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). A cut surface of a rock sample and a thin section illustrating the oxidation halo in contrast to the non-oxidized host rock are presented in Figure 2. This figure clearly shows the sharp transition from the orange to reddish-brown hues of the oxidized zone to the greyish-blue and beige tones of the non-oxidized host rock, further confirming the presence and intensity of oxidation halos at a finer scale.

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 3).

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).

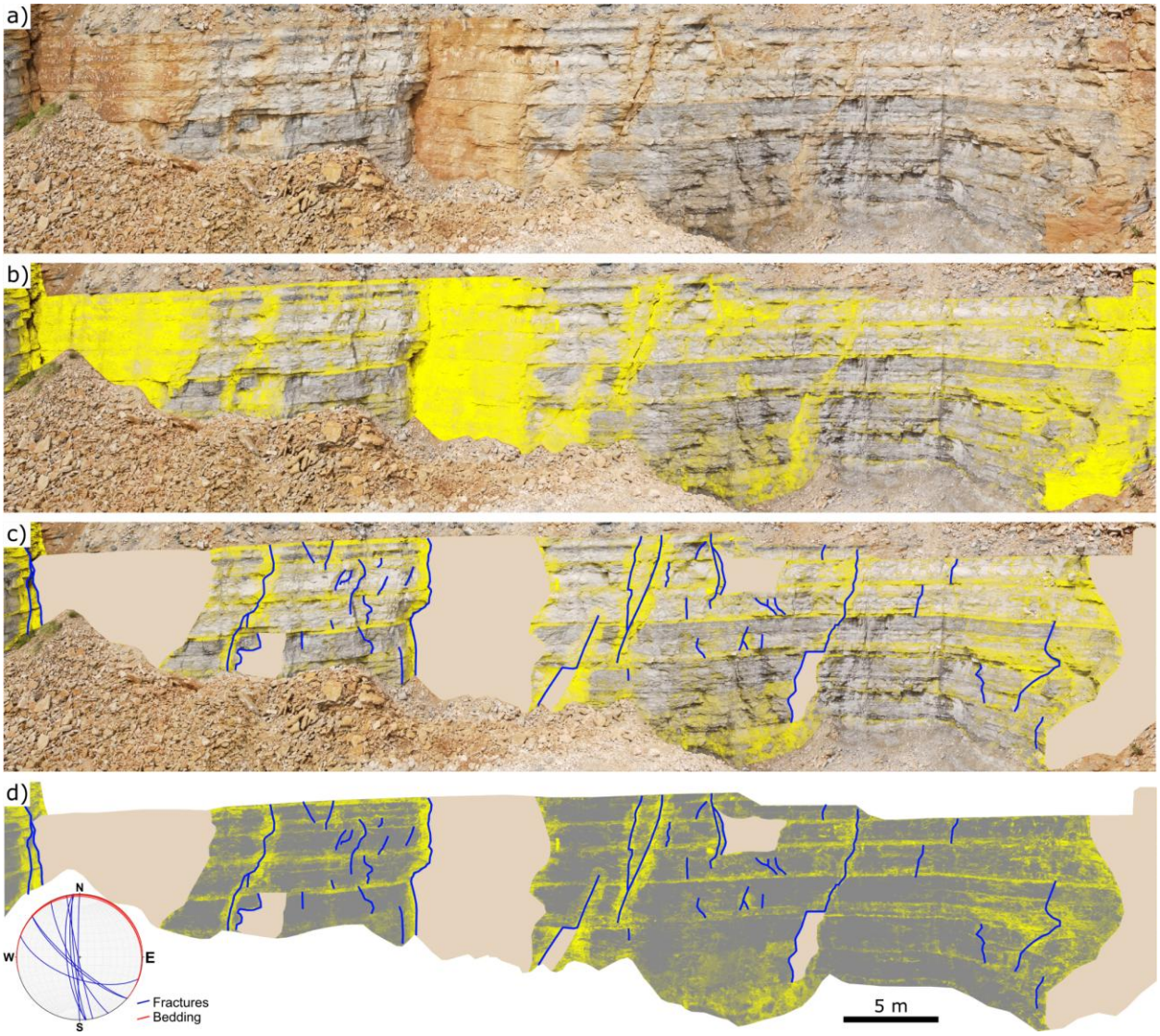


Figure 1. (a) Panoramic view of the studied outcrop. (b) Image processing enhances the visibility of oxidation halos, highlighted in yellow. (c) Fracture traces are shown in blue, while fracture surfaces are marked in brown. (d) Same as (c), but without the original image background. The inset shows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

