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Microstructures and rheology of a calcite-shale thrust fault

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ABSTRACT

A thin (~2 cm) layer of extensively sheared fault rock decorates the ~15 km displacement Copper Creek thrust at an exposure near Knoxville, TN (USA). In these ultrafine-grained (<0.3 μm) fault rocks, interpenetrating calcite grains form an interconnected network around shale clasts. One cm below the fault rock layer, sedimentary laminations in non-penetratively deformed footwall shale are cut by calcite veins, small faults, and stylolites. A 350 μm thick calcite vein separates the fault rocks and footwall shale. The vein is composed of layers of (1) coarse calcite grains (>5 μm) that exhibit a lattice preferred orientation (LPO) with pores at twin–twin and twin-grain boundary intersections, and (2) ultrafine-grained (0.3 μm) calcite that exhibits interpenetrating grain boundaries, four-grain junctions and lacks a LPO. Coarse calcite layers crosscut ultrafine-grained layers indicating intermittent vein formation during shearing.

Calcite in the fault rock layer is derived from vein calcite and grain-size reduction of calcite took place by plasticity-induced fracture. The ultrafine-grained calcite deformed primarily by diffusion-accommodated grain boundary sliding and formed an interconnected network around shale clasts within the shear zone. The interconnected network of ultrafine-grained calcite indicates that calcite, not shale, was the weak phase in this fault zone.

1. Introduction

How large thrust sheets move long distances along thin fault zones has been debated since the recognition of thrust faults in the mid-19th century. In early work to resolve this problem, Hubbert and Rubey (1959) proposed that increased fluid pressure along a thrust fault reduced effective normal stress sufficiently to enable relatively rigid sheets of uniform thickness to slide 10 s of km on thin fault zones. Kehle (1970) argued that viscous shearing within shales might accommodate thrust sheet movement without the need for high stresses along the trailing edge of a sheet, while Chapple (1978) adopted the notion of sheet movement by viscous flow of a weak layer, and introduced the concept that thrust belts are tapered wedges; Chapple's model paired a wedge-shaped perfectly plastic sheet and wedge-shaped rigid 'cap' required to produce reasonable stress distributions within the sheet. Davis et al. (1983), Dahlen et al. (1984), Davis and Engelder (1985), and Dahlen (1990) proposed that thrust sheets deform internally until a critical taper is reached, at which point the wedge moves by frictional sliding along a basal thrust. Low resistance to basal sliding must be maintained for wedges with taper angles comparable to those observed in modern orogenic settings (Suppe, 2007).

The models listed above require low resistance to basal sliding. A common observation in exposures of faults in fold-thrust belts is shale in either the hangingwall or footwall strata; shale has thus been thought to act as a weak layer allowing large displacements (e.g., Kehle, 1970; Wiltschko and Chapple, 1977; Thomas, 2001; Ikari et al., 2009), possibly by increasing pore-fluid pressure when shales compact or undergo pressure-related structural changes (e.g., Bolton and Maltman, 1998; Bolton et al., 1998, 1999; Vrolijk and van der Pluijm, 1999; Cobbold et al., 2009), thereby reducing frictional resistance. Other workers have taken a different tack on this problem, focusing on the character and evolution of the fault rocks from thrust zones (e.g., Schmid, 1983; Mitra, 1984; Wojtal and Mitra, 1986, 1988; O'Hara, 1988, 1990; Newman and Mitra, 1993, 1994; Kennedy and Logan, 1997, 1998; Kennedy and White, 2001; Liu et al., 2002). These workers have suggested that processes other than frictional sliding contribute to, or are responsible for, the motion along the base of large thrust sheets.

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The Copper Creek thrust fault in the southern Appalachian Valley and Ridge Province (Fig. 1) is a typical upper crustal fault in a fold-thrust belt with moderate to large displacement (~15 km) (e.g., Suppe, 1985; Wojtal and Mitra, 1986). Where the thrust surface is exposed near Knoxville, Tennessee (USA), a thin (~2 cm) layer of extensively sheared carbonate fault rocks separates unmetamorphosed shale in both the footwall and hangingwall. Previous studies of carbonate fault rocks from the Copper Creek thrust, the Hunter Valley thrust in the southern Appalachians, and the McConnell thrust in the Canadian Rockies suggest that fluids played an important role in deformation, mainly by enhancing diffusive mass transfer (e.g., Wojtal and Mitra, 1986) and/or dislocation creep (Kennedy and Logan, 1997, 1998; Kennedy and White, 2001) instead of lowering shear resistance by increasing fluid pressure. These previous studies included optical microscopy and transmission electron microscopy (TEM) to document contributions by fracture, diffusive mass transfer, and intracrystalline plasticity. However, due to limitations on the resolution of the optical microscope and limits on the area observed using TEM, interactions between deformation mechanisms, and their relative contributions, are difficult to discern. Using a high-resolution scanning electron microscope, this study documents microstructures at a scale that allows observation of spatial relations between microstructures in a transect across the thin fault zone, thereby addressing 1) the relative contributions of shale and calcite to the deformation and 2) the role of different deformation mechanisms, and their interactions, in the development of the thin, strongly-sheared layer of fault rocks.

