Journal of Structural Geology 32 (2010) 1866–1872

Contents lists available at ScienceDirect

Journal of Structural Geology

journal homepage: www.elsevier.com/locate/jsg

Structural diagenesis

S.E. Laubach[a,*], P. Eichhubl[a], C. Hilgers[b], R.H. Lander[c]

[a] Bureau of Economic Geology, Jackson School of Geosciences, The University of Texas at Austin, Austin TX, USA
[b] Department of Reservoir-Petrology, RWTH Aachen University, 52056 Aachen, Germany
[c] Geocosm, 3311 San Mateo Drive, Austin TX, USA

ARTICLE INFO

Article history:
Received 29 July 2010
Received in revised form
27 September 2010
Accepted 2 October 2010
Available online 12 October 2010

Keywords:
Coupled deformation-fluid flow-thermal transport-chemical reaction
Diagenesis
Fault
Fracture
Mechanics
Rate
Timing

ABSTRACT

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.

1. Introduction

An understanding of interactions of structure and diagenesis is increasingly important in a wide range of applications, including predicting the fate of fluids injected deep underground (Stephansson et al., 1996; Tsang, 1999, 2005; Dockrill and Shipton, 2010) and extracting hydrocarbon resources from unconventional, deep reservoirs (Knipe, 1993; Philip et al., 2005; Lander et al., 2008; Olson et al., 2009). Interaction of chemical and mechanical processes is unsurprising in sedimentary rocks that contain hot, reactive fluids and that are subject to dissolution, cement precipitation, and other chemical reactions. In the high-temperature realm of metamorphism, these interactions are so important that metamorphic petrology is a fundamental part of the structural geology curriculum. Indeed, it is essential to the success of structure research, manifest in extensive coverage of metamorphic petrology in the Journal of Structural Geology and frequent contributions of structural geologists to metamorphic petrology literature.

Yet at the other end of the temperature spectrum, in the low-temperature realm of diagenesis (below about 300 °C), systematic student cross-training in sedimentary petrology and structural geology is rare, owing, perhaps, to decades of petroleum industry focus on shallow parts of sedimentary basins, in which original depositional fabrics may dominate petrophysical properties and structures are rarely penetrative. Although diagenesis, *as defined*, includes both chemical and mechanical processes that affect sediments prior to the onset of metamorphism, much of the literature on postdepositional sediment alteration has focused on chemical processes without reference to structure or mechanics (Milliken, 2003). A review of papers in the Journal of Sedimentary Research (JSR) and Sedimentary Geology and a textbook (Giles, 1997) shows that structures have been mostly overlooked, with the exception of compaction and pressure solution (Bjørlykke, 1999; Gundersen et al., 2002). No paper on the diagenesis of fractures or faults has been published in JSR. Mechanics is neither central to the training of most sedimentary petrologists nor an integral part of their world view. Likewise, in structural geology, diagenetic processes are curiously neglected. For example, as of 2010 only 21 papers in the Journal of Structural Geology (JSG) mention diagenesis in title, abstract, or keywords. A third of these papers are actually about low-grade metamorphism. Only five papers, all published in the last 5 years, cover aspects of diagenesis, compaction, and/or fracture (~0.1% of all JSG papers). The role of diagenesis in fault-rock properties *has* received attention in JSG and elsewhere (Chester and

* Corresponding author. Tel.: +1 512 471 6303.
E-mail address: steve.laubach@beg.utexas.edu (S.E. Laubach).

0191-8141/$ – see front matter © 2010 Elsevier Ltd. All rights reserved.
doi:10.1016/j.jsg.2010.10.001

Logan, 1986; Knipe, 1993; Hacker, 1997; Vrolijk and van der Pluijm, 1999), such that about half the JSG papers that mention diagenesis concern faults. This work and a growing body of cross-disciplinary research on other topics show increasing awareness of diagenesis as vital, although, in the area of brittle structure, they are neither central to research nor a required part of student training.

This anecdotal evidence suggests that disciplinary barriers need to fall through mutual awareness, cross-disciplinary outreach, and changes in training. Our shorthand for this effort is *structural diagenesis*. The aim is to promote curricular focus on chemical and mechanical processes that affect structures at all scales in sedimentary rocks prior to the onset of metamorphism; application of mechanics to an understanding of diagenetic rock fabrics, particularly in little-deformed rocks; awareness of the impact of chemical processes on the evolution of rock mechanical properties and structures; and appreciation of genetic linkages or feedbacks that apply in some cases between chemical and mechanical processes. Reactions in host rock and associated structures are not *necessarily* coupled, and in many cases they may not be (Maliva et al., 1995). But we believe that it will be the rare case in which information about diagenesis does not advance structural understanding and vice versa. Papers in this theme section and some that have been published elsewhere arose from a 2004 AAPG Hedberg research conference and a 2008 Geological Society of America session convened by people from both disciplines who have recognized the disciplinary divide and the value of bridging it. As recent work outlined here shows, the fused perspective of structural diagenesis also yields opportunities for solving longstanding structural problems such as dating fault and fracture movement, measuring rate of fracture growth, and locating open fractures. In this paper we provide a brief review to place the papers in the special theme section in context.

2. Examples

Compaction is a topic in which mechanics is yielding insights into diagenetic processes. Compaction of porous clastic sediment or sedimentary rock has been viewed as a predominantly mechanical or coupled mechanical–chemical process (Bjørlykke, 1999). Localization of compaction along pressuresolution seams or stylolites, accommodating band-perpendicular or -oblique shortening by solution-precipitation creep, has received consideration from both diagenetic and structural communities in both clastic and carbonate rocks (Sprunt and Nur, 1977; Rutter, 1983; Gundersen et al., 2002). More recently, discussion of these structures and the related processes of distributed pressure solution and porosity reduction have been extended to include surface-charge differences between adjacent dissimilar grain surfaces in contact, such as mica and quartz (Bjørkum, 1996; Renard et al., 1997; Sheldon et al., 2003; Greene et al., 2009). In contrast to pressure solution, structure localization during predominantly mechanical compaction and resultant formation of compaction bands has only recently been recognized (Mollema and Antonellini, 1996; Schultz, 2009). Eichhubl et al. (in this volume) considered the effect of shear on formation of compaction bands in sandstone and contrasted these structures with shear bands. Shear bands, like compaction bands, which are part of a class of structures collectively referred to as deformation bands (Aydin et al., 2006), have been described in sandstone from a variety of depositional and structural settings (Aydin, 1978; Fossen et al., 2007). Few such bands have been described in mudstone (Byrne et al., 1993). Using high-resolution SEM imaging techniques, Milliken and Reed (in this volume) described porosity reduction in deformation bands in mudstone from the Nankai accretionary prism as a dominantly mechanical process. These studies and microstructure studies in sedimentary rocks having no visible macroscopic structures (e.g., Gomez and Laubach, 2006) suggest that a wealth of spaced and penetrative structural features exists in otherwise undeformed rocks and that much remains to be learned about them through advances in imaging (Fig. 1) and structural petrology.

