Geological Magazine

www.cambridge.org/geo

Introduction: Faults and fractures in rocks: mechanics, occurrence, dating, stress history and fluid flow

Olivier Lacombe[1], Stefano Tavani[2,3], Juliette Lamarche[4], Fabrizio Balsamo[5] and Fabrizio Agosta[6]

[1]Sorbonne Université, CNRS-INSU, Institut des Sciences de la Terre de Paris – ISTeP, UMR 7193, Paris, France; [2]Università degli Studi di Napoli Federico II, Naples, Italy; [3]Consiglio Nazionale delle Ricerche, IGAG, Rome, Italy; [4]Aix Marseille Univ., CNRS, IRD, INRAE, CEREGE, Aix-en-Provence, France; [5]Università di Parma, Parma, Italy and [6]Università della Basilicata, Dipartimento di Scienze, Potenza, Italy

Preface

Cite this article: Lacombe O, Tavani S, Lamarche J, Balsamo F, and Agosta F (2022) Introduction: Faults and fractures in rocks: mechanics, occurrence, dating, stress history and fluid flow. *Geological Magazine* **159**: 1847–1854. https://doi.org/10.1017/S0016756823000031

Received: 14 January 2023
Accepted: 15 January 2023

Author for correspondence:
Olivier Lacombe,
Email: olivier.lacombe@sorbonne-universite.fr

1. Introduction

Fractures and faults are common structural elements of shallowly deformed rocks. They result from processes controlled by physical forces and/or chemical potentials and by the rheology of rocks. These elements might form at all stages of rock history, from early/burial diagenesis to major tectonic events, and play a fundamental role in fluid migration and accumulation within the upper crust. Fractures and faults hence are the focus of detailed studies conducted during exploration and production/storage of subsurface renewable and fossil energy, as well as for waste repositories assessment. In fact, defining the parameters that control fracturing and faulting in rocks is key for a better understanding of fluid–rock interactions, time-dependent stress evolution and present-day earthquake hazards. The dynamic feedbacks between fluid flow, permeability rise/fall, chemical reactions and rock failure, however, are difficult to decipher, and remain challenging tasks to tackle. For example, the role of chemistry in fracture pattern development has recently been emphasized by Laubach *et al.* (2019), who documented that a fracture may grow under subcritical stress conditions in response to the chemical weakening occurring at its tip, hence at a much lower stress level than would otherwise be required. Embrittlement enhanced by early diagenesis in carbonates has been shown to trigger shallow, early, low-stress, burial fractures in platform carbonates (LaBruna *et al.* 2020). The current structural configurations must therefore be interpreted as the result of coupled mechanical and chemical processes, which took place in the past with changing environmental conditions (temperature T, pressure P, fluid pressure P_f) over geological timescales (e.g. Ankit *et al.* 2015). Ongoing work on the origin, occurrence, 3D spatial arrangement, evolution and mechanics of faults and fractures and their controlling parameters (e.g. Guiton *et al.* 2003; Lamarche *et al.* 2012; Lavenu *et al.* 2013; Lavenu & Lamarche, 2017; Laubach *et al.* 2019; Prabhakaran *et al.* 2019, 2021; Passchier *et al.* 2021; Correa *et al.* 2022) will provide new insights into the role these structures exert on the storage and migration paths of geofluids, natural hazards and overall shaping of the Earth's surface. This knowledge is fundamental to mitigate the risks associated to exploitation of subsurface energy, as well as the risks associated to earthquakes and landslides, and to better preserve water resources hosted within fractured reservoirs. These themes deserve a close inspection by Earth scientists, who will take advantage of the opportunities provided by advancing technologies to better decipher the physical–chemical–mechanical processes occurring at depth in the upper crust.

The geometrical and structural properties of fractures and faults are very difficult to assess for underground rocks due to lack of resolution for detailed interpretations. Rocks with a high value of primary porosity commonly include deformation bands (Aydin, 1978), which might dramatically reduce the fluid storage and migration properties of the rock mass. Conversely, those characterized by a low amount of primary porosity often deform by means of combined opening-mode and/or pressure solution-assisted deformation mechanisms (Rispoli, 1981). All resulting structural elements form sub-seismic-scale heterogeneities affecting the reservoir characteristics. However, the interplay among them often forms complex structural networks that are difficult to characterize in terms of resulting bulk petrophysical properties. In this regard, discrete fracture network (DFN) modelling of geocellular volumes representative of the subsurface rock volumes has been employed in the last two decades as a valid tool to compute the values of fracture porosity and of an equivalent permeability. Furthermore, the advent of 3D virtual outcrop models in conjunction with the proliferation of unmanned aerial vehicles has boosted the use of multiscalar 3D fracture data from large-scale outcrop (e.g. Bistacchi *et al.* 2015; Bisdom *et al.* 2017; Corradetti *et al.* 2018), and multiscalar fracture network attributes retrieved from the analysis of 2D satellite and aerial images (e.g. Palamakumbura *et al.* 2020; Ceccato *et al.* 2022) are nowadays routinely used to generate DFN (e.g. Healy *et al.* 2017).

Giuffrida *et al.* (2020) showed the problems arising in the computation of the scaling factors, as well as in the detailed characterization of both mechanical and hydraulic apertures of single fracture sets. Fault zones can be simplistically considered as comprising two main domains commonly labelled as fault cores and damage zones (Caine *et al.* 1996; Faulkner *et al,* 2010). The fault cores include both main slip surfaces and breccias, cataclasites and gouges, and are often associated with syn-tectonic veining and mineralization. In the brittle regime, fault core rocks often form due to cataclasis, a process responsible for grain size reduction, grain shape evolution, and production of a powder-like matrix due to microscale intragranular extensional fracturing and chipping. Ferraro *et al.* (2019, 2020) showed that the diagenetic history of cataclastic fault rocks profoundly affects their present-day porosity and permeability properties, supporting the idea that structural diagenesis analysis (Laubach *et al.* 2010) is required to fully assess the control exerted by localized strain on the storage and migration fluid properties of fractured reservoirs. The fault damage zones commonly flank the fault cores, and consist of fractured and fragmented rock volumes still preserving the original fabrics. Across the latter zones, even if many studies have documented common trends of both fracture density and intensity, fracture parameters do not always scale proportionally with fault displacement (Faulkner *et al.* 2006; Balsamo *et al.* 2019; Volatili *et al.* 2022) likely due to the heterogeneous stress distribution around the evolving main slip surfaces (Cowie & Scholz, 1992; Mayolle *et al.* 2021).

