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Strain partitioning and batholith emplacement at the root of a transpressive magmatic arc

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Abstract

An integrative study of the high-pressure Ecstall batholith and its country rocks (Prince Rupert area, British Columbia) reveals the interplay of deformation and plutonism produced in the largest Cordilleran magmatic arc (i.e. the Coast Plutonic Complex) during mid-Cretaceous convergence between the Farallon oceanic plate and North America. The results emphasize the interference between three strain fields: (1) an early (>92 Ma) crustal wedge produced by orogen-perpendicular, SW-vergent thrusting, (2) an orogen-parallel sinistral strike-slip shear zone active until 87 Ma, and (3) the lateral expansion of the batholith (93–91 Ma) against the shear zone. The batholith expanded in a direction oblique with respect to the shear zone trend (+20°) by extruding country rocks against its head in a direction normal to its expansion direction during sinistral, strike-slip partitioned transpression. The batholith's emplacement combined far-field batholith boundary-normal translation, extrusion-related rotation and radial and concentric elongation in its structural aureole. This case study may typify the process by which a modern magmatic arc grows longitudinally at depth during transpression, the direction and sense of growth being determined by the direction of plate motion relative to the magmatic arc and the degree of strike-slip partitioning of transpression. © 2002 Elsevier Science Ltd. All rights reserved.

Keywords: Pluton emplacement; Transpression; Oblique plate convergence; British Columbia

1. Introduction

Transpression describes the processes by which oblique convergence is accommodated in three dimensions by the crust and/or the lithosphere along plate or terrane boundaries (Harland, 1971; Sanderson and Marchini, 1984; Holdsworth et al., 1998). It involves a combination of horizontal shortening, horizontal and vertical stretching and transcurrent displacements that take place along steep, crustal- or lithospheric scale shear zones (e.g. Teyssier et al., 1995). These structures connect the mid-crust to the lower crust and/or to the mantle, and can enable voluminous magmatic activity (e.g. Hutton and Reavy, 1992). This is typically exemplified within magmatic arcs that develop at active plate margins during oblique convergence (de Saint Blanquat et al., 1998). In such environments, plutonism can lead to significant continental growth in association with terrane accretion.

Plutons interfere with regional strain and/or structures during and/or after their emplacement. Numerous studies have demonstrated the usefulness of plutons as strain markers and thermomechanical and kinematic gage of continental deformation (e.g. Brun and Pons, 1981; Hutton, 1988; Brun et al., 1990). In a transpressional context, and especially within magmatic arcs, investigations addressing the issue of interplay between three-dimensional strain partitioning and pluton emplacement should help evaluating the relations between magmatic accretionary processes (ascent and emplacement) and the kinematic and thermomechanical evolution of obliquely convergent plate margins.

In the present paper, the interplay of transpression and plutonism in the lower crust is examined by studying the structural relations between the Ecstall batholith (Prince Rupert area, NW British Columbia) and its country rocks within the Coast Plutonic Complex (CPC), the largest magmatic arc in the North American Cordillera (Fig. 1). This batholith is one of the several large, magmatic epidote-bearing plutonic bodies that crystallized at 8–10 kbar during the mid-Cretaceous at the roots of magmatic arcs (Zen, 1985) at the time the Cordillera was recording the subduction of the Farallon oceanic plate under cratonic North America (Oldow et al., 1989).

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2. Geological setting

2.1. The Coast Plutonic Complex in west-central British Columbia (Figs. 1 and 2)

Magmatic accretion took place in the CPC (Fig. 1) from the Jurassic to the Paleogene (van der Heyden, 1992). This magmatic arc marks the transition between two major tectonic elements of the North American Cordillera, the Insular superterrane to the west and the Intermontane superterrane to the east (Fig. 1) and represents the core of the Coast orogen (Rusmore and Woodsworth, 1991). In west-central British Columbia, the CPC consists of several NW-trending plutonic belts ranging from Jurassic to Eocene in age from the SW to the NE (Fig. 2).

The structure of the CPC is controlled by several subvertical, orogen-parallel shear zones (Woodsworth et al., 1991; Chardon et al., 1999; Figs. 1 and 2). The Coast shear zone is the longest tectonic feature affecting the magmatic arc and coincides with the western Paleogene magmatic front of the Canadian Cordillera (e.g. Hollister and Andronicos, 1997; Chardon et al., 1999; Fig. 1). Dextral transpression (83?–57 Ma) took place in the Coast shear zone across a 100- to 15-km-wide deformation belt flanking to the east today's trace of the 1- to 5-km-wide mylonite zone (Andronicos et al., 1999). This mylonite zone, labeled as the Coast shear zone in Fig. 2, or the Work Channel lineament in Fig. 5b (Crawford and Hollister, 1982), was produced by Late (57–55 Ma) dip-slip, west-side-up shearing (Klepeis et al., 1998). The shear zone was intruded by the Great Tonalite Sill (Ingram and Hutton, 1994), a belt of steep sheeted plutons, i.e. the Quottoon pluton in the study area (Figs. 2 and 5) that has been dated at 59 Ma along the Skeena River by Gehrels et al. (1991). West of the Coast shear zone, the arc is affected by three sinistral, crustal-scale shear zones (the Principe–Laredo, the Kitkatla and the Grenville Channel shear zones) that were sequentially active from ~110 to 87 Ma and from West to East (Chardon et al., 1999; Figs. 1 and 2).

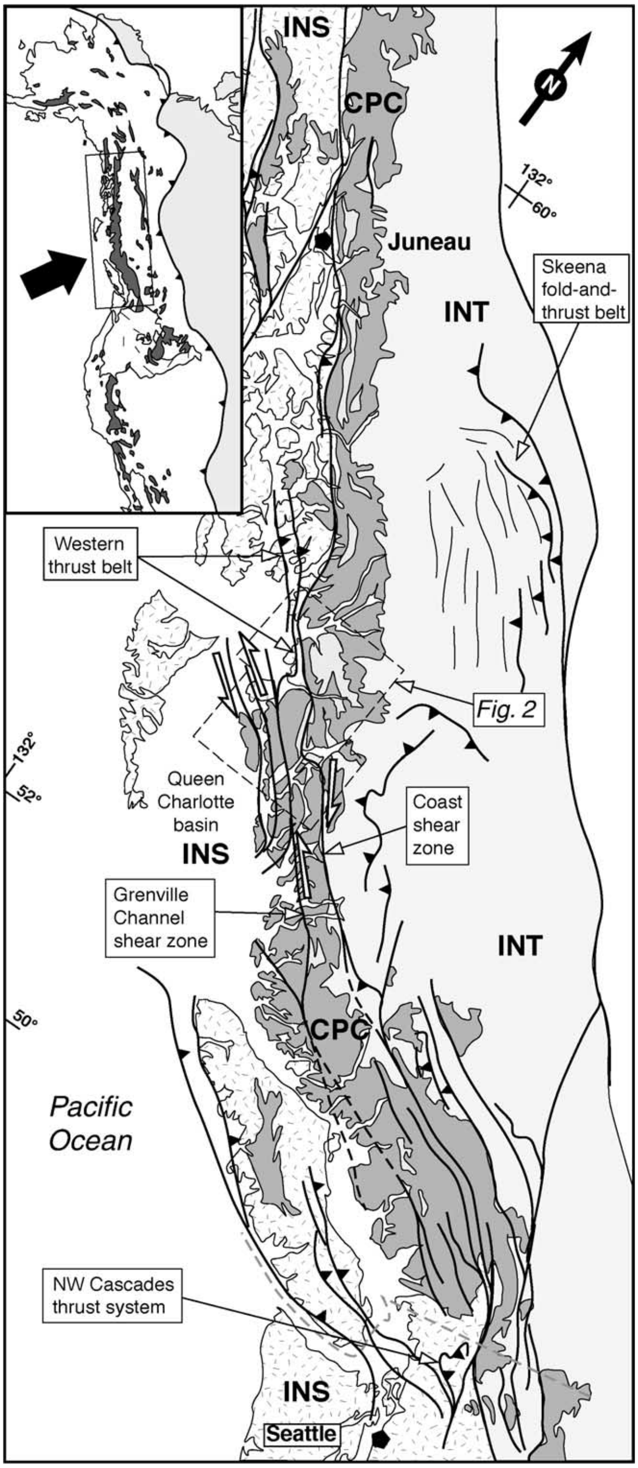

Fig. 1. Simplified structural map of the Coast Plutonic Complex (adapted from Chardon et al., 1999). Abbreviations are as follows: INT—Intermontane superterrane, CPC—Coast Plutonic Complex, INS—Insular superterrane. The inset shows the distribution of the main magmatic arcs in the North American Cordillera (modified after Oldow et al., 1989).

