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Northeast-trending folds in the western Skeena Fold Belt, northern Canadian Cordillera: a record of Early Cretaceous sinistral plate convergence

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Abstract

The western portion of the Skeena Fold Belt, northern Canadian Cordillera, contains northeast-trending folds that are highly oblique to northwest-trending folds in the eastern portion of the fold belt, and to most Mesozoic contractional structures in the northern Cordillera. The northeast-trending folds locally interfere with the northwest-trending folds, and one region includes transected folds. Geometric relationships within and between the two fold sets are not easily reconciled by notions of the northeast-trending folds resulting from vertical axis rotation of blocks, influence of basement features, or lateral variations in magnitude of shortening. The northeast-trending folds are inferred to result from sinistral plate convergence early in the history of the fold belt (Early Cretaceous).

Northeast-trending folds in the Skeena Fold Belt are the most conspicuous elements of a seldom-studied group of similarly oriented contractional structures, which collectively define a belt at least 1700 km long, within and bordering the Coast Belt. The extent of Early Cretaceous structures potentially related to sinistral convergence supports them having originated in response to the relative plate motion rather than local controls (e.g. indentors). This agrees with relative plate motion studies based on ocean floor reconstructions, which suggest a mid-Cretaceous change from sinistral to dextral convergence. Crown Copyright © 2001 Published by Elsevier Science Ltd. All rights reserved.

1. Introduction

The Skeena Fold Belt is a Cretaceous thin-skinned fold and thrust belt in the west-central Canadian Cordillera (Evenchick, 1991a,b; Fig. 1). Its western side includes domains of northeast-trending folds, an orientation orthogonal to contractional structures in the eastern two-thirds of the fold belt as well as the vast majority of Middle Jurassic through early Tertiary contractional structures in the Canadian Cordillera. This paper presents the geometry and constraints on timing of the northeast-trending folds, and discusses their origin in the context of Mesozoic tectonics and proposed relative plate motions of the northern Cordilleran margin. The interpretation presented herein builds on previous speculation that they are a result of sinistral convergence between the North American Plate and plates of the Pacific Ocean in the Cretaceous (Evenchick, 1995). Because many factors may govern the orientation of folds, they can seldom be directly related to relative plate motion. Fold orientations are, however, potentially useful in determining the *sense* of oblique convergence. Regional examination of Cretaceous structures aids in providing a tectonic framework for the unusual fold trends.

The western Skeena Fold Belt is the most extensive area available to examine upper crustal structures which formed proximal to the Early Cretaceous North American Plate margin. Unlike their deeper crustal, high-strain counterparts, upper crustal structures potentially preserve early-formed structures. These structures are of Cretaceous (and possibly earliest Tertiary) age and have not been overprinted by younger structural, magmatic, or metamorphic events. Correlation of geologic features of the northern Cordillera with motions between the North American Plate and plates of the Pacific Ocean relies on determining relative plate motions (Coney, 1972; Engebretson et al., 1985). Dextral oblique relative plate motions for the North American Cordilleran margin are well constrained for the Tertiary from the global plate circuit and hot spot reference frame methods of study, but interpretations for Cretaceous and Jurassic time are limited by the decrease in amount of

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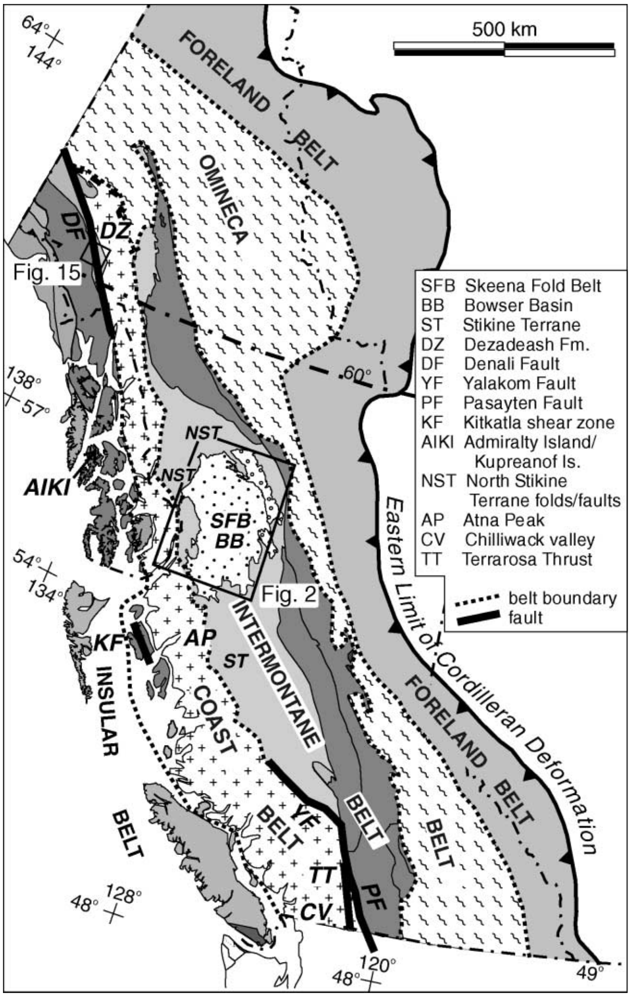


Fig. 1. Regional tectonic framework of the Canadian Cordillera, with location of Skeena Fold Belt and Figs. 2 and 15. Regional features referred to are listed in the inset. Map modified from Wheeler and McFeely (1991) to show physiographic belts, and major terrane boundaries for geographic reference.

preserved seafloor farther back in time (Engebretson et al., 1985; Stock and Molnar, 1988). The analyses of plate motions from Engebretson et al. (1985) and Kelley (1993) (based on the hot spot reference frame) indicate sinistral convergence along the western margin of the (present) northern Canadian Cordillera from Early Jurassic into earliest Late Cretaceous time (95–80 Ma). Evidence for Jurassic sinistral structures and their relationship to relative plate motions have been discussed by Avé Lallemant and Oldow (1988), but the interpretation of sinistral convergence into mid-Cretaceous time has not been addressed on a regional scale in previous structural studies. Mid-Cretaceous sinistral displacement is inferred for parts of the Pasayten fault zone at the southeast terminus of the Coast Belt (Hurlow, 1993 and references therein). Hurlow (1993) concluded that the sinistral displacement was a consequence of either sinistral plate convergence, or an indenting block. Duplication of Jura/Cretaceous arcs in the southwest Canadian Cordillera has been ascribed to sinistral convergence (Monger et al., 1994), although no sinistral fault was identified. The Kitkatla shear zone, in the northern Cordillera appears from reconnaissance study to have accommodated sinistral displacement in the Early Cretaceous (Gehrels and Boghossian, 1999). It is argued below, from a complex data set, that northeast-trending folds in the Skeena Fold Belt are a result of Cretaceous sinistral convergence, and that they are part of a belt of similar features over 1700 km long. The paucity of known Cretaceous sinistral structures may be explained in part by the long history of Late Cretaceous and younger dextral convergence, which would have obliterated older structures in high-strain zones, in part by exhumation and erosion of Early Cretaceous mid-crust high-strain zones, and in part by the absence of a regional tectonic framework for interpretation of apparently anomalous structures. A goal of this paper is to provide such a framework.

2. Regional geologic framework

2.1. Cordilleran geology

Mesozoic oblique convergence between Pacific plates and the North American Plate (e.g. Engebretson et al., 1985) resulted in the amalgamation of terranes along the North American Cordilleran margin (e.g. Coney et al., 1980; Gabrielse and Yorath, 1991). Concomitant localization of contraction (and translation?) in discrete zones of mid-crustal deformation resulted in two orogen-parallel belts of metamorphic and plutonic rock known as the Omineca and Coast belts of the Canadian Cordillera (e.g. Monger et al., 1982; Gabrielse and Yorath, 1991; Fig. 1). Each is bounded on the east by a well preserved easterly vergent fold and thrust belt. In the east, the Alberta Foreland Basin and Rocky Mountain Fold and Thrust Belt (Foreland Belt) are dynamically linked to the Omineca Belt (Price, 1973; Beaumont, 1981). The most widespread exposure of Cretaceous contractional structures east of the Coast Belt is in the Skeena Fold Belt (Evenchick, 1991a,b). Structures there are coeval with northeast contraction in, and west of, the Coast Belt (e.g. Crawford et al., 1987; Rubin et al., 1990; McClelland et al., 1992). They are inferred to root in the Coast Belt, and to be representative of a much larger region (Evenchick, 1991a,b) including, mid- and Late Cretaceous folds and thrust faults bordering the southern Coast Belt (e.g. Journeay and Friedman, 1993; Rusmore and Woodsworth, 1994). Contractional structures in the Coast Belt/Skeena Fold Belt are broadly contemporaneous with the younger period of contraction in the Omineca Belt/Foreland Belt, prompting speculation that a structure below the Skeena Fold Belt transferred displacement eastward to the eastern orogen (Evenchick, 1991a). This paper is concerned with structures at the western side of the Skeena Fold Belt, closest to the active plate margin in Cretaceous time.

2.2. Skeena Fold Belt overview

The Skeena Fold Belt is best displayed in subgreenschist facies marine and nonmarine clastic strata of the Bowser and Sustut basins, which range in age from Middle Jurassic to latest Cretaceous (Figs. 1 and 2). The clastic successions overlie Paleozoic and Mesozoic strata of Stikine Terrane (Stikinia), the upper part of which is predominantly Mesozoic volcanic arc material. The Skeena Fold Belt is characterized by northwest-trending folds and (less common) thrust faults, and they clearly involve Stikinia, as shown by folded contacts, structural culminations of Stikinian rocks within the fold belt, and klippen of early Mesozoic volcanic rocks on Cretaceous strata (Evenchick, 1991b). Upper Cretaceous sediments of the Sustut Basin, on the east side of the fold belt, were eroded from the emerging fold belt, and Sustut Basin strata were subsequently cannibalized by the fold belt as it propagated northeast (Eisbacher, 1974; Evenchick, 1991a). The fold belt accommodated a minimum of 44% (160 km) northeasterly shortening, and terminates to the northeast in a classic triangle zone within strata of the Sustut Basin (Evenchick, 1991a).

