Long-term orogenic-scale paleofluid system across the Tuscan Nappe – Umbria-Marche Apennine Ridge (northern Apennines, Italy) as revealed by mesostructural and isotopic analyses of stylolite-vein networks

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Faults, joints and stylolites are ubiquitous features in fold-and-thrust belts commonly used to reconstruct the past fluid flow (or plumbing system) at the scale of folded reservoir/basins. Through the textural and geochemical study of the minerals that fills the fractures, it is possible to understand the history of fluid flow in an orogen, requiring a good knowledge of the burial history and/or of the past thermal gradient. In most of the case, the latter derives from the former, itself often argued over, limiting the interpretations of past fluid temperatures. We present the results of a multi-proxy study that combines novel development in both structural analysis of a fracture-stylolite network and isotopic characterization of calcite vein cements/fault coating. Together with new paleopiezometric and radiometric constraints on burial evolution and deformation timing, these results provide a first-order picture of the regional fluid systems and pathways that were present during the main stages of contraction in the Tuscan Nappe and Umbria-Marche Apennine Ridge (Northern Apennines). We reconstruct four steps of deformation at the scale of the belt: burial-related stylolitization, Apenninic-related layer-parallel shortening with a contraction trending NE-SW, local extension related to folding and late stage fold tightening under a contraction still striking NE-SW. We combine the paleopiezometric inversion of the roughness of sedimentary stylolites - that provides a temperature-free constraint on the range of burial depth of strata prior to layer-parallel shortening - , with burial models and U-Pb absolute dating of fault coatings in order to determine the timing of development of mesostructures. In the western part of the ridge, layer-parallel shortening started in Langhian time (~15 Ma), then folding started at Tortonian time (~8 Ma), late stage fold tightening started by the early Pliocene (~5 Ma) and likely
lasted until recent/modern extension occurred (~3 Ma onward). The textural and geochemical (δ¹⁸O, δ¹³C, Δ⁴⁷CO₂ and ⁸⁷Sr/⁸⁶Sr) study of calcite vein cements and fault coatings reveals that most of the fluids involved in the belt during deformation are basinal brines evolved from various degree of fluid rock interactions between pristine marine fluids (δ¹⁸O fluids = 0‰ SMOW) and surrounding limestones (δ¹⁸O fluids = 10‰ SMOW). The precipitation temperatures (35°C to 75°C) appear consistent with the burial history unraveled by sedimentary stylolite roughness paleopiezometry (600 m to 1500m in the range) and geothermal gradient (23°C/km). However, the western edge of the ridge recorded isotopically depleted past fluids of which corresponding precipitation temperature (100°C to 130°C) are inconsistent with local burial history (1500m). We interpret then pulses of eastward migration of hydrothermal fluids (>140°C), driven by the tectonic contraction and by the difference in structural style of the subsurface between the eastern Tuscan Nappe and the Umbria-Marche Apennine Ridge. Allowed by an unprecedented combination of paleopiezometry and isotopic geochemistry, this fluid flow model illustrates how the larger scale structures control the fluid system at the scale of the range.