2.2. Geology of the Ecstall batholith and its country rocks

The Ecstall batholith belongs to a crustal panel that is bounded by the Grenville Channel shear zone to the SW and the Coast shear zone to the NE (Fig. 2; Chardon et al., 1999). The outcrop map pattern of the batholith has an asymmetrical tadpole shape (Hutchison, 1982) that is oblique (~20°) with respect to the regional shear zones trend (Fig. 2). The batholith is more than 100 km long with a maximum width of 28 km. Its tail roots into the head of the epidote-bearing Butedale batholith to the southwest (Roddick, 1970; Fig. 2). The composition of the Ecstall batholith ranges from quartz dioritic to granodioritic. The head of the pluton is concentrically zoned (Fig. 3), with an inner part being more leucocratic, which can locally reach quartz-monzonitic compositions (Hutchison, 1970, 1982). U–Pb dating of the batholith gives a zircon crystallization age of 91 Ma and 93.5 ± 1 Ma for its head and its tail, respectively (van der Heyden, 1989; Crawford et al., 2000). The head of the Butedale batholith displays similar

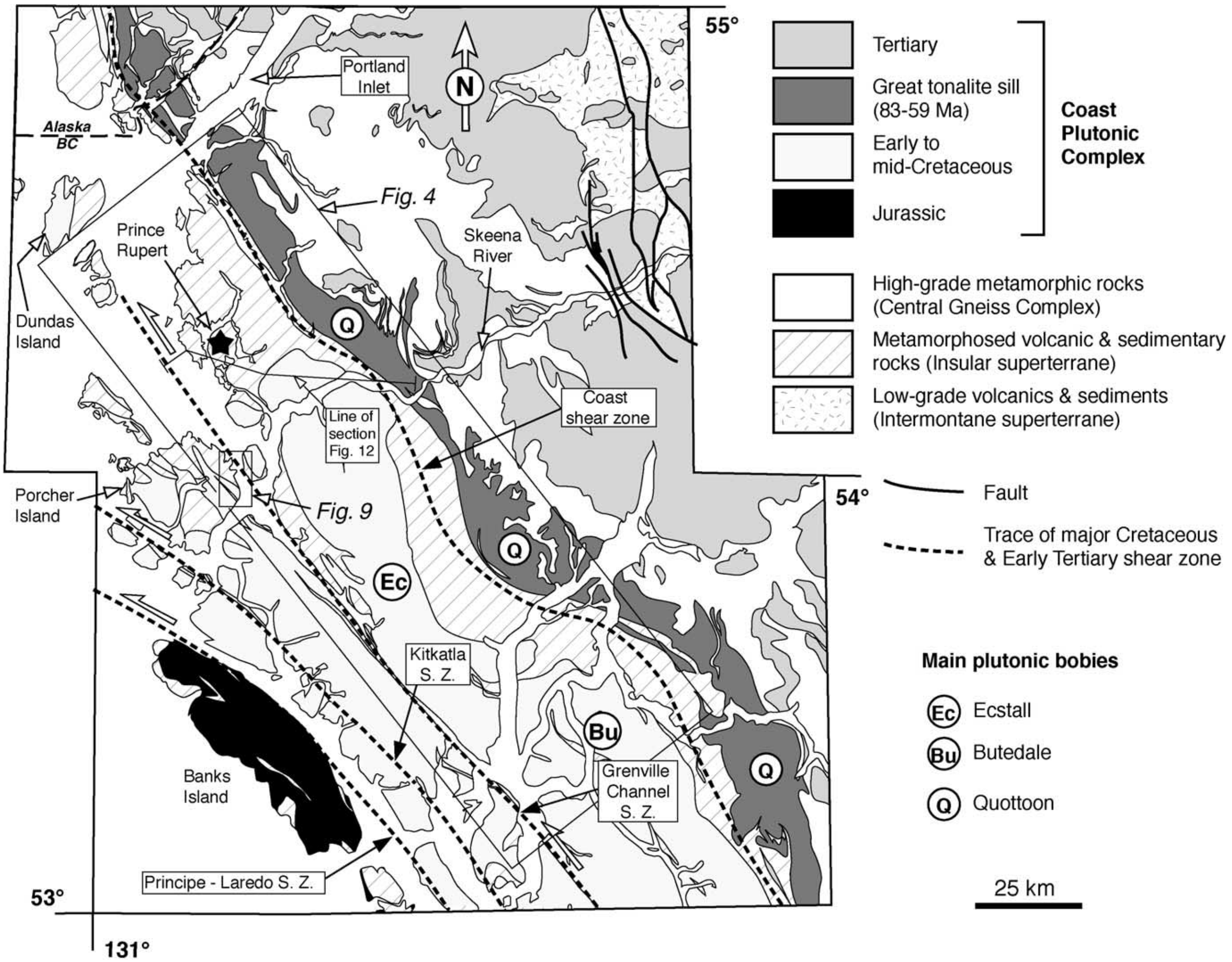

Fig. 2. Geology and structure of the Coast Mountains between 53 and 55°N (modified after Chardon et al., 1999). The geology is compiled after Roddick (1970), Hutchison (1982) and Woodsworth et al. (1985) and new observations (location in Fig. 1).

U–Pb ages (between 93.5 and 95 Ma; van der Heyden, 1989).

Rocks surrounding the Ecstall batholith consist of metamorphosed Late Proterozoic to Jurassic sediments (mainly turbidites) and volcanics with minor, strongly deformed, Late Paleozoic and Triassic orthogneisses (e.g. Crawford et al., 2000; Gareau and Woodsworth, 2000). In the Prince Rupert area and southeasternmost Alaska, these rocks are involved in the SW-vergent Western thrust belt (Fig. 1). It has been proposed that several batholiths, including the Ecstall, were emplaced within the thrust belt during its development (Crawford et al., 1987, 2000; Crawford and Crawford, 1991; Rubin and Saleeby, 1992). Crawford et al. (1987) concluded that mid-Cretaceous ductile faulting and plutons emplacement in the Western thrust belt took place during orthogonal plate convergence. A recent large-scale, integrative study suggests that the Ecstall batholith and other neighboring plutons were emplaced during regional sinistral transpression partitioned between the root of the Coast Plutonic Complex (mainly along the Principe–Laredo, Kitkatla and Grenville Channel shear zones) and the thrust belts of the Coast orogen between 110 and 85 Ma (Chardon et al., 1999). The present study therefore provides the opportunity to address the detailed relations, in time and space, between the development of the Western thrust belt, strike-slip shearing and the growth of the CPC through the emplacement of the Ecstall batholith.

3. Large-scale structural pattern

Foliations within the Ecstall batholith underline its tadpole shape and reveal a spoon-shape structure for its head (Fig. 4). Within its tail, one distinguishes NW-trending foliations along the SW contact that parallel the trace of the Grenville Channel shear zone (Fig. 4) and E–W-trending foliations in the northwestern part of the tail, mimicking the spoon shape of the head. Elsewhere, the dominant foliation trend in the tail parallels the map-view long axis of the batholith. On a large scale, toward the SE, planar fabrics

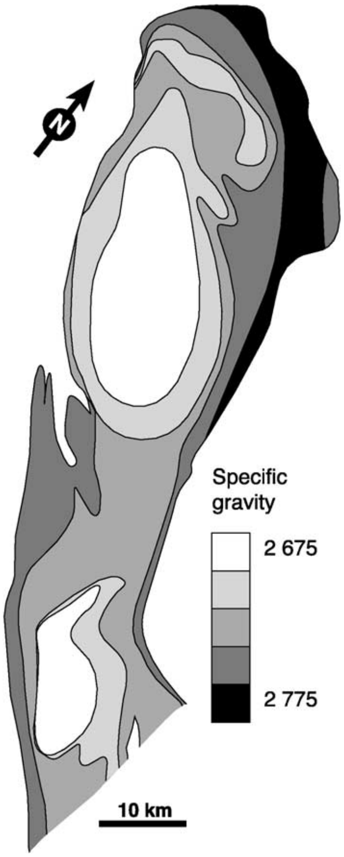

Fig. 3. Specific gravity contour map (in kg/m^3) of the Ecstall batholith from hand sample measurements (adapted from Hutchison, 1982).

from the batholith's tail become pinched off underneath the head of the Butedale batholith and against the Grenville Channel shear zone (Fig. 4).

Country rock foliations systematically parallel foliations in the batholith in the vicinity of the contact (Fig. 4). East of the batholith, foliations strike sub-parallel to the boundaries and outer foliations of the Ecstall and Butedale batholiths. This results in a regional deflection of the foliations (the Hawkesbury warp; Roddick, 1970) in the vicinity of the relay zone between the tail of the Ecstall and the head of the Butedale batholiths (Fig. 4). A foliation triple point is interpreted as an interference between Ecstall and Butedale-related fabrics and warp-related foliations. Comparison of Figs. 3 and 4 reveals no obvious crosscutting relations between internal foliation trajectories and the compositional zoning of the Ecstall batholith. The plastically foliated, southwestern contact of the Quottoon pluton that coincides with the northeastern margin of the Coast shear zone, parallels regional foliations and follows the Hawkesbury warp (Fig. 4).

