Cement deposits in opening-mode fractures in sandstone: implications for size, spacing, connectivity, and erosion

Stephen E. Laubach[1*^], Qiqi Wang[1,2], Rodrigo Corrêa[2], Stephanie R. Forstner[1,2], Mahmood Shakiba[3], Byungtark Lee[3], Nina Hebel[4], Sara Elliott[1] and John N. Hooker[5]

[1] Bureau of Economic Geology, The University of Texas at Austin, Austin, TX, USA
[2] Department of Geological Sciences, The University of Texas at Austin, TX, USA
[3] Department of petroleum & Geosystems Engineering, The University of Texas at Austin, TX, USA
[4] Energy & Earth Resources, The University of Texas at Austin, TX, USA
[5] University of the Incarnate Word, San Antonio, TX USA
* Corresponding author information: steve.laubach@beg.utexas.edu 1-512-471-6303
^ Presenting author

1. Abstract

In the case of opening-mode fractures in sandstone that formed or resided at depth in diagenetic conditions (ca. 50 to 200 ℃) a chemical perspective helps guide characterization of open fracture size, spatial arraignment, and connectivity. Partial quartz fill and microfractures create weakness susceptible to reactivation and may impart strength anisotropy. Studies that account for both chemical and mechanical processes have great potential to solve challenging practical problems in subsurface science and to help interpret outcrop fracture patterns.

2. Introduction

How fracture patterns develop has been a challenging research question in the earth sciences for more than 100 years. A recent review of the role of chemistry in fracture pattern development and of prospects for future research (Laubach et al. 2019) describes how many tools of chemical analysis, experiment, modeling, and theory can be brought to bear on understanding how fracture patterns develop at geological time scales. A major conclusion is that chemical and mechanical investigations together have great potential to solve challenging practical problems in subsurface science. A chemical perspective helps solve challenges to understanding subsurface fractures, including how to better use limited subsurface samples, how to interpret ambiguous outcrop analogs, and how to overcome difficulties determining which models are correct from observations.

This extended abstract summarizes and expands on several points made in the 2019 review paper. Although chemical effects are important at all depths (e.g., Eppes et al. 2019), here our focus is on opening-mode fractures in sandstone that formed or that have resided at depths of ca. 1 km or more (diagenetic settings, ca. 50 to 200 ℃). Although in this setting rock-water interaction, fluid type, and salinity affect fracture rates (Rijken et al. 2002; Viswanathan et al. 2022), we restrict or focus to the chemical effect of the formation of mineral deposits, specifically quartz accumulation (Lander & Laubach 2015). At depth, such fractures may influence the success of engineering operations in geothermal reservoirs, for example, by governing flow paths and heat exchange surface area (e.g., Ghassemi 2012). Near or at the surface (Fig. 1), such fractures can be conduits for groundwater flow. If well exposed, they may be used as guides or analogs for fractures existing at greater depths, where inherent sampling precludes pattern characterization (e.g., Ukar et al. 2019). The examples summarized here offer a glimpse of topics that can be addressed by geologic field and laboratory studies of fractures in sandstone outcrops.

Figure 1. Fracture trace patterns (dark lines) in outcrop, Cambrian sandstone, North America. Plan view of vertical fracture traces on bed surface. Note the prominent north-striking set. For fractures that formed or resided at depth, size, spatial arrangement, and connectivity *of open fractures depends on fracture diagenesis—cement deposits or dissolution features—and thus actual values may not correspond to those derived from traces patterns visible on remote images. Analysis of cement deposits needs to be part of the characterization protocol. Thin NS and EW white lines crossing outcrop are measuring tapes for 1D scanlines. 30-m height drone image: R. Correa, 2022.*

3. Size, spatial arrangement, and connectivity

For opening-mode fractures, size, spatial arrangement, and connectivity are essential elements defining fracture patterns. For fluid flow and rock strength, the specific pattern that is present —the sizes and arraignments of fractures—can have a profound effect of rock behavior (e.g., Olson et al. 2007; Prabhakaran et al. 2021). A review of sandstone opening-mode fracture size, spatial arrangement, and connectivity is beyond the scope of this note. Useful background references include Hooker et al. (2014 size distribution), Laubach et al. (2018 spatial arraignment); and Sanderson and Nixon (2018 connectivity). Here we illustrate several ways cement deposits modify these attributes.

