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Clay gouge

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Abstract

Clays are a common component of fault gouge, but their genesis and importance in fault evolution is poorly understood. We present preliminary evidence that clays participate in extensive mineral reactions and microfabric changes during faulting. Rather than thinking of clay reactions as a consequence of mechanical processes or fault localization following diagenetically altered horizons, we see the interplay between clay mineral reactions and mechanical processes as a single, integrated process. Furthermore, faulting may lower kinetic barriers to low-temperature (∼100°C) mineral reactions that are common in sedimentary rocks.

Our most striking example of fault diagenesis-deformation is a profile of %illite in mixed-layer illite/smectite in shales beneath the Lewis Thrust, Canada. Whereas burial diagenesis caused minimal smectite-to-illite reaction, shales within meters of the thrust are almost completely converted to illite. The consequences of these changes are manifested in geochemical, geochronologic and microfabric characteristics of clay gouge. In this example, faulting has helped overcome a kinetic barrier in the smectite-to-illite reaction without appreciable addition of heat. In another example we infer that dissolution–precipitation reactions continue during faulting even when smectite has already been completely transformed to illite.

If mineral reactions intimately interact with mechanical processes in shallow-crustal faults, then our current understanding of the mechanical and hydraulic properties of fault zones may be incomplete. Syndeformational mineral reactions and associated fabric changes could make faults much weaker than would be expected from evaluation of the static mineral assemblage of gouge and single crystal properties. Syndeformational mineral reactions may promote fault slip (affecting earthquake activity) in gouge-bearing faults under stress conditions considerably lower than predicted from static mineral properties. In addition, fault-induced dissolution-precipitation reactions may contribute to fault localization.

1. Introduction

Gouge, a low-temperature type of fine-grained fault rock, is a common product of near-surface faulting (e.g. Sibson, 1977). Commonly it is assumed that these rocks are a result of brittle deformation processes, such as cataclasis (e.g. Scholz, 1990), and indeed, brittle deformation processes are important in creating gouge in quartzo-feldspathic rocks. In this paper we discuss gouge that is dominated by clays. We use the term clay gouge from the field perspective of a light to dark-colored, clay-rich material that becomes sticky mud when wet. We imply no mechanistic connotations (i.e. cataclasite) with the term clay gouge, similar to the modern, non-genetic use of the term mylonite.

In spite of their common occurrence and likely importance for fault dynamics, our understanding of the important processes in natural clay gouge is limited (e.g. Chester and Logan, 1986; Chester et al., 1993; Evans and Chester, 1995; Rutter et al., 1986; Schulz and Evans, 1998). In large part, the very small grain size that is inherent in these rocks hinders approaches that have worked so well in medium- to high-grade fault-rocks (i.e. phyllonites and mylonites).

The aim of this paper is to identify and explore the consequences of the processes that may occur in clay gouge based on preliminary mineralogic, isotopic and textural observations made in natural fault exposures.