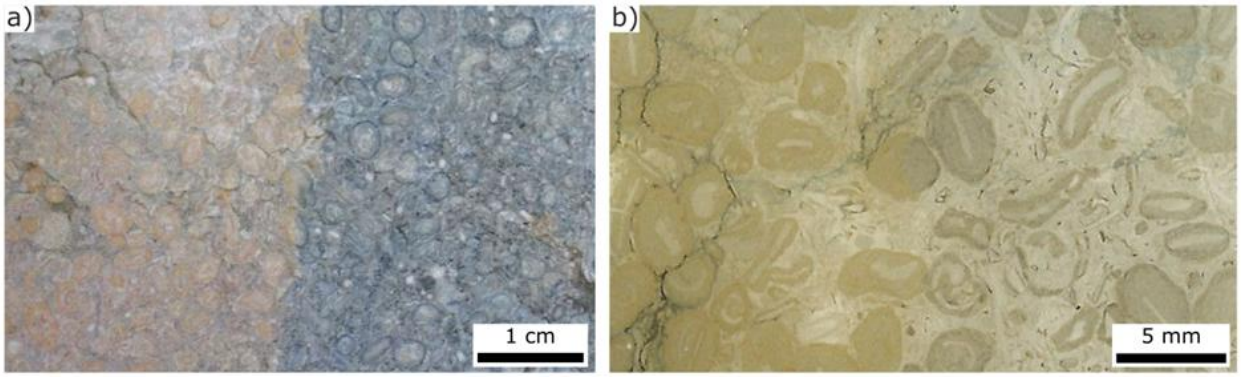
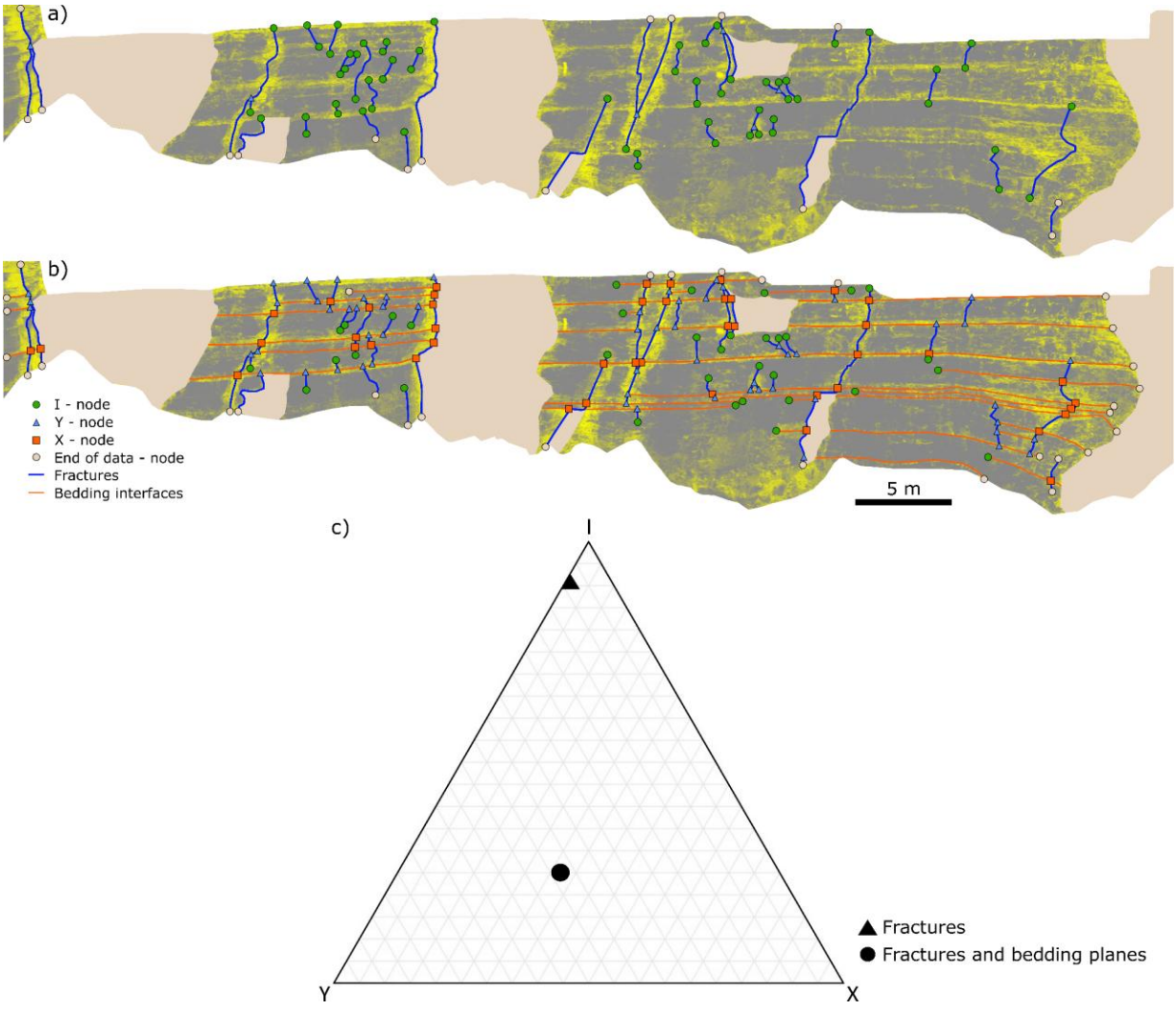


