Structural Overprinting in the Northwestern Skeena Fold Belt (NTS 104B, H), Northwestern British Columbia[1]

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INTRODUCTION

The Skeena Fold Belt, as defined by Evenchick (1991a), is located in northwestern British Columbia, in the Stikine Terrane of the Intermontane Belt of the Canadian Cordillera (Fig 1). The distribution of the Skeena Fold Belt roughly mirrors the location of the Mesozoic Bowser Basin, and the fold belt is predominantly developed in the Middle Jurassic – Early Cretaceous Bowser Lake Group of the Bowser Basin. The Early Jurassic Hazelton Group and the Late Cretaceous Sustut Group are also affected by folding and thrust faulting. Two regional fold trends are present within the Skeena Fold Belt: northwest-trending folds are dominant in the eastern two-thirds of the fold belt, and northeast-trending folds are present in the western third (Fig 1). Locally, these fold trends are found outside their dominant domains and overprint each other (Evenchick, 1991a; Evenchick, 2001). It is the aim of this study to evaluate overprinted structures and their timing relationships. Fieldwork was conducted in 2006 as a follow-up to fieldwork carried out in the summer of 2005 and reported on by Waldron *et al.* (2006). This work accompanies that reported by Gagnon *et al.* (2007).

In an effort to aid in hydrocarbon exploration within the Bowser Basin, recent studies of its petroleum potential by the Geological Survey of Canada and BC Ministry of Energy, Mines and Petroleum Resources (Osadetz *et al.*, 2003; Evenchick *et al.*, 2003) have focused on updating the thermal maturity models of Bustin and Moffat (1989), which predicted unfavourably high heat flow to much of the Bowser Basin, and on developing models for assessing the effectiveness of petroleum systems. In addition to conventional petroleum, there is potential for coalbed methane and conventional coal. Mineral potential exists in volcanic rocks on the flanks of the basin (Fig 1), as shown by the high-grade stratiform volcanogenic massive sulphide (VMS) Au-Ag deposits at Eskay Creek (Roth *et al.*, 1999).

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Understanding the structural history of the region will contribute to exploration and evaluation of these resources.

REGIONAL STRATIGRAPHIC FRAMEWORK

The mapped regions of the Skeena Fold Belt expose rocks of the Middle Jurassic – Early Cretaceous Bowser Lake Group, including the Ritchie-Alger, Eaglenest and Skelhorne lithofacies assemblages, described in Evenchick and Thorkelson (2005). The lack of regionally correlative boundaries in the Bowser Lake Group makes the use of formal formation/group designations difficult. Synchronous deposition of shallow and deep marine facies occurred; the Bowser Lake Group reflects an overall progradational depositional history.

The Ritchie-Alger assemblage comprises sandstone, siltstone and shale, with rare chert-rich conglomerate. Sheet-like intervals of fine to medium-grained sandstone, separated by shale intervals that are metres thick, have been interpreted to relate to submarine fan deposition (Evenchick and Thorkelson, 2005). Evidence of turbidite accumulation within the submarine fan complexes includes normal grading, groove casts, dewatering structures and Bouma cycles. The Ritchie-Alger assemblage is estimated to reach thicknesses of 1800 m in the western third of the Bowser Basin (Evenchick and Thorkelson, 2005).

The Skelhorne lithofacies assemblage comprises more than 1000 m of siltstone, sandstone and conglomerate (Evenchick and Thorkelson, 2005). Common medium to thick-bedded coarsening-upward cycles, marine and plant fossils, wave-generated ripples and bioturbation are interpreted to record a moderate-energy deltaic depositional environment (Evenchick and Thorkelson, 2005). The Skelhorne assemblage is most common in the west-central part of the Bowser Basin.

The Eaglenest lithofacies assemblage comprises a high percentage (up to 80%) of rusty- weathering conglomerate and sandstone, with minor siltstone and shale, and reaches thicknesses of 1000 m (Evenchick and Thorkelson, 2005). Conglomerate clasts are well-rounded and well-sorted pebbles composed predominantly of chert. Plant fossils, including substantial silicified trees, are abundant, whereas marine fossils are rare. The abundance of conglomerate, coarsening-upward cycles and tree fossils all suggest a high-energy deltaic depositional environment (Evenchick and Thorkelson, 2005).