In the upper crust, fractures are the most common response of deformed rocks submitted to tectonic stresses (e.g, Hancock, 1985; Tavani *et al.* 2015) and they have long been used as palaeostress indicators (Gauthier & Angelier, 1986). Interpretation of fractures and faults in terms of palaeostress analysis has received continuing attention over the last decade (Gudmundsson and Bergerat, 2012; Lacombe, 2012; Simon, 2019; Pascal, 2021), with ongoing improvements of techniques to reconstruct the stress history from inversion of populations of veins and mesoscale striated faults (Shan *et al.* 2021; Pascal *et al.* 2022). A blind spot for most of these analyses has long been the lack of constraints on the absolute timing of brittle deformation. This absolute timing is never resolved through detailed inspection of the abutting/cross-cutting relations among individual fracture and fault sets, so the relevance and meaning of specific sets with respect to regional-scale deformation has been disputable, especially in regions that underwent polyphase tectonics, stress and/or block rotations and stress perturbations (e.g. Beaudoin *et al.* 2018). Recent improvements of absolute dating techniques have allowed for major progress in constraining the rate of development and lifetime of individual fracture and fault sets, as well as the timing of fluid flow in fractured rock volumes. Dating of shallow crustal faults may be achieved by geochronology of fault-generated materials such as fault gouge, slip-surface hematite, opal, pseudotachylyte and calcite steps/slickenfibres. A fault gouge forms by a combined process of mechanical comminution and *in situ* instantaneous neoformation of illite that is related to the energetics of faulting and fluid flow during faulting. Thus, isotopic dating of illites in fault gouge by K–Ar or Ar–Ar geochronology might provide a powerful tool to directly date the main episodes of fault slip depending on our technical ability to characterize the clay populations and to quantify the amounts of detrital (wall-rock inheritance) and authigenic phases (related to one or to multiple clay-generating slip events) (van der Pluijm *et al.* 2001; Viola *et al.* 2016). Alternatively, vein opening and fault activity can be dated by U–Pb geochronology of syn-tectonic calcite cements (Roberts *et al.* 2020). However, fault rocks and veins may show a variety of calcite cements, and may also be affected by fluid–rock interactions subsequent to syn-tectonic cement precipitation, for instance during rock exhumation from depth (e.g. Aubert *et al.* 2020). For this reason, microstructurally constrained geochronology analyses are required to ensure that the sampled calcite cements grew syn-kinematically, and careful geochemical, compositional and microstructural characterization is necessary to guarantee that the dated isotopic system has remained undisturbed by later thermal or fluid-related activity (Roberts & Holdsworth, 2022). Beyond providing absolute ages of fault slip and fracture development, geochronological dating of calcite cements from faults and veins has paved the way to estimate the duration of contractional stages associated with the folding event (Lacombe *et al.* 2021). Alternatively, coupling the $\Delta_{47}CO_2$ temperature of cement precipitation in a closed fluid system to a 1D burial-time model yields the absolute timing of veins that formed during these contractional stages (Labeur *et al.* 2021).

Fluid sources, modalities of fluid flow and degree of fluid–rock interactions vary spatially and temporally as a function of crustal structural evolution. For this reason, the characterization of the fluid system (origin and nature of the fluid; *T*, *P*, timing of mineral precipitation, degree of fluid–rock interaction, hydraulic structure of the fractured reservoirs) and its evolution through time remains a challenging task (Aubert *et al.* 2019, 2021; Petit *et al.* 2022). Fluids affect crustal rock strength by permitting pressure solution and chemical reactions to occur, thus stiffening the rock by precipitating cements and/or weakening it through development of low-strength hydrated mineral phases such as phyllosilicates. Fluids also reduce rock strength by overpressure. Conversely, the structural permeability architecture influences fluid migration pathways. The relations among fluid migration, fluid storage and rock deformation still remain to be further documented, quantified and integrated in comprehensive models of short-term and long-term fault and fracture behaviours and crustal mechanics, with implications for mineralization pattern and geothermal resources in ancient and active structurally complex, tectonic settings (e.g. Clemenzi *et al.* 2015). The occurrence and time–space evolution of supra-hydrostatic fluid pressures are also key issues for understanding processes such as inherited fault reactivation, seismic swarming, gravitational sliding of rocks and pervasive hydrofracturing (Guglielmi *et al.* 2021). Fluid (over)pressure is also a governing factor for the evolution of permeability and porosity of rocks and the generation, maturation and migration of economic fluids like hydrocarbons or ore forming hydrothermal fluids, and is therefore a key parameter in basin modelling. Performing and combining new techniques for better quantifying and modelling the role of fluid overpressures and their spatial/temporal variations in sedimentary basins (Berthelon *et al.* 2021), but more broadly in the crust in diverse environments, e.g. magma-driven emplacement of sills and dikes, is a challenge for the forthcoming years for both academy and industry.

The occurrence, patterns and mechanics of faults and fractures and their relation to chemistry, fluid flow and stress therefore are long-lasting, intriguing and fundamental topics in the geosciences owing to their importance for both academy and industry. The guest editors of this Special Issue have been involved in the production of several dedicated volumes on these topics during the last decade (Agosta & Tondi, 2010; Smith *et al.* 2012; Lacombe *et al.* 2012, 2014; Lacombe & Bergerat, 2013; Iannace *et al.* 2015; Agosta *et al.* 2016; Tondi *et al.* 2016; Lacombe & Rolland, 2016;

Laubach *et al.* 2018; Agosta *et al.* 2019; Balsamo *et al.* 2020). This new Special Issue follows up a successful session in the European Geosciences Union (EGU) Vienna 2021 meeting and gathers articles from scientists from diverse countries working in the field, in the lab and on simulations, and belonging to both industry and academy. The 28 articles, either original research or review, cover various fields and disciplines including structural geology, geomechanics, isotope geochemistry, hydrogeology and numerical modelling, with the common goal of better appraising and comprehending the development of fracture and fault systems in both space and time, as well as their coevolution and reciprocal interactions with underground fluids in a variety of geological settings. The papers provide enlightening examples of multidisciplinary research carried out by an international scientific community and offer a showcase for the efforts made by earth science researchers to assess the fault- and fracture-controlled fluid flow and stress state distribution in the subsurface. It is our hope that the present Special Issue will not only be of interest to the structural geologists, geophysicists and geochemists dealing with upper crustal rocks, but also be of use to the wider geoscience community.

