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Nano-kinematic indicators (Gulf of Aqaba, Saudi Arabia)

Alessandro Genovese (✉ alessandro.genovese@kaust.edu.sa)  
King Abdullah University of Science and Technology  https://orcid.org/0000-0001-8154-3098

Jakub Fedorik (✉ jakub.fedorik@kaust.edu.sa)  
King Abdullah University of Science and Technology

Abdulkader Afifi (✉ abdulkader.alafifi@kaust.edu.sa)  
KAUST  https://orcid.org/0000-0002-3193-4792

Grasemann Bernhard (✉ bernhard.grasemann@univie.ac.at)

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ABSTRACT

Strain and kinematic indicators are frequently investigated to assess the type, magnitude, and orientation of deformation fields. Typically, their analysis ranges from the outcrop to the thin section scale. The present study characterizes the structural and mineralogical development of a phyllosilicate-rich fault gouge from the core of a major strike-slip fault on the eastern margin of the Gulf of Aqaba. We used transmission electron microscopy and focused ion beam techniques to explore shear deformation structures down to the nanoscale. The fault gouge was differentiated at the micron-submicron scale into chlorite-rich and illite-rich bands. The observed nano-kinematic shear sense indicators were SC/SCC’ fabrics in phyllosilicate bands, inclined axial planes in kink-folded illite and chlorite plates, platy hematite clasts inclined against the shear direction, and a σ-type clast system with recrystallized material in strain shadow wings around the clasts. These indicators provide a consistent set of criteria to determine shear sense in phyllosilicate-rich fault gouges.

INTRODUCTION

Shear and kinematic indicators are deformation structures with a monoclinic symmetry and useful for deriving the shear sense of brittle fault rocks and ductile shear zones. Although some kinematic indicators, like Riedel shears and folds, may develop at the size of map-scale, e.g.,, most shear sense indicators are described at the outcrop, hand sample or microscale. Besides the importance of deciphering the displacement sense along faults and shear zones, which is not always an easy task, shear indicators can be used to derive the mean kinematic vorticity number, which is useful for quantifying the contribution of simple and pure shear.
In the past two decades, studies of fault rocks have focused mainly on the fabric developed in natural and experimental brittle and ductile shear zones to discriminate the deformation mechanisms and evaluate seismic or aseismic slips e.g., 7, 8, 9. Some of these studies have documented cataclastic flow processes, grain fracturing, abrasion and comminution 10, 11, which rarely result in the formation of micro monoclinic structures. Other studies have shown that ductile processes, like pressure solutions and dynamic recrystallization, may result in monoclinic fabrics like SC/SCC’ fabrics, which can be used to derive the shear sense 12, 13. In the present work, we demonstrate that a variety of kinematic indicators exist even at the nanoscale in phyllosilicate-rich fault gouges from the Dead Sea Transform (DST), including SC/SCC’ fabrics, cataclasts and kink-folds. The DST is an active, left-lateral, strike-slip boundary between the Sinai microplate and the Arabian plate 14. Active deformation in the DST southernmost segment is currently focused within the Gulf of Aqaba (GOA) (Figure 1). However, both GOA shoulders were deformed by an earlier network of strike-slip faults 15.
Figure 1. Study area. Image of the eastern margin of the Gulf of Aqaba Landsat showing the network of strike-slip faults (white). The sample location (white star, 28.537991°N and 34.817592°E) from a major strike-slip fault offsets the contact (yellow) between two basement granite plutons by 5.6 km (red line).

For this study, we sampled a fault gouge from a polished fault surface. At this locality, the fault zone is an 8-meter-wide cataclastic breccia composed of intermingled blocks of granite and sandstone (Figure 2a). Within the fault zone, rotated granite blocks are dissected by a braided network of subvertical anastomosing microfaults that are coated with a dark greenish-grey fault gouge with a glossy luster. Such glossy friable greenish-grey fault gouges are present along fault surfaces cutting hard granitic rocks. Figure 2b shows details of the sample location from a granite block within the fault zone.
Figure 2. Overview and detail of the fault outcrop. a) Overview of the primary fault zone, Southeast orientation, showing the contact between the Red Sea Rift Sediments and Precambrian Basement. b) Outcrop detail showing several microfault planes and the exact sample area of the rock specimens.

