channel to eastern France. This major tectonic structure was reactivated during the Meso-Cenozoic period (Bergerat et al., 2007) and has been reported as a major corridor for paleo-circulation of geothermal fluids within the Paris Basin, facilitating connections between the Dogger and Triassic reservoirs (Bril et al., 1994).

In the studied outcrop, fractures exhibit approximately NW-SE strikes, with an average dip of 80˚, while the bedding planes are nearly horizontal, dipping on average 3˚ towards the NNE (as shown in the inset in Figure 1). Oxidation halos, which serve as key indicators of past fluid flow, are observed surrounding both fractures and bedding planes (Figure 1). To enhance the examination of these halos, field observations were supplemented with image processing techniques to improve their visibility. A virtual outcrop model (VOM) and a 2D orthorectified image of the quarry working face were created from digital images collected by an unmanned aerial vehicle (UAV). Subsequently, Inkscape software was used to apply a fluorescence filter to increase the contrast between the halos and the surrounding rock matrix, allowing for the detection of subtle oxidation variations that might otherwise go unnoticed. Additionally, a saturation map filter was used to adjust colour intensities, further enhancing the clarity of the halos. These image manipulations, combined with adjustments to contrast and brightness, enabled more precise identification of the halos and allowed for detailed mapping of both fractures and bedding planes that facilitated past fluid flow (Figures 1 and 2).

The resulting maps were used to analyse the connectivity and estimate the intensity and density of fractures and bedding planes. Connectivity analysis involved mapping the spatial distribution of three node types, as defined by Manzocchi (2002): isolated tips (I-nodes), crossing fractures/bedding planes (X-nodes), and abutments or splays (Y-nodes). The terminology by Dershowitz and Herda (1992) is followed for the intensity of fractures and/or bedding planes (P21), which is defined as the length per unit area, and their density (P20), which is defined as the number of features per unit area. These metrics were calculated using the method of Mauldon et al. (2001) and implemented with FracPaq v. 2.8 (Healy et al., 2017).