2. Content of the volume

The volume is divided into the following five chapters:

Fracture occurrence, patterns and properties

In their paper, **Bowness *et al.*** study the lithostratigraphic and 3D fracture arrangement in layered rocks in a Cretaceous carbonate succession at Canyon Lake Gorge, Texas. Layers have variable clay and silicate minerals vs carbonate content. The authors show the sensitivity of fault and fracture arrangement to the mineralogy as well as the inhibition of fracture propagation when the thickness of incompetent layers increases. These results are of prime importance for modelling underground fractured reservoirs, because fracture connectivity, and therefore fluid flow, is shown to be dependent not only on bed thickness, but also on rock lithology and its mechanical-stratigraphic settings.

Manniello *et al.* use the case study of the Mesozoic shallow-water carbonates of Agri Valley (southern Italy) to assess the influence exerted by depositional and diagenetic heterogeneities on fracture geometry, distribution and multiscale properties. Stratigraphic, petrographic, mineralogical and meso-scale structural analyses indicate that burial-related, physical–chemical compaction and cementation processes have remarkably conditioned the evolution of the fracture stratigraphy of the studied carbonates.

Mercuri *et al.* analyse the intensity, distribution and orientations of the pre-folding fracture pattern affecting the Pietrasecca Anticline (Apennines, Italy). They recognize longitudinal and transverse joints, oriented approximately perpendicular to bedding, which predated the development of the pressure-solution cleavage and the intensity of which is not correlated with the structural position along the anticline. These observations suggest that jointing occurred in a foredeep environment before the Pietrasecca Anticline growth, which warned about the potentially erroneous interpretation of joints striking parallel and orthogonal to the main fold axis as representing syn-folding deformation structures.

Richard *et al.* use a case study of a carbonate reservoir in Egypt to illustrate the discrepancy between observations required to build a thorough geological understanding of the subsurface and the simplification imposed by modelling in fractured reservoirs. Observations on reservoir architecture, fracture typology and fracture connectivity are integrated with the regional geological context to build a conceptual fracture model, which is then drastically simplified to generate 3D discrete fracture network scenarios that are calibrated using exploration wells.

Formenti *et al.* investigate a natural outcrop located in Ontario, Canada, along the Niagara Escarpment. The outcrop exposes Palaeozoic sedimentary rocks cross-cut by high-angle fractures, which disarticulate large rock blocks and pose a serious hazard for the local population due to rock fall. The authors analyse and quantify the natural fracture network by means of combined field and numerical analyses. Specifically, they carry out discrete fracture network modelling of a geocellular volume representative of the study rock volume. Results show that the high degree of fracture connectivity contributes to the local geohazard. In fact, together with bedding planes that might act as free surfaces, the well-connected fractures bound cuboid rock blocks prone to rock fall in the presence of circulating meteoric water.

Fracture mechanics

Bons *et al.* review the formation and evolution of non-igneous hydrofractures. The authors show that both Terzaghi's and Biot's theories can be reconciled if the appropriate boundary conditions are considered. They discuss the propagation of hydrofractures after initial rock failure, and address the question of how to ascertain whether a fracture is a hydrofracture or not. As a result, the authors propose that extensional or dilational fractures forming under normal circumstances below 2–3 km depth are often hydrofractures, whereas at shallower depths usually they are not. Furthermore, they critically assess which vein structures in the geological record can, and which do not necessarily, indicate hydrofracturing.

Gudmundsson investigates how hydrofractures select their propagation paths, particularly in layered and faulted rocks, and proposes that among all the possible paths, a hydrofracture selects the path of minimum action as determined by Hamilton's principle. This means that the selected path is that along which the energy released multiplied by the time taken for the propagation is a minimum. Hydrofractures advance their tips/fronts in steps, with a time lag between the fracture front and the fluid front, each step being controlled by Hamilton's principle. Hydrofracture path is expected to be everywhere perpendicular to the trajectory of $\sigma 3$ and along the trajectory of $\sigma 1$ in homogeneous rocks, faults may be used as part of this path primarily if the fault is steeply dipping and with close to zero tensile strength.

Hobbs and Ord address the implications of adding a cap to the yield surface for elastic–plastic and elastic–viscoplastic solids with coupling between deformation, fluid flow and mineral reactions. A capped yield surface means that a deforming fluid-saturated rock mass automatically oscillates between a low stress – high fluid pressure, low-permeability state and a high stress – low fluid pressure, high-permeability state controlled by competition between dissolution and precipitation. Failure at the cap results in opening-mode veins normal to compression in low-permeability rocks if the deformation is coupled to mineral reactions with negative ΔV in the rock matrix. This mode-switching process is a coupled mineral reaction – deformation – fluid flow cyclic mechanism that is an alternative to the fault-valve process. It does not depend on fluids breaching a permeability 'seal' and is intrinsically aseismic, although it can, in principle, nucleate a seismic cycle process.

Hooker *et al.* show that calcite veins from the Marcellus Formation (USA) grew via a combination of continuous fibrous growth related to pressure-solution creep and growth of a pressure fringe around a pre-existing, sealed fracture, and punctuated fracture-opening increments linked to an overpressured, mineral-saturated fluid. Calcite stable isotopic signatures support a regional opening-mode vein set that formed in response to catagenetic fluid overpressures within a tectonically imposed regional stress field.

Massaro *et al.* propose a new granular rock for simulation of multiscale fault and fracture processes in analogue experiments. They used silica sand and hemihydrate powder to form cohesive aggregates capable of deforming by tensile and shear failure under variable stress conditions, providing suitable conditions to study fracture processes in fault zones during different stages of fault evolution in dynamically scaled analogue experiments.

The paper by **Gage *et al.*** deals with the winter weathering of fractured sedimentary rocks on the Niagara Escarpment, Ontario. They examined the temperature of the rock surface and fractures at three *in situ* sites for >1 year, concluding that site-specific factors and pre-existing fractures moderate the influence of air temperature and insolation on thermal gradients, ultimately controlling the overall weathering regime.

