Abstract: This study reveals mineral and deformation processes associated with faulting of lacustrine unconsolidated sediments in the Guadix-Baza Basin (Betic Cordillera, S Spain) affected by the Baza Fault. Brittle carbonate and silt sediments develop deformation bands frequently sealed by dolomite crystallization, whereas ductile clay-rich sediments form clay smearing bands where late crystallization of gypsum can be observed. Granular flow and local cataclasis were the main deformation mechanisms in the brittle deformation bands. Flow alignment, grain-boundary sliding, and extrusion were predominant in the clay smearing bands. These water and clay-rich bands reduced shear strength of the faulting process due to their lubricating effect. Beidellitic smectite defines shear foliation of the smeared bands, but Mg-Fe, a K-rich smectite (Fe + Mg > 1 and K content up to 0.8 a.p.f.u), crystallizes in the micropores surrounding brittle clasts produced by deformation pressure shadows. These data suggest that the interaction of micromechanical events, which increased sediment porosity by the generation of pressure shadows, and the flow and concentration of saline fluids in these pores promoted structural diagenesis processes that favoured the beginning of local illitization.

Keywords: structural diagenesis; smectite; smearing; deformation

1. Introduction

Clay-rich beds play an important role in accommodating fault deformation, mainly by clay smearing processes [1]. Interbedded clay-poor sediments in fault areas develop small fractures and, frequently, deformation bands [2,3]. When materials are poorly lithified and water-rich, sediments from the fault area are mechanically mixed even to the microscale [4]. The clay mineral fraction in fault zones can be produced by mechanical transformation, both brittle (disaggregation, fracturing, cataclasis, grain-boundary sliding), e.g., [5,6], and ductile (grain deformation, smearing, injection), e.g., [7–9] and/or mineral/chemical changes during diagenetic/metamorphic reactions (pressure dissolution, diffusive mass transfer, clay precipitation), e.g., [10–13]. Moreover, water saturation during deformation can especially promote mineral chemical transformations [14–16]. Therefore, the origin of small-sized clay minerals in clay bands from fault areas can be associated with detrital, cataclastic and neoformation processes. Laurich et al. [17] suggested that in clay gouges, neoformation can contribute more significantly to producing small-sized clay grains than mechanical deformation processes. Solum et al. [16] indicated that clay authigenesis in fault areas is very frequent in many geological contexts, suggesting that fluids related with fault activity were responsible for transformation processes.

These reactions, commonly referred to as structural diagenesis, contrast with the mineral formation controlled by time and temperature during burial diagenesis. Nanometre-sized clay grains produced by deformation increase reactive clay surfaces which are responsible for processes of adsorption–desorption involved in many clay transformations. Moreover, tectonically controlled fluid flow in fault areas can generate high salinity pore areas that favour changes in the charge of the octahedral layer (i.e., by the substitution of...
Al for Fe-Mg), leading to the transformation of smectite to illite [18] and promoting a rapid crystallization of neoformed clay minerals [16,17,19–21].

Previous fault zone studies have shown that the production of submicron clay grains during deformation affects hydraulic properties by the formation of barriers to flow produced by disaggregation and redistribution of framework clays [11] and networks of clay microshears [6] (collapse sealing), or by the precipitation of phases in the fault (cement sealing) [3,22]. In these cases, clays play an important role in trapping hydrocarbons, carbon dioxide and nuclear waste [22–24]. Moreover, clay minerals are commonly significant components of fault gouges and have been found to play a significant role in controlling fault strength by facilitating shear localization in the weak clay matrix, controlling the seismic behaviour of the fault and damage zone due to their low friction coefficients [25].

The Baza Fault is an important normal fault area in the south of Spain where some segments are characterized by the mechanical juxtaposition of different types of sediments poorly consolidated with an excess of water during deformation, which develop diverse strain varieties [26]. This study aims to contribute to improving knowledge of the mineral processes occurring in fault areas promoted by deformation and fluids, through the description and interpretation of a mineral dataset from clay smearing bands in a strand of the Baza Fault (S Spain) which affect water-saturated and poorly lithified sediments.

2. Geological Context and Materials

We studied deformed materials from the Baza Fault, a 37-km-long structure, striking N–S to NW–SE and dipping around 65° to the east (Figure 1) [27,28], which is situated in the central Betic Cordillera. This is an active structure which has been controlling the tectonic and sedimentary development of the Guadix-Baza Basin since the Miocene due to an extensional process that created normal faults [29]. The width of the fault area oscillates from a narrow zone less than 300 m in the northern segment, due to the presence of only one main surface, to a wider southern part (around 7000 m), where it appears up to 13 strands. A 2000 m fault throw was accumulated [29]. Slip rate estimations for the fault oscillate from 0.49 to 0.12 mm/year [27,28,30].

The studied materials belong to the east segment of the Guadix-Baza Basin (Figure 1a), the most important basin of the Betic Cordillera (Spain) during the Neogene. The basin is filled with marine sediments (upper Miocene) and continental materials (fluvial and lacustrine, Pliocene/Pleistocene) [31]. Gibert et al. [32] distinguished three facies zones in the basin (marginal, intermediate and inner). We characterized a set of samples from the “Benamaurel Unit”, which comprises sediments of the intermediate and inner facies areas of the basin, including lacustrine carbonates, gypsum-rich sediments, marls, and dark clays with native sulphur.