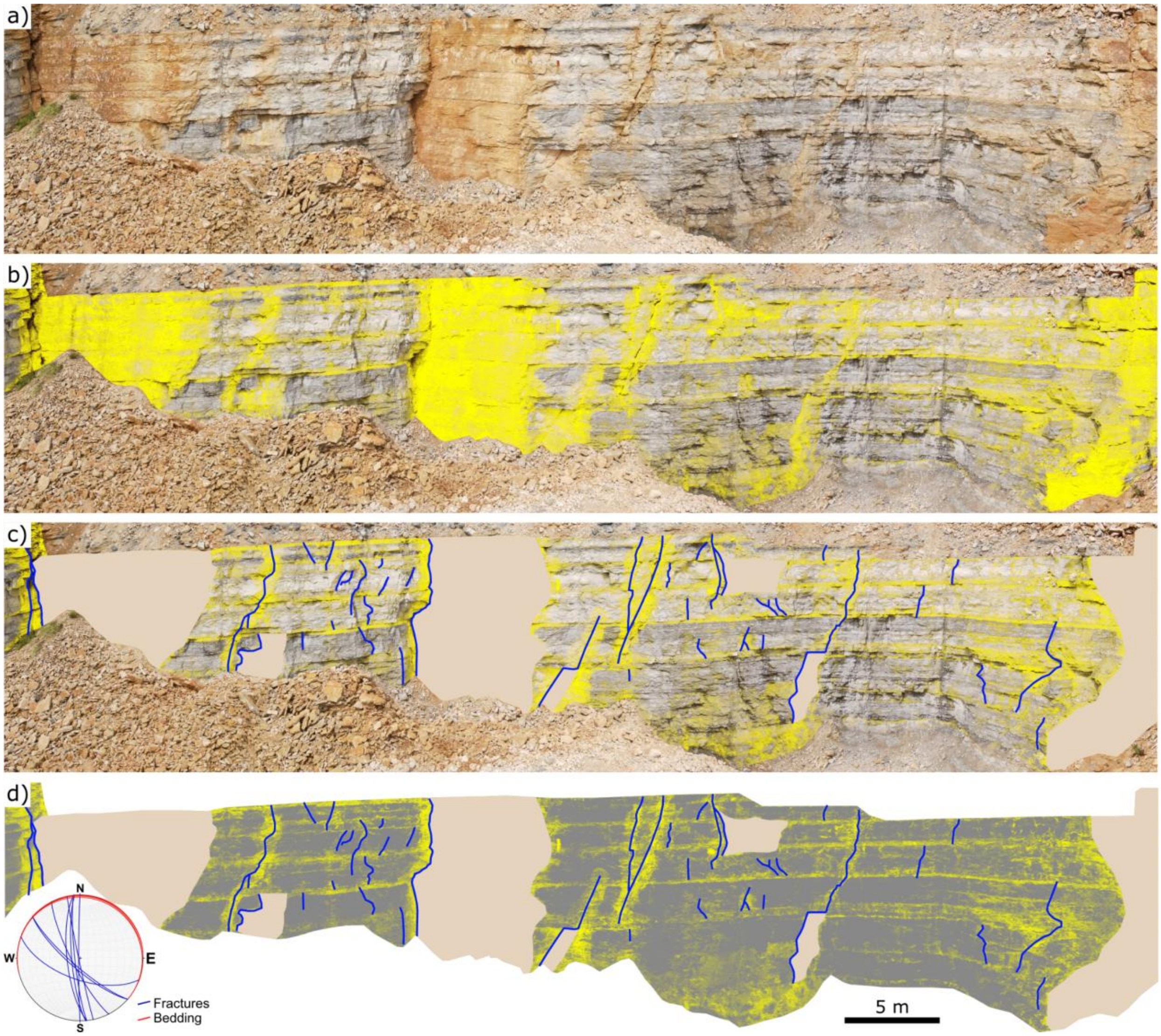

Figure 1. (a) Panoramic view of the studied outcrop. (b) Image processing enhances the visibility of oxidation halos, highlighted in yellow. (c) Fracture traces are shown in blue, while fracture surfaces are marked in brown. (d) Same as (c), but without the original image background. The inset shows the orientation of fractures and bedding planes as great circles on a lower hemisphere, equal-area projection.

3 Results

This section highlights the critical importance of integrating both fractures and bedding planes when analyzing fluid flow in sedimentary formations. Figure 2 (a and b) presents connectivity maps comparing two different scenarios: (a) fractures only, and (b) both fractures and bedding planes. These maps clearly demonstrate a marked increase in connectivity when bedding planes are considered alongside fractures. Furthermore, Figure 2c shows a ternary plot based on I-Y-X connectivity analysis (Manzocchi, 2002), comparing the fracture network alone (from Figure 2a) with the combined network of fractures and bedding planes (from Figure 2b). Networks showing improved connectivity are positioned towards the base of the triangle, indicating a higher proportion of X and Y nodes. This shift towards the base in the combined network plot highlights the enhanced connectivity provided by bedding planes, demonstrating quantitatively how their inclusion can lead to more efficient fluid flow within the well-bedded sedimentary sequence. This enhanced connectivity not only supplements the vertical pathways provided by fractures but also introduces vital horizontal routes that could facilitate broader fluid distribution across the formation. This effectively links isolated fractures, turning bedding planes into critical conduits that increase overall system connectivity. It is worth noting, however, that the aforementioned connectivity properties of the fracture network primarily reflect only the vertical direction, influenced by the nature of the available data (e.g., cross-sectional view of the quarry face). However, given the measured orientations of fractures (as shown in the inset of Figure 1), the fracture network is expected to exhibit lateral connectivity, which would further facilitate lateral fluid movements.

Maps of the estimated intensity and density of (a) fractures only and (b) both fractures and bedding planes are presented in Figure 3. These maps indicate that areas with combined fracture and bedding plane networks have higher P21 and P20 values, suggesting a denser and potentially more permeable structure conducive to fluid migration. These parameters are crucial as they directly influence the fluid flow properties of the formation, with higher values generally indicative of increased potential for fluid storage and transport. Complementing the connectivity maps shown in Figure 2, these P21 and P20 maps further demonstrate how apparently isolated fracture corridors become interconnected through fluid flow along the bedding planes.