Figure 2. (a) Cut surface of the rock sample and (b) thin section showing both the oxidation halo (left side) and the non-oxidized host rock (right side). A sharp transition from the orange to reddish-brown hues of the oxidized zone to the grayish-blue and beige tones of the non-oxidized host rock is observed.

3 Results

This section highlights the critical importance of integrating both fractures and bedding planes when analyzing fluid flow in sedimentary formations. Figure 3 (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 3c shows a ternary plot based on I-Y-X connectivity analysis (Manzocchi, 2002), comparing the fracture network alone (from Figure 3a) with the combined network of fractures and bedding planes (from Figure 3b). 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-

125 sectional view of the quarry face). However, given the measured orientations of fractures (as
126 shown in the inset of Figure 1), the fracture network is expected to exhibit lateral connectivity,
127 which would further facilitate lateral fluid movements.



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129 **Figure 3.** Connectivity maps showing the spatial distribution of different node types (I, Y and X)
130 for (a) fractures only, and (b) both fractures and bedding planes at the studied outcrop. (c)
131 Ternary plot of I-Y-X connectivity analysis (Manzocchi, 2002) comparing the fracture network
132 alone (as in a) with the combined fracture and bedding plane network (as in b) at the studied
133 outcrop. Better-connected networks are plotted toward the base of the triangle indicating a
134 higher proportion of X and Y nodes.

Maps of the estimated intensity and density of (a) fractures only and (b) both fractures and bedding planes are presented in Figure 4. 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 3, these P21 and P20 maps further demonstrate how apparently isolated fracture corridors become interconnected through fluid flow along the bedding planes.

