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Evidence for reactivation of Eocene joints and pre-Eocene foliation planes in the Okanagan core-complex, British Columbia, Canada

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Abstract

We studied the brittle deformational history of the Okanagan metamorphic core complex, and its hanging wall carapace, in the Canadian Cordillera, in southern British Columbia by an extensive structural investigation at mesoscopic scale. The deformational history reveals that the transition from ductile to brittle deformation occurred during the early-middle Eocene and was associated with cooling due to tectonic and/or extensive erosional unroofing of the Okanagan portion of the Sushwap metamorphic core complex. Our study is based on mesostructures because in this region macro-structures are rarely exposed, although their existence can be deduced from field relationships. Measured fault systems that are either perpendicular to bedding, or which were sub-vertical to inferred paleohorizontal and with very small dispersion of strike are interpreted as faulted joints, i.e. joints that were reactivated by subsequent shear due to a relative change in stress orientation. The faulted joints are similar to observed open-mode I fracture system that exhibit no evidence for subsequent reactivation. In this study we suggest that fault sets characterized by consistent attitude with a very small dispersion can be interpreted as faulted joints using only their stereographic projection pattern relative to the inferred paleohorizontal. The first brittle deformation was a pervasive open-mode fracturing in the hanging wall carapace of both Eocene sedimentary and volcanic rocks and Eocene and older igneous rocks characterized by a N-S trend, with a very small dispersion, which formed either perpendicular to bedding or was sub-vertical with respect to the inferred paleohorizontal. These fractures are of similar trend to a middle Eocene dyke swarm in part of the study area and beyond. The Okanagan core complex metamorphic rocks exhibit brittle fractures that are interpreted as metamorphic foliation planes which were reactivated as faults in response to the same E-W extension recorded by the joints and dykes. Subsequent shear deformation, associated with normal dip-slip motion along the open-mode fractures, is explained by either regional tilting of the area in the presence of a similar stress orientation accompanying continued extension, or as the result of a minor reorientation of the stress field. Later deformations, suggested by strike-slip and reverse motions indicate significant changes in the stress field orientation.

Keywords: Reactivation; Mesostructures; Joints; Faults; Striations; Sense of motion

1. Introduction

Reactivation of pre-existing planar structural fabrics has important implications for both the stress/strain history of geological structures and the bulk transmissivity of rock bodies and regions. In addition, knowledge of fracture reactivation is essential for economic and environmental considerations, e.g. hydrogeological and petroleum geology characteristics as well as for a risk assessment for high-level radioactive waste disposal and geotechnical hazards.

Both ductile and brittle structures develop in metamorphic core complexes. However the role of brittle deformation following the core complex exhumation is usually a less

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well-described aspect of core complex evolution. In this paper we study brittle reactivation phenomena of the Okanagan portion of the Sushwap metamorphic core complex (OCC) in the Canadian Cordillera, southern British Columbia (Fig. 1). For this goal we use a large mesostructural data set, measured in crystalline rocks of the OCC and in its unmetamorphosed cover comprised of Eocene and younger sedimentary and volcanic rocks. We performed this study both to characterize the reactivation itself and as an initial step toward a kinematic analysis and interpretation of the brittle deformational history of the Okanagan metamorphic core complex.

The use of the terms fractures, joints and faults in this study follows that of Zhao and Johnson (1992) and Peacock (2001). Joints are mode I fractures (Pollard and Aydin, 1988) that

