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Co-axial refolding and inverted regional metamorphism in the Tonga formation: Cretaceous accretionary thrust tectonics in the Cascades crystalline core

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Abstract: The Cascades crystalline core forms part of the Cretaceous magmatic belt of western North America and exposes a crustal section composed of primarily tonalitic plutons that intruded siliciclastic metasediments of an arc-derived accretional system, and local meta-basalt/chert sequences. This study is the first attempt to correlate the well-understood intrusive and P-T-t history of the metasedimentary and plutonic terrane with the kinematics and tectonic boundary conditions by rigorous analysis of structures documented in the Tonga formation exposed at the western edge of the core. The Tonga formation comprises pelite-psammite metasediments, which increase from greenschist (~300-350 °C) to amphibolite grade (~500-600 °C) from south to north. This metamorphic gradient is inverted relative to a major westward-verging and downward-facing fold system that dominates the internal architecture of the formation and implies that the initial regional metamorphic signature was established prior to the early fold generation. Subsequent co-axial fold superposition is seen as a consequence of the persistent accretional W-vergent thrusting in the foreland of the magmatic arc.

Keywords: fold, interference, co-axial, Cascades, Tonga.

The central section of the Cascades Range, exposed in Washington state, forms part of the Cretaceous accretional/magmatic arc extending over 4,000 km along western North America from Baja California to British Columbia (Fig. 1a) (e.g. Misch, 1966; Brown, 1987; Tabor *et al.*, 1989). Two models exist for the evolution of the Cascades crystalline core with one invoking magmatic loading (e.g. Brown and Walker, 1993) as the major cause for rapid loading, consequent regional metamorphism and vertical uplift (Evans and Berti, 1986). Conversely, other workers favor a model that suggests loading as a consequence of tectonic, thrust-related thickening, followed by rapid exhumation of the exposed crustal section of 10 to 40 km paleodepth (e.g. Matzel, 2004; Patterson *et al.*, 2004; Stowell *et al.*, 2007). In this context, the Tonga formation, on the westernmost boundary of the Cascades crystalline core, records Cretaceous plutonism, contact to regional metamorphism, and multiple episodes of folding, evidencing intense, arc-perpendicular contractional deformation, similar to that observed in the neighboring Chiwaukum schist to the