The study of faults and fault rocks is an area in which diagenesis is yielding insights into structural processes, and vice versa (Knipe, 1993; Vrolijk and van der Pluijm, 1999; Fisher and Knipe, 2001; Fisher et al., 2003; Caine and Minor, 2009; Eichhubl et al., 2009; Mitchell and Faulkner, 2009). Faults have potential for feedback between deformation, fluid flow, chemical reactions, changing rock properties, and thermal gradients (Phillips, 1991; Hobbs et al., 2000; Ireland et al., 2010). Fault-slip and associated fracture may increase or decrease fault-zone porosity and permeability, potentially focusing or impeding fluid flow, perturbing thermal gradients, enhancing or restricting reactions and transport of chemical components, and altering porosity, permeability, mineralogy, texture, and mechanical properties of fault and host rock (Chester et al., 1993; Sibson, 1996; Muchez and Sintubin, 1998; Eichhubl and Boles, 2000a, b; Tenthorey et al., 2003; Woodcock et al., 2007). Although it is beyond our scope to review fault-diagenesis literature, two papers in this theme section contribute to our understanding of the role of diagenesis in fault systems. Solum et al. (in this volume) showed that fault-related clay minerals formed largely as a result of cement deposition rather than through

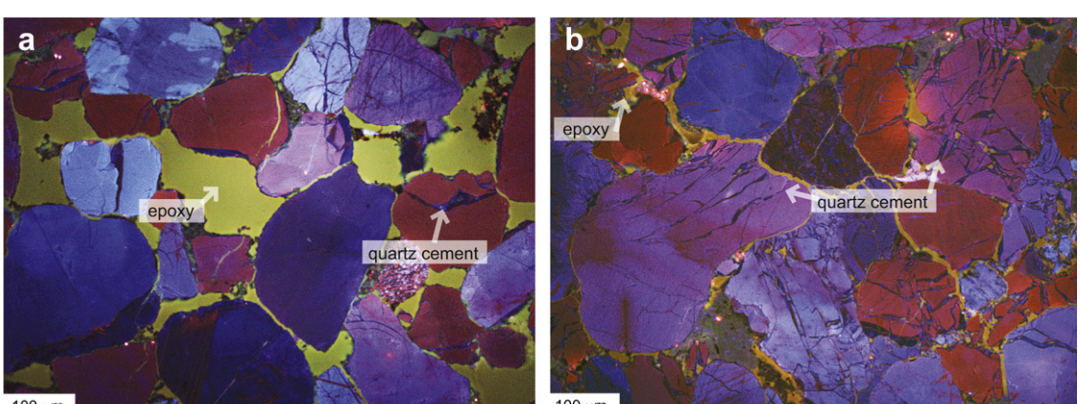

Fig. 1. SEM-cathodoluminescence (CL) images of (a) host rock and (b) deformation band Jurassic Aztec Sandstone, Valley of Fire, NV. Deformation band, b, contains a higher abundance of quartz-cemented microfractures (dark-blue CL color) than surrounding sandstone, a, reflecting greater propensity of quartz to precipitate on fresh fracture surfaces compared with detrital grain surfaces.

mechanical mixing of protolith clays and discussed the interplay of clay-mineral precipitation and evolving fault-zone strength and hydrologic attributes. Onasch et al. (in this volume) described evidence from quartzose fault rocks of tabular bands of microcrystalline quartz resembling cataclasite that are instead cement deposits, implying that brittle deformation of well-cemented, quartz-rich rocks deformed at low temperatures involves much more dilation and cementation than were previously recognized. They suggested that microcrystalline quartz reflects rapid cementation under highly supersaturated conditions, possibly with a silica gel precursor that is generated during seismic-slip events on nearby faults.

These and other recent fault-diagenesis studies point to as-yet-undeveloped opportunities for using recently developed quartz and clay-mineral authigenesis models to improve predictions of fault and deformation-band properties (Lander et al., 2008, 2009; Lander and Bonnell, 2010) (Fig. 2). The success of these diagenetic models rests on recent insights into cement-precipitation processes. Applied to structures, these diagenetic concepts can provide methods of obtaining structural timing information (not merely *relative* timing) where it would otherwise be lacking. Determining the timing and rates of fold, fault, and fracture growth is a central concern of structural geology. Particularly for fractures, such estimates are frequently problematic. For quartz, some clay minerals, and some carbonate minerals, precipitation-rate behavior is well described using Arrhenius kinetics (Walderhaug, 1996; Lander and Walderhaug, 1999; Lander et al., 2008; Gale et al., 2010; Lander and Bonnell, 2010). Model predictions and empirical confirmation of cement patterns in undeformed host rocks suggest that for a wide range of structures and settings, reconstructed thermal histories, together with evidence of sequence and relative timing of cement deposits within faults, provide accurate estimates of cement accumulation rates and allow quantitative estimates of cement accumulation timing to be applied to associated structures. Such models explain the sensitivity of fault-rock porosity and permeability to thermal exposure (Fisher et al., 2003). Makowitz et al. (in this volume) showed that empirical-kinetic modeling of quartz-cement deposits in Middle Pennsylvanian sandstones and associated fault rocks constrains the timing of the Pine Mountain Overthrust.

