Predicting Fracture Porosity Evolution in Sandstone

Final Report

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Abstract

To better understand the porosity, strength, chemical reactivity, and patterns of fractures in the subsurface, we used evidence from mineral deposits in open fractures to unravel how fracture growth and diagenesis interact to create and destroy fracture porosity. Quartz cement textures and associated fluid inclusions and thermal histories provided data used to infer the duration and rates at which fractures open.

We developed and tested a structural diagenetic model that accounts for how fracture porosity and rock properties change as a function of thermal exposure and how fracture patterns evolve. We also documented the opening histories of entire fractures and fracture arrays in contrasting tectonic and thermal regimes and developed and tested a fully coupled diagenetic-geomechanical model that has the potential to accurately predict fluid flow characteristics of fractured rocks based on coupled effects of diagenesis and deformation.

A central theme of our research was the investigation of feedbacks between chemical and mechanical processes in opening-mode fracture growth in subsurface settings.

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Our cross-disciplinary efforts in fracture and diagenesis research involved characterization, modeling, and laboratory tests. This work built on the breakthrough of successfully reconstructing the timing and opening rates of parts of single fractures and portions of fracture arrays to document the growth and linkage of fracture arrays, and accomplishment of this grant. One goal of this research was to understand the effects of variable degrees of fracture cement fill in partitioning progressive deformation between existing fractures and the host rock and how this process affects fracture spatial distributions (whether fractures are clustered in space or not). To aid this effort we developed and published new methods and software for quantifying fracture spatial arrangements. The 1D versions of the software are widely disseminated and have been extensively used and cited and we developed and have published papers on 2D approaches.

Determining the rates at which natural fracture systems grow has long been a refractory challenge in geoscience but such information is essential information for improving predictive models. Fluid inclusion assemblages sequenced via cement texture mapping allowed us to unravel the rates and patterns of growth of entire fracture systems and the role of coupled structural and geochemical processes in governing this development. We collected fluid-inclusion data keyed to opening increments to constrain fracture event chronology. We reconstructed fracture histories from core and outcrop examples using high resolution Scanning Electron Microscope-Cathodoluminescence (SEM-CL) images along entire fractures and across multiple fractures within arrays.

The imaging and mapping protocol, in conjunction with fluid-inclusion analysis, was crucial for fracture opening and length growth history reconstructions. This approach takes advantage of an automated SEM-CL imaging system that may be used for large-area (multiple thin section) imaging that we developed. Additionally, for high resolution work, a full color SEM-CL field emission scanning electron microscope with imaging resolution of 3 to 5 nm increases the already rich textural evidence to be found in fracture cement deposits that are contemporaneous with fracture opening; we developed and published methods for optimally using this instrument.

We applied CL imaging methods, compositional analysis, electron backscatter diffraction (EBSD), and cement strength experiments to constrain the controls on, and the rates and patterns of, cement precipitation in fractures. Accounts of this work have been published and are widely cited.

This characterization work was conducted in tandem with development of linked geomechanical and diagenetic models that account for cement accumulation patterns within evolving fracture arrays and experiments designed to constrain model parameters. Model developments accomplished include 3D cement growth in the geomechanical model at all spanning nodes and mechanical partitioning of fractures into host rock. Results suggest that our integrated approach explains fracture attributes that cannot be accounted for when diagenesis or mechanics are treated as separate, isolated processes.

Five field and core-based efforts incorporating the methodology described above were conducted as parts several geoscience and engineering Ph.D dissertations M.S. theses, as documented in numerous detailed progress reports and the published literature. Follow on work is underway as part of our current BES grant.

In the following we mention some of the highlights of the research. A comprehensive review of all the publications and dissertations from this program would necessitate a book-length document. A succinct synthesis is in Laubach et al. (2019).

Selected Technical Summary of Highlights

Fracture diagenesis

A new model (Lander and Laubach, 2015) accounts for crystal growth patterns and internal textures in quartz cement in sandstone fractures, including massive sealing deposits, thin rinds or veneers that line open fracture surfaces, and bridge structures that span otherwise open fractures. High-resolution cathodoluminescence imaging of bridge structures and massive sealing deposits indicates that they form in association with repeated micron-scale fracturing whereas thin rinds do not.