The age of the youngest folded marine Bowser Basin strata is at the Jurassic/Cretaceous boundary (Evenchick et al., 2001). Sustut Basin strata unconformably overlie contractional structures in Bowser Basin strata, and the youngest Sustut strata (latest Maastrichtian) are the youngest folded rocks (Sweet and Evenchick, 1990). From these relationships, the Skeena Fold Belt could have initiated as early as earliest Cretaceous time; at least some deformation was pre-Albian, and it lasted into latest Cretaceous or earliest Tertiary time. Synorogenic clastic rocks include: (i) a piggyback basin in the north-central part of the fold belt, which records mid-Cretaceous subaerial erosion of topographic highs in the central fold belt (Evenchick, 1994; Fig. 2), and (ii) more than 1500 m of strata in the Sustut Basin, which record a western source of clastic material from Albian or Cenomanian through Maastrichtian time (Eisbacher, 1974; Sweet and Evenchick, 1990).

3. Structures in the Skeena Fold Belt

3.1. Northwest-trending folds

Folds in the Skeena Fold Belt have two dominant orientations. Northwest-trending folds occupy the central and eastern parts of the fold belt and parts of the western fold belt (Fig. 2). Most verge northeast, vary from upright to overturned, and have wavelengths of several hundred metres to more than a kilometre. Larger folds occur near culminations that expose Stikinian volcanic rocks, and their scale is inferred to be controlled by the relatively competent and thick units of Stikinia. Elsewhere, fold wavelength is typically a few hundred metres in the thinly layered, mechanically heterogeneous Bowser Basin strata, and the lack of laterally continuous markers inhibits recognition of larger order culminations. An exception is in the piggyback basin, where thick competent sheets of conglomerate dominate the succession, and folds with one to several kilometres wavelength define a synclinorium. Mesoscopic folds are rare. Southwest-verging folds are of similar scale and style to north-verging ones, but are uncommon. Folds have broad rounded to narrow angular hinges, and interlimb angles ranging from 140 to 30°, with the majority at 90–60° (Figs. 4–9 of Evenchick, 1991a). Bedding-plane slickenlines indicate that flexural slip was an important folding mechanism. There is little or no thinning of fold limbs in sandstone or conglomerate, but siltstone, shale, mudstone and coal are thickened in hinges to accommodate the generally concentric nature of more competent units. Cleavage has a range of forms, including fracture cleavage, spaced (pressure solution) cleavage, and slaty cleavage. Cleavage is commonly, but not everywhere, developed in siltstone and shale. It is rare in sandstone, and very rare in conglomerate. Where present, it is parallel with, or fans through, the axial surfaces of folds.

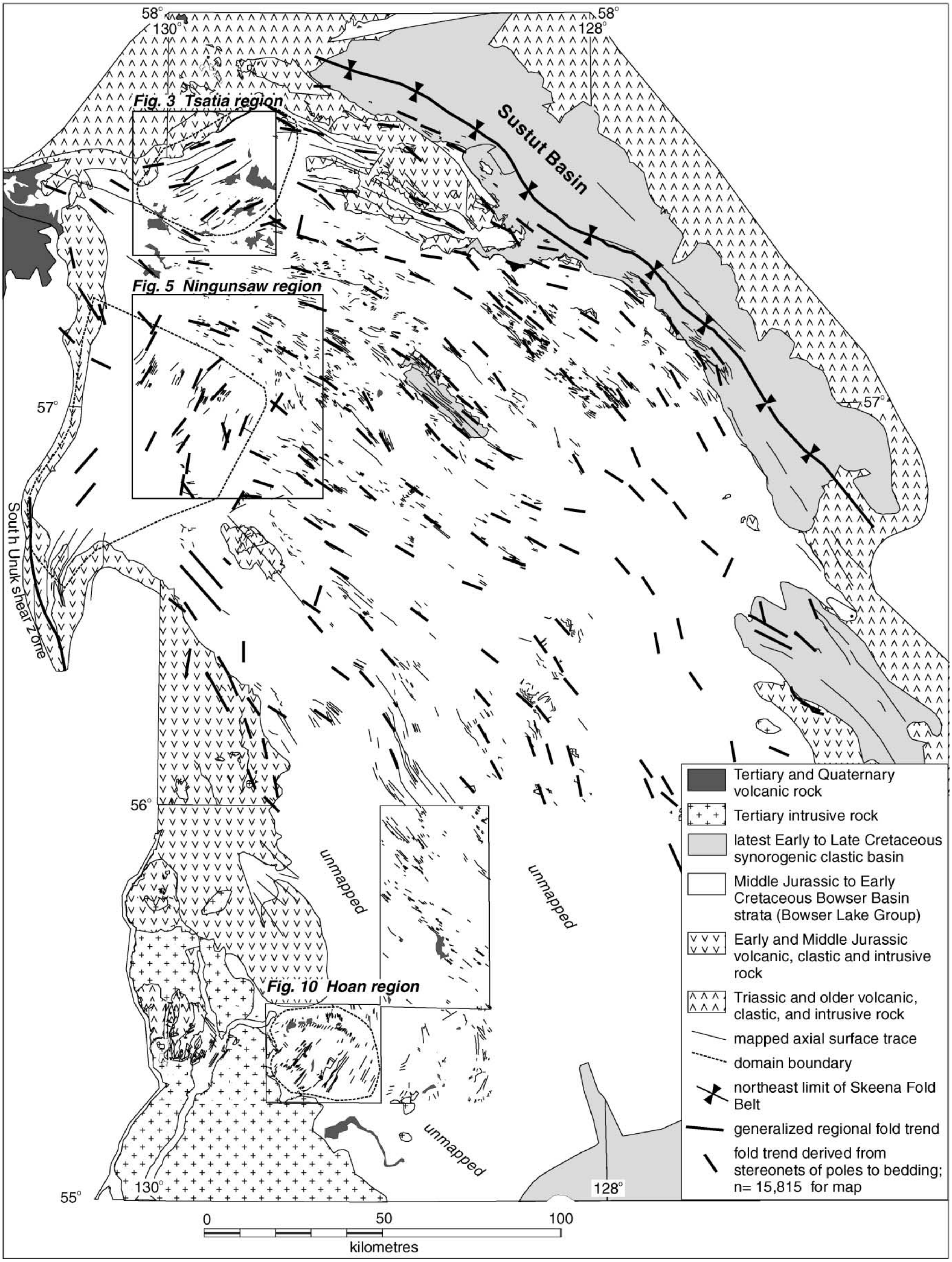
Thrust faults are recognized at the northeast side of the fold belt where different map units are present, but they are difficult to identify within Bowser Basin strata unless hanging wall or footwall cutoffs are exposed. They are required by the style of folding, and are inferred to be bedding-parallel blind thrusts.

3.2. Northeast- to north-northeast-trending folds

The second set of folds, forming domains along the west side of the fold belt, trend northeast and north-northeast (Fig. 2). There are few places where the relative timing of the two sets of folds can be resolved. The folds are of similar geometry and scale as northwest-trending folds, and also formed in part by flexural slip; they verge both southeast and northwest. With notable exceptions (discussed below), cleavage is parallel with the axial surface. Fold interference occurs locally at the boundary between domains of northeast- and northwest-trending folds, and within the western domains. On stereograms, this interference is expressed most commonly, and at various scales, as widely dispersed poles-to-bedding. Large-scale dome and basin fold interference patterns occur locally where folds are open-to-closed and topographic relief is minimal. In much of the fold belt, however, alpine physiography provides poor conditions for expression of fold interference patterns, given the scale of folds. Structural geometries of three areas with northeast- and north-northeast-trending folds, and transitions from domains of northwest- to northeast-trending folds are examined to illustrate variations in fold style and to provide a base for interpretations.

3.2.1. Northwest Bowser Basin (Tsatia region)

At the north-northwest limit of the Bowser Basin (Figs. 2 and 3), northeast-trending folds are gentle (interlimb


58°
130°
58°
128°
Fig. 3 Tsatia region
Sustut Basin
Fig. 5 Ningunsaw region
57°
57°
South Unuk shear zone
56°
unmapped
unmapped
Fig. 10 Hoan region
unmapped
55°
130°
128°
Tertiary and Quaternary volcanic rock
Tertiary intrusive rock
latest Early to Late Cretaceous synorogenic clastic basin
Middle Jurassic to Early Cretaceous Bowser Basin strata (Bowser Lake Group)
Early and Middle Jurassic volcanic, clastic and intrusive rock
Triassic and older volcanic, clastic, and intrusive rock
mapped axial surface trace
domain boundary
northeast limit of Skeena Fold Belt
generalized regional fold trend
fold trend derived from stereonets of poles to bedding; n= 15,815 for map
0
50
100
kilometres