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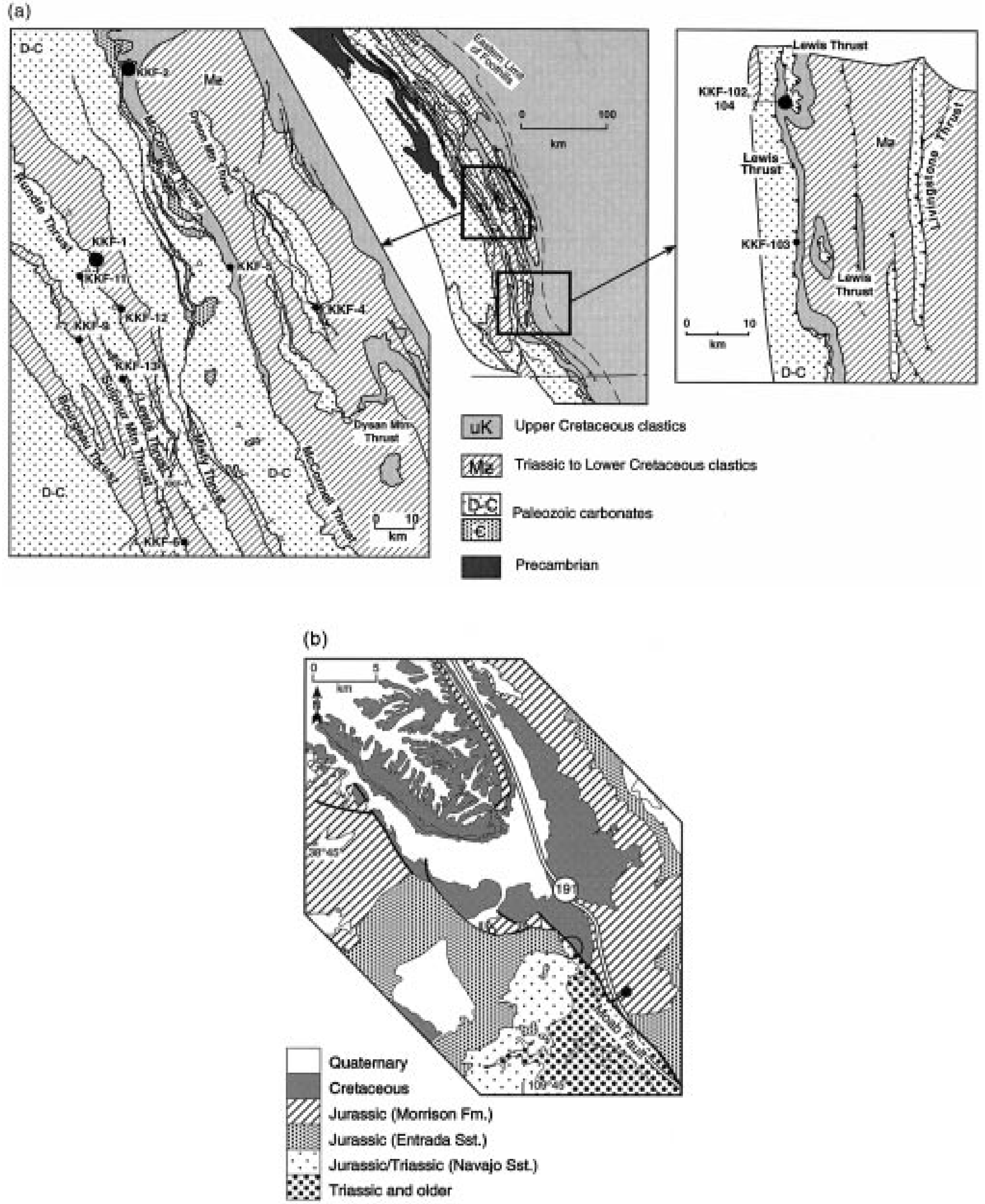

Fig. 1. Sample location maps. (a) Canadian Rockies: Kananaskis area (left map and upper box on central regional map) and Crowsnest Pass area (right map and lower box on regional map). Sample locations discussed in this study are identified with large solid circles. (b) Moab Fault in southern Utah: open circle identifies sampling location.

We focus on faults with smectite- and illite-rich gouge for the following reasons:

1. Smectite and illite are the most common clay minerals in sedimentary rocks.
2. The smectite-to-illite reaction is controlled by Arrhenius-type kinetics in the shallow crust (e.g. Huang et al., 1993). This means that smectite-rich rocks can be in the equilibrium stability field for illite, but the smectite-to-illite reaction is prevented by insufficient system energy required to overcome a kinetic reaction barrier. These conditions are important to consider because anomalous fluid chemistry introduced by synfaulting fluid flow need have no effect on reaction progress. Thus, we can largely ignore the difficult-to-quantify effect of fluid flow on the reactions we consider.
3. Gouge with illite provides us the opportunity to bring K/Ar dating to bear on the problem. No other clay minerals have built-in radiometric clocks.

Whereas interactions between deformation and mineral reactions that typify processes in metamorphic rocks generally seek a minimum energy state (e.g. Spiess and Bell, 1996), comparable reactions appear to be primarily limited by kinetics at near-surface conditions. Thus, an important element of the ideas expressed in our paper and an area for fruitful future research is that reactions occur in near-surface fault zones that otherwise would be barred by kinetic processes, but not thermodynamic equilibrium.

2. Structural setting of samples

Two examples of natural clay gouge illustrate processes observed in many faults. Clay gouge was collected from several thrust faults in the Canadian Rockies (McConnell Thrust at Mount Yamnuska and Compression Ridge; Rundle Thrust at Mount Kidd; Lewis Thrust at Gould Dome, north of Crowsnest Pass; Fig. 1) and a normal fault (Moab Fault in south-central Utah; Fig. 1).