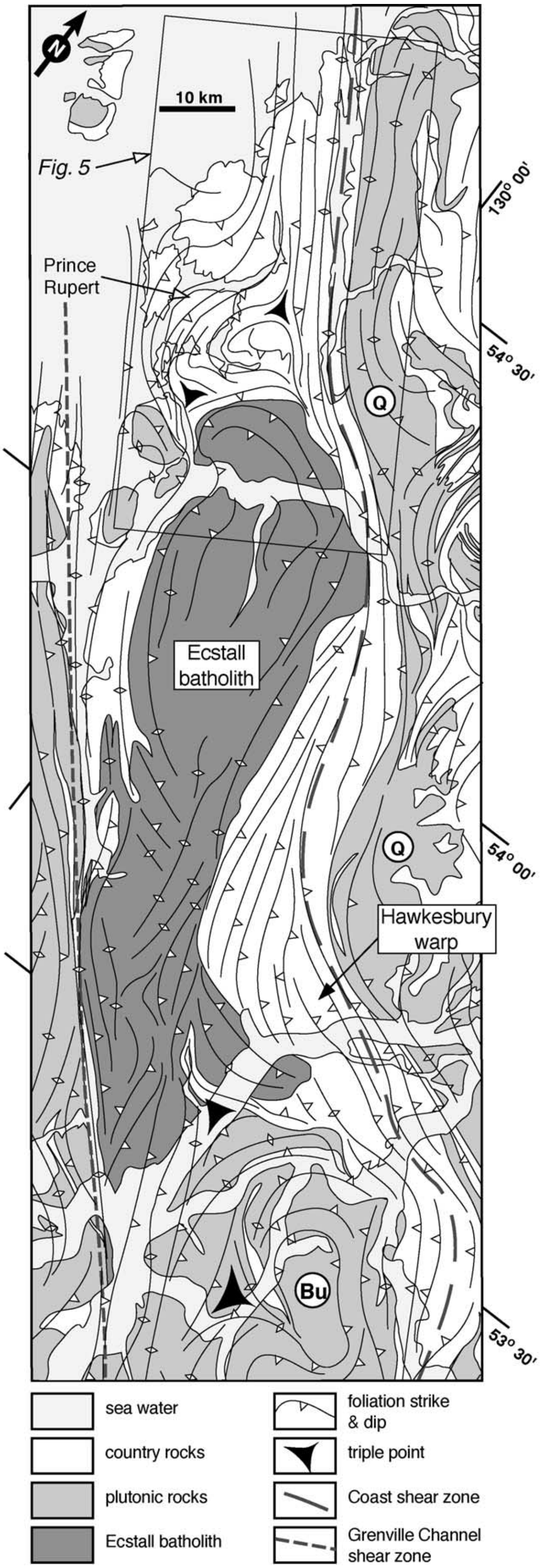

Fig. 4. Foliation trajectory map of the Ecstall batholith and surrounding areas. Sources for measurements: Roddick (1970), Runkle (1979), Hutchison (1982) and Gareau (1990). Q—Quottoon pluton; Bu—Butedale batholith. Location in Fig. 2.

Northwest of the head of the Ecstall batholith, in the Prince Rupert area, foliation trajectories in country rocks define an interference pattern (Hutchison, 1970, 1982). The present study focuses on this key area, given its fairly good accessibility and the amount of data available from the literature.

4. Deformation within and around the batholith in the Prince Rupert area

4.1. Foliation trajectories (Figs. 5b and 6a)

In the northwestern part of the study area, the foliations have a consistent arc-parallel strike (N 140) with shallow dips to the NE and progressively steeper dips towards Work Channel. From Port Simpson toward the Ecstall batholith, foliation trajectories are deflected into NE strikes in the Prince Rupert area, then are curved into arc-parallel strikes and acquire shallower dips and finally steepen to become pinched off between the Smith Island pluton and the Ecstall batholith. East of Prince Rupert, structurally higher foliations deviate into NE strikes. These foliations end up dipping beneath the head of the batholith, parallel to the contact. These diverging foliation trajectories and foliations conformable with the envelope of the head of the batholith define a first foliation triple point (labeled *A* in Fig. 5b). A second triple point (labeled *B* in Fig. 5b) results from the interference between the foliations that are deflected toward Prince Rupert, Work Channel-parallel foliations and the NE striking trajectories of the dome formed at the front of the batholith.

4.2. Deformation fabrics and strain patterns

The attitude of the stretching/mineral lineation is strongly dependent on the attitude of the foliation (Figs. 5b, 6 and 7). From Port Simpson toward the Ecstall batholith and from west to east across the thrust belt, progressive variations in the orientation of the lineation accompany the reorientation of the foliation. In order to quantitatively perceive those variations, six fabric domains are defined (Fig. 7a).

4.2.1. Pristine Western thrust belt-related features (domains 1 and 2)

In the external domain (domain 1), foliations are shallowly NE to SE dipping and the pitch of the lineations is generally high (from 60 to 90°; Fig. 7b). In the internal domain (domain 2), foliations become gradually steeper, parallel to Work Channel and the lineations have a preferential down-dip orientation. The Western thrust belt here is wedge-shaped and leans against the Coast shear zone that virtually acts as a back stop for the belt.

The southern part of domain 1 has been described by Hutchison (1982) and Crawford and collaborators (summarized in Crawford et al., 2000). The foliation is axial planar to folds with shallowly NE-dipping axial surfaces and sub-horizontal axes. Crawford and Hollister (1982) attribute these structures to an early D_1 deformation episode. NW-trending, upright folds developing a crenulation cleavage refold F_1 folds in the westernmost part of domain 1 (Crawford et al., 2000). The same authors document top-to-the-SW thrusting on the shallowly NE-dipping fabrics before development of the upright folds. In the northern part of the study area (Figs. 5 and 7), close to the Alaska–British Columbia border, where the thrust belt narrows (i.e. the northwestern extension of domains 1 and 2), deformation is controlled by pervasive, down-dip, top-to-the-SW shearing (Klepeis et al., 1998). Towards Work Channel, thrust belt-related fabrics are transposed into the Coast shear zone across a sharp strain gradient (Klepeis et al., 1998). Those relations were also suggested in the southeastern part of the study area (Crawford and Hollister, 1982; Crawford et al., 1987). This interpretation was confirmed by the recent ACCRETE wide-angle seismic experiment performed along a transect passing by Dundas Island and Portland Inlet (Fig. 2). This study imaged three NE-dipping, crustal-scale reflecting boundaries in the Western thrust belt, that do not extend under the surface trace of the Coast shear zone (Morozov et al., 1998).

4.2.2. Interference zone (domains 4 and 5)

In the vicinity of Prince Rupert, where foliations are bent into NE and then SE strikes and shallow to moderate SE to NE dips, the pitch of the lineation becomes small (from 0 to 25°; Fig. 7b). Domain 3 represents an intermediate fabric configuration (i.e. with intermediate pitches; Fig. 7b) as it marks the transition from domains 1 and 2 to the north to domains 4 and 5 to the south.

The most striking structural feature in this area (especially around location A; Fig. 7a) is the pervasive development of meter-scale lens-shaped foliation domains where the foliation trajectories trend to the NE, best seen in the city of Prince Rupert (Fig. 6b). These lenses are analog to the ones developed during heterogeneous deformation of granites by the development of a network of anastomosed shears (Choukroune and Gapais, 1983). The stretching lineation is systematically shallowly plunging to sub-horizontal within or on the envelopes (i.e. shear) of the lenses that are flattened perpendicular to the main foliation plane. This implies that λ_1 is sub-horizontal and that the $\lambda_1\lambda_2$ plane of the strain ellipsoid is a symmetry plane for the lenses. Aspect ratios of the sections of the lenses are comparable within the $\lambda_1\lambda_3$ plane and in the $\lambda_2\lambda_3$ plane (Fig. 6b). The sections of the lenses do not show any asymmetry and poor, conflicting kinematic indicators are seen on the lenses' envelopes. These observations imply that the metamorphic rocks record plane strain during bulk inhomogeneous shortening (Gapais et al., 1987).

