

Pressure solution and mica in quartzose sandstone: Observations and experiments

JAMES R. BOLES¹, JACOB ISRAELACHVILI^{2,5,6},
NORMA ALCANTAR³, ALESSANDRO ANZALONE³,
EMILY MEYER⁴, WREN GREENE⁵
AND MARGARET PATAKI¹

¹Dept. of Geological Sciences, UCSB, USA
(boles@geol.ucsb.edu)

²Dept. of Chemical Engineering, UCSB, USA
(jacob@engineering.ucsb.edu)

³Dept. of Chemical Engineering, Univ. So. Florida, USA
(alcantar@eng.usf.edu)

⁴Dept. of Physics, UCSB, USA

⁵Materials Dept., UCSB, USA

⁶Materials Research Laboratory, UCSB, USA

Observations and experiments show that quartz pressure solution is greatly accelerated in the presence of micaceous clays. Quartz grains typically flatten against detrital muscovite but enhanced dissolution is not a general effect with all clays (cf., kaolinite, chlorite). In a North Sea oil reservoir, quartz dissolution causes micaceous organic lamina to deform into irregular stylolites in which the wavelength and amplitude is several times the magnitude of the mean grain diameter. No stylolites develop in lamina free sandstones. Modeling of the formation of these stylolites shows that they develop by a more complicated process than simple random differences in solubility of grains. Thus, stylolites must provide feedback to the dissolving grains. Furthermore, the tips of some stylolites have dissolution fronts or spaces that advance ahead of the stylolite, precluding a simple pressure solution mechanism for their development. Rocks from 10² to 10³ m.y. show well developed pressure solution compared with younger rocks. However, incipient pressure solution occurs in marine sedimentary rocks as young as 6 m.y at burial conditions as low as 40-50°C and lithostatic pressures of <22 M Pa (<1 km burial depth).

Using a Surface Forces Apparatus (SFA) we have measured the repulsive 'hydration' forces and water and ionic diffusion rates in nm-thin water films confined between mica surfaces in various electrolyte solutions. We observe (1) strong short-range repulsive hydration forces, determined by the bound solution ions to the clay surfaces, with Na⁺ and Ca²⁺ having antagonistic effects, and (2) rapid ion transport rates. We have also performed SFA experiments with 'asymmetric' systems of mica sheets pressed against quartz crystal and silica surfaces. Unlike the symmetric systems, with the asymmetric systems we observe 'pressure solution,' i.e., quartz (but not mica) dissolution. Given the angstrom resolution of the optical interference technique used in the SFA, we can monitor typical geologic dissolution rates in hours and *in situ*, rather than over months or years.

The evolution of grain contacts undergoing pressure solution – Unique insights from a confocal viewpoint

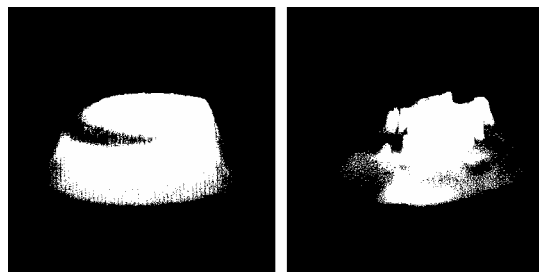
Z. KARCZ^{1,2}, E. AHARONOV³, D. ERTAS²,
R. POLIZZOTTI² AND C.H. SCHOLZ¹

¹Lamont-Doherty Earth Observatory, Columbia University,
New York, USA (zk17@columbia.edu)

²ExxonMobil Research and Engineering, New Jersey, USA

³Weizmann Institute, Rehovot, Israel

We used a confocal microscope to follow the evolution of a contact between a fluid saturated cone-shaped halite indenter undergoing pressure solution and a flat silicate plate. The top of the indenter initially undergoes axi-symmetric inward dissolution along its perimeter at rates that are highest at the contact plane and decrease at more elevated surfaces. During this initial phase, which generally lasts tens of hours, the surfaces of the indenter remain relatively smooth. As the contact approaches a critical size, plastic flow ensues, the contact becomes larger and its geometry becomes more complex. We observe a mesa-like structure at the contact, standing tens of microns above relatively smooth planes, that is incised by steep interconnecting channels. The location of this structure and its internal geometry constantly change, a feature we attribute to the competition between plastic flow that drives material from above downward and outwards, and strain-energy driven dissolution, which consumes the contact region along its perimeter.



