Geospatial Structural Analysis of the Terrace Area, West-Central British Columbia (NTS 103I/08, 09, 10, 16)

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KEYWORDS: Stikinia, Terrace, structure, geospatial analysis, down-plunge projection

INTRODUCTION

In this study, geographic information system (GIS)–based geospatial analysis is used to assist in the interpretation of a large database of georeferenced structural measurements, in order to reconstruct the structural history of the Terrace area in west-central British Columbia (Figure 1). This area has been the target of a multiyear regional geological mapping and mineral potential evaluation project conducted by the BC Geological Survey from 2005 through 2008.

Field structural measurements were taken in NTS 1:50 000 scale map areas 103I/08, 09, 10 and 16 during the course of regional mapping in the summers of 2005 through 2007. In this study, the structural data were sorted into domains in a GIS program and then plotted by structure type using stereonets. One of the key findings of this study is a series of folds with northeast-trending hinge lines. This implies a northwest-southeast compressional event. Northeasterly fabrics associated with this event affect latest Cretaceous granitoid plutons along the Skeena River west of the map area (Heah, 1991). They are cut by Eocene intrusions. There are no structures yet documented regionally that correspond to a compressional event of this orientation and age; therefore, its cause and extent are somewhat enigmatic.

Northeasterly-trending folds occur in both the footwall and hangingwall of the Skeena River fault zone, a postulated northeasterly-vergent thrust fault that places Paleozoic and younger strata southeast of the Skeena River on top of Jurassic and younger, more metamorphosed strata to the northwest. The Skeena River fault zone was possibly reactivated as a top-to-the-northeast detachment during early stages of Eocene extension. The later stages of this extensional regime are recorded by steep, north-northwest-striking normal faults. The local expression of this high-angle brittle regime is the Kitsumkalum-Kitimat graben, which underlies a broad valley in which the towns of Terrace and Kitimat are situated (Figure 1). The graben is bounded to the east along Kitsumkalum Lake by a well-exposed normal fault. Brittle and ductile deformation are recorded along the extent of this fault, showing down-to-the-southwest motion.

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OVERVIEW OF GEOLOGICAL UNITS

The Terrace area is located near the western margin of Stikinia (as defined by Colpron et al., 2007), along the eastern margin of the Coast Plutonic Complex and the southern margin of the Bowser Lake Group. Stikinia is the largest intermontane terrane, formed dominantly by island-arc volcanism, along with clastic and calcareous sedimentation, through Paleozoic and into Mesozoic time (Nelson et al., 2006). The Coast Plutonic Complex is a belt of granitoid and metamorphic rocks formed by continental-arc magmatism along western North America from mid-Jurassic to Eocene time. The Bowser Lake Group is a sequence of Late Jurassic–Early Cretaceous siliciclastic sedimentary rocks deposited in a broad successor basin, the Bowser Basin, in central Stikinia.

This section presents an overview of the rock units in the Terrace area, whose distribution is shown in Figure 2. More detailed descriptions can be found in Nelson et al. (2006), Nelson and Kennedy (2007) and Nelson et al. (2008).

Stratified Units

ZYMOETZ GROUP

The oldest rocks in the region belong to the Permian and older Zymoetz Group. It consists of a lower volcaniclastic-dominated unit, the Mount Attree volcanic complex, overlain by a limestone unit that has been correlated with the Permian Ambition Formation, as defined by Gunning et al. (1994). The Mount Attree volcanic complex comprises dark green andesite flows, tuff and volcanic breccia, along with minor siliceous and calcareous sedimentary strata. A U-Pb zircon date of ca. 285 Ma for tuff within the upper extent of this unit by Gareau et al. (1997a) is interpreted as the age of deposition. The Mt. Attree volcanic complex is metamorphosed in greenschist and lower amphibolite facies.

Where unmetamorphosed, the Ambition Formation limestone consists of thinly to thickly bedded fossiliferous limestone. Bedding-controlled hematite and silica replacement has led to the development of highly fossiliferous, pink beds that are exceptionally well preserved (Figure 3). In other areas, it consists of coarsely recrystallized marble. An Early Permian age was reported by Duffell and Souther (1964) on the basis of macrofossil assemblages.

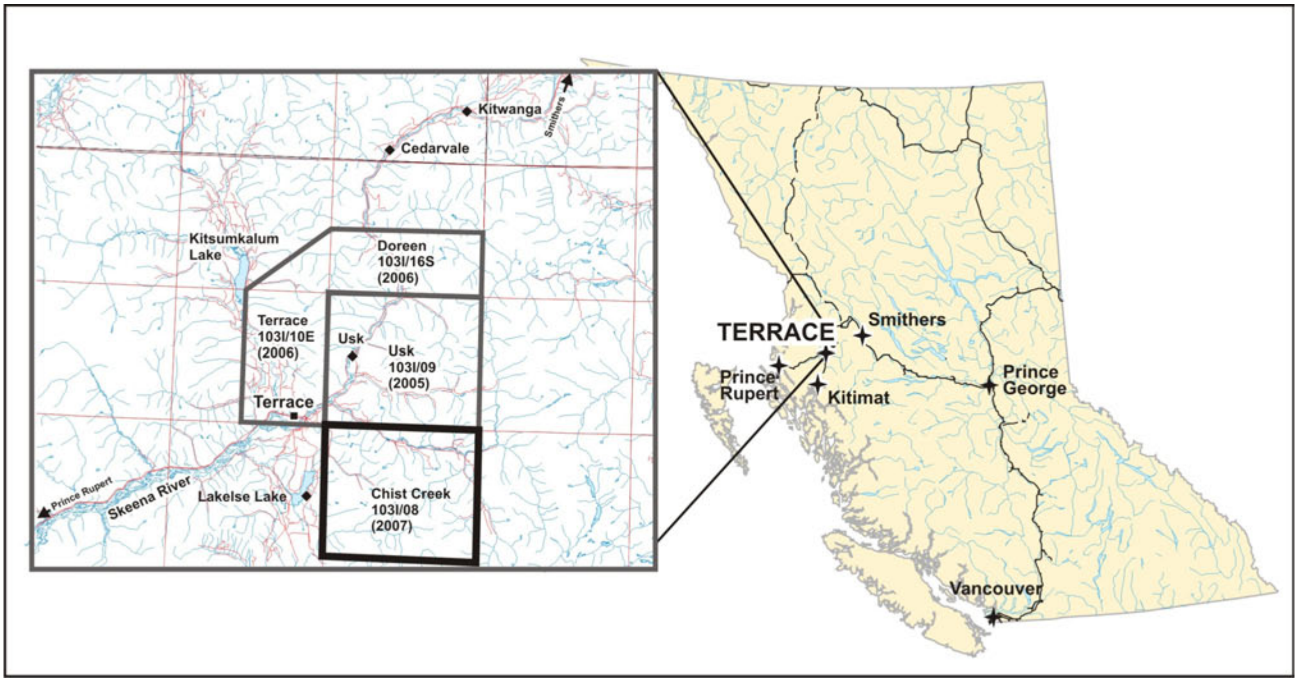


Figure 1: Location of the Terrace map area within British Columbia. The mapping completed in the summers of 2005, 2006 and 2007 is outlined.