3.1. Size

Opening-mode fracture size can be specified by the height, length, and aperture of individual fractures. However, since fractures tend to grow by linkage over a wide range of scales, defining height and length can be problematic. Opening displacement (kinematic aperture) measures on 1D lines of observation tend to be repeatable, and extensive aperture size distribution data sets exist for sandstones (Hooker et al. 2014). Although many fracture populations that formed in the subsurface in sandstone have aperture size distributions that can be described by power laws, other have narrow aperture size ranges (e.g., Laubach et al. 2016). The difference may be due to how quartz deposits mechanically interact with fracture growth and nucleation (Hooker et al. 2012).

For fractures at depth, a pattern found in both fractures having power-law aperture size distributions and those without is the tendency for narrow fractures to seal more readily than wide fractures, leading to aperture-size dependent sealing (Laubach 2003). Although this phenomenon is partly a consequence of the smaller volume relative to surface area of narrow fractures, the pattern is a predictable consequence of the systematics of quartz accumulation (Lander & Laubach 2015). Calculations of fracture porosity and permeability can take this process into account.

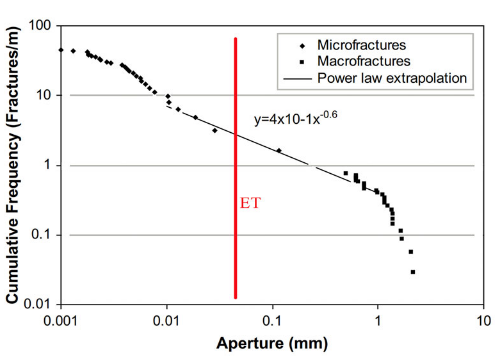

Figure 2. Fracture aperture size and size-dependent sealing. Cumulative frequency versus kinematic aperture. Microfracture (diamonds) and macrofractures (squares) same set, horizontal core 1D scanline. Power law extrapolation from largest microfractures toward larger fracture sizes. ET marked by red line is the emergent threshold aperture size below which fractures are fully sealed with quartz. In part after Hooker et al. 2009.

3.2. Spatial arrangement

A fundamental characteristic of opening-mode arrays is the pattern of their positions in space. New methods that allow these patterns to be quantified efficiently are among the factors driving research on this topic (e.g., Laubach et al., 2018). Although patterns that appear to be regularly spaced are common

(Fig. 1), studies of horizontal wells and image logs are revealing many patterns that are strongly clustered (e.g., Li et al. 2018; Wang et al. 2020). A correlation between clustered patterns and copious amounts of quartz deposited during fracture growth and vice versa (Fig. 3) suggests that the mechanical effects of quartz deposits could promote clustering.

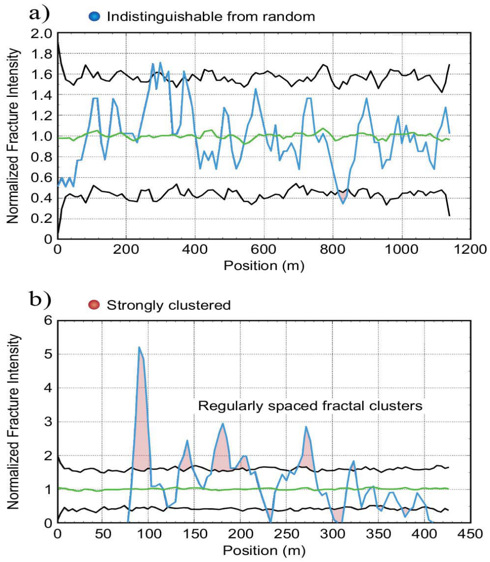

Figure 3. Contrasts in fracture spatial arrangement correlate with differences in the degree of quartz spanning between fracture walls during fracture growth. Curves: data (blue line); randomized data (green line), 95% confidence envelope (black lines). (a) Normalized fracture intensity versus for case of quartz accumulation with minimal spanning. Pattern is indistinguishable from random. (b) Normalized fracture intensity versus for case of quartz accumulation with extensive spanning. Pattern is clustered. Observations from Cretaceous sandstone, same fracture set, having different thermal histories. Modified from Laubach et al., 2019, after Li et al., 2018.

3.3. Connectivity

Another measure of fracture size is that of the interconnected fractures. Even fully disconnected fracture arrays can have a substantial impact on fluid flow and rock strength (Philip et al. 2005). But for rocks having very low intrinsic porosity and permeability such as crystalline rocks, interconnected fracture paths may be the only way for fluid to transit the rock body even on long time scales, and so mapping network interconnections has long been a part of fracture pattern description (e.g., Sanderson & Nixon 2018). Diagenetically modified sandstones are intermediate cases, with the reduction in host rock porosity and permeability depending on progress of sandstone diagenesis. Because fractures have a range of widths, narrow tips, and some mechanical interconnections may tend to be composed of narrow segments, quartz accumulations will tend to systematically reduce fracture length and close off interconnections, modifying connectivity for flow and system permeability values (Fig. 4) a phenomenon that has been modeled (Olson et al. 2007). For geothermal applications, this could be beneficial if fractures sufficitly enhance permeability without interconnecting into fast pathways. Systematic patterns of quartz accumulation impose a scale on network open fracture connectivity (S. Forstner et al. in progress 2022).