EXISTING STRUCTURAL FRAMEWORK

The Skeena Fold Belt overlies the Stikine Terrane of the Intermontane Belt (Evenchick, 1991a). The Skeena

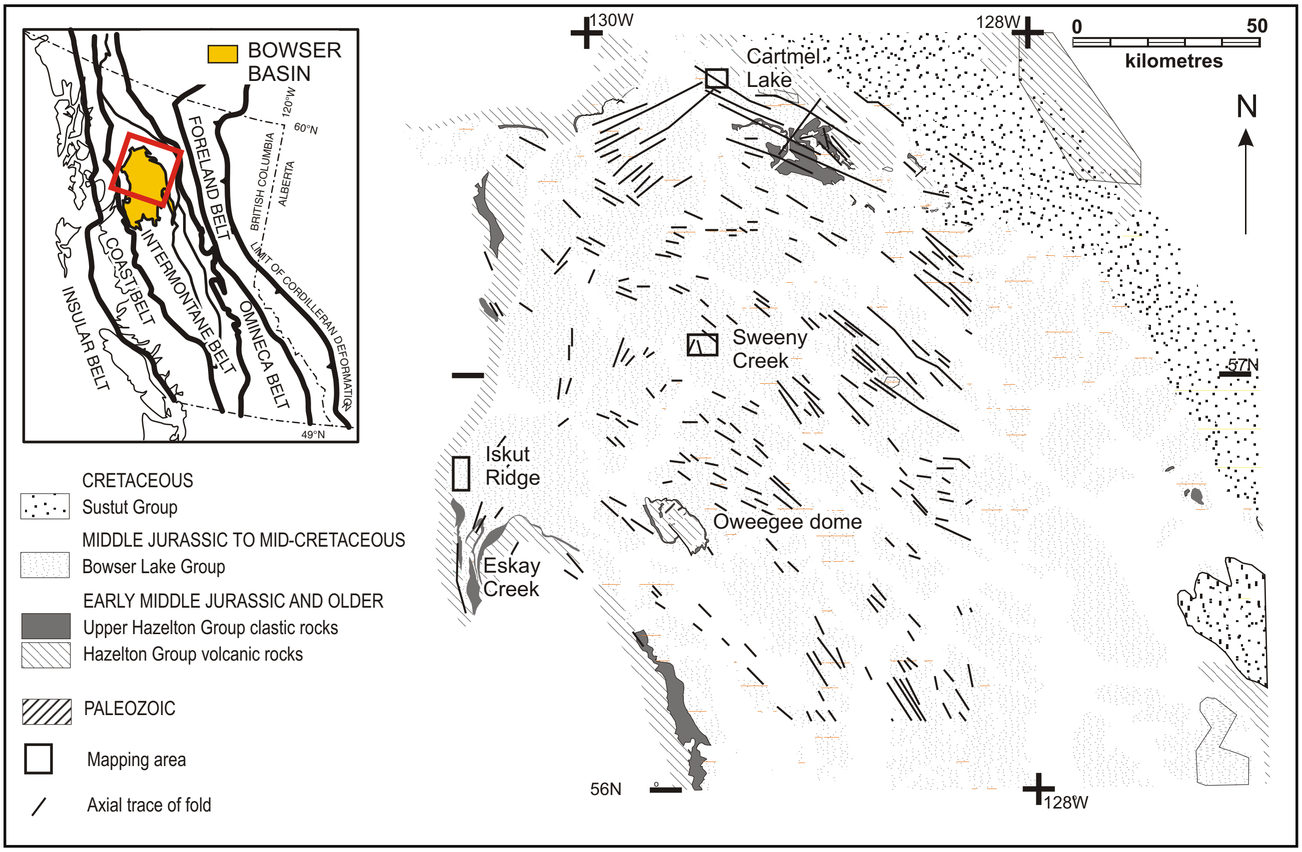

Figure 1. Simplified regional geology of the northwestern Skeena Fold Belt (*compiled from* Evenchick, 1991a; Bone, 2002; Evenchick and Thorkelson, 2005; Waldron *et al.*, 2006), showing fold axial traces and study areas referred to in the text; inset shows location of figure within the Canadian Cordillera.

Fold Belt was formed between the Albian and early Tertiary (Evenchick, 1991a; Evenchick and Thorkelson, 2005). The fold belt has been interpreted as a fold-and-thrust belt rooted in the Coast Mountains (Evenchick, 1991b). Evenchick (2001) suggested that oblique northwest-southeast shortening occurred first, affecting the western Bowser Basin, and was followed by a long period of northeast-southwest shortening that generated northwest-trending folds, parallel to the surface strike of the Canadian Cordillera. On the basis of work conducted in the Groundhog coalfield, Moffat and Bustin (1993) proposed three periods of shortening: initial northeast-southwest shortening, then northwest-southeast shortening and lastly northeast-southwest shortening. Bone (2002) examined a basinal fold-interference pattern identified by Evenchick (1991a), formed by intersection of two similar-scale synclines, confirming the presence of type I fold interference (Ramsay, 1967); interference of this type can produce domes favourable to petroleum accumulation.

