Corrugated architecture of the Okanagan Valley shear zone and the Shuswap metamorphic complex, Canadian Cordillera

Sarah R. Brown1,2,*, Graham D.M. Andrews1,3, and H. Daniel Gibson2

1DEPARTMENT OF GEOLOGICAL SCIENCES, CALIFORNIA STATE UNIVERSITY–BAKERSFIELD, 9001 STOCKDALE HIGHWAY, BAKERSFIELD, CALIFORNIA 93311, USA
2DEPARTMENT OF EARTH SCIENCE, SIMON FRASER UNIVERSITY, 8888 UNIVERSITY DRIVE, BURNABY, BRITISH COLUMBIA V5A 1S6, CANADA
3DEPARTMENT OF GEOLOGY AND GEOGRAPHY, WEST VIRGINIA UNIVERSITY, 98 BEECHURST AVENUE, MORGANTOWN, WEST VIRGINIA 26506, USA

ABSTRACT

The distribution of tectonic superstructure across the Shuswap metamorphic complex of southern British Columbia is explained by east-west–trending corrugations of the Okanagan Valley shear zone detachment. Geological mapping along the southern Okanagan Valley shear zone has identified 100-m-scale to kilometer-scale corrugations parallel to the extension direction, where synformal troughs hosting upper-plate units are juxtaposed between antiformal ridges of crystalline lower-plate rocks. Analysis of available structural data and published geological maps of the Okanagan Valley shear zone confirms the presence of ≤40-km-wavelength corrugations, which strongly influence the surface trace of the detachment system, forming spatially extensive salients and reentrants. The largest reentrant is a semicontinuous belt of late Paleozoic to Mesozoic upper-plate rocks that link stratigraphy on either side of the Shuswap metamorphic complex. Previously, these belts were considered by some to be autochthonous, implying minimal motion on the Okanagan Valley shear zone (≤12 km); conversely, our results suggest that they are allochthonous (with as much as 30–90 km displacement). Corrugations extend the Okanagan Valley shear zone much farther east than previously recognized and allow for hitherto separate gneiss domes and detachments to be reconstructed together to form a single, areally extensive Okanagan Valley shear zone across the Shuswap metamorphic complex. If this correlation is correct, the Okanagan Valley shear zone may have enveloped the entire Shuswap metamorphic complex as far east as the east-vergent Columbia River–Slocan Lake fault zones.

INTRODUCTION

Ductile shear zones are rarely planar across large areas (Candela et al., 2009). Nonplanar geometry is manifested by linear features normal to the strike of the mean plane and parallel to the direction of slip, e.g., slickenlines, mullions, and, at the largest scales, corrugations. Corrugations differ from slickenlines and mullions in that they are large enough (with wavelengths of hundreds of meters to tens of kilometers) to deform the entire shear zone and the rocks of the adjacent upper plate and lower plate. Corrugations are common in extensional shear zones and metamorphic core complexes in both continental and oceanic crust (Whitney et al., 2013), suggesting a genetic link between the formation of core complexes and corrugated detachments (Singleton, 2013). Corrugations have been recognized on detachments in the southwest United States (John, 1987; Spencer and Reynolds, 1991; Davis et al., 1993; Mancktelow and Palvis, 1994; Frost et al., 1996; Fowler and Calzia, 1999; Singleton, 2013), Baja California, Mexico (Seiler et al., 2010, 2011), western Norway (Johnston and Hacker, 2005), the Aegean Sea (Wawrzinz and Krohe, 1998), the Swiss Alps (Mancktelow and Palvis, 1994), Papua New Guinea (Spencer, 2010; Daczko et al., 2011), central Sulawesi (Spencer, 2010), the Himalaya (Murphy and Copeland, 2005; Spencer, 2010), the Mid-Atlantic Ridge (Tucholke et al., 1998), and the Philippine Sea (Harigane et al., 2008; Spencer and Ohara, 2013).

