Fluid-flow properties of faults in sandstone: The importance of temperature history

Quentin J. Fisher
Martin Casey
Simon D. Harris
Robert J. Knipe
Rock Deformation Research Group, School of Earth Sciences, University of Leeds, Leeds LS2 9JT, UK

ABSTRACT

Sandstone rheology and deformation style are often controlled by the extent of quartz cementation, which is a function of temperature history. Coupling findings from deformation experiments with a model for quartz cementation provide valuable insights into the controls on fault permeability. Subsiding sedimentary basins often have a transitional depth zone, here referred to as the ductile-to-brittle transition, above which faults do not affect fluid flow or form barriers and below which faults will tend to form conduits. The depth of this transition is partly dependent upon geothermal gradient. In basins with a high geothermal gradient, fault-related conduits can form at shallow depths in high-porosity sandstone. If geothermal gradients are low, and fluid pressures are hydrostatic, fault-related conduits are only formed when the sandstones have subsided much deeper, where their porosity (and hence fluid content) is low. Mineralization of faults is more likely to occur in areas with high geothermal gradients because the rocks still have a high fluid content when fault-related fluid-flow conduits form. The interrelationship between rock rheology and stress conditions is sometimes a more important control on fault permeability than whether the fault is active or inactive.

Keywords: faulting, fluid flow, quartz cementation, geothermal gradient.

INTRODUCTION

Understanding the fluid-flow properties of faults within sandstone is important in fields such as water-resource management, petroleum production, mineral exploration, and waste disposal. Hydrothermal systems (e.g., Sibson, 1981) and hydrocarbon seepages (e.g., Link, 1952) provide evidence that faults and fractures can focus fluid flow. Faults can also restrict fluid flow, as is often observed in petroleum reservoirs (e.g., Watts, 1987). It is often argued that the reason for this seemingly paradoxical behavior is that active faults act as conduits, unlike those that are not critically stressed (e.g., Barton et al., 1995). Although this statement is probably true for crystalline rocks, here we investigate whether it holds for faults in porous sandstone by combining results from studies of natural fault rocks, sandstone diagenesis, and experimental rock mechanics.

The model we present explains why some faults act as conduits while others act as barriers to fluid flow, without having to invoke large changes in permeability as a function of fault activity. The model may also have implications for the distribution of fault-related mineralization and the depth to the top of the seismogenic zone.

NATURAL FAULT ROCKS

Large databases on the microstructural and petrophysical properties of faults within petroleum reservoirs have been collected (e.g., Fisher and Knipe, 1998, 2001). Here we summarize observations from three areas that provide a pertinent comparison with findings from deformation experiments.

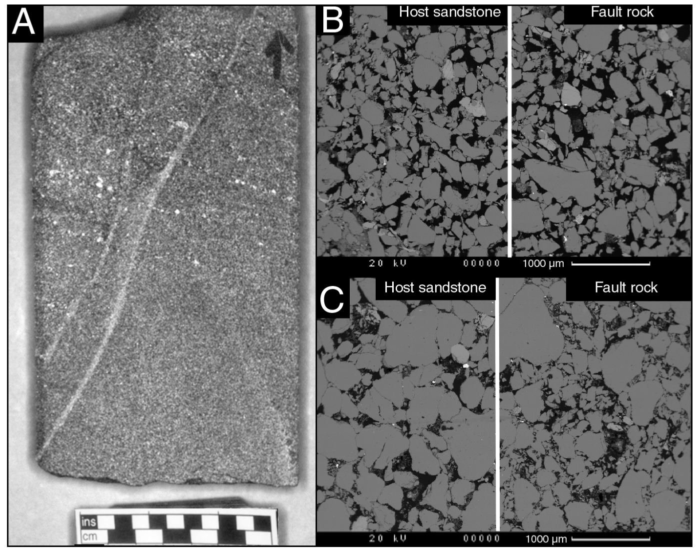

Figure 1. A: Hand specimen containing isolated fault developed in Brent North Sea sandstone. B and C: Backscattered-electron images showing microstructure of (B) disaggregation zone and (C) cataclasite, along with their associated undeformed sandstones.