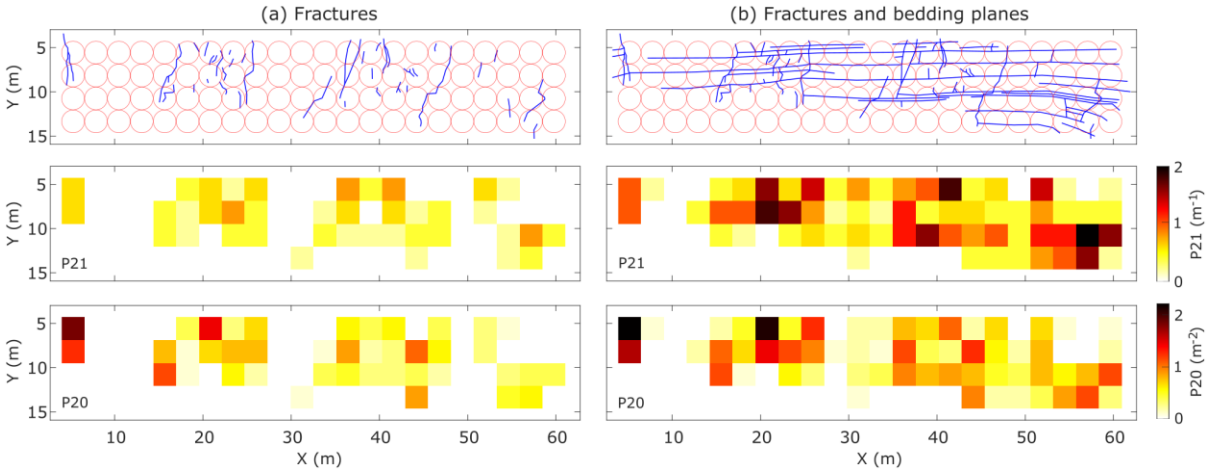

Figure 4. Estimated fracture intensity (P21) and fracture density (P20) maps for (a) fractures only, and (b) both fractures and bedding planes at the studied outcrop. Fracture traces and fracture plus bedding plane traces (depicted in blue) are shown at the top, indicating the locations of the scan circles 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 5, 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 3. 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.