TELKWA FORMATION

The Early Jurassic Telkwa Formation is the lowest unit of the Hazelton Group. It unconformably overlies the Zymoetz Group. It consists of dominantly andesitic and dacitic subaerial volcanic units with minor associated, volcanic-derived sedimentary beds. Where thinly bedded units were observed within the lower Telkwa, they are parallel to bedding in the underlying limestone. The base of the Telkwa Formation is a disconformity because, in some areas, the Telkwa is depositionally on top of the Mount Attree volcanic complex and the limestone is absent. In most areas, this relationship is obscured by the irregular topography and abrupt facies changes inherent in volcanic provinces and high-energy sedimentary environments. The basal unit of the Telkwa Formation is a highly variable polymictic conglomerate, containing clasts derived from the underlying Paleozoic strata as well as from Telkwa volcanic rocks. Above this, the lower Telkwa consists dominantly of volcaniclastic units; andesite breccia and crystal lithic lapilli tuff are common constituents. The upper Telkwa is dominated by amygdaloidal andesite and dacite flows, with lesser volcaniclastic and sedimentary components. Regionally, faunal assemblages of sedimentary layers within the Telkwa Formation indicate a Sinemurian (Early Jurassic) age (Tipper and Richards, 1976). The Telkwa Formation has undergone regional zeolite to lowest greenschist facies metamorphism.

KITSELAS FACIES

The Kitselas facies is a dominantly felsic volcanic unit restricted to the footwall of the Skeena River fault system. Its bounding faults are poorly exposed, obscured both by Eocene intrusions and by recent fluvial deposits along the Skeena River. The unit is dominated by well-bedded volcaniclastic rhyolite that shows eutaxitic, strongly welded textures in places. Andesite flows in the Kitselas resemble those in the Telkwa. The Kitselas has been interpreted as a local felsic centre within the Telkwa Formation. A U-Pb zircon date of ca. 195 Ma is documented as the age of deposition, reinforcing the interpretation of the Kitselas facies as a metamorphosed equivalent to the Telkwa Formation (Gareau et al., 1997a). The Kitselas rocks have been metamorphosed in the greenschist to lower amphibolite facies.

SMITHERS FORMATION

The Middle Jurassic Smithers Formation paraconformably overlies the upper Telkwa and is composed of uniform, thinly bedded, tuffaceous greywacke. Macrofossils and trace fossils are common. An Aalenian (Middle Jurassic) age has been established on the basis of macrofossil assemblages (G. Woodsworth and H. Tipper, unpublished data, 1985, as a pers comm from J. Nelson, 2008).

TROY RIDGE FACIES

The Smithers Formation is overlain by the ‘pyjama beds’, which derive their name from their striped appearance. This unit is composed of thinly bedded black chert and siliceous argillite, commonly with interbeds of white to pink siliceous tuff. These strata are correlative with the Troy Ridge facies in the Iskut region, which has been dated as Bajocian (Middle Jurassic; K. Simpson and V. McNicoll, unpublished data, 1994, as a pers comm from J. Nelson, 2008). Together with the underlying Smithers Formation, the pyjama beds form a distinctive marker unit between the volcanic Telkwa Formation and the Bowser Lake Group, and can be used to trace regional folds and faults.

BOWSER LAKE GROUP

Bowser Lake Group sedimentary strata crop out in the northern part of the map area. They conformably overlie the ‘pyjama beds’. Regionally, the Bowser Lake Group is characterized by siltstone to cobble conglomerate of dominantly chert clasts derived from the Cache Creek Terrane to the northeast. In its southern exposures near Terrace and Smithers, there is significant input of volcanic-derived clasts from the uplifted Skeena arch. These volcanic-protolith sedimentary beds cause the Bowser Lake Group to weather an off-white colour (leading to the field name of 'white Bowser'). Deposition of the Bowser Lake Group occurred between the Late Jurassic and Early Cretaceous (Tipper and Richards, 1976).

Intrusive Rocks

EARLY JURASSIC PLUTONIC SUITE

These are the oldest intrusions large enough to be mapped at 1:50 000 scale. The largest of these is the Kleanza pluton, which typifies this suite in its significant heterogeneity, varying from gabbro to quartz-rich granitoid. A sample from the Kleanza pluton yielded a U-Pb zircon date of ca. 200 Ma (Gareau et al., 1997a). This date, interpreted as the age of crystallization, along with similar lithological characteristics between this intrusive suite and the Telkwa volcanic rocks, suggests that it forms the middle to upper crustal roots of the Telkwa arc.

EARLY TERTIARY GRANITOID ROCKS

The Kitsumkalum suite occurs within one plutonic body that consists of granite with lesser granodiorite and diorite. It is variably to strongly foliated. Gareau et al. (1997a) dated it as ca. 59 Ma by U-Pb methods on zircon. The Eocene Carpenter Creek suite includes the Carpenter Creek, Newtown and Williams Creek plutons, and an unnamed pluton that is exposed along the Kitimat River. They are composed predominantly of granite and granodiorite, compositionally similar to the Kitsumkalum suite. Like it, they commonly contain small, clear, euhedral titanite grains. They are interpreted as postkinematic to the ductile deformation event that affected the Kitsumkalum suite, due to their lack of a penetrative foliation. The Carpenter Creek pluton provided a U-Pb zircon date of ca. 53 Ma (Gareau et al., 1997a).

STRUCTURAL GEOLOGY

Stratified rocks at deeper levels in the Terrace area are deformed into regional-scale northeasterly-trending folds (Figure 2). Most prominent among these is an anticline cored by Mount Attree volcanic complex and Ambition Formation limestone in the area between the Skeena River, the lower Zymoetz (Copper) River and the Kitimat River. Northeasterly folds are also well developed within the Kitselas volcanic rocks. At higher stratigraphic levels in the Hazelton and Bowser Lake groups, strata form homoclinal, fault-bounded panels. These may represent a more brittle expression of the folds, or they may have formed as a response to unrelated fault activity.