3D projections of the top of the indenter immediately after brine was added to the system (left) and 120 hours later. During this period the indenter accrued 60µm of vertical displacement. Field of view ~500µm

Does stress affect the dissolution of calcite?

J. BISSCHOP¹, C. PUTNIS², B. JAMTVEIT¹
AND D.K. DYSTHE¹

¹Physics of Geological Processes, University of Oslo, Postbox 1048 Blindern, 0316 Oslo (jan.bisschop@fys.uio.no, bjorn.jamtveit@geo.uio.no, d.k.dysthe@fys.uio.no)

²Institut für Mineralogie WWU Münster, Corrensstrasse 24, D-48149 Münster, Germany (putnis@uni-muenster.de)

In order to understand how fluids interact with loaded rocks it is important to know how much stress affects the chemical potential and dissolution-precipitation rates of common rock-forming minerals. We investigated the effect of stress (elastic strain) on the development of dissolution patterns on free surfaces of calcite single-crystals using 'wet' Atomic Force Microscopy. Samples were stressed in the AFM by means of bending. Thin-sections (80 μm) of Iceland Spar crystals were prepared on a microscope cover glass (200 μm) and glued into a concave holder with constant curvature. Stress-distributions in the elastically bend doubly-layer were calculated by numerical modeling. Calcite samples were curved to a degree close to the elastic limit in compression, i.e., just below the critical curvature at which first mechanical twins were observed. The initial sample surface was ultrapolished, either parallel to (10-14) cleavage planes or, to increase the number of initial reaction sites, inclined to these crystallographic planes by 5 degrees. Experiments were carried out in freshly deionized water and ran for up to 3 hours.

The surface patterns of the 22 studied samples (12 stressed, 10 stress-free) showed significant variation, making it difficult to determine whether an effect of stress on pattern formation existed. Sample surfaces polished parallel to (10-14) showed dissolution by etch-pit formation, both with and without stress. Sample surfaces inclined to (10-14), both with and without stress, dissolved along parallel steps not originating from dislocation, but (like etch-pit walls) with a preferred orientation parallel to one of the cleavage plane direction. After strong initial (~30 minutes) bunching of dissolution steps, an apparent steady state pattern was usually reached with only minor variation across a single sample surface. From sample to sample much variation existed in the length and width of terraces in between bunched dissolution steps. Compared to stress-free samples, stressed samples showed more heterogeneous dissolution patterns on the micrometer scale and, on average, a higher number of growth features, preferably at elevated (stress-free) sites on the roughening sample surfaces.

Modelling localized volume changes: Application to pressure solution and stylolites

R. KATSMAN AND E. AHARONOV

Weizmann Institute of Science, Rehovot, Israel
(regina.katsman@weizmann.ac.il,
einat.aharonov@weizmann.ac.il)

A newly developed two-dimensional elasto-plastic numerical model is used to study the evolving interaction between stress distribution in a soluble elastic matrix and a resulting pressure solution (PS) distribution. Spatial distributions of PS resulting from different dominant PS mechanisms are compared (e.g. thin-film and undercutting). The model is used to study growth of a single stylolite, as well as stylolite interactions under a variety of boundary conditions. Results suggest that 1) Other PS mechanisms in addition to (or instead of Thin-Film PS take place in stylolites. 2) Spacing between stylolites might be controlled by elastic mechanisms and rock heterogeneity, similarly to controls on spacing between cracks and compaction bands.

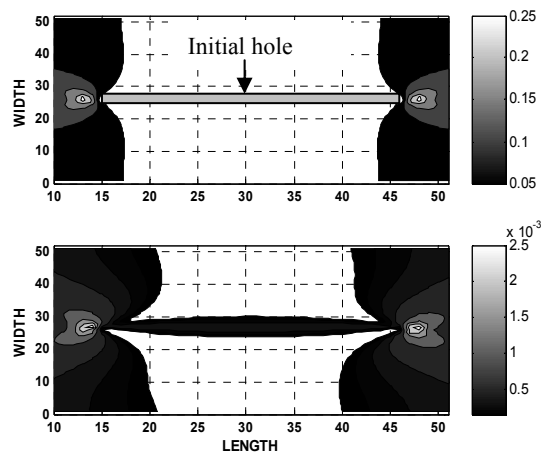


Figure 1. PS evolving around a compressed crack. Gray shading indicates rates of dissolution in non-dimensional units (here white is used for the highest dissolution, black for the lowest one; white area with grid in the middle of the picture corresponds to area where there is no dissolution occurs). a) Dissolution resulting from PS dominated by normal stress (thin-film) is concentrated at the crack tips. b) PS controlled by strain-energy (undercutting) is concentrated both at the tips and the walls of the initial crack.