Absolute dating of faults and fractures

Parizot *et al.* address the question of whether intraplate deformation related to far-field stress transmission from distant plate boundaries occurs during tectonic pulses marked by high strain rates at plate boundaries, or if it corresponds to low-intensity but regional continuous deformation through time. To do so, the authors have dated syn-kinematic calcite cements using U–Pb geochronology along the Cévennes Fault System (SE France). Following an Albian activity, the fault system underwent a continuous compressional activity during the whole Eocene and probably during the Late Cretaceous – Palaeocene, which emphasizes that intraplate deformation occurred rather continuously and not only during pulses of high rates of contraction at the Iberian–Eurasian plate boundary as previously interpreted from the sedimentary record.

Blaise *et al.* constrain the timing of brittle deformation and associated calcite cementation in Jurassic carbonates of the eastern Paris basin by means of U–Pb geochronology. They show that almost all the sampled veins were nearly continuously cemented between 48 and 33 Ma by low-temperature meteoric fluids. Most veins oriented NNE–SSW formed either in response to the far-field transmission of Pyrenean compressional stress (48–43 Ma) or in response to extension related to European Cenozoic Rift System (ECRIS) (~35–33 Ma), with some veins recording the progressive transition from compression to extension (43–35 Ma). A few late veins oriented NNW–SSE and dated 32 and 18 Ma may be related to either the Alpine compression or to late Pyrenean deformation.

Torgersen *et al.* reconstruct multiple brittle reactivations of a long-lived, regional-scale mylonitic shear zone in SE Norway by integrating structural and micro-textural analyses with K–Ar and ^{40}Ar–^{39}Ar geochronology. The study demonstrates that multiple geologically significant K–Ar ages can be constrained from fault gouges within the same fault core provided a combination of careful field sampling, structural characterization, detailed mineralogy and illite crystallinity analysis is conducted. Further, brittle faulting is controlled by mechanical anisotropy of parallel-oriented, through-going phyllosilicate-rich foliation planes within the mylonitic fabric.

Pavlovskaia *et al.* reconstruct the tectonic evolution of the northern Verkhoyansk fold-and-thrust belt in the Siberia Craton using palaeostress data and U–Pb calcite dating on fault slickenfibres. They documented changes in the stress regimes encompassing Early Permian strike-slip faulting, Early Cretaceous compression, Late Cretaceous compressional reactivation and finally late-stage Palaeocene extension.

Fluid flow and mineralization in faults and fractures

Beaudoin *et al.* provide a critical review of the geochemical techniques applied on syn-kinematic calcite cements and associated trapped fluids and show how they can constrain the temperature, pressure, origin and pathways of fluids during deformation and allow the characterization of the past fluid system. Taking orogenic forelands as a playground, they show that the past fluid system generally evolves from being rather closed to external fluids when deformation is bounded to mesoscale structure development to opening to vertical flow when thrusts and folds develop. The past fluid system also evolves under the influence of the structural style, fault geometry and lithology of the sedimentary succession. This review illustrates the concept of geochemistry-assisted structural geology, with the geochemistry of calcite cements constraining subsurface geometries and structural development.

Dielforder *et al.* analysed the ^{87}Sr/^{86}Sr ratios of vein carbonates from the Infrahelvetic flysch units in the Swiss Alps and show that the vein carbonates trace the Sr isotopic evolution of pore fluids from an initial seawater-like signature towards the Sr isotopic composition of the host rock with increasing metamorphic grade, which reflects the progressive equilibration of the pore fluid with the host rock. This paves the way to the reconstruction of the prograde to early retrograde tectonic evolution of a fold-and-thrust belt and helps understand the relative timing of deformation events.

Gottardi and Hughes address the role of fluids in mid-crustal shear zones in the Raft River Mountains, Utah, USA, documenting ductile overprint of brittle microstructures. Such results suggest that, during exhumation, the Raft River detachment shear zone crossed the brittle–ductile transition repeatedly, providing pathways for fluids to permeate through this shear zone.

The paper by **Berger and Herwegh** deals with deformation and fluid flow processes in the Grimselpass Breccia Fault, a hydrothermally active strike-slip structure in the Central Alps (Switzerland). They documented feedback cycles of episodic deformation, mass/volume and clogging preserved hydrothermal circulation and deformation over the last 3.4 Ma, thus presenting a case study for the long-term preservation of orogenic hydrothermal system.

Zucchi *et al.* describe in detail a fossil exhumed geothermal system exposed in eastern Elba Island, that can be an analogue for geothermal systems in a polyphase folded and faulted setting and refines the geothermal conceptual models. The fault zones and the extensional jogs at their tips channel the deep fluids. Pre-existing normal and oblique-slip faults served as feeder conduits for geothermal fluids and hydraulically connected the metasiliciclastic rock bodies previously deformed by two generations of folds, leading to reprecipitation of quartz, Fe-oxides and sulphides.

Smith *et al.* focus on the digital structural analysis of Late Jurassic rocks of the Franconian Basin (Germany). They make use of an open pit quarry to investigate both geometry and distribution of the fracture network cropping out at different sites located at various distances from a large-scale reverse fault.

Results are employed in a finite-element modelling aimed at simulating the fluid flow through the fracture medium. The authors assess the control exerted by the fault-related fractures on the size and shape of the permeability ellipses derived from the modelling. The permeability ellipse computed for the outcrop close to the reverse fault is elongated parallel to the main slip surface, whereas those computed for the outcrops away from the fault do not show significant anisotropy.

By means of geochemical modelling, **Koehn *et al.*** explore the modalities of outcrop-scale ore mineralization due to flow of a metal-rich fluid through a faulted rock volume. The authors simulate a number of scenarios, which deal with the fluid infiltration through a low-permeability rock cross-cut by two high-permeability fault zones. By solving the advection–diffusion equation for 12 chemical species at varying temperatures, the authors document that ore mineralization localizes within the fault zones, specifically at the boundary with the encompassing host rock. Results are therefore consistent with mineral precipitation depending on the dominant transport process, with mineralization predominant where local diffusion dominates.

Faults, fractures and stress

Tranos and Osman describe previously ignored or falsely interpreted hydroplastic structures, which are 'odd' kinematic indicators in the basal part of the Eocene Middle Rus Formation. These structures occur in relation to a principal displacement zone along the boundary/interface between the Lower and Middle Rus, the so-called Rus soft-sediment detachment, that displays transport/slip towards the NNW. Palaeostress analysis indicates an Andersonian transtensional stress regime, under which the activation of the Rus soft-sediment detachment would hardly occur except for a negative effective principal stress $\sigma3$ and an abnormally low frictional coefficient caused by fluid pressure. The soft-sediment Rus detachment is interpreted as an early (Late Eocene) witness of the inception of the Zagros collision.