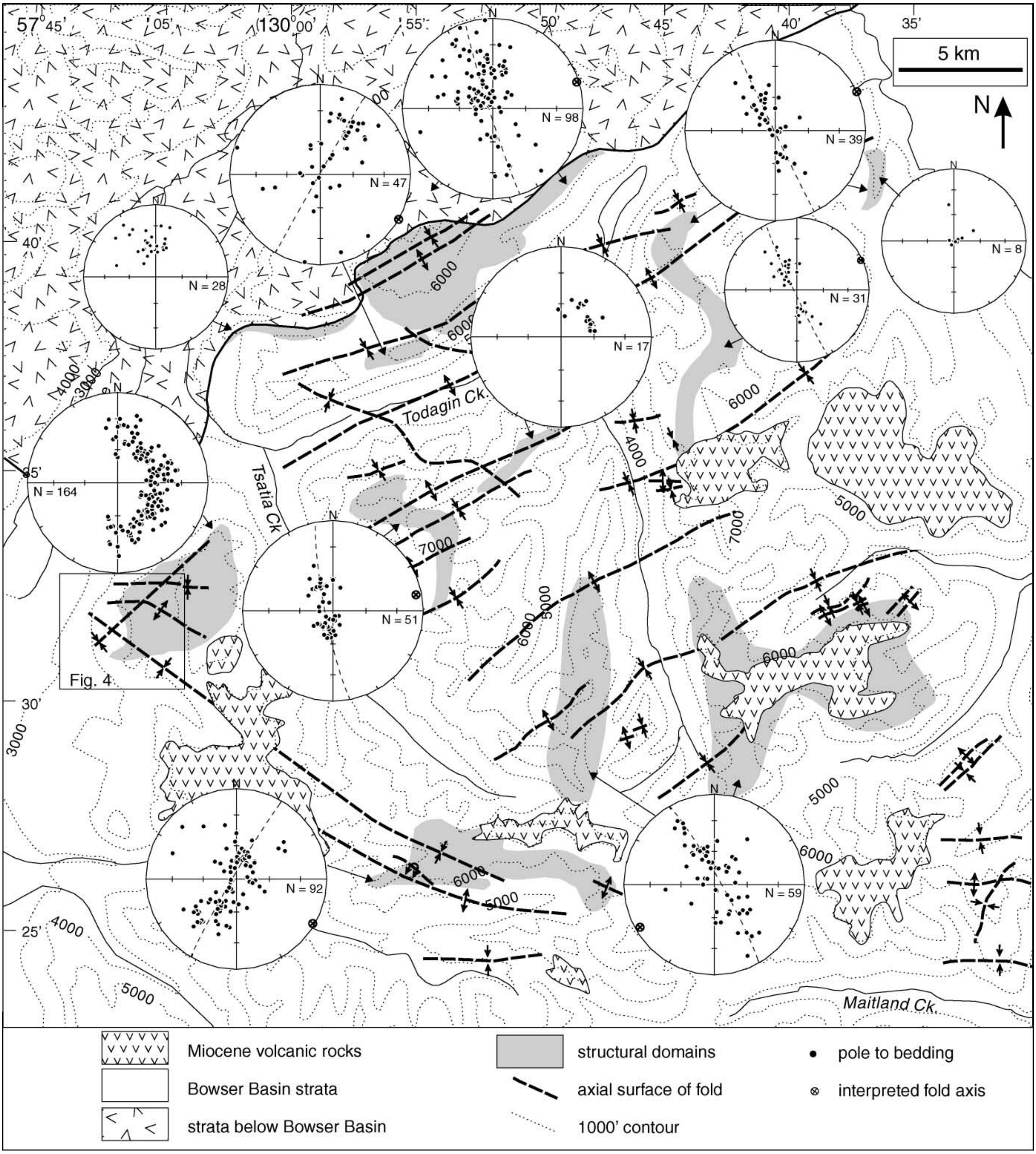


Fig. 3. Structural domains in the Tsatia region (see Fig. 2 for location). Geology from Evenchick and Thorkelson (1993) and unpublished data. Plots are equal area lower hemisphere projections of poles to bedding.

Fig. 2. Map of fold trends and regional geology of the Skeena Fold Belt. Location of Figs. 3, 5 and 10 are outlined. Compiled from Evenchick and Thorkelson (1993), Evenchick (1996, and references therein; unpublished data), Evenchick et al. (2000) and Lewis (1996). Some large variations in trend of axial surface traces in the central part of the map are a result of the intersection of gently dipping surfaces with alpine topography. The map does not include northeast trending warps in the northeast fold belt discussed by Moffat and Bustin (1993). Those folds accommodated little shortening (less than 5%) and are considered here to be a likely result of minor changes in plunge resulting from: (1) variations in shortening along the dominant northwest trending folds, and (2) primary variations in thickness of units. They are not believed to be evidence for two or three superposed deformations (Moffat and Bustin, 1993).

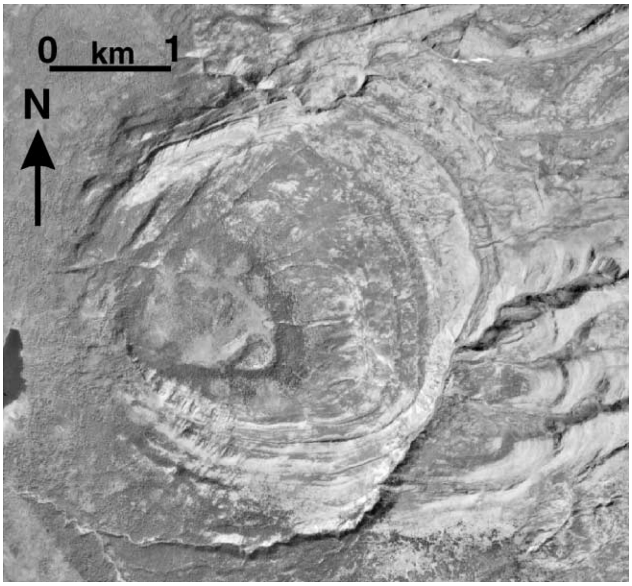


Fig. 4. Aerial photograph of fold interference pattern (basin) in western Tsatia region. Location is shown in Fig. 3.

angles 160–130°), upright to inclined, and 2–5 km in wavelength; inclined folds have subhorizontal or gently dipping limbs several kilometres long, and shorter, moderately southeast-dipping limbs. These folds account for about 5% shortening, and are responsible for the northeast strike of the basal contact of Bowser Basin strata. North and south of Todagin Creek (Fig. 3), they interfere with northwest-trending folds which are tighter, spaced several kilometres, and have vertical or northeast-dipping axial surfaces. They do not affect the basal contact of Bowser Basin strata significantly in Fig. 3, but result in a mappable change of plunge of northeast-trending folds south of Todagin Creek, which is also expressed in plots of poles to bedding (Fig. 3). In the southwestern Tsatia region, the major folds trend northwest and have interlimb angles ranging from 130 to 110°. This is the north part of a large region of northwest and west-northwest-trending folds. Interference of the most continuous northwest-trending syncline with northeast-trending warps is responsible for observed minor changes in plunge of the syncline; at the west side of Fig. 3 the syncline interferes with an open northeast-trending syncline to result in a well exposed dome and basin interference pattern (Figs. 3 and 4). Farther northwest, this syncline (or an en échelon one) results in a map-scale fold of the basal contact of Bowser Basin strata (Fig. 2). Few cleavage data are available; where observed cleavage is parallel with the axial surface of the tighter local fold. Cleavage is strongly developed locally near the basal contact of Bowser Basin strata and in hinges of tight mesoscopic folds in a fault zone in the hinge of a northwest-trending fold. Relative ages of the two fold sets is unclear.

3.2.2. West-central Bowser Basin (Ningunsaw region)

A domain of northeast- and north-northeast-trending folds, 50 km wide and 70 km long, includes the northwest boundary of Bowser Basin strata (Fig. 2). Folding of the boundary at regional map scale is displayed at the south end of the domain by folds with 5 km wavelength (Fig. 2). Only the northeast part of the domain, referred to as the Ningunsaw region (Fig. 5), is discussed.

Northeast-trending folds in the Ningunsaw region have a wide range of geometries. Hinges vary from narrow and angular to broad and rounded, and are open to tight (e.g. Figs. 6 and 7). Fold profiles locally change markedly along strike over several kilometres, and axial surfaces are inclined to both southeast and northwest (e.g. Figs. 6 and 7).

The change from northwest- to northeast-trending folds (Fig. 8) occurs across an arcuate boundary zone, 10–15 km wide. Fig. 5 illustrates that poles to bedding define moderately well-developed great circle girdles outside of the boundary zone, and that abrupt changes from northwest to northeast fold trends occur within or near the boundary zone (e.g. Fig. 5, stereoplots: A, B, D1, D3). Poles to bedding are widely dispersed in some subdomains within or near the boundary zone (e.g. Fig. 5, stereoplots: D2, F). Across the boundary zone in the south, fold trends change westward from west-northwest (H), to northeast (I), to northwest (D3), to unknown, but possibly two orientations (D2), to northeast (D1). The domain boundary zone is structurally complex, possibly including fold interference on a range of scales; importantly, the data do not illustrate a gradual change between northeast and northwest fold trends. Cleavage, where observed, strikes subparallel with the axial surface of the tighter local fold. In two places, within or near the domain boundary, the strike of cleavage is significantly oblique to axial surfaces (Fig. 5, stereoplots: F, G). The relative age of the two fold sets has not been resolved.

3.2.3. Southwest Bowser Basin (Hoan region)

Northeast-trending folds occupy at least 900 km^2 near the southwest extent of the Bowser Basin (Fig. 2). They verge southeast, are upright to overturned, with narrow hinges, and wavelengths a few hundred metres to 2 km (Figs. 9 and 10). Northwest-trending warps are apparent on gently-dipping limbs of northeast-trending folds.

The transition of fold trends from northeast to northwest is shown in Fig. 10. In the west (domain 1), poles to bedding define a moderately well-developed great circle girdle whose pole is in the plane of mapped northeast-striking axial surfaces. Poles to cleavage define a moderately good cluster, with the mean plane dipping 85° southeast, approximately parallel with mapped axial surfaces. To the east, in domain 2, poles to bedding define a girdle similar to that of domain 1, but the poles to bedding are more widely dispersed. The distribution of poles to bedding portrays the northeast-trending folds observed in the field. The scatter from a girdle is a result of northwest-trending warps, and of subdomains of differently oriented folds (described below). Poles to cleavage form a moderately well defined cluster with mean plane dipping 60° west, oblique to axial surfaces of observed map-scale folds, which strike northeast and are vertical to northwest-dipping (Figs. 9 and 10). The general relationship of cleavage to axial surfaces of folds in the Hoan region is shown in Fig. 11. They have the geometry of large-scale counter-clockwise, axially transected folds (Powell, 1974), as described using the parameters and terminology of Borradaile (1978) and Johnson (1991). The transection angle is the angle between the mean cleavage plane and the fold axis, measured in the plane perpendicular to cleavage and containing the fold axis (Fig. 11; Borradaile, 1978). The transection angle of folds in the Hoan region appears to be large in Fig. 10, but there is wide scatter of poles to bedding and cleavage. Plots of poles to bedding and cleavage of selected subdomains illustrate that this scatter is a result of spatial variations in trends and plunges of folds (Fig. 11). Mean transection angle for a large subdomain in the south half of domain 2 is 39°. Different parts of that subdomain made of overturned folds (2A1) and upright or steeply inclined folds (2A2) have transection angles of 37 and 38°, respectively (Fig. 11). Subdomain 2B has cleavage which appears to be fanned, but not about the fold axis, indicating that folds in this subdomain are also transected.