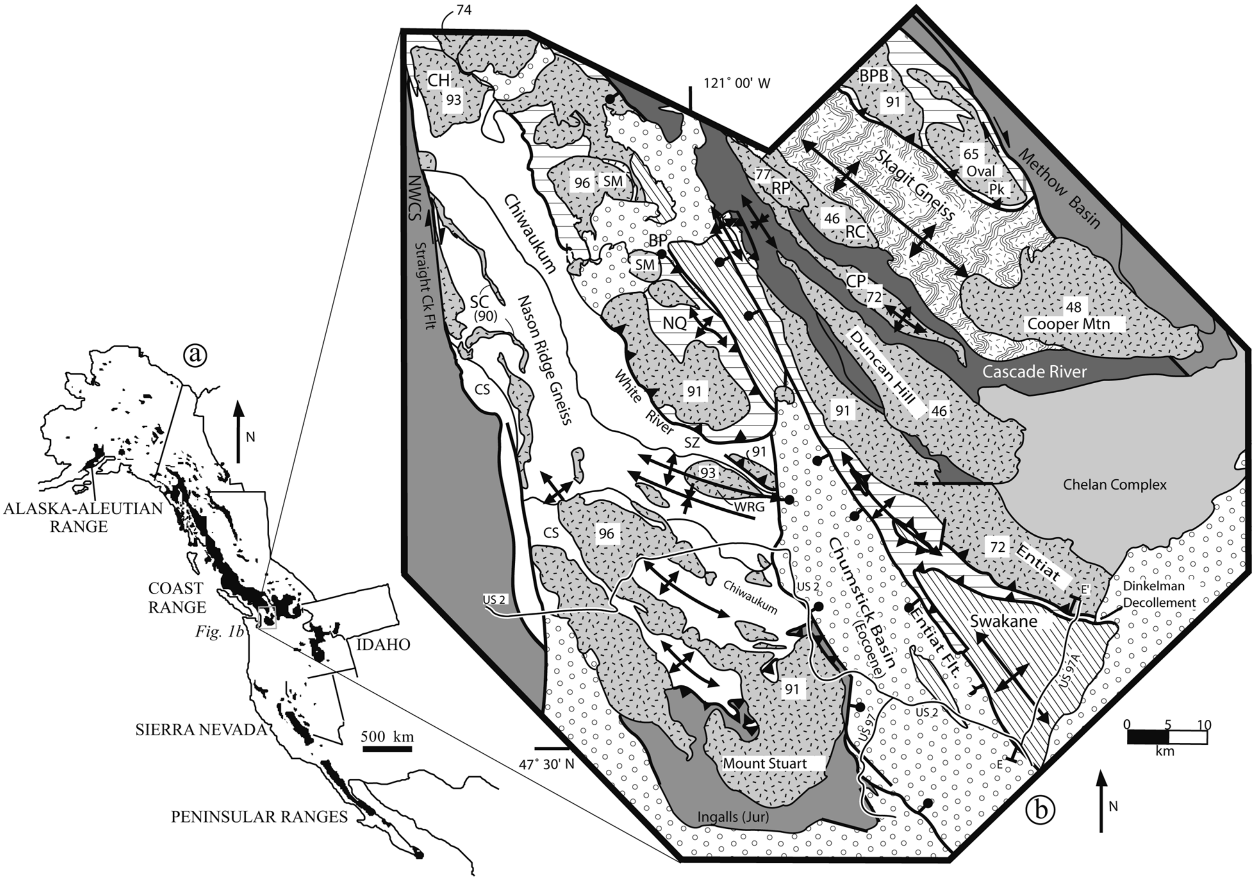

Figure 1. (a) Regional map showing location of the Cascades crystalline core (gray rectangle, detailed in figure 1b) relative to the Cretaceous magmatic arc complexes of western North America, (b) regional map of the Cascades crystalline core showing the two major tectonic domains (Wenatchee block, west; and Chelan block, east) and their respective geologic units and ages (from Miller *et al.*, 2006). Plutons are shaded with random dashes, and numbers indicate crystallization ages in millions of years. BP: Buck Pass area, BPB: Black Peak batholith, CH: Chaval pluton, CP: Cardinal Peak pluton, CS: Chiwaukum schist, TF: Tonga formation, NQ: Napeequa unit, NWCS: Northwest Cascades system, RC: Railroad Creek pluton, RP: Riddle Peaks pluton, SC: Sloan Creek plutons, SM: Sulphur Mountain pluton, SZ: shear zone, WRG: Wenatchee Ridge gneiss. Open circle pattern: Middle Eocene and younger rocks. The location of major highways is also shown for orientation.

east (Miller and Paterson, 1992; Miller *et al.*, 1993; Paterson and Miller, 1998; Miller *et al.*, 2006). Building on previous extensive mapping and metamorphic and petrologic analysis in the Cascades, we use the Tonga formation as a means to a comprehensive tectonic synthesis incorporating detailed analysis of the kinematics and timing of structural evolution, magma emplacement, and metamorphism.

Geological setting

The Cascades crystalline core is divided into two major domains, the Wenatchee block to the west and Chelan block to the east, which are separated by the brittle, Eocene Entiat fault (Fig. 1b). Both domains are characterized by voluminous tonalitic intrusions of Cretaceous ages in the Wenatchee domain and Cretaceous to Eocene ages in the Chelan domain (Matzel, 2004; Miller *et al.*, 2006). The predominant country rock in the Wenatchee domain is the Chiwakum schist, a Late Jurassic-Early Cretaceous siliciclastic sequence probably derived from a volcanic arc (Duggan and Brown, 1994; Brown and Gehrels, 2007), and revealing a multi-stage history of deformation and contact and regional metamorphism. Amphibolite-grade regional metamorphism (M1), which is poorly preserved in other parts of the Wenatchee block, is accompanied by intense regional deformation and isoclinal folding. Extensive plutonism represented by the Mt. Stuart batholith and related intrusives generated contact metamorphism (M2). An increase in pressure on the contact assemblages and the formation of high-pressure mineral phases occurred, reflected by a second, well-expressed phase