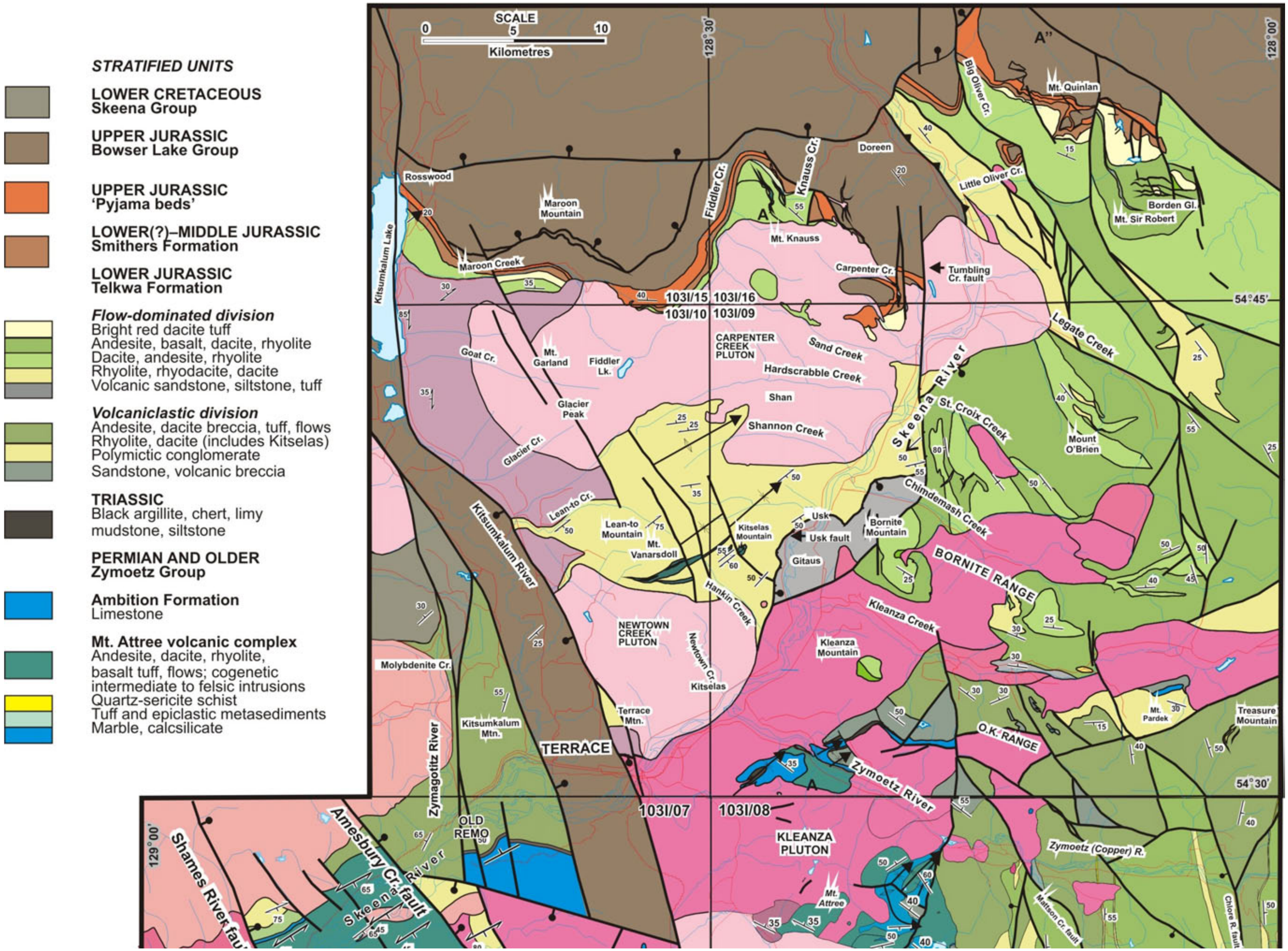
Methods

A geospatial structural analysis of the Terrace area was conducted by digitally partitioning the Terrace regional map (Figure 2) into structurally coherent domains and plotting the structures for each domain on separate stereonet projections. The result is a structural history that constrains models of the geological evolution of the region. The structural domains, shown in Figure 4, were defined visually as sets of geological polygons in a GIS (Manifold®) file that showed consistent structural characteristics. A simplified map was created that includes layers for only the linework, geology polygons and structures. Then all of the polygons in a given domain were selected and a query was done to select all structural data within the indicated area. In Manifold, this task is done using the selector function at bottom of the window (All objects in Structures   Select Contained within   All objects in Polygons   Apply). The structures table was then opened with the selected structural data already highlighted. A 'Domain name' column was added to the table and all of the selected structures were labelled by typing the name in one of the highlighted rows. That name is automatically applied to all of the other highlighted structures. Once all of the domains had been selected and labelled, the entire table was exported as an Excel® file. This file was simplified to contain only the domain name, structure type and structural measurement. A separate file was created for each structure type represented within each domain (S0, layering; Sn, foliation; Ln, lineation; Bs, brittle shear; Bl, brittle lineation; Lf, fold hinge). These were then saved as tab-delimited text files and imported into Spheristat™ 2.2 to produce lower-hemisphere stereonet projections.

Once all of the first draft stereonets had been produced, they were assessed and modifications to the domains were made to refine insights into specific deformational events. The process was repeated to produce a final set of stereonets for analysis. A Gaussian density distribution was applied to each stereonet to give the average orientation of that structure type; where folds were suspected, an eigenvector principal direction analysis was also applied. Both of these analysis methods are found under the analysis menu in SpheriStat™ 2.2. An eigenvector analysis is represented as three mutually perpendicular planes. The stereonets with poles to bedding and foliation plotted are presented in the context of regional geology in Figures 5 and 6, respectively. Other structure types, such as fold axes and slickensides, are not well enough represented regionally to be of statistical significance and so were not presented in the same way. Note that, in some areas, there were two observed foliations but insufficient data were available to plot them separately.

Results

The bedding measurements within the map area, compiled in Figure 5, show several common themes. There is a broad east-dipping homocline defined by the Telkwa bedding attitudes in the southeastern part of the map area. The dip of bedding varies from shallow (5) to vertical, and strike is consistently northerly. The average poles to bedding plunge between 26 and 41 towards 270 , leading to an average bedding plane of 000 /57 . This homocline can also be observed within the underlying Zymoetz Group in the Gazelle domain, although it is possible that this is a coincidental feature. Bedding measurements within the Telkwa Formation farther to the north are highly variable, possibly due to control by local rhyolitic centres, which would have generated irregular paleotopography. The mid-Jurassic to Cretaceous strata that crop out along the northern boundary of the map area define a broad homocline that dips northeast. This domain is characterized by a pole to bedding of orientation 214 /65 , with an average bedding orientation of 294 /35 .


STRATIFIED UNITS
LOWER CRETACEOUS
Skeena Group
UPPER JURASSIC
Bowser Lake Group
UPPER JURASSIC
'Pyjama beds'
LOWER(?)–MIDDLE JURASSIC
Smithers Formation
LOWER JURASSIC
Telkwa Formation
Flow-dominated division
Bright red dacite tuff
Andesite, basalt, dacite, rhyolite
Dacite, andesite, rhyolite
Rhyolite, rhyodacite, dacite
Volcanic sandstone, siltstone, tuff
Volcaniclastic division
Andesite, dacite breccia, tuff, flows
Rhyolite, dacite (includes Kitselas)
Polymictic conglomerate
Sandstone, volcanic breccia
TRIASSIC
Black argillite, chert, limy mudstone, siltstone
PERMIAN AND OLDER
Zymoetz Group
Ambition Formation
Limestone
Mt. Attree volcanic complex
Andesite, dacite, rhyolite, basalt tuff, flows; cogenetic intermediate to felsic intrusions
Quartz-sericite schist
Tuff and epiclastic metasediments
Marble, calcsilicate
SCALE
0
5
10
Kilometres
128°30'
128°00'
54°45'
54°30'
129°00'
103I/15
103I/16
103I/10
103I/09
103I/07
103I/08
A
A''
Rosswood
Maroon Mountain
Maroon Creek
Kitsumkalum Lake
Fiddler Cr.
Knauss Cr.
Mt. Knauss
Doreen
Big Oliver Cr.
Mt. Quinlan
Little Oliver Cr.
Borden Gl.
Mt. Sir Robert
Carpenter Cr.
Tumbling Cr. fault
CARPENTER CREEK PLUTON
Sand Creek
Hardscrabble Creek
Shan
Shannon Creek
Legate Creek
Goat Cr.
Mt. Garland
Fiddler Lk.
Glacier Peak
Glacier Cr.
Skeena River
St. Croix Creek
Mount O'Brien
Chimdemash Creek
Lean-to Cr.
Lean-to Mountain
Mt. Vanarsdoll
Kitselas Mountain
Usk
Usk fault
Bornite Mountain
Gitaus
BORNITE RANGE
Kitsumkalum River
Hankin Creek
Kleanza Creek
NEWTOWN CREEK PLUTON
Newtown Cr.
Kitselas
Kleanza Mountain
Molybdenite Cr.
Kitsumkalum Mtn.
Terrace Mtn.
TERRACE
O.K. RANGE
Mt. Pardek
Treasure Mountain
Zymoetz River
Zymagotitz River
OLD REMO
KLEANZA PLUTON
Zymoetz (Copper) R.
Amesbury Cr. fault
Skeena River
Shames River fault
Mt. Attree
Mattson Cr. fault
Chiore R. fault