We studied deformed sediments from a trench (Carrizal trench) near the Barranco del Agua, located at the central part of the Baza Fault (Figures 1b and 2). These materials are affected by two main strands (NNW–SSE orientation) of the Baza Fault, which concentrate most of the movement. The three main types of sediments can be observed in the trench (Figure 3): white lacustrine carbonates where dolomite predominates over calcite, dark grey lutite/clays, and silts. The ages of these materials oscillate between 3 and \(1 \times 10^6\) years [28].

These materials are situated between two surfaces of the fault zone where deformation is concentrated, producing intense fracturation and disruption of the carbonate, silts and clay levels. Faults are more common in carbonate and silt levels but they are not propagated into the clay beds. Medina-Cascales et al. [26] described the fact that that clay beds are partially continuous and frequently form thin, smeared and injected levels. We collected 11 clay bodies and 12 carbonate and silt levels. Samples were collected from an excavated trench at the Carrizal fault strand (Figure 2), mostly oriented perpendicular to the fault strike, resulting in a total excavation volume of \(\sim 15 \times 15 \times 4\) m (See Medina-Cascales et al. [26] for details). Oriented sediment cores were obtained with a stainless tube, ensuring no disruption to the microstructure.
Figure 1. (a) Geological situation of the Betic Cordillera. (b) Geological map of the Baza Fault. Modified from Torabi et al. [3].

Figure 2. Geological map of an area of the central sector of the Baza Fault (Carrizal and Barranco del Agua), where the trench was located. Modified Torabi et al. [3].
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Figure 3. (a,b) Pictures of the materials exposed in the Carrizal trench. Carbonate beds appear as thick white layers. Silt beds occur as disrupted brown and grey layers. Clay beds develop thin, dark grey linear laminations.

3. Methods

Milled powders and oriented preparations (total sample and <2 μm fractions) were used for the X-ray-diffraction (XRD) study of the sediments. Materials were treated with ultrapure water for salt elimination. Centrifugation was used for obtaining <2 μm and <0.2 μm fractions. We applied ethylene glycol (EGC) for the identification of expandable clays. An XDR study was carried out with a PANalytical X’Pert Pro diffractometer (CuKα emission, 40 mA, 45 kV) including an X’Celerator solid-state linear detector. A step increment of 0.008° 2θ and a total counting time of 10 s/step was used. Dry samples were scanned from 3° to 62° 2θ on, and glycolated preparations were studied from 2° to 30° 2θ. HighScore 5.1 software, PANalytical (Eindhoven, The Netherlands) with decomposition routines was used. A mixed Gaussian and Lorentzian Voigt function was applied for peak fitting.

Polished sections were used for textural and compositional characterization with scanning electron microscopy (SEM, Merlin Carl Zeiss electron microscope) operating with a back-scattered electrons (BSE) detector under atomic number contrast mode. Sediment portions were studied by secondary electrons (SE). BSE pictures were acquired using an AsB detector. Conventional and In-Lens detectors were used for obtaining SE images at 15 kV.
Nanometer scale characterization was carried out with a transmission electron microscopy (TEM). Coated Au and Cu nets were employed for preparing samples from a dispersion of finely ground minerals. We checked the monomineralic character of grains with electron diffraction patterns. Moreover, we extracted lamellae from selected smeared samples impregnated with a Dual Beam Helios 650 Focused Ion Beam (FIB). We obtained ~4 μm × 3.5 μm lamellae, ~60–70 nm thick.

The TEM data was obtained using a HAADF FEI TITAN G2 instrument, working at 300 kV. Analytical electron microscopy (AEM) was used for obtaining quantitative analyses of clays with an EDAX detector coupled to the HAADF FEI TITAN G2 electron microscope. The counting time was established as 100 s except for Na and K (15 s), to avoid problems of alkali-loss [33]. Cliff and Lorimer [34] procedures were employed for obtaining k factors from the following standards: CaS, MnS, albite, spessartine, biotite, titanite, muscovite and olivine.

4. Results
4.1. Carbonate Levels

XRD data indicate that dolomite is the most abundant component of the carbonate sediments (Figure 4a). Phyllosilicates, quartz and feldspars have low contents. The clay assemblage of the total sample and the <2 μm fraction is mainly made of muscovite, paragonite, and kaolinite. A low quantity of smectite (the peak at 14.40 Å) is also detected in the clay assemblage (Figure 4b). A <0.2 μm size fraction was characterized to determine the specific minerals forming the 14.40 Å peak (Figure 4c). Air-dried (AD) and EGC patterns completely overlap around the 9° 2θ (002) area, suggesting the absence of an illite-smectite mixed layers phase. SEM images show that smectite appears as dispersed flakes in the carbonate matrix (Figure 5). Moreover, AEM analyses reveal that the nature of the smectite of the carbonate sediments is Al-rich dioctahedral. Fe, Mg and K contents are very low in these smectites (Table 1).

![Figure 4. XRD diagrams of the carbonate sediments of the trench. (a) Total powder diagram. (b) Diffractogram of oriented aggregate (<2 μm fraction). (c) Diffractogram of oriented aggregate (<0.2 μm fraction). AD: air dried (in red), and EGC: treated with ethylene-glycol (in blue). Dol: dolomite, Kin: kaolinite, Ms: muscovite, Pg: paragonite, Qz: quartz, Cal: calcite, Fsp: feldspar, Sm: smectite, Chl: chlorite, Phy: phyllosilicates.](image-url)
Figure 5. SE image of a carbonate sample from the trench. Dol: dolomite, Sm: smectite.