Faults in the Brent Group (Middle Jurassic), Northern North Sea, UK

The Brent Group reservoirs underwent a major period of extensional faulting in the Late Jurassic, while they were shallowly buried, and did not undergo significant fault development or reactivation during deeper burial. In hand specimen, faults in clean sandstones are usually subtle, isolated features (Fig. 1A). Most are classified as disaggregation zones; these do not contain fractured grains and have the same microstructure (Fig. 1B) and permeability as their hosts (Fisher and Knipe, 1998, 2001). Some, however, underwent minor cataclasis (Fig. 1C) and have lower permeability than their hosts (Fisher and Knipe, 1998, 2001). Externally derived cements are not present along these faults.

Faults in the Rotliegend (Lower Permian), Southern North Sea, UK

Extensional faulting within the Rotliegend probably occurred during an accelerated phase of rifting in the Jurassic, when the Rotliegend was buried beneath several kilometers of overburden (Glennie et al., 1978). Cataclastic faults within the high-porosity eolian sandstones that dominate these reservoirs occur as isolated features (Fig. 2A) or in dense clusters (Fig. 2B), and lack externally derived cements. The isolated features contain a mixture of large, mostly unfractured grains, and small fragments produced by cataclasis (Fig. 2C). The fault clusters often contain discrete slip surfaces with massive grain-size reductions (Fig. 2D). Microstructural analysis indicates that most cataclastic faults within the Rotliegend formed before extensive quartz cementation and have permeabilities that are 10 to 10^6 lower than their protolith (Fisher and Knipe, 2001).

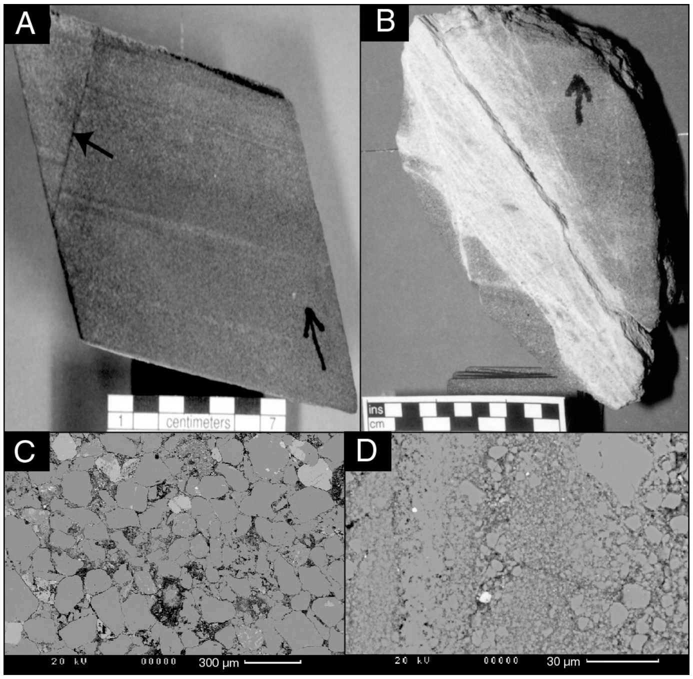

Figure 2. A and B: Hand specimens of (A) isolated and (B) clustered cataclastic faults developed in Rotliegend reservoir from southern North Sea. C and D: Backscattered-electron images showing cataclastic faults from Rotliegend having (C) minor grain fracturing and broad grain-size distribution and (D) intense grain fracturing and narrow grain-size distribution.