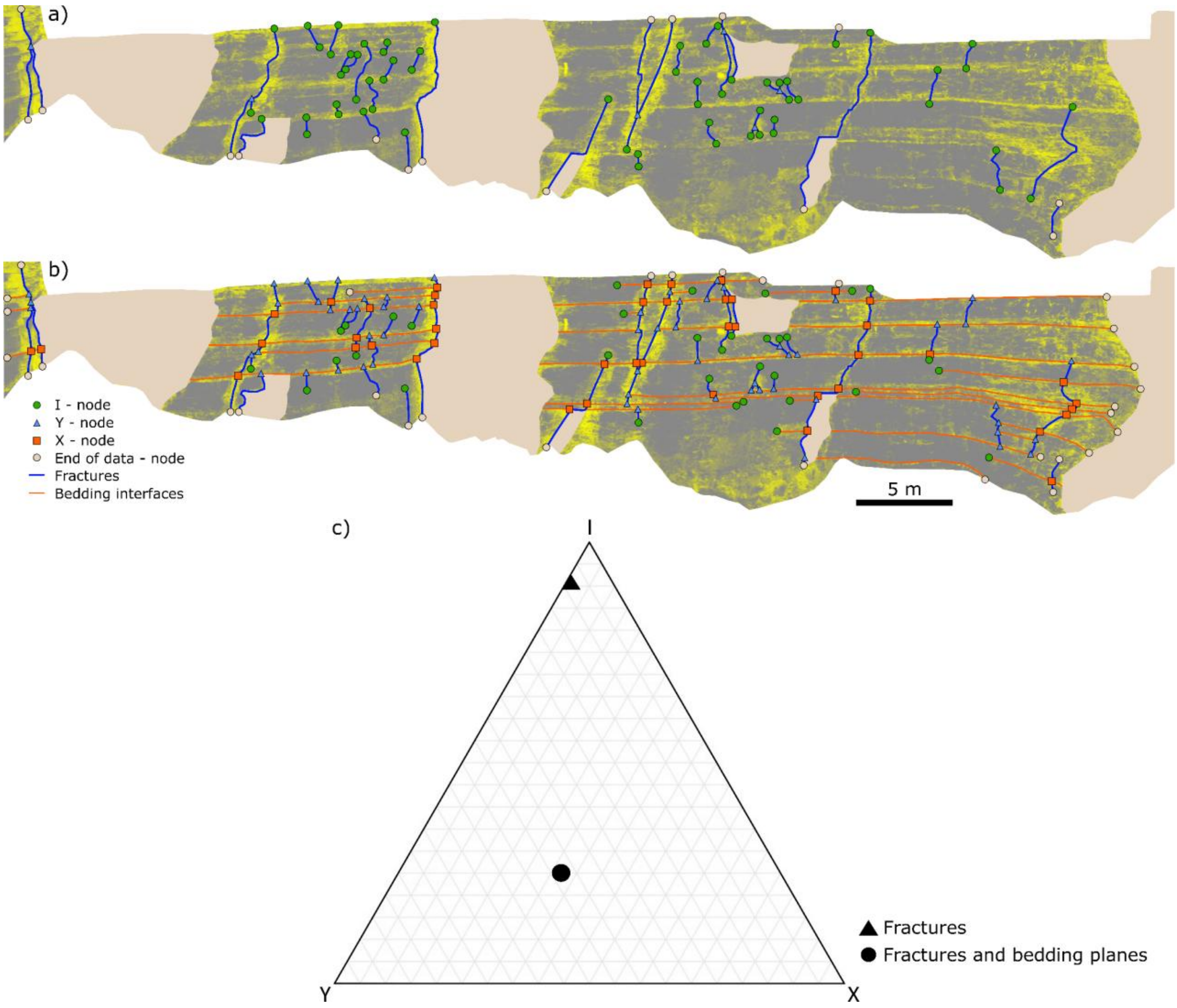

Figure 2. Connectivity maps showing the spatial distribution of different node types (I, Y and X) for (a) fractures only, and (b) both fractures and bedding planes at the studied outcrop. (c) Ternary plot of I-Y-X connectivity analysis (Manzocchi, 2002) comparing the fracture network alone (as in a) with the combined fracture and bedding plane network (as in b) at the studied outcrop. Better-connected networks are plotted toward the base of the triangle indicating a higher proportion of X and Y nodes.