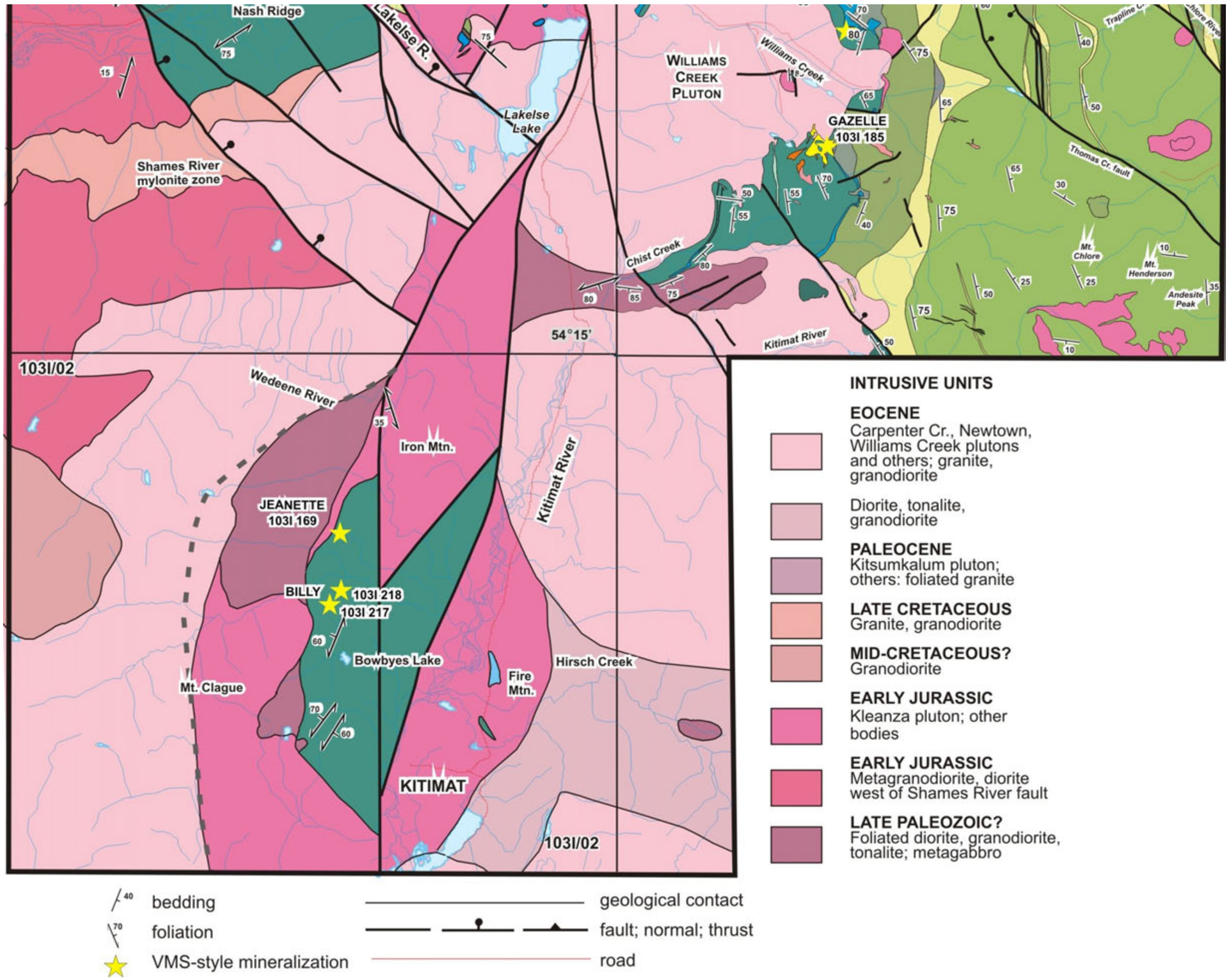


Figure 2. Geology of the Terrace area, compiled from the Terrace regional mapping project (*from* Nelson, 2009).

Folds are evident within the Zymoetz Group and lower Telkwa Formation, particularly in the Kitselas facies. The four stereonets with eigenvectors shown highlight folds with hinge lines plunging shallowly to moderately northeast. The hinge lines described by each domain vary somewhat: Antiform, 038 /10 ; Sausage, 052 /52 ; Kitselas, 074 /07 ; Zymoetz, 054°/31°. The two remaining domains for which layering data were collected, Chist Creek and Camp 1, seem to define two limbs of an overturned fold with a hinge line plunging southeast. This feature is not discussed in detail here, as limited data prevented a proper analysis.

Foliation data are presented in Figure 6. Foliation, in the form of mineral and clast flattening, is developed only locally within the upper Telkwa and younger stratigraphy. Where it is observed, it is parallel to layering and poorly developed. The Kitselas facies of the Telkwa is well foliated and, in areas, two phases of foliation were observed. One phase, described by mineral flattening, is dominantly bedding parallel and developed prior to the deformation of layering described above. There is another foliation developed parallel to the axial plane of northeasterly-plunging folds at an orientation of 240 /85 (one measurement documented as axial planar in the field). This foliation shows mineral flattening, as well as weak cleavage development. The northeasterly hinge lines lie within this plane. The Gitaus domain also shows a well-developed foliation for the Telkwa Formation. The poles to foliation lie on a great circle similar to what is seen in the Kitselas domain, suggesting this is likely the same bedding-parallel foliation. The Kitsumkalum pluton has a well-developed foliation defined by biotite aggregates and stretching lineations. Analysis of the data collected shows a strong clustering of foliation data, with an average pole orientation of 010 /55 . The mineral lineations, mainly stretched quartz crystals on foliation-parallel surfaces, show an almost perfect down-dip orientation of 259 /44 (Figure 7a). The brittle shear and brittle lineation orientation pairs show the same down-dip sense of motion, with an average orientation of 259 /45 (Figure 7b). Shear-sense indicators, both tails on mineral grains and steps on brittle shear surfaces, show top-down-to-the-west motion.

DOWN-PLUNGE PROJECTION

Methods

A semiquantitative axial-plunge projection that proxies as a crustal cross-section can be developed using a graphics program, such as CorelDraw®, by using a command to 'squeeze' the geological map image in a direction parallel to the trend of the hinge line (Johnston, 1999). The orientation of the down-plunge projection was determined by taking a weighted average of hinge-line orientations for each domain that contains a known fold. This was done in Spheristat by plotting the four different hinge lines on the same stereonet. Each hinge line was duplicated to the number of data points represented by it, and the average orientation of this plot was used. The resulting average hinge-line orientation is 057 /29 . The Terrace regional map (Figure 2) was rotated by 57 and compressed in the vertical direction by a factor of 0.48. This value was calculated by taking the sine of 29 , which gives the ratio of the cross-section height over the map height. The resulting down-plunge projection is presented in Figure 8.

Figure 3. Silica- and hematite-replaced crinoid fossil within the Ambition Formation. Note the exceptional preservation of the calyx on the right side of the photo.

Results

The down-plunge projection provides an approximate cross-section through the upper crust (Figure 8). The section shows a nearly 10 km thick sequence of Telkwa volcanic rocks. Part of the thickness is probably due to repetition across reverse faults, such as those that bound the Treasure Mountain, Mattson Creek and Big Three domains. The upper sedimentary stratigraphy does not project well in this cross-section because it dips shallowly to the north, but it is worth noting that the sequence from Telkwa Formation to Bowser Lake Group is repeated across a fault running along the Skeena River, the Skeena River fault zone (Nelson and Kennedy, 2007). The base of the section is dominated by laterally extensive and bulbous plutons of varying age. The most interesting of these is the Kleanza pluton, which cuts through the entire Telkwa Formation; it is interpreted as the feeder for Telkwa. Another feature highlighted on the section is that the Ambition Formation, which dips to the northeast, resurfaces southeast of the Kleanza pluton. Further discussion is provided with the structural interpretations.