2006 FIELD MAPPING

During the 2006 field season, six areas were mapped at 1:25 000 scale from helicopter-positioned fly camps (Fig 1). Results from three of these areas are reported on here. The Iskut ridge area was selected due to its proximity to the Eskay Creek area, an area known to have multiple generations of folds (Read *et al.*, 1989; Lewis, 1992; Waldron *et al.*, 2006). The Cartmel Lake area was selected as an area dominated by northwest-trending folds with possible overprinting of northeast-trending folds, recognized by Evenchick and Green (2004). The Sweeny Creek area was chosen for its convergence of fold trends, as shown by Evenchick (2004).

Iskut Ridge

A small ridge, east of the Iskut River and north of Palmiere Creek at the western margin of the Bowser Basin, is herein referred to as ‘Iskut ridge’ (Fig 1). All rock units observed in this area are assigned to the Ritchie-Alger lithofacies assemblage (Evenchick *et al.*, 2004). Structure in the Iskut ridge area is dominated by north and north-northeast-trending folds traceable throughout much of the map area (Fig 2). North-trending folds are rounded and open to tight. Mappable deflections in north-trending axial traces occur near southeast-trending minor folds. Minor folds are open to tight, and commonly plunge steeply (~60º) southeast.

Equal-area projections of poles to bedding (Fig 3a) show a diffuse girdle distribution with an eigenvector 1 plunging steeply toward the southeast. These data suggest small-scale folding about a southeast-plunging axis, in contrast to map-scale relationships that indicate north-trending folds as the dominant structure. Cleavage is ubiquitous within fine units of the turbidite succession and sporadic in coarser sandstone. Pencil lineations are widespread, defined by intersection of steep bedding and steep cleavage. Cleavage data shown in Figure 3b lie in two clusters: a dominant steeply dipping cleavage that strikes northwest,

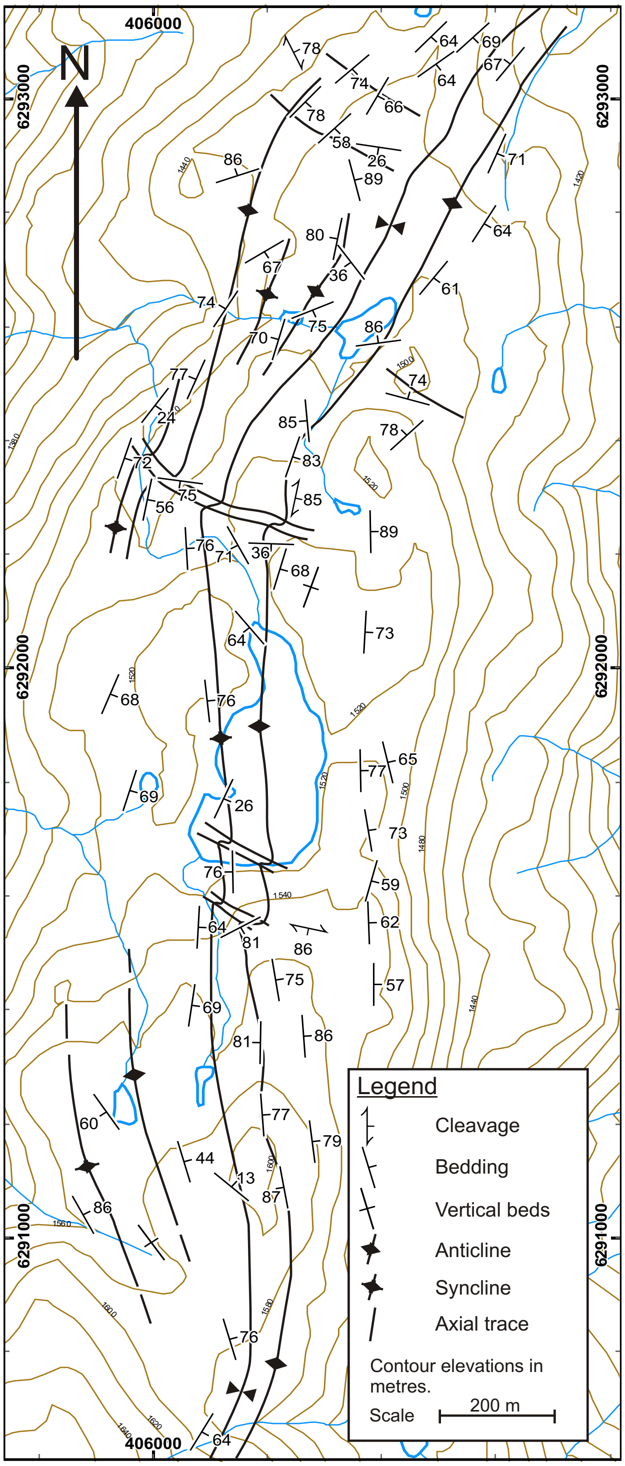

Figure 2. Structure of the Iskut Ridge area, showing bedding orientations and mapped axial traces.