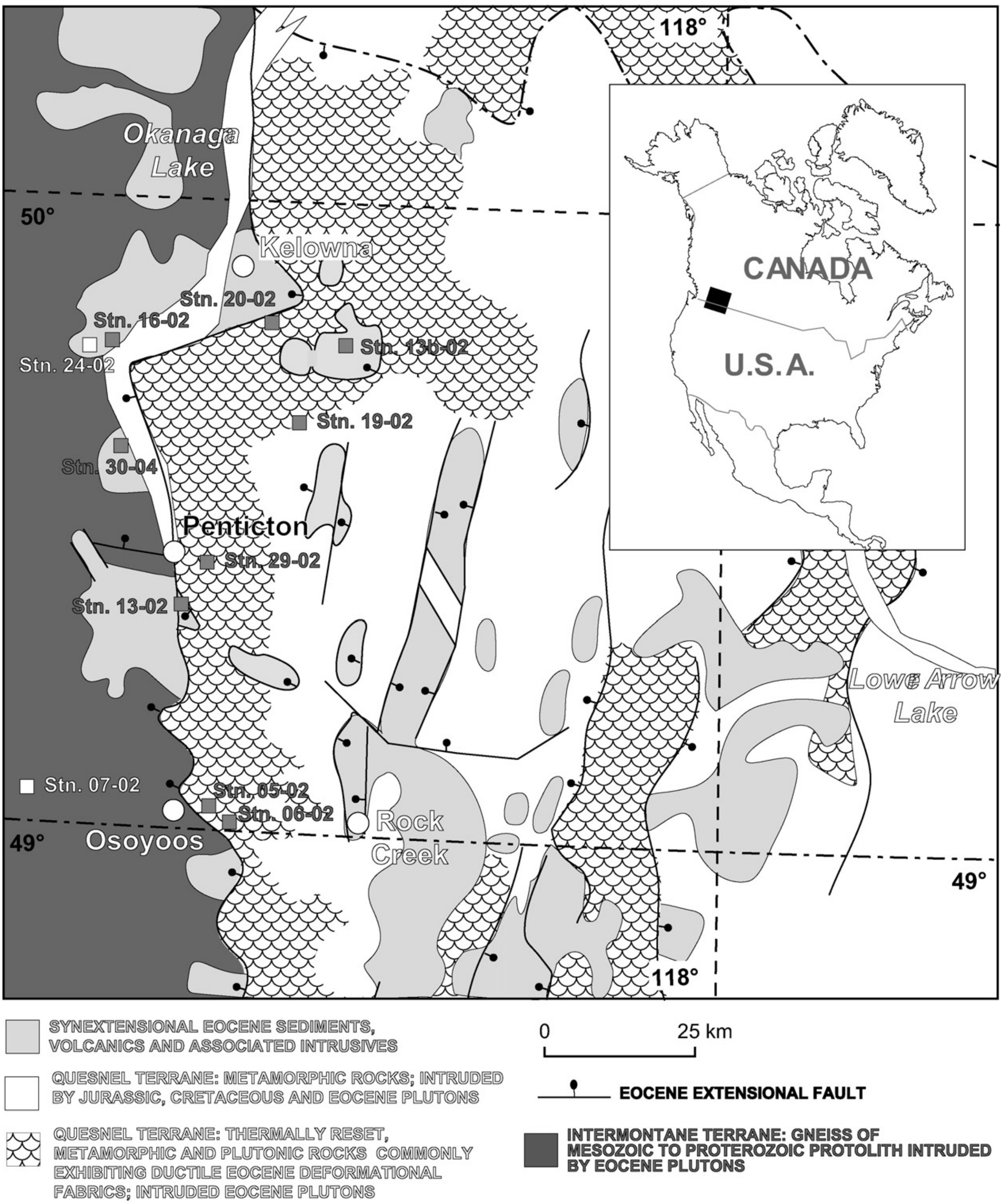

Fig. 1. Location map of the Okanagan Core complex, indicating the location of station described and analyzed in this study, relative to the major rock units and structures. The map shows the setting of the study region relative to the boundaries of allocthonous terranes accreted to North America during the Cordilleran orogeny (following Wheeler and McFeely, 1991).

formed normal to σ3; and faults are fractures that underwent wall-parallel displacement either by mode II or mode III (Lawn and Wilshaw, 1975). Many studies discuss the reactivation of joints as faults due to later shearing along the joints (Cruikshank et al., 1991; Zhao and Johnson, 1992; Martel, 1990) or faults that subsequently opened up like joints due to a later mode I deformation (Peacock, 2001). Segall and Pollard (1983) present evidence for jointing that occurred by extension normal to the joint planes. Based on sheared mineral fillings they suggest a subsequent strike-slip displacement along the pre-existing joints. Wilkins et al. (2001) conclude that parallel joints in layered sandstone were reactivated, and changed to faulted joints, due to a change in their attitude relative to the stress field. Here, we show that both joints, developed during the Eocene regional extension that formed the OCC, and planar deformational fabrics, such as the metamorphic foliation planes formed during terrane accretion, were reactivated subsequently, in some cases, several times. Possible conditions for this reactivation are changes in rheology of metamorphic rocks that enabled brittle deformation along foliation planes or changes in the geometrical relationships between the pre-existing planes and the regional stress field. Reactivation is widespread in the OCC, occurring in a variety of lithologies and exploiting two different types of pre-existing planes, probably because motion on pre-existing planes is energetically more efficient than the formation of new joints or faults.

Faults and joints are the result of brittle deformation. New faults (''neoformed faults''; Wilkins et al., 2001) are formed due to shear along the future fault plane and start with growing and coalescence of flaws and micro-cracks to larger faults (e.g. Lockner et al., 1992; Reches and Lockner, 1994). Faults are commonly associated with breccia zone or gouge, structures such as striations, slickolites and mineralization in pull-aparts, and fault-zones consisting of sub-parallel and very closely spaced fault planes (Ramsay and Huber, 1987; Twiss and Moores, 1992, Eyal and Reches, 1983; Angelier, 1979) with indications of shearing. New regional fault sets are formed in response to remote stresses, commonly attributed to plate interactions (Zoback, 1992; Zoback and Zoback, 1980, 1991), and the strike of faults formed under one stress field is scattered around the maximum principal stress direction (σ1). Sometimes, conjugate sets are formed in which σ1 is found in the plane of the acute bisector of the conjugate faults. However, a remote stress field may result in both the formation of new faults, and at the same time the reactivation of pre-existing faults or other discontinuity planes whose orientation is appropriate for slip.

Joints, as well as other extensional structures such as dykes and veins, are formed normal to the least principal stress σ3 and, consequently, their plane contains the two other principal stresses, σ1 and σ2. Therefore, joint patterns may serve as good paleostress indicators (Bahat and Grossmann, 1988; Delaney et al., 1986; Engelder and Geiser, 1980; Eyal et al., 2001; Hancock, 1991; Hancock and Engelder, 1989; Nakamura, 1977). Because joints are formed as a pure opening-mode fracturing no evidence for shear or displacement is found along them. Commonly, individual mode I fractures belonging to a joint set are sub-parallel, sub-vertical or perpendicular to bedding, and in layered rocks their spacing is determined by the thickness of the mechanical layer, especially the first generation ''systematic joints'' (Gross, 1993; Narr, 1991; Narr and Suppe, 1991). Stress field reorientation changes the geometrical relationships among the principal stresses and the pre-existing planes, which, therefore may result in a reactivation of pre-existing joints.

2. Tectonic setting

The Canadian Cordillera formed in response to complicated plate interactions that include the Mesozoic subduction of ocean basins, the accretion of allocthonous terranes onto the western margin of the North American craton, transtensional extension within the contractional orogen and a variety of syn-, post- and epeirogenic magmatic events (Monger, 1967; Wheeler and McFeely, 1991; Price, 1994). The study area, in the vicinity of Lake Okanagan (Fig. 1), is part of the Shuswap complex, a Paleogene and younger metamorphic core complex (Armstrong, 1982). In addition, it forms the boundary between Intermontane Terrane, which was separated from North America by the Cache Creek Ocean until Jurassic time, and Quesnel Terrane (Quesnellia), which was located on the western margin of Mesozoic North America.