DISCUSSION

Folding

Northeasterly folds were likely formed with a horizontal hinge line (discussed later), in response to a principal compressive stress oriented northeast-southwest and vertical minimum compressive stress. It is plausible that the east- and northeast-dipping homoclines are two limbs of a large, regional-scale fold with the same orientation as the smaller folds. The folds in the Kitselas facies rocks restrict the age of this northwest-southeast compression to post–Early Jurassic. West of the study area, Heah (1991) and Nelson (2009) reported strong northeasterly fabrics within Late Cretaceous granitoid bodies, as well as in metamorphosed volcanic rocks likely correlative with the Mount Attree volcanic complex and Telkwa Formation. Massive

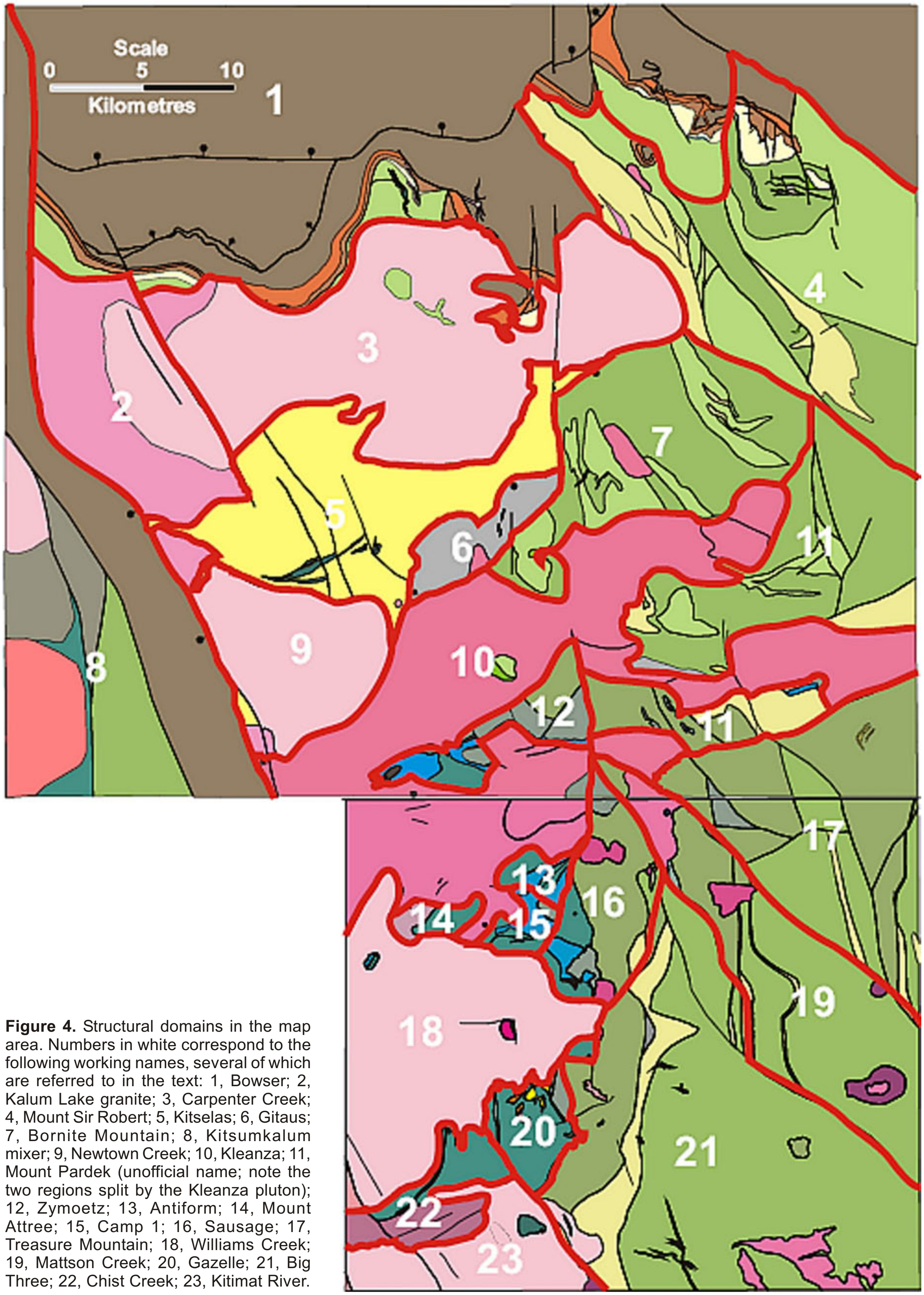


Figure 4. Structural domains in the map area. Numbers in white correspond to the following working names, several of which are referred to in the text: 1, Bowser; 2, Kalum Lake granite; 3, Carpenter Creek; 4, Mount Sir Robert; 5, Kitselas; 6, Gitaus; 7, Bornite Mountain; 8, Kitsumkalum mixer; 9, Newtown Creek; 10, Kleanza; 11, Mount Pardek (unofficial name; note the two regions split by the Kleanza pluton); 12, Zymoetz; 13, Antiform; 14, Mount Attree; 15, Camp 1; 16, Sausage; 17, Treasure Mountain; 18, Williams Creek; 19, Mattson Creek; 20, Gazelle; 21, Big Three; 22, Chist Creek; 23, Kitimat River.