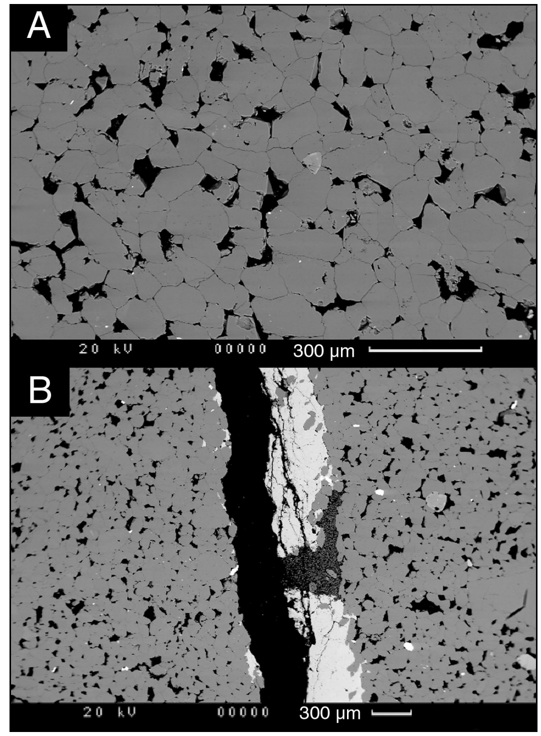

Figure 3. Backscattered-electron images of quartz-cemented sandstone from South American oil field, showing (A) unfaulted sandstone and (B) calcite-cemented dilational fault.

Faults in a Quartz-Cemented Sandstone, Onshore South America

Sandstones in this reservoir are composed almost entirely of quartz and have a porosity of 5% to 15% (Fig. 3A). Quartz cementation is the main diagenetic process to have affected these sandstones. Deformation of these sandstones after quartz cementation produced dilatant faults that are now cemented by calcite (Fig. 3B).

SANDSTONE DEFORMATION EXPERIMENTS

Laboratory experiments on arenites produce two end-member modes of deformation that may be distinguished based on the postyield macroscopic structure of samples (e.g., Griggs and Handin, 1960). In the first, localized or brittle deformation, most strain is accommodated by discrete slip planes. In the second, distributed or ductile deformation, strain is accommodated throughout the sample, instead of along discrete slip surfaces. A transitional regime, often referred to as the brittle-to-ductile transition, exists in which multiple deformation bands form (Scott and Nielsen, 1991). Localized deformation leads to dilation and permeability increase if porosity is $<$15% but permeability decrease if porosity is $>$15% (Zhu and Wong, 1997). Sandstone deformed in a ductile manner or at the brittle-to-ductile transition undergoes compaction and permeability reduction.

In log-log space, a negative linear correlation exists between the critical effective pressure for the onset of grain crushing under hydrostatic conditions, p^*, and the product of grain radius and porosity (Fig. 4B). A regression line through the data within Wong et al. (1997) provides the relationship $\log(p^*) = 3.9 - 1.1 \log(r\phi)$, where p^* is in MPa, ϕ is the fractional porosity, and r is the grain radius (μm).

Wong et al. (1997) gave yield and failure criteria for arenites in a plot of differential stress, q, against effective mean stress, p, each normalized to p^*. Dilatant brittle failure occurs when the ratio p/p^* is $<$0.25 and brittle-to-ductile transition or compaction involving grain crushing occurs at higher values. Note that the value of 1.1 is the slope of the regression, whereas Wong et al. (1997) refered to a slope of $-3/2$, as predicted by a Hertzian fracture model.

NATURE VERSUS LABORATORY

The faults within the Brent and the South American reservoirs appear similar to those formed in the laboratory by shear localization, whereas the clusters of deformation bands in the Rotliegend are similar to features formed at the brittle-to-ductile transition. It is therefore possible that faults in the Brent and South American reservoirs formed when p/p^* was $<$0.25, whereas the clusters of deformation bands within the Rotliegend formed when p/p^* was $>$0.25. The faults within the South American reservoir have since been cemented by calcite, indicating that they were significant conduits for fluid flow, probably because sandstone porosity was $<$15% at the time of faulting. Externally derived cements are not present along the faults within the Brent or the Rotliegend cataclasites; faulting did not increase permeability because the porosity of the sandstones was $>$15%, and in some cases p/p^* was $>$0.25.