East of the domains with northeast-trending folds are two domains with northerly-trending folds (domains 3 and 4; Fig. 10). In domain 3, cleavage appears to be fanned about an axis subparallel with the fold axis. Whether or not it transects folds (in profile) is unclear because mesoscopic folds were not observed. Domain 4 has north-northwest-trending folds and northwest-trending cleavage. These are inferred to be counter-clockwise axially transected folds, but the paucity of data, spread of cleavage, and absence of mesoscopic folds precludes calculation of the transection angle. Domain 5 has fold orientations and bedding/cleavage relationships typical of the central and eastern Skeena Fold Belt. Mapped folds trend northwest and have subhorizontal plunge. Poles to bedding form a well defined great circle girdle, and poles to cleavage define a moderate cluster with mean plane parallel with axial surfaces of mapped folds. Differences in fold trend between the northern and southern parts of the domain, illustrated by mapped axial surfaces and bedding traces (Fig. 10), are the cause of some of the spread in cleavage strike.

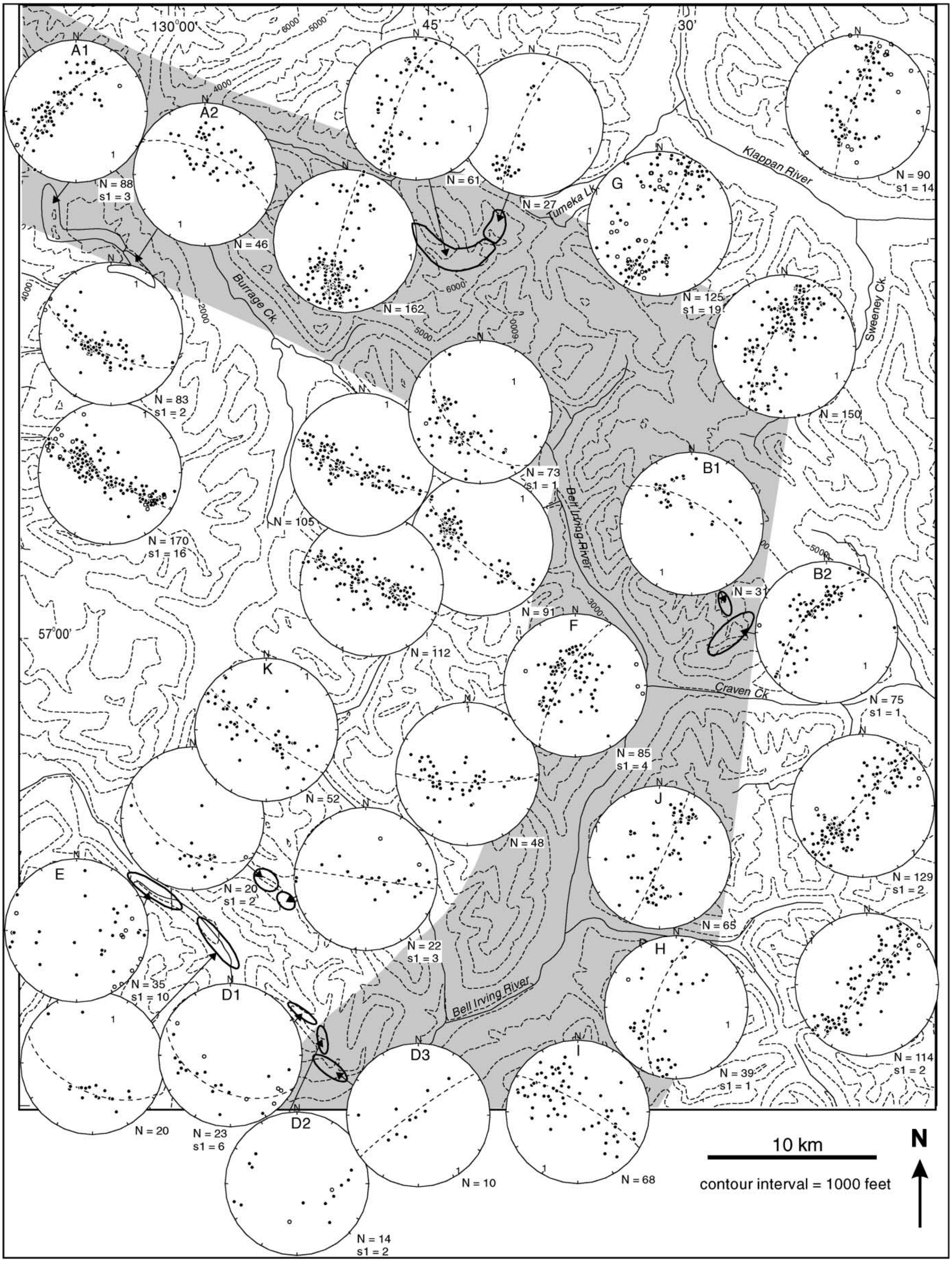
3.3. *Summary of fold geometry in western Skeena Fold Belt*

The western Skeena Fold Belt contains domains of northeast-trending folds bounding a large eastern domain of northwest-trending folds. Fold geometry, relationship of cleavage to folds, and character of transition to the domain of northwest-trending folds, vary widely. In the north (Tsatia) region, changes in plunge because of fold interference, and a well defined fold interference pattern, illustrate that there is not a gradual transition from one fold trend to another. Similarly, in the west-central (Ningunsaw) region, the mixing of subdomains of northeast- and northwest-trending folds across the boundary zone between the two major domains precludes a gradual change in trend of folds belonging to a single population. In the southwest (Hoan) region, there is an eastward transition from northeast- to north-northwest-trending folds, with fold interference locally in the southwest. Cleavage exhibits a similar change in trend, but the transition occurs west of the fold transition, so that there are two domains where cleavage strikes oblique to the axial surface, resulting in transected folds. Overprinting of north-trending cleavage on northeast-trending folds in domain 2, demonstrated by the lack of dispersion of cleavage by folds (Fig. 10), shows that southeast contraction expressed as folds there was followed by east–west contraction expressed as cleavage.

4. Discussion–interpretation of Skeena Fold Belt structural relationships

Folds in the Skeena Fold Belt have consistent orientations over large regions. Northwest-trending folds, found in the eastern two-thirds of the fold belt, have cleavage parallel with axial surfaces. The folds generally verge northeast and accommodated northeasterly shortening. The absence of strike-slip faults cutting this part of the fold belt, or the basal contact of Bowser Basin strata, and the consistency of orientation suggest that transpression or wrenching were not significant factors controlling fold orientation in the eastern fold belt. Instead, following the critical taper model for the formation of fold and thrust belts (Davis et al., 1983), northwest-trending folds in the Skeena Fold Belt are interpreted to have formed as part of a thickening and northeastward expanding orogenic wedge. In this scenario, the wedge included a thickening Coast Belt bounded on the west by a west-vergent thrust belt (e.g. Crawford et al., 1987; Rubin et al., 1990; McClelland et al., 1992). All were possibly related to northeastward subduction beneath the Coast Belt (e.g. Armstrong, 1988, van der Heyden, 1989) in the manner modelled by Willett et al. (1993) for doubly vergent orogens. Orthogonal, dextral or sinistral plate convergence could all result in a margin-parallel zone of crustal thickening, now seen as a northwest-trending Coast Belt, and all could result, therefore, in a fold belt with northwest-trending contractional structures. Margin-parallel components of convergence would be accommodated within or west of the Coast Belt.

Contrary to the above, the domains of north-northeast-trending folds in the western Skeena Fold Belt, in their present orientation, express east-southeasterly shortening which cannot be explained by a similar mechanism because they are highly oblique to the zone of crustal thickening. Interpretations for evolution of the northeasterly trending folds must account for transected folds in the Hoan region and be consistent with the regional tectonic setting in Cretaceous time.


130°00'
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6000
5000
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A1
A2
N = 88
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N = 61
N = 27
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N = 125
s1 = 19
Klappan River
N = 90
s1 = 14
Burrage Ck
2000
N = 83
s1 = 2
Sweeney Ck.
N = 150
N = 73
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D1
Bell Irving River
N = 114
s1 = 2
D3
I
N = 39
s1 = 1
D2
N = 20
N = 23
s1 = 6
N = 10
N = 68
N = 14
s1 = 2
10 km
contour interval = 1000 feet
N

Fig. 6. Photograph of north-northeast-trending angular folds in northwest Ningunsaw region. View is to the south-southwest; cliff face is about 500 m high.

Fig. 7. Photograph of north-northeast-trending folds with curved axial surface; view is north. Location is about 10 km north of Fig. 6.

4.1. Origin of northeasterly trending folds

Potential explanations for the geometry of the folds are: (i) lateral differences in the amount of shortening within the fold belt, (ii) rotation of previously formed folds about a vertical axis attributable to drag or accommodating space for indentors, (iii) influence of basement features, or (iv) transpression bordering the plate margin.

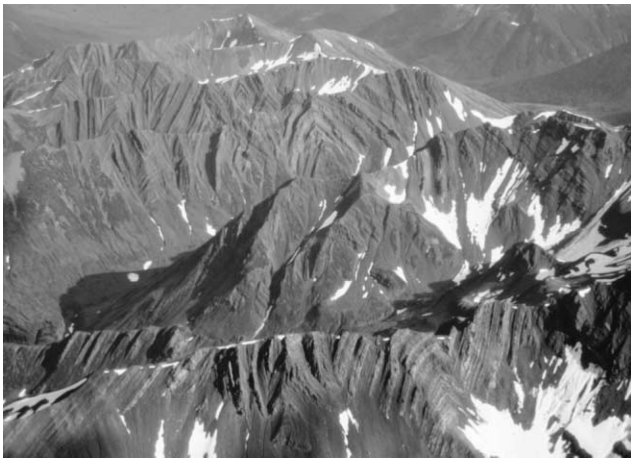


Fig. 8. Photograph of northwest-trending, upright, narrow-hinged folds in the central Skeena Fold Belt. Width of view is about 2 km.