RESULTS AND DISCUSSION

The SEM investigations focused on a <1 mm-wide fault gouge coating the microfault surface in order to study the mineralogy, fabric development and chemical differentiation at nanoscale. The foliated fault gouge showed a clear lineation (Figure 3a) that was well discernible by SEM imaging of the slip surface (i.e. the xy plane parallel to foliation) as slickensides resulting in grooves and ridges (Figure 3b, dotted yellow arrows). Figure 3b also shows a relatively smooth area with no height variations in the x-direction and located between two parallel ridges. This region was selected for the FIB thin foil and Slice&View milling.

HAADF STEM imaging of the thin foil (Figure 3c) revealed four fault-parallel zones (z1-z4) with different fabrics and mineral compositions based on the elemental mapping (Figure 4):
- **z1**: A 0.5-1-μm thick zone of illite nano-crystallites along the microfault surface. This zone lacks visible clasts.

- **z2**: A 1-2.5-μm thick zone consisting mainly of well foliated chlorite as well as rounded nano-clasts up to 1 μm long and locally a weak SCC’ fabric defined by hematite plates.

- **z3**: A 1-μm thick zone with up to 1 μm of well foliated illite plates aligned parallel to the microfault surface with delaminated structures. Locally, an SC/SCC’ fabric is developed.

- **z4**: A thicker marginal zone containing up to 4-μm long kink-folded chlorite/illite plates with an SC fabric and ~1 μm micro-clasts.

Figure 3d shows two 3D views of the FIB Slice&View analysis, covering a 4x3x2 μm³ volume. These views reveal micro-discontinuities (red surfaces) at acute angles to the fault surface and an elongated clast of a few hundred nanometers parallel to the lineation direction (green object).

**Figure 3. From the hand sample to the nanometric scale. a)** Fault rock sample of the greenish fault gouge with striations (dotted yellow arrows) and the SEM regions of interest (white square)
depicted. b) SEM image of the fault surface (xy plane) with lineation (dotted yellow arrows) and location for the FIB thin foil and Slice&View sectioning (c blue rectangle, d blue square, respectively). c) HAADF STEM image of the thin foil (xz plane) showing the fault surface with nano-roughness, nano-clasts of different sizes, and the z1-z4 subparallel zones. The thin foil is coated with a Pt protective layer. d) 3D FIB Slice&View projections with planar discontinuities (red) and a nano-clast (green) elongated parallel to the rock lineation (dotted yellow arrows). Voxel size, 12x12x25 nm$^3$ in the x, y, z directions. Red arrows, shear directions.

The STEM-EDS mapping (Figure 4) revealed mineralogical differences between the four zones: z1 and z3 are enriched in Si, Al, K and Na and are composed mainly of illite; and z2 and z4 are enriched in Mg, Fe, Al and Si and are composed mainly of illite and chlorite. Additionally, z2 and z4 contain nano-clasts of quartz (Si), feldspar (K, Na and Ca), platy Fe-oxide (mostly hematite), some ilmenite plates (high Fe and Ti) and nano-pores, which are revealed by the black holes in the oxygen map.
Figure 4. STEM-EDS chemical analysis. HAADF STEM reference image (xz plane).

Elemental distribution for Si (ochre), Al (light blue), Mg (light green), K (magenta), O (yellow), Na (light turquoise), Fe (red), Ca (orange), and Ti (blue). Note the chemical differentiation into illite-rich layers z1 and z3 (high Si, K, Na, Al) and chlorite-rich layers z2 and z4 (high Mg, Fe), which contain nano-clasts of feldspar (high K, Na, Ca) and hematite (high Fe).

Figures 5a and 5b show the TEM and SAED characterizations of the thin foil. Along the fault surface, z1 has weak foliation due to the poor crystallinity of the phyllosilicates, as confirmed by the corresponding SAED pattern displaying broad rings, consistent with the 110 reflections at 4.5 Å of the mica-group (illite). Zone z2 is characterized by intermediate crystallinity with additional reflections indexed as chlorite 002 and 003 basal planes at 7 Å and 4.7 Å, respectively. The transition between z3 and z4 shows a polycrystalline structure with
apparent basal planes delineating the main foliation of the rock. In particular, the z4 foliation is defined by both chlorite and illite plates, as shown by the SAED indexing. Figure 5c panels display the HRTEM analysis of the nano-sheets of the four zones, z1-z4, and reveal mica-group phyllosilicates (basal planes at 10 Å) for z1 and z2, chlorite (basal planes at 14 Å) for z3, and both mica-group phyllosilicates and chlorite for z4.