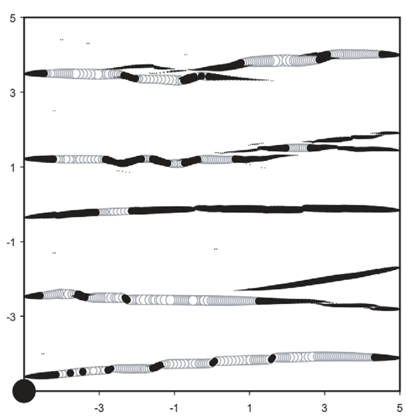

Figure 4. Connectivity and cement deposits. Numerical model showing fractures and sealed segments (black, below aperture 6×10^{-4} m). Diameter of black circle scale is 2×10^{-3} m. Similar connectivity reduction is observed in natural examples. In part after Olson et al., 2007.

4. Implications for fractured outcrops

The mechanical properties of partly or completely quartz filled fractures can markedly influence the strength and weathering of sandstones. Quartz-filled microfractures having strong preferred orientations can impart strength anisotropy that manifests as barren macroscopic fractures. Reactivation of partly quartz filled fractures is prevalent in alpine environments. Outcrop examples from a range of alpine and subglacial settings illustrate how partial to complete quartz fill in otherwise similar quartz arenites affects outcrop appearance. Examples are from Cambrian quartz cemented marine sandstones from Argentina (Hooker et al. 2013), Scotland (Laubach & Diaz-Tushman 2009), Wyoming, and New York. Subtle evidence of quartz cement in fractures can be detected in the field but needs to be corroborated with microscopy.

5. Conclusions

Much has been learned about the size, spatial and temporal complexity inherent to opening-mode fracture systems, but severe challenges remain. The 2019 article in Reviews of Geophysics describes how future advances will require new approaches based on a chemical perspective. Chemical processes play a larger role in opening-mode fracture pattern development than has hitherto been appreciated. Examples summarized here show how cement deposits in fractures can influence effective (open) size, spatial arrangement, and connectivity. Partial quartz fill and microfracture populations modify how dense quartz-cemented sandstones weather and erode in alpine environments. Fracture characterization and modeling protocols need to include cement deposits if fractures formed or resided at depth.

6. Acknowledgments

Our research on fracture pattern development is funded by grant DE-FG02-03ER15430 from Chemical Sciences, Geosciences and Biosciences Division, Office of Basic Energy Sciences, Office of Science, U.S. Department of Energy. Our work on fractures is partly supported by the Fracture Research and Application Consortium at The University of Texas at Austin.

7. References

Eppes, M.C., Hancock, G.S., Chen, X., Arey, J., Dewers, T., Huettenmoser, J., Kiessling, S., Moser, F., Tannu, N., Weiserbs, B., & Whitten, J. 2019. Rates of subcritical cracking and long-term rock erosion. Geology, 46 (11), 951–954. doi:10.1130/G45256.1.

Hooker, J.N., Laubach, S.E., Marrett, R. 2014. A universal power-law scaling exponent for fracture apertures in sandstone. Geological Society of America Bulletin 126 (9-10), 1340–1362. doi: 10.1130/B30945.1

Hooker, J.N., Gomez, L.A., Laubach, S.E., Gale, J.F.W., Marrett, R. 2012. Effects of diagenesis (cement precipitation) during fracture opening on fracture aperture-size scaling in carbonate rocks. In J. Garland, J.E. Neilson, S.E. Laubach, K.J. Whidden (eds.), Advances in Carbonate Exploration and Reservoir Analysis, Geological Society of London Special Publications 370, 187–206. doi:10.1144/SP370.9.