Corrugations are upright or steeply inclined, open, parallel folds of detachment shear zones (Fig. 1), typically with wavelengths of 200 m to 20 km and amplitudes of 30–2000 m. The fold axes of corrugations are characteristically parallel to the principal stretching lineation within the shear zone (Spencer and Reynolds, 1991). Some corrugations within core complexes in southwest Arizona can be followed for up to 40 km parallel to the extension direction (Spencer and Reynolds, 1991). Late-stage doming of the detachment surface causes corrugations to become doubly plunging and to produce a dome-and-basin structural topography (Fletcher et al., 1995).

Corrugations are typically recognized by map-scale features (Fig. 1), including: (1) sinuous detachment fault traces; (2) juxtaposed antiforms and synforms, which result in a convolute map trace of shear zone salients and reentrants, respectively; and (3) klippen of upper-plate rocks with spoon-shaped geometries isolated on top of the surrounding lower plate (Chauvet and Sérrane, 1994; Frost et al., 1996) and elongated parallel to the transport direction. The juxtaposition of alternating ridges of resistant lower-plate rocks with keels of recessive upper-plate rocks affects the topographic expression of the detachment surface so that structurally lower units are topographically higher.

Corrugations may form during the exhumation of core complexes, and some precede brittle deformation and cooling below the Curie temperature (Livaccari et al., 1995), whereas others form primarily in the brittle regime. The origins of corrugations (Singleton, 2013) include: (1) uniaxial (σz > σx = σy; e.g., Fletcher and Bartley, 1994) and triaxial strain (σx > σy > σz; Fig. 1; e.g., Fossen et al., 2013), resulting in horizontal shortening perpendicular to the extension direction; (2) synplacement warping of the surface by plutons or diapiric gneiss domes; and (3) rheological contrasts between upper- and lower-plate rocks. The importance of triaxial strain regimes and high viscosity contrasts (~600:1) has been demonstrated in experiments, especially under transtension (e.g., Grujic and Mancktelow, 1995; Venkat-Ramani and Tikoff, 2002; Le Pourhiet et al., 2012).
This paper describes synextensional corrugations of the Okanagan Valley shear zone, which forms part of the western boundary of the Shuswap metamorphic complex in the southern Canadian Cordillera (Fig. 2). We used field observations and analysis of geological maps to demonstrate how kilometer-scale corrugations influence the surface trace of the Okanagan Valley shear zone, and how they control the distributions of hanging-wall (upper-plate) and footwall (lower-plate) lithologies. We then applied this knowledge to examine competing models of the tectonostratigraphic architecture of rocks in the upper plate of the Shuswap metamorphic complex and to reconcile different estimates of crustal extension across the Okanagan Valley shear zone.

GEOLOGICAL SETTING

The Shuswap metamorphic complex is the largest metamorphic core complex in North America (Coney, 1980), and it underpins the southern Canadian Cordillera in British Columbia and adjacent parts of Washington State (Fig. 2; Armstrong, 1982; Parrish et al., 1988). The western margin of the Shuswap metamorphic complex was exhumed from midcrustal levels in the Eocene along a 450-km-long, west-dipping, low-angle detachment system (Johnson and Brown, 1996). Herein, we refer to the segment south of 51°N latitude as the Okanagan Valley shear zone, including a 1–2-km-thick distributed brittle to ductile shear zone (Fig. 1; Brown et al., 2012).

The lower plate is composed of Proterozoic to Mesozoic high-grade metamorphic rocks (sillimanite-bearing, amphibolite and granulite facies); peak metamorphism occurred at ca. 98–92 Ma, followed by exhumation during ca. 60–48 Ma (Brown et al., 2012). The upper plate consists of (1) greenschist- to amphibolite-facies Paleozoic and Mesozoic marine metasedimentary and metavolcanic rocks, and (2) nonmetamorphosed Eocene terrestrial sedimentary and volcanic rocks deposited in supra-detachment basins (McClaughry and Gaylord, 2005) and NNE-trending grabens (Suydam and Gaylord, 1997) on the upper plate. Paleozoic rocks belong to both the parautochthonous Kootenay terrane within the Omineca morphostratigraphic belt (Fig. 2, inset) and the accreted Quesnel terrane within the Intermontane belt (Okulitch, 1979; Gabrielse et al., 1991). Some Eocene rocks were deposited directly onto exhumed basement (Glombick et al., 1999). Late, high-angle normal faults disrupt the Okanagan Valley shear zone and locally juxtapose lower-plate rocks against the upper plate, including at the margins of the horst-like Kettle–Grand Forks and Valhall gneiss domes (Fig. 2).