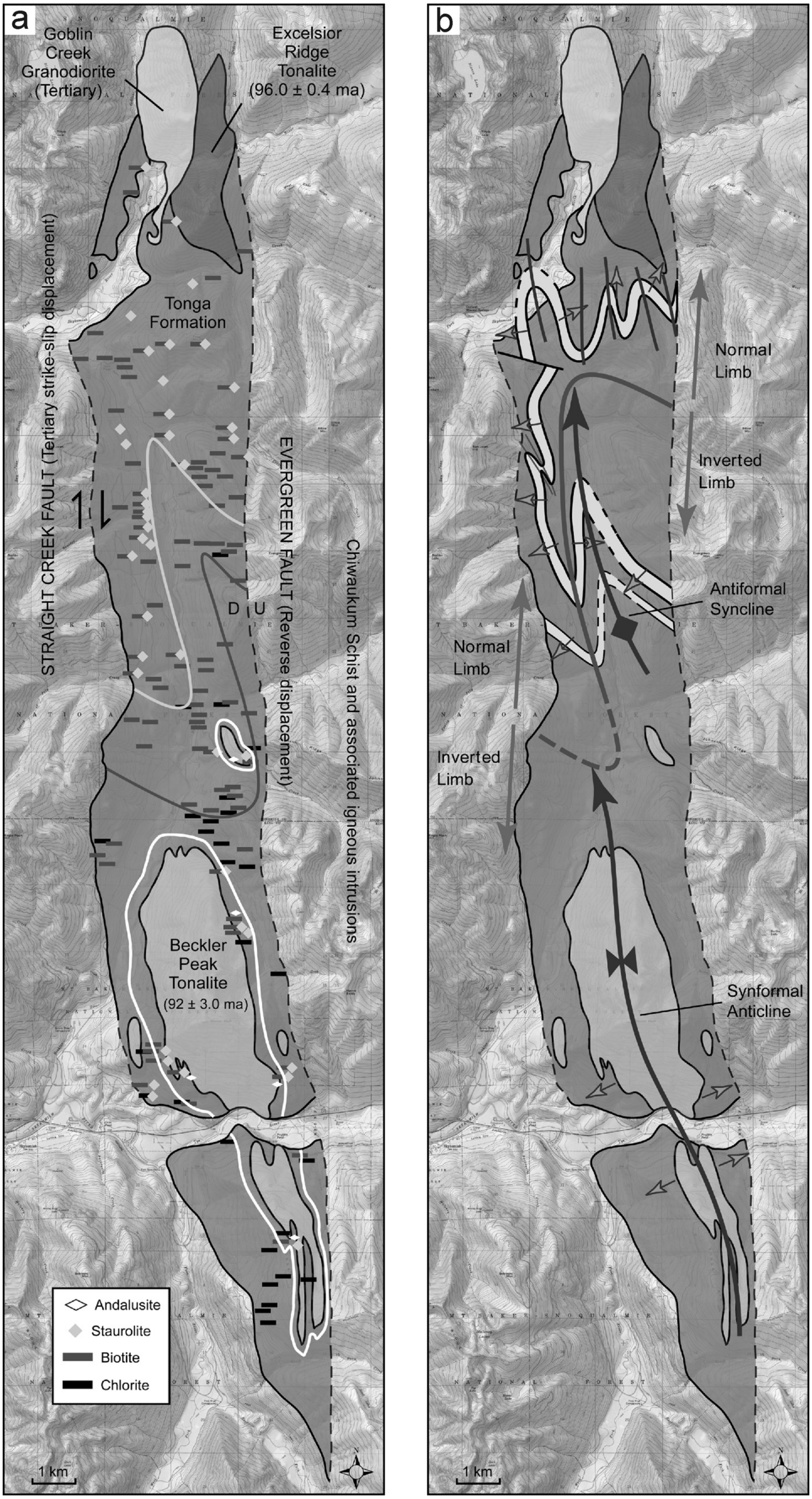

Figure 2. (a) Map showing tectonic boundaries, intrusions, and metamorphic index mineral distributions in the Tonga formation. Regional metamorphic gradient increases roughly from south to north from chlorite (black rectangles) to biotite (dark gray rectangles) to staurolite (light gray rhombuses) grade. Andalusite (white rhombuses) occurs only in pluton contact aureoles (white line). Note the curvilinear shape of the regional metamorphic isograds (biotite: dark gray line; staurolite: light gray line), which mimics the observed fold interference pattern shown in figure 2b, (b) map showing antiformal syncline (NE) and synformal anticline (SW) pair, gently plunging to the NNW, which dominates the structure of the Tonga formation. Prominent meta-quartzite bed trace is shown in light gray. Younging directions are indicated by the small outlined arrows. The oldest generation of fold axial traces has a sigmoidal shape shown in medium gray, while the youngest generation of fold axial traces is shown in dark gray. Synthesis of these observations with the geometries of metamorphic mineral isograds (Fig. 2a), which are inverted relative to the exposed fold system, reveals a coaxial, type III, fold interference pattern.

of regional metamorphism (M3), indicating substantial loading (Brown and Walker, 1993; Evans and Davidson, 1999; Stowell *et al.*, 2007).

Analysis

Tonga formation

The Tonga formation is exposed in a fault-bounded, N-S elongate tectonic domain that comprises pelite-psammite metasediments ranging from greenschist to amphibolite grade (Fig. 2a). Metamorphic grade increases roughly from south to north across sigmoidally curved, acute metamorphic isograds, indicating a metamorphic gradient that is inverted relative to a major westward-verging and downward-facing fold system that dominates the internal architecture of the formation (Fig. 2b). Metamorphic index mineral occurrences were compiled from this and previous studies (Yeats, 1958; Heath, 1971; Duggan, 1992; Tabor *et al.