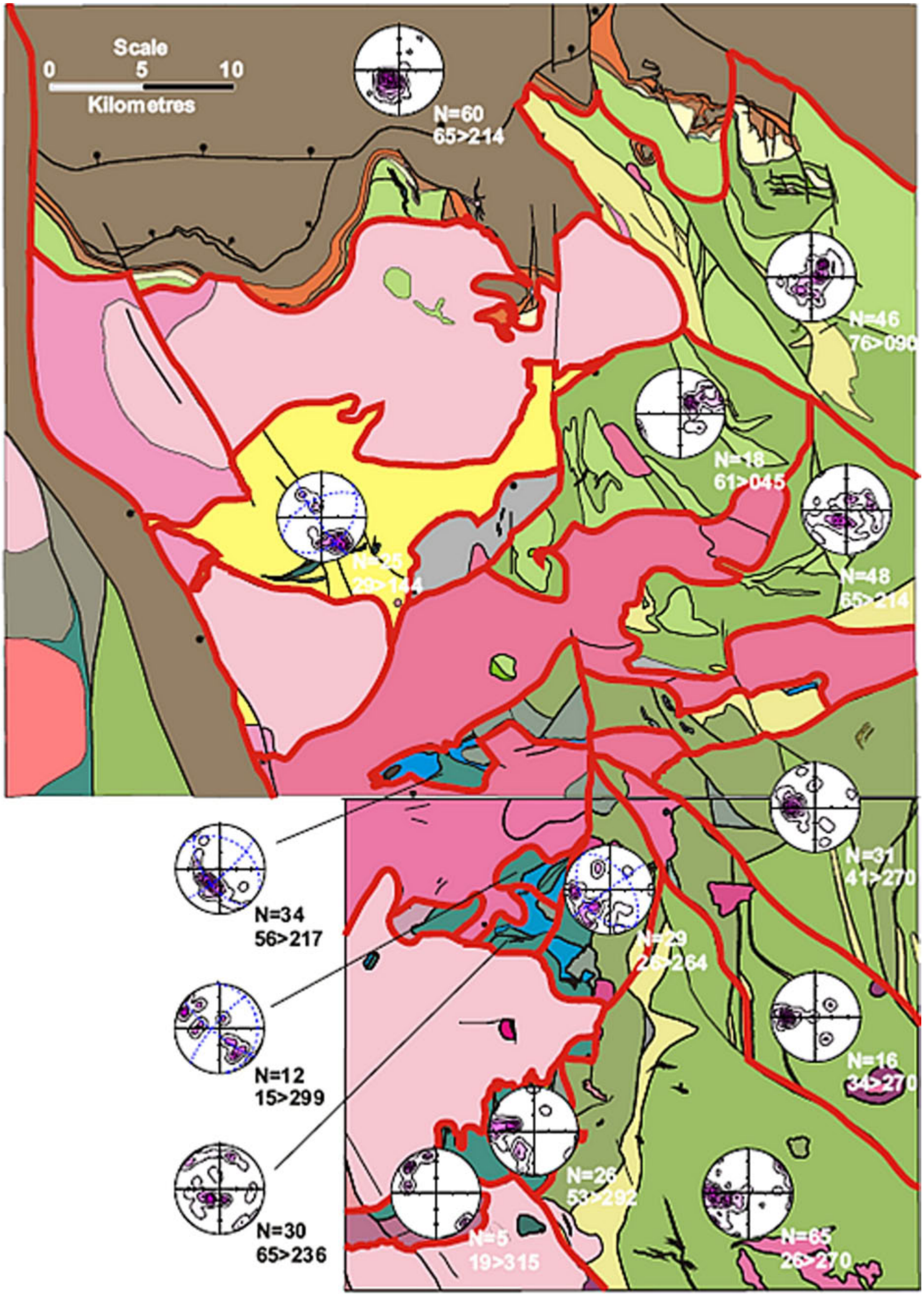


Figure 5. Stereonet projections of poles to bedding (N is the number of data points included). The average trend and plunge of each stereonet is included. A principal direction analysis was done for the domains with observable folds. The intersection of the two blue planes that does not lie within the data concentration indicates the hinge line of the fold.

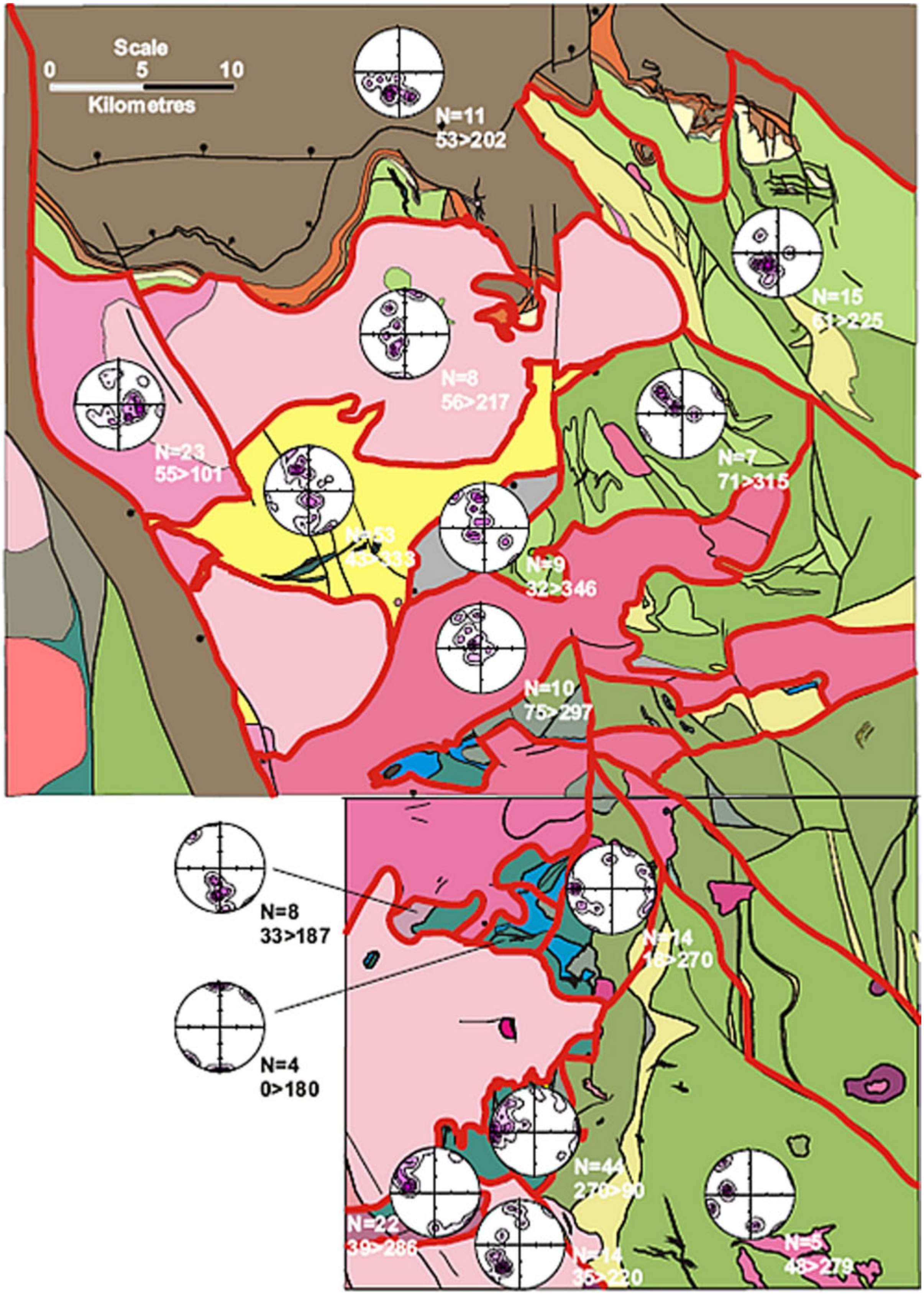


Figure 6. Stereonet projections of poles to foliation (N is the number of data points included). The average trend and plunge of each stereonet is included.

plutons of the Carpenter Creek suite cut across folds and foliations in both the Kitselas block and the Williams Creek–Kitimat River area. Thus, the main age of northeasterly folding is constrained to between 70 and 53 Ma, or earliest Tertiary.

Northeast-trending folds of regional magnitude are uncommon in the Cordillera; they are orthogonal to the dominant northwesterly structural trend, which may be controlled by the margin of ancestral North America as well as the present plate margin. Hinge lines in the Terrace area are parallel to the trend of the Skeena arch. Little is known about the mechanics of how the Skeena arch actually formed. It was a prominent feature by Late Jurassic time, as it forms the southern boundary of the Bowser Basin. Tipper and Richards (1976) interpreted it as a simple uplift with no associated compression. A detailed analysis of the folds here could provide insight into potential reactivation of the Skeena arch during Early Tertiary orogen-parallel compression. The two homoclines could be two limbs of a large fold. The presence of large folds affecting all of the stratigraphy present in the map area is permissible, as the Telkwa Formation is involved in the deformation event and there is a near-continuous stratigraphy starting with the Telkwa in the early Jurassic through to the Cretaceous Bowser Lake Group. The only significant unconformity lies between the top of the Telkwa and the Smithers Formation. This interpreted paraconformity would imply that the Telkwa was not folded prior to deposition of the Smithers Formation.

The lower Telkwa and underlying stratigraphic units were near the brittle-ductile boundary for crustal rocks (10 km depth) in Middle Jurassic time, when Telkwa volcanism was coming to an end, and much deeper with deposition of the Bowser Lake Group. These burial depths are supported by regional zeolite to lowest greenschist facies metamorphic grade within the Telkwa, and greenschist to lower amphibolite grade in the stratigraphically and structurally underlying rocks of the Zymoetz Group and Kitselas facies. This model would explain the prevalence of brittle rather than ductile features within the upper Telkwa and higher stratigraphy associated with this event, compared to folding and development of cleavage at deeper crustal levels.