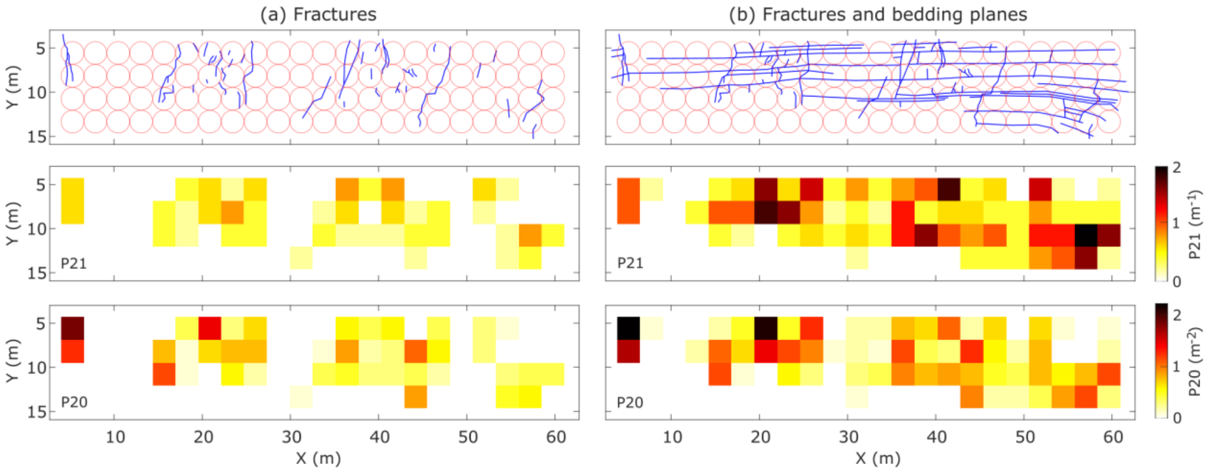

Figure 3. Estimated fracture intensity (P21) and fracture density (P20) maps for (a) fractures only, and (b) both fractures and bedding planes at the studied outcrop. Fracture traces and fracture plus bedding plane traces (depicted in blue) are shown at the top, indicating the locations of the scan circles used to estimate intensity (m^{-1}) and density (m^{-2}).

While this study demonstrates that bedding planes can serve as horizontal pathways for fluid flow, they also have the capacity to restrict both fracture propagation and associated vertical fluid movements. In Figure 4, the fracture on the right and its associated oxidation halo terminate abruptly at a bedding plane, acting as a barrier to fluid migration below this plane and to downward fracture propagation. Despite this abrupt termination, the presence of the halo along the corresponding bedding plane indicates fluid flow along it, resulting in a Y-node connection as shown in Figure 2. Conversely, the fracture on the left is not restricted by any bedding plane, and its associated halo gradually terminates upwards, becoming well-rounded at the fracture tip. These observations, further highlight the well-documented influence of mechanical stratigraphy on fracture propagation across different bedding planes (e.g., Renshaw and Pollard, 1995; McGinnis et al., 2017), illustrating the complex interplay between bedding planes, fracture growth, and fluid dynamics.