Following the accretion of Intermontane Terrane onto Quesnel Terrane, the structurally thickened orogenic belt was intruded by a Jurassic and Early Cretaceous synkinematic plutonic suite. The deformation migrated eastward onto and incorporating the Paleozoic passive margin succession of North America, while shedding and cannibalizing its own foreland basin (Coney and Harms, 1984; Brown et al., 1986; Price, 1986, 1994). Structural thickening and burial were followed by high-temperature metamorphism and partial crustal melting (Carr, 1992; Nyman et al., 1995; Sevigny et al., 1989; Vanderhaeghe and Teyssier, 1997). In the hinterland, the deeper, high-grade metamorphic orogenic root was exhumed during Paleogene time with extension and crustal attenuation that resulted in uplifted metamorphic core complexes (Ewing, 1981; Carr, 1991; Struik, 1993; Crowley, 1997a,b; Johnston, 1998; Parkinson, 1991, 1992; Parrish, 1995; Parrish and Armstrong, 1987; Parrish and Wheeler, 1983), including the Shuswap complex (Vanderhaeghe et al., 1999, 2003). Core complex formation occurred at the same time as variations in the relative plate motions between North America and the Pacific Basin (Engebretson et al., 1985; Stock and Molnar, 1988; Price, 1994) and was accompanied by an epeirogenic magmatic suite (Adams et al., 2005).

The formation of the Shuswap metamorphic core complex can be summarized by a two-stage deformational and cooling history. Ductile deformation accompanied cooling from temperatures of 700–300 °C during the interval ~56–48 Ma, which was succeeded by brittle deformation accompanying cooling from ~350–150 °C during the interval ~48–45 Ma (Lorencak et al., 2001; Vanderhaeghe et al., 1999, 2003). The second stage, characterized by brittle deformation, was accompanied by basic magmatism, including both north-south trending dykes (Monger, 1967; Sevigny and Thériault, 2003; Adams et al., 2005) and volcanic eruptions (Church, 1973; Ewing, 1981).

The Eocene succession in the Okanagan and Kettle River regions (Church, 1973, 1985; Tempelman-Kluit and Parkinson, 1986; Bardoux and Irving, 1989; Templeman-Kluit, 1989; Wingate and Irving, 1994; Rittenhouse-Mitchell, 1997; Matthews, 1997; McClaughry and Gaylord, 2005) consists of Marron Group and Marama Formation (∼48.4–53.1 Ma) which occur as structural and erosional remnants of an originally much thicker (Ross, 1974,1981), and more extensive succession that was extruded and deposited coincident with the second stage of core complex cooling. This succession is also deformed within the hanging-wall carapaces of the metamorphic core complexes. Structural and metamorphic features of the Lake Okanagan and Greenwood faults include: large-scale grooves on the detachment plane that preserve fragments of the hanging-wall Eocene stratigraphic succession on the footwall block (Tempelman-Kluit and Parkinson, 1986; Templeman-Kluit, 1989), K-Ar and vitrinite reflectance thermal history indicators (Ross, 1974, 1981) and a north-south trending dyke swarm which where probable feeders to the Eocene volcanic flows (Monger, 1967). These features are consistent with both, major extension in a generally east-west direction, and with the regional models of the Shuswap Complex development (Lorencak et al., 2001; Vanderhaeghe et al., 1999, 2003).

3. Method

3.1. Station distribution and number of measurements at each station

We measured small-scale faults with striae, joints, and fold axes in 58 stations which are widely distributed throughout the hanging-wall and footwall successions of the OCC in the Penticton 1:250,000 NTS Map Sheet (118°40′ to 120°00′ N. longitude and 049°00′ to 50°00′ W. latitude). A "station" is an outcrop of a few tens of meters long, usually along a roadcut, where exposures are best and most accessible, where at least a few tens fractures could be measured. At each station we measured the orientation of 30–130 structures identifiable at the mesoscopic scale.

3.2. Structures measured

The majority of the measured structures are faults and joints, whereas only several small scale folds could be found. In each station we measured all fractures, with no preference of specific orientation. Among the faults we measured both those with only striations, as well as those on which the sense of motion could be determined, mainly from mineralization in small pull-aparts, slickolites or relation between striation-plunge and stratigraphic separation. Both joints and faults are observed on a variety of scales from a few cm to tens of meters. We distinguish reactivated joints from newly formed faults among the faults measured. Our stations are measured in both the middle Eocene succession and igneous and metamorphic rocks of the Okanagan core complex. We infer that the observed structures formed not earlier than the onset of the brittle deformation that was characteristic of the second cooling stage of Shuswap core complex (Vanderhaeghe et al., 1999,2003). This stage is simultaneous with Marron Group extrusion and the intrusion of associated dykes (Monger, 1967; Adams et al., 2005). However, since some of our stations occur in rocks that never reached temperatures greater than150 °C (Ross, 1973, 1974), we infer that some of the observed structures formed at temperatures lower than those estimated by previous work (Vanderhaeghe and Teyssier, 1997; Vanderhaeghe et al., 2003).

A common feature of joints pattern at all scales (from a few centimeters to tens of meters) in this study, as well as joints described previously (e.g. Engelder and Geiser, 1980) is their sub-parallel trend with little dispersion, as viewed on stereographic projections (Fig. 2). We observe multiple closely spaced fault planes that are typically sub-parallel and commonly parallel to joints, which have no indications for subsequent shear. Generally, joint sets are sub-vertical unless they underwent later tilting accompanying Eocene extension. In station 16, a outcrop of Eocene Marron Group volcanic and volcaniclastic rocks, in the hanging-wall complex of the Okanagan detachment (Fig. 3A), we observe that many of the fracture planes belong to a large joint set. These planes are sub-vertical, consistently parallel and closely spaced.