Along strike, the northern continuation of the Prince Rupert shear-lenses system, where lineation pitches are greater, lenses are not present; they are replaced by SE dipping thrust faults and asymmetric folds (Crawford et

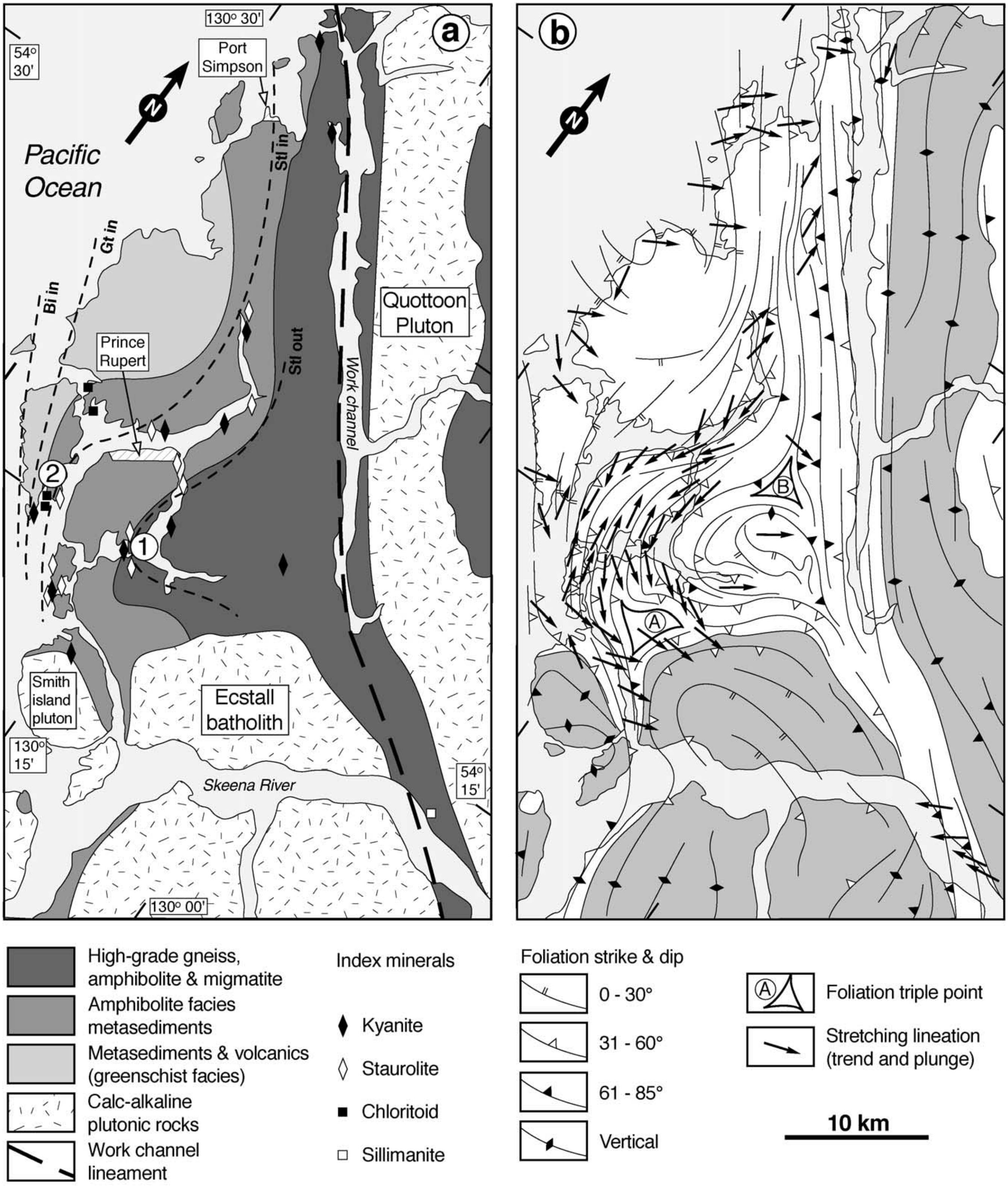

Fig. 5. Geological (a) and structural (b) maps of the Prince Rupert area. (a) Is compiled after Hutchison (1982), Crawford et al. (1979) and Crawford and Hollister (1982). (b) Is based on measurements and photointerpretation by Hutchison (1970, 1982), measurements by Crawford et al. (2000) and data from the present study (location in Fig. 3).

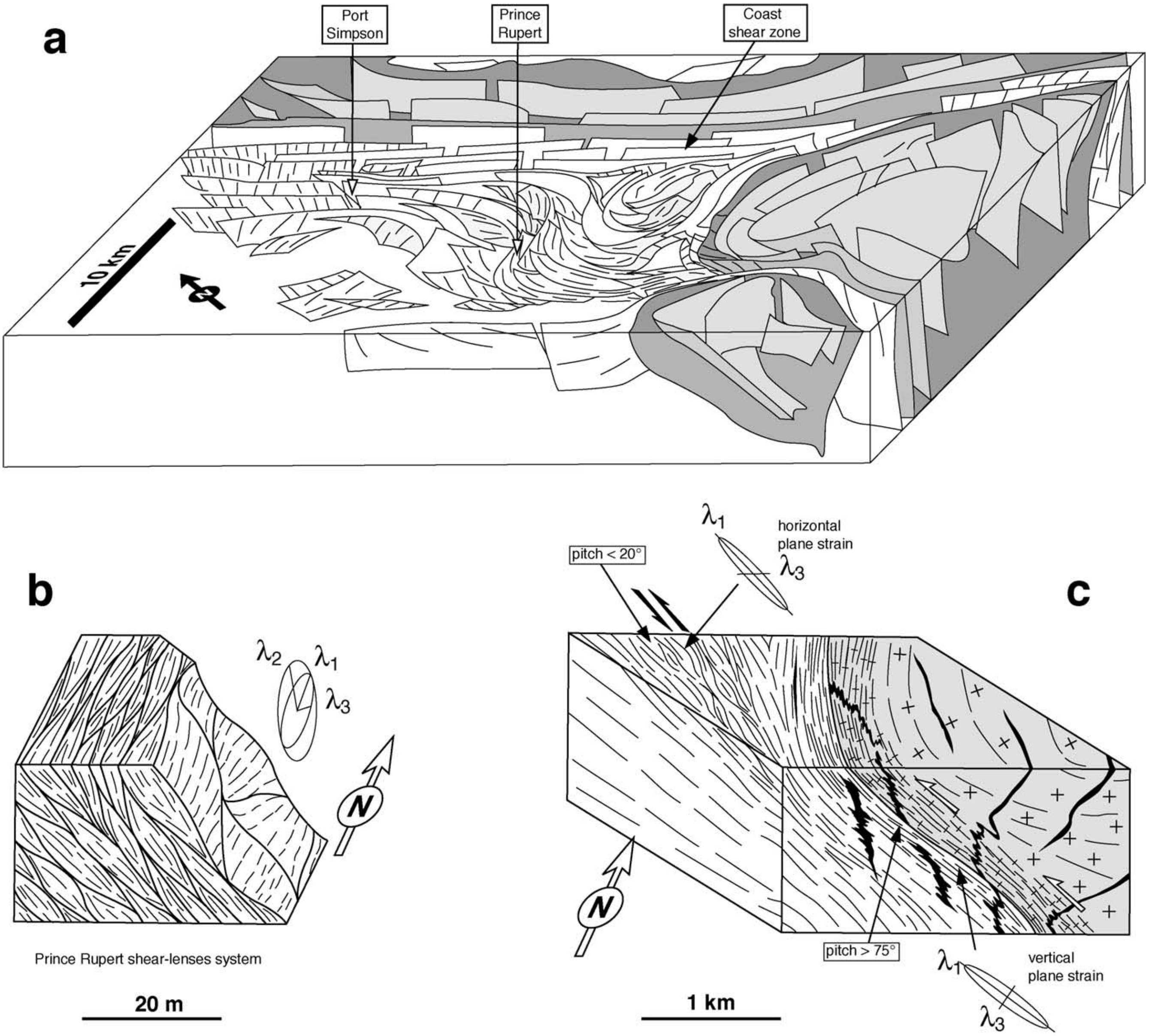

Fig. 6. (a) Block-diagram illustrating the finite strain pattern within and around the head of the Ecstall batholith in the Prince Rupert area. Lines on the foliation planes ($\lambda_1\lambda_2$) indicate the trace of the mineral–stretching lineation (λ_1). (b) 3D sketch summarizing the strain pattern within the city of Prince Rupert (location A; Fig. 7a). (c) 3D sketch summarizing the relations between the Ecstall batholith and its country rocks south of triple point *A* (locations D to B; Fig. 7a).

al., 2000). The southern continuation of the lenses-bearing belt (around location B; Fig. 7a), displays structural patterns resulting from a different strain regime (i.e. there is an along-strike change in the kinematic record from north to south around the bend). In this area, m-scale asymmetrical sigmoid lenses are observed. The rocks show strong LS tectonites and numerous structures indicative of non-coaxial deformation from the outcrop- to microscopic scale. Numerous C' shear bands bound m-scale mafic boudins and the lenses within the schist matrix. Pervasive asymmetrical boudinage resulting in large finite extension of thin, late kinematic quartz veins, attest to the large shear strain undergone by the rocks. All these structures indicate systematic sinistral sense of shear (Fig. 8a).