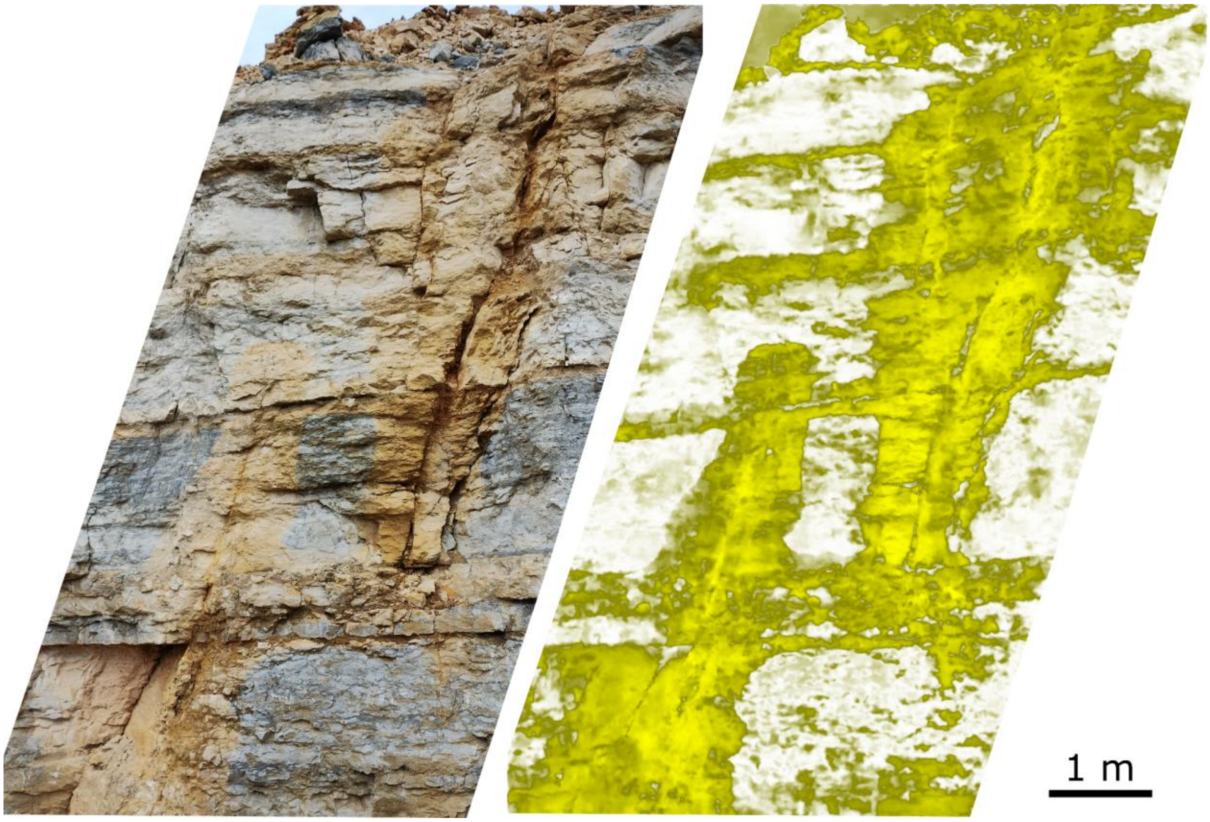

Figure 4. Close-up photograph of the outcrop on the left, and the same image after processing to enhance the visibility of oxidation halos, which are highlighted in yellow on the right.

4 Discussion

4.1 Factors controlling fluid flow along bedding planes

Through semi-quantitative analysis involving geometrical and topological assessments, this study demonstrates that bedding planes not only complement the vertical and lateral fluid pathways provided by fractures but also significantly enhance system connectivity through horizontal routes.

Previous research on fluid flow along bedding planes, although less common than studies on fractures, primarily focuses on phenomena such as karstification and cave genesis (Cooke et al., 2006; Filipponi et al., 2010; Sauro et al., 2013; Frumkin et al., 2017; Roded et al., 2024). For example, Filipponi et al. (2010) identified three distinct types of inception horizons that promote cave development and, consequently, concentrate fluid flow. These types are differentiated by differences in permeability and the presence of fractures along bedding interfaces. Additionally, Sauro et al. (2013) reported that flexural slip surfaces between beds are particularly conducive to the development of conduits and deep karst systems. In another study focusing on hydrocarbon migration, Noufal and Obaid (2017) noted that sheared bedding planes acted as primary corridors in the migration of hydrocarbons within Abu Dhabi's sedimentary basins. Furthermore, Skurtveit et al. (2021) found that the fractures along bedding interfaces and the petrophysical properties of the rock sequence-controlled layer-parallel CO2 migration away from fault zones, which serve as the main pathways for CO2 migration in Humbug Flats, Utah, USA. A recurrent theme in all these studies is the role of shearing and fracturing along bedding interfaces in promoting bed-parallel fluid flow. Given that bed-parallel shearing is quite commonly observed in both compressional (e.g., Sanderson, 1982; Tanner, 1989) and extensional (e.g., Delogkos et al., 2022) tectonic settings, it is plausible that such shearing can also enhance fluid flow along these bedding planes.

