

# The role of penetrative deformation in orogenic processes. An example from the Eastern Cordillera of Colombia

## Vortrag

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The Lower Cretaceous units of the Eastern Cordillera of Colombia have been deposited during a stage when the area where nowadays lies a contractional orogen was an actively deforming rift. Therefore, they are syn-rift sedimentary units. These rocks have a unique feature in the Cretaceous sedimentary column of this mountain chain. This is a widespread planar fabric expressed mostly as a penetrative slaty cleavage. This planar fabric is only macroscopically evident in Cretaceous units older than Barremian. Planar fabric (e.g. slaty cleavage) is one of the products of internal or penetrative deformation (i.e. contractional deformation at microscopical scale in rock units). Pressure solution and even cleavage have been recently reported in areas undergoing only subtle burials (Engelder & Marschak 1985). However, in the Eastern Cordillera, the units where planar fabric is evident are the base of a sequence of at least 5 km and they have vitrinite reflectance values up to 2. These data and the formation of clorithoid contemporary with the slaty cleavage, allow us to propose that this planar fabric was developed when the Lower Cretaceous units had an amount of overburden close to the thickness of the entire Cretaceous sequence.

We carried out finite strain measure-

ments using the enhanced normalized Fry method (Erslev 1988) in order to quantify the shortening by internal deformation in various localities in the Eastern Cordillera. For this purpose we used thin sections of sandstones containing macroscopically evident planar fabrics as recommended by Dittmar et al. (1994). In some cases we deduced 3D-strain ellipsoids from individual Fry-method measurements following von Winterfeld & Oncken (1995). In addition we took strike and dip measurements of all the observed structural features observed in the outcrop to carry out a structural and orientation analysis mostly in the same localities where finite deformation was measured. Finally we also produced stratigraphic profiles in some of the locations in order to check relationships between lithology and deformation features.

First finite strain measurements allowed us to quantify an additional amount of shortening by penetrative deformation (i.e. contractional deformation at the microscopical scale that mostly produces slaty cleavage) in the Eastern Cordillera that is locally near 20%. Shortening by internal deformation is localized in the steeply dipping limbs of anticlines, the hinge zones of some synclines and the contractionally reactivated boundaries of former normal faults. As the observed planar fabric (e.g. slaty cleavage) is mostly continuous throughout different lithologies rather than discontinuous cleavage within spaced deformation zones; we assumed that shortening by penetrative deformation is not discrete. Thus, we propose that it represents a homogeneous flattening of the outcropping units in those localities where it is present. We calculated that shortening

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by folding in the Eastern Cordillera is close to 20%. This means that shortening by penetrative deformation compared to shortening by folding is not minor.

Orientation analysis of fractures and SiO<sub>2</sub>-filled or CaCO<sub>3</sub>-filled veins was done when these features were spatially associated with the planar fabric. With the collected data we propose that planar fabric and fractures have been formed mostly at the early stages of folding under a dominant WNW–ESE to E–W compressional stress field. For instance, fractures present in tilted beds only give a consistent pattern of compressional stress if they are restored to a prefolding position. In such cases the obtained direction is coincident with the direction of maximum finite deformation (This direction is assumed to be roughly perpendicular to the plane of slaty cleavage when finite strain measurements are not available at a given location). After restoring the fractures to a prefolding position their dip is vertical and perpendicular to bedding. In the folded state fracture orientation strongly depends on their position within the folded structures. However fracture intensity appears to depend both on structural position and lithology.

In addition, we found the presence of similar sets of fractures with similar orientations in different Lower-Cretaceous lithologies along the stratigraphic sections. However, fractures found in terrigenous pelrites always lack any kind of filling. In contrast when found in terrigenous sandstones they have SiO<sub>2</sub> filling and in carbonates they are filled with CaCO<sub>3</sub>. When evaporites are the host rocks of mineralization the veins have the paragenesis of albite, pyrite,

calcite and emeralds. This paragenesis is a guide for emerald exploration and therefore represents the only mineralization of economic interest. In such evaporitic facies, fracture density reaches a maximum. Thus, evidence of mineralization strongly dependent on lithology, allow us to we hypothesize about a closed mineralization system, at least partially. However, by the field evidence the possibility of the influence of fluids coming from outside the formations cannot be discarded completely. In addition, in some of the analyzed localities we have found specific types of deformation, only observed when the sequence is composed of interbedded medium to thick layers of terrigenous mudstones with marls: A close association of slaty cleavage restricted to calcareous beds with CaCO<sub>3</sub>-filled veins restricted to adjacent terrigenous mudstones. In such localities both features have been formed under the same stress field. The exposed relationships allow us to propose the following situation. Fluids ascending from terrigenous mudstones to adjacent marls. They ascend due to them being expelled because of a reduction in porosity caused by pressure solution processes. The exposed mineralization scenario would be then a highly autochthonous one.

The paragenesis of the veins associated with evaporites provides the entire Colombian emerald production, which in fact is one of the largest in the world. In such context those veins in the emerald-bearing areas have been dated (Cheilletz et al. 1996) as old as  $37 \pm 0.1$  My in the western flank of the Eastern Cordillera and  $65 \pm 3$  My in its eastern flank. We propose that the mentioned ages are giving a proxy of the age of the kinematic indicators

deduced from fracture and vein orientations. Fluid inclusion studies demonstrate that these mineralizations occurred at more than 250°C (Cheilietz et al 1996). Thus fluid inclusions and vitrinite reflectance data illustrate that at this time exhumation of the Cretaceous rocks was minor or absent.

Mineralization is also present as hydrothermal breccia frequently localized in the hinge zones of folds. In some cases those areas are also the location of intense finite deformation values. Therefore we propose that mineralization associated with Lower Cretaceous units were formed in presence of high fluid pressure during folding and internal deformation under epithermal conditions. With all the collected evidence it appears that penetrative deformation (Slaty cleavage) is instrumental for mineralization.

Therefore, our contribution shows pieces of evidence supporting that the role of penetrative deformation has been underestimated in the Eastern Cordillera. Penetrative deformation does not only account for important additional crustal shortening in this orogen, but also plays a role in the formation of prolific economic mineral deposits.

## References

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