Although the Okanagan Valley shear zone appears to be an important bounding structure along which significant exhumation of the Shuswap metamorphic complex was accommodated, the magnitude of extension across the Okanagan Valley shear zone is widely debated (e.g., Whitney et al., 2013). Estimates of the magnitude of extension across the shear zone vary from 0 to 90 km, without any along-strike correlation to latitude (Brown et al., 2012, and references therein). In some areas, for example, between 49°N and 49°30′N, at Kelowna, and north of 51°45′N (Fig. 2), extension is estimated at 30–90 km based on shear zone geometry, the depth from which lower-plate rocks were exhumed, and possible Eocene magmatic pinning points (e.g., Tempelman-Kluit and Parkinson, 1986; Bardoux, 1993; Johnson and Brown, 1996; Brown et al., 2012). In contrast, at Vernon and Osoyoos (Fig. 2), apparent extension is much less, and it is less clear that the Mesozoic upper plate is allochthonous (Okulitch, 1987; Thompson and Unterschutz, 2004; Glombick et al., 2006b). Glombick et al. (2006b) estimated horizontal extension across the Okanagan Valley shear zone at Vernon (50°15′N; Fig. 2) to be 0–12 km, based on the apparent lateral continuity of Paleozoic stratigraphy across the Shuswap metamorphic complex (Thompson et al., 2006). This is important because the Paleozoic rocks straddling the Shuswap metamorphic complex at 50°15′N are critical to understanding the pre–Okanagan Valley shear zone extent of Quesnella and Kootenay terrane stratigraphy and the late Paleozoic paleogeography and metallogeny of the southern Canadian Cordillera (Paradis et al., 2006; Thompson et al., 2006; Lemieux et al.,

![Figure 1. Schematic model of a corrugated detachment and core complex, adapted from Fossen (2010). Note the presence of upper-plate rocks preserved on the corrugated detachment surface as klippen and reentrants, and the curvilinear surface trace of the detachment.](https://pubs.geoscienceworld.org/gsa/lithosphere/article-pdf/8/4/412/3040331/412.pdf)
Evidence for corrugations includes outcrop-scale folds, the sinusous trace of the Okanagan Valley shear zone, and the map patterns of upper-plate (supradetachment basins and outliers) and lower-plate (inliers) lithologies in the southern Okanagan valley (Fig. 3; “grooves” of Tempelman-Kluit and Parkinson, 1986; Tempelman-Kluit, 1989).

Small-scale, open, upright, parallel folds, tens to hundreds of meters in wavelength and amplitude, are observed in outcrop within the Okanagan gneiss (Figs. 4A–4C), the principal lithological unit within the southern Okanagan Valley shear zone (Brown et al., 2012). The axial traces of these folds consistently trend toward 290°, parallel to the local stretching lineation (Fig. 3); poles to foliation measured across corrugations form symmetrical girdle distributions with interlimb angles greater than 120° (Fig. 3, inset). Smaller-scale folds are associated with thinner mechanical layering, such that 100-m-amplitude folds of the Okanagan gneiss contain parasitic 10-m- and 1-m-scale folds of the gneissic foliation (Figs. 4A and 4B). Upright folds refold earlier intrafolial folds within the Okanagan gneiss (Figs. 4A–4C), the principal lithological unit within the southern Okanagan Valley shear zone (Fig. 3, inset). Smaller-scale folds are associated with thinner mechanical layering, such that 100-m-amplitude folds of the Okanagan gneiss contain parasitic 10-m- and 1-m-scale folds of the gneissic foliation (Figs. 4A and 4B). Upright folds refold earlier intrafolial folds within the Okanagan gneiss (Figs. 4A–4C), but they are not associated with a penetrative axial plane cleavage. We interpret these upright, open, parallel folds to be displacement-parallel corrugations of the Okanagan Valley shear zone.