In a quarry east of location B (Fig. 7a), superimposed deformation patterns show that down-dip stretching took place within the foliation plane (now dipping 45° to the NE) before the shallowly plunging regional lineation develops (pitch is generally less that 20°; Fig. 7b and d). Early, cylinder-shaped quartz boudins with horizontal axes lie with the foliation plane. Early tension gashes, perpendicular to the foliation, intersect the planar fabric along a horizontal axis. The shape and orientation of the boudins and the gashes indicate that the maximum stretching axis at the time they formed had a down-dip orientation within

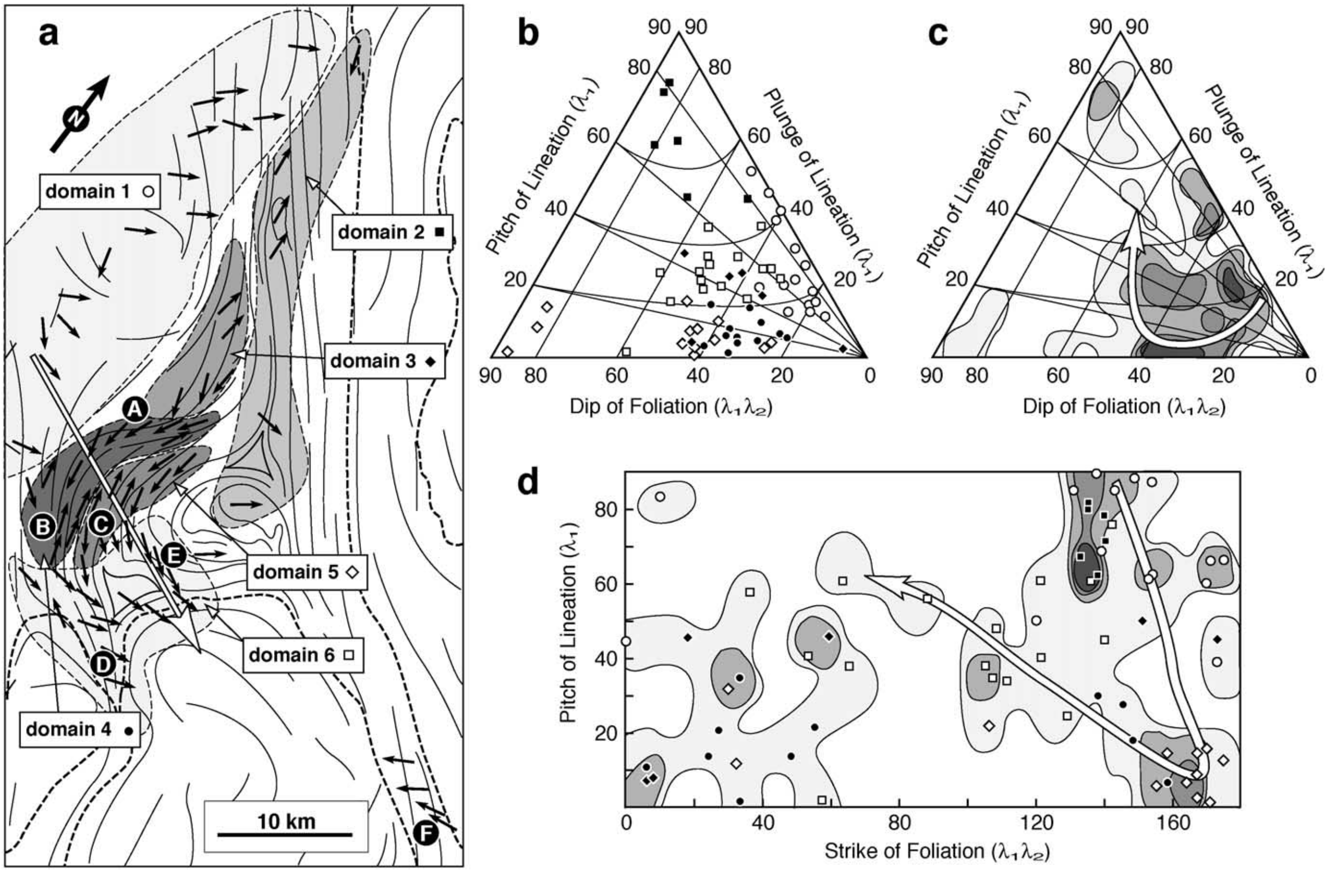

Fig. 7. (a) Foliation and lineation map of the study area. The plutons–country rocks contacts are shown by thick dashed lines. (b) Diagram showing the relative attitude of foliations ($\lambda_1\lambda_2$ plane) and stretching lineations (λ_1 axis) (after Balé and Brun, 1989). The symbols correspond to each domain defined in (a). (c) Density contours of the data plotted in (b). (d) Diagram showing the relations between the strike of the foliation and the pitch of the lineation (after Bouhallier et al., 1995). The symbols are the same as in (a) and (b). The path underlined by the curved white arrows on diagrams (c) and (d) correspond to an east-directed transect across the structural domains, shown by a straight white arrow on the map (a). In (b) and (c), the data is contoured at 1.5, 3, 4.5 and 6%. On the map (a), letters A to F refer to specific areas or locations discussed in the text.

the foliation plane. The finite, pervasive, regional stretching lineation, that is sub-horizontal, is superimposed on these preexisting structures (Fig. 8b).

Deformation is heterogeneous within the southern part of domain 5, where a few lenses bearing belts alternate with zones of transposed fabrics. A typical high strain zone affecting graphite–kyanite schists is exposed at location C (Fig. 7a). In this area, kyanite occurs in the quartz-filled necks of highly stretched, symmetrical foliation boudins (Crawford et al., 1979) and the syn-kinematic tails of garnet porphyroclasts (Fig. 8c). The sub-vertical foliation is axial planar to centimeter- to meter-scale isoclinal folds affecting thin layers of felsic volcanic rocks. The sub horizontal fold axes parallel the mineral-stretching lineation. C$'$ shears cutting the quartz–kyanite veins and the amphibolite layers indicate dextral sense of shear. This zone typifies interplay of early, possibly down-dip stretching (cf. previous paragraph) and superimposed strike-slip shearing. West of this high-strain zone, vertical sections of some lenses, taken perpendicular to the foliation strike, can be asymmetrical, suggesting east-over-west sense of shear, although the penetrative stretching lineation is sub-horizontal.

4.2.3. Within and around the batholith (domain 6)

Toward the batholith (domain 6), in the vicinity of triple point *A*, foliations are moderately NE- to SE-dipping. Lineations generally plunge toward the SE (beneath the batholith) and have intermediate pitches (from 30 to 60°; Fig. 7b) and large pitches close to the Ecstall batholith (Fig. 5b).

Within the head of the batholith, the foliation is generally characterized by centimeter- to decimeter-thick layers with varying feldspar and hornblende phenocryst contents and elongated mafic enclaves. These phenocrysts are generally randomly oriented. The envelope of the batholith is a 300- to 500-m-thick zone of plastically deformed Ecstall plutonic rocks. This orthogneiss displays strong planar and linear fabrics that parallel the batholith's contact and the LS tectonites in the country rocks immediately surrounding the batholith (Figs. 6a and c and 8e). The parallelism of the fabrics within the batholith, the orthogneiss, the country rocks and the batholith's contact points to the syn-emplacement development of those fabrics.

A population of meter-scale, generally SW-dipping leucocratic dikes is seen in the vicinity of the batholith's contact and within the batholith. They are undeformed