Other factors reported to promote fluid flow along bedding planes include differences in the petrophysical properties between different layers such as permeability (e.g., Filipponi et al., 2010) and sedimentological processes. For example, Cooke et al. (2006) concluded that continuous flow along bedding planes may promote dissolution, which over time could lead to development of regionally extensive, bed-parallel, high-permeability features. Frumkin et al. (2017) also observed that bedding planes can initially have sub-millimetre to sub-centimetre width, which subsequently increases due to dissolution enlargement. Furthermore, Golab et al. (2017) reported that bioturbation-influenced porosity enhances horizontal fluid flow within a carbonate platform system in otherwise low porosity and permeability sediments. Finally, it is worth mentioning that horizontal fluid flow pathways can be highly variable in three dimensions due to the inherent variability of petrophysical and sedimentological properties. Thomas et al. (2021) demonstrated the presence of such three-dimensional heterogeneities of facies, porosity, and permeability within the Middle Jurassic carbonate reservoirs in Paris Basin.

In the studied area, the factors controlling fluid flow along these bedding planes have not yet been identified. Therefore, future work should aim to determine these factors, and to clarify the timing, depth, and nature of the involved fluids. Additionally, the presence of karstification in the examined area is noteworthy as it can significantly influence subsurface fluid flow by potentially complicating pre-existing pathways and enhancing permeability and connectivity (e.g., Moore and Walsh, 2021). This highlights the complex, multifaceted nature of fluid flow in the subsurface and emphasizes the necessity of integrating various geological features and processes in subsurface flow modelling - an aspect often underestimated in prior studies.

4.2 Implications

The insights gained from this study have significant implications for various subsurface activities. Models that focus exclusively on fractures may underestimate fluid storage and transport potential, potentially leading to suboptimal decisions in reservoir management or waste disposal. By incorporating bedding planes into fluid flow models, predictions of fluid movement in reservoirs and aquifers can become more accurate, which is crucial for effective resource extraction, including groundwater, geothermal energy, and hydrocarbons, and environmental management, such as carbon capture and storage (CCS) and contamination control. For example, in geothermal energy production, understanding the dual role of fractures and bedding planes can refine recovery strategies by optimizing well placements and enhancing recovery methods. This is particularly valuable for the Paris Basin, known for its geothermal energy resources, as well as for other basins where the Dogger Formation is present and exhibits high geoenergy potential, such as the Upper Rhine Graben. Furthermore, the findings of this study can contribute to a deeper understanding of fundamental geological processes such as karstification, speleogenesis, and diagenesis, advancing our knowledge of their development and distribution.

5 Conclusions

The examination of the exceptionally well exposed oxidation halos within the well-bedded carbonate sequence in the Paris Basin, France, reveals that subsurface fluid flow is more complex than previously understood. This study demonstrates that fluids can preferentially flow horizontally along bedding planes, complementing vertical and lateral flows along fracture networks. Bedding planes thus can act as critical conduits for fluid migration, especially in regions with low fracture density or poorly connected fractures. This challenges the conventional focus solely on fractures and highlights the need for bedding planes to be more thoroughly considered in fluid flow models.

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Open Research - Availability Statement

A textured 3D virtual outcrop model (VOM) of the studied outcrop is available for exploration and download on the Sketchfab repository at: https://skfb.ly/pqSwC.

References

Agosta, F., Alessandroni, M., Antonellini, M., Tondi, E. and Giorgioni, M., 2010. From fractures to flow: A field-based quantitative analysis of an outcropping carbonate reservoir. Tectonophysics, 490(3-4), pp.197-213.

Bear, J., Tsang, C.F. and De Marsily, G., 2012. Flow and contaminant transport in fractured rock. Academic Press.

Bergerat, F., Elion, P., De Lamotte, D.F., Proudhon, B., Combes, P., André, G., Willeveau, Y., Laurent-Charvet, S., Kourdian, R., Lerouge, G. and d'Estevou, P.O., 2007. 3D multiscale structural analysis of the eastern Paris basin: the Andra contribution. Mém. Soc. Géol. France, 178, pp.15-35.