Modelling the formation of stylolites as a competition between elastic forces, surface tension and noise

D. KOEHN¹ AND F. RENARD^{2,3}

¹Institute of Geosciences, University of Mainz, Germany
(koehn@uni-mainz.de)

²University of Grenoble, France
(francois.renard@ujf-grenoble.fr)

³PGP, University of Oslo, Norway

Stylolites are rough dissolution seams in natural rocks. They are a very common feature with a roughness on a large range of scales. Stylolites are usually used to identify the orientation of the largest compressive stress and the maximum amplitude of their peaks is used to estimate compaction in sedimentary basins. Why and how the stylolite roughness develops in detail is still debated. We present a new numerical model that is used to study the roughness development of stylolites in time and 2D space. A particle model is used with a linear elastic spring network where particles dissolve as a function of elastic and surface energies as well as normal stress on reactive interfaces. An initial quenched noise on the dissolution constants of particles is used to initiate the roughness. The initial configuration in the model is a perfectly flat dissolution surface that represents an initial heterogeneity in the rock. This surface remains flat when no initial noise is used in the system indicating that elastic and surface energies as well as the normal stress on the surface smoothen the interface and prevent roughness development. Systems with an initial noise, however, develop a significant roughness within a relatively short time. Over time the mean position of the stylolites remains fixed whereas their mean and maximum amplitude scale as a function of the square root of time. Elastic energy, normal stress and surface energy influence the roughness growth and thus the scaling properties of the stylolites. Fast Fourier Transforms of time and space series indicate that the stylolites may show self-affinity in both, time and space. We compare the results of the numerical model with natural systems and discuss the implications of our study.

Physical chemistry of replacement: Consequences for petrology and reaction-transport modeling

ENRIQUE MERINO

Geology Dept, Indiana Univ, Bloomington, IN 47405, USA
(merino@indiana.edu)

Mineral replacement, characteristically preserving both volume and morphological features of the host, is widespread in rocks of all kinds. Crystal aggregates that grow in a rock exert a local stress on adjacent mineral grains as they grow. This *induced stress* depends on the kinetics of crystal growth that causes it, the shape of the aggregate, the pre-existing macroscopic stress, and the host rock's response to the growth (Fletcher & Merino, 2001). Possible responses are pressure-solution, deformation, and fracturing of the host rock.

I. Replacement takes place where the A growing crystals are accommodated only by pressure-solution of adjacent B-host grains. The induced stress between A and B forces the crystal growth rate of A and the pressure solution rate of B to become equal. This is why replacement is always isovolumetric. Adjusting the replacement of B by A on volume often provides unsuspected insight. Adjusting the weathering replacement of feldspar by gibbsite on volume provides the thread to grasp the feedback (between the leaching and the accumulation zones) at the core of all weathering (Merino et al, 1993). It is thanks to this feedback that the two zones remain associated as they dynamically "eat" their way into parent rock, as confirmed by dynamic modeling (Wang et al, 1995), and as observed.

II. If the B host rock has low strength and/or a low dissolution rate constant, then the growing crystal(s) of A are accommodated by local deformation of the B host rock. If A grows as dispersed crystals or nodules their aggregate mechanical effect is to overpressure a large volume of host rock, on a scale much larger than the size of each nodule.

III. If A grows in a host rock subjected to unequal principal stresses, then A grows as displacive *veins*. Vein-shaped growth injects the least strain energy into the host, compared to spherical and rod-like growths. Displacive vein examples: septarian concretions; zebra veins in dolomites, evaporites, serpentized gabbros; veins normal to stylolites.

Dynamic reaction-transport modeling including the growth-induced stress and its consequences – replacement or displacive growth – can better integrate modeling and petrology (Merino & Dewers, 1998).