Model results indicate that the three morphology types develop in response to (1) the ratio of the rates of quartz growth to fracture opening and (2) the substantially faster growth rate that occurs on non-euhedral surfaces in certain crystallographic orientations. Rind morphologies develop when the fracture opening rate exceeds two times the fastest rate of quartz growth (along the c-axis on non-euhedral surfaces) because growing crystals develop slow-growing euhedral faces. Massive sealing, on the other hand, develops where the net rate of fracture opening is less than half the rate of quartz growth on euhedral faces because all quartz nucleation surfaces along the fracture wall seal the fracture between fracturing events.

Bridge structures form at fracture opening rates that are intermediate between the massive sealing and rind cases and are associated with crystallographic orientations that allow growth to span the fracture between fracturing events. Subsequent fractures break the spanned crystal, introducing new, fast-growing non-euhedral nucleation surfaces that grow more rapidly than the euhedral faces of non-spanning crystals.

As the ratio of fracture opening to quartz growth rate increases, the proportion of overgrowths that span the fracture decreases and the c-axis orientations for these crystals gets progressively closer to perpendicular to the fracture wall until the maximum spanning limit is reached. Simulation results also reproduce “stretched crystal”, “radiator structure”, and “elongate blocky” textures in metamorphic quartz veins.

Although the East Texas example shown above considers extremely slow opening rates in a passive-margin setting, the model is applicable to other fracture types in sedimentary basins, as well as to some aspects of metamorphic vein formation. For example, the model reproduces both “stretching” and “elongate blocky” textures in metamorphic veins as shown here.

Animations above in Lander and Laubach 2015, figures 18 and 20b.

Among papers of ours that further explore these issues are Laubach et al. (2016), Hooker et al. (2018); English and Laubach (2017); Ukar et al. (2016) and Fall et al. (2016). Earlier work that informed these studies include Laubach et al. (2004a, b).

We demonstrated that diagenesis also has important implications for the evolution of rock properties and fracture patterns (Laubach et al., 2009).

Testing the fracture cement model

Becker et al. (2010) describe a test of this model. Quartz cement bridges across opening-mode fractures of the Cretaceous Travis Peak Formation provide a textural and fluid inclusion record of incremental fracture opening during the burial evolution of this low-porosity sandstone. Incremental crack-seal fracture opening is inferred based on the banded structure of quartz cement bridges, consisting of up to 700 cement bands averaging ~5 µm in thickness as observed with SEM-cathodoluminescence. Crack-seal layers contain assemblages of aqueous two-phase fluid inclusions.

Based on fluid inclusion microthermometry and Raman microprobe analyses, we determined that these inclusions contain methane-saturated brine trapped over temperatures ranging from ~130°C to ~154°C. Using textural cross-cutting relations of quartz growth increments to infer the sequence of cement growth, we reconstructed the fluid temperature and pore fluid pressure evolution during fracture opening. In combination with published burial evolution models, this reconstruction indicates that fracture opening started at ~48 Ma and above-hydrostatic pore fluid pressure conditions and continued under steadily declining pore fluid pressure during partial exhumation until present times. Individual fractures opened over a ~48 m.y. time span at rates of 16-23 µm/m.y. These slow opening rates may be characteristic of fracture systems forming in passive margin settings undergoing slow exhumation.

Using the model and fluid inclusion observations to understand fracture formation

Fall et al. (2015) describe testing our model of quartz accumulation in the Upper Cretaceous Mesaverde Group in the Piceance Basin, Colorado, considered a continuous, basin-centered gas accumulation in which gas charge of the low-permeability sandstone occurs under high pore-fluid pressure in response to gas generation. High gas pressure favors formation of pervasive systems of opening-mode fractures. This view contrasts with that of other models of low-permeability gas reservoirs in which gas migrates by buoyant drive and accumulates in conventional traps, with fractures an incidental attribute of these reservoirs. We tested aspects of the basin-centered gas accumulation model as it applies to the Piceance Basin by determining the timing of fracture growth and associated temperature, pressure, and fluid composition conditions using microthermometry and Raman microspectrometry of fluid inclusions trapped in fracture cement that formed during fracture growth. Trapping temperatures of methane-saturated aqueous fluid inclusions record systematic temperature trends that increase from ~140 to 185 °C and then decrease to ~158 °C over time, which indicates fracture growth during maximum burial conditions.