and a lesser steep cleavage that strikes northeast. In outcrop, cleavage appears to be a spaced pressure-solution fabric. Slaty cleavage characterized by penetrative mineral alignment is rare. Oriented samples were collected and will be used for future petrographic analyses of cleavage. Because of the scarcity of mineral alignment, overprinted cleavage does not display crenulation. The clusters of cleavage poles in Figure 3b are attributed to superposition of two episodes of shortening. There is no girdle distribution, such as might be expected if an earlier cleavage were refolded by later shortening. This is likely because extension directions during both deformation episodes were nearly parallel and approximately vertical. Mapped deflections of north-south axial traces by southeast-trending folds (Fig 2) indicate that the north to north-northeast-striking folds formed first and were subsequently overprinted by relatively minor southeast-trending folds. This is consistent with overall folding of bedding about a southeast-plunging axis (Fig 3a), suggesting that minor folds are part of a larger structure.

Equal-area plots of bedding-cleavage intersection lineations in Figure 3c show a scattered cluster centred on a northwest-trending axis. The scatter is attributed to the relative scarcity of northeast-striking cleavage in comparison to northwest-striking cleavage.

Faults are relatively rare in this area compared with the rest of the western Skeena Fold Belt. Brittle structures observed include *en échelon* veins at a number of locations. There are a number of 'S' and 'Z' asymmetric veins interpreted to record sinistral and dextral movement, respectively. In some cases, both asymmetries can be observed at a single locality (Fig 4, 5). The presence of *en échelon* veins suggests a component of brittle strain, possibly related to the nearby Forrest Kerr fault (Read *et al.*, 1989) and faults interpreted by Logan *et al.* (2000).

Cartmel Lake

An area exposing rocks of the Eaglenest assemblage approximately 3 km southwest of Cartmel Lake was selected for study of previously recognized overprinted folds (Evenchick and Green, 2004). The topography is dominated by cliff-forming conglomerate beds in which a near-vertical rough cleavage dominates the exposed surfaces.

The structure at Cartmel Lake is dominated by three major folds that trend southeast (Fig 6). At map scale, a gently dipping surface in the northern section of the map area truncates bedding at a low angle and is interpreted as a *décollement*. A fault in the southern section of the map area truncates bedding in a similar fashion and is interpreted as a continuation of the same *décollement* (Fig 6). Bedding cutoffs indicate that this detachment climbs upsection to the southeast. Associated outcrop-scale folds face and verge southeast. A northeast-trending map-scale fold at the southern extremity of the area is presumed to be related to the same deformation that produced the southeast-verging detachment. Map-scale southeast-trending folds can be traced through the detachment without offset, implying that it must have been folded.

Numerous steep northwest-striking faults, traceable over less than a kilometre, offset cliff-forming conglomerate in a dextral sense, with offsets ranging from metres to tens of metres (Fig 6). Slickenline lineations indicate dextral strike-slip motion. Rare sinistral faults of similar size and scale, but traceable over just a few metres, are present. These faults offset the mapped trace of the low-angle *décollement* by similar amounts. The sinistral faults may be conjugate to dextral faults, as suggested by their clockwise orientation relative to the dextral faults and similar offset of strata. The orientations of the conjugate faults suggest an approximate north-south shortening direction.