Table 1. AEM data of smectites normalized to $O_{10}(OH)_2$.

|   | Si  | Al IV | Al VI | Fe | Mg | Mn | Ti | $\Sigma$ VI | O.C. * | Ca | K | Na | $\Sigma$ XII |
|---|-----|------|------|----|----|----|----|-------------|--------|----|---|---|-------------|
| a. Smectite in carbonate beds | 1   | 3.67 | 0.33 | 1.91 | 0.06 | 0.07 | 0.00 | 0.00 | 2.04 | 0.05 | 0.09 | 0.06 | 0.02 | 0.17 |
|   | 2   | 3.71 | 0.29 | 1.89 | 0.06 | 0.08 | 0.00 | 0.00 | 2.03 | 0.01 | 0.10 | 0.05 | 0.01 | 0.16 |
|   | 3   | 3.75 | 0.25 | 1.86 | 0.08 | 0.10 | 0.00 | 0.00 | 2.04 | 0.02 | 0.11 | 0.06 | 0.02 | 0.19 |
| b. Smectite in smearing bands | 4   | 3.80 | 0.20 | 1.84 | 0.11 | 0.09 | 0.00 | 0.00 | 2.04 | 0.03 | 0.04 | 0.09 | 0.01 | 0.14 |
|   | 5   | 3.70 | 0.30 | 1.88 | 0.08 | 0.09 | 0.00 | 0.00 | 2.05 | 0.06 | 0.07 | 0.07 | 0.02 | 0.16 |
|   | 6   | 3.66 | 0.34 | 1.90 | 0.07 | 0.08 | 0.00 | 0.00 | 2.05 | 0.07 | 0.06 | 0.08 | 0.02 | 0.16 |
|   | 7   | 3.73 | 0.27 | 1.87 | 0.08 | 0.11 | 0.00 | 0.00 | 2.06 | 0.07 | 0.04 | 0.08 | 0.02 | 0.14 |
|   | 8   | 3.78 | 0.22 | 1.87 | 0.08 | 0.10 | 0.00 | 0.00 | 2.05 | 0.05 | 0.04 | 0.09 | 0.02 | 0.15 |
|   | 9   | 3.66 | 0.34 | 1.83 | 0.13 | 0.09 | 0.00 | 0.00 | 2.05 | 0.06 | 0.07 | 0.11 | 0.03 | 0.21 |
| c. Smectite in pressure shadows | 10  | 3.74 | 0.26 | 1.05 | 0.57 | 0.52 | 0.00 | 0.00 | 2.14 | 0.15 | 0.04 | 0.55 | 0.12 | 0.71 |
|   | 11  | 3.64 | 0.36 | 1.01 | 0.54 | 0.58 | 0.00 | 0.00 | 2.13 | 0.15 | 0.01 | 0.62 | 0.11 | 0.74 |
|   | 12  | 3.73 | 0.23 | 1.13 | 0.52 | 0.48 | 0.00 | 0.00 | 2.13 | 0.13 | 0.02 | 0.45 | 0.15 | 0.62 |
|   | 13  | 3.69 | 0.31 | 1.06 | 0.55 | 0.52 | 0.00 | 0.00 | 2.13 | 0.16 | 0.03 | 0.46 | 0.15 | 0.64 |
|   | 14  | 3.64 | 0.36 | 1.20 | 0.41 | 0.50 | 0.00 | 0.00 | 2.11 | 0.08 | 0.04 | 0.41 | 0.18 | 0.63 |
|   | 15  | 3.64 | 0.36 | 1.03 | 0.54 | 0.57 | 0.00 | 0.00 | 2.14 | 0.12 | 0.01 | 0.46 | 0.14 | 0.61 |

*O.C.: Octahedral charge. IV: tetrahedral positions; VI: octahedral positions; XII: dodecahedral positions.

4.2. Silt Levels

Silt levels are characterized by the presence of quartz, feldspars, and muscovite, paragonite, and chlorite as phyllosilicates. These minerals form a massive matrix hosting irregular deformation bands, which contain clasts with irregular morphologies of quartz, feldspars and detrital phyllosilicate. Two types of deformation bands are identified:

(a) Disaggregation bands. The sediments with coarser grains (50–200 μm) show thick bands (up to 300 μm) developing granular flow processes (grain-boundary sliding or grain rolling) (Figure 6). Mixing with sediments of smaller size is also observed at distinct bands (Figure 6a). An increase of grain angularity and a decrease of grain size occur due to local grain cracking (Figure 6b,c). Dolomite appears as cement in these bands.
Phyllosilicate bands. Sediments with high contents of coarse muscovite, paragonite and chlorite grains (around 30 µm) develop shear-induced rotation producing phyllosilicate alignment, which forms a special kind of disaggregation band with local fabrics, where the disposition of platy minerals favours frictional grain-boundary sliding (Figure 6d). Dolomite can be observed as cement also in these bands.

Figure 6. BSE images of silt sediments. (a–c) Disaggregation bands. Quartz and feldspars are the dominant grains of these bands. (d) Phyllosilicate band. Muscovite, paragonite, chlorite (brighter grains) are the predominant platy minerals. Angular grains are mainly quartz. Dol: dolomite, Qz: quartz, GFB: granular flow band, SSMB: mixing with sediments of smaller size band. The arrow in (b) indicates a band with smaller grain size. Black areas are pores.