MODEL FOR FAULTS IN SANDSTONE

Rheological Evolution of Sands and Sandstones During Burial

Quartz cementation is the most important diagenetic process responsible for the densification of sandstones during burial (Worden and Morad, 2000). This process is largely temperature controlled and does not become significant until $>$90 °C (Walderhaug, 1996). Above ~90 °C, the extent of quartz cementation increases with time and temperature, resulting in decreased porosity and increased strength.

Walderhaug (1996) presented a model to estimate the quartz-cement content of sandstone on the basis of its reactive quartz surface area and temperature history. The model is simple and contains many assumptions, but has provided accurate estimates of the quartz-cement content of reservoirs with a wide range of geological ages, as well as thermal and burial histories (Lander and Walderhaug, 1999). Assuming the same kinetic constants used by Walderhaug (1996), we used this model to calculate how r and ϕ, and hence p^*, vary during burial for a variety of geothermal gradients and burial rates (Figs. 4A and 4B).

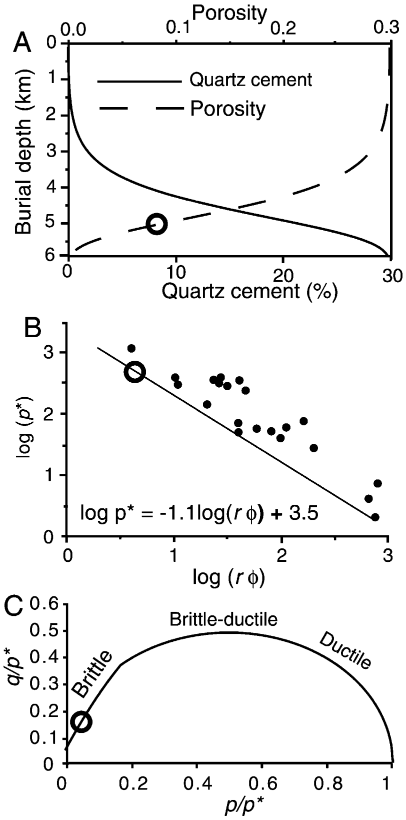

Figure 4. Outline of model used to calculate deformational behavior of arenites during burial. A: Porosity is calculated during burial using quartz-cement model of Walderhaug (1996). B: Product of porosity and grain-size is used to calculate *p (see text) using data presented by Wong et al. (1997). Included is regression line through data that provides lower bound to *p** values. C: Ratio *p*/*p** needed to intersect elliptical approximation of yield/failure envelope of Wong et al. (1997) is calculated. Black circles on each diagram represent calculation run for single burial depth.**

We also assumed that quartz cementation was the only diagenetic process occurring and that the sand was composed entirely of spherical quartz grains. To calculate p^*, the lower bound to the data shown in Figure 4B was taken; this choice accounts for rocks being weaker in nature than in the laboratory experiments due to scale (e.g., Singh and Huck, 1973) and time (e.g., Lawn, 1993) effects. We determined the vertical stress at each depth by assuming lithostatic loading and hydrostatic pore-fluid pressures. The yield and failure curves of Wong et al. (1997, their Fig. 8) were approximated by an elliptical form (Fig. 4C), and, with the assumption of an extensional regime, the ratio p/p^* required to reach yield or failure was determined. Figure 4 summarizes the various steps within the model.