Cement deposits have long been known from arrays of joints, cleats, and other opening-mode fractures, but the pervasive influence of diagenesis on such fracture systems is only beginning to be appreciated. Although information on fracture timing is notoriously challenging to obtain, as with fault rocks, workers can use cement accumulation in fractures to specify when the fractures formed by either tying fracture-cement sequences to dated cement sequences in the rock mass or using cement accumulations and thermal history to estimate fracture age (Nollet et al., 2005a; Peres and Boles, 2005; Laubach and Ward, 2006; Laubach and Diaz-Tushman, 2009). Timing information, of course, constrains processes that produced the fractures.

As with veins in metamorphic environments (Ramsay, 1980; Urai et al., 1991; Bons, 2000; Hilgers and Urai, 2002; Safaricz and

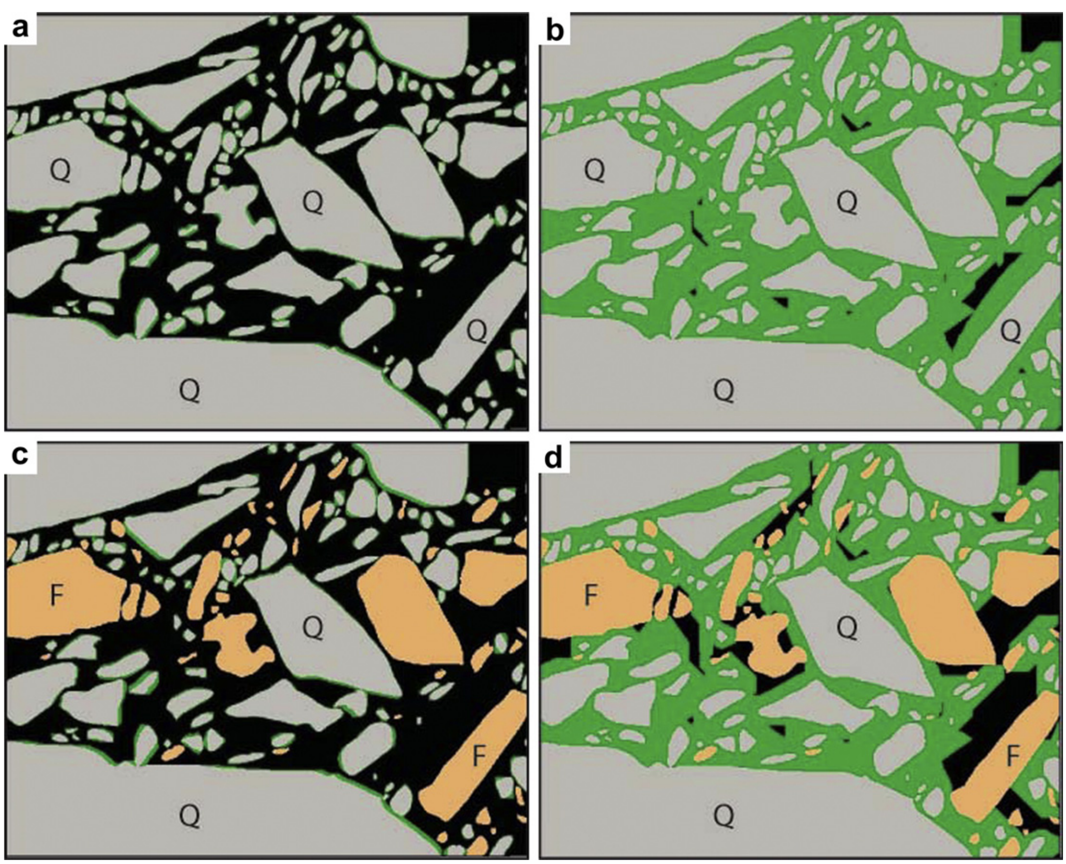

Fig. 2. Models of quartz-cementation in fractured and intact sandstone, illustrating effect of grain composition on quartz-cement (green) and porosity (black) distribution and abundance. (a) Deformation band composed entirely of quartz grains, after 5 m.y. of heating from 25 °C to 100 °C. (b) Same deformation band after an additional 10 m.y. heating from 100 °C to 150 °C. (c, d) As in a and b, except band is composed of 25% feldspar (orange) and 75% quartz (gray). Note lesser quartz-cement abundance and greater porosity in d than in b. See Lander et al. (2008) for information on modeling software Prism2D and Touchstone™. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

Davison, 2005), in diagenetic environments, crack-seal texture is present in some fractures but commonly is localized in cement deposits in otherwise nearly barren fractures (Laubach et al., 2004b; Laubach and Ward, 2006) (Fig. 3). Such textures show coupling between mechanical fracture opening and synkinematic precipitation of fracture-cement that might influence, for example, how fracture-size patterns evolve (Clark et al., 1995; Hooker et al., 2009). These crack-seal textured-cement deposits contain fluid-inclusion assemblages that can be used together with structural information and thermal history to independently test premises of the diagenetic models. They can also provide insight into fractureopening rates (Hilgers et al., 2001; Nollet et al., 2005a,b).

Fluid-inclusion studies demonstrate that fracture opening and concomitant fracture-cementation occur at rates that are comparable to growth rates of pore-filling quartz-cement in the host rock and, thus, to rates of regional burial diagenetic processes (Becker et al., 2010). A combination of fluid inclusions, diagenetic models, fine resolution of cementdeposit sequence (Fig. 3), and widespread occurrence of crack seal in moderately to deeply buried sedimentary rock fractures provides a key to unlocking the timing, sequence, and rate of fracture development in a wide range of structures. For simple regional fracture systems, individual fractureopening rates can be remarkably slow, on the order of tens of millions of years (Becker et al., 2010).

Paleomagnetic analysis is another way that diagenesis can provide constraints on structural timing. Elmore et al. (in this volume) used paleomagnetism to date breccia fills associated with faults cutting Paleozoic dolostones in the Caledonian foreland of NW Scotland. They highlighted a type of breccia-vein assemblage that is being recognized in a variety of settings. Dating brecciation and associated fluidflow events dates the faults as well. This study also provides evidence of basin-scale fluid flow and reaction. Such kilometer-scale chemicalreaction patterns in sedimentary rocks (Davies, 2006; Davies and Cartwright, 2007; Ireland et al., 2010) could mark chemically reactive systems that might have feedbacks in which strength, strain, fracture, and fault populations and permeability interact in a regional-scale coupled mechanical, hydraulic, and thermal regime (Nollet et al., 2005a; Hilgers et al., 2006; Holland et al., 2009).