The 100-m- to kilometer-scale folds of the Okanagan Valley shear zone are exhibited in local- and regional-scale geological maps as highly sinusous lithological contacts, foliations, and traces of the Okanagan Valley shear zone (Figs. 1 and 3; Tempelman-Kluit and Parkinson, 1986; Tempelman-Kluit, 1989). The fault trace is strongly curvilinear immediately south and east of Okanagan Falls (OF; Fig. 3), where it bounds a prominent southeast-closing reentrant of Eocene rocks (Dusty Mac), and the Okanagan Valley shear zone must be absent or insignificant at 50°15′N, but present and significant (>30 km extension) to the north and south (Brown et al., 2012). It is unlikely that even a nascent midcrustal channel flow would have been restricted to the Vernon area only.

OUTCROP- TO MAP-SCALE ANALYSIS OF CORRUGATIONS ALONG THE OKANAGAN VALLEY SHEAR ZONE

The Okanagan Falls reentrant can be extrapolated to the southeast to the Venner Meadows klippen and west further into the White Lake Basin (Fig. 3), both of which are composed of similar Eocene rocks. Synformal structure is evident from mapping and exploratory drilling; at
Corrugated architecture of the Okanagan Valley shear zone, Canadian Cordillera | RESEARCH

Figure 3. Geological map and cross section of the southern Okanagan Valley shear zone (OVsz) modified from Church (1973) and Brown et al. (2012). Below: Stereonet projections of linear (stretching lineations [maximum eigenvector 01/115] and fold hinges [06/311]) and planar data (poles to foliation, Kamb contoured [minimum eigenvector 05/316]) from the Okanagan gneiss; masl—meters above sea level; OF—Okanagan Falls.
Dusty Mac and Venner Meadows, drilling penetrated the Okanagan Valley shear zone and the underlying Okanagan gneiss (Morin, 1989; Evans, 1990). The White Lake Basin is mapped as a supradetachment basin on top of the Okanagan Valley shear zone (Church, 1985; McClaughry and Gaylord, 2005; Brown et al., 2012), and we infer that these locations can be reconstructed as a single, WNW-trending, synformal corrugation, the White Lake–Venner Meadows reentrant (WLB–VM; Fig. 5). The White Lake–Venner Meadows reentrant is bounded to the north by a prominent west-closing salient that exposes a ca. 104 Ma hornblende-diorite pluton of the lower plate (Kbs; Fig. 3) as an inlier exposed through the Okanagan gneiss (Brown et al., 2012). Weakly developed foliation within the diorite is antiformal and parallel to the adjacent covering gneiss.

Prominent arrays of high-angle (dipping 50°–80°), N-, NNE-, and NE-trending fractures and normal faults are superimposed on the corrugated Okanagan gneiss and its plutonic inliers (Figs. 4D and 5; Ross, 1974; Eyal et al., 2006; Brown et al., 2012). The apparent extension direction responsible for the formation of these high-angle fractures and faults parallels the net displacement vector for the Okanagan Valley shear zone (toward the WNW). These are inferred to be late-stage brittle structures developed during and after exhumation of the lower plate of the Okanagan Valley shear zone as it approached the surface, and they may be related to faults that bound the overlying supradetachment basins.

Analysis of regional-scale geological maps of immediately adjacent sections of the Okanagan Valley shear zone reveals a similar pattern of corrugations. To the north, Okanagan Mountain (Fig. 2) is a prominent, heavily fractured salient where a lower-plate pluton is exposed through the Okanagan gneiss. The Okanagan Mountain salient (Fig. 5) is bounded north and south by reentrants dominated by Eocene supradetachment basins at Kelowna (Bardoux, 1993; Bardoux and Mareschal, 1994; Okulitch, 2013) and Summerland, respectively. To the south, within the U.S. portion of the Okanagan Valley shear zone, the Okanogan Dome (Fig. 5) is a large salient and corrugated gneiss dome where doubly plunging sub-domes of paragneiss alternate with synforms of structurally higher orthogneiss (Kruckenber et al., 2008). The Okanogan Dome is truncated to the east by the N-trending Eocene Republic graben and is heavily fractured by the same array of N- and NE-trending fractures and normal faults as the Okanagan gneiss. WNW-trending corrugations are also described in the far northern Okanagan Valley shear zone (Johnson, 1994) and within the Thor-Odin and Kettle–Grand Forks gneiss domes (Fig. 2; Cubley and Pattison, 2012).