Figure 5. TEM, SAED, and HRTEM imaging. a) TEM image showing zones z1-z4 with highlighted the SAED regions, and a σ-type clast (dotted white square). b) SAED patterns for z1, z2, and z4 regions with the corresponding diffraction indexing revealing the increase of crystallinity from amorphous/paracrystalline in z1, an intermediate crystallinity in z2, and a polycrystalline structure in z4. The z2 diffraction spots are consistent with chlorite 111, 002 and
003 reflections at 4.5 Å, 7.1 Å and 4.7 Å (red). The z4 diffraction indexing confirmed both
clorite 001 and 002 reflections at 14 Å and 7.1 Å (red) and mica-group 002 and 004 reflections
at 10 Å and 5 Å (yellow). c) HRTEM z1-z4 images displaying mica-phyllosilicates (10 Å basal
plane) in z1 and z3, chlorite (14 Å basal plane) in z2, and mica-phyllosilicate/chlorite mixture in
z4. d) TEM image of the σ-type clast with strain shadow wings following the S-planes. e) TEM
detail of one of strain shadow wings of the σ-type clast and HRTEM image at atomic spatial
resolution of the strain shadow wing showing the mica-group nano-sheets (10 Å basal plane)
parallel to the wing elongation. f) Strain model showing the S-planes, strain shadow wings, and
the clast synthetic rotation sense. Red arrows define the shear direction.

In z4, rounded to elliptical nano-clasts with partly sigmoidal wings in the strain shadows
occurred within the phyllosilicate matrix, that shows an SC fabric (Figure 5a). The long axes of
the clasts and the wings are either oriented parallel to the C-planes or parallel to the S-planes.
The HRTEM analysis of one of those clasts with the S-plane orientation (Figure 5d) shows,
inside the strain shadow, nano-sheets of mica-group phyllosilicates with basal 10 Å planes
parallel to the long axis of the wings (Figure 5e). The monoclinic symmetry of the nano-clasts
and local stair-stepping of the wings in the strain shadow confirm the overall shear sense of the
fault (top-to-the right) and synthetic rotation of the clast. The corresponding shear model with
shear direction is depicted in the schema of Figure 5f.

The resulting shear sense is further supported by several other nanoscale structural
observations: (i) the phyllosilicates form SC/SCC’ fabrics in z2 and z4 (nicely shown in the Mg
element map); (ii) packages of phyllosilicates are stretched when they are inclined toward the
shear direction (i.e. in S-orientation); (iii) packages of phyllosilicates, which are inclined against
the shear direction, are kinked; and (iv) elongated nano-minerals in z2 and z4 (e.g. ilmenite in the Fe maps) form sigmoids inclined to the shear direction. The fault gouge consists of a mixture of newly formed, synkinematic illite and chlorite along with minor amounts of comminuted fragments of the host rocks (mainly quartz and feldspar) and exhibits a progressive increase in grain size and crystallinity from the microfault surface toward the margin. The abundance of chlorite and illite greatly exceeds the abundance in the host granite. This observation, along with the foliated and layered character of the fault gouge, indicates that the phyllosilicates crystallized in the solid state during or shortly after slips along microfaults cutting the granite block (Fig. 2b).

The fault gouge formation is therefore attributed to frictional heating of a comminuted ultracataclasite under hydrous conditions and a significant confining pressure but insufficient to cause melting or the formation of pseudotachylites.