Assie *et al.* investigate the late Cenozoic evolution and deformation of the Fanshi Basin, (Shanxi rift, North China Craton). By means of palaeostress analysis of mesoscale fault-slip data, they unravel a multiphase deformation history since late Cenozoic time, including possible $\sigma2$/ $\sigma3$ stress permutations related to structural inheritance: (1) a Neogene strike-slip stress ($\sigma1$ NE–SW and $\sigma3$ NW–SE), activating the large NNE faults as right-lateral strike-slip faults; (2) a short-lived early Pleistocene NE–SW extension; and (3) a NW–SE to NNW–SSE extension continuing since the late Pleistocene and giving the current half-graben geometry of the Fanshi Basin by activating the Fanshi fault as a normal fault in the southern part of the graben.

Köhler *et al.* reconstruct the spatio-temporal variations of post-Triassic palaeostress fields in the Franconian Platform (SE Germany) using stylolites and mesoscale faults. Two cycles of stress evolution, from normal stress to thrusting, strike-slip and back to normal, are reconstructed, recording the stress evolution in an intraplate compressional setting during Mesozoic Africa–Iberia–Europe convergence and later Cenozoic Alpine orogeny.

Bhowmick and Mondal present a field study of veins, fractures and faults from metavolcanic rocks of the Chitradurga region (India). Dilation and slip tendency, and fracture susceptibility analysis allows the authors to recognize that pre-existing anisotropies represented the main discontinuities for fracture propagation and vein emplacement, which has occurred during multiple cycles of fluid pressure variation.

Zhao *et al.* investigate the present-day stress field in a small rock volume of the Tarim Basin, China, cross-cut by a sub-vertical, strike-slip fault zone. The authors build a 3D geomechanical model aimed at assessing the possible control exerted by the sub-vertical fault zone on the stress state. They show that the direction of the maximum horizontal principal stress axis is deflected near the fault zone, aligning almost parallel to the fault strike. Results are therefore discussed to emphasize the role exerted by local stress fields on the propagation direction of hydraulic fractures, an attitude in the subsurface that is not easy to predict in the vicinity of large fault zones.

Maerten *et al.* describe and apply a new multiparametric inversion technique based on geomechanics that can invert for both the far-field stress attributes and the internal pressure of magma chambers or stocks, constrained by observed dike or eruptive fissure orientations. The technique uses linear elastic models that are solved using a 3D boundary element method. Then the effectiveness of this technique and its practical use is demonstrated through its application to natural examples.

Acknowledgements. The Guest Editors would like to thank all the reviewers of the manuscripts submitted to this Special Issue, who have played a crucial role in maintaining a high level of rigour to the scientific contributions. Miss Susie Cox is warmly acknowledged for the great help she provided during the whole editorial process.

References

Agosta F, Longhitano S, Mazzoli S, Minelli G and Tondi E (2019) Special Issue 'Geofluids and Energy for the XXI Century'. *Geofluids*, https://doi.org/10.1155/2019/7097252.

Agosta F, Luetkemeyer PB, Lamarche J, Crider JG and Lacombe O (2016) Introduction to the Special Issue: 'The role of fluids in faulting and fracturing in carbonates and other upper crustal rocks". Tectonophysics 690, part A, 1–3

Agosta F. and Tondi E. (2010) Editorial: Special Issue "Faulting and fracturing of carbonate rocks: new insights into deformation mechanisms, petrophysics and fluid flow properties". *Journal of Structural Geology* **32**, 1185–6.

Ankit K, JL Urai and Nestler B (2015) Microstructural evolution in bitaxial crack-seal veins: a phase-field study. Journal of Geophysical Research: Solid Earth 120, 3096–118.

Assie KR, Wang Y, Tranos MD, Mah H, Kouamelan KS, Thompson Brantson E, Zhou L, Blaise Y and Ketchaya Y (2022) Late Cenozoic faulting deformation of the Fanshi Basin (northern Shanxi rift, China), inferred from palaeostress analysis of mesoscale fault-slip data. *Geological Magazine* **159**, 2306–22.

Aubert I, Lamarche J and Léonide P (2019) Deciphering background fractures from damage fractures in fault zones and their effect on reservoir properties in microporous carbonates (Urgonian limestones, SE France) *Petroleum Geoscience* **25**, 443–53.

Aubert I, Lamarche J and Leonide P (2021) Ternary fault permeability diagram: an innovative way to estimate fault zones hydraulics. *Journal of Structural Geology* **147**, 104349

Aubert I, Philippe L, Lamarche J and Salardon R (2020) Diagenetic evolution of fault zones in Urgonian microporous carbonates, impact on reservoir properties (Provence – SE France). *Solid Earth* **11**, 1163–86.

Aydin A (1978) Small faults formed as deformation bands in sandstone. *Pure and Applied Geophysics* **116**, 913–30.

Balsamo F, Clemenzi L, Storti F, Solum J and Taberner C (2019) Tectonic control on vein attributes and deformation intensity in fault damage zones affecting Natih platform carbonates, Jabal Qusaybah, North Oman. *Journal of Structural Geology* **122**, 38–57.

Balsamo F, Soliva R, Eichhubl P, Williams R and Krawczyk C (2020) Editorial: Special Issue "Faults, fractures, and fluid flow in the shallow crust". Solid Earth. EGU Copernicus publications. https://se.copernicus.org/articles/special_issue1050.html

Beaudoin N, Lacombe O, Hoareau G and Callot JP (2022) How the geochemistry of syn-kinematic calcite cement depicts past fluid flow and assists structural interpretations: a review of concepts and applications in orogenic forelands. *Geological Magazine* **159**, 2157–90.

Beaudoin N, Lacombe O, Roberts NMW and Koehn D. (2018) U-Pb dating of calcite veins reveals complex stress evolution and thrust sequence in the Bighorn Basin, Wyoming, USA, *Geology* **46**, 1015–18

Berger A and Herwegh M (2022) Grain-size-reducing- and mass-gaining processes in different hydrothermal fault rocks. *Geological Magazine* **159**, 2219–37.