At the regional scale, the Okanagan Mountain and Okanogan Dome salients are separated by a laterally extensive belt of semicontinuous Paleozoic marine metasedimentary and metavolcanic upper-plate rocks of the Osoyoos-Greenwood reentrant between Osoyoos and Greenwood, British Columbia, at ~49°N (Fig. 5; Okulitch, 1987; Massey, 2006; Massey and Duffy, 2008). It is partly buried by the Eocene Toroda Creek graben and associated sedimentary and volcanic rocks (Suydam and Gaylord, 1997), and it is truncated to the east by the Kettle–Grand Forks gneiss dome. The reentrant extends 20 km west of Osoyoos across the previously mapped Okanagan Valley shear zone in the Okanagan Valley north to Keremeos (Fig. 5; Okulitch, 1973). The Paleozoic succession is composed of marine metasedimentary and metavolcanic rocks of the Kobau and Anarchist Groups (Okulitch, 1973), and the ophiolitic Knob Hill complex (Massey, 2006); all have uncertain affinity and are variably assigned to the allochthonous Okanagan or Quesnel terranes. The Knob Hill complex is repeated in a series of pre-Jurassic, north-dipping, south-vergent thrusts sheets south of Greenwood (“G” in Fig. 5; Fyles, 1990; Massey, 2006), forming a broad, open synform about a NNW-trending axis. Lineations on shear surfaces within and between the thrust sheets trend ENE–WNW (i.e., broadly parallel to the present strike of the thrust planes); the shear
Corrugated architecture of the Okanagan Valley shear zone, Canadian Cordillera

Figure 5. Schematic geological map of the distribution of upper-plate and lower-plate rocks in the Shuswap metamorphic complex, corrugations, and our new interpretation of the trace of the Okanagan Valley shear zone. Abbreviations are as in Figure 2; WLB-VM—White Lake Basin–Vernor Meadows. Figure is adapted from Okulitch (1987) and Kruckenberg et al. (2008).

sense is not recorded (Fyles, 1990). Most thrusts in this part of the Canadian Cordillera typically strike SSE and dip westward, corresponding to repeated east-directed shortening throughout the late Paleozoic and Mesozoic as Panthalassan terranes accreted to Laurentia (Dickinson, 2004; Colpron et al., 2007). We interpret the north-dipping Greenwood thrusts as having been folded during Eocene extension about an ESE–WNW axis, parallel to the original pre-Jurassic shortening direction.

We interpret this belt to be a large-scale reentrant of the Okanagan Valley shear zone hanging wall, based on (1) the broad synformal nature of the Paleozoic lithostratigraphy; (2) its presence between lower-plate highs dominated by gneiss-crested salients; and (3) the presence of north-dipping,Upper Paleozoic to Triassic thrusts. If this interpretation is correct, some of the lithostratigraphic complexity within the reentrant may be due to hitherto unrecognized dismemberment during stretching of the upper plate (e.g., Fig. 1).

A second, larger belt of Paleozoic and Mesozoic marine metasedimentary and metavolcanic rocks juxtaposed against high-grade basement straddles the Shuswap metamorphic complex between Vernon and Fauquier (Fig. 5) at ~50°15′N: the Vernon-Fauquier reentrant. The belt is ~40 km wide and over 150 km long, and it extends across both the Okanagan Valley shear zone and Shuswap metamorphic complex, where it is disrupted by numerous NNE-trending normal faults. It is a broad, WNW-trending, synformal structure (Carr, 1995) that includes 10-km-scale, upright antiforms and synforms (e.g., Chase antiform—Okulitch, 1984; Vernon antiform—Glombick et al., 2006a) and the south-dipping, top-to-the-N Pinnacles thrust (Fig. 5). Okulitch (1984) interpreted the southern margin of the belt as a compressional shear zone within the underlying Shuswap metamorphic complex, but everywhere the contacts are ambiguous because of complex small-scale deformation, metamorphism, and often very poor exposure.