4.3. Dark Clays

Dark clay-rich levels are characterized by the abundant presence of phyllosilicates, quartz and feldspars. XRD data (total sediment and <2 µm fractions) show a clay assemblage made of smectite, muscovite and low quantities of kaolinite, chlorite and paragonite. The presence of chlorite, slightly hidden by the smectite (001) reflection in AD diagrams, is revealed in the EGC treated samples (Figure 7). Broad (001) 12–15 Å peaks appear around 17 Å in the ethylene glycol treated samples. When the AD and EGC treated diagrams are superposed, the EGC diagram shows a slightly asymmetric area of higher intensity around the theoretical position of the (002) smectite peak around 8.5 Å, which could be produced by the presence of dispersed illitic layers in some smectites [35].

From the textural point of view, clay minerals show evidence of flow, reorientation and extrusion produced by deformation to form clay smearing bands at micrometric scale (Figure 8a–c), where slip surfaces can also occur.
A late gypsum precipitation is observed sealing some deformation bands (Figure 8d). TEM images of the clay smearing bands reveal the presence of oriented beidellitic smectite with very fine grain size, muscovite, and paragonite defining the shear foliation produced by strain (Figure 9a). Bigger grain clasts of quartz, calcite and feldspar appear inside the clay smearing bands. These irregular large grains are enclosed by the oriented phyllosilicates (Figure 9b). Clay bending of the minerals surrounding the clasts can be observed.

**Figure 7.** XRD diagram of an oriented aggregate (<2 µm fraction) of dark clay sediments from the trench. AD: air dried (in red), and EGC: treated with ethylene-glycol (in blue). Kln: kaolinite, Ms: muscovite, Pg: paragonite, Sm: smectite, Chl: chlorite.

**Figure 8.** BSE images of dark clay sediments. (a–c) Clay smearing bands with evidence of flow, reorientation and extrusion produced by deformation. (d) Gypsum sealing of the band. Cal: calcite, Sm: smectite; Gy: gypsum, SS: Slip surfaces, Ms: muscovite, Qz: Quartz.
Pressure shadow micropores are developed by the clast fragments. Small nanoparticles of smectite, with random orientation, rich in Fe, Mg and K crystallize in these micropores (Figure 9c).

The AEM microanalyses reveal two groups of smectite composition. Smectites defining shear foliation in the clay smearing bands have beidellitic composition with high Al diocahedral contents and low Mg, Fe, and K contents. However, smectites crystallized in the micro pressure shadows are richer in octahedral Mg and Fe (Mg + Fe > 0.9, a.p.f.u. adjusted to 11 oxygens), which produces an octahedral sum appreciably greater than 2 (Table 1). Regarding the interlayer composition, the amounts of Na and K are high with a sum of interlayer cations frequently greater than 0.6 a.p.f.u. In some cases, K + Na content can be close to 0.8, near to an illitic composition. Assignation of Mg to the octahedral is
only considered for presentation purpose, but part of Mg could probably be present in the interlayer [36].

5. Discussion
5.1. Mechanical Deformation

The predominant mechanism of deformation (brittle or ductile) can be controlled by pore fluid pressure [6] and mineral composition of the shear band, e.g. [9]. Overburdened water-saturated sediments that undergo deformation can experience fluidization processes that produce fluid-like and oriented structures, due to lateral escape [37,38]. Fluidization has been frequently related to seismic activity [28,39]. Moreover, platy morphology and low friction coefficients of phyllosilicate favour ductile deformation and foliation structure development [40]. Therefore, high content in water and clays favours ductile deformation. Sediments from the studied trench show a variety of deformation styles developed in poorly lithified sediments saturated in water during the deformation processes: (a) brittle deformation (fracturation and grain size reduction concentrated in deformation bands) in carbonate and silt sediments; and (b) ductile deformation (folding and smearing) in clay-richer sediments.

SEM images suggest shearing processes of carbonate beds and silicate-rich layers of silts, which developed flow and local cataclasis of grains leading to the formation of deformation bands. Rotevatn et al. [41] and Torabi et al. [42] described similar structures (e.g., millimetric local shear zones rather than individual glide surfaces, localized grain size reduction) during the fracturation process of partially unconsolidated sediments developed by grain cataclasis. Medina-Cascales et al. [26] suggested that the predominance of silts in the stratigraphic column affected by the Baza fault led to more brittle deformation.

The presence of dolomite and gypsum cements in these structures reveals intense fluid flow during deformation and late microsealing by precipitation from fluids during this process. Torabi et al. [3] and Romher et al. [43] indicated that precipitation of carbonates is responsible for permeability reduction in deformed sediments due to microsealing of fluid flow.

Clay smearing bands are mainly characterized by fluid-like features and ductile deformation. Shear strength can be reduced by the inclusion of water and clay-rich sediments along deformation bands, due to the lubricating effect of adsorbed water on the mineral surfaces by electrochemical forces [44,45]. In the studied sediments, the presence of beidellite smectite in the shear structure of the bands, which is bent around the brittle clasts could produce a reduction of strength due to the microphysical processes (rotation, delamination and breaking of bonds) working during clay deformation [46–48].