MODEL RESULTS

Deformational Behavior of Arenites During Burial

We first investigated how p/p^* and ϕ varied with burial depth. We simulated a medium-grained sandstone ($r = 150$ μm) with an initial porosity of 30% during burial at 0.05 km/m.y. under a geothermal gradient of 30 °C/km. The results (Fig. 5) show that at burial depths <2.3 km, p/p^* is <0.25; this suggests that deformation occurs by brittle faulting, producing disaggregation zones at low stresses and cataclasites under higher effective stress conditions. Cataclasites will undergo a permeability reduction because the sandstone porosity is >15%. Deformation becomes more ductile during deeper burial, resulting in the development of compactional cataclasites with a lower permeability than their host sandstone. At depths of >4.7 km, p/p^* is <0.25, suggesting that the failure mode returns to brittle dilational faulting. However, faulting will increase permeability because the sandstone porosity is <15%. These results confirm the idea of Scott and Nielsen (1991), that sandstones could "exhibit ductile to brittle behavior with increasing depth." The change from ductile to brittle faulting is an important transition, here referred to as the ductile-to-brittle transition; it marks a change from where faults will either not affect fluid flow or form barriers to where they are likely to be conduits.

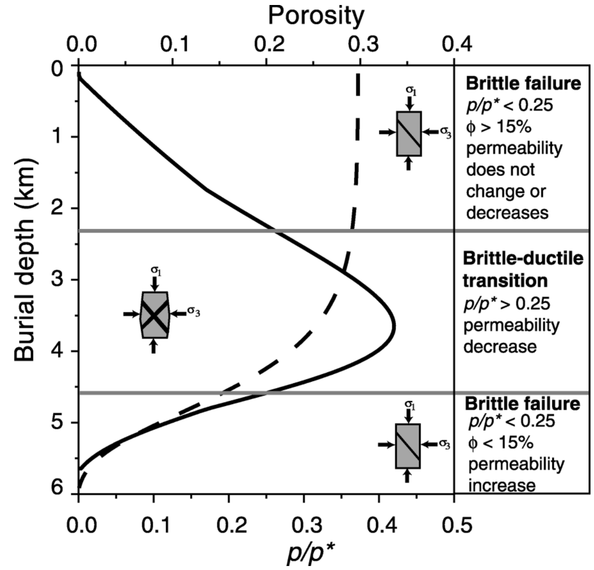

Figure 5. Plot of porosity (dashed line) and *p*/*p (continuous line; see text) vs. burial depth for medium-grained sandstone (r = 150 μm) with initial porosity of 30% buried at rate of 0.05 km/m.y. under geothermal gradient of 30 °C/km. Predicted modes of deformation, based on porosity and *p*/*p**, and their consequences for fault permeability are shown.**

Controls on the Depth of the Ductile-to-Brittle Transition

Simulations were run with various burial rates and geothermal gradients to investigate the controls on the depth of the ductile-to-brittle transition (Fig. 6A). The simulations suggest that increases in geothermal gradient are associated with reductions in the depth of the transition. For example, the transition occurs at 13–19 km under a