Lander R.H., Laubach, S.E. 2015. Insights into rates of fracture growth and sealing from a model for quartz cementation in fractured sandstones. Geological Society of America Bulletin 127 (3-4), 516–538. doi: 10.1130/B31092.1

Hooker, J.N., Laubach, S.E., & Marrett, R. 2013. Fracture-aperture size–frequency, spatial distribution, and growth processes in strata-bounded and non-strata-bounded fractures, Cambrian Mesón Group, NW Argentina. Journal of Structural Geology, 54, 54–71. doi.org/10.1016/j.jsg.2013.06.011

Hooker, J.N., Gale, J.F.W., Gomez, L.A., Laubach, S.E., Marrett, R., Reed, R.M. 2009. Aperture-size scaling variations in a low-strain opening-mode fracture set, Cozzette Sandstone, Colorado, Journal of Structural Geology, 31, 707-718. doi: 10.1016/j.jsg.2009.04.001

Laubach, S.E. 2003. Practical approaches to identifying sealed and open fractures. AAPG Bulletin 87 (4), 561–579. doi: 10.1306/11060201106

Laubach, S.E. & Diaz-Tushman, K. 2009. Laurentian paleostress trajectories and ephemeral fracture permeability, Cambrian Eriboll Formation sandstones west of the Moine thrust zone, northwest Scotland. Journal of the Geological Society (London), 166 (2), 349–362.

Laubach, S.E., Fall, A., Copley, L.K., Marrett, R., Wilkins, S. 2016. Fracture porosity creation and persistence in a basement-involved Laramide fold, Upper Cretaceous Frontier Formation, Green River Basin, U.S.A. Geological Magazine 153 (5/6), 887–910. doi:10.1017/S0016756816000157

Laubach, S.E., Lamarche, J., Gauthier, B.D.M., Dunne, W.M., Sanderson, D.J. 2018. Spatial arrangement of faults and opening-mode fractures. Journal of Structural Geology 108, 2–15. doi.org.10.1016/j.jsg.2017.08.008

Laubach, S.E., Lander, R.H., Criscenti, L.J., et al. 2019. The role of chemistry in fracture pattern development and opportunities to advance interpretations of geological materials. Reviews of Geophysics, 57 (3), 1065–1111. doi:10.1029/2019RG000671

Li, J.Z., Laubach, S.E., Gale, J.F.W., & Marrett, R. 2018. Quantifying opening-mode fracture spatial organization in horizontal wellbore image logs, core and outcrop: application to Upper Cretaceous Frontier Formation tight gas sandstones, USA. Journal of Structural Geology 108, 137-156. doi.org/10.1016/j.jsg.2017.07.005

Olson, J.E., Laubach, S.E., & Lander, R.L. 2007. Combining diagenesis and mechanics to quantify fracture aperture distributions and fracture pattern permeability. In L. Lonergan, R.J. Jolley, D.J. Sanderson, K. Rawnsley (eds.), Fractured Reservoirs, Geological Society of London Special Publication 270, 97–112.

Philip, Z.G., Jennings, J.W., Jr., Olson, J.E., Laubach, S.E., & Holder, J. 2005. Modeling coupled fracture-matrix fluid flow in geomechanically simulated fracture networks: SPE Reservoir Evaluation & Engineering, 8 (4), 300–309.

Prabhakaran, R., Bertotti, G., Urai, J., Smeulders, D. 2021. Investigating spatial heterogeneity within fracture networks using hierarchical clustering and graph distance metrics. Solid Earth 12 (10), 2159-2209. https://doi.org/10.5194/se-12-2159-2021

Rijken,P., Holder, J., Olson, J.E., Laubach, S.E. 2002. Predicting fracture attributes in the Travis Peak Formation using quantitative mechanical modeling and structural diagenesis, GCAGS Transactions, 52, 837–847.

Sanderson, D.J., Nixon, C.W. 2018. Topology, connectivity and percolation in fracture networks. Journal of Structural Geology 115, 167–177.

Ukar, E., Laubach, S.E., & Hooker, J.N. 2019. Outcrops as guides to subsurface natural fractures: Example from Late Jurassic to Early Cretaceous Nikanassin Formation, Grande Cache, Alberta Foothills, Canada. Marine & Petroleum Geology, 103, 255–275. doi:10.1016/j.marpetgeo.2019.01.039

Viswanathan, H.S., Ajo-Franklin, J., Birkholzer, J.T., Carey, J.W., Guglielmi, Y., Hyman, J.D., et al. 2022. From fluid flow to coupled processes in fractured rock: recent advances and new frontiers. Reviews of Geophysics, 60 (1), e2021RG000744.

Wang, Q., Narr, W., Laubach, S.E. 2020. Characterizing subsurface fracture spatial distribution in the East Painter Reservoir anticline, Wyoming. SPE/AAPG/SEG Unconventional Resources Technology Conference, URTeC-3265, 12 p. doi: 10.15530/urtec-2020-3265