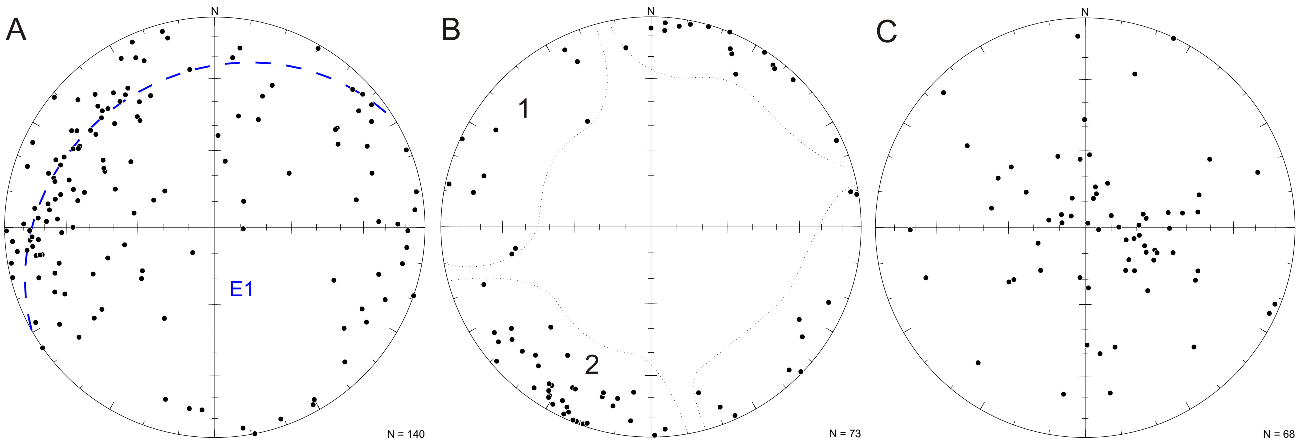

Figure 3. Lower-hemisphere equal-area projection of structural data collected in the Iskut ridge area: A) poles to bedding; E1, eigenvector 1; dashed line shows principal E1 girdle plane; B) poles to cleavage, dotted lines outline interpreted distributions of cleavage clusters 1 and 2; C) bedding-cleavage intersection lineations.

Spaced cleavage is well developed in conglomerate of the Cartmel Lake area, with some outcrops showing three distinct cleavage sets. The high percentage (75–90%) of coarse-grained rock types within the Eaglenest lithofacies assemblage may account for the common occurrence of cleavage within conglomerate; lithology is relatively homogeneous and therefore strain is not partitioned to finer grained rock types. The cleavage distribution is unusual compared to other Bowser Lake Group assemblages that have a bulk fine-grained composition and only rarely develop cleavage in coarse rock types. Cleaved conglomerate shows smooth weathering surfaces instead of the 'bumpy' weathering pattern of pebble conglomerate elsewhere in the basin, as cleavage planes cut through pebbles. Despite deformation of pebbles, significant porosity is observed to have been retained between the clasts. Equal-area plots of cleavage poles in Figure 7b show a widely scattered distribution, consistent with multiple phases of deformation. Equal-area plots of bedding poles in Figure 7a show a diffuse girdle normal to an east-southeast-trending, shallowly plunging eigenvector 1, consistent with mapping showing folding of the low-angle detachment by northwest-trending folds.

Sweeny Creek

The area around the headwaters of Sweeny Creek was mapped, expanding mapping of the Tumeka Creek study area reported in Waldron *et al.* (2006). Rock units in this area belong to the Skelhorne assemblage of the Bowser Lake Group (Evenchick, 2004). Prior mapping in the Sweeny Creek area revealed north-northeast and north-northwest-trending folds converging without intersection,

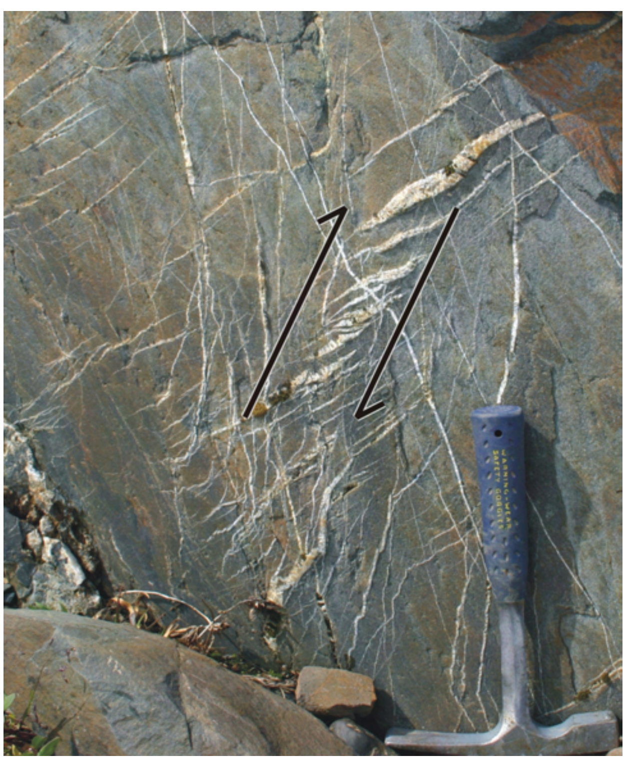

Figure 4. Z-asymmetric *en échelon* quartz veins, indicating dextral and reverse sense of shear; arrows indicate interpreted sense of shear; view towards the west-northwest.