*, 1993), and associated isograd maps were constructed on the basis of the occurrence of chlorite to the south, andalusite and *local* overprinting staurolite within pluton aureoles, and staurolite (with the absence of chlorite or any contact metamorphic minerals) to the north. Based on bulk rock composition of the Tonga formation using the original samples obtained for Rb-Sr analysis (courtesy of Ned Brown, Western Washington University), a pseudosection was constructed (courtesy of Michael Brown and Tim Johnson, University of Maryland) in order to examine the P-T-t history synergistically with the observed deformation and structures.

Unlike in the neighboring, more highly metamorphosed meta-sediments to the east (i.e. the Chiwaukum Schist), sedimentary structures are remarkably well-preserved in the Tonga formation. Recognizable depositional features, including graded bedding, laminae, rip-up clasts, and flute casts, allowed for the determination of younging directions throughout the unit. These features are particularly evident in the lower section of the Tonga formation, which crops out as decameter-scale meta-sandstones used as the primary marker horizon to track the folding patterns (Fig. 2b). Using facing directions and bedding-cleavage relationships, detailed field mapping indicates a stratigraphically overturned section that forms a large-scale *antiformal syncline* (exposed in the NE domain) and related *synformal anticline* (SW domain). The overturning of the strata and the geometry of gently N-plunging minor folds imply up-section a pre-existing tight, recumbent anticline refolded into a co-axial (Type III) fold interference pattern (Fig. 3). The core of this early anticline, exposed in the northern domain, corresponds with the higher metamorphic conditions of the inverted metamorphic gradient and early Cascades regional metamorphism, rarely decipherable in the adjacent Chiwaukum schist. In the latter, the M1 phase is largely obscured due to overprinting by later high-grade regional metamorphism (M3), related to its deeper Mesozoic burial and crustal loading within the accretional/magmatic arc complex.