We interpret this belt to be a Shuswap metamorphic complex–spanning reentrant, based on (1) the broad, WNW-trending (i.e., parallel to extension across the Okanagan Valley shear zone) synformal geometry; (2) the presence of kilometer-scale upright parasitic folds; and (3) the presence of mutually divergent compressional shear zones. If this interpretation is correct, many, if not all, of the high-angle normal faults that disrupt the reentrant may root into the underlying detachment surface.

The Upper Devonian Silver Creek Formation can be traced continuously through the reentrant and across the Shuswap metamorphic complex, providing a definitive stratigraphic correlation between the Kootenay arc to the east and the Eagle Bay assemblage to the west on either side of the Shuswap metamorphic complex (Kraft, 2013), and across the southern Omineca belt (Fig. 2, inset; Fig. 5). This correlation cannot be made other than in the reentrant and was used by Glombick et al. (1999, 2006b) to support the interpretation that the Okanagan Valley shear zone is absent or insignificant at Vernon; however, this interpretation contrasts with the many studies of the Okanagan Valley shear zone to the north and south of 50°15′N, where estimates of significant extension (~30–90 km) have been made (e.g., Tempelman-Kluit and Parkinson, 1986; Bardoux, 1993; Johnson and Brown, 1996; Brown et al., 2012). The identification of synextensional, displacement-parallel corrugations within the Shuswap metamorphic complex allows for this to not be a zero-sum problem. If our corrugation model is correct, then the Okanagan Valley shear zone passes under the Vernon-Fauquier reentrant and is not exposed at Vernon other than where it bounds the Aberdeen Gneiss (Kalamalka shear zone; Glombick et al., 2006a) around the Oyama Lake salient (Fig. 5). Instead, the surface trace of the Okanagan Valley shear zone is the margin of the Vernon-Fauquier reentrant.

Combined, these observations suggest the presence of WNW-trending corrugations all along the Okanagan Valley shear zone and the southern
and central Shuswap metamorphic complex, and they allow constraint of the maximum wavelength to \(~40\) km and the maximum amplitude to \(2–3\) km based on the present relief and inferred thickness of the Okanagan Valley shear zone.

**DISCUSSION**

Meter- to kilometer-scale elongated antiforms and synforms within the Okanagan Valley shear zone and adjacent Shuswap metamorphic complex have hitherto been interpreted as the result of a late-stage, N–S compressional folding event (e.g., “Phase 2”—Preto, 1970; “Phase 4”—Ryan, 1973; “Phase 5”—Ross, 1974, 1981; Ross and Christie, 1979; “D4”—Cubley and Pattison, 2012). However, the N–S–directed shortening must be synextensional and of early Eocene age, because it folded the then-active Okanagan Valley shear zone (53–48 Ma; Brown et al., 2012), and the folds themselves are offset by nonfolded, high-angle, brittle normal faults (Figs. 4D and 5; e.g., Eyal et al., 2006), similar to those bounding the Toroda Creek (51–48 Ma; Suydam and Gaylord, 1997) and the Kettle–Grand Forks gneiss dome (ca. 51 Ma; Cubley and Pattison, 2012). The upright folds are crosscut by nonfolded N- and NNE-trending, alkaline dikes that intrude the Okanagan Valley shear zone, and both upper- and lower-plate lithologies (48–42 Ma—Ross, 1974; ca. 48–46 Ma—Parrish et al., 1988; Bardoux, 1993; 54–49 Ma—Holder et al., 1990; ca. 48 Ma—Adams et al., 2005). Although invoked often, no geodynamic model explains a phase of early Eocene, N–S–directed shortening independent of top-to-the-W extension along the Okanagan Valley shear zone. Moreover, there is no evidence of an Eocene (i.e., late) N–S shortening event elsewhere in the southern Canadian Cordillera or adjacent parts of Washington State; the E–W–trending Yakima fold-and-thrust belt in southern Washington State is a Neogene structure (Campbell, 1989). Postdetachment buckling has been documented in the Himalayan South Tibetan detachment (e.g., Godin et al., 2006; Kellett and Grujic, 2012), but there shortening is perpendicular to the detachment displacement direction (i.e., the buckle folds are parallel to the strike of the detachment); in the Okanagan Valley shear zone, the corrugations are parallel to displacement.