Calculated pore-fluid pressures for methane-rich aqueous inclusions of 55 to 110 MPa indicate fracture growth under near-lithostatic pressure conditions consistent with fracture growth during active gas maturation and charge. Lack of systematic pore-fluid pressure trends over time suggests dynamic pressure conditions requiring an active process of pressure generation during maximum burial conditions. Such a process is consistent with gas generation within the Mesaverde Group or by gas charge from deeper source rocks along fracture and fault systems but is inconsistent with significant high pressure generation by compaction disequilibrium during earlier stages of burial. Because of a comparison of trapping temperatures with burial and thermal maturity models, we infer that active gas charge and natural fracture growth lasted for 35 m.y. and ended about 6 Ma. Our results demonstrate that protracted growth of a pervasive fracture system is the consequence of gas maturation and reservoir charge and is intrinsic to basin-centered gas reservoirs.

Hooker et al. (2015) further tested this approach. Crack-seal texture within fracture cements in the Triassic El Alamar Formation, NE Mexico, shows that the fractures opened during precipitation of quartz cements; later, overlapping calcite cements further occluded pore space. Previous workers defined four systematic fracture sets, A (oldest) to D (youngest), with relative timing constrained by crosscutting relationships. Quartz fluid inclusion homogenization temperatures are higher within Set B (148±20°C) than in Set C (105±12°C). These data and previous burial history modelling are consistent with Set C forming during exhumation. Fluid inclusions in Set C quartz have higher salinity than those in Set B (22.9 v. 14.2wt% NaCl equivalent, respectively), and Set C quartz cement is more enriched in 18O (20.2 v. 18.7‰ VSMOW).

Under most assumptions about the true temperature during fracture opening, the burial duration, the amount of cement precipitated and fluid-flow patterns, it appears that the fracture fluid became depleted in 18O and enriched in 13C. This isotopic evolution, combined with increasing salinity, suggests that throughout fracture opening there was a gravity-driven influx of fluid from upsection Jurassic evaporites, which form a regional décollement. Fracture opening amid downward fluid motion suggests that fracturing was driven by external stresses such as tectonic stretching or unloading, rather than increases in fluid pressure.

Denny et al. (2020) reported on pore water oxygen isotope results that bear on testing the model. Oxygen isotope analyses of diagenetic cements can provide detailed evidence of sedimentary burial processes and conditions, as the δ18O values of precipitating minerals reflect contemporaneous local δ18Owater and temperature conditions. Uncertainties in the timing and rates of pore water δ18O evolution in sedimentary basins can complicate interpretation of these records. Fracture-bridging (0.5–1 mm) quartz cements observed in sandstones of the Cretaceous Travis Peak Formation in the East Texas basin show clear growth-zoning by cathodoluminescence and contain detailed fluid inclusion records of temperature that make them excellent candidates for interrogating prolonged histories of basin temperature and the evolution of δ18O in basin pore water.

New secondary ion mass spectrometer (SIMS) δ18Oquartz isotopic data from fluid inclusion-rich quartz bridges in Travis Peak sandstones record a steady increase of pore water δ18O values from ∼5 to 7‰ (VSMOW; Vienna Standard Mean Ocean Water) as the sandstone warms from ∼130 to 150 °C. To help evaluate whether this trend could be generated solely from local water-rock interactions in response to burial compaction, a one-dimensional closed system isotopic burial model was created to simulate how δ18Owater values change in a quartz-dominated sandstone during diagenesis. Using both directly measured and inferred rates of Travis Peak compaction, the magnitude of change in δ18Owater that we calculate from quartz bridge geochemistry cannot be reasonably modeled solely by local quartz mechanical compaction, pressure solution, and cementation processes, necessitating significant fluxes of silica and high-δ18O water from outside of the sandstones prior to maximum burial. This indicates that even units which appear surrounded by significant barriers to fluid flow (i.e., mudrock-bounded channel sandstones) may have been infiltrated and diagenetically modified by large fluxes of fluid on geologic time scales.