Discussion

The co-axial, superposed folding in the Tonga formation and the overall N-S arrangement of the con-

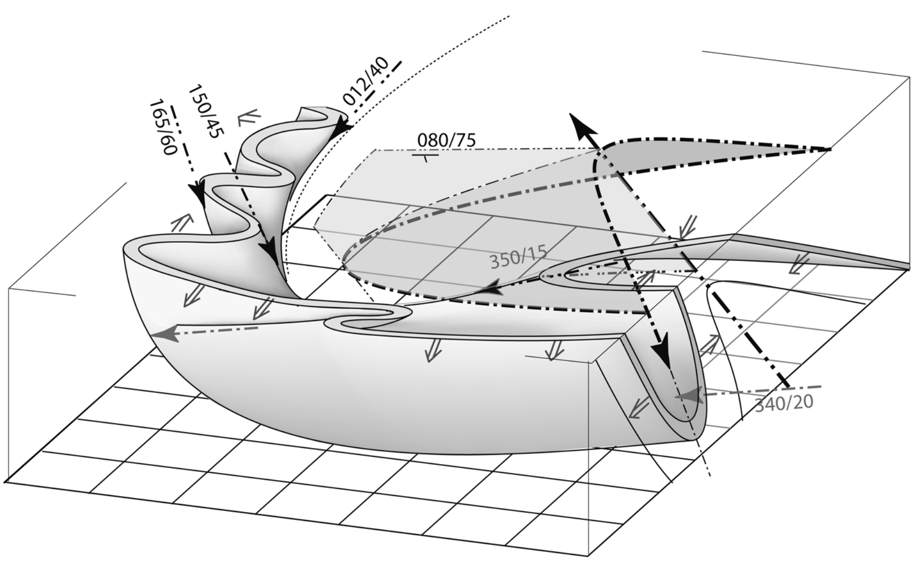

Figure 3. Block diagram outlining the geometry of a major meta-sandstone marker horizon of the lower Tonga formation and the geometry of the fold interference pattern. The axes of the component fold generations form an angle of approximately 10-25° between the older (light gray arrows) and younger (dark gray arrows) fold generations.

stituent fold generations suggests a strong component of E-W shortening in the foreland of the Cascades core. The initial folding may correspond to the initiation of subduction processes and related accretion in the sedimentary wedge. The first, isoclinal fold generation is exposed in the Tonga formation primarily as a large overturned limb, as a preserved expression of a much larger fold system whose deeper and more internal levels are observed to the east (e.g. Chiwaukum schist). The overturned geometry in conjunction with the observed inverted metamorphic zonation, implies that the regional metamorphic (M1) signature was established prior to or immediately preceded the early fold generation (Fig. 4). The metamorphic isograds were observed to cut up-section across the meta-sedimentary sequence such that horizontally restored isograds suggest bedding initially inclined towards the east. Such dip would be in accordance with the eastward polarity of Cretaceous subduction and an early accretionary geometry in the Cascades.

The isoclinal folds and related inverted regional metamorphic zonation are superposed by a generation of close, upright, W-vergent folds. The axial trends of both fold generations are sub-parallel, resulting in a Type III fold interference pattern. This type of approximately co-axial fold superposition is common in accretionary systems and intense fold-and-thrust belts dominated by nappe tectonics (e.g. Alps). Such systems display successive fold generations that express repeated instability and amplification within a persistent bulk kinematic regime, again implying an E-W-oriented contractional system for the Cascades. The late fold generation also appears to control the emplacement of magmatic intrusions in the Tonga formation, as plutons are localized along and elongate parallel to the regional fold hinges. The hook- or mushroom-shaped map pattern of the Mt. Stuart igneous intrusion (Fig. 1b) serves as an example of such a relationship where episodes of magma intrusion correlate with different regional folding events (Miller *et al.*, 2006).