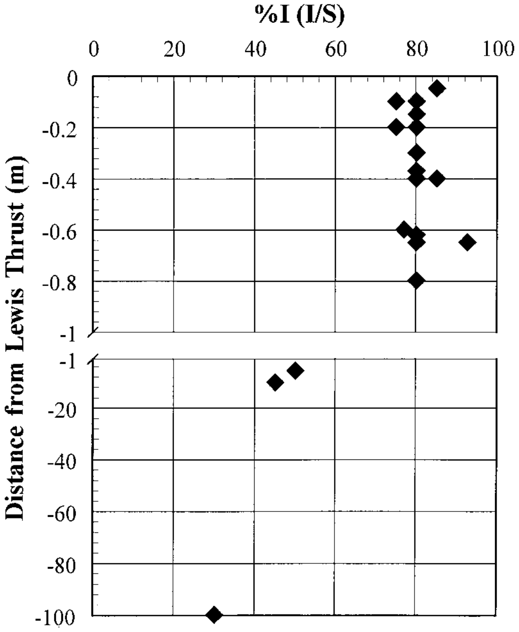

Fig. 2. Illite/smectite profile beneath the Lewis thrust, Gould Dome (KKF-102, -104), Alberta, Canada. The high degree of smectite-to-illite transformation is limited to distances on the order of meters below the hanging wall contact. Note the axis break from 1 to 5 m and the change in scale across the break. Estimates of %I in I/S are derived from modeling XRD patterns of medium (< 0.2 μm) and fine (< 0.02 μm) size fractions.

The three thrust faults form part of the Front Ranges of the Canadian Rockies (e.g. Price, 1981). In each case the faults place Paleozoic limestones on Mesozoic shales and sandstones (Table 1). The Moab Fault is a normal fault that cuts Paleozoic–Mesozoic sandstones, siltstones and shales. The fault has a long history associated with salt tectonism of the Paradox Basin. Dramatic lateral changes in Permian–Triassic sediment thickness due to salt movement and thickness changes in Cretaceous strata across similar faults to the north suggest that the Moab Fault was active intermittently from the Permian to the Cretaceous.

Table 1
Fault samples

Fault	Hanging wall	Footwall	Approx. displacement	Faulting temperature[a]	Fault type[b]
McConnell	Cambrian Eldon Fm.	U. Cret. Belly River Fm.	> 27 km	130–158°C	IS Thrust
Rundle	Devonian Palliser Fm.	Jurassic Kootenay Fm.	10–15 km	155–178°C	IS Thrust
Lewis	Miss. Rundle Fm.	U. Cret. Belly River Fm.	60–100? km	114–153°C	OOS Thrust
Moab	U. Jurassic Morrison Fm.	Triassic–Jurassic Navajo Fm.	70–90 m	100 ± 10°C	Reactivated Normal

[a] Faulting temperature estimated from vitrinite reflectance values in footwall shales (three thrusts) and from burial history modeling constrained by vitrinite, I/S, and fission track paleothermometry (Moab Fault).

[b] IS = in-sequence; OOS = out-of-sequence.

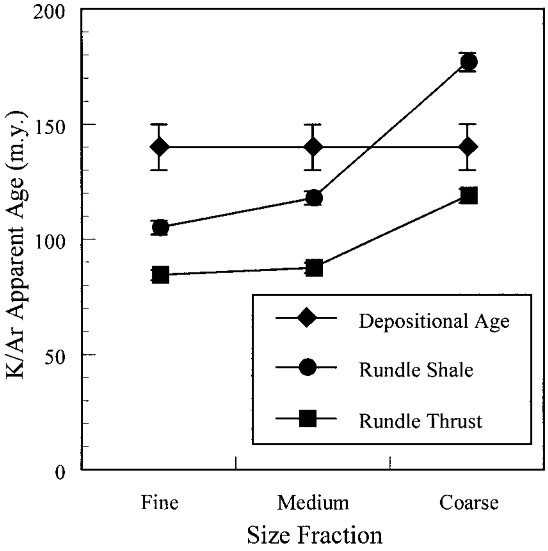

Fig. 3. Distribution of K/Ar ages for Rundle Fault and Kootenay shale samples for fine (< 0.02 μm), medium (0.2–0.02 μm), and coarse (2.0–0.2 μm) size fractions. Note that the apparent age of any undeformed size fraction is greater than in the fault sample, the progression of ages differs with decreasing grain size between shale and fault samples, and the relationships of apparent ages to the stratigraphic age is different.