Böcker, J., Littke, R. and Forster, A., 2017. An overview on source rocks and the petroleum system of the central Upper Rhine Graben. International Journal of Earth Sciences, 106, pp.707-742.

Bourbiaux, B., 2010. Fractured reservoir simulation: a challenging and rewarding issue. Oil & Gas Science and Technology–Revue de l’Institut Français du Pétrole, 65(2), pp.227-238.

Brigaud, B., Durlet, C., Deconinck, J. F., Vincent, B., Pucéat, E., Thierry, J., & Trouiller, A. (2009). Facies and climate/environmental changes recorded on a carbonate ramp: a sedimentological and geochemical approach on Middle Jurassic carbonates (Paris Basin, France). Sedimentary Geology, 222(3-4), 181-206.

Bril, H., Velde, B., Meunier, A. and Iqdari, A., 1994. Effects of the “pays de bray” fault on fluid paleocirculations in the Paris basin dogger reservoir, France. Geothermics, 23(3), pp.305-315.

Cooke, M.L., Simo, J.A., Underwood, C.A. and Rijken, P., 2006. Mechanical stratigraphic controls on fracture patterns within carbonates and implications for groundwater flow. Sedimentary Geology, 184(3-4), pp.225-239.

De Dreuzy, J.R., Méheust, Y. and Pichot, G., 2012. Influence of fracture scale heterogeneity on the flow properties of three-dimensional discrete fracture networks (DFN). Journal of Geophysical Research: Solid Earth, 117(B11).

Delogkos, E., Roche, V. and Walsh, J.J., 2022. Bed-parallel slip associated with normal fault systems. Earth-Science Reviews, 230, p.104044.

Dershowitz, W.S. and Herda, H.H., 1992, June. Interpretation of fracture spacing and intensity. In ARMA US rock mechanics/geomechanics symposium (pp. ARMA-92). ARMA.

Filipponi, M., Jeannin, P.Y. and Tacher, L., 2010. Understanding cave genesis along favourable bedding planes. The role of the primary rock permeability. Zeitschrift für Geomorphologie. Supplementband, 54(2), p.91.

Frumkin, A., Langford, B., Lisker, S. and Amrani, A., 2017. Hypogenic karst at the Arabian platform margins: Implications for far-field groundwater systems. Bulletin, 129(11-12), pp.1636-1659.

Golab, J.A., Smith, J.J., Clark, A.K. and Morris, R.R., 2017. Bioturbation-influenced fluid pathways within a carbonate platform system: the Lower Cretaceous (Aptian–Albian) Glen Rose Limestone. Palaeogeography, Palaeoclimatology, Palaeoecology, 465, pp.138-155.

Healy, D., Rizzo, R.E., Cornwell, D.G., Farrell, N.J., Watkins, H., Timms, N.E., Gomez-Rivas, E. and Smith, M., 2017. FracPaQ: A MATLAB™ toolbox for the quantification of fracture patterns. Journal of Structural Geology, 95, pp.1-16.

Lei, Q., Latham, J.P. and Tsang, C.F., 2017. The use of discrete fracture networks for modelling coupled geomechanical and hydrological behaviour of fractured rocks. Computers and Geotechnics, 85, pp.151-176.

Lopez, S., Hamm, V., Le Brun, M., Schaper, L., Boissier, F., Cotiche, C. and Giuglaris, E., 2010. 40 years of Dogger aquifer management in Ile-de-France, Paris Basin, France. Geothermics, 39(4), pp.339-356.

Manzocchi, T., 2002. The connectivity of two-dimensional networks of spatially correlated fractures. Water Resources Research, 38(9), pp.1-1.

Mauldon, M., Dunne, W.M. and Rohrbaugh Jr, M.B., 2001. Circular scanlines and circular windows: new tools for characterizing the geometry of fracture traces. Journal of structural geology, 23(2-3), pp.247-258.

McGinnis, R.N., Ferrill, D.A., Morris, A.P., Smart, K.J. and Lehrmann, D., 2017. Mechanical stratigraphic controls on natural fracture spacing and penetration. Journal of Structural Geology, 95, pp.160-170.