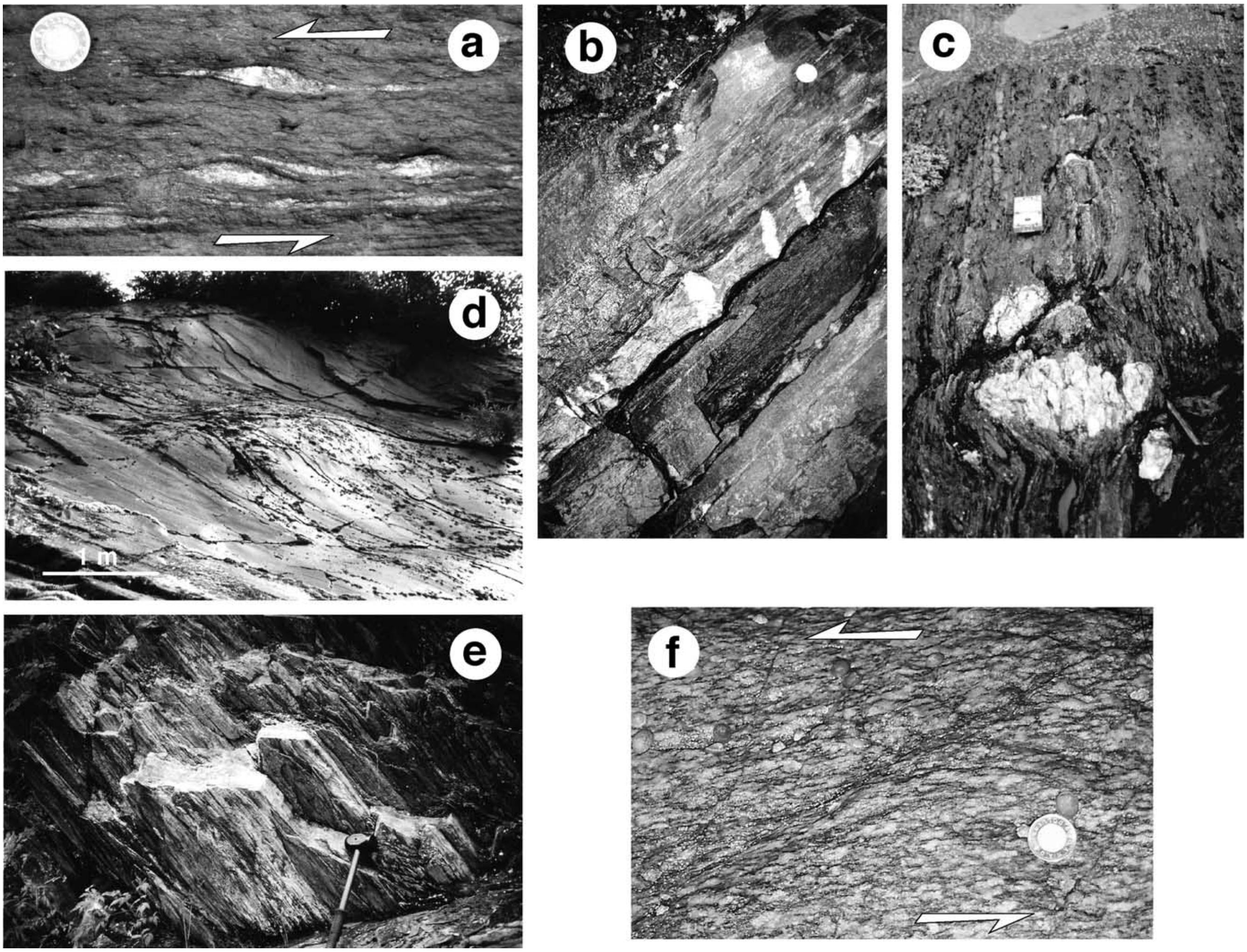

Fig. 8. (a) Sigma-shaped quartz aggregates showing sinistral sense of shear on the southwestern limb of the interference zone (location B; Fig. 7a). (b) Section perpendicular to the foliation and the stretching lineation showing early tension gashes east of location B (Fig. 7a). (c) Graphite schists showing kyanite bearing quartz-filled boudins'necks (location C; Fig. 7a). (d) Outcrop showing the envelope foliation of the shear-lenses system at location E (Fig. 7a). (e) LS tectonites in the country rocks at the batholith's contact (location D; Fig. 7a). (f) Mylonitic orthogneiss from the core of the Grenville Channel shear zone (Fig. 9) showing a syn-cooling C′ sinistral shear band affecting the pervasive high-temperature plastic fabric (this station is located in Fig. 9). See text for discussion.

within the batholith outside the gneissic contact zone and are intensely folded and plastically deformed within the orthogneiss envelope, the axial planar foliation for these folds coinciding with the main orthogneissic foliation. Within the enveloping country rocks, similar fabric-free intrusions (Fig. 6c) crosscut the foliation but are also injected as sills. Those relations suggest that injection and crystallization of those dikes and sills took place during ongoing emplacement and cooling of the Ecstall batholith.

At the batholith's contact, the lineations display moderate to high pitches toward the SE (location D; Fig. 7a) or the NE (SW of location E; Fig. 7a). The strong LS tectonites are associated with C′ shear bands indicating east-over-west sense of shear. From this area toward the WNW, there is a transition from high-angle oblique, top-to-the-west shearing (under the batholith) to almost pure sinistral strike-slip shearing (location B; Fig. 7a; see Section 4.2.1) associated with the gradual decrease in the pitch of the lineation. This transition implies a flip in space between λ_1 and λ_2 principal axes of the strain ellipsoid (Fig. 6c).

NW of the batholith (location E; Fig. 7a), the country rocks show a similar, although less developed, shear-lenses system to the one seen in Prince Rupert (Fig. 8e). The lineation displays intermediate pitches in this area and becomes almost down-dip at the contact with the batholith. Note that those lenses bound foliation triple point *A* to the north.

4.2.4. Grenville Channel Shear zone

The shear zone flanks to the SW the root of the batholith along Grenville Channel and is well exposed along the northeastern shore of Porcher Island (Fig. 9). In this area, the center of the shear zone is a mylonitic orthogneiss showing evidence for syn-cooling (from upper amphibolite to greenschist facies conditions) pervasive horizontal stretching and sinistral shearing (Chardon et al., 1999; Figs. 8f and 9).

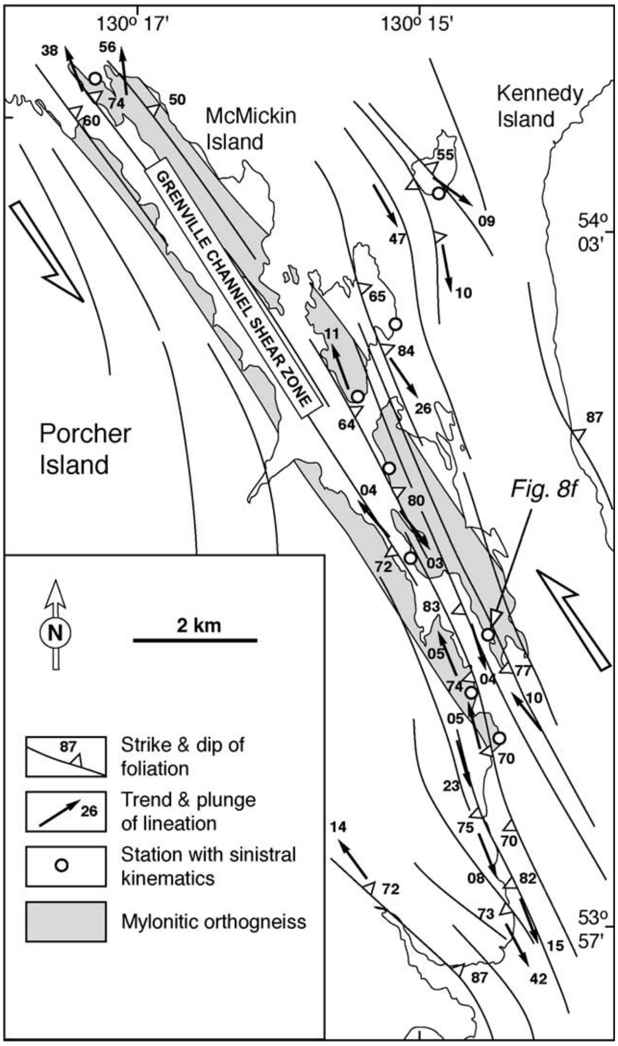

Fig. 9. Strain pattern of the Grenville Channel shear zone along the eastern shore of Porcher Island (adapted from Chardon et al., 1999). Location in Fig. 2.

Along the channel, the shear zone develops an intense plastic fabric in the batholith (Roddick, 1970).

4.2.5. Coast Shear zone

In the study area (Fig. 5), the Coast shear zone is associated with subvertical (to the NW) to moderately SW-dipping foliations running parallel to Work Channel. SE of the tip of the channel, foliations are deflected and tend to parallel the envelope of the Ecstall batholith. In the area of location F (Fig. 7a) foliation in the Coast shear zone steeply dips to the SW (70–80°) and the stretching lineation and isoclinal fold axes are down-dip (location F; Figs. 5b, 6 and 7a). The growth of sillimanite is syn-kinematic with respect to the development of the LS fabrics (e.g. Crawford et al., 1987). In this area, numerous sub-horizontal, meter-scale shear zones with apparent top-to-the-NE sense of shear affect the steeply dipping mylonitic foliation. Those features could have accommodated late, syn-cooling west-side-up movements in the shear zone.