The effect of diagenetic solution/precipitation reactions on fracture nucleation and propagation is still poorly understood. The crack-seal mechanism of repeated fracture opening and cementation has been contrasted with fracture opening driven by ion diffusion and forces generated by cement growth (Wiltschko and

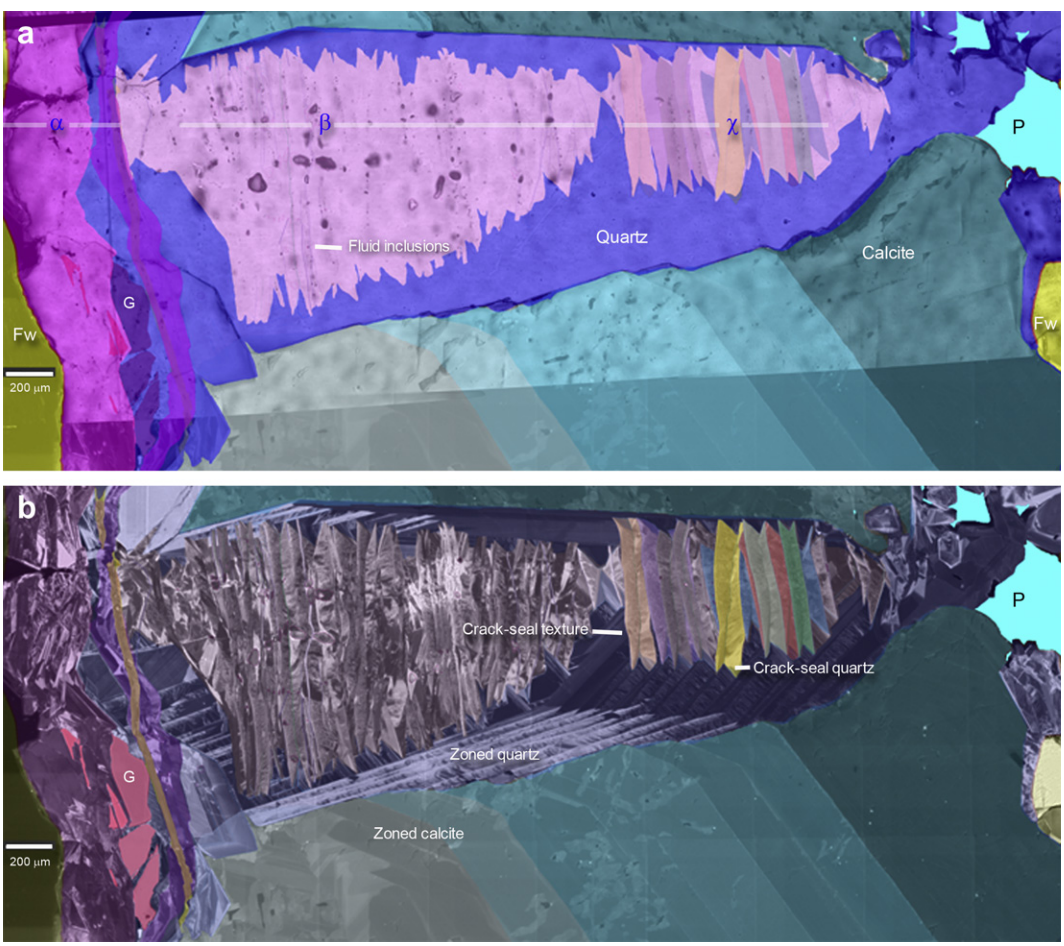

Fig. 3. Structure map of quartz-cement deposit, Cretaceous Cotton Valley sandstone, East Texas, depth 2818 m. Opening history is recorded by crack-seal texture. (a) Transmitted light (TL) and cathodoluminescence (CL) base image reveals fluid-inclusion assemblages trapped by individual crack and seal sequences by quartz growing from opposite fracture walls; α, β, and χ mark progressively younger parts of the quartz bridge identified by mapping crosscut and overlap relations of crack-seal fractures and quartz. Fw, fracture walls; G, broken grains entrained in bridge; P, residual fracture pore space. Other pore space present during quartz bridge growth is now filled with zoned calcite that grew during fracture opening. This calcite lagged quartz, lacks crack-seal texture, and bridged fracture only late in growth history. (b) SEM-CL/TL montage and map of bridge zone χ showing opening increment fracture surfaces, quartz deposits filling opening increment gaps, and overlap (zoned lateral) quartz deposits surrounding, and partly cut by, crack-seal fractures. Note crosscutting relations and scale.

Morse, 2001; Fletcher and Merino, 2001; Noiriel et al., 2010), although the significance of these processes to fracture opening and growth under deep burial conditions remains to be assessed (Elburg et al., 2002). Coupling among solution/precipitation reactions in the host rock and fracture opening has been inferred on the basis of fracture geometry and textural relations between fracture and pore cement (Eichhubl and Boles, 1998; Iyer et al., 2008; Jamtveit et al., 2009), suggesting in some cases that hostrock chemical reactions may drive fracture opening (Eichhubl et al., 2001; Eichhubl, 2004).

In some areas of potential collaboration there has as yet been little interaction between structure and diagenesis research. Among these, scale and rates of masstransfer processes between fracture-cement deposits and the rocks surrounding fractures are not well documented. In contrast to quartz and dolomite deposits in which cement abundance and texture reflect rate of fracture opening and thermal exposure—and are thus likely to be less sensitive to recording flow patterns—many carbonate minerals have marked heterogeneity in their distribution within fracture systems and are commonly present or absent in both host rock and fractures (Laubach, 2003; Laubach and Ward, 2006). Such fracture-cement deposits can record a history of advective mass transfer (Hilgers et al., 2004; Cox, 2007). Distribution and origin of such fracture-filling cements, where present in host rock, have not been a *focus* of diagenetic research, probably because they are commonly present in trace amounts. An understanding of the distribution of these cements in host rock and fractures can help explain the location of open fractures (Laubach et al., 2004a, b).