Metamorphism of the Kitselas Facies

The Kitselas facies has been metamorphosed to greenschist to lower amphibolite facies, whereas the coeval Telkwa Formation is only metamorphosed to zeolite or lowest greenschist facies. The difference in metamorphic grade has been explained by a thrust fault along the Skeena River fault zone, placing Telkwa on top of Kitselas and younger strata, as seen in Figure 8 (Gareau et al., 1997b; Nelson and Kennedy, 2007). Gareau et al. (1997b) interpreted this fault as a top-to-the-northeast detachment. The structural data show limited evidence of these low-angle structures. Four elongation lineations with values of approximately 035 /10 were measured within the Gitaus domain. If these are stretching fabrics, then foliation observed within this domain could be a tectonic fabric along a curviplanar detachment surface. Given the parallelism of these lineations with the hinge-line orientation and the similar attitudes of foliations between the Gitaus and Kitselas domains, it is likely that these lineations are associated with northeast-southwest compression, not extension. However, the duplication of the stratigraphy noted at the northwest edge of the down-plunge projection associated with the Skeena River fault zone still supports the possibility of top-to-the-northeast thrust imbrication. This thrust is restricted to post–Early Cretaceous, as it affects the Bowser Lake Group, and pre-Eocene as it is crosscut by Eocene intrusions. In terms of style, timing and the observed orientation of the thrust (cutting up-section towards the northeast),

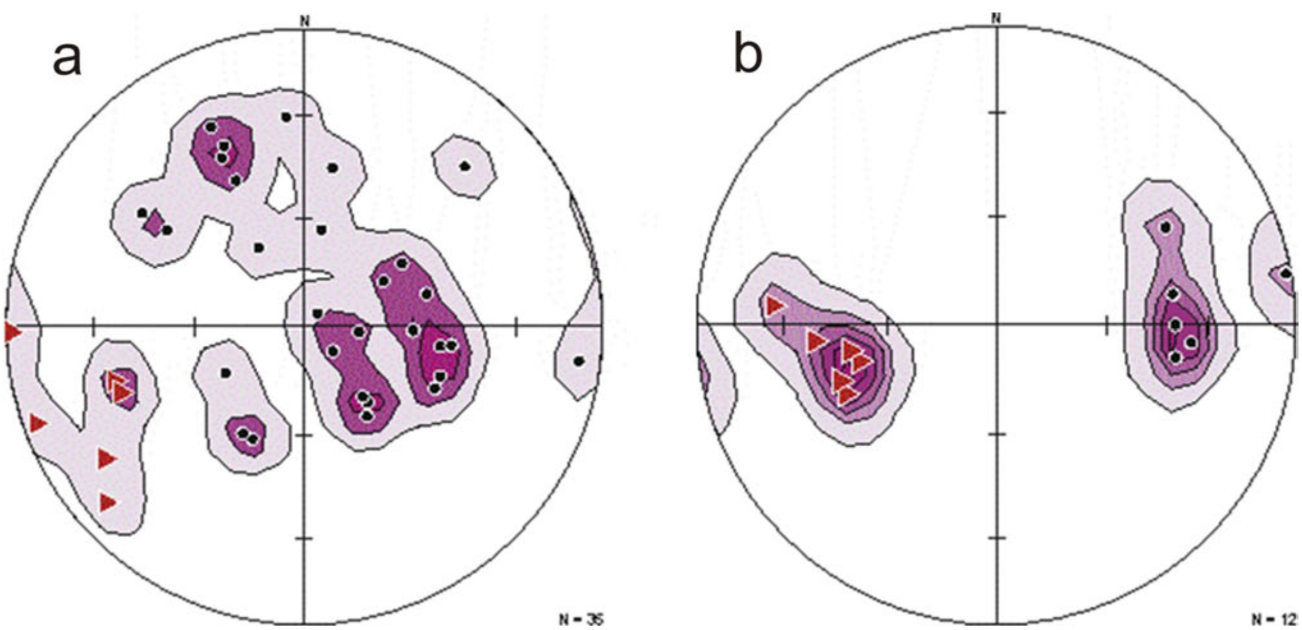


Figure 7. Stereonets describing deformation associated with the formation of the Kitsumkalum-Kitimat graben: **a)** poles to foliation (black dots) and elongation lineations (red triangles); **b)** poles to brittle shear surfaces (black dots) and slickenlines (red triangles). These represent the ductile and brittle phases of the normal fault defining the eastern edge of the Kitsumkalum-Kitimat graben. The motion, described by ductile and brittle lineations, is at an orientation of 259 /45 .

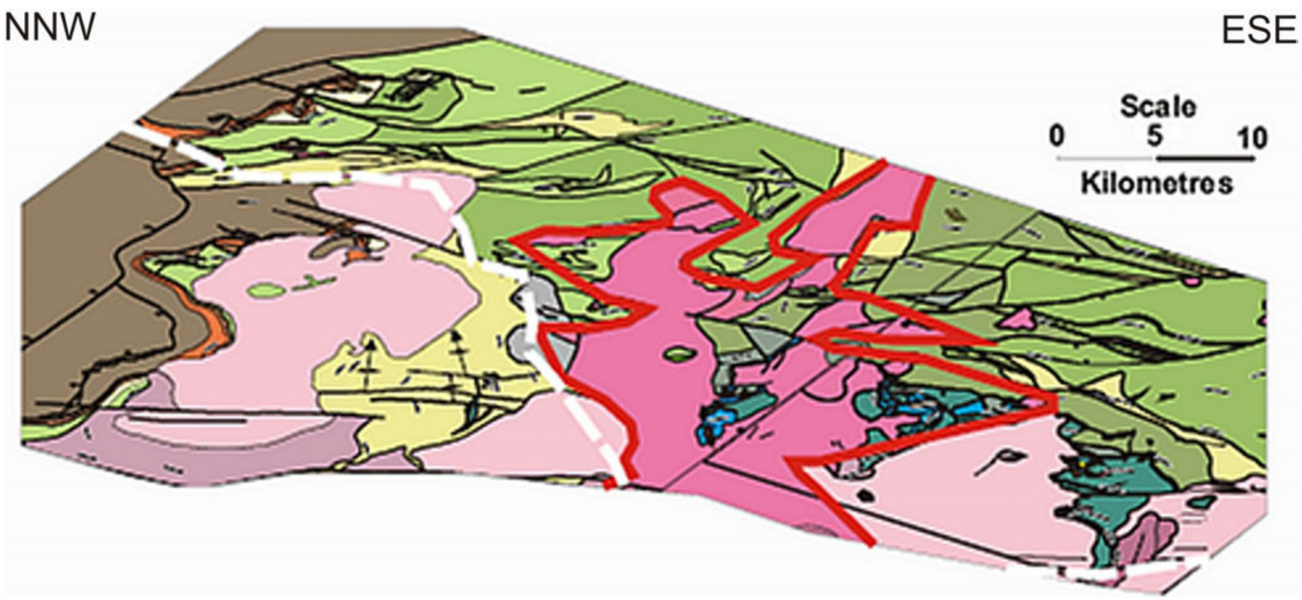


Figure 8. Down-plunge projection (without vertical exaggeration). The base of the projection follows the trace of the Kitsumkalum-Kitimat graben. The red lines highlight the approximate extent of the Kleanza pluton, indicating its 'Christmas tree' form. The white line traces the approximate orientation of the Skeena River fault zone.

the Skeena River fault zone matches other structures attributed to the Skeena fold-and-thrust belt by Evenchick (1991).

Two sets of southwest-verging thrust faults active between 87 and 59 Ma have been documented in the region west of the map area (Andronicus et al., 2003). Neither mapped relations in the Terrace area nor the structural data set in this study can be linked to this faulting. Northeastward detachment along the Skeena River fault zone, although not well documented in this study, may have occurred contemporaneous with the Shames River mylonite zone and other northeastward-directed shearing at approximately 54–47 Ma (Heah, 1991; Andronicus et al., 2003).

Kitsumkalum-Kitimat Graben

The most recent major structural event in the Terrace area is extension associated with the Kitsumkalum-Kitimat graben. The Kitsumkalum pluton is cut by a normal fault along which both brittle and ductile deformation are apparent. The fault strikes south-southeast and dips moderately southwest, perpendicular to axes of northeast-plunging folds, leading to the interpretation that the a-c joint plane of the folds was an initial weakness along which the fault developed. Top-down-to-the-west motion on a fault of this orientation would lead to rotation of the footwall block, giving the regional east-northeast plunge of the hinge lines and dip of the layering.