Cement accumulation systematics also affect fault rocks, as discussed by Laubach et al. (2014). Small, meter-to decimeter-displacement oblique-slip faults cut latest Precambrian lithic arkose to feldspathic litharenite and Cambrian quartz arenite sandstones in NW Scotland. Despite common slip and thermal histories during faulting, the two sandstone units have different fault-core and damage-zone attributes, including fracture length and aperture distributions, and location of quartz deposits. Fault cores are narrow (less than 1 m), low-porosity cataclasite in lithic arkose/feldspathic litharenites.

Damage zone-parallel opening-mode fractures are long (meters or more) with narrow ranges of lengths and apertures, are mostly isolated, have sparse quartz cement, and are open. In contrast, quartz arenites, despite abundant quartz cement, have fault cores that contain porous breccia and dense, striated slip zones. Damage-zone fractures have lengths ranging from meters to centimeters or less, but with distributions skewed to short fractures, and have power-law aperture distributions.

Owing to extensive quartz cement, they tend to be sealed. These attributes reflect inhibited authigenic quartz accumulation on feldspar and lithic grains, which are unfavorable precipitation substrates, and favored accumulation on detrital quartz. In quartz breccia, macropores >0.04 mm wide persist where surrounded by slow-growing euhedral quartz.

Differences in quartz occurrence and size distributions are compatible with the hypothesis that cement deposits modify the probability of fracture reactivation. Existing fractures readily reactivate in focused growth where quartz accumulation is low and porosity high. Only some existing, partly cemented fractures reactivate and some deformation is manifest in new fracture formation in partitioned growth where quartz accumulation is high. Consequences include along-strike differences in permeability and locus of fluid flow between cores and damage zones and fault strength.

Our insights have practical value. Two examples that quantify this value are Weisenberger et a. (2019) and Almansour et al. (2019).

Diagenesis and fluid flow: geomechanical model results

Olson et al. (2009) describe some of the progress we made on understanding how fractures and diagenesis interact.

Accurate predictions of natural fracture flow attributes in sandstones requires an understanding of the underlying mechanisms responsible for fracture growth and aperture preservation. Poroelastic stress calculations combined with fracture mechanics criteria show that it is possible to sustain opening mode fracture growth with sub-lithostatic pore pressure without associated or pre-emptive shear failure. Crack-seal textures and fracture aperture to length ratios suggest that preserved fracture apertures reflect the loading state that caused propagation. This implies that for quartz-rich sandstones, the synkinematic cement in the fractures and in the rock mass props fracture apertures open and reduces the possibility of aperture loss on unloading and relaxation.

Fracture pattern development due to subcritical fracture growth for a limited range of strain histories is demonstrated to result in widely disparate fracture pattern geometries. Substantial opening mode growth can be generated by very small extensional strains (on the order of 10-4); consequently, fracture arrays are likely to form in the absence of larger scale structures. The effective permeabilities calculated for these low strain fracture patterns are considerable. To replicate the lower permeabilities that typify tight gas sandstones requires the superimposition of systematic cement filling that preferentially plugs fracture tips and other narrower portions of the fracture pattern.

These insights suggest that the disciplinary boundaries that impede progress need to be broken down. Our program contributed to this with a special issue of the Journal of Structural Geology that introduced the concept of structural diagenesis: Structural diagenesis is the study of the relationships between deformation or deformational structures and chemical changes to sediments. The alliance of structural geology and metamorphic petrology is essential to an understanding of high-temperature deformation. But no such alliance supports research on the increasingly important structural and diagenetic phenomena in sedimentary basins. As papers in this theme section and in recent literature show, such an alliance—structural diagenesis—can help unlock scientific knowledge about the low-temperature realm of sedimentary basins that is of great intrinsic and practical interest.

The role of chemistry in fracture pattern development was further advanced by another paper from our program, Laubach et al. (2019). Natural fractures are increasingly recognized to result from processes that couple mechanical failure and chemical reactions. Chemical reactions aid fracture growth through stress corrosion, whereas sealing, tip blunting, and crack-jump in response to chemical mass transfer and creep processes can impede further fracture growth and alter size and spacing patterns. Chemical-mechanical interactions affect spatial and temporal patterns of fracture network evolution and their interpretation, fault stability, and fracture and fault flow properties.