The central and southern portion of Tonga formation records subsequent contact (M2) and regional (M3) metamorphism, and appears to be a lower-grade equivalent of the Chiwaukum schist, as protoliths and

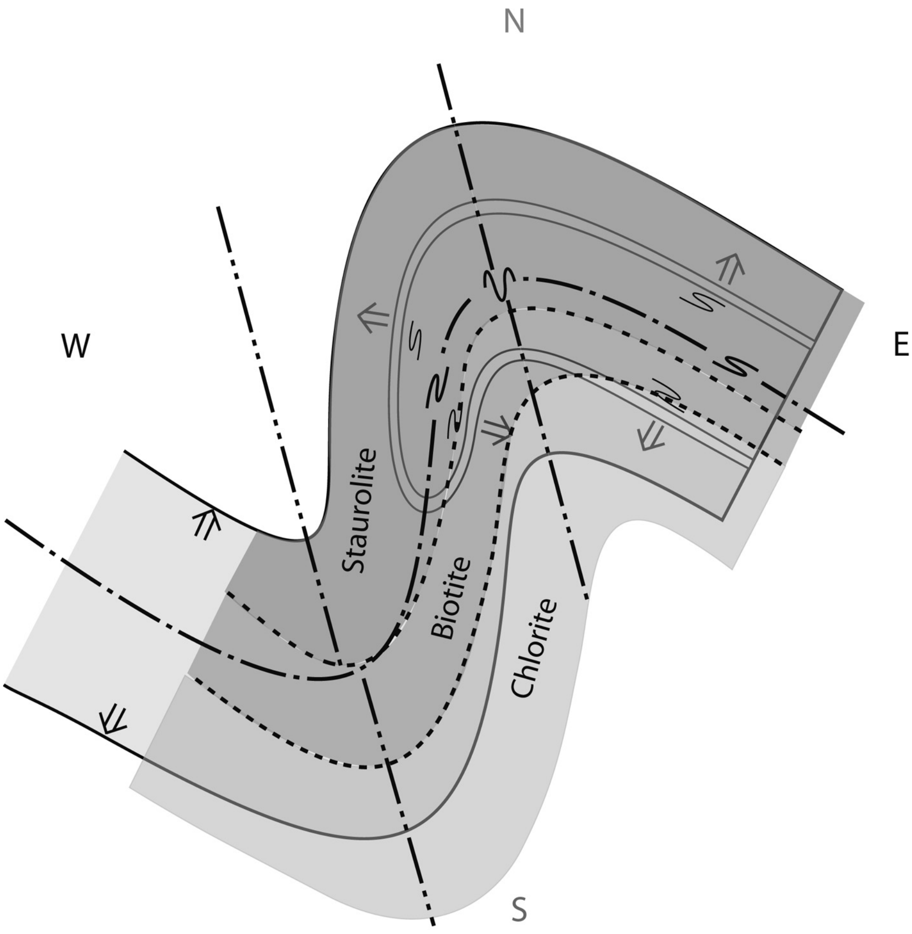

Figure 4. Schematic, profile section across the Tonga formation revealing the refolded fold pattern and its relationship to the metamorphic isograds, which cut up-section.

bulk rock composition of each unit are also similar (Tinkham, 2002). Exposure of the Tonga formation's bounding faults is limited, but the observed structural and metamorphic relationships suggest that a late, E-dipping reverse fault (Evergreen fault) placed the deeper, higher-grade Chiwaukum schist adjacent to the lower-grade Tonga formation.

Conclusions

The Tonga formation provides a unique geological unit for understanding the interplay between deformation and metamorphism within the Cretaceous arc system of western North America. Within the Tonga formation, excellent marker beds and preserved sedimentary younging directions, distinct within the Cascades, facilitated identification of a downward-facing fold system and an inverted metamorphic gradient. The first episode of regional metamorphism (M1), which is difficult to discern in higher-grade metamorphic rocks such as the Chiwaukum schist due to overprinting, is shown to have formed prior to the earliest fold generation. Subsequent phases of deformation, plutonism, and metamorphism (M2 and M3) correlate with those observed more readily in the Chiwaukum schist to the east. Detailed structural mapping and analysis, mated with metamorphic studies, reveal that the Tonga formation records sequential episodes of W-vergent, arc-perpendicular contractional deformation in the form of superposed folds, substantiating a co-axially deformed accretionary system for the Cascades.

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