In addition to information on timing, unraveling the textures and reactions in fractures can constrain precipitation conditions and possible fluid-transport mechanisms (Cox, 2007; Nollet et al., 2009). Fibrous vein microstructures are frequently used to infer the fracture opening direction (Durney and Ramsay, 1973) with the vein crystal-shape pointing to the growth conditions and crack widths (Hilgers et al., 2001; Nollet et al., 2005b). These cement textures and structural and geochemical evidence have also been used to infer opening, sealing and fluid-transport mechanisms and have been linked to basin subsidence and basin inversion.

Cement deposits strongly influence, in ways that would not be apparent from geometric or mechanical characterization, how fracture arrays conduct fluid, even where fluid flow is through disconnected fractures and host rock (Philip et al., 2005). Studies that consider the entire cement-distribution pattern could help explain large-scale fluid-circulation systems, such as cement-sealing fluid pathways and isolating overpressure cells (Nollet et al., 2005a; Hilgers et al., 2006). These studies show that much remains to be learned from structural and diagenetic interactions between wider, regional/basin-scale fracture and fault-host systems.

Another way that diagenesis and structure interact is through alteration of rock properties. On the scale of intact rock, mechanical properties evolve through progressive diagenesis (Shackleton et al., 2005; Laubach et al., 2009). Properties can begin to change soon after deposition and can continue to the present day, sometimes changing only gradually over tens or hundreds of million years, sometimes abruptly. Ortega et al. (in this volume) described how original depositional stratigraphy and diagenetic change interacted to govern fracture size and abundance patterns in carbonate rocks in NE Mexico. Studies that show protracted deformation underline the importance of progressive rock-property changes during deformation and of assigning rock properties that are characteristic of the system at the time of deformation rather than presentday properties in numerical simulations of brittle deformation. Moreover, fluids arising from diagenetic reactions can enhance or impede fracture and fault growth through chemical effects on subcritical crack growth (Atkinson, 1982).

Because cement deposition and resulting mechanical properties are sensitive to burial history, different cement patterns and strength histories could exist in parts of structures having differing thermal histories—for example, adjacent growing synclines and anticlines, potentially feeding back to changing structural style. Likewise, concurrent fracture growth, mechanical property changes, fluid flow, and cement precipitation can result in cement content, porosity structure, and fracture spatial arrangement and size distribution that differ from those arising where these processes are merely sequential (and uncoupled) (for example, Tsang, 1999; Olson et al., 2007).

These examples are not exhaustive and focus mostly on how diagenesis can inform structural interpretation, but structural information can also constrain timing of diagenetic processes (Burley et al., 1989) and provide independent tests of diagenetic concepts. With greater depth and higher temperature, the chemical component of deformation most likely is increasingly pervasive and penetrative in time and space (Regenauer-Lieb et al., 2009).

3. Conclusions

Sub-metamorphic grade reactions are dominated by fluid-rock reactions and these reactions interact with compaction, fracture growth, frictional failure and slip that occur in this regime. Yet, efforts to specifically look at the linkages between upper crustal deformations and structures, and diagenesis are few except in some niche topics (faults, veins). A broader field of structural diagenesis is needed to address these issues. Studies that combine structural analysis and diagenesis are increasingly prevalent and are central to an understanding of fluid flow and storage and other processes in deep basins. At these depths and temperatures, chemical and mechanical processes are likely to interact, as they do at the higher temperatures of metamorphism. To some extent all sedimentary petrology and structural geology studies of deeply buried (or formerly deeply buried) rocks would benefit from a holistic structural diagenesis perspective, helping to eliminate blind spots (Kock, 2007) and broadening overly narrow views entrenched in the curriculum that can impede science (Weiler, 2007). Although sedimentary basin studies have been central to geology since its inception, parts of sedimentary basins below about 5 km are hard to sample. Consequently, the characteristics of disseminated structures like fractures and faults are little known. A structural diagenesis perspective would benefit many practitioners challenged to understand deep-seated processes in a domain from which meaningful samples are rare. This theme section highlights some examples.

Acknowledgments

This research was partly supported 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, and by sponsors of the Fracture Research & Application Consortium. PE was supported in part through the Center for Frontiers of Subsurface Energy Security, an Energy Frontier Research Center funded by the U.S. Department of Energy, Office of Science, Office of Basic Energy Sciences, under Award Number DE-SC0001114. We are grateful for stimulating discussions with L.M. Bonnell, W.M. Dunne, J.F.W. Gale, R. Marrett, K. Milliken, J.E. Olson, and N.B. Woodward and review comments from Nick Hayman and Bill Dunne. *Brittle Deformation and Diagenesis as Coupled Processes* was jointly sponsored by GSA's Structural Geology and Tectonics Division, Geophysics Division, Sedimentary Geology Division, and the Gulf Coast Association of Geological

Societies. We thank the authors and reviewers who helped make this theme section possible.

References

Atkinson, B.K., 1982. Subcritical crack propagation in rocks: theory, experimental results and applications. Journal of Structural Geology 4, 41–56.

Aydin, A., 1978. Small faults formed as deformation bands in sandstone. Pure and Applied Geophysics 116 (4–5), 913–930.

Aydin, A., Borja, R.I., Eichhubl, P., 2006. Geological and mathematical framework for failure modes in granular rock. Journal of Structural Geology 28 (1), 83–98.

Becker, S.P., Eichhubl, P., Laubach, S.E., Reed, R.M., Lander, R.H., Bodnar, R.J., 2010. A 48 m.y. history of fracture opening, temperature, and fluid pressure: cretaceous Travis Peak Formation, East Texas basin. Geological Society of America Bulletin 122 (7–8), 1081–1093.

Bjørkum, P.A., 1996. How important is pressure in causing dissolution of quartz in sandstones? Journal of Sedimentary Research 66 (1), 147–154.

Bjørlykke, K., 1999. An overview of factors controlling rates of compaction, fluid generation and fluid flow in sedimentary basins. In: Jamtveit, B., Meakin, P. (Eds.), Growth, Dissolution and Pattern Formation in Geosystems. Kluwer Academic Publishers, pp. 381–404.

Bons, P., 2000. The formation of veins and their microstructures. Electronic Edition. In: Jessell, M., Urai, J. (Eds.), Stress, Structure and Strain: A Volume in Honour of Win D. Means. Journal of the Virtual Explorer. ISSN: 1441-81422. doi:10.3809/jvirtex.2000.00007 (4).