3. A question of mineralogy

3.1. Observation

Minerals in low-grade gouge are generally considered to be derived from the adjacent wall rocks through mechanical processes. However, detailed X-ray diffraction (XRD) analyses of clay gouge reveal that gouge mineralogy is distinct from that of neighboring shales. Fig. 2 shows the percentage of illite (I) in mixed-layer illite/smectite (I/S) as a function of distance from the hanging wall in Lewis Thrust samples. Shales in the footwall contain ~30% I in I/S, which changes over a distance of ~20 m toward the contact into ~80% I in I/S. A similar contrast in %I(I/S) is found beneath the McConnell Thrust.

In contrast, the mineralogy of clay minerals in the Moab Fault remains unchanged from the adjacent shales of the Morrison Formation. Shales in the Brushy Basin Member of the Morrison Formation are derived in part from volcanogenic sources based on relic shard textures observed in thin-section. Detrital volcanic glass reacted early in the diagenetic history to smectite, which, with subsequent burial and heating, reacted to an illite-rich I/S (80% I in I/S; Pevear et al., 1997a). We observe similar illite-rich I/S in fault and shale samples from the Rundle Thrust. Thus, we observe that where shales are initially smectite-rich, fault samples become anomalously illitic, whereas the mineralogy of illite-rich I/S remains unchanged.

3.2. Inference

Smectite-rich I/S is thermally stable in shales beneath the Lewis Thrust. If those shales had been subjected to increased temperature, we expect that smectite would have reacted to form illite in a dissolution–precipitation process. The kinetics of this reaction are controlled by temperature, time, and fluid chemistry (Ahn and Peacor, 1986; Pytte and Reynolds, 1988; Velde and Vasseur, 1992; Huang et al., 1993; Elliot and Matisoff, 1996), with temperature by far the main factor.

If we accept the kinetic framework of smectite-to-illite reaction, then fault temperature or fluid chemistry must be responsible for the high %I in I/S that is found in the Lewis thrust. If we try to model the I/S aureole beneath the Lewis thrust by considering a thermal transient along the fault, we find that heating times may persist for no more than tens of years. Longer heating times would allow heat conduction far from the fault, and this is prohibited by observations of unreacted shales 100 m from the fault. With heating times lasting only years, kinetic models require unreasonable temperatures of the order of 500–600°C to achieve the observed high degrees of reaction (80% I in I/S).

K-rich or SiO_2-poor pore fluids can also overcome kinetic barriers to reaction, but there are three reasons why we consider anomalous fluid flow an unlikely candidate to explain the observed properties.

1. Faults such as the Lewis Thrust and Moab Fault are devoid of veins in the footwall that might indicate extensive fluid flow. Hanging wall carbonates in the Lewis Thrust are full of veins, but at least some veins formed before the carbonates thrust over the shales.
2. Bentonite-rich beds beneath the Lewis thrust compress the smectite-to-illite transition to a zone only about 20% as wide as the corresponding I/S aureole in structurally interlayered shales. If fault temperature or pervasive fluid flow of compositionally extreme pore fluids are responsible for the accelerated smectite-to-illite transition, then we might expect little difference between the extent of reaction in bentonites and shales that are deformed equally.
3. If we assume the kinetic model of Huang et al. (1993) and a 5-year temperature spike of 230°C along the Lewis Thrust, a K concentration of 20,000 ppm is required to achieve the observed I/S profile. This K concentration is ~100× greater than that found in normal sedimentary brines (Huang et al., 1993; Hanor, 1994) and is 50× greater than the K-concentration of seawater (Drever, 1988). Moreover, there is no independent evidence of this level of K-metasomatism on the Lewis Thrust.