Berthelon J, Brüch A, Colombo D, Frey J, Traby R, Bouziat A, Cacas-Stentz MC and Cornu T (2021) Impact of tectonic shortening on fluid overpressure in petroleum system modelling: insights from the Neuquén basin, Argentina. *Marine and Petroleum Geology* **127**, 104933

Bhowmick S and Mondal TK (2022) Influence of fluid pressure changes on the reactivation potential of pre-existing fractures: a case study in the Archaean metavolcanics of the Chitradurga region, India. *Geological Magazine* **159**, 2346–60.

Bisdom K, Nick H and Bertotti G (2017) An integrated workflow for stress and flow modelling using outcrop-derived discrete fracture networks. *Computers and Geosciences* **103**, 21–35.

Bistacchi A, Balsamo F, Storti F, Mozafari M, Swennen R, Solum J, Tueckmantel C and Taberner C (2015) Photogrammetric digital outcrop reconstruction, visualization with textured surfaces, and three-dimensional structural analysis and modeling: innovative methodologies applied to fault-related dolomitization (Vajont Limestone, Southern Alps, Italy). *Geosphere* **11**, 2031–48.

Blaise T, Khoudja SAA, Carpentier C, Brigaud B, Missenard ., Mangenot X, Boulvais PH., Landrein PH and Cochard J (2022) Far-field brittle deformation record in the eastern Paris Basin (France). *Geological Magazine* **159**, 2095–2119.

Bons PD, Cao D, De Riese T, Gonzalez-Esvertit E, Koehn D, Naaman I, Sachau T, Tian H and Gomez-Rivas E (2022) A review of natural hydrofractures in rocks. *Geological Magazine* **159**, 1952–77.

Bowness NP, Cawood AJ, Ferrill DA, Smart KJ, and Bellow HB (2022) Mineralogy controls fracture containment in mechanically layered carbonates. *Geological Magazine* **159**, 1855–73.

Caine JS, Evans JP and Forster CB (1996) Fault zone architecture and permeability structure. *Geology* **24**, 1025–8.

Ceccato A, Tartaglia G, Antonellini M and Viola G (2022). Multiscale lineament analysis and permeability heterogeneity of fractured crystalline basement blocks. *Solid Earth* **13**, 1431–53

Clemenzi L, Storti F, Balsamo F, Molli G, Ellam R, Muchez P, and Swennen, R (2015) Fluid pressure cycles, variations in permeability and weakening mechanisms along low-angle normal faults: the Tellaro Detachment, Italy. *Geological Society of America Bulletin* **127**, 1689–1710.

Corradetti A, Tavani S, Parente M, Iannace A, Vinci F, Pirmez C, Torrienri S, Giorgioni M, Pignalosa A and Mazzoli S (2018) Distribution and arrest of vertical through-going joints in a seismic-scale carbonate platform exposure (Sorrento peninsula, Italy): insights from integrating field survey and digital outcrop model. *Journal of Structural Geology* **108**, 121–36.

Correa RSM, Marret E and Laubach SE (2022) Analysis of spatial arrangement of fractures in two dimensions using point process statistics. *Journal of Structural Geology* **163**, 104726.

Cowie PA and Scholz CH (1992) Growth of faults by accumulation of seismic slip. *Journal of Geophysical Research: Solid Earth* **97**, 11085–95

Dielforder A, Villa IM, Berger A and Herwegh M (2022) Tracing wedge-internal deformation by means of strontium isotope systematics of vein carbonates. *Geological Magazine* **159**, 2191–2205.

Faulkner DR, Jackson CAL, Lunn RJ, Schlische RW, Shipton ZK, Wibberley CAJ and Withjack MO (2010) A review of recent developments concerning the structure, mechanics and fluid flow properties of fault zones. *Journal of Structural Geology* **32**, 1557–75

Faulkner DR, Mitchell TM, Healy D and Heap MJ (2006) Slip on "weak" faults by the rotation of regional stress in the fracture damage zone. *Nature* **444**, 922–5.

Ferraro F, Agosta F, Prasad M, Vinciguerra S, Violay M and Giorgioni M (2020) Pore space properties in carbonate fault rocks of peninsular Italy. *Journal of Structural Geology* **130**, 103913

Ferraro F, Agosta F, Ukar E, Grieco DS, Cavalcante F, Belviso C and Prosser G (2019) Structural diagenesis of carbonate fault rocks exhumed from shallow crustal depths: an example from the central-southern Apennines, Italy. *Journal of Structural Geology* **122**, 58–80.

Formenti S, Peace A, Eyles C, Lee R and Waldron JW (2022) Fractures in the Niagara Escarpment in Ontario, Canada: distribution, connectivity, and geohazard implications. *Geological Magazine* **159**, 1936–51

Gage HJM, Eyles CH and Peace AL (2022) Winter weathering of fractured sedimentary rocks in a temperate climate: observation of freeze–thaw and thermal processes on the Niagara Escarpment, Hamilton, Ontario. *Geological Magazine* **159**, 2060–81.

Gauthier BDM and Angelier J (1986) Distribution et signification géodynamique des systèmes de joints en context distensif: un exemple dans le rift de Suez. *Comptes Rendus de l'Académie des Sciences, Paris* **303**, 1147–52.

Giuffrida A, Agosta F, Rustichelli A, Panza E, La Bruna V, Eriksson M, Torrieri S and Giorgioni M (2020). Fracture stratigraphy and DFN modelling of tight carbonates: the case study of the Lower Cretaceous carbonates exposed at the Monte Alpi (Basilicata, Italy). *Marine & Petroleum Geology* **112**, 104045

Gottardi R and Hughes B (2022) Role of fluids on deformation in mid-crustal shear zones, Raft River Mountains, Utah. *Geological Magazine* **159**, 2206–18.

Gudmundsson A (2022) The propagation paths of fluid-driven fractures in layered and faulted rocks. *Geological Magazine* **159**, 1978–2001.