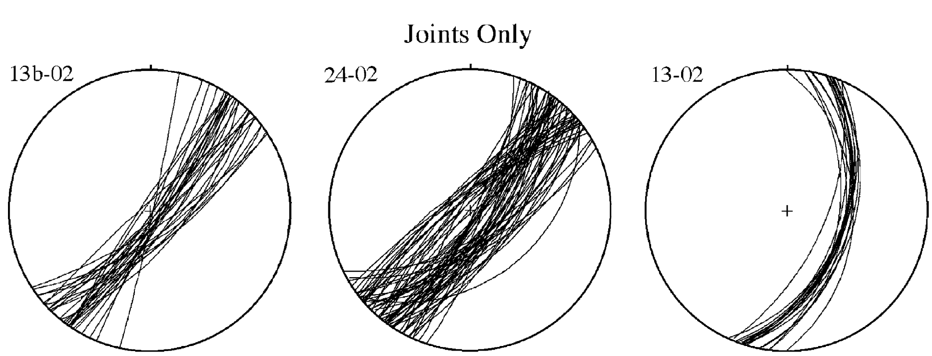

Fig. 2. Stereograms of joint sets without any evidence for later reactivation from stations 13b-02 (Eocene Springbrook Formation conglomerates and sandstones); 24-02 (Eocene Marron Group Volcanics); 13-02 (Eocene White Lake Formation sediments).

Fig. 3. Field photographs of reactivated planar structures of the Okanagan Core Complex. (A) Sub-vertical regional joints and faulted joints developed in Eocene Marron Group volcanic rocks in the hanging wall complex of the Okanagan detachment (Station 16-02). (B) Sub-horizontal mega-striae developed following a reactivated plane of the dominant regional joint set in Eocene Marron Group volcanics (Station 16-02). (C) Sub-horizontal striae developed on a reactivated plane of one of the local joint surfaces in Eocene Marron Group volcanics (Station 24-02, 12 cm long camera case for scale). (D) Striated calcite mineralization in a pull-apart developed along irregularities of a faulted joint surface in Eocene Marron Group volcanics (Station 16-02). (E) Shallowly dipping gneissosity and reactivated gneissic planes developed in the footwall Monashee gneiss of the Okanagan core complex (Station 29-02). Monashee gneiss has a Proterozoic and Paleozoic protolith that was thermally overprinted during the Eocene extension (Ross, 1973, 1974). (F) A series of striated calcite pull-aparts developed on a large faulted joint surface in Eocene Marron Group volcanics (Station 16-02). (G) A series of striated quartz pull-aparts developed in reactivated metamorphic foliation planes (Station 07-02). (H) Linear inter-penetrating pressure-solution slickolites fabric developed along irregularities on a faulted joint surface in Eocene Marron Group volcanics (Station 16-02). (I) Two generations of striae on calcite mineralization on a faulted joint surface (Station 16-02). (J) Two generation of striae on faulted joint surface (Station 30-04).

They cross the entire 20 m high outcrop and are parallel to other planes, of identical orientation, that are regarded as faulted joints because they underwent later shear as indicated by striations (Fig. 3B and C) and striations on calcite mineralization in small pull-aparts along some of the planes (Fig. 2D). Hence, we assume that these faults, as well as faults in other stations, of similar characteristics, that have a ‘‘joint-like’’ pattern in stereographic projections developed as a joint set that was later reactivated as faulted joints. At station 16, both the joints and the faulted joints are closely spaced relative to their height. Further, the joints and faulted joints measured in thinly bedded sediments of White Lake formation at station 13 are small and closely spaced. Both observations are consistent with the predictions of joint spacing theory as a function of the thickness of the mechanical layering (Gross, 1993; Narr and Suppe, 1991) and intensity of strain (e.g. Becker and Gross, 1996; Gross et al., 1997). Other subparallel joints, such as those at station 13b, are developed in 5–30 cm long plutonic clast pebbles embedded in less competent sedimentary matrix. Similar structures were described elsewhere by Eidelman and Reches (1992).

Consistently and regardless of lithology and structural position in the OCC, at each station there is at least one group of sub-parallel faults, which either was observed in the field to be similar to joints, or the pattern of which has the stereogram appearance of a joint-set (Figs. 4 and 5). Many of the joints and