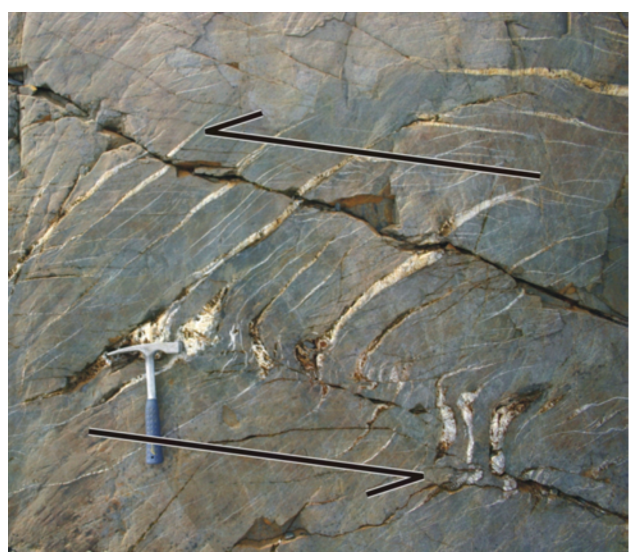

Figure 5. S-asymmetric *en échelon* quartz veins, indicating sinistral and reverse sense of shear; arrows indicate interpreted sense of shear; view towards the west-southwest.