4.1.1. Lateral changes in amount of shortening

Variations in structural trend can be caused by lateral changes in amount of shortening; the result is a gradual change in fold or fault orientation. This mechanism is discounted for northeast-trending folds in the Skeena Fold Belt because: (i) the change in strike is both marked (~90°) and abrupt, (ii) it occurs (in Tsatia and Ningunsaw regions) through a zone of complex folding or fold interference, rather than a gradual change in fold orientation, and (iii) the consistency and magnitude of southeasterly shortening in the Ningunsaw and Hoan regions (minimum 25 and 20 km, respectively) precludes them being zones of reducing shortening at the ends of northeast-vergent structures.

4.1.2. Rotation about a vertical axis

Rotation of pre-existing folds about a vertical axis is discounted because: (i) the consistency of paleocurrent directions from the Tsatia region across the domain boundary into the region of northwest-trending folds indicates that rotation between the two domains was insignificant, (ii) block rotation of 90° is expected to be accompanied by strike-slip faults and manifestations of space accommodation

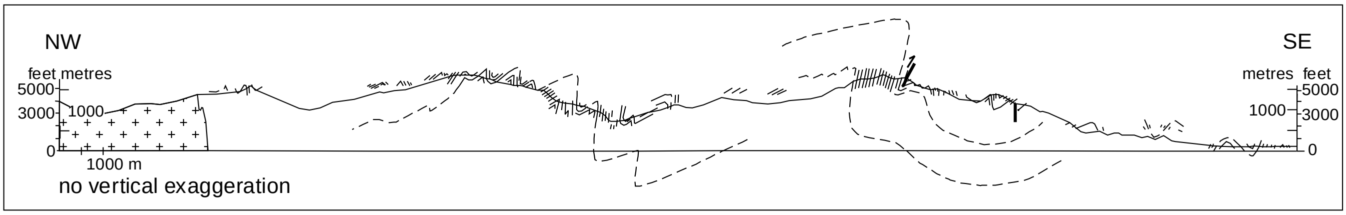
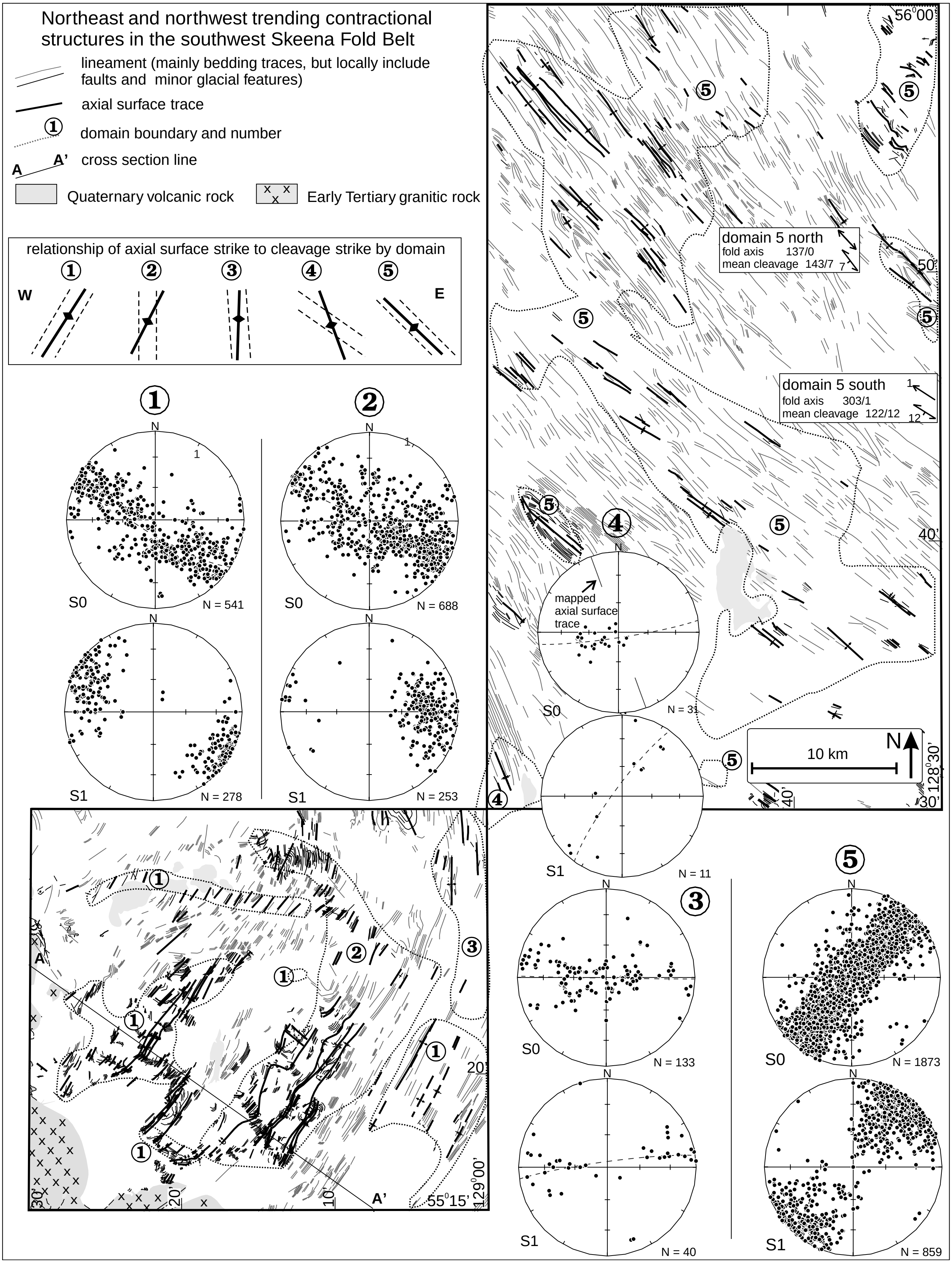


Fig. 9. Cross-section of southern Hoan region; structural style is displayed by bedding traces. Location is shown on Fig. 10.

Fig. 5. Equal area lower hemisphere projections of poles-to-bedding (closed circles) and -cleavage (open circles) in the central Ningunsaw region, showing transition from northeast- to northwest-trending folds. Each projection is centred on areas of study about 3–8 km long (roughly the diameter of the stereogram), which cross structural trend. Ovals outline areas that have been divided into smaller domains. The shaded region is the boundary zone referred to in the text.


Northeast and northwest trending contractional structures in the southwest Skeena Fold Belt
lineament (mainly bedding traces, but locally include faults and minor glacial features)
axial surface trace
① domain boundary and number
A A' cross section line
Quaternary volcanic rock
Early Tertiary granitic rock
relationship of axial surface strike to cleavage strike by domain
① ② ③ ④ ⑤
W
E
S0
N = 541
S1
N = 278
S0
N = 688
S1
N = 253
domain 5 north
fold axis 137/0
mean cleavage 143/7
domain 5 south
fold axis 303/1
mean cleavage 122/12
mapped axial surface trace
N = 31
N = 11
N = 133
N = 40
N = 1873
N = 859
10 km
56°00'
50'
40'
30'
128°30'
20'
10'
55°15'
129°00'