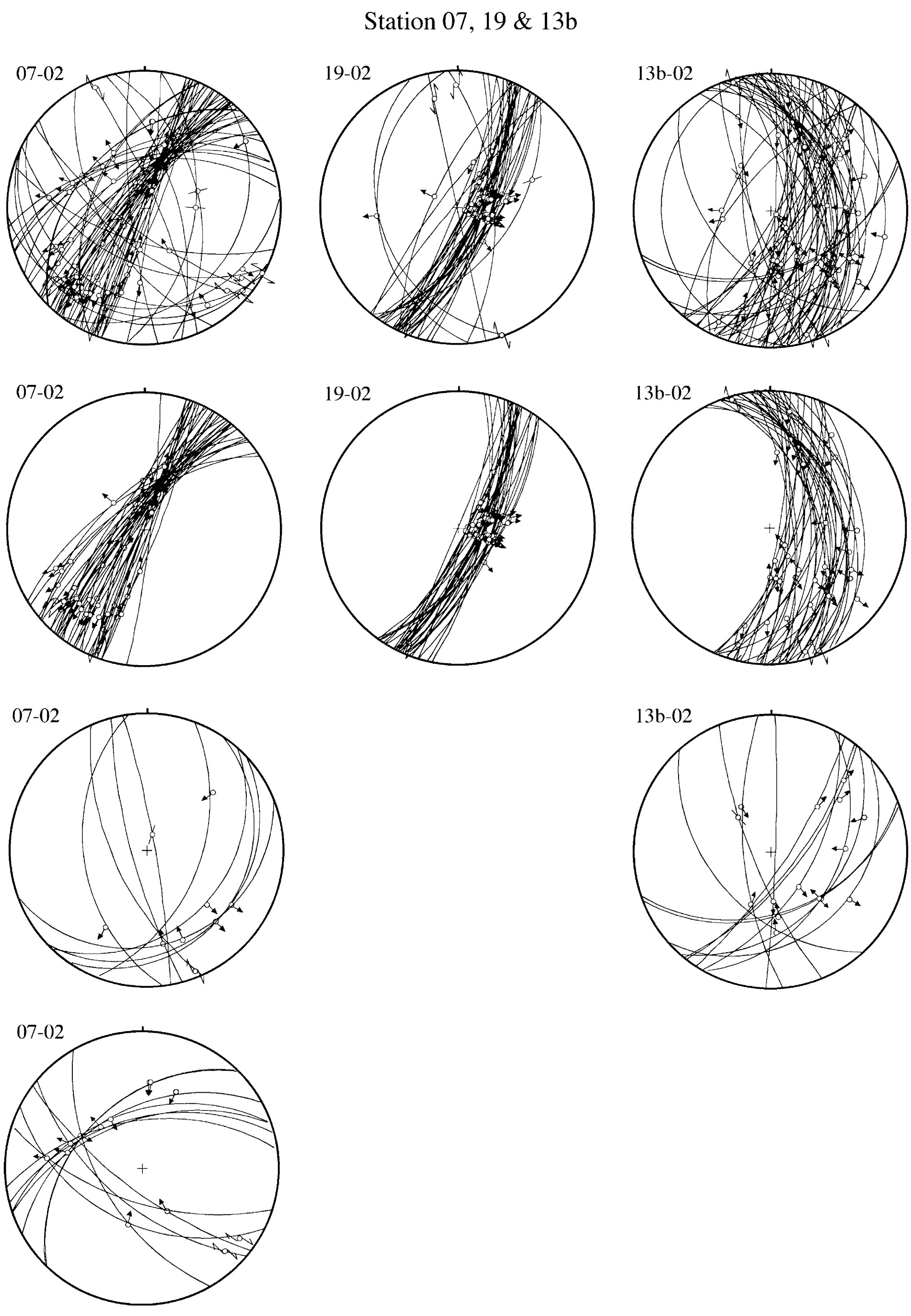

Fig. 4. Stereograms of structural elements for stations 07-02 (Kruger Syenite), 19-02 (Late Jurassic and Early Cretaceous Okanagan batholith), and 13b-02 (Eocene Springbrook Formation conglomerate), displaying, from top to bottom: all measured data; reactivated joints from the regional joint set; and both the N-S or NNE-SSW conjugate fault sets and the E-W conjugate fault sets which both formed when the joints were reactivated. Arrows indicate striations trend and upper block movement direction.

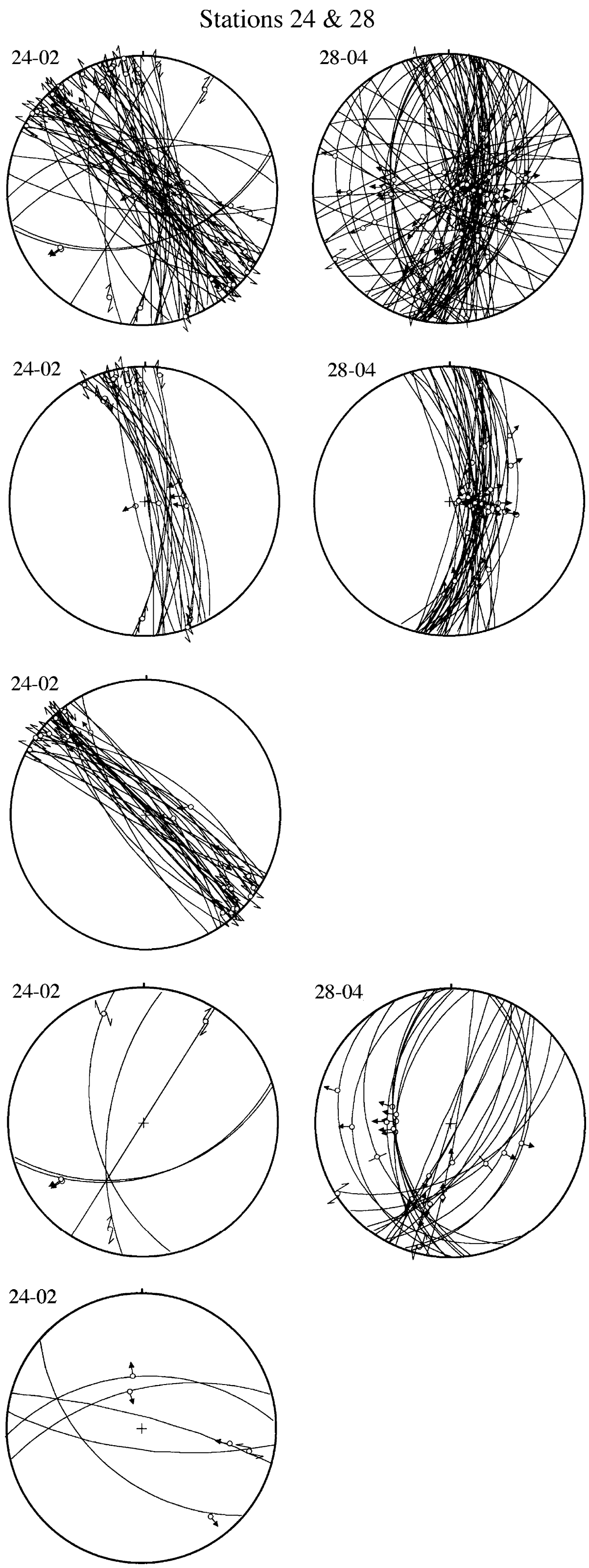

Fig. 5. Stereograms of structural elements of widely separated stations 24-02 and 28-04, both in Eocene Marron Group volcanics. The figures display, from top to bottom: all measured data; reactivated joints from the regional joint set; reactivated joints from the local joint set for station 24-02; and both the N-S or NNE-SSW conjugate fault sets and the E-W conjugate fault sets which formed when the joints were reactivated, as was observed for station 07-02 in Fig. 4.

faulted joints belong to a regional N-S to NNE-SSW trending set, however, other planar structures form local sets with distinct different orientation (e.g. Fig. 5). Therefore, where the orientation pattern of a group of faults is similar to the characteristic pattern of a joint group, which does not exhibit any later shear displacement, we assume that this group of faults was originally formed as a joint set.