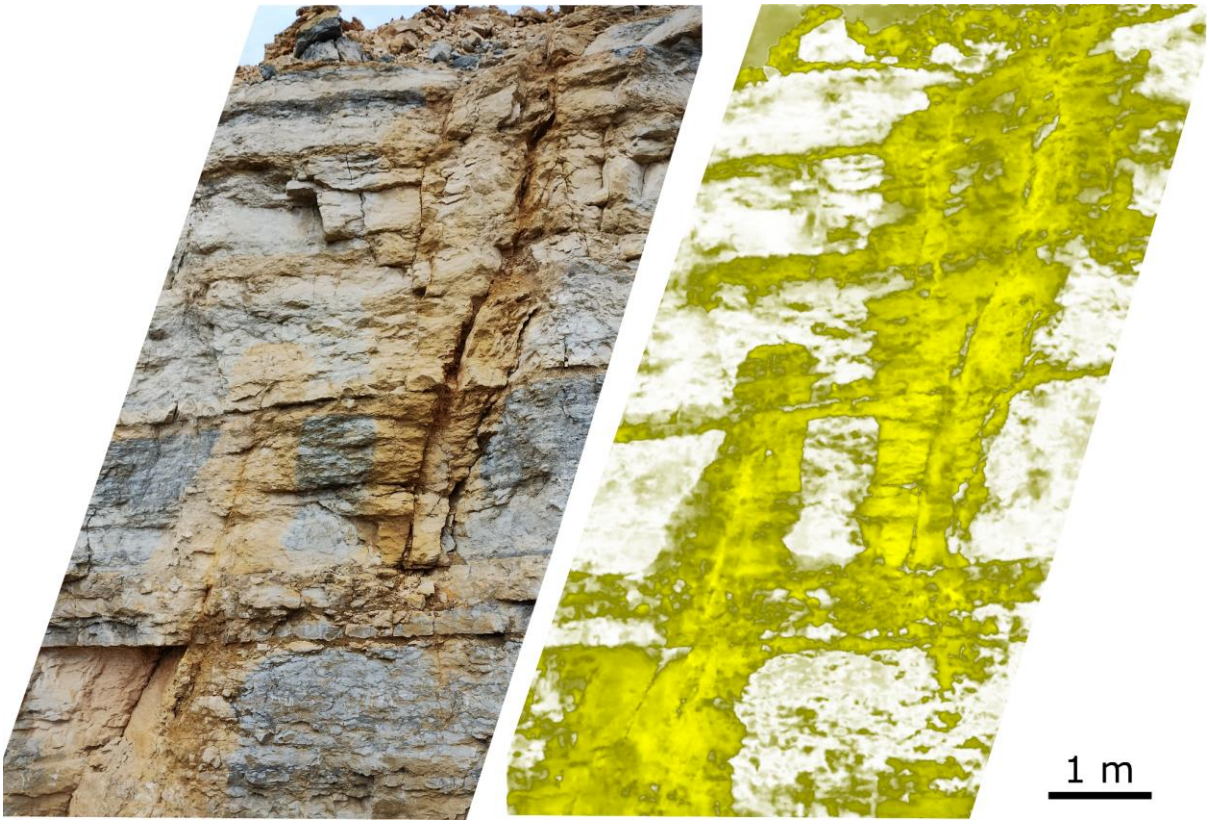

Figure 5. Close-up photograph of the outcrop on the left, and the same image after processing to enhance the visibility of oxidation halos, which are highlighted in yellow on the right.

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.

The factors controlling fluid flow along bedding planes in the studied area have not yet been fully identified. However, preliminary observations suggest that dissolution processes, particularly pressure-solution of the cement between detrital and precipitated grains, are likely responsible for the development of porosity and permeability within the marly limestone layers.

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.

Additionally, the presence of karstification features 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 Conditions of formation of oxidation halos

Oxidation halos are typically associated with shallow subsurface conditions, where oxidizing fluids circulate, but their depth range can vary depending on the fluid source and redox conditions. In most cases, oxidation halos form due to meteoric groundwater infiltration, generally within the upper few hundred meters of the subsurface (0–500 m). However, oxidation at greater depths can also occur when oxidized fluids originate from deep-seated reservoirs, such as hydrothermal systems or basinal brines (e.g., Grare et al., 2018).

In the studied area, XRF measurements of rock samples indicate that iron content remains similar in both the oxidized zone and the host rock, with values ranging between 7000 and 8000 ppm. This suggests that iron was not significantly leached or transported, but rather that oxygen introduced through meteoric groundwater infiltration converted Fe^{2+} to Fe^{3+} in situ at relatively shallow depths.

Although oxidation halos can, in certain settings, form under stagnant water conditions (Balsamo et al., 2013), observations in the studied area suggest a different scenario. The oxidation halos exhibit elongated and interconnected patterns that align with structural

discontinuities, such as bedding planes and fractures. This geometry, which reflects structural anisotropy, is more characteristic of advective flow pathways, where fluids migrate through preferential conduits rather than diffusing isotropically in stagnant conditions.

Furthermore, if oxidation had occurred under fully stagnant conditions, Fe oxidation would be expected to be uniform throughout the rock mass. However, XRF measurements indicate that iron content remains similar across the entire rock mass, confirming that iron was not leached or transported in significant amounts. The fact that oxidation is localized along fractures and bedding planes suggests that an oxidizing (O-rich) fluid must have circulated advectively, even if the surrounding rock was immersed in a stagnant, reduced water environment.

Future geochemical and isotopic analyses could further refine this interpretation and provide a more detailed understanding of the fluid origins and migration history.

4.3 Implications

Although, the examined oxidation halos are potentially associated with near-surface conditions, the fundamental processes governing fluid flow, connectivity, and permeability are not necessarily depth-dependent. The oxidation halos in our study serve as natural tracers of paleo-fluid pathways, providing direct evidence of preferential flow along bedding planes. This has implications for deeper subsurface reservoirs, where similar structural and stratigraphic controls on fluid migration can be expected. Therefore, despite the shallow setting of our dataset, the observed fluid flow patterns provide insights into permeability anisotropy, which can be extrapolated to deeper subsurface environments, where direct observations are inherently limited.

The findings of this study, therefore, can have significant implications for various subsurface activities. Reservoir 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 (a) resource extraction, including groundwater, geothermal energy, and

hydrocarbons, and (b) 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.

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