We infer from the presence of laterally extensive, WNW-trending, upright synforms and antiforms that the Okanagan Valley shear zone and the adjacent upper- and lower-plate lithologies are corrugated (Fig. 5). The wavelengths and amplitudes of corrugations are controlled by the thicknesses of layering in the host lithologies (i.e., buckle folds) and are observed from \(1\) m scale to tens-of-kilometers scale. These corrugations are identified throughout the Okanagan Valley shear zone (e.g., Okanagan Mountain, Okanagan Dome; Fig. 2), and the adjacent Shuswap
metamorphic complex (e.g., Kettle–Grand Forks and Valhalla gneiss domes; Fig. 2). The geologic relationships and limited range of ages (ca. 54–48 Ma) imply strongly that the corrugations formed during synextension and as part of a continuous and evolving process of extension along a low-angle, ductile detachment (the Okanagan Valley shear zone) that evolved to be dissected by high-angle, brittle normal faults. The most plausible explanation for the formation of corrugations is, therefore, horizontal shortening perpendicular to extension (i.e., in the σ1 direction) along the contemporaneous Okanagan Valley ductile shear zone detachment (Fig. 2; e.g., Singleton, 2013). As the Shuswap metamorphic complex was gradually exhumed along the Okanagan Valley shear zone, it passed through the brittle-ductile transition diachronously (50–48 Ma), allowing for brittle fractures and faults to progressively overprint slightly older ductile shear fabrics and corrugations (e.g., John, 1987; Frost et al., 1996; Eyal et al., 2006). The southern Canadian Cordillera experienced the onset of trans-tensional deformation during the early Eocene (ca. 52 Ma; Price, 1979; Price et al., 1981; Price and Carmichael, 1986; Harms and Price, 1992; Struik, 1993; Andronicus et al., 2003) following plate reorganization at the North America–Farallon margin (Lonsdale, 1988; Monger and Price, 2002). Activity on the Okanagan Valley shear zone (ca. 54–48 Ma) was contemporaneous with the phase of transtensional deformation and supports other studies where corrugation formation has been associated with transtensional strain (e.g., Bartley et al., 1990; Chauvet and Sérrane, 1994; Venkat-Ramani and Tikoff, 2002).

Is the Shuswap Metamorphic Complex Bounded by a Single Disrupted Detachment?

The Shuswap metamorphic complex is distinctive for its size and in having several discrete gneiss domes (Fig. 2), but there are few studies that have attempted to integrate them in a single model. Parrish et al. (1988) explained each gneiss dome as a Proterozoic basement–cored nappe thrust eastward in the Cretaceous–Paleocene and then reversed and extended in the Eocene. This is, however, inconsistent with the following: (1) The only deep-rooted shear zones imaged by Lithoprobe seismic experiments are the Shuswap metamorphic complex–bounding Okanagan Valley shear zone and Slocan Lake fault (Carr, 1995), and (2) there is no evidence for Proterozoic basement coring the Okanagan, Kettle–Grand Forks, and/or Valhalla gneiss domes (e.g., Brown et al., 2012). Models of midcrustal channel flow (e.g., Brown and Gibson, 2006; Gervais and Brown, 2011) adopt the Okanagan Valley shear zone as the upper margin of the channel throughout the Cretaceous–Paleocene midcrustal flow phase, satisfying the Lithoprobe data; however, they do not attempt to explain the presence of the other faults, shear zones, and gneiss domes.