Our ongoing research is testing how natural cement accumulates in fractures, how cement deposits can be used to reconstruct fracture history, and how interacting chemical-mechanical processes affect the size distribution, spatial organization, strength, porosity, and permeability of fracture arrays. Fracture mechanics has been central to interpreting opening-mode fractures in rock, but our results show that mechanics must be coupled with geochemical principles to understand how fracture porosity, spacing, size and connectivity evolve. We are developing crystal growth models that predict cement accumulation patterns and volumes in fractures and are incorporating these diagenetic features into geomechanical models of fracture pattern evolution, showing how evolving rock mechanical properties and the mechanical interaction of cement accumulation and fracture growth can influence pattern geometry and fluid flow attributes.

We recently developed new approaches and software to quantify spatial organization. Laboratory tests we are developing provide key rock and fracture mechanical constraints. A breakthrough is our demonstration that fracture growth and diagenesis interact to create and destroy fracture porosity, and evidence of this process is preserved in quartz cement deposits in partially open fractures. We showed that using cement textures and fluid inclusion data combined with burial histories allows inference of duration and rates at which fractures open, allowing unprecedented comparison of fracture growth models with natural examples.

Our results show that these structural-diagenetic principles apply to all rock types. Using fracture pattern reconstruction approaches on subsurface data sets we are testing the evolving models. But for fully testing predictions of fracture size and spatial arrangements, models require validation in special outcrops, where fractures have diagnostic features that show they are like those in the deep subsurface. In September 2018, we led a symposium field trip to some of these outcrops, as described on our site under field symposia.

Two PhD dissertation projects focused on outcrop and horizontal core data sets. The studies investigated examples where the interaction between cement deposition and fracture widening correlates with differences in many key fracture pattern attributes, including length, height, and aperture.

Fluid inclusion assemblages: new insights

The history of the pressure, temperature, and composition of fluids is fundamental to understanding how the Earth works. This type of information is also of great practical value to ore deposit and hydrocarbon exploration. Such thermometric data is obtained from minute amounts of fluids trapped by various natural processes within minerals. Our research revealed new insights about fluid inclusions, described by Fall and Bodnar (2018).

Analysis of fluid inclusions is a standard approach for research on sedimentary, metamorphic and igneous rocks. As part of the Structural Diagenesis Initiative, we are using fluid inclusions to help find out when and why fractures form.

A key idea in the study of fluid inclusions is that of the fluid inclusion assemblage, defined as the most finely discriminated, petrographically associated group of coeval inclusions. Fluid inclusion assemblages, or FIAs, are the basic building blocks of fluid inclusion studies.

Although a rigorous methodology for the collection of fluid inclusion data has been developed over the years, acceptable or achievable ranges in temperature data for groups of coeval fluid inclusions have not been rigorously evaluated and defined. The goal of the recently published paper by Fall and Bodnar is to determine ranges in homogenization temperature (Th) for well-characterized fluid inclusion assemblages (FIAs) from various geologic environments to provide guidance concerning the achievable range in Th.

The reconstruction of fracture histories is part of this work (e.g., Alzayer et al., 2015).

Fracture spatial arrangement: new methods

A grant paper, Marrett et al. (2018) received the AAPG Petroleum Structure & Geomechanics Division Best Recent Paper Award. The paper, Correlation analysis of fracture arrangement in space was published in the March 2018 issue of Journal of Structural Geology.