Newly formed faults can be identified by breccia and/or shear zone along the fault plane, by scattered strike trends or by a conjugate pattern. These characteristics are absent in the group of subvertical fractures with similar strike and evidence for displacement, and therefore strengthen our interpretation that the arrays of subparallel fractures are faulted joints.

Similarly, in the data collected from metamorphic rocks one or two fault groups parallel the metamorphic foliation planes were observed both in the field (Fig. 3E) and in stereographic projections (Fig. 6). The foliation planes, schistosity and gneissosity, were formed in earlier stages by ductile deformation in the deep crust. Subsequently these planes were reactivated by brittle deformation at shallow depth much like the faulted joints in the Eocene succession, as described above. The rheological change in the metamorphic rocks from ductile to brittle accompanied exhumation or tectonic unroofing associated with formation of the OCC.

3.3. Retilt of data

Our orientation data from tilted Eocene sedimentary and volcanic successions were restored to horizontal along the strike of the bedding. Commonly, tilting resulted in rotated planes becoming closer to vertical. In station 07-02, we retilted the Jurassic Kruger Syenite, above the Lake Okanagan detachment, to the Eocene paleohorizontal using regional paleomagnetic data from overlying Eocene strata (Bardoux and Irving, 1989; Wingate and Irving, 1994). The retilting using the paleomagnetic analysis resulted in a sub-vertical and consistent trending group of faults whose pattern is identical, in orientation and character, to the joint set observed at other stations (Fig. 7A). At station 20-02, where faults were measured in metamorphic rocks lying immediately below the Lake Okanagan detachment, we used the local dip of Eocene volcanics immediately above the detachment, nearby, to retilt the faults to paleohorizontal. Subsequent to this retilting, the inclination of the metamorphic foliation planes is sub-horizontal (Fig. 7B), similar to the observed relationships at other stations in metamorphic rocks (e.g. stations 5 and 6).

Striations alone are good evidence for shear along any plane, but they do not permit the determination of the true sense of motion and the amount of displacement. However, the existence of striations enables us to differentiate among pure opening-mode fractures and faults or faulted-joints (Wilkins et al., 2001). The true sense of motion along the faults can be determined by: (a) striated mineralization (calcite or quartz, depending on the parent rock), in pull-aparts developed along irregularities of a fault surface (Fig. 3D, F, and G); (b) slickolites — linear inter-penetrating "teeth" and compatible cavities, formed by pressure-solution along irregularities on a fault