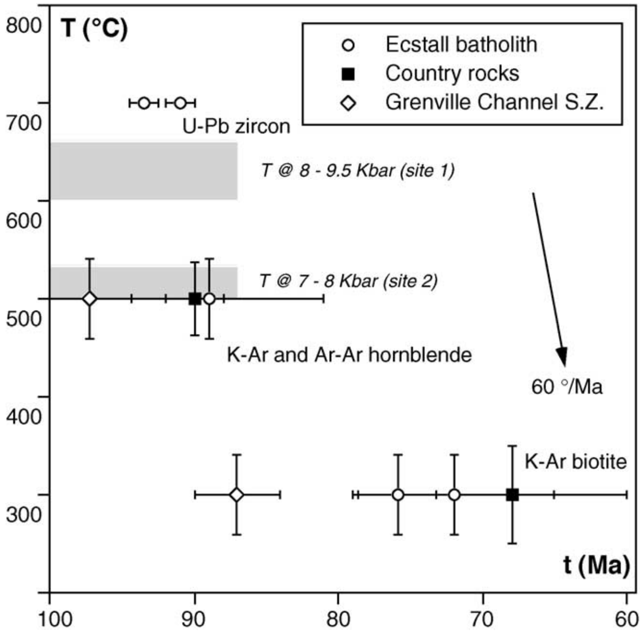

Fig. 10. Cooling history of the Ecstall batholith and its country rocks. Sources: Hutchison (1982), Sutter and Crawford (1985), van der Heyden (1989) (see Chardon et al., 1999) and Crawford et al. (2000). The old U–Pb date is from the tail of the batholith whilst the younger age is from the northern part of the head. The hornblende Ar–Ar date comes from lower amphibolite facies schists in the Prince Rupert area. K–Ar date for the batholith comes from the head of the batholith. The biotite K–Ar date of the country rocks is from location 1 (Fig. 5b). Temperature estimates at locations 1 and 2 (Fig. 5a) are from Crawford et al. (1979).

5. Physical conditions and timing of plutonism and deformation

5.1. Deformation–metamorphism relationships

In the area of Fig. 5, the mapping of metamorphic facies (Hutchison, 1982), index minerals occurrences, and isograds (Crawford et al., 1979; Crawford and Hollister, 1982) reveals a regional NE-directed metamorphic gradient across the foliation's strike (Fig. 5). At location 1 (Fig. 5a), P–T determinations (Crawford et al., 1979) yield 8–9 kbar and 600–650 °C (note that this site corresponds to the sheared graphite–kyanite schists near location C; Fig. 7a; discussed in Section 4.2.2). At location 2 (Fig. 5a), phase equilibria indicate pressures from 7 to 8 kbar and temperatures around 550 °C (Crawford et al., 1979; Fig. 10). Our work and porphyroblast–matrix relationships studies by Crawford and Hollister (1982) and Crawford et al. (1987), point to the synchronism of the main fabric development episode and peak metamorphism, especially in the interference zone (index minerals such as Biotite, Garnet, Staurolite and especially Kyanite were used; see also Section 4.2.2).

The pressure range expected for the crystallization of the batholith (Zen and Hammarstrom, 1984; Hollister et al., 1987) agrees with pressure estimates based on phase

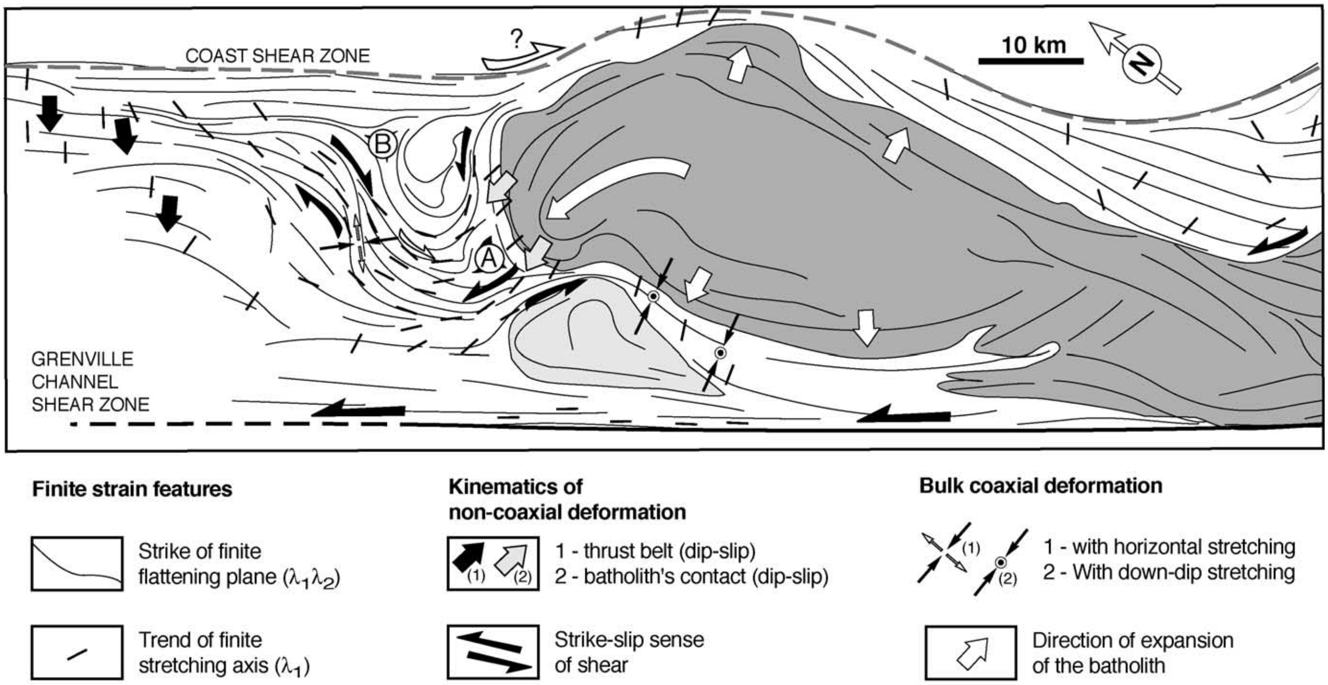

Fig. 11. Synthetic representation of the Mid-Cretaceous finite strain and kinematic pattern of the Prince Rupert area. Complementary data in country rocks from the region south of Prince Rupert (outside the frame of Fig. 5) are from Gareau (1989); Chardon et al. (1999) and C. Andronicos (personal communication).

equilibria in the surrounding metamorphic rocks (e.g. at location 2; Fig. 5a; Crawford et al., 1979, 1987).

5.2. Timing constraints

Top-to-the-SW shear thrusting in the Western thrust belt in the northern part of the study area took place until 92 ± 2 Ma, based on U–Pb dating of a late kinematic felsic dike (Klepeis et al., 1998). Lower amphibolite facies schists from the Prince Rupert area went through hornblende Ar–Ar closure temperature (ca. 500 °C) 90 ± 1 Ma ago (Sutter and Crawford, 1985). The head of the batholith crystallized at 91 Ma (Crawford et al., 2000; Fig. 10).

Although error bars on K–Ar dates are large, rapid cooling of the batholith between 93 and 89 Ma (up to 60 °C/Ma) is inferred from Fig. 10. Then, the batholith and its country rocks appear to have spent ca. 15 Ma in a thermal environment near the K–Ar biotite closure temperature (ca. 300 °C; Fig. 10).

Shearing along the Grenville Channel shear zone likely lasted until 87 ± 3 Ma based on a K–Ar biotite date from an orthogneiss along the trace of the shear zone near Porcher Island (van der Heyden, 1989; Chardon et al., 1999). This is especially attested to by field evidence for progressive strain localization during ongoing sinistral shearing in the shear zone (i.e. from ductile to brittle–ductile; Fig. 8e). The same sample yields a K–Ar hornblende date of 97 ± 3 Ma (closure temperature of ca. 500 °C) that overlaps with the U–Pb zircon age range of the rock (van der Heyden, 1989) (Fig. 10). This age together with the field evidence for early feldspar plasticity (>500 °C) during shearing in the Grenville Channel shear zone (Chardon et al., 1999) suggests that the shear zone was already active 97 ± 3 Ma ago (Fig. 10). This is compatible with the fact that the shear zone induces solid-state deformation at the southwestern margin of the batholith that yields a zircon U–Pb crystallization age of 93.5 ± 1 Ma in this area.

North of the Skeena River (Fig. 2), gneisses from the Coast shear zone went through Hornblende Ar–Ar closure temperature 56–57 Ma ago (Sutter and Crawford, 1985), shortly after the emplacement of the Quottoon pluton (59 Ma). This, together with U–Pb ages of pre- to post-kinematic melts in the shear zone (Klepeis et al., 1998), shows that the rear of the thrust belt has undergone reheating related to the Coast shear zone activity at least from 60 to 56 Ma (Crawford et al., 1987). The end of the relative thermal stability period of the Ecstall batholith and its country rocks between ~80 and 60 Ma (Fig. 10) is to be linked to late west side-up shearing in the shear zone that drove the exhumation and tilting of the Western thrust belt as suggested by Cook and Crawford (1994) in southeasternmost Alaska.