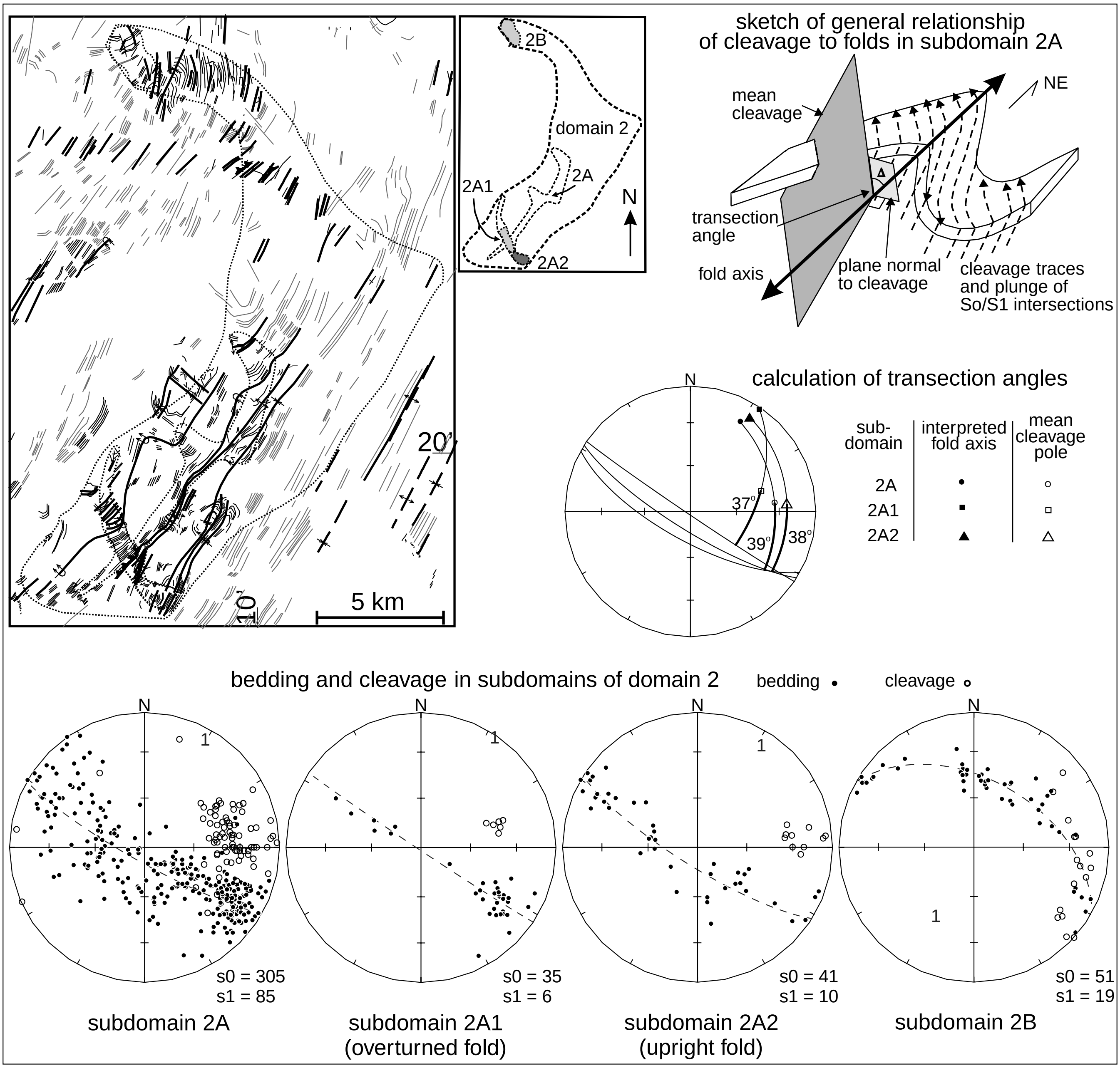


Fig. 11. Subdomains of domain 2 of the Hoan region, illustrating the discordance between cleavage and the axial surface of folds. Map at upper left is domain 2 in Fig. 10, with subdomains outlined. Sketch at upper right shows the general relationship between folds and cleavage, and the angle defined as the transection angle. Lower row of stereograms shows data for subdomains, and the plot above shows calculation of transection angles from mean cleavage and interpreted fold axes of subdomains following the method of Johnson (1991). Stereograms are equal area lower hemisphere projections of poles-to-bedding (closed circles) and -cleavage (open circles).

for which there is no evidence, and (iii) to result in the transected folds it would require a complicated scenario of shortening of only part of a rotating block, and successively different parts of the block.

4.1.3. *Influence of basement*

Basement features can cause large variations in strike of contractional structures if strata moved over basin margin promontories, or if basement structures oblique to the

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Fig. 10. Structural domains in the Hoan region, showing the transition from northeast- to northwest- trending folds displayed by bedding traces, axial surface traces, and plots of poles-to-bedding (top) and -cleavage (bottom). Plots for each domain are equal area lower hemisphere projections. Some large variations in trend of bedding traces and axial surface traces in the southern third of the map are a result of the intersection of dipping surfaces with alpine topography. Geology simplified from Evenchick (1996).

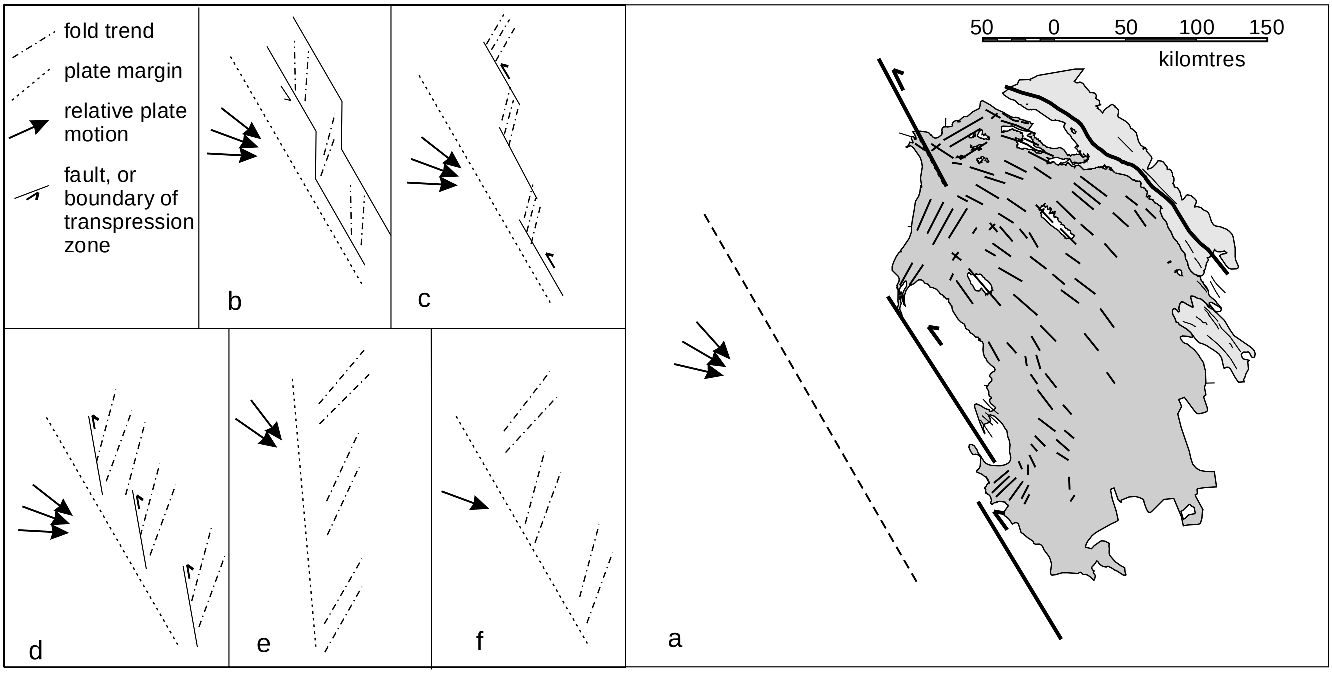

Fig. 12. Model for development of northeast-trending folds in the Skeena Fold Belt (b)–(f), and application of (c) to the fold geometries in the fold belt (a). See text for explanation; arrow array shows variation of possible relative plate motion directions. Fig. 12b is modified from Fig. 11 of Sanderson and Marchini (1984).

structural grain were reactivated. The case of primary basin geometry influencing fold orientation as, for example, in the Appalachians (Thomas, 1977) is difficult to envision for the Skeena Fold Belt because the eastern fold belt does not mirror the variations in trend at its west side. A case in point is the Ningunsaw region, which ends abruptly to the southeast and northeast against the domain of northwest-trending structures. In addition, the across-strike distance from the northwest side of the Hoan region to the present south limit of basin strata is 100 km. Southeasterly shortening of at least 50% over this distance, in a direction perpendicular to the dominant structural trend of the fold belt, is difficult to reconcile as simply the result of promontories influencing trends in an otherwise northeast-vergent system. There is no evidence to suggest that promontories existed on a basin margin south of the Hoan region. The fact that Stikinia rocks are themselves involved in northeast-trending folds further suggests that the primary configuration of the Bowser Basin was not an influence on fold orientation.

Reactivated basement structures could potentially result in northeast-trending folds. Hypothetical northeast-trending pre-Cretaceous faults in Stikinia could be reactivated to result in zones of southeasterly shortening in the Skeena Fold Belt during northeasterly through southeasterly convergence. Stikinia west of the Bowser Basin does not contain a suite of pre-existing northeast-trending faults, nor is there significant differential uplift along northeast-trending zones that might reflect cryptic structures. Alternatively, the fold trends could reflect either dextral or sinistral wrenching along easterly or northerly trending basement faults, respectively. Easterly trending dextral faults of significant magnitude are not known. Northerly trending sinistral faults are uncommon, but include the South Unuk Shear Zone of Jurassic age (Fig. 2; Lewis, 1996). It is conceivable that wrenching along reactivated hypothetical relatives of this fault resulted in northeast-trending folds.

4.1.4. Oblique convergence and transpression

Orientations of structures expected at obliquely convergent margins vary widely depending on the amount of strain, the angle of convergence, the degree of partitioning into strike-slip and convergent zones, and the percentage of strike-slip partitioning (e.g. Sanderson and Marchini, 1984; Fossen and Tikoff, 1998; Teyssier and Tikoff, 1998). Models for the development of folds in transpression zones such as those of Harland (1971) and Teyssier and Tikoff (1998) predict the initiation of folds (maximum instantaneous shortening) at a maximum of 45° to the plate boundary for the end-member of wrenching with no convergence, and at significantly lower angles in zones of transpression with increasingly oblique angles of convergence, and/or increasing proportion of strike-slip partitioning. With continued boundary-parallel displacement and/or convergence, the folds would be expected to rotate to even lower angles with the plate boundary. Application of these concepts to folds in the western Skeena Fold Belt requires assumptions to be made as to the orientation of the plate boundary in Cretaceous time. Because the Coast Belt represents the magmatic arc resulting from plate consumption

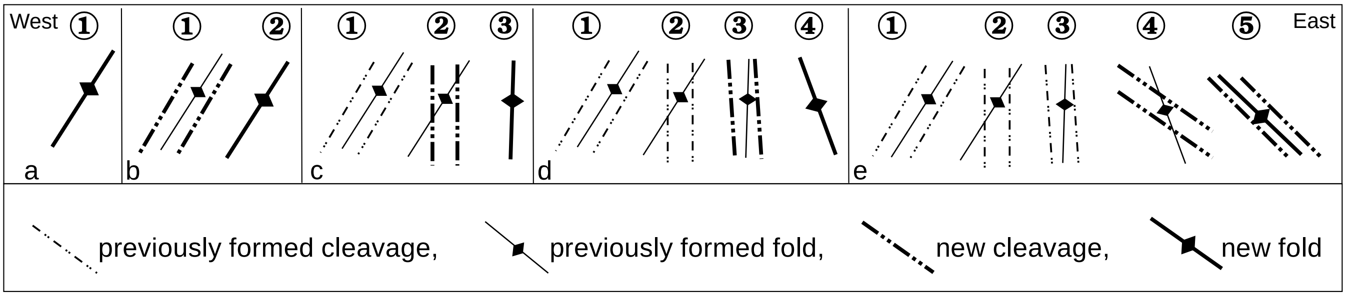

Fig. 13. Model for stages of formation of transected folds in the Hoan region of the Skeena Fold Belt Circled numbers are the domains shown in Fig. 10.