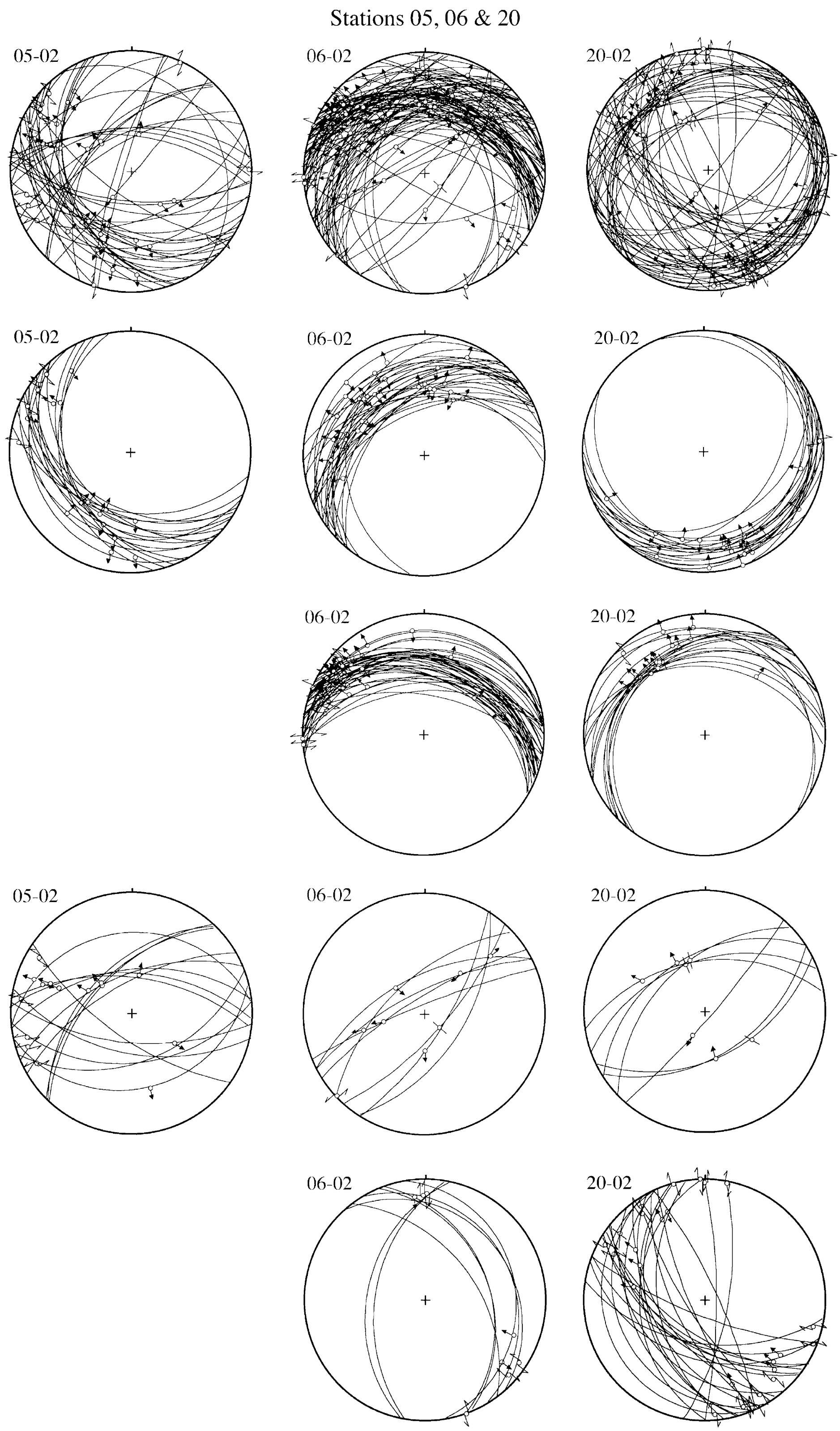

Fig. 6. Stereograms of structural elements of stations 05-02 and 06-02 (both Middle Jurassic Nelson Cordilleran synkinematic plutonic suite) and 20-02 (Okanagan Gneiss, which is composed of older protolith that were thermally reset during the Eocene). Each figure displays, from top to bottom: all measured data; reactivated joints from two shallowly dipping regional foliation sets (probably due to folding of the shallowly dipping metamorphic foliation); both the N-S or NNE-SSW conjugate fault sets and the E-W conjugate fault sets both of which formed when the metamorphic foliation was reactivated in the Eocene, like the joint sets.

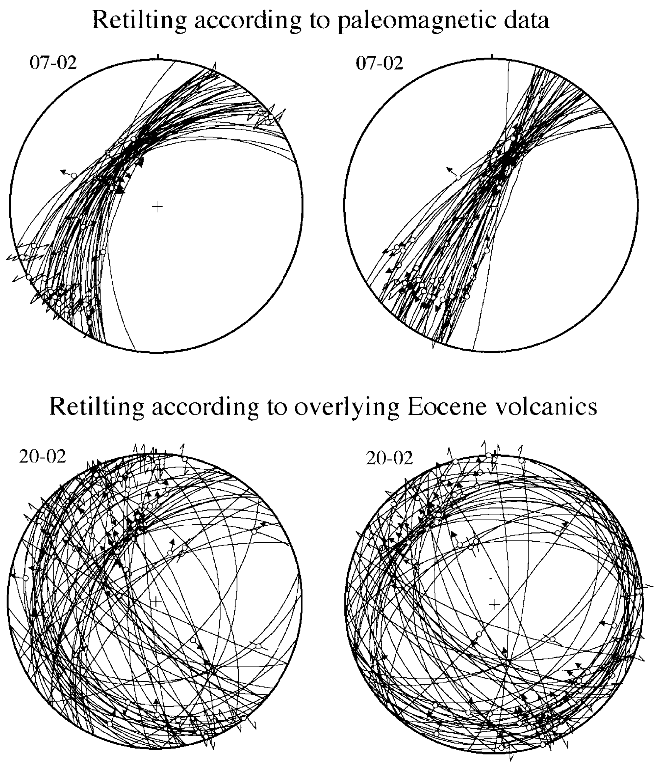

Fig. 7. Stereograms of faulted joints in both (A) Jurassic Kruger Syenite (07-02) lying above the Lake Okanagan detachment. The faulted joints are illustrated (left) in-situ and (right) after retilting to Eocene paleohorizontal using regional paleomagnetic data from Eocene rocks (Bardoux and Irving, 1989; Wingate and Irving, 1994) and (B) reactivated metamorphic foliation planes lying immediately below the Lake Okanagan detachment at Station 20-02. The faulted foliation is illustrated (left) in-situ and (right) after retilting to Eocene paleohorizontal using the local dip of Eocene volcanics immediately above the detachment, at the same location.

(Fig. 3H); and (c) known geometric relations between uplifted block, fault-dip and attitude of striations. Determination of the true sense of motion along many faults enables the calculation of the stress tensors for every set of faults at a station.

3.4. Evidence for reactivation

In addition to the brittle reactivation of both joints and metamorphic foliation as faults we often find evidence that the faults themselves exhibit several distinct reactivation phases. In this study we use the following criteria to identify reactivation of pre-existing planes: (a) two, or more, directions of striation formed on the same fault plane (Fig. 3I–J), where each attitude of striae was formed in response to a different stress orientation. Our data reveals that, in most cases, the horizontal or sub-horizontal striations, inferred to represent strike-slip motions, are superimposed on the dip-slip or highly inclined striations that are inferred to represent extension and normal faulting (Fig. 3I–J). Knowledge of the true sense of motion is required for the determination of whether the dip-slip motion was normal or reverse and the strike-slip left-lateral or right-lateral. (b) The existence of striations formed by brittle deformation on earlier deformation planes, such as foliation, schistosity or mylonitic planes. Metamorphic ductile fabrics were formed while the rocks were deeply buried and under high temperatures and pressures. Hence, brittle deformation along metamorphic planes is an indication of a profound change in the rheology of the rocks accompanying changes in pressure and temperature. (c) Evidence for shear along planes that originally formed as a joint set. As described above, we infer that a group of faults that has a stereogram pattern like a joint set, developed originally as a joint set. The sub-vertical joint set was formed under extension, whereas the subsequent shear along the joint planes indicates a relative change between the orientations of the planes and the principal stress directions.