6. Interpretation

The present work goes towards emphasizing the interference between different strain fields to produce the strain

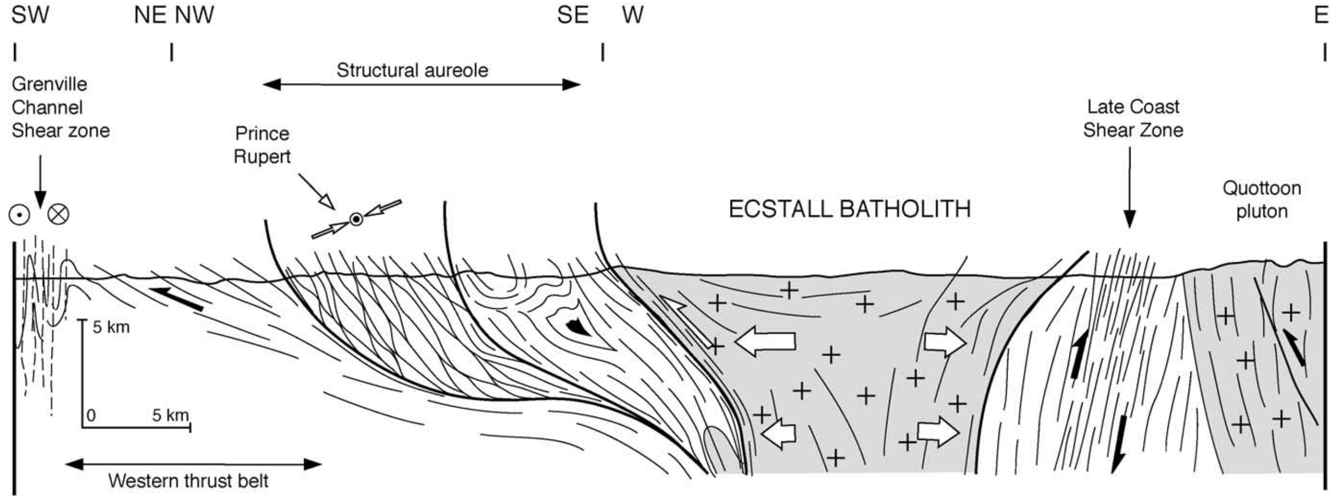

Fig. 12. Cross-section through the Ecstall batholith and its country rocks in the Prince Rupert area (the line of section is located in Fig. 2). Thin lines represent the foliation trace and kinematic indicators relate to syn-emplacement deformation except for black arrows that indicate Western thrust belt kinematics west of the batholith and Late Coast shear zone deformation east of the batholith.

pattern summarized in Fig. 11. These strain fields are controlled by head-member structural processes associated with specific geometrical boundary conditions. These are: (1) the development of the Western thrust belt, (2) the emplacement of the batholith, and (3) regional deformation coeval with the intrusion of the batholith, during sinistral strike-slip shearing along the Grenville Channel shear zone.

6.1. Batholith—Western thrust belt interference

In the western and northwesternmost parts of the study area, structures of the thrust belt, simple planar (orogen-parallel, NE dipping) and linear (down-dip) fabrics pattern associated with pervasive top-to-the-SW shearing reflect stacking of crustal units that generated the regional inverted metamorphic gradient (Fig. 11).

The shape of the batholith controls the overall geometry of the interference zone that has to be seen as a structural aureole generated during its emplacement. The apparent complexity of the aureole results from the fact that the batholith's emplacement is accommodated by spatial strain partitioning in the country rocks due to the presence of the preexisting, thrust-related pervasive fabric. The geometrical and kinematic coherence and compatibility in the spatial distribution of strain and kinematic indicators shown in Fig. 11 resolves this apparent complexity.

The concentric interference foliation trajectories were bent and extruded toward the SW at the NW front of the batholith (Fig. 11). Opposed strike-slip shearing on both limbs of the interference domal structure accompanies the extrusion as shown by the foliation trajectories north of Prince Rupert (northwestern limb, dextral) and field kinematic analysis on the southeastern limb (sinistral). Along the southeastern limb, syn-plutonic dip-slip reverse shearing at the floor of the batholith is gradually transformed into extrusion-related sinistral strike-slip shearing (Fig. 6c). Whereas at the root of the northwestern limb, thrust belt-related oblique to down-dip lineations and SW-vergent reverse shearing is replaced by extrusion-related dextral shearing (Fig. 11). Dextral shearing also took place along the inner foliation trajectories of the northwestern limb as exemplified in the graphite schists at location C (Figs. 7a and 11). South of triple point *B* (Fig. 11), down-dip lineations at the base of the batholith are transformed into shallowly plunging lineations on the southern limb of the dome. Foliation patterns in this area suggest that this change in the pitch of lineations is associated with batholith boundary-parallel sinistral shearing (Fig. 11). This shearing is also interpreted as accommodating the extrusion process along the inner foliations of the southern limb of the structure (i.e. symmetrical with respect to the dextral graphite schists shear on the other limb).

The concentric foliation trajectories indicate dominantly radial shortening in the aureole. This is more particularly attested to by the attenuation of the regional isograds in the SW part of the aureole (area of location 2; Fig. 5a). Bulk inhomogeneous contraction recorded by the Prince Rupert shear-lenses system (Fig. 11) accommodates radial shortening combined concentric stretching. It is explained by its position within the aureole. Indeed, this zone corresponds to the portion of the northwestern limb of the aureole that parallels the nearest batholith–country rocks contact and where the foliation trajectory curvature is the highest in the aureole outside the influence of escape-related strike-slip shearing.

The extrusion phenomenon expressed on the map (Fig. 11) may also be evaluated on cross-section (Fig. 12). Lateral expansion of the batholith led to reverse shearing along its inward-dipping floor (Fig. 12). Expansion is transferred and accommodated in the aureole by pinching of the metamorphic rocks that acquire a shallower foliation (Fig. 6a) and confers to the structural aureole a fan geometry in cross-section (Fig. 12). Those features accompany horizontal extrusion of the aureole accommodated by concentric strike-slip shearing, radial shortening (concentric foliations and bulk inhomogeneous contraction in the Prince Rupert shear lenses system) and horizontal concentric stretching (attested to by the pervasiveness of shallowly plunging lineations in the interference zone). A minor component of vertical extrusion may be expected (i.e. local asymmetry of the lenses).

The high-pressure mineral assemblages are syn-kinematic with respect to strain fabrics developed in the aureole. Given the hornblende Ar–Ar 90 Ma date for the aureole's schists, the structural relations between the batholith and its country rocks, and the inferred pressure range of crystallization of the batholith, this means that batholith emplacement and aureole tectonics took place at ca. 30 km depth during regional metamorphic climax. The fact that thrust belt-related isograds are deformed in accordance with the foliation trajectories into the aureole suggests that the batholith intruded after significant crustal thickening took place in the thrust belt. This also indicates that the high-pressure inverted metamorphic pattern in the thrust belt was already achieved at the time of batholith emplacement. This statement agrees with the geochronological constraints (Section 5.2) and the structural evidence for earlier down-dip stretching at several locations in the aureole.

At the regional scale (Fig. 11), it appears that dip-slip non-coaxial deformation at the batholith's contact is restricted to the region of triple point *A* (Fig. 11). Indeed, rocks at the western margin of the batholith primarily record bulk coaxial deformation and down-dip stretching across steeply, batholith-ward dipping foliations (C. Andronicos, personal communication) (Fig. 11) and similar relations are suggested east of the batholith (Gareau, 1989, 1990).

6.2. Sinistral strike-slip shearing and pluton expansion

The core of the Grenville Channel shear zone records horizontal finite elongation and pervasive sinistral strike-slip shearing (Chardon et al., 1999; Figs. 9 and 11). Thrust belt-related features interfere with the shear zone outside the structural aureole as exemplified WNW of Prince Rupert where shear zone-parallel upright folds affect the shallowly dipping thrust fabrics and develop a crenulation cleavage (Fig. 12). Sinistral slip along the shear zone (97 ± 3–87 ± 3 Ma) has taken place before, during and slightly after crystallization of the batholith (93–91 Ma). This, together with the overall geometry of the interference zone could suggest that at least parts of the structural aureole results from the indentation of the thrust belt by the fully crystallized batholith as a consequence of sinistral slip along the shear zone. However, the rigid indentation hypothesis would imply arc-parallel thrusting and associated stretching of the country rock envelope of the head of the batholith. That is not the case as syn-plutonic shearing is preserved at the floor of the pluton and directed toward the West and not toward the NW (Fig. 11). This hypothesis would also preclude the continuity of fabrics across the batholith–country rocks contact. Accordingly, the contribution of arc-parallel rigid-body translation of the batholith to the building of the interference pattern appears negligible.

Batholith inflation is favored as a cause for the interference pattern, although the stretching direction associated with shearing at the floor of the batholith is not radial with respect to its head. This relation rather suggests that the batholith locally expanded toward the West into the interference zone by lateral spreading beyond Smith Island Pluton during overall northwestward-directed expansion (Fig. 11). This is supported by the attenuation seen on the zoning pattern of the batholith in the northwestern part of its head (Fig. 3). The geochronological data