The contact between clay and silt/carbonate beds is frequently characterized by detachment structures produced by the behaviour of the clay-rich beds. The attractive forces between clay and other mineral surfaces can allow easy mechanical disaggregation that favours detachment during shear [49]. Clay beds are strongly deformed to accommodate deformation by thinning and smearing, whereas the brittle silt layers adjust to deformation by fracturation. Sometimes, microsilty beds are inserted between the clay smears. Ductile layers enriched in clays can accommodate large proportions of strain during faulting [26,50–52].

Deformation styles of clay and silty layers are interconnected. The sediments in the trench were saturated in water during deformation. Deformation of highly water-rich clay beds may produce fluidization processes leading to the release of fluids and material from the layered clay, causing a collapse [53,54]. The breakdown of these layers can produce fracturation and tilting of the adjacent brittle sediments of the studied trench. Fluidized clay can escape by these fractures, favouring smearing and injection structure development [1,55,56].
5.2. Chemical Deformation: Illitization Process

The results of this study suggest that the interaction of micromechanical processes that generated pores by pressure shadow, and the flow and concentration of saline fluids in these pores may have been involved in the authigenesis of clays. Thus, the presence of pressure shadow micropores promoted the interaction of beidellitic smectite of sedimentary origin, with the Mg- and Fe-rich saline fluids produced in the lacustrine basin where sediments were deposited.

A detrital origin for chlorite and mica (muscovite and paragonite) in sediments for the lacustrine sequence of the area has been suggested by Jiménez-Millán et al. [57] and Sánchez-Roa et al. [53], who proposed the metamorphic rocks of the Betic Cordillera as the source region. These original detrital minerals were transformed to kaolinite and smectite during wet climate events favouring the deposition of clay-rich levels in the lake.

Gypsum and dolomite crystal precipitation that seals microstructures produced by deformation, indicates that fluids integrated in the sediments by deformation were of high salinity. Gibert et al. [32] indicated that hydrological conditions in the eastern part of the lake in the Guadix-Baza Basin favoured the creation of Mg-rich hypersaline evaporitic brines. Deocampo [58], Deocampo [59], and Deocampo et al. [60] suggested that porewater hydrochemistry controls the crystallization and nature of neoformed clay minerals, favouring Mg incorporation in phyllosilicates when Mg/Ca ratios rise in the remaining fluid. Diffusive mass transport during deformation favours pressure shadows produced in sediments rich in high salinity waters acting as restricted sites with extreme conditions that favour the processes of mineral alteration by pressure dissolution and authigenesis during clay smearing processes. In these environments, saline fluids can react with pre-existing clays, producing fast mineral transformations that favour K, Mg or Fe uptaking from fluids [61]. Clay mineral reactive surfaces play an important role in the adsorption of elements that can be included in the neoformed clays. Deocampo [59] showed that clays in saline fluids produced octahedral cation modifications that could raise layer charge, promoting the conversion of smectite to illite. The uptake of Mg and Fe and the beidellitic replacement created enough negative charge to enable the inclusion of K to begin an illitization process of low temperature related to microsites formed during clay smearing. Thus, the reaction of the illitization process in the pressure shadows was promoted by high K concentration in the pore waters and the Mg and Fe uptake in the octahedral sheet, which was produced by the coupled substitutions of Al for Si in the tetrahedral sheet and of Mg and Fe for Al. However, at a late stage, dolomite crystallization could have diminished Mg availability in the fluid, decreasing porosity of sediment, which weakened the processes of interaction between smectite and fluid and limited the advance of the illitization process.

6. Conclusions

1. Mineral composition of the sediment is an important factor controlling brittle or ductile mechanism of deformation in the unconsolidated sediments of the Guadix-Baza Basin (Betic Cordillera, S Spain).
2. SEM and TEM images suggest that flow and local cataclasis of grains were the main mechanisms involved in the shearing processes of carbonate beds and silicate-rich layers of silts, producing deformation bands.
3. The predominance of beidellitic smectite in the shear structure of the clay smearing bands produced by the phyllosilicate-rich sediments, as well as the bending of these smectites around the brittle clasts suggest a ductile behaviour of these sediments.
4. Precipitation of gypsum and dolomite sealing deformation bands could indicate that fluids integrated in the sediments by deformation were of high salinity, which may be related to the lacustrine waters of the basin.
5. The interaction of micromechanical processes that generated pores as pressure shadow, and the flow and concentration of saline fluids in these pores were important variables promoting the authigenesis of clays and the structural diagenesis process.
6. Hypersaline-restricted sites at the pressure shadows formed during clay smearing can react with pre-existing clays, promoting fast mineral transformations that could favour K, Mg or Fe uptaking from fluids.

7. A future characterization of in situ measurements of rock properties (e.g., permeability and Young’s modulus) will help to clarify the influence of mechanical deformation and the formation of authigenic clays on the variation of permeability in the Baza fault zone.