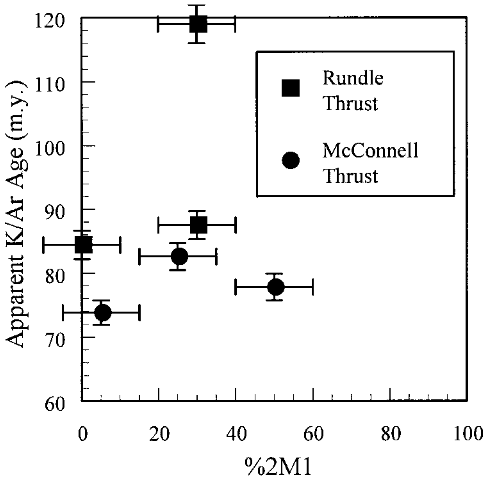

Fig. 4. Comparison of the amount of $2M_1$ mica in fault samples vs apparent K/Ar ages showing how ages of size-separated samples can be the same even when the amount of old, detrital mica changes. Because maximum temperature experienced by these samples is inferred to be below 200°C (based on vitrinite reflectance values of footwall shales), new $2M_1$ mica growth is an unlikely cause of the observed age distribution.

> Based on our analysis of the Lewis thrust, it appears that the smectite-to-illite reaction responds to other controls, which we explore in subsequent sections.

The Moab fault offers contrasting, and probably more typical, results. Evidence for mineral reactions is not detected in bulk mineralogy. Whether this precludes mineral reactions is examined with geochemical methods.

4. A question of isotope geochemistry

4.1. Observation

K/Ar and oxygen isotope systematics of clay gouge distinguish gouge samples from undeformed shales. For example in the Rundle Thrust (Fig. 3), the apparent K/Ar ages of fault and shale samples differ both when comparing ages of size-segregated sub-samples, and when comparing the distribution of ages within a single sample. We find that the apparent K/Ar age of any size fraction of a fault sample is younger than the corresponding size fraction of undeformed shale (Fig. 3). Also, in undeformed shales we find a progression of apparent ages decreasing from coarse to fine size fractions. The age of the coarse (2.0–0.2 μm) size fraction exceeds the depositional age of the shale and reflects the dominance of detrital illite. Medium (0.2–0.02 μm) and fine fractions (< 0.02 μm) of shales are younger than the depositional age and reflect the dominance of diagenetic illite in the sample. The age of all measured size fractions in fault samples is younger than the depositional age of the protolith shale.

Three processes can change the apparent K/Ar ages of clays in faults.

1. Ar can be lost from clays during faulting by diffusion processes, causing resetting of the K/Ar clock.
2. New clays can grow and dilute the age of the preexisting material.
3. Existing clays can dissolve and new clays grow during faulting, causing the mean age of the illite population to young with increasing reaction progress.

Some Ar diffuses from illite during deformation, which we infer from determinations of the amounts of old, detrital clay and newly grown, diagenetic clay in a sample (Pevear, 1992). Measurements of the amount of the $2M_1$-mica polytype in shale and fault samples indicate how much detrital illite is in the sample. ($2M_1$-mica is interpreted as detrital clay because its crystallization temperature exceeds 280°C; Srodon and Eberl, 1984.) $1M/1M_d$ polytypes in shale and fault samples represent illites grown after deposition. A striking observation in fault samples is that even when the amount of $2M_1$ mica varies among clay size fractions, the apparent K/Ar age remains constant (Fig. 4). This contrasts with undeformed shales where age decreases as the amount of detrital, $2M_1$ mica decreases.

Comparisons of oxygen isotope data between host rock and gouge provides information on clay recrystallization during deformation. Oxygen isotope data are more challenging to interpret than comparisons of K/Ar ages because there are few K-bearing minerals in natural shales, but most minerals found in shales contain oxygen. Thus, we can only draw significant conclusions from samples that are nearly monomineralic and where we find strong oxygen-isotope signals. The Moab Fault offers such a contrast. In addition to K/Ar ages of the fine fractions that are younger than ages in corresponding size fractions of the undeformed protolith, the oxygen isotope ratios are as much as 5‰ lower in the gouge samples than the shale (Pevear et al., 1997b). This observation indicates that dissolution–reprecipitation processes can be important during faulting.