Gudmundsson A and Bergerat F (2012) Crustal stresses, fractures, and fault zones: the legacy of Jacques Angelier. *Tectonophysics* **581**, 1–246

Guglielmi Y, Nussbaum C, Cappa F, De Barros L, Rutqvist J, Birkholzer J (2021) Field-scale fault reactivation experiments by fluid injection highlight aseismic leakage in caprock analogs: implications for CO_2 sequestration. *International Journal of Greenhouse Gas Control* **111**, 103471

Guiton MLE, Sassi W, Leroy YM and Gauthier BDM (2003) Constraints on the chronology of fracture activation in folded Devonian sandstone of the western Moroccan Anti-Atlas. *Journal of Structural Geology* **25**, 1317–30

Hancock PL (1985) Brittle microtectonics: principles and practice. *Journal of Structural Geology* **7**, 437–57

Healy D, Rizzo RE., Cornwell DG, Farrell NJ, Watkins H, Timms NE, Gomez-Rivas E and Smith M (2017) FracPaQ: A MATLAB™ toolbox for the quantification of fracture patterns. *Journal of Structural Geology* **95**, 1–16.

Hobbs B and Ord A (2022) Failure modes in fluid saturated rocks: deformation processes and mode-switching. *Geological Magazine* **159**, 2002–19.

Hooker JN, Cartwright J, Stephenson B and Day CC (2022) Continuous versus punctuated vein widening in the Marcellus Formation, USA: the fine line between pressure fringes and hydraulic fractures. *Geological Magazine* **159**, 2020–35.

Iannace A, Storti F, Antonellini A, Agosta F and Tondi, E (2015) Special issue "Fractured Carbonate Reservoirs", 1st volume, *Italian Journal of Geosciences* **134**, 196 pp.

Koehn D, Kelka U, Toussaint R, Siegel C, Mullen G, Boyce A, and Piazolo S (2022) Outcrop scale mixing enhanced by permeability variations: the role of stationary and travelling waves of high saturation indices. *Geological Magazine* **159**, 2279–92.

Köhler S, Duschl F, Fazlikhani H, Koehn D, Stephan T and Stollhofen H (2022) Reconstruction of cyclic Mesozoic–Cenozoic stress development in SE Germany using fault-slip and stylolite inversion. *Geological Magazine* **159**, 2323–45.

Labeur A, Beaudoin NE, Lacombe O, Emmanuel L, Petracchini L, Daëron M, Klimowicz S and Callot J-P (2021) Burial-deformation history of folded rocks unraveled by fracture analysis, stylolite paleopiezometry and vein cement geochemistry: a case study in the Cingoli Anticline (Umbria-Marche, Northern Apennines). *Geosciences* **11**, 135

La Bruna V, Lamarche J, Agosta F, Rustichelli A, Giuffrida A, Salardon R and Marié L (2020) Structural diagenesis of shallow platform carbonates: role of early embrittlement on fracture setting and distribution: case study of Monte Alpi (Southern Apennines, Italy). *Journal of Structural Geology* **131**, 103940

Lacombe O (2012) Do fault slip data inversions actually yield "paleostresses" that can be compared with contemporary stresses? A critical discussion. *Comptes Rendus Geosciences* **344**, 159–73

Lacombe O, Beaudoin N, Hoareau G, Labeur A, Pecheyran C and Callot JP (2021) Dating folding beyond folding, from layer-parallel shortening to fold tightening, using mesostructures: lessons from the Apennines, Pyrenees and Rocky Mountains. *Solid Earth* **12**, 2145–57

Lacombe O and Bergerat F (2013) Editorial: Special Issue "Faults, stresses and mechanics of the upper crust: a tribute to Jacques Angelier". *Bulletin de la Société Géologique de France* **184**, 291–7

Lacombe O and Rolland Y (2016) Editorial: Special Issue "Fluids in crustal deformation: fluid flow, fluid-rock interactions, rheology, melting and resources". *Journal of Geodynamics* **101**, 1–4

Lacombe O, Swennen R and Caracausi A (2014) Editorial: Special Issue "Fluid-rock-tectonics interactions in basins and orogens". *Marine and Petroleum Geology* **55**, 1–5.

Lacombe O, Tavani S and Soto R (2012) Editorial: Special Issue "Into the deformation history of folded rocks". *Tectonophysics*, **576–577**, 1–3.

Lamarche J, Lavenu APC, Gauthier BDM, Guglielmi Y and Jayet O (2012) Relationships between fracture patterns, geodynamics and mechanical stratigraphy in Carbonates (South-East Basin, France). *Tectonophysics* **581**, 231–45.

Laubach SE, Eichhubl P, Hilgers C and Lander RH (2010) Structural diagenesis. *Journal of Structural Geology* **32**, 1866–72.

Laubach S. E., Lamarche J., Gauthier B. D., Dunne W. M. and Sanderson D. J. (2018) Spatial arrangement of faults and opening-mode fractures. *Journal of Structural Geology* **108**, 2–15.

Laubach SE, Lander RH, Criscenti LJ, Anovitz LM, Urai JL, Pollyea RM, Hooker JN, Narr W, Evans MA, Kerisit SN, Olson JE, Dewers T, Fisher D, Bodnar R, Evans B, Dove P, Bonnell LM, Marder MP and Pyrak-Nolte L (2019). The role of chemistry in fracture pattern development and opportunities to advance interpretations of geological materials. *Reviews of Geophysics* **57**, 1065–111.

Lavenu APC and Lamarche J (2017) What controls diffuse fractures in platform carbonates? Insights from Provence (France) and Apulia (Italy). *Journal of Structural Geology* **108**, 94–107.

Lavenu APC, Lamarche J, Gallois A and Gauthier BDM (2013) Tectonic versus diagenetic origin of fractures in a naturally fractured carbonate reservoir analog (Nerthe anticline, southeastern France). *AAPG Bulletin* **97**, 2207–32.

Maerten F, Maerten L, Plateaux R and Cornard PH (2022) Joint inversion of tectonic stress and magma pressures using dyke trajectories. *Geological Magazine* **159**, 2379–94.

Manniello C, Agosta F, Todaro S, Cavalcante F and Prosser G (2022) Fracture stratigraphy of Mesozoic platform carbonates, Agri Valley, southern Italy. *Geological Magazine* **159**, 1874–96.

Massaro L, Adam J, Jonade E and Yamada Y (2022) New granular rock-analogue materials for simulation of multi-scale fault and fracture processes. *Geological Magazine* **159**, 2036–59.

Mayolle S, Soliva R, Dominguez S, Wibberley C and Caniven Y (2021) Nonlinear fault damage zone scaling revealed through analog modeling. *Geology* **49**, 968–72.

Mercuri M, Smeraglia L, Curzi M, Tavani S, Maffucci R, Pignalosa A, Billi A and Carminati E (2022) Pre-folding fracturing in a foredeep environment: insights from the Carseolani Mountains (central Apennines, Italy). *Geological Magazine* **159**, 1897–1013.