(Armstrong, 1988; van der Heyden, 1989) the plate margin is assumed to have lain somewhere in, or west of, and subparallel to the Coast Belt. The trend of the Coast Belt is presently 330°; allowing for primary variations and later modification, it is assumed to have had a trend in Cretaceous time between 310 and 350° (present coordinates, using an arbitrary 20° deviation from the present orientation). The kinematics, age, and magnitude of transcurrent faults in the Coast Belt are not well known, but given that none are significantly oblique to the orogen, they are not considered to have modified the orientation of the belt significantly. Using the range of fold orientations expected in transpression noted above and the assumed range of margin azimuth, the maximum ranges of fold trends expected in dextral and sinistral transpression are 265–350° and 310–035°, respectively (dihedral angles). Folds in the Hoan and Ningunsaw regions range in trend from 025 to 035°, whereas those in the Tsatia region trend about 065°. Therefore, folds in the Hoan and Ningunsaw regions can be attributed to sinistral transpression, but only in the extreme case of wrenching with little or no convergence and the most northerly option of plate margin orientation. All northeasterly trending folds can be accounted for if additional conditions are entertained, for example: (i) lateral changes in azimuth of the boundary (e.g. Fig. 12b), (ii) zones of high-angle structures at the termination of wrenching (Fig. 12a and c), (iii) transtension (e.g. bottom of Fig. 5 from Sanderson and Marchini, 1984), (iv) the plate boundary, although on a large scale north-northwest-trending, comprised more northerly trending en échelon transpression zones (Fig. 12d), (v) the plate boundary was more northerly than assumed (Fig. 12e), or (vi) pure shear in a zone oblique to the convergence direction, along a belt roughly parallel with the plate margin (Fig. 12f). One or more of these options may have operated in the western Skeena Fold Belt. For example, a more northerly deviation in plate boundary orientation may have caused the folds in the Tsatia region, while folds in the Ningunsaw region may have formed at the end of a wrench zone. In all cases, the Coast Belt likely absorbs significant orthogonal convergence. These options are simplistic, and many more could be envisioned with different combinations of strain partitioning or local deviations in boundary orientation. Nevertheless, the significant relationship is that folds with western Skeena Fold Belt trends are, in all cases, compatible with sinistral plate convergence. The orientation of folds is used to infer the *sense* of convergence, rather than the direction.

4.2. Transected folds

Folds in domain 2 of the Hoan region have the geometry of counter-clockwise, axially transected folds with transection angles of 37 and 38° (Fig. 11). They are not considered to be the products of two unrelated deformational events because: (i) there is no regional evidence for another post-Jurassic contractional event restricted to the western side of the fold belt, (ii) the orientations of bedding and cleavage in the Hoan region define a successive eastward change of shortening direction, that, as a result of unrelated deformations, would require three separate deformations, which coincidentally give the appearance of a gradual change in trend, and which are restricted in area, and (iii) the intermediate ‘deformation’ resulting in north-trending folds is found only in the Hoan region, and the cleavage in any one domain is parallel with the axial surface of folds only in the domain on its east. These relationships are difficult to explain by unrelated superposed deformations.

Transected folds, if not a result of superposed deformations, may arise from folding of a plane oblique to incremental strain axes (Borradaile, 1978; Treagus and Treagus, 1981). To account for Skeena Fold Belt transected folds by this means would require that: (i) the regional cleavage be oriented consistently, and (ii) because of the high transection angle, the particular case of single phase constrictional folding and regional dip of 20° or more (Treagus and Treagus, 1981). Instead, cleavage changes orientation by 90°, and although constrictional strain cannot be ruled out, it is unlikely that primary regional dip in the submarine fan facies of the Bowser Basin was greater than 10°. Moreover, large primary dips would result in moderately or steeply plunging folds, whereas most folds in the Hoan region, including those where transection angles were calculated, are gently plunging (Figs. 10 and 11).

Transected folds may also be produced by relative rotation of incremental strain axes and a short time gap between development of folds and cleavage (Powell, 1974). This explanation has been applied to transected folds in the

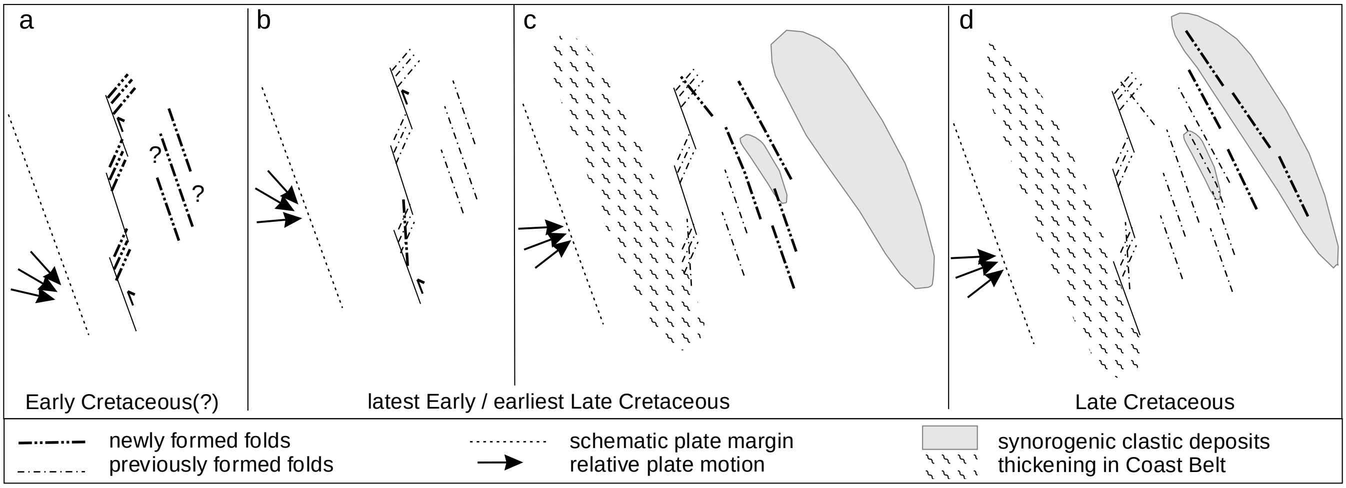

Fig. 14. Model for evolution of the Skeena Fold Belt (see text for explanation).

Appalachians and British Caledonides (e.g. Borradaile, 1978; Soper, 1986; Blewett and Pickering, 1988; Pratt and Fitches, 1993), amongst other options (e.g. Treagus and Treagus, 1981; Lafrance et al., 1989). Those who favor rotation of incremental strain axes commonly cite transpression as the cause, although interpretations of specific cases are debated. Transected folds resulting from homogeneous transpression of initially gently dipping layers should have small transection angles (Treagus and Treagus, 1992), as is the case in the Appalachian/Caledonide orogen (commonly less than 20°). Transection angles in the Skeena Fold Belt of up to 38° are, therefore, difficult to explain by homogeneous transpression. Treagus and Treagus (1992) noted that large transection angles could result from initial horizontal layering given a deformation history of non-uniform transpression.

One explanation for the transected folds in the Skeena Fold Belt is an eastward migrating deformation zone, with the formation of cleavage lagging behind the formation of folds (Fig. 13). The inference is that north-trending cleavage, which overprints northeast-trending folds in domain 2, formed at the same time as north-trending folds farther east (domain 3; Fig. 13c), and that later, northwest-trending cleavage overprinted the north-trending folds in domain 4 during the formation of northwest-trending folds farther east (Fig. 13e). This explanation is consistent with the large scale framework of the fold belt, and fold belts in general (e.g. Wiltschko and Dorr, 1983), in that rather than folds forming instantaneously across the whole region, a front of deformation migrated cratonward, in this case northeastward, as the fold belt evolved. In this interpretation, the transected folds are a result of relative rotation of incremental strain axes in response to either changes in the direction of plate convergence or changes in how regional strain was partitioned, i.e. some sort of non-constant deformation history. In both cases, the plate margin, including the western Hoan region, was experiencing sinistral convergence, but the Hoan region itself was not a zone of constant homogeneous transpression.

4.3. Model for evolution of the Skeena Fold Belt

A model for evolution of the Skeena Fold Belt must explain the large domains of folds highly oblique to the dominant shortening direction, their restriction to the western side of the fold belt, and the transected folds. Although specific processes controlling orientation of the northeast-trending folds is unclear, it is most reasonably explained by some mode of sinistral convergence on the Cordilleran margin. Fig. 14 shows fold development for the case of shortening at terminations of transcurrent faults, but the evolution described applies to the other viable options (Fig.13). Overprinting relationships in the Hoan region indicate that southeasterly shortening there was early in the history of the fold belt (Early Cretaceous; Fig. 14a). Relative timing of folds is less clear, however, in the Ningunsaw and Tsatia regions. It is permissible (but not demonstrated) that a portion of the orthogonal component of plate convergence was transferred to the east via local strain partitioning, allowing the formation of northwest-trending structures at this time in some areas (question marks in Fig. 14a). After northeast-trending folds developed, rotation of incremental strain axes resulted in transected folds in the Hoan region (Fig. 14b). It is unclear precisely when this change happened, but sinistral convergence continued at least until this time, and possibly continued if the change in local strain axes arose from a change in strain partitioning rather than a change from sinistral to dextral plate convergence. The latter could not strictly be the cause according to Fossen and Tikoff (1998), who point out that the plate motion vector is not parallel with incremental shortening direction in areas of oblique convergence. Nevertheless, the change in plate motion could have initiated a change in strain partitioning.

Significant crustal thickening in the Coast Belt and development of the west vergent thrust belt in mid-Cretaceous time (e.g. Crawford et al., 1987; Rubin et al., 1990; Journeay and Friedman, 1993) may have been the cause of northeastward migration of the front of the fold belt (and northwest-trending folds) as the orogenic wedge expanded in order to maintain critical taper (Fig. 14c). Structures transferring displacement to the front of the fold belt would have carried the earlier formed ones piggy-back, locally overprinting northeast-trending folds with northwest-trending warps. The timing of events in the Coast Belt relative to the fold belt is poorly constrained, but the oldest synorogenic clastic deposits in the central and eastern fold belt, of latest Early Cretaceous age, and their overlap on contractional structures, are a manifestation of northeast shortening, crustal thickening, and uplift in the central fold belt during this period. If the transition from sinistral to dextral convergence was accompanied by appreciable crustal thickening, this is the first indication of that change. The next development which might reflect the transition was an influx of coarse clastics into the upper part of the synorogenic (Sustut) basin beginning in Campanian time (ca. 80 Ma). Formation of northwest-trending folds continued into latest Cretaceous or earliest Tertiary time (Fig. 14d), concurrent with dextral transpression in the Coast Belt which was ongoing at 76 Ma and continued to 59 Ma (Andronicos et al., 1999).