The microstructure, shape and lattice orientation of clay particles play a critical role in fault frictional behavior e.g. 17. Frictional sliding experiments suggest that thin localized zones of phyllosilicates along principal slip surfaces and Riedel shears significantly reduce the friction coefficient and the porosity of fault gouges e.g. 8, 18, 19, 20. A complex interaction of processes, such as dissolution-precipitation, particle reorientation, pore collapse, grain boundary sliding, cataclastic flow and nano-particle formation, may lead to an extreme, localized anastomosing network of shear zones with homogeneous gouges and a well-developed oblique SC/SCC’ foliation in between e.g. 8, 21, 22, 23, 24. However, other high-resolution studies of preferred orientations of clays in fault gouges of various fault zones have revealed very weak fault gouge fabrics e.g. 25, 26, 27. analyzed fault gouges from the San Andreas Fault observatory in detail and found distinct zones of locally aligned and randomly oriented clay minerals. The lack of a strong
fabric may be attributed to newly formed clay minerals, folded and kinked clay minerals and clay particles that are wrapped around the clasts.

Most of the above studies focused on deformation mechanisms and used microstructures like secondary shear planes, SC/SCC' fabrics and clast systems to derive weakening processes and to discriminate between seismic and aseismic slips. Interestingly, only a few studies address kinematic indicators in fault gouges at the microscale, and we are not aware of studies focusing on kinematic indicators at the nanoscale.

Building on the observations that fault gouges may be layered parallel to the fault surface in micrometer-long thin zones of different microstructures and element distributions, we demonstrate that various nano-kinematic indicators in these zones consistently confirm the shear sense along the principal slip surface. These nano-kinematic shear sense indicators can be classified into three groups (Figures 3-5):

- **SC/SCC'** fabrics in fault gouge layers with a high content of phyllosilicates that have strong mechanical anisotropy (zones z2, z3 and z4).

- **Kink-folds** in phyllosilicate packages with axial planes inclined into the shear direction or in a direction of instantaneous shortening (zones z3 and z4). Although the kink-folds in the investigated sample have consistent orientations of axial planes, shear zone-related folds might have a complex deformation history and are difficult to use as kinematic indicators.

- Two different types of clasts are observed in the investigated sample: mineral fish (mostly hematite) with an elongated high-aspect shape and a preferred orientation inclined against the shear direction in zones z2 and z4; and clast systems consisting of well-rounded equant feldspar grains and σ-type clast systems with recrystallized material in strain shadow wings.
around the clasts (zones z2 and z4). Some of the wings have clear stair stepping (Fig. 5), which can be used to constrain the shear sense.

CONCLUSIONS

The chemical and nano-kinematical investigations performed in this study suggest the presence of two correlated mechanisms active on the fault system: shear deformation followed by a water-rock reaction. Together, they give rise to a mutual effect of chemical and structural layering at the micro-to-nanoscale. On one side, the fluids circulating through the fault gouge react with protolith minerals, giving secondary paragenesis along with chemical differentiation processes, resulting in element depleted/enriched bands at the micro-to-nanoscale. That is the case for phyllosilicates, whose formation can be ascribed to alteration reactions of previous feldspar clasts. On the other hand, pervasive deformation can generate mechanical/thermal processes. In this direction, intense shear deformation gives rise to the comminution of mineral grains with the development of kinematic indicators down to the nanoscale, and the associated heat caused by friction can trigger amorphization reactions of some minerals, like the phyllosilicates in zone z1, directly at the contact with the fault surface.

METHODS

Thin foil, Slice&View analysis, and scanning electron microscopy (SEM) imaging of fault gouges were performed using a Thermo Scientific Dual Beam Helios G4 SEM and Focused Ion Beam (FIB) microscope. The sample was coated with carbon and then platinum to protect it during the FIB processing. The FIB Slice&View results and 3D models of the nanostructures were processed using Thermo Scientific Amira-Avizo software. Transmission electron microscopy (TEM), high-resolution TEM (HRTEM), selected area electron diffraction (SAED), scanning TEM (STEM), high-angle annular dark-field (HAADF)
STEM investigations, and energy dispersive spectroscopy (EDS) chemical analysis were performed using a double Cs-Corrected Thermo Scientific™ Titan Themis-Z microscope operating at 300 kV with a spatial resolution of 0.7 Å (TEM, STEM), and equipped with an ChemiSTEM™ system for EDS analysis, and a Ceta™ camera 16 M.

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AUTHOR CONTRIBUTIONS

COMPETING INTERESTS

The authors declare no competing interests.

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