Coaxial refolding and inverted regional metamorphism in the Tonga Formation: Evidence for Cretaceous thrust tectonics in the Cascades crystalline core

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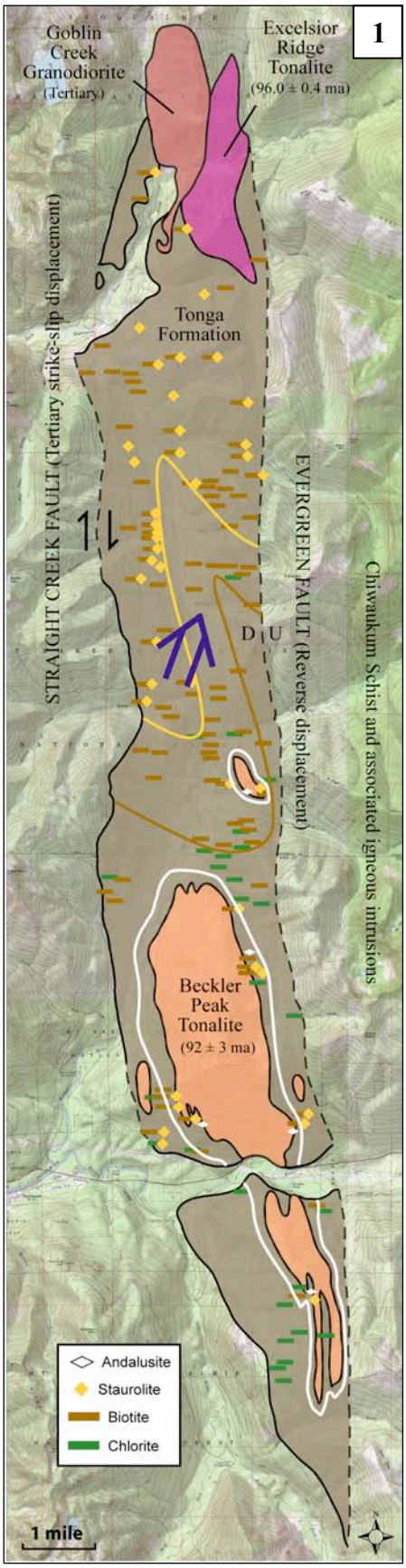
The Tonga Formation, on the westernmost boundary of the Cascades crystalline core, records Cretaceous plutonism, contact to regional metamorphism, and multiple episodes of folding related to intense east-west contractional deformation. The Tonga Formation is exposed in a fault-bounded, north-south elongate tectonic domain that comprises pelite-psammite metasediments ranging from greenschist to amphibolite grade (Figure 1). Metamorphic grade increases from south to north across acute metamorphic isograds, indicating an inverted metamorphic gradient relative to a major westward verging and downward facing fold system that dominates the internal architecture of the formation.