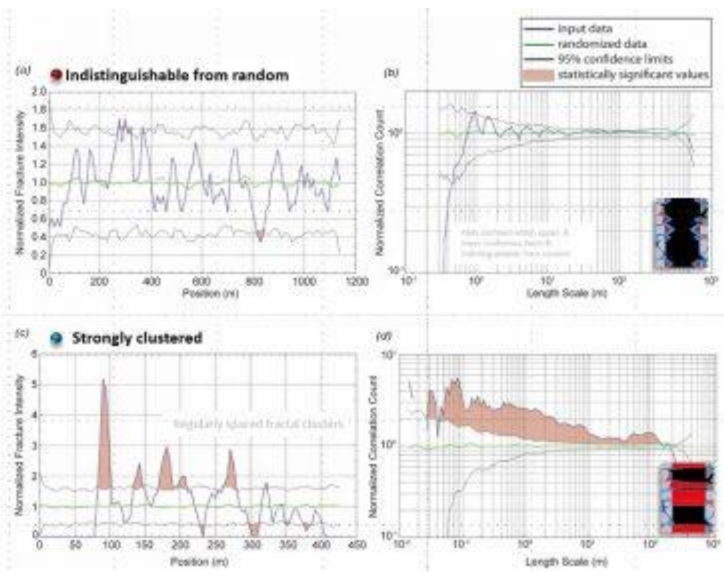
Marrett et al. present new techniques that overcome limitations of standard approaches to documenting spatial arrangement. The new techniques directly quantify spatial arrangement by normalizing to expected values for randomly arranged fractures. The techniques differ in terms of computational intensity, robustness of results, ability to detect anti-correlation, and use of fracture size data. Variation of spatial arrangement across a broad range of length scales facilitates distinguishing clustered and periodic arrangements—opposite forms of organization—from random arrangements. Moreover, self-organized arrangements can be distinguished from arrangements due to extrinsic organization. Traditional techniques for analysis of fracture spacing are hamstrung because they account neither for the sequence of fracture spacings nor for possible coordination between fracture size and position, attributes accounted for by our methods.

All the new techniques reveal fractal clustering in a test case of veins, or cement-filled opening-mode fractures, in Pennsylvanian Marble Falls Limestone. The observed arrangement is readily distinguishable from random and periodic arrangements. Comparison of results that account for fracture size with results that ignore fracture size demonstrates that spatial arrangement is dominated by the sequence of fracture spacings, rather than coordination of fracture size with position. Fracture size and position are not completely independent in this example, however, because large fractures are more clustered than small fractures. Both spatial and size organization of veins here probably emerged from fracture interaction during growth. The new approaches described here, along with freely available software to implement the techniques, can be applied with effect to a wide range of structures, or indeed many other phenomena such as drilling response, where spatial heterogeneity is an issue.

Correlation analysis of fracture arrangement in space makes the case that opening-mode fracture or fault spacings cannot be effectively characterized using traditional statistical techniques because most ignore the sequence of fracture spacings and therefore are not designed to study spatial arrangement. For instance, datasets with different spatial arrangements can have identical statistics of spacing, such as average or median.

The paper and software, CorrCount, are both published open access. Since the technique was invented, we have used the time to explore possible uses of NCC and to learn the nuances of interpreting NCC plots. For instance, we have documented a range of spatial arrangement patterns in outcrop and subsurface fracture data, including some described in companion papers in the special issue of the journal in which this paper appeared (some of which are listed below).

The implications for better understanding of fracture processes generally are substantial. We think the paper and associated software will have a long life contributing to practical and fundamental progress in petroleum structure and geomechanics.



One example of the use of the technique is illustrated here. The figure is modified from John Li et al.'s 2018 Journal of Structural Geology paper that shows evidence of mechanical impact of cement on spatial arrangement. The diagram compares fractures in Cretaceous Frontier Formation sandstone sharing ENE strike but differing burial conditions and degrees of quartz cement spanning potential. Here clustering is quantified using Marrett et al.'s normalized correlation count method. The insets illustrate the contrast in degree of cement spanning fractures at the localities (the diagrams are quartz rinds and quartz bridges from Lander and Laubach 2015). Shaded areas of curves show statistically significant values.

In the first row, (a) shows normalized fracture intensity variation and (b) shows normalized correlation count for spatial arrangements. The diagrams show values are within a 95% confidence envelope, so patterns are indistinguishable from random. This pattern is from outcrop, where cool temperature histories during fracture led to low spanning potential, and little mechanical interaction between quartz cement bonds and fracture opening.