4.2. Inference

Younger apparent K/Ar ages in fault samples imply more advanced reactions in faults than adjacent, undeformed shales, even when the original shale is illite-rich. Oxygen isotope data suggest that in certain situations recrystallization may be an important factor in altering isotope systematics. Detrital and diagenetic

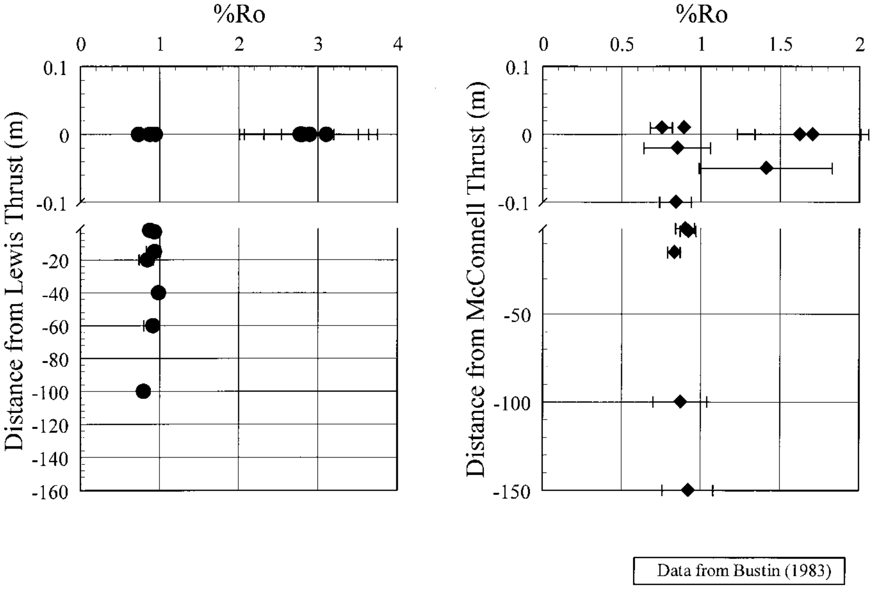

Fig. 5. Vitrinite reflectance profiles below the Lewis and McConnell thrust, showing anomalously high reflectance values in each fault that are restricted to shales within 10 cm of the contact. Note the break in distance axis between 0.1 and 1.5 m and the change in length scale across the break.

illites may both be subject to recrystallization during faulting. In fact, a single clay particle may dissolve and reprecipitate many times during the life of a fault, but we have no methods at our disposal to test such an idea.

The observation that apparent K/Ar ages are independent of the amount of $2M_1$ mica in some samples suggests that the K/Ar system can be disturbed without dissolution and reprecipitation of illite, or well-ordered micas crystallize at unexpectedly low temperatures in fault zones. Preliminary Ar-diffusion modeling suggests that minimal Ar-loss is possible at the inferred faulting temperatures. We suggest that illite deformation may promote Ar-diffusion (e.g. Kramar et al., 1998). If Ar diffusion is enhanced by deformation (e.g. by kinking or ‘riffling’ the mica layers to periodically increase the local d-spacing), then this may be a clue to explain enhanced reaction rates.

5. A question of process by analogy

Other geologic materials besides clays exhibit accelerated kinetic reaction rates in faults. Reflectance values of vitrinite particles, for example, obey a kinetic reaction rate that depends primarily on temperature, but also on time (e.g. Sweeney and Burnham, 1990). Vitrinite reflectance values increase with increasing temperature in sedimentary basins. Bustin (1983) describes anomalous reflectance values in samples from the same faults we examined. Fig. 5 shows reflectance values in the Lewis thrust (Marias Pass, Montana) and McConnell thrust (Mount Yamnuska, Alberta). Although Bustin (1983) interpreted these results as a consequence of shear heating along the faults, he recognized that restriction of anomalous reflectance values to the fault surfaces implies short heating times (minutes to hours) and high temperatures (up to 650°C, which is as much as 500°C above ambient temperatures). Suchy et al. (1997) reported similar results and interpretations in faults in the Helvetic nappes of the European Alps. In both cases, the authors infer some degree of shear heating to generate the high observed reflectance values but at the same time acknowledge a possible association between reflectance values and strain intensity.

The analogy between clay and vitrinite diagenesis/metamorphism is important, because the increase in reflectance values is considered a fluid-free reaction. Vitrinite reflectance and coal rank increase as oxygen and hydrogen atoms are cleaved from carbon rings, increasing the aromaticity and carbon concentration of the remaining material. If we consider that localized heating provides only a fraction of the energy required to drive each of these reactions, then we must conclude that part of the energy imposed during faulting results in increased reaction rates. Bustin et al. (1995) documented the increase in graphite formation from kerogen through simple shear in a series of experimental tests, and proposed mechanisms of molecule alignment to account for the anomalous reflectance values.