References

- Fletcher R C & Merino E (2001) *GCA* **65**, 3733-3748.
Merino E, Nahon D, & Wang Y (1993) *AJS* **293**, 135-155.
Merino E & Dewers T (1998) *J. Hydrology* **209**, 137-146.
Wang Y, Wang Y, & Merino E (1995) *GCA* **59**, 1559-1570.

Pore-scale coupling of dissolution, diffusion, and crystallization forces during alteration of vesicular lavas

JANE E GUSTAVSON AND PHILIP S. NEUHOFF

Department of Geological Sciences, University of Florida,
USA (geojane@ufl.edu, neuhoff@ufl.edu)

Time-progressive infilling of vesicular pore space by secondary minerals is a common textural feature of zeolite facies metabasalts. For instance, individual vesicles are often rimmed by one or more generations of mafic phyllosilicates and silica phases, with later infillings of one or more generations of zeolites and other silicates. Infilling of pore space is due to formation of secondary mineral phases that are considerably less dense than the basalt. Digital analysis of pore geometries and mineral parageneses at the thin section scale show that the thickness of phyllosilicate linings is independent of pore size within a sample leading to an increased percentage of phyllosilicate occlusion of porosity as pore size decreases. However, the preservation of residual pore space after alteration is a function of pore size, with larger pores being more likely to retain porosity after alteration. In rare instances, alteration aureoles are observed around pores. We propose a model to explain these observations that involves coupled diffusion of water into the matrix of the lavas and ions into the vesicle that is governed by the amount of available open volume necessary to accommodate new mineral formation. Mass balance calculations indicate that the volume of mafic phyllosilicates formed during alteration is smaller than that of the lava dissolved. However, reaction path modeling indicates that at low degrees of reaction, mafic phyllosilicates form first with an early net gain in solid volume. Further reaction leads to stabilization of zeolites along with mafic phyllosilicates, which leads to a dramatic increase in total solid volume of up to ~30 % for complete reaction of the lava. Paragenetically late infilling of vesicles by zeolites without phyllosilicates suggests that phyllosilicate formation during zeolitization is restricted to pseudomorphic replacement of primary phases, consistent with petrographic observations. The fact that the progressive infilling textures are consistent from vesicle to vesicle, and that mineral volumes are not averaged between vesicles, indicates that these processes are controlled by local scale diffusion and volume availability at the scale of individual pores. Temporal variations in mineral stability and net volume changes during reaction thus drive net transport of components between vesicles and the lava matrix in response to restrictions on the space necessary for authigenic mineral formation.

Dissolution-precipitation creep under cyclic stress

GUNTRAM JORDAN¹, KIRILL ALDUSHIN¹,
THOMAS LOHKÄMPER¹ AND WOLFGANG W. SCHMAHL²

¹Institut für Geologie, Mineralogie und Geophysik, Ruhr-Universität Bochum, 44780 Bochum, Germany
(guntram.jordan@rub.de)

²Dept. für Geo- und Umweltwissenschaften, Sektion Kristallographie, Theresienstr. 41, 80333 München, Germany

Dissolution-precipitation creep (DPC) is one of the main deformation mechanisms in natural systems. Common models for DPC assume a steady state process in a closed system consisting of three steps: i) dissolution at the grain-to-grain interfaces of non-hydrostatically stressed surfaces, ii) transport of the solute in interfaces, iii) precipitation at grain-to-pore interfaces or at hydrostatically stressed crystals.

The deformation is ultimately driven by the potential energy of the system (Weyl, 1959) and the kinetics of DPC is assumed to be transport controlled. However, recent investigations (He et al., 2003; Lohkämper et al., 2003) show that open systems, capillary forces, or temperature variations can significantly affect the rate of DPC. Here, we investigate the influence of cyclic stress on the deformation rate of halite crystals in contact with silica. In low stress periods, transport within the interface is noticeably enhanced in comparison to high stress periods. Therefore during low stress periods, material, which was plastically deformed in previous high stress periods, can be quickly removed and transported out of the interface.

Regardless of the interface morphology, reducing the load enhances material transport. Therefore, cyclic variations of stress provide an efficient deformation mechanism by permanently increasing the internal energy of the crystal via plastic deformation in high stress periods and reducing the energy via dissolution and transport in low stress periods.

As evident from seismic activities, cyclic variations of stress are common in geological systems. Therefore, we expect from our results that cyclic build up and release of stress can become key factors for fluid assisted deformation of rocks.