In the second row, (c) shows normalized fracture intensity variation and (d) normalized correlation count. Patterns exceed the 95% confidence envelope. An interpretation of the pattern based on Marrett et al. is that the patterns reflect regularly spaced fractal clusters. For these patterns, from deep cored wells, high spanning potential led to significant mechanical interaction between spanning quartz cement deposits in fracture opening.

Some other recent papers that use or discuss the CorrCount software include Laubach et al., (2018a, b); Li et al. (2018), Gale et al. (2018, 2019), and Wang et al. (2019).

Implications for size scaling

We developed systemic methods to study fracture size scaling (Ortega et al., 2006) and demonstrated that natural systems show universal patterns (Hooker et al. (2014).

Hooker et al. (2014) used a high-resolution data set of kinematic aperture (opening displacement) of opening-mode fractures, from large (up to 2 m long) quartz-cemented sandstone samples, shows that microfractures are ubiquitous and that most natural-fracture sets are better fit by power-law size distributions than by exponential, normal, or log-normal distributions. The data set includes 3822 fractures within 68 scanlines from eight formations on three continents. Kinematic apertures were measured along scanlines using scanning electron microscope cathodoluminescence (SEM-CL) and, for field data, using a hand lens. Microtextural evidence from SEM-CL shows that power law–distributed fractures typically have crack-seal texture and are composed of opening increments having a narrow (characteristic) aperture size range. In contrast, rare non-power-law–distributed fracture populations lack crack-seal texture. Power-law exponents, as measured in one dimension, have values of –0.8 ± 0.1. Most variation among fracture sets results from power-law coefficients, which constitute a scale-invariant measure of fracture intensity. We show how observed scaling patterns can be used to improve estimations of large-fracture spacing in cases where fracture sampling is limited, as by the width of cores. The low (<1) value of the power-law scaling exponent reflects but a gentle increase in fracture frequency with decreasing size, such that microfracture abundances in core are commonly too low for statistically robust sampling. On the other hand, the consistency of the scaling exponent among fracture sets within various tectonic settings is such that the exponent can be assumed, facilitating large-fracture spacing estimations. The assumption of the scaling exponent should be supported by the presence of crack-seal texture within fractures.

Diagenesis affects fracture scaling and height patterns (Hooker et al., 2012, 2013). In Cambrian Mesón Group, NW Argentina, small faults and three opening-mode fracture sets defined by orientation and cement texture (Sets 1–3) formed sequentially in sandstone that most likely had constant mechanical properties throughout deformation. Yet the opening-mode sets display contrasting fracture-aperture-size distributions, spacing patterns, and tendency to be bed bounded. Set 1 fractures are quartz-filled or -lined opening-mode fractures with crack-seal texture, having a wide range of opening-displacement (kinematic aperture) sizes; they are irregularly spaced and non-strata-bounded fractures. Set 1 macro and microfracture-opening-displacement sizes are well described by a power law with slope −0.8. Set 2 fractures are microscopic, mostly quartz filled and have characteristic aperture sizes, are probably not bed bounded and have either a near-random or clustered spatial distribution. Set 3 fractures are quartz-lined, opening-mode fractures with extensive open pore space, having a narrow (characteristic) opening-displacement size distribution; they are regularly spaced and stratabounded. Differences between Sets 1 and 3 can be accounted for by quartz deposition resisting fracture reopening to a greater extent for Set 1 during repeated, episodic growth, where crack-seal texture is present in fracture-spanning quartz. In contrast Set 3 fractures are nearly barren with only trace-cement deposits that did not resist opening. Power-law opening-displacement size distributions may be favored in cases where fracture growth is unequally partitioned amongst variably cemented fractures, whereas a characteristic size is favored where growth is unaffected by cementation. Results imply that thermal history and diagenesis are important for fracture-size-distribution patterning.

We reviewed microfractures. The attributes of microfractures are strongly sensitive to diagenetic history (Anders et al., 2014) with important implications for deep basin setting (e.g., Laubach et al., 2023).

Implications of other rock types

Although our program focused on fractures in sandstone, our results are applicable across a wide range of rock types and fracture sizes. Some examples include Baques et al. (2020) and Ukar et al. (2020) and Ukar and Laubach (2016) for carbonate rocks, Gale et al. (2014) for shale.

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