Mégnien, C., 1980. Synthèse géologique du Bassin de Paris, I, Stratigraphie et paléogéographie. In: Mémoires du Bureau de Recherches Géologiques et Minières, vol. 101, 466 pp.

Moore, J.P. and Walsh, J.J., 2021. Quantitative analysis of Cenozoic faults and fractures and their impact on groundwater flow in the bedrock aquifers of Ireland. Hydrogeology Journal, 29(8), pp.2613-2632.

Nelson, R.A., 1985. Geologic analysis of naturally fractured reservoirs (Vol. 1). Gulf Professional Publishing.

Noufal, A. and Obaid, K., 2017, November. Bedding Corridors as Migration Pathways in Abu Dhabi Fields. In Abu Dhabi International Petroleum Exhibition and Conference (p. D011S003R003). SPE.

Odling, N.E., Gillespie, P., Bourgine, B., Castaing, C., Chiles, J.P., Christensen, N.P., Fillion, E., Genter, A., Olsen, C., Thrane, L. and Trice, R., 1999. Variations in fracture system geometry and their implications for fluid flow in fractures hydrocarbon reservoirs. Petroleum Geoscience, 5(4), pp.373-384.

Pomerol, C., 1978. Paleogeographic and structural evolution of the Paris Basin, from the Precambrian to the present day, in relation to neighboring regions. Geologie En Mijnbouw Journal of Geosciences, 57, pp.533-543.

Renshaw, C.E. and Pollard, D.D., 1995, April. An experimentally verified criterion for propagation across unbounded frictional interfaces in brittle, linear elastic materials. In International journal of rock mechanics and mining sciences & geomechanics abstracts (Vol. 32, No. 3, pp. 237-249). Pergamon.

Roded, R., Langford, B., Aharonov, E., Szymczak, P., Ullman, M., Yaaran, S., Lazar, B., Frumkin, A., 2024. Hypogene speleogenesis in carbonates by cooling, confined hydrothermal flow: The case of Mt. Berenike caves, Israel. International Journal of Speleology, 53(2), 191-209.

Sanderson, D.J., 1982. Models of strain variation in nappes and thrust sheets: a review. Tectonophysics, 88(3-4), pp.201-233.

Sanderson, D.J. and Nixon, C.W., 2015. The use of topology in fracture network characterization. Journal of Structural Geology, 72, pp.55-66.

Sauro, F., Zampieri, D. and Filipponi, M., 2013. Development of a deep karst system within a transpressional structure of the Dolomites in north-east Italy. Geomorphology, 184, pp.51-63.

Skurtveit, E., Torabi, A., Sundal, A. and Braathen, A., 2021. The role of mechanical stratigraphy on CO2 migration along faults–examples from Entrada Sandstone, Humbug Flats, Utah, USA. International Journal of Greenhouse Gas Control, 109, p.103376.

Tanner, P.G., 1989. The flexural-slip mechanism. Journal of Structural Geology, 11(6), pp.635-655.

Thomas, H., Brigaud, B., Blaise, T., Saint-Bezar, B., Zordan, E., Zeyen, H., Andrieu, S., Wennberg, O.P., Casini, G., Jonoud, S. and Peacock, D.C., 2016. The characteristics of open fractures in carbonate reservoirs and their impact on fluid flow: a discussion. Petroleum Geoscience, 22(1), pp.91-104.

Vincent, B., Chirol, H., Portier, E. and Mouche, E., 2021. Contribution of drone photogrammetry to 3D outcrop modeling of facies, porosity, and permeability heterogeneities in carbonate reservoirs (Paris Basin, Middle Jurassic). Marine and Petroleum Geology, 123, p.104772

Wilson, C.E., Aydin, A., Karimi-Fard, M., Durlofsky, L.J., Amir, S., Brodsky, E.E., Kreylos, O. and Kellogg, L.H., 2011. From outcrop to flow simulation: Constructing discrete fracture models from a LIDAR survey. AAPG bulletin, 95(11), pp.1883-1905.

Zhu, W., Khirevich, S. and Patzek, T.W., 2021. Impact of fracture geometry and topology on the connectivity and flow properties of stochastic fracture networks. Water Resources Research, 57(7), p.e2020WR028652.