Our identification of corrugations and spatially extensive reentrants extends the footprint of the Okanagan Valley shear zone much further east than previously thought (Fig. 5) and implies structural connections between detachments and gneiss domes that have hitherto been considered as discrete (Fig. 6). For example, the Osoyoos-Greenwood reentrant extends eastward toward the western margin of the Kettle–Grand Forks gneiss dome along the Granby fault (Preto, 1970; Parrish et al., 1988; Carr and Parkinson, 1989; Laberge and Patterson, 2007; Cubley et al., 2013), implying that the Okanagan Valley shear zone and the Granby fault are part of the same W-directed extensional system (Fig. 6B). The Okanagan Valley shear zone and the Granby fault share many common characteristics. The Granby fault (1) is a top-down-to-the-W, low-angle detachment (Carr and Parkinson, 1989; Laberge and Patterson, 2007; Cubley et al., 2013) that juxtaposes green-schist- to lower-amphibolite-facies Paleozoic and Mesozoic upperplate rocks against sillimanite-grade, upper-amphibolite- to granulite-facies crystalline basement with Paleocene to early Eocene peak metamorphic ages (59–50 Ma), and (2) has rapid Eocene exhumation ages (55–51 Ma). However, the Granby fault is interpreted to be largely brittle in nature and only responsible for the latest, low-temperature exhumation of the Grand Forks complex. The mechanism for its more significant Eocene (52–50 Ma) high-temperature decompression of at least 2.5 kbar remains elusive (Cubley and Patterson, 2012; Cubley et al., 2013), but our model suggests that the Okanagan Valley shear zone may have been the exhuming structure that was progressively overprinted by the W-directed brittle deformation of the Granby fault. On the basis of these data, we propose that the Granby fault is the easternmost brittle expression of the Okanagan Valley shear zone along the margin of the Osoyoos-Greenwood reentrant (Fig. 6B).

The Vernon-Fauquier reentrant extends as far east (~200 km) as the western margin of the Valhalla gneiss dome (Fig. 2, inset; Carr et al., 1987; Simony and Carr, 1997), where the kinematics of extension reverse, accommodated by broadly coeval top-to-the-E shear zones that include the Valkyr shear zone and the Columbia River fault farther north (e.g., Parrish et al., 1988; Johnson and Brown, 1996). Thus, we tentatively suggest that the Valkyr shear zone marks the eastern termination of the Okanagan Valley shear zone along the eastern margin of the Vernon-Fauquier reentrant (Fig. 6B). If this is correct, activity on the Okanagan Valley shear zone was probably coeval with, or only slightly older than, the Valkyr–Columbia River fault system, and the maximum total displacement as measured along the axes of antiformal corrugations would be up to 150 km.

The presence of discrete gneiss domes within the Shuswap metamorphic complex is explained by their position in the footwall of E-thrashing, high-angle normal faults (Kettle River fault, ca. 51 Ma—Cubley and Patterson, 2012; Slocan Lake fault, ca. 54–47 Ma—Carr et al., 1987). These faults have similar geometry to those disrupting the Okanagan Valley shear zone in the Okanagan Valley (Eyal et al., 2006; Brown et al., 2012). In both cases, the amount of vertical motion on brittle high-angle faults is poorly constrained and probably ≤3 km (e.g., Cubley and Patterson, 2012); however, this is more than sufficient to disrupt the upper plate, which would otherwise cover the gneiss domes (cf. Carr, 1995). The high-angle normal faults likely also explain the relatively steep, 30°–35° westerly dips of the Valkyr shear zone and the Granby fault by footwall uplift and horizontal axis rotation. The progressive cutting off of earlier low-angle ductile shear zones by high-angle brittle normal faults (e.g., the Slocan Lake fault) and the development of horsts and grabens that dismembered the primary detachment surface and its lower- and upper-plate architecture are characteristic of the later stages of large-scale exhumation of a buoyant core complex (e.g., Wernicke and Axen, 1988). The presence of discrete gneiss domes in the Shuswap metamorphic complex does not, therefore, preclude their formation as part of a single, much larger detachment system (the Okanagan Valley shear zone), and instead likely reflects the effects of only the latest stages of crustal extension.

**CONCLUSIONS**

Field observations and the interpretation of published geological maps have identified corrugations that deform the Okanagan Valley shear zone and the juxtaposed upper and lower (Shuswap metamorphic complex) plates. Corrugations explain the undulating trace of the Okanagan Valley shear zone and allow for structural linkages between klippen of similar-aged lithologies. Two 40-km-wide synforms form reentrants of upper-plate lithologies that extend far across the Shuswap metamorphic complex. The recognition of large-scale corrugations provides a permissible explanation for the differences determined for the magnitude of extension of the Okanagan Valley shear zone, allows for models of Shuswap metamorphic complex—spanning Paleozoic–Mesozoic stratigraphy to coexist with the presence of a major Shuswap metamorphic complex–bounding detachment, and explains the