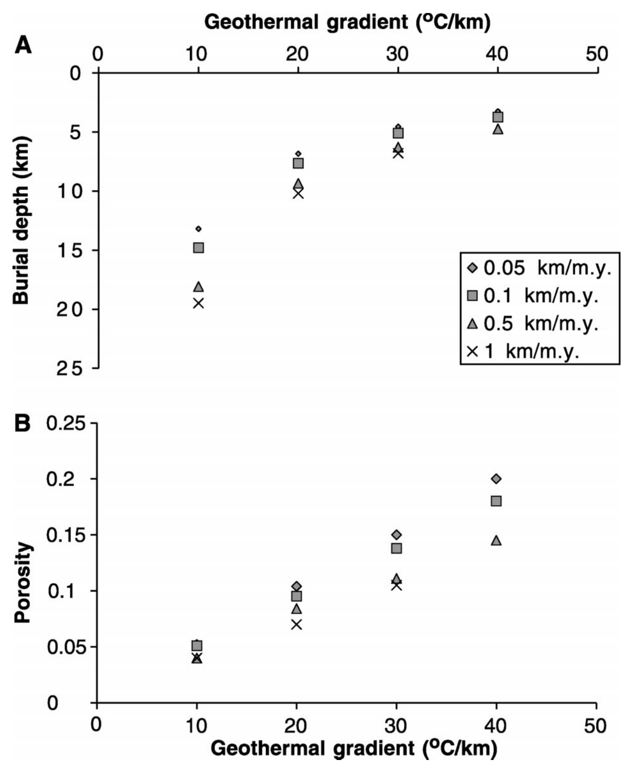

Figure 6. Plots of (A) depth of ductile-to-brittle transition (DBT) and (B) porosity at DBT vs. geothermal gradient for medium-grained sandstone (r = 150 μm) with initial porosity of 30% buried at rates of 0.05–1 km/m.y.

geothermal gradient of 10 °C/km, whereas under a geothermal gradient of 40 °C/km it occurs at ~2 km. Simulations indicate that sandstone (with $r = 150$ μm) would be subject to brittle failure throughout burial if deposited under higher geothermal gradients (i.e., >50 °C/km). In this case, faults may be expected to act as barriers to fluid flow if formed during shallow burial where sandstone porosity is >15%, but would act as conduits for fluid flow if formed at great depth. There is a general decrease in the depth of the ductile-to-brittle transition with decreasing burial rate, although this effect is small in comparison to that caused by variations in geothermal gradient.

The ductile-to-brittle transition in sandstone deposited under high geothermal gradients occurs at shallow depths where porosities are high (Fig. 6B). At geothermal gradients of 40 °C/km, the transition occurs when sandstones have a porosity of >15%, suggesting that fault-related barriers to fluid flow could still form in a small depth interval below the transition. Sandstones deposited under low geothermal gradients continue to behave in a ductile manner during deep burial, when quartz-cement contents are high and porosities are low. It seems that early cementation by quartz strengthens the sandstone during shallow burial, reducing the depth of the ductile-to-brittle transition. Sands deposited under low geothermal gradients become buried under very high confining stresses while they are still weakly cemented—a condition that favors ductile behavior.

Note that the presence of mineral grains other than quartz (e.g., clay, K-feldspar) would tend to retard quartz cementation and hence increase the depth of the ductile-to-brittle transition. Early cementation by other cements (e.g., carbonate) would reduce the depth of the ductile-to-brittle transition. Despite these qualifications, our observations from a wide range of petroleum reservoirs support the general applicability of the model.

DISCUSSION

Our results indicate that faulting of porous sandstones often leads to permeability reduction until they are buried below the ductile-to-brittle transition, when they deform to produce conduits for fluid flow. This explains why some faults act as barriers to fluid flow and others act as conduits without invoking dramatic changes in fault permeability with activity. This is an improvement to many existing models, because observations of fault rocks in nature clearly show that they have never been significant conduits for fluid flow, despite being once active (e.g., Fisher and Knipe, 2001).

For significant fluid flow to occur along faults it is necessary that they have a higher permeability than the surrounding rock mass and that significant amounts of fluid are present to be transported. Faults are most likely to act as conduits for appreciable fluid flow and hence potential sites for mineralization if they form when there are still significant amounts of fluid within the rock. Our model indicates that these conditions are favored by a steep geothermal gradient.

The onset of brittle behavior within accretionary prisms has been suggested to mark the top of the seismogenic zone and occurs at a specific temperature related to the onset of late-stage diagenetic alteration (e.g., Moore and Saffer, 2001). If so, the model we present may be used to investigate other controls on the depth to the top of the seismogenic zone, such as burial rate, grain size, and geothermal gradient.