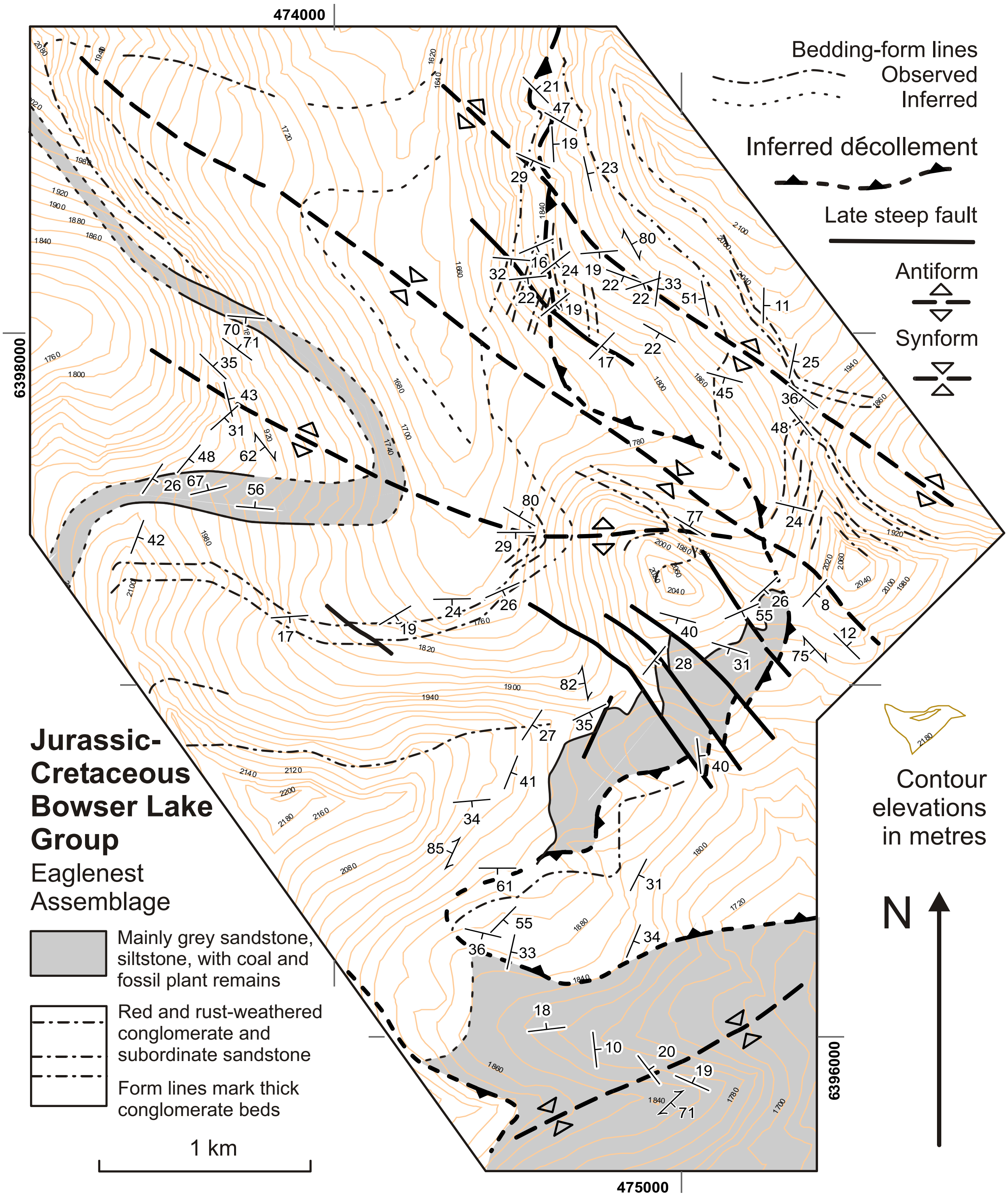

Figure 6. Structure of the Cartmel Lake area; note distribution of early *décollement* and later folds.

within an area dominated by northwest-trending folds (Evenchick, 2004). Folds mapped in the Sweeny Creek area have variable orientations, plunging between north-northwest and north-northeast. Figure 8 shows axial traces that converge with each other but do not crosscut. The map pattern suggests that these folds are of the same generation and are part of a larger system of conical folds. Map relationships also show that all north to northeast folds appear to increase in plunge toward the northeast. All bedding in the northern part of the study area dips to the northeast; regionally, the structures in this area are part of the southwest limb of a gentle northwest-trending syncline, with a wave-

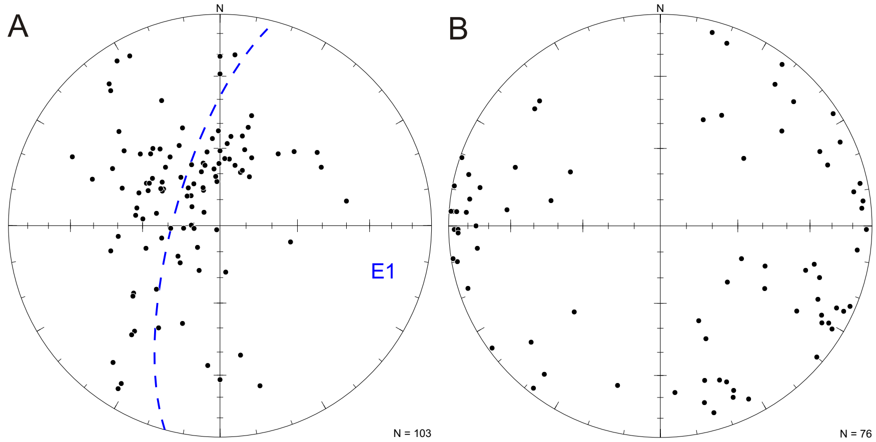

Figure 7. Lower-hemisphere equal-area projection of structural data collected in the Cartmel Lake area: A) poles to bedding; E1, eigenvector 1; dashed line shows principal E1 girdle plane; B) poles to cleavage.