6. A question of microfabric

6.1. Observation

Anastomosing arrays of aligned phyllosilicate particles are a common microfabric in clay gouge, which is considered primarily a result of rotation and alignment of nonreactive particles (e.g. Moore et al., 1986; Rutter et al., 1986; Chester and Logan, 1986). We found a progressive change in the orientation and intensity of clay fabrics below and within the Lewis Thrust using X-ray texture goniometry (XTG). Samples from the undeformed footwall of the Lewis Thrust show a well-developed compaction fabric that parallels the regional bedding orientation. Advancing from the footwall toward the fault, we see progressive fabric rotation into parallelism with the fault surface. Perhaps most significantly for the properties of gouge, we find that fabric intensity decreases by as much as 25% toward the contact, as measured by XTG of representative areas in the samples (van der Pluijm et al., 1997).

6.2. Inference

The observation of bulk clay reorientation into parallelism with a fault comes as no surprise. In addition, we find that clay fabrics are folded in some samples. The lesser preferred alignment implied by lower XTG intensity, on the other hand, seems to belie petrographic observations of zones of strong preferred alignment. The overall decrease in fabric intensity near the Lewis Thrust may reflect the effect of volume reduction of the solid phase (see below) and consequent destruction of the clay fabric on the particle scale. Whereas we find strong particle alignment on the thin-section scale, the dispersion of orientation on submicroscopic scale as seen by XTG is large enough to result in a bulk reduction of preferred orientation.

7. A question of volume

The smectite-to-illite reaction involves liberation of a large volume of water, because smectite is expected to have three layers of water in the smectite interlayer (Huang et al., 1994; Wu et al., 1997). Non-hydrostatically stressed smectite may contain less interlayer water (Fitts, 1997). The effects of variable shear stress and strain rate (i.e. seismic rupture vs creep) on interlayer water remain to be explored.

We expect the solid volume of pure, smectite shale to decrease by 33–47% as 150–190 nm thick smectite collapses to 100 nm thick illite. The effect of water generation depends first on shale porosity during the reaction (initially 5–20%), but also on the density of interlayer water relative to pore water. Huang et al. (1994) suggested that interlayer water is denser than pore water, which has the result of increased fluid pressure in a constant-volume system. An alternative hypothesis is that the smectite-to-illite reaction results in reduced total volume, implying that this reaction may induce infiltration into an underpressured fault zone (c.f. Rumble et al., 1982 for similar processes in metamorphic rocks). At this point most available data favor pressure increase in a constant volume system as interlayer water is lost during the smectite-to-illite reaction.

An observation that may prove pertinent to the question of volume change during faulting is the morphology of illite particles in fault rocks. In undeformed shales, illite particles usually grow as platelets with crystallographic axes $a \approx b \gg c$. We find similar platelets in clay gouge, but in about 25% of samples analyzed we find illite laths with $a \gg b > c$. Lath-like morphologies are common in porous sandstones (i.e. 'hairy' illites) where water-filled pores offer unhindered growth in all crystallographic directions without using existing phyllosilicate minerals as hosts for growth (e.g. Pevear et al., 1997; Kennedy and Logan, 1998). If the analogy between illite growth in porous sandstones and fault rocks is appropriate, then we can infer that illite laths grow when deformation creates pore space in otherwise low porosity and permeability materials, perhaps via shear dilation effects.

8. A question of strength

Mineralogy, fluid activity, microfabric and volume change all have different, and sometimes contrasting implications for the mechanical properties and strength of shallow-crustal segments of faults (e.g. Summers and Byerlee, 1977; Logan et al., 1981). Ultimately, the role of gouge in fault strength is the central question that may determine the resistance to movement and catastrophic displacement vs steady-state creep on faults. We recognize several competing factors that may be important:

1. Changing strength as clay gouge changes from smectite-dominated to illite-dominated mineralogy;
2. Production of water associated with dehydration reactions that influence fluid pressure;
3. Bulk volume and mineral fabric changes that affect rock permeability;
4. Changing habit and defect state of mineral constituents through neocrystallization;
5. Reduced kinetic barriers that promote local dissolution–precipitation reactions.