The scenario described above satisfies the major structural and depositional relationships in the Skeena Fold Belt. The general evolution of structures is similar to other fold belts (e.g. Wiltschko and Dorr, 1983), with older structures (in this case those trending north-northeast) forming closer to the plate margin, and younger structures carried them (cratonward) into undeformed regions as the fold belt widened to maintain critical taper of the orogenic wedge. The model is consistent with structural development in the Coast Belt, and with relative plate motion studies, which indicate sinistral convergence in Early Cretaceous time followed by a transition to dextral convergence in mid-Cretaceous time (Engebretson et al., 1985; Kelley, 1993).

4.4. Other regional features related to Early Cretaceous sinistral convergence

The timing of the transition from sinistral to dextral convergence is not tightly constrained by structures in the Skeena Fold Belt. Other regions with sinistral faults, or with structures consistent with sinistral convergence, but not previously inferred as such, are examined to: (i) provide better constraints on the age of the transition, (ii) determine their regional extent, and (iii) elucidate the regional tectonic setting of the Skeena Fold Belt.

4.4.1. Northwest-trending Cretaceous faults with sinistral displacement

Of the few reported Cretaceous sinistral faults in the North American Cordillera, the most thoroughly studied is a system of faults bordering the southern Coast Belt. They include the Pasayten fault zone (Lawrence, 1978; Greig, 1992; Hurlow, 1993) and offset segments to the north in the vicinity of the Yalakom Fault (Miller, 1988; Schiarizza et al., 1990; Fig. 1). Constraints on sinistral displacement for different parts of the fault system and its relationship to the tectonic evolution of the North Cascades orogen are reviewed by Hurlow (1993), who concluded that the Pasayten fault zone underwent 20 km of sinistral displacement between 109 and 95 Ma, and that northwest-vergent contractional structures were kinematically linked to the sinistral strike-slip. Explanations for sinistral displacement on the Pasayten fault zone and related features are that it accommodated: (i) sinistral plate convergence, or (ii) lateral escape of a crustal sliver (Hurlow, 1993).

Mesozoic faults in the northern Cordillera are less well understood. Gehrels and Boghossian (1999) describe the northwest-trending Kitkatla fault zone in the western Coast Belt (Fig. 1) as a sinistral shear zone which was active between ca. 130 and 100 Ma, based on geochronometry of van der Heyden (1989). An analysis of foliations derived from reconnaissance maps led Chardon et al. (1999) to a similar interpretation for this and other faults. Farther northwest, a suite of north- to northwest-vergent thrust faults and nappes on Admiralty and Kupreanof Islands, southeast Alaska (Fig. 1), are inferred to have developed between 110 and 102 Ma; a change from northwest- to west- or southwest-vergence was complete by 102 Ma (Haeussler et al., 1999). These, as well as southeast vergent thrusts farther south, and a 113 Ma sinistral ductile shear zone on Chichagof Island may be the result of sinistral transpression (P. Haeussler, personal communication, 2000).

4.4.2. Contractional structures potentially related to sinistral convergence

Numerous domains of southeasterly contraction within or east of the Coast Belt are compatible with sinistral convergence in their present orientation. Detailed discussion of the context of each to determine its relationship to Early Cretaceous tectonics is beyond the scope of this paper. Some examples are given to illustrate the range of locales and styles.

Uncommon northeast-trending folds and thrust faults occur in Stikinia east of the Coast Belt between 56.5 and 58°N (Read, 1983; Read et al., 1989). Because some involve Jurassic rocks and one is overlapped by the Sustut Group, Read et al. (1989) concluded that all of the structures were Early Cretaceous age. A northeast-trending tight to isoclinal upright anticline of Stikinian rocks, at least 10 km in wavelength, occurs at Atna Peak in the east-central Coast Belt (Fig. 1; Evenchick, 1979); its age is latest Early Cretaceous based on unpublished U–Pb data for an intrusion considered to be synkinematic with the fold (G.J. Woodsworth, personal communication, 2000). The south-southeast directed Terrarosa Thrust and recumbent folds occur in the Fire Lake area of the southeast Coast Belt (Fig. 1; Lynch, 1990). The age of southeast contraction is constrained by

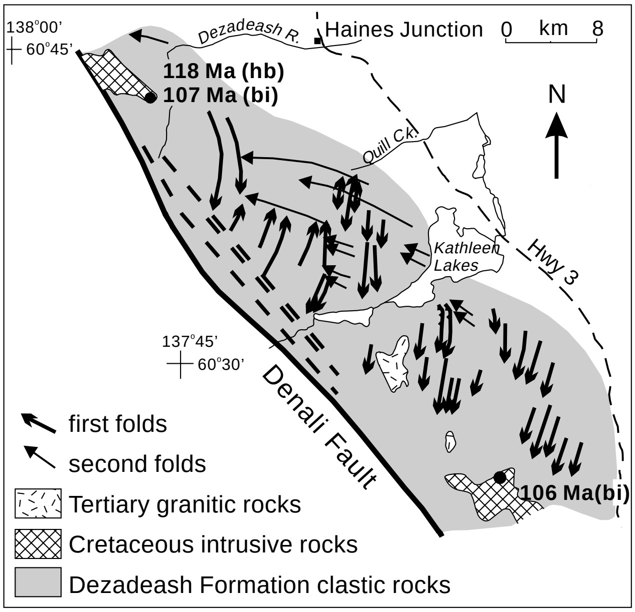

Fig. 15. Map of axial surface traces in the Dezadeash Formation, Yukon Territory (arrows point to direction of plunge). Simplified from Eisbacher, 1976.

a Barremian to Middle Albian youngest age for the Fire Lake Group, and an earliest Late Cretaceous age (96 Ma) for overprinting, north-northwest trending contractional structures (Journeay and Friedman, 1993). Northwest-vergent recumbent folds occur in the Chilliwack Valley, southern Coast Belt (ca. 49°N), and are also overprinted by northwest-trending contractional structures. The early folds are interpreted to be mid-Cretaceous age (Monger, 1966).

In southwest Yukon Territory, the Hauterivian to Valanginian Dezadeash Formation has two sets of superimposed folds and is bounded on the west by the Denali Fault (Eisbacher, 1976; Fig. 15). The first set of folds, with north-northeast trends, were speculated to have been a result of the same tectonic slope which controlled earlier syndepositional slump folds (Eisbacher, 1976). Their trend, however, is about 30° from the inferred northeast-dipping paleoslope, and they do not show the wide range of fold axes documented for the slump folds. An alternative interpretation, suggested here, is that the north-northeast-trending folds can be a result of sinistral displacement on a proto-Denali fault in one of the options considered viable for the northeast-trending folds in the Skeena Fold Belt (Fig. 12). Based on the Valanginian age of the rocks and the first folds being cut by a pluton with a K–Ar (biotite) age of 106 Ma, Eisbacher (1976) concluded that the north-northeast-trending folds formed between 130 and 106 Ma. If the assumption that the region has not rotated significantly about a vertical axis since the first folds formed is valid, sinistral convergence is inferred to have been ongoing at this time.

In summary, structures interpreted to be related to sinistral convergence of demonstrable Cretaceous age can now be inferred for several areas bounding the south, central, and north Coast Belt, a distance of over 1700 km. At the southern terminus of the Coast Belt, they span the width of the belt. Sinistral displacements in the southern, central, and northern Coast Belt can be shown to continue into ca.100 Ma. It is unclear in each situation whether the change in local shortening direction reflects a change in strain partitioning or change in direction of plate motion. The prominence of dextral structures of Late Cretaceous age, however, as manifested in the Coast Belt by dextral transpression starting in the south at ca. 96 Ma (Journeay and Friedman, 1993) and ongoing in the north at 76 Ma (Andronicos et al., 1999), as well as dextral faults in the northern Omineca Belt synkinematic with the latest stages (ca. 98 Ma) of intrusion of the Cassiar plutonic suite (Gabrielse, 1985), indicates that the change in plate motion was around 100 to 95 Ma. This is broadly contemporaneous with the transition from sinistral to dextral convergence predicted by relative plate motion studies based on ocean floor reconstructions. The change could well have been diachronous along the plate margin, and the possibility that some sinistral structures overlapped in age with dextral ones during orthogonal, or near orthogonal, convergence must be considered.

5. Conclusions

Three large domains with northeast-trending folds at a high angle to other contractional features in the Skeena Fold Belt, and to the presumed North American Plate margin in Cretaceous time, are described and possible explanations for their origin are explored from a complex dataset. They are an example of complex structures formed in the upper crust marginal to a plate boundary in oblique convergence. Although the specific origin of the northeast-trending folds remains enigmatic, they are deduced to be a result of sinistral convergence. The fold belt is interpreted as having evolved from a first stage in which structures with anomalous orientations formed close to the plate margin in response to the *sense* of oblique plate convergence. The fold belt progressed to a stage which produced structures more inboard whose orientation, subparallel to the Coast Belt, was controlled by the thickened orogenic wedge, and which could be achieved in any sense of oblique convergence. Overprinting relationships suggest that northeast-trending folds were some of the earliest formed, and therefore are of Early Cretaceous age. Other examples of Early Cretaceous structures, including several not previously considered to be related to sinistral convergence, define a zone over 1700 km long within and immediately adjacent to the Coast Belt, which experienced sinistral convergence into ca. 100 Ma. Collectively, they lend independent support to models of relative Pacific (Kula)–North American plate motions which infer sinistral convergence into mid-Cretaceous time (Engebretson et al., 1985; Kelley, 1993). Recognition of the regional nature of faults and folds related to sinistral convergence provides a regional tectonic framework for interpretation of Early Cretaceous structures in the northern Cordillera.

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