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References

1. Schmatz, J.; Vrolijk, P.; Urai, J. Clay smear in normal fault zones—The effect of multilayers and clay cementation in water-saturated model experiments. J. Struct. Geol. 2010, 32, 1834–1849. [CrossRef]

2. Fossen, H.; Johansen, T.E.S.; Rotevatn, A.; Hesthammer, J. Fault interaction in porous sandstones. AAPG Bull. 2005, 89, 1593–1606. [CrossRef]

3. Torabi, A.; Jiménez-Millán, J.; Jiménez-Espinosa, R.; García-Tortosa, F.J.; Abad, I.; Ellingsen, T.S.S. Effect of Mineral Processes and Deformation on the Petrophysical Properties of Soft Rocks during Active Faulting. Minerals 2020, 10, 444. [CrossRef]

4. Giorgetti, C.; Collettini, C.; Scuderi, M.M.; Barchi, M.R.; Tesei, T. Fault geometry and mechanics of marly carbonate multilayers: An integrated field and laboratory study from the Northern Apennines, Italy. J. Struct. Geol. 2016, 93, 1–16. [CrossRef]

5. Yielding, G. Shale Gouge Ratio—Calibration by Geohistory. In Hydrocarbon Seal Quantification: Norwegian Petroleum Society Special Publication; Koelsler, A.G., Hunsdale, R., Eds.; Norwegian Petroleum Society: Oslo, Norway, 2002; Volume 11, pp. 1–15.

6. Faulkner, D.R.; Rutter, E.H. The gas permeability of clay-bearing fault gouge at 20°C. Geol. Soc. Lond. Spec. Publ. 1998, 147, 147–156. [CrossRef]

7. Hippler, S.J. Deformation microstructures and diagenesis in sandstone adjacent to an extensional fault: Implications for the flow and entrapment of hydrocarbons. AAPG Bull. 1993, 77, 625–637. [CrossRef]

8. Farrell, N.J.C.; Debenham, N.; Wilson, L.; Wilson, M.J.; Healy, D.; King, R.C.; Holford, S.P.; Taylor, C.W. The effect of authigenic clays on fault zone permeability. J. Geophys. Res. Solid Earth 2021, 126, e2021JB022615. [CrossRef]

9. Vrolijk, P.J.; Urai, J.L.; Kettermann, M. Clay smear: Review of mechanisms and applications. J. Struct. Geol. 2016, 86, 95–152. [CrossRef]

10. Rutter, E.H. Pressure solution in nature, theory and experiment. J. Geol. Soc. 1983, 140, 725–740. [CrossRef]

11. Knipe, R.J. Faulting processes and fault seal. In Structural and Tectonic Modelling and Its Application to Petroleum Geology: Norwegian Petroleum Society Special Publications; Larsen, R.M., Brekke, H., Larsen, B.T., Talleraas, E., Eds.; Elsevier: Amsterdam, The Netherlands, 1992; Volume 1, pp. 325–342. [CrossRef]

12. Cavaillès, T.; Soliva, R.; Labaune, P.; Wibberley, C.; Sizun, J.P. Phyllosilicates formation in faults rocks: Implications for dormant fault-sealing potential and fault strength in the upper crust. Geophys. Res. Lett. Am. Geophys. Union 2013, 40, 4272–4278. [CrossRef]

13. Haines, S.H.; Van Der Pluijm, B.A.; Ikari, M.J.; Saffer, D.M.; Marone, C. Clay fabric intensity in natural and artificial fault gouges: Implications for brittle fault zone processes and sedimentary basin clay fabric evolution. J. Geophys. Res. 2009, 114, B05406. [CrossRef]

14. Eichhubl, P.; D’Onfro, S.; Aydin, A.; Waters, J.; McCarty, D.K. Structure, petrophysics, and diagenesis of shale entrained along a normal fault at Black Diamond Mines, California—Implications for fault seal. AAPG Bull. 2005, 89, 1113–1137. [CrossRef]

15. Laubach, S.E.; Eichhubl, P.; Hilgers, C.; Lander, R.H. Structural diagenesis. J. Struct. Geol. 2010, 32, 1866–1872. [CrossRef]

16. Solum, J.G.; Davatzes, N.C.; Lockner, D.A. Fault-related clay authigenesis along the Moab Fault: Implications for calculations of fault rock composition and mechanical and hydrologic fault zone properties. J. Struct. Geol. 2010, 31, 1899–1911. [CrossRef]

17. Laurich, B.; Urai, J.L.; Vollmer, C.; Nussbaum, C. Deformation mechanisms and evolution of the microstructure of gouge in the Main Fault in Opalinus Clay in the Mont Terri rock laboratory (CH). Solid Earth 2018, 9, 1–24. [CrossRef]
18. Clauer, N.; Techer, I.; Nussbaum, C.; Laurich, B. Geochemical signature of paleofluids in microstructures from Main Fault in the Opalinus Clay of the Mont Terri rock laboratory, Switzerland. *Swiss J. Geosc.* 2017, 110, 105–128. [CrossRef]

19. Haines, S.H.; Marone, C.; Saifer, D. Frictional properties of low-angle normal fault gouges and implications for low angle normal fault slip. *Earth Planet. Sci. Lett.* 2014, 408, 57–65. [CrossRef]

20. Warr, L.N.; Wojatschke, J.; Carpenter, B.M.; Marone, C.; Schleicher, A.M.; van der Pluijm, B.A. A “slice-and-view” (FIB-SEM) study of clay gouge from the SAFOD creeping section of the San Andreas Fault at 2.7 km depth. *J. Struct. Geol.* 2014, 69, 234–244. [CrossRef]

21. Buatier, M.D.; Cavailhes, T.; Charpentier, D.; Lerat, J.; Sizun, J.P.; Labaume, P.; Gout, C. Evidence of multi-stage faulting by clay mineral analysis: Example in a normal fault zone affecting arkosic sandstones (Annot sandstones). *J. Struct. Geol.* 2015, 75, 101–117. [CrossRef]