The microstructures described here underscore the critical role of fluids in the initial and continued deformation in a thin layer. Calcite veins parallel to the fault rock layer suggest at least intermittent high fluid pressures in the vicinity of the fault. Increased pore fluid pressure during the emplacement of these veins may have contributed to repeated fracturing along the fault and the formation of veins, but the veins themselves are perhaps more significant as starting material for the fault zone rocks. Observations that we report here indicate that the deformation of coarse-grained calcite in these veins led to the development of a layer of ultrafine-grained (<1.0 μm) calcite that exhibits evidence for significant shearing. Thus, it is by way of vein emplacement, which was critical to the formation of the distinctive fault rock layer that accommodated significant, localized shearing, that increased pore fluid pressure facilitated sheet movement.

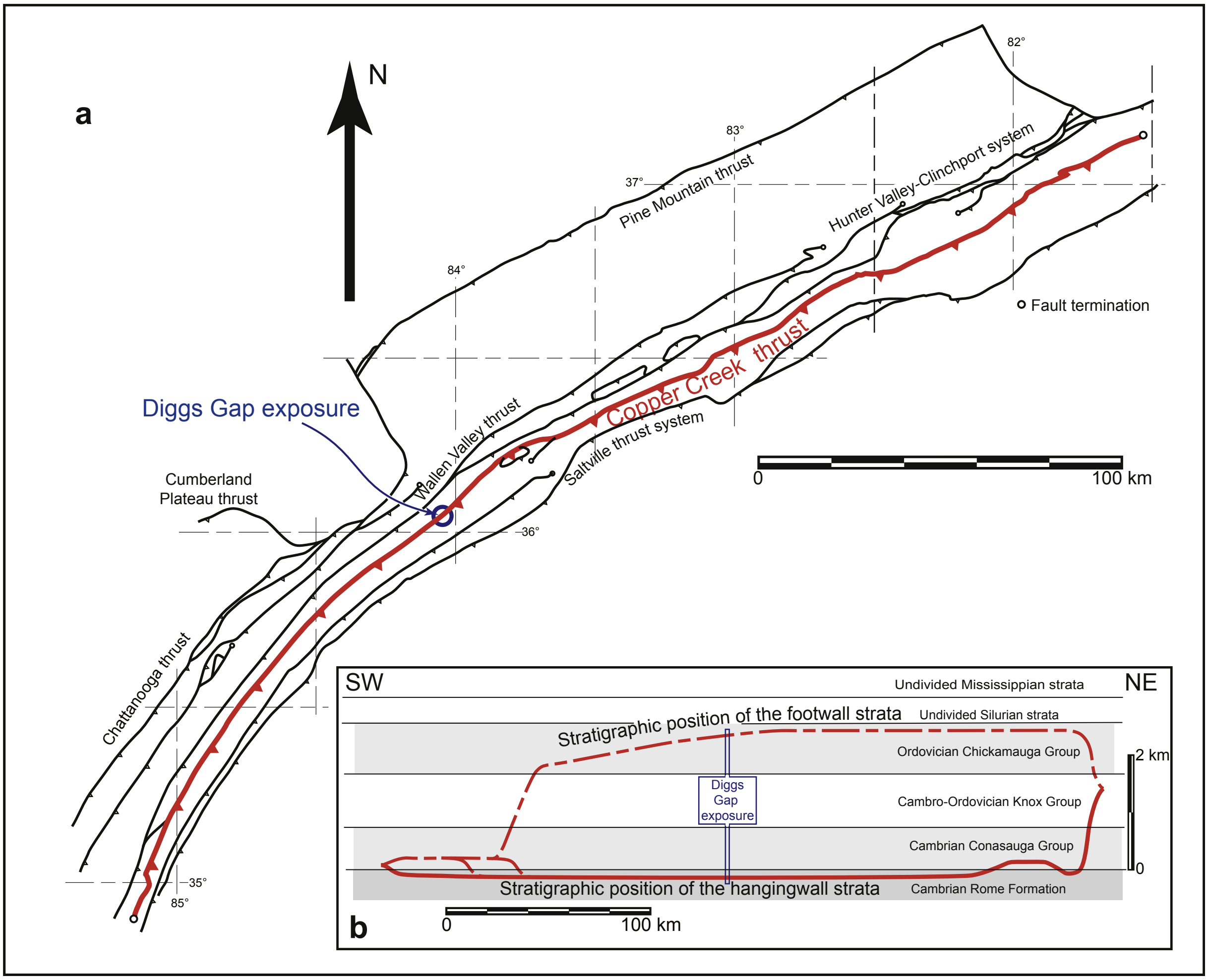

Fig. 1. (a) Map showing the traces of the major thrusts in the western portion of the southern Appalachian Valley and Ridge Province. The Copper Creek thrust is shown in red, and the location of the Diggs Gap exposure described here is indicated. The Saltville, Copper Creek, Wallen Valley, Hunter Valley-Clinchport, and Chattanooga thrusts all carry Cambrian Rome Formation strata in their hangingwalls. (b) A stratigraphic separation diagram for the Copper Creek thrust, which plots the stratigraphic position of the hangingwall (solid line) and footwall (dashed line) at different positions along the trace of the fault. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)