References

- He W., Hajash A., Sparks D., (2003), *Am. J. Sci.* **303**, 73-93.
Lohkämper T.H.K., Jordan G., Costamagna R., Stöckhert B., and Schmahl W.W., (2003), *Contr. Mineral. Petrol.* **146**, 263-274.
Weyl P.K., (1959), *J. Geophys. Res.* **64**, 2001-2025.

The importance of plastic flow in the deformation of a sodium chloride indenter undergoing pressure solution

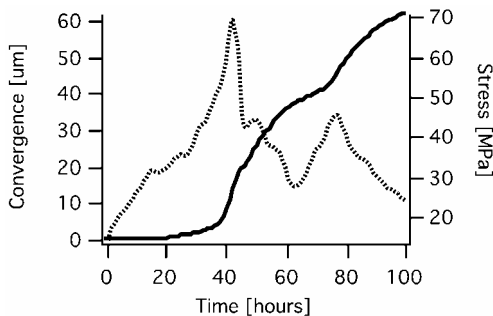
Z. KAR CZ^{1,2}, E. AHARONOV², D. ERTAS²,
R. POLIZZOTTI² AND C.H. SCHOLZ¹

¹Lamont-Doherty Earth Observatory, Columbia University,
New York, USA (zk17@columbia.edu)

²ExxonMobil Research and Engineering, New Jersey, USA

³Weizmann Institute, Rehovot, Israel

We conducted experiments to study the deformation of a loaded single crystal sodium chloride indenter immersed in saturated solution. The contact between the indenter and an inert silicate window was viewed with a confocal microscope. The indenter exhibits two stages of deformation: The first involves rapid inward dissolution of the contact (undercutting) accompanied by slow vertical convergence caused by the elastic response to the shrinking contact and vertical (“thin-film”) dissolution. The second stage consists of rapid vertical convergence by plastic flow and removal of the flowed material by strain-energy driven inward dissolution. The transition from stage 1 to stage 2 occurs when the contact stress is 75MPa on average, which indicates that the indenter undergoes significant strain hardening to this point. During the second stage we observe oscillations in the rate of convergence, which are closely related to oscillations in the area of the contact. These oscillations reflect the counteraction of plastic flow and inward dissolution.



Convergence (solid) and stress (dashed) curves for experiment 45. $t=0$ is the time when brine was added to the system.

3D microtomography of a salt aggregate during pressure solution

FRANÇOIS RENARD^{1,2}

¹LGIT-CNRS-OSUG, University J. Fourier, BP 53, F-38041
Grenoble, France (francois.renard@ujf-grenoble.fr)

²Physics of Geological Processes, University of Oslo, Norway

Pressure solution creep is one of the possible processes of mechano-chemical deformation that controls porosity and permeability variations in the upper crust. The three-dimensional geometry of the porous network of halite aggregates was imaged during compaction driven by pressure solution creep using X-ray synchrotron computed microtomography. With this technique the whole aggregate textural changes during deformation (Fig. 1a) as well as individual grain contacts (Fig. 1b) were imaged at several stages of the deformation. By reconstructing subvolumes, the 3D porosity of the aggregates was extracted. The time-resolved decrease in permeability during porosity reduction was calculated by solving the Stokes equations. The permeability remained isotropic and decreased from 2.1 to 0.15 Darcy after 18.2% compaction. Two microscopic mechanisms can explain the permeability reduction: grain indentation and pore connectivity reduction by precipitation on the free surface of pore throats.

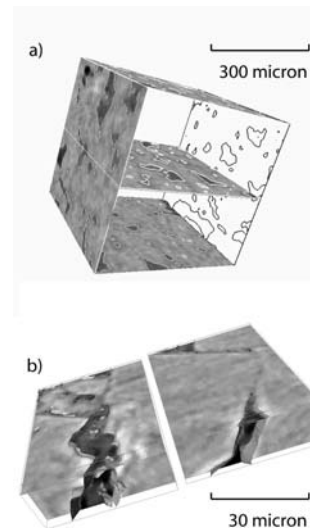


Figure 1: a) X-ray tomography of a salt aggregate during compaction in the presence of a saturated brine. Individual grains appear in light gray, whereas the pores are dark. b) Zoom on two salt grains before (left) and after compaction (right).