There are numerous smaller faults to the east of the main normal fault that are parallel to it. Some of these are cut by apophyses of the Kleanza pluton, whereas others offset them. Their sense of motion is also variable: some are top-down-to-the-west, others are top-up-to-the-east. Thus, they cannot be simply coeval with the eastern fault of the Kitsumkalum-Kitimat graben. The younger (post-Kleanza) faults can be explained by local stress being accommodated by the same a-c joint plane in folds.

The age of the Kitsumkalum-Kitimat graben is Eocene or younger because it truncates both the deformed Kitsumkalum pluton and plutons of the undeformed 53 Ma Carpenter Creek suite. This age is consistent with steeper normal faulting succeeding the shallow detachments of the Skeena River fault zone and the Shames River mylonite

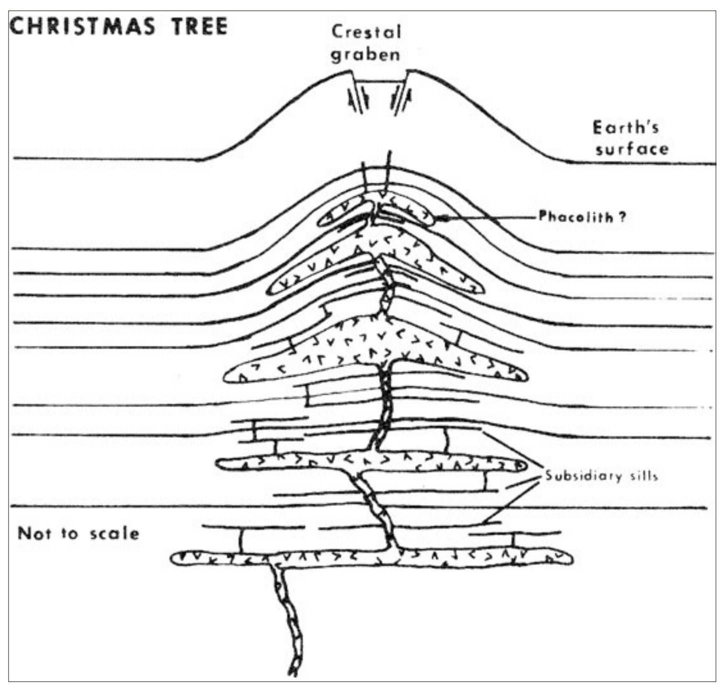


Figure 9. Schematic diagram of a 'Christmas tree' laccolith, representing the extreme end-member case. The Kleanza pluton shows some of the characteristics of a Christmas tree laccolith but differs from this model because it is actually feeding a volcanic vent above (Corry, 1988).

zone, but being a result of the same extensional event (Heah, 1991).

Kleanza Pluton

The shape of the Kleanza pluton in the down-plunge projection (Figure 8) is similar to that of 'Christmas tree' laccoliths (Corry, 1988). A Christmas tree laccolith (Figure 9) forms when parts of an intrusion spread out parallel to layering at various depths. For all intrusions, rising magma becomes neutrally buoyant and stops when the density of the magma equals that of the surrounding country rock. The Kleanza pluton seems to be ordered into several (paleo-) horizontally extensive layers, as outlined on Figure 8. Since the pluton is interpreted as the dominant local feeder for the Telkwa volcanic rocks, each layer would have led to a thickening of the overlying volcanic package, resulting in increased pressure inside the magma chamber. This would have made the magma positively buoyant, leading to the formation of a shallower magma chamber. Emplacement of the Kleanza suite could have led to the irregular layering of the domains that lie above it, in cross-section, both through paleoslopes of the volcanic edifice(s) and through doming over the intrusion.

Implications for Geological History

Analysis of structural data collected during the Terrace regional mapping project has contributed to an understanding of the local geological history in the area. The sequence of events recorded by these rocks is as outlined below. Volcanic and associated intrusive units of the Mount Attree volcanic complex developed in an island-arc setting during late Paleozoic time. This arc became dormant, allowing for the prolific biological activity that gave rise to Ambition Formation limestone in Permian time, followed by deep-water, starved basinal conditions in the Triassic. The magmatic arc was reactivated in the Early Jurassic. A nearly 10 km thick succession of Telkwa volcanic rocks was deposited, together with intrusion of the Kleanza pluton. In mid-Jurassic time, volcanism was succeeded by subaqueous deposition of the Smithers Formation. The shift from subaerial to subaqueous conditions suggests subsidence associated with the cooling of the island-arc root. Continued subsidence would allow deposition of the fine-grained Troy Ridge facies, possibly accompanied by regional extension (J-F. Gagnon, pers comm to J. Nelson, 2008). Clastic influx began in the Late Jurassic (Oxfordian) and deposition into the Bowser Basin continued up to Early Cretaceous time.

Northeast-vergent thrusting along the Skeena River fault zone buried the Kitselas facies of the Telkwa Formation under a hangingwall of Paleozoic and younger strata during the mid-Cretaceous. The Paleocene Kitsumkalum pluton intruded this assemblage and was later deformed with it. Similarly, latest Cretaceous granitoid rocks intruded the hangingwall and were folded along with it into gently northeast-plunging folds with steep axial planes.

Megascopic northeasterly folds lie in the hangingwall of the Shames River fault zone, a listric, northwest-striking, down-to-the-east Eocene normal fault exposed 20 km west of Terrace. West of the Shames River fault, mylonitized deeper crustal rocks were exposed by a shallowly dipping, top-to-the-northeast detachment zone. The Shames River fault is regarded as a late-stage expression of the same crustal extension event, which overall occurred between 54 and 47 Ma (Andronicos et al., 2003). This mid-crustal extension was coeval with postkinematic plutons of the Carpenter Lake suite, which cut northeasterly-trending folds east of the Shames River fault. Therefore, the folding, which is post 69 Ma, predated Eocene top-to-the-northeast extension.

Tertiary northeasterly folds along the Skeena arch allow the hypothesis that it could have been reactivated as an orogen-normal compressional structure. Late Cretaceous to Eocene dextral strike-slip motion was widespread in the Cordillera. The Skeena arch may have acted as a restraining bend, with transcurrent motion stepping west from the Cordilleran interior into the Coast Plutonic Complex and farther outboard.

In the Terrace area, continued east-northeast-directed extension during the early Eocene reactivated the Skeena River fault zone and gave rise to the Kitsumkalum-Kitimat graben. Originally horizontal, northeasterly-trending folds to the east of the graben were rotated into their current northeast-plunging orientation.

CONCLUSIONS

Three deformation events were identified in the Terrace area. The first produced the northeast-vergent Skeena fold-and-thrust belt in mid-Cretaceous time. The second involved northwest-southeast compression, which gave rise to folds that affected the Paleozoic to Early Cretaceous succession and plutons as young as Late Cretaceous. Folds trend parallel to the Skeena arch, suggesting this compressional event involved structural reactivation of the arch. This was succeeded by extension and the formation of steep, west-southwest- and east-northeast-dipping normal faults that define the eastern and western edges of the Kitsumkalum-Kitimat graben, respectively. The eastern bounding fault is interpreted to have formed along the a-c joint set of the earlier folds, and was likely responsible for rotating the footwall block to the east, giving rise to the northeast plunge of hinge lines and eastward dip of layering. This block rotation affected an approximately 10 km thick section through the upper crust, exposing the relationships between the local strata and the underlying intrusions.

The most prominent unanswered question resulting from the analysis presented here is the nature of regional compression leading to the northeast-trending folds. A more detailed study can also provide insight into the nature of the Skeena arch.

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