Burley, S.D., Mullis, J., Matter, A., 1989. Timing diagenesis in the Tartan Reservoir (UK North Sea): constraints from combined cathodoluminescence microscopy and fluid inclusion studies. Marine and Petroleum Geology 6 (2), 98–104.

Byrne, T., Maltman, A., Stephenson, E., Soh, W., Knipe, R., 1993. Deformation structures and fluid flow in the toe region of the Nankai Accretionary Prism. In: Hill, I.A., Taira, A., Firth, J.V., et al. (Eds.), Proceedings of the Ocean Drilling Program, Scientific Results, vol. 131. ODP, pp. 83–101.

Caine, J.S., Minor, S.A., 2009. Structural and geochemical characteristics of faulted sediments and inferences on the role of water in deformation, Rio Grande Rift, New Mexico. Geological Society of America Bulletin 121 (9–10), 1325–1340.

Chester, F.M., Evans, J.P., Biegel, R.L., 1993. Internal structure and weakening mechanisms of the San Andreas fault. Journal of Geophysical Research 98, 771–786.

Chester, F.M., Logan, J.M., 1986. Implications for mechanical properties of brittle faults from observations of the Punchbowl Fault, California. Pure and Applied Geophysics 124, 79–106.

Clark, M.B., Brantley, S.L., Fisher, D.M., 1995. Power-law vein-thickness distributions and positive feedback in vein growth. Geology 23 (11), 975–978.

Cox, S.F., 2007. Structural and isotopic constraints on fluid flow regimes and fluid pathways during upper crustal deformation: an example from the Taemas area of the Lachlan Orogen, SE Australia. Journal of Geophysical Research 112, B08208. doi:10.1029/2006JB004734.

Davies, G.R., Smith Jr., L.B., 2006. Structurally controlled hydrothermal dolomite reservoir facies: an overview. AAPG Bulletin 90 (11), 1641–1690.

Davies, R.J., Cartwright, J.A., 2007. Kilometer-scale chemical reaction boundary patterns and deformation in sedimentary rocks. Earth & Planetary Science Letters 262 (1–2), 125–137.

Dockrill, B., Shipton, Z.K., 2010. Structural controls on leakage from a natural CO_2 geologic storage site: central Utah, U.S.A. Journal of Structural Geology. doi:10.1016/j.jsg.2010.01.007.

Durney, D.W., Ramsay, J.G., 1973. Incremental strains measured by syntectonic crystal growth. In: de Jong, K.A., Scholten, R. (Eds.), Gravity Tectonics, pp. 67–96.

Eichhubl, P., 2004. Growth of ductile opening-mode fractures in geomaterials. In: Cosgrove, J.W., Engelder, T. (Eds.), The Initiation, Propagation, and Arrest of Joints and Other Fractures. Geological Society London Special Publication, vol. 231, pp. 11–24.

Eichhubl, P., Aydin, A., Lore, J., 2001. Opening-mode fracture in siliceous mudstone at high homologous temperature—effect of surface forces. Geophysical Research Letters 28 (7), 1299–1302.

Eichhubl, P., Boles, J.R., 1998. Vein formation in relation to burial diagenesis in the Miocene Monterey formation, Arroyo Burro Beach, Santa Barbara, California. In: Eichhubl, P. (Ed.), Diagenesis, Deformation, and Fluid Flow in the Miocene Monterey Formation of Coastal California. SEPM Pacific Section Special Publication, vol. 83, pp. 15–36.

Eichhubl, P., Boles, J.R., 2000a. Focused fluid flow along faults in the Monterey Formation, coastal California. Geological Society of America Bulletin 112, 1667–1679.

Eichhubl, P., Boles, J.R., 2000b. Rates of fluid flow in fault systems-evidence for episodic rapid fluid now in the Miocene Monterey Formation, coastal California. American Journal of Science 300 (7), 571–600.

Eichhubl, P., Davatzes, N.C., Becker, S.P., 2009. Structural and diagenetic control of fluid migration and cementation along the Moab fault, Utah. AAPG Bulletin 93 (5), 653–681.

Eichhubl, P., Hooker, J.N., Laubach, S.E. Pure and shear-enhanced compaction bands in Aztec Sandstone. Journal of Structural Geology, in this volume. doi:10.1016/j.jsg.2010.02.004.

Elburg, M.A., Bons, P.D., Foden, J., Passchier, C.W., 2002. The origin of fibrous veins: constraints from geochemistry. Geological Society, London, Special Publication 200 (1), 103–118.

Elmore, R.D., Burr, R., Engel, M., Parnell, J. Paleomagnetic dating of fracturing using breccia veins in Durness Group carbonates, NW Scotland. Journal of Structural Geology, in this volume. doi:10.1016/j.jsg.2010.05.011.

Fisher, Q.J., Casey, M., Harris, S.D., Knipe, R.J., 2003. Fluid-flow properties of faults in sandstone: the importance of temperature history. Geology 31 (11), 965–968.

Fisher, Q.J., Knipe, R.J., 2001. The permeability of faults within siliciclastic petroleum reservoirs of the North Sea and Norwegian Continental Shelf. Marine & Petroleum Geology 18 (10), 1063–1081.

Fletcher, R.C., Merino, E., 2001. Mineral growth in rocks: kinetic-rheological models of replacement, vein formation, and syntectonic crystallization. Geochimica et Cosmochimica Acta 65, 3733–3748.

Fossen, H., Schultz, R.A., Shipton, Z.K., Mair, K., 2007. Deformation bands in sandstone: a review. Journal of the Geological Society 164 (4), 755–769.

Gale, J.F., Lander, R.H., Reed, R.M., Laubach, S.E., 2010. Modeling fracture porosity evolution in dolostone. Journal of Structural Geology 32. doi:10.1016/j.jsg.2009.04.018.

Giles, M.R., 1997. Diagenesis: a Quantitative Perspective. Kluwer Academic Publishers, 526 pp.

Gomez, L.A., Laubach, S.E., 2006. Rapid digital quantification of microfracture populations. Journal of Structural Geology 28 (3), 408–420.

Greene, G.W., Kristiansen, K., Meyer, E.E., Boles, J.R., Israelachvili, J.N., 2009. Role of electrochemical reactions in pressure solution. Geochimica et Cosmochimica Acta 73 (10), 2862–2874.