4. Discussion

The structures that we observed and analyzed comprise part of the brittle deformation of the Shuswap core complex and its sedimentary cover that began about 50 Ma (Church, 1973, 1985; Vanderhaeghe et al., 2003; Adams et al., 2005). Our study is restricted to the brittle deformation of all rock units in both the crystalline core complex and the volcanic and sedimentary cover succession. The inferred timing of the brittle deformation in the OCC is as follows: Eocene extension and brittle deformation post-date the last ductile deformation that occurred in the form of a sub-horizontal mylonite (Fig. 3E). The mylonitization was probably associated with the early stages of the Okanagan detachment and the first deformation and cooling phase in the Shuswap complex (Vanderhaeghe et al., 2003) and the re-setting of K/Ar radiometric clocks (Ross, 1973, 1974). The estimated displacement of the hanging-wall along this detachment is up to 80–100 km (Tempelman-Kluit and Parkinson, 1986) toward the WNW. The intrusion of the mafic dykes into the crystalline rocks of the OCC, which feed Marron Group volcanics indicates a fundamental change in rheological conditions associated with the extension and brittle deformation conditions at approximately 50 Ma. The dominant N-S to NNE-SSW trend of these dykes (Monger, 1967; Adams et al., 2005) parallels the main sets of the observed joints and faulted joint set that we measured in the OCC. The change to a brittle rheology in the crystalline rocks of the OCC resulted from cooling due to tectonic unroofing, associated with either tectonic motion on the extensional detachment or major erosional exhumation of the core complex (Vanderhaeghe et al., 2003).

4.1. New criterion for faulted joints

In the present study we propose an additional criterion for reactivation of joints as faults. Previous criteria suggesting that fault planes originated as an open-mode fractures include: a set of fault planes which is perpendicular to bedding, confined to a mechanical layer, and with a regular spacing of the faults (Wilkins et al., 2001); a fault which is part of a set of fractures that also includes open-mode joints (Segall and Pollard, 1983). This study reveals that joint sets without later reactivation, joint sets including several reactivated joints and fault sets in the OCC have the same stereogram pattern, including consistent orientation and very small dispersion, and sub-vertical inclination. Hence the stereogram pattern of a fault set that is similar to that of open-mode fractures can serve as a criterion that they originated as joint set that later experienced reactivation.

4.2. First brittle deformation in the OCC

Faults trending N-S to NNE were found in almost all stations indicating their widespread distribution in the study area. These faults were developed in sedimentary units and homogeneous plutonic rocks but rarely in foliated metamorphic rocks. Their abundance indicates a regional pervasive deformation due to a regional E-W extension. Commonly the stereogram pattern of the N-S fault sets is identical to that of open-mode fractures, suggesting that the initial brittle deformation in the OCC was a pervasive open-mode joint formation. The parallel trend of the N-S to NNE fractures and Eocene dykes (Monger, 1967) indicate that the pervasive deformation is part of the first, extensional deformation, that followed the ductile-brittle transition. The behavior of metamorphic rocks is significantly different because planar structures, such as foliation and schistosity, already existed since the Jurassic-Cretaceous ductile deformation.

4.3. Reactivation

There are several indications for joint or fault reactivation in the OCC. The first criterion is the reactivation of open-mode fractures into faulted joints. Studying the striation trends measured on pre-existing joints reveals that, in a few cases (e.g. station 19-02, Fig. 4), only dip-slip motion is found. However, in most cases multiple displacements are observed (e.g. stations 24-02 and 07-02, Figs. 4, 5) in which the dip-slip motion predates the strike-slip one as evidenced by remnants of dip-slip striations between the horizontal ones. Therefore, we infer that the WNW-ESE extension that formed the open-mode joint sets extended to the time in which dip-slip motion occurred. The change from open-mode to shear deformation can be explained either by a small change in the orientation of the principal stresses or by steady orientation of the principal stress and tilting of the jointed area due to the displacement along the uneven detachment plane. Evidence for the second possibility is found in station 07-02 (Fig. 7) where restoration of the data to Eocene paleohorizontal using regional paleomagnetic data from Eocene rocks (Bardoux and Irving, 1989; Wingate and Irving, 1994) restores an inclined set of faulted joint to a sub-vertical attitude.

In many cases the reactivation indicates strike-slip motion (e.g. station 24-02, 07-02, 05-02, Figs. 4, 5, 6). Strike-slip motion along pre-existing open-mode I fractures requires a significant change of the stress field. A kinematic analysis of the OCC based on meso-structures (will be discussed in another manuscript) reveals several different stress field orientations, among them, N-S and E-W shortening, and N-S and E-W extensions associated with sub-vertical $\sigma1$.

Evidence for the new orientations of stress field is the two conjugate sets, one suggesting E-W extension and one N-S extension. These conjugate sets show that a few new faults were formed despite the fact that most deformation occurred by the reactivation of pre-existing planes.

5. Conclusions

- An extensive structural study at the mesoscopic scale in the Okanagan core complex and overlying succession indicates few stages of brittle deformation including reactivation of pre-existing planar deformational fabric. The sense of motion along reactivated pre-existing planes represents the response of the evolving Okanagan core complex to changes in rheology and stress history due to unroofing and variations in geometrical relation between plans and stress orientations.
- Brittle deformation in the Okanagan core complex started with the development of pervasive subvertical joints and reactivation of the pre-existing shallow ductile planar fabric. Subvertical joints were formed in plutonic rocks of the core complex, and the overlying volcanic rocks and sediments, while the shallow planes were formed following the shallow pre-existing fabric in the metamorphic rocks.
- Regional joint sets in some stations were clearly formed prior to the regional tilt as evidenced either by inclined bedding or paleomagnetic data.
- The trends of different joint sets are consistent with the trends of map scale extension faults in Lake Okanagan core-complex and its carapace.
- The second brittle deformation phase is indicated by striations that resulted primarily in the reactivation of previously formed joint and other planes by dip-slip and/or strike-slip displacements.
- The third brittle deformation phase resulted in strike-slip displacements and new conjugate fault planes oriented in accordance with the sense of displacement on the reactivated planes.
- The ductile displacement along the detachment, the dyke intrusion and subsequent brittle jointing and the reactivation by normal faulting occurred all under a principal E-W to ESE-WNW extension. The later deformational events are dominated by N-S to NNE-SSW, and E-W compression directions.

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