CONCLUSIONS

Sandstone strength increases as a function of temperature history. Timing of deformation in relation to the strength evolution of sandstones is a fundamental control on the permeability of the resulting faults. Faults formed in sandstones prior to extensive quartz cementation tend not to affect fluid flow or produce flow barriers. Faults formed in sandstones after pervasive quartz cementation tend to form conduits to fluid flow. The ductile-to-brittle transition in sandstone marks the boundary between the depth where faults tend to act as conduits to fluid flow and where they will act as barriers. The depth of this transition varies depending upon sedimentation rate, geothermal gradient, and time.

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REFERENCES CITED

Barton, C.A., Zoback, M.D., and Moos, D., 1995, Fluid flow along active faults in crystalline rocks: Geology, v. 23, p. 683–686.

Fisher, Q.J., and Knipe, R.J., 1998, Fault sealing processes in siliciclastic sediments, *in* Jones, G., et al., eds., Faulting and fault sealing in hydrocarbon reservoirs: Geological Society [London] Special Publication 147, p. 117–134.

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

Glennie, K.W., Mudd, G.C., and Nagtegaal, P.J.C., 1978, Depositional environment and diagenesis of Permian Rotliegend sandstone in Leman Bank and Sole Pit areas of the UK southern North Sea: Geological Society [London] Journal, v. 135, p. 25–34.

Griggs, D., and Handin, J., 1960, Observations on fracture and a hypothesis of earthquakes, *in* Griggs, D., and Handin, J., eds., Rock deformation: Geological Society of America Memoir 79, p. 347–364.

Lander, R.H., and Walderhaug, O., 1999, Porosity prediction through simulation of sandstone compaction and quartz cementation: American Association of Petroleum Geologists Bulletin, v. 83, p. 433–449.

Lawn, B., 1993, Fracture of brittle solids (second edition): Cambridge, Cambridge University Press, 378 p.

Link, W.K., 1952, Significance of oil and gas seeps in world oil exploration: American Association of Petroleum Geologists Bulletin, v. 36, p. 1505–1539.

Moore, J.C., and Saffer, D., 2001, Updip limit of the seimogenic zone beneath the accretionary prism of southwest Japan: An effect of diagenetic to low-grade metamorphic processes and increasing effective stress: Geology, v. 29, p. 183–186.

Scott, T.E., and Nielsen, K.C., 1991, The effects of porosity on the brittle-ductile transition in sandstones: Journal of Geophysical Research, v. 96, p. 405–414.

Sibson, R.H., 1981, Fluid flow accompanying faulting: Field evidence and models, *in* Simpson, D.W., and Richards, P.G., eds., Earthquake prediction: An international review: American Geophysical Union Maurice Ewing Series, v. 4, p. 593–603.

Singh, M.M., and Huck, P.J., 1973, Large scale triaxial tests on rocks, *in* Hardy, H.R., and Stefanko, R., eds., New horizons in rock mechanics, Proceedings, 14th Symposium on Rock Mechanics: State College, Pennsylvania State University, American Society of Civil Engineers, p. 35–60.

Walderhaug, O., 1996, Kinetic modeling of quartz cementation and porosity loss in deeply buried sandstone reservoirs: American Association of Petroleum Geologists Bulletin, v. 80, p. 731–745.

Watts, N.L., 1987, Theoretical aspects of cap-rock and fault seals for single and two phase hydrocarbon columns: Marine and Petroleum Geology, v. 4, p. 274–307.

Wong, T.-F., David, C., and Zhu, W., 1997, The transition from brittle faulting to cataclastic flow in porous sandstones: Mechanical deformation: Journal of Geophysical Research, v. 102, p. 3009–3025.

Worden, R.H., and Morad, S., 2000, Quartz cementation in oil field sandstones: A review of the key controversies, *in* Worden, R.H., and Morad, S., eds., Quartz cementation in sandstones: International Association of Sedimentology Special Publication 29, p. 1–20.

Zhu, W., and Wong, T.-F., 1997, The transition from brittle faulting to cataclastic flow: Permeability evolution: Journal of Geophysical Research, v. 102, p. 3027–3041.

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