Gundersen, E., Renard, F., Dysthe, D.K., Bjørlykke, K., Jamtveit, B., 2002. Coupling between pressure solution creep and diffusive mass transport in porous rocks. Journal of Geophysical Research 107 (B11), 2317.

Hacker, B.R., 1997. Diagenesis and fault valve seismicity of crustal faults. Journal of Geophysical Research 102 (11), 24459–24467.

Hilgers, C., Dilg-Gruschinski, K., Urai, J., 2004. Microstructural evolution of syntaxial veins formed by advective flow. Geology 32 (3), 261–264.

Hilgers, C., Kirschner, D.L., Breton, J.-P., Urai, J.L., 2006. Fracture sealing and fluid overpressures in limestones of the Jebel Akdhar dome, Oman mountains. Geofluids 6, 168–184.

Hilgers, C., Koehn, D., Bons, P.D., Urai, J.L., 2001. Development of crystal morphology during unitaxial growth in a progressively widening vein: II. Numerical simulations of the evolution of antitaxial fibrous veins. Journal of Structural Geology 23, 873–885.

Hilgers, C., Urai, J.L., 2002. Microstructural observations on natural syntectonic fibrous veins: implications for the growth process. Tectonophysics 352, 257–274.

Hobbs, B.E., Zhang, Y., Ord, A., Zhao, C., 2000. Application of coupled deformation, fluid flow, thermal and chemical modelling to predictive mineral exploration. Journal of Geochemical Exploration 69–70, 505–509.

Holland, M., Urai, J.L., Muchez, P., Willemse, E.J.M., 2009. Evolution of fractures in a highly dynamic thermal, hydraulic, and mechanical system—(I) field observations in Mesozoic carbonates, Jabal Shams, Oman Mountains. GeoArabia 14 (1), 57–110.

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.

Ireland, M.T., Goulty, N.R., Davies, R.J., 2010. Influence of pore water chemistry on silica diagenesis: evidence from the interaction of diagenetic reaction zones with polygonal fault systems. Journal of the Geological Society 167 (2), 273–279.

Iyer, K., Jamtveit, B., Mathiesen, J., Malthe-Sørenssen, A., Feder, J., 2008. Reaction-assisted hierarchical fracturing during serpentinization. Earth and Planetary Science Letters 267 (3–4), 503–516.

Jamtveit, B., Putnis, C., Malthe-Sørenssen, A., 2009. Reaction induced fracturing during replacement processes. Contributions to Mineralogy and Petrology 157 (1), 127–133.

Knipe, R., 1993. The influence of fault zone processes and diagenesis on fluid flow. In: Horbury, A.D., Robinson, A.G. (Eds.), Diagenesis and Basin Development. Studies in Geology 36. American Association of Petroleum Geologists, pp. 135–154.

Kock, B., 2007. Challenges to fostering interdisciplinary graduate education. EOS 88, 37.

Lander, R.H., Bonnell, L.M., 2010. A model for fibrous illite nucleation and growth in sandstone. AAPG Bulletin 94 (8), 1–27.

Lander, R.H., Larese, R.E., Bonnell, L.M., 2008. Toward more accurate quartz cement models—The importance of euhedral vs. non-euhedral growth rates. AAPG Bulletin 92 (11), 1537–1564.

Lander, R.H., Solano-Acosta, W., Thomas, A.R., Reed, R.M., Kacewicz, M., Bonnell, L.M., Hooker, J.N. Simulation of fault sealing from quartz cementation within cataclastic deformation zones. In: AAPG Hedberg Conference Basin and Petroleum Systems Modeling: New Horizons in Research and Applications, May 2009, Napa, California.

Lander, R.H., Walderhaug, O., 1999. Porosity prediction through simulation of sandstone compaction and quartz cementation. AAPG Bulletin 83, 433–449.