Palamakumbura R, Krabbendam M, Whitbread K, and Arnhardt C (2020) Data acquisition by digitizing 2-D fracture networks and topographic lineaments in geographic information systems: further development and applications. *Solid Earth* **11**, 1731–46,

Parizot O, Missenard Y, Barbarand J, Blaise T, Benedicto A, Haurine F and Sarda P (2022) How sensitive are intraplate inherited structures? Insight from the Cévennes Fault System (Languedoc, SE France). *Geological Magazine* **159**, 2082–94.

Pascal C (2021) *Paleostress Inversion Techniques: Methods and Applications for Tectonics*. Amsterdam: Elsevier, 400pp.

Pascal C, Jaques L and Yamaji A (2022) Full paleostress tensor reconstruction using quartz veins of Panasqueira Mine, central Portugal, part II: Final results. *Journal of Structural Geology* **162**, 104688.

Passchier, M, Passchier, CW, Weismüller, C and Urai, JL, (2021) The joint sets on the Lilstock Benches, UK: observations based on mapping a full resolution UAV-based image. *Journal of Structural Geology* **147**, 104332.

Pavlovskaia EA, Khudoley AK, Ruh JB, Moskalenko AN, Guillong M and Malyshev SV (2022) Tectonic evolution of the northern Verkhoyansk Fold-and-Thrust Belt: insights from palaeostress analysis and U–Pb calcite dating. *Geological Magazine* **159**, 2132–56.

Petit JP, Chemenda AI, Minisini D, Richard P, Bergman S and Gross M (2022) When do fractures initiate during the geological history of a sedimentary basin? Test case of a loading-fracturing path methodology. *Journal of Structural Geology* **164**, 104683,

Prabhakaran R, Bertotti G, Urai J and Smeulders D, (2021) Investigating spatial heterogeneity within fracture networks using hierarchical clustering and graph distance metrics. *Solid Earth* **12**, 2159–209

Prabhakaran R, Bruna PO, Bertotti G and Smeulders D (2019) An automated fracture trace detection technique using the complex shearlet transform, *Solid Earth* **10**, 2137–66.

Richard PD, Bazalgette L, Volery C and Toukhi A (2022) Scale discrepancy paradox between observation and modelling in fractured reservoir models in oil and gas industry. *Geological Magazine* **159**, 1914–35.

Rispoli R (1981) Stress fields about strike-slip faults inferred from stylolites and tension gashes. *Tectonophysics* **75**, T29–T36.

Roberts N M W, Drost K, Horstwood M S A, Condon D J, Chew D, Drake H, Milodowski A E, Mclean N M, Smye A J, Walker R J, Haslam R, Hodson K, Imber J, Beaudoin N and Lee J K (2020) Laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS) U–Pb carbonate geochronology: strategies, progress, and limitations. *Geochronology* 2, 33–61.

Roberts NMW and Holdsworth RE (2022) Timescales of faulting through calcite geochronology: a review. *Journal of Structural Geology* **158**, 104578.

Shan Y, Zheng J, Hu S, and Yeh EC (2021) Hard classification of polyphase fault-slip data: improvement and application. *Journal of Structural Geology* **150**, 104415.

Simón JL (2019) Forty years of paleostress analysis: has it attained maturity? *Journal of Structural Geology* **125**, 124–33.

Smith RY, Lesueur M, Kelka U, Poulet T and Koehn D (2022) Using fractured outcrops to calculate permeability tensors: implications for geothermal fluid flow and the influence of seismic-scale faults. *Geological Magazine* **159**, 2262–78.

Smith S, Agosta F, Toussaint R and Holdsworth B (2012) Editorial: Special Issue "Fault zone structure, mechanics and evolution in nature and experiment". *Journal of Structural Geology* **45** 1–2.

Tavani S, Storti F, Lacombe O, Corradetti A, Muñoz J and Mazzoli S (2015) A review of deformation pattern templates in foreland basin systems and fold-and-thrust belts: implications for the state of stress in the frontal regions of thrust wedges. *Earth-Science Reviews* **141**, 82–104.

Tondi E, Iannace A, Storti F, Antonellini A, Agosta F and Mazzoli S (2016) Special issue "Fractured Carbonate Reservoirs, IInd volume". *Italian Journal of Geosciences* **135**, 82 pp.

Torgersen E, Gabrielsen RH, Ganerød M, van der Lelij R, Schönenberger J, Nystuen JP and Brask S (2022) Repeated brittle reactivations of a pre-existing plastic shear zone: combined K–Ar and $^{40}Ar–^{39}Ar$ geochronology of the long-lived (> 700 Ma) Himdalen–Ørje Deformation Zone, SE Norway. *Geological Magazine* **159**, 2110–31.

https://doi.org/10.1017/S0016756823000031 Published online by Cambridge University Press

Tranos MD and Osman MS (2022) Rus detachment in Dammam Dome, Eastern Saudi Arabia: a new soft-sediment structure as a 'sensitive stress sensor' for the Zagros collision. *Geological Magazine* **159**, 2293–2305.

van der Pluijm BA, Hall CM, Vrolijk PJ, Pevear DR and Covey MC (2001) The dating of shallow faults in the Earth's crust. *Nature* **412**, 172–5.

Volatili F, Agosta F, Cardozo N, Zambrano M, Lecomte I and Tondi E (2022) Outcrop-scale fracture analyses and seismic modelling of a basin-bounding normal fault in platform carbonates, central Italy. *Journal of Structural Geology* **155**, 104515.

Viola G, Scheiber T, Fredin O, Zwingmann H, Margreth A and Knies J (2016) Deconvoluting complex structural histories archived in brittle fault zones. *Nature Communications* **7**, 1–10.

Zhao T, Zhang J, Ding W, Zhao R, Radwan AE, Wang X (2022) Characteristics and application of present *in situ* stress field of a strike-slip fault: a 3D finite-element simulation study. *Geological Magazine* **159**, 2361–78.

Zucchi M, Brogi A, Liotta D, Caggianelli A, Dini A, Ventruti G, Ruggieri G and Matera PF (2022) Fractures, fluid flow and inherited structures in geothermal systems: inputs from the Fe-ore deposits of eastern Elba Island (Northern Apennines, Italy). *Geological Magazine* **159**, 2238–61.