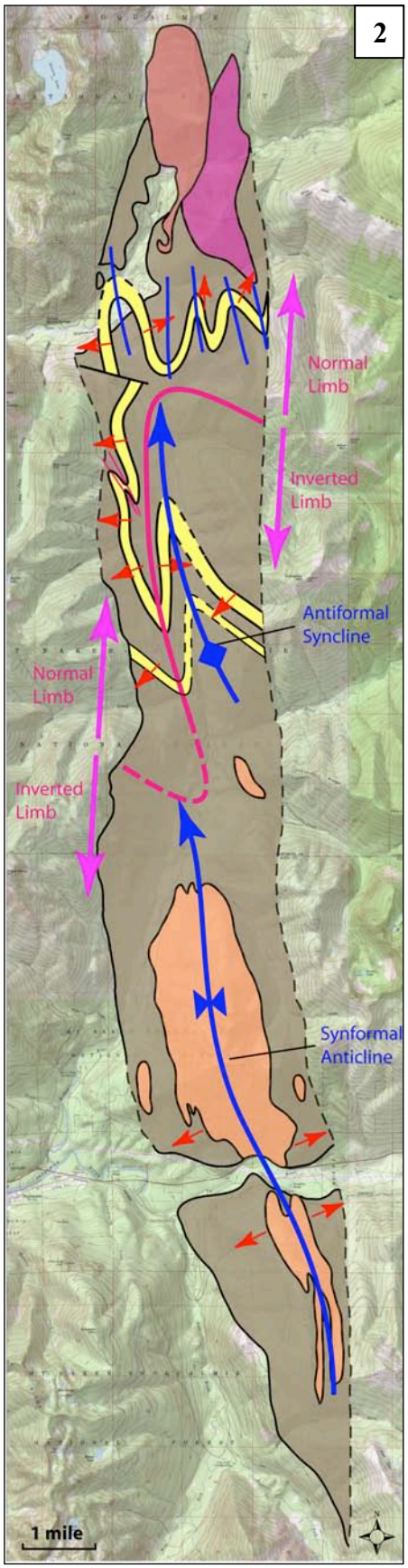
Sedimentary structures are remarkably well-preserved in the Tonga Formation, unlike in the neighboring metasediments to the east (Chiwaukum Schist). Recognizable depositional features include graded bedding, laminae, rip-up clasts, and flute casts, which allowed for the determination of younging directions throughout the unit. 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 northern and eastern domain) and related *synformal anticline* (southern and western domain). The overturned nature of the strata and the geometry of gently north-plunging folds imply upsection a pre-existing tight, recumbent anticline refolded into a co-axial (type III) fold interference pattern (Figure 2). 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 ("M1") rarely decipherable in the adjacent Chiwaukum Schist.

The co-axial, superposed folding in the Tonga Formation and the overall N-S arrangement of the component fold generations suggests a strong component of east-west shortening in the foreland of the Cascades core. Fold geometries account for the inverted metamorphic zonation as well as control the localization of plutons, which are also elongate parallel to the regional fold axes. The central and southern and 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 of each unit are also similar. Exposure of the Tonga Formation's bounding faults is limited, but the observed structural and metamorphic relationships suggest that a late, east-dipping reverse fault (Evergreen fault) placed the deeper, higher-grade Chiwaukum Schist structurally above the lower-grade Tonga Formation.

Figure 1. Map showing tectonic boundaries, intrusions, and metamorphic index mineral distributions in the Tonga Formation. Regional metamorphic gradient increases from southwest to northeast, as indicated by the blue arrow, from chlorite (green rectangles) to biotite (brown rectangles) to staurolite (yellow prisms) grade. Andalusite (white prisms) occurs only in pluton contact aureoles. Note the curvilinear shape of the metamorphic isograds, which mimics the observed fold interference pattern shown in Figure 2.

Figure 2. Map showing synformal anticline (southwest) and antiformal syncline (northeast) pair, plunging gently to the NNW, which dominates the structure of the Tonga Formation. Prominent meta-quartzite bed trace is shown in yellow. Younging directions are indicated by red arrows. Oldest generation fold axial trace is shown in pink; youngest generation fold axial traces are shown in blue. Synthesis of these observations with the metamorphic mineral gradient (Figure 1), which is inverted relative to the exposed fold system, reveals a co-axial, type III, fold interference pattern.


1
Goblin Creek Granodiorite (Tertiary)
Excelsior Ridge Tonalite (96.0 ± 0.4 ma)
Tonga Formation
STRAIGHT CREEK FAULT (Tertiary strike-slip displacement)
EVERGREEN FAULT (Reverse displacement)
D
U
Chiwaukum Schist and associated igneous intrusions
Beckler Peak Tonalite (92 ± 3 ma)
Andalusite
Staurolite
Biotite
Chlorite
1 mile


2
Normal Limb
Inverted Limb
Antiformal Syncline
Normal Limb
Inverted Limb
Synformal Anticline
1 mile