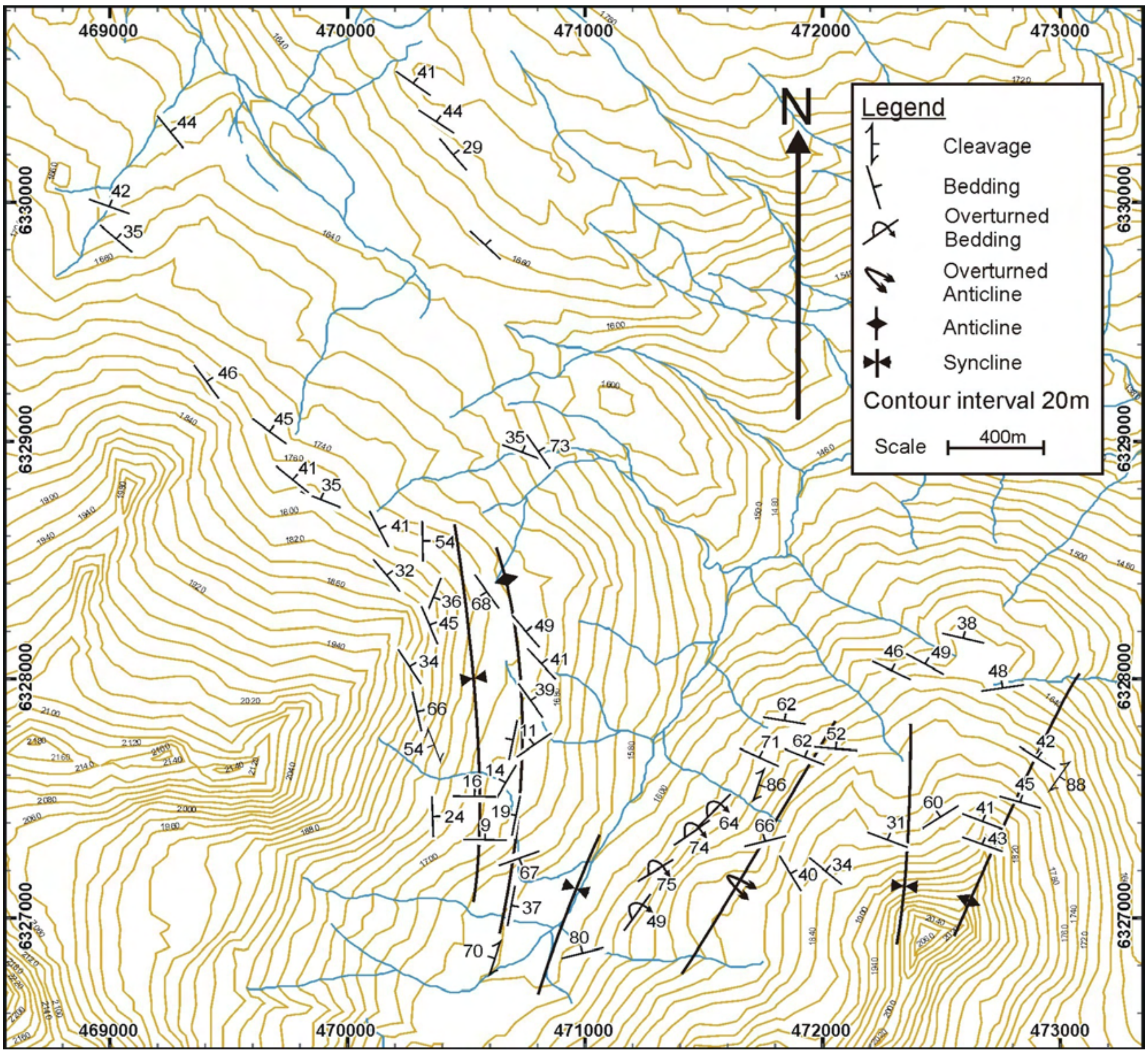

Figure 8. Structure of the Sweeny Creek area, showing orientations of structures and axial traces.

length on approximately the 5 km scale, observed to the north of Sweeny Creek. The syncline is interpreted to have increased the plunge of north-trending folds.

DISCUSSION

All three areas mapped show overprinting of structures. At Iskut ridge, a major north to north-northeast-trending fold is refolded by smaller, southeast-trending structures. The Cartmel Lake area is characterized by overprinting of northwest-trending folds on an earlier detachment; folds associated with the earlier detachment show northeast trends. The Cartmel Lake area may record the importance of detachments in the deformation history of the area, as suggested by Evenchick (1991b). Overprinting is less clearly displayed at Sweeny Creek, but progressive down-plunge steepening of northeast-trending folds is consistent with refolding by folds with northwest trends. Thus, structures in all three areas are consistent with early, generally northwest-southeast shortening, followed by northeast-southwest shortening.

The development of type I dome-and-basin interference patterns is dependent upon overprinting of folds at a high angle. Large domes prospective for petroleum accumulation result from in-phase interference of anticlines of similar amplitude. Where structures of different wavelengths or amplitudes interfere, the resulting patterns are more complex. Fold amplitudes, wavelengths and intersection angles are variable in the Skeena Fold Belt. At Iskut ridge, the early north to north-northeast folds are map scale, and folds with southeast trends are relatively minor structures. If present in the subsurface, such a structural pattern could serve as an array of small petroleum traps, as southeast-trending folds could trap petroleum located in early folds. At Sweeny Creek, there is a northwest-trending kilometre-scale syncline and the north-trending folds have wavelengths on the hundred metre scale. Down-plunge steepening of early folds by a northwest-trending fold of this type could drive subsurface petroleum migration to the south, forming a broad pool with several pockets within early folds. The Cartmel Lake area includes multiple sets of spaced pressure-solution cleavage within conglomerate that dissolves pebbles but does not obliterate porosity in the matrix. At Cartmel Lake, early folds are likely associated with *décollements*. Locating such structures in the subsurface would provide insights on the location of potential petroleum traps.

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