The relatively low shear strength of clay gouge implies that faults support only small differential stresses, so clay gouge requires a relatively small tectonic load imposed on a isotropically stressed initial state before failure begins (Scholz, 1990). Soil mechanics research at very low confining pressures and rock experiments at 100 MPa and more indicate that the strength of smectite is at least half that of illite (e.g. Wang et al., 1980; Mitchell, 1993). In fact, the smectite-to-illite reaction is implicated as a possible contributor to the onset of earthquakes in sediment-bearing subduction zones (Vrolijk, 1990). But if this reaction is critical in determining the strength of faults, then why do we see continued strain localization in faults such as the Lewis thrust even though the reaction to illite is near completion? Whereas the strength of illite exceeds that of smectite, perhaps the associated changes in microfabric and rock volume are more important than single-crystal properties. Moreover, fluid penetration lowers the frictional resistance of faults, which is further amplified by the introduction of locally derived fluid from the smectite-to-illite transformation at grain–grain contacts. Such grain boundary effects will probably dominate the strength of the fault rather than the bulk composition. Or is the solution to this dilemma found in the isotopic data that suggest that illites continue to recrystallize during deformation and/or that the bulk microfabric shows lesser grain alignment in high strain regions? Does recrystallization enable strain localization in illite-rich intervals, even when weaker smectite-rich horizons are only meters away? If so, then the way we look at faults in the shallow crust must change in order to detect the subtle evidence of reactions.

9. Final considerations

Our preliminary observations point out that clay gouge actively evolves during the faulting process, which indicates that studies of fault properties based on static conditions of mineralogy, fabric, fluid content, and volume are incomplete. We first need to examine fault rocks for mineral reactions, using modern methods such as quantitative XRD and TEM to examine clay mineralogy. Secondly, we need to evaluate the impact of mineral reactions on the physical properties of gouge as it undergoes deformation. This raises several important questions. Do syntectonic reactions alter the failure properties of the sample? Does a fault undergoing certain types of mineral reactions support lower shear stresses than a mineralogically static fault? Thirdly, we need to understand the physical geometry of mineral constituents (microfabric) in gouge, raising questions about the relative importance for strength of individual minerals vs monomineralic aggregates. Finally, we need to develop tests and experiments to assess what aspect of deformation catalyzes mineral reactions. Do clay minerals fracture and break and become more susceptible to reaction during faulting? Does faulting induce crystal defects in the smallest phyllosilicates and leave them more susceptible to reaction? Is syntectonic fluid flow required?

Our understanding of the genesis and significance of clay gouge has evolved. In many cases, especially sedimentary environments where faults cut shales, physical incorporation of clay particles is seen as the main mechanism of clay gouge formation (e.g. Lindsay et al., 1993; Lehner and Pilaar, 1997). Growth of clays through alteration of adjacent rocks is becoming increasingly recognized as an important source of clay gouge in faults (e.g. Evans and Chester, 1995; Wintsch et al., 1995), but gouge is viewed as the end-product of deformation and mineral reaction. Rather, we emphasize that the mineral reactions that led to the creation of clay gouge continue as fault activity continues.

Does incorporating syndeformational clay reactions make a difference? Chester (1995) introduced a modified rheologic model for a wet crust, developed for quartz gouge, where localized slip (i.e. mechanical) processes control the strength of the upper crust. Solution-transfer mechanisms in this model only become important in the middle crust. This model would change significantly if syndeformational solution-transfer mechanisms dominate at near-surface conditions, as suggested by our results in thrust and normal fault settings.

Finally, an unresolved question in our discussion is why mineral reactions occur in faults that are prohibited by kinetic barriers in adjacent rocks. In the case of the Lewis thrust, we ruled out the effects of heat and fluid chemistry based on a kinetic model of the smectite-to-illite reaction. If this conclusion is true (i.e. if the kinetic model applied is appropriate for the problem), then barriers to dissolution and precipitation are the next obstacles to overcome. Both the kinetics of dissolution and precipitation can be controlled by grain surface texture. For example, the surface area of quartz seems to limit the rate of precipitation of quartz cement in sandstones (e.g. Walderhaug, 1996). Moreover, compaction of albite sand has shown to be faster under stressed conditions because new, fresh surface area for reaction is created (Hajash et al., 1998). By analogy, it therefore seems logical that faulting alters the surface properties of clays such that reaction rates increase. This hypothesis requires laboratory testing incorporating direct observations of surface textures of clays.

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