22. Torabi, A.; Fossen, H.; Braathen, A. Insight into petrophysical properties of deformed sandstone reservoirs. *AAPG Bull.* 2013, 97, 619–637. [CrossRef]

23. Pei, Y.; Paton, D.A.; Knipe, R.J.; Kongyou, W. A review of fault sealing behaviour and its evaluation in siliciclastic rocks. *Earth-Sci. Rev.* 2015, 150, 121–138. [CrossRef]

24. Orellana, L.; Giorgetti, C.; Violay, M. Contrasting mechanical and hydraulic properties of wet and dry fault zones in a proposed shale-hosted nuclear waste repository. *Geophys. Res. Lett.* 2019, 46, 1357–1366. [CrossRef]

25. Behnsen, J.; Faulkner, D.R. The effect of mineralogy and effective normal stress on frictional strength of sheet silicates. *J. Struct. Geol.* 2012, 42, 49–61. [CrossRef]

26. Medina-Cascales, I.; Koch, L.; Cardozo, N.; Martín-Rojas, I.; Alfaro, P.; García-Tortosa, F.J. 3D geometry and architecture of a normal fault zone in poorly lithified sediments: A trench study on a strand of the Baza Fault, central Betic Cordillera, south Spain. *J. Struct. Geol.* 2019, 121, 25–45. [CrossRef]

27. Alfaro, P.; Delgado, J.; Sanz de Galdeano, C.; Galindo-Zaldívar, J.; García, P.A.; López-Garrido, A.C.; Casado, C.L.; Marín-Lechado, C.; Gil, A.J.; Borque, M.J. The Baza Fault: A major extensional fault in the central Betic Cordillera (south Spain). *Int. J. Earth Sci.* 2007, 97, 1353–1365. [CrossRef]

28. García Tortosa, F.J.; Alfaro, P.; Sanz de Galdeano, C.; Galindo-Zaldívar, J. Glacis geometry as a geomorphic marker of recent tectonics: The Guadix–Baza basin (South Spain). *Geomorphology* 2011, 125, 517–529. [CrossRef]

29. Galindo-Zaldívar, J.; Lodeiro, F.G.; Jabaloy, A. Stress and palaeostress in the Betic-Rif cordilleras (Miocene to the present). *Tectonophysics* 1993, 227, 105–126. [CrossRef]

30. Sanz de Galdeano, C.; García, P.A.; Peláez, J.; Alfaro, P.; Azañón, J.; Galindo-Zaldívar, J.; Casado, C.L.; López-Garrido, A.; Rodríguez-Fernández, J.; Ruano, P. Main active faults in the Granada and Guadix-Baza Basins (Betic Cordillera). *J. Iber. Geol.* 2012, 38, 209–223. [CrossRef]

31. Vera, J.A. Estudio estratigráfico de la depresión de Guadix-Baza. *Bol. Geol. Min.* 1970, 91, 429–462.

32. Gibert, L.; Orti, F.; Rosell, L. Plio-Pleistocene lacustrine evaporites of the Baza Basin (Betic Chain, SE Spain). *Sediment. Geol.* 2007, 200, 89–116. [CrossRef]

33. Nieto, F.; Ortega-Huertas, M.; Peacor, D.R.; Aróstegui, J. Evolution of illite/smectite from early diagenesis through incipient metamorphosis in sediments of the Basque-Cantabrian Basin. *Clays Clay Miner.* 1996, 44, 304–323. [CrossRef]

34. Clift, G.; Lorimer, G. The quantitative analysis of thin specimens. *J. Microsc.* 1975, 103, 203–207. [CrossRef]

35. Moore, D.M.; Reynolds, R.C.J. *X-ray Diffraction and the Identification and Analysis of Clay Minerals*; Oxford University Press: New York, NY, USA, 1997; p. 378.

36. Sánchez-Roa, C.; Vidal, O.; Jiménez-Millán, J.; Nieto, F.; Faulkner, D.R. Implications of sepiolite dehydration for earthquake nucleation in the Galera Fault Zone: A thermodynamic approach. *Appl. Geochem.* 2018, 89, 219–228. [CrossRef]

37. Allen, J.R.L. *Sedimentary Structures: Their Character and Physical Basis*; Elsevier: New York, NY, USA, 1982; Volume II, p. 663.

38. Owen, G. Deformation processes in unconsolidated sands. In *Deformation of Sediments and Sedimentary Rocks*; Special Publication; Jones, M.E., Preston, R.M.F., Eds.; Geological Society: London, UK, 1987; Volume 29, pp. 11–24. [CrossRef]

39. Strachan, L.J. Slump-initiated and controlled syndepositional sandstone remobilization: An example from the Namurian of County Clare, Ireland. *Sedimentology* 2002, 49, 25–41. [CrossRef]

40. Sánchez-Roa, C.; Faulkner, D.R.; Boulton, C.; Jiménez-Millán, J.; Nieto, F. How phyllosilicate mineral structure affects fault strength in Mg-rich fault systems. *Geophys. Res. Lett.* 2017, 44, 5457–5467. [CrossRef]