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

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., Olson, J.E., Gale, J.F.W., 2004a. Are open fractures necessarily aligned with maximum horizontal stress? Earth & Planetary Science Letters 222 (1), 191–195.
Laubach, S.E., Olson, J.E., Gross, M.R., 2009. Mechanical and fracture stratigraphy. AAPG Bulletin 93 (11), 1413–1426.
Laubach, S.E., Reed, R.M., Olson, J.E., Lander, R.H., Bonnell, L.M., 2004b. Coevolution of crack-seal texture and fracture porosity in sedimentary rocks: cathodoluminescence observations of regional fractures. Journal of Structural Geology 26 (5), 967–982.
Laubach, S.E., Ward, M.W., 2006. Diagenesis in porosity evolution of opening-mode fractures, Middle Triassic to Lower Jurassic La Boca formation, NE Mexico. Tectonophysics 419 (1–4), 75–97.
Makowitz, A., Lander, R.H., Milliken, K.L. Chemical diagenetic constraints on the timing of gouge development, Pine Mountain overthrust, Eastern Kentucky. Journal of Structural Geology 32, in this volume. doi:10.1016/j.jsg.2010.04.014.
Maliva, R.G., Dickson, J.A.D., Smalley, P.C., Oxtoby, N.H., 1995. Diagenesis of the Machard Field (British North Sea) chalk; evidence for decoupling of diagenesis in fractures and the host rock. Journal of Sedimentary Research 65, 105–111.
Milliken, K.L., 2003. Diagenesis. In: Middleton, G.V. (Ed.), Encyclopedia of Sediments and Sedimentary Rocks. Kluwer Academic Publishers, pp. 214–219.
Milliken, K.L., Reed, R.M. Multiple causes of diagenetic fabric anisotropy in weakly consolidated mud, Nankai Accretionary Prism, IODP Expedition 316. Journal of Structural Geology 32, in this volume. doi:10.1016/j.jsg.2010.03.008.
Mitchell, T.M., Faulkner, D.R., 2009. The nature and origin of off-fault damage surrounding strike-slip fault zones with a wide range of displacements: a field study from the Atacama fault system, northern Chile. Journal of Structural Geology 31 (8), 802–816.
Mollema, P.N., Antonellini, M.A., 1996. Compaction bands: a structural analog for anti-mode I cracks in aeolian sandstone. Tectonophysics 267 (1–4), 209–228.
Muchez, P., Sintubin, M., 1998. Contrasting origin of palaeofluids in a strike-slip fault system. Chemical Geology 145 (1–2), 105–114.
Noiriel, C., Renard, F., Doan, M.-L., Gratier, J.-P., 2010. Intense fracturing and fracture sealing induced by mineral growth in porous rocks. Chemical Geology 269 (3–4), 197–209.
Nollet, S., Hilgers, C., Urai, J.L., 2005a. Sealing of fluid pathways in overpressure cells: a case study from the Buntsandstein in the Lower Saxony Basin (NW Germany). International Journal of Earth Sciences 94, 1039–1055.
Nollet, S., Koerner, T., Kramm, U., Hilgers, C., 2009. Precipitation of fracture fillings and cements in the Buntsandstein (NW Germany). Geofluids 9 (4), 373–385.
Nollet, S., Urai, J.L., Bons, P.D., Hilgers, C., 2005b. Numerical simulations of polycrystal growth in veins. Journal of Structural Geology 27, 217–230.
Olson, J.E., Laubach, S.E., Lander, R.H., 2007. Combining diagenesis and mechanics to quantify fracture aperture distributions and fracture pattern permeability. In: Lonergan, L., Jolley, R.J., Sanderson, D.J., Rawnsley, K. (Eds.), Fractured Reservoirs. Geological Society of London Special Publication, vol. 270, pp. 97–112.
Olson, J.E., Laubach, S.E., Lander, R.H., 2009. Natural fracture characterization in tight gas sandstones: integrating mechanics and diagenesis. AAPG Bulletin 93 (11), 1535–1549.
Onasch, C.M., Farver, J.R., Dunne, W.M. The role of dilation and cementation in the formation of cataclasite in low temperature deformation of well cemented quartz-rich rocks. Journal of Structural Geology 32, in this volume. doi:10.1016/j.jsg.2010.04.013.
Ortega, O.O., Gale, J. F.W., Marrett, R. Quantifying the diagenetic and stratigraphic controls on fracture intensity in platform carbonates: an example from the Sierra Madre Oriental, northeast Mexico. Journal of Structural Geology 32, in this volume. doi:10.1016/j.jsg.2010.07.004.
Peres, R.J., Boles, J.R., 2005. Interpreting fracture development from diagenetic mineralogy and thermoelastic contraction modeling. Tectonophysics 400 (1–4), 179–207.
Philip, Z.G., Jennings Jr., J.W., 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.
Phillips, O.M., 1991. Flow and Reactions in Permeable Rocks. Cambridge University Press.
Ramsay, J.G., 1980. The crack-seal mechanism of rock deformation. Nature 284, 135–139.
Regenauer-Lieb, K., Hobbs, B., Ord, A., Oliver Gaedeb, O., Vernon, R., 2009. Deformation with coupled chemical diffusion. Physics of the Earth and Planetary Interiors 172 (1–2), 43–54.
Renard, F., Ortoleva, P., Gratier, J.P., 1997. Pressure solution in sandstones: influence of clays and dependence on temperature and stress. Tectonophysics 280 (3–4), 257–266.
Rutter, E.H., 1983. Pressure solution in nature, theory and experiment. Journal of the Geological Society London 140 (5), 725–740.
Safaricz, M., Davison, I., 2005. Pressure solution in chalk. AAPG Bulletin 89 (3), 383–401.
Schultz, R.A., 2009. Scaling and paleodepth of compaction bands, Nevada and Utah. Journal of Geophysical Research 114 (B3), B03407.
Shackleton, J.R., Cooke, M.L., Sussman, A.J., 2005. Evidence for temporally changing mechanical stratigraphy and effects on joint-network architecture. Geology 33 (2), 101–104.
Sheldon, H.A., Wheeler, J., Worden, R.H., Cheadle, M.J., 2003. An analysis of the roles of stress, temperature, and pH in chemical compaction of sandstones. Journal of Sedimentary Research 73 (1), 64–71.
Sibson, R.H., 1996. Structural permeability of fluid-driven fracture meshes. Journal of Structural Geology 18, 1031–1042.
Solum, J., Davatzes, N., Lockner, D. Fault-related clay authigenesis along the Moab Fault: implications for calculations of fault rock composition and mechanical and hydrologic fault zone properties. Journal of Structural Geology 32, in this volume, doi:10.1016/j.jsg.2010.07.009.
Sprunt, E.S., Nur, A., 1977. Experimental study of the effects of stress on solution rate. Journal of Geophysical Research 82 (20), 3013–3022.
Stephansson, O., Jing, L., Tsang, C.-F., 1996. Coupled Thermo-Hydro-Mechanical Processes of Fractured Media. Elsevier Science B.V., Amsterdam.
Tenthorey, E., Cox, S.F., Todd, H.F., 2003. Evolution of strength recovery and permeability during fluid-rock reaction in experimental fault zones. Earth & Planetary Science Letters 206, 161–172.
Tsang, C.-F., 1999. Linking thermal, hydrological, and mechanical processes in fractured rocks. Annual Review of Earth and Planetary Sciences 27, 359–384.
Tsang, C.-F., 2005. Is current hydrogeologic research addressing long-term predictions? Groundwater 43 (3), 296–300.
Urai, J.L., Williams, P.F., van Roermund, H.L.M., 1991. Kinematics of crystal growth in syntectonic fibrous veins. Journal of Structural Geology 13 (7), 823–836.
Vrolijk, P., van der Pluijm, B., 1999. Clay gouge. Journal of Structural Geology 21 (8–9), 1039–1048.
Walderhaug, O., 1996. Kinetic modelling of quartz cementation and porosity loss in deeply buried sandstone reservoirs. AAPG Bulletin 80, 731–745.
Weiler, C.S., 2007. Meeting Ph.D. graduates' needs in a changing global environment. EOS 88 (13), 149–151.
Wiltschko, D.V., Morse, J.W., 2001. Crystallization pressure versus "crack seal" as the mechanism for banded veins. Geology 29 (1), 79–82.
Woodcock, N.H., Dickson, J.A.D., Tarasewicz, J.P.T., 2007. Transient permeability and reseal hardening in fault zones: evidence from dilation breccia textures. In: Lonergan, L., Jolley, R.J., Sanderson, D.J., Rawnsley, K. (Eds.), Fractured Reservoirs. Geological Society of London Special Publication, vol. 270, pp. 43–53.