41. Rotevatn, A.; Thorstein, E.; Bastesen, E.; Fossmark, H.S.; Torabi, A.; Sælen, G. Sequential growth of deformation bands in carbonate grainstones in the hangingwall of an active growth fault: Implications for deformation mechanisms in different tectonic regimes. *J. Struct. Geol.* 2016, 90, 27–47. [CrossRef]

42. Torabi, A. Cataclastic bands in immature and poorly lithified sandstone, examples from Corsica, France. *Tectonophysics* 2014, 630, 91–102. [CrossRef]

43. Rohmer, J.; Nguyen, K.; Torabi, A. Off-fault shear failure potential enhanced by high stiff/low permeable damage zone during fluid injection in porous reservoirs. *Geophys. J. Int.* 2015, 202, 1566–1580. [CrossRef]

44. Moore, D.E.; Lockner, D.A.; Shengli, M.; Summers, R.; Byerlee, J.D. Strengths of serpentinite gouge at elevated temperatures. *J. Geophys. Res.* 1997, 102, 14787–14801. [CrossRef]

45. Sakuma, H.; Suehara, S. Interlayer bonding energy of layered minerals: Implication for the relationship with friction coefficient. *J. Geophys. Res. Solid Earth* 2015, 120, 2212–2219. [CrossRef]
46. Ibanez, W.D.; Kronenberg, A.K. Experimental deformation of shale: Mechanical properties and microstructural indicators of mechanisms. *Int. J. Rock Mech. Min. Sci.* **1993**, *30*, 723–734. [CrossRef]

47. Mares, V.M.; Kronenberg, A.K. Experimental deformation of muscovite. *J. Struct. Geol.* **1993**, *30*, 1061–1075. [CrossRef]

48. French, M.E.; Chester, E.M.; Chester, J.S. Micromechanisms of creep in clay-rich gouge from the Central Deforming Zone of the San Andreas Fault. *J. Geophys. Res. Solid Earth* **2015**, *120*, 827–849. [CrossRef]

49. Kluger, M.O.; Moon, V.G.; Kreiter, S.; Lowe, D.J.; Churchman, G.J.; Hepp, D.A.; Seibel, D.; Jorat, E.; Mörz, T. A new attraction-detachment model for explaining flow sliding in clay-rich tephras. *Geology* **2017**, *45*, 131–134. [CrossRef]

50. Donath, F.A. Some information squeezed out of rock. *Am. Sci.* **1970**, *58*, 54–72.

51. Donath, F.A.; Fruth, L.S., Jr. Dependence of strain-rate effects on deformation mechanism and rock type. *J. Geol.* **1971**, *79*, 347–371. [CrossRef]

52. Ferrill, D.A.; Morris, A.P. Fault zone deformation controlled by carbonate mechanical stratigraphy, Balcones fault system, Texas. *AAPG Bull.* **2008**, *92*, 359–380. [CrossRef]

53. Sánchez-Roa, C.; Jiménez-Millán, J.; Abad, I.; Faulkner, D.R.; Nieto, F.; García-Tortosa, F.J. Fibrous clay mineral authigenesis induced by fluid–rock interaction in the Galera fault zone (Betic Cordillera, SE Spain) and its influence on fault gouge frictional properties. *Appl. Clay Sci.* **2016**, *134*, 275–288. [CrossRef]

54. Alfaro, P.; Gibert, L.; Moretti, M.; García-Tortosa, F.J.; Sanz de Galdeano, C.; Galindo-Zaldívar, J.; López-Garrido, A.C. The significance of giant seismites in the Plio-Pleistocene Baza palaeo-lake (S. Spain). *Terra. Nova* **2010**, *22*, 172–179. [CrossRef]

55. Van der Zee, W.; Urai, J.L. Lateral clay injection into normal faults. *GeoArabia* **2003**, *8*, 501–522. [CrossRef]

56. Van der Zee, W.; Urai, J.L. Processes of normal fault evolution in a siliciclastic sequence: A case study from Miri, Sarawak, Malaysia. *J. Struct. Geol.* **2005**, *27*, 2281–2300. [CrossRef]

57. Jiménez-Millán, J.; Abad, I.; García-Tortosa, F.J.; Nieto, F.; Jiménez-Espinosa, R. Clay saline diagenesis in lake Plio-Pleistocene sediments rich in organic matter from the Guadix-Baza Basin (Betic Cordillera, SE Spain). *Appl. Clay Sci.* **2020**, *195*, 105739. [CrossRef]

58. Deocampo, D.M. Authigenic clays in East Africa: Regional trends and paleolimnology at the Plio-Pleistocene boundary. Olduvai Gorge, Tanzania. *J. Paleolimnol.* **2004**, *31*, 1–9. [CrossRef]

59. Deocampo, D.M. Authigenic clay minerals in lacustrine mudstones. *Geol. Soc. Am. Spec. Pap.* **2015**, *515*, SPE515-03.

60. Deocampo, D.M.; Berry, P.A.; Beverly, E.J.; Ashley, G.M.; Jarrett, R.E. Whole-rock geochemistry tracks precessional control of Pleistocene lake salinity at Olduvai Gorge, Tanzania: A record of authigenic clays. *Geology* **2017**, *45*, 683–686. [CrossRef]

61. Cuadros, J.; Andrade, G.; Ferreira, T.O.; de Moya Partiti, C.S.; Cohen, R.; Vidal-Torrado, P. The mangrove reactor: Fast clay transformation and potassium sink. *App. Clay Sci.* **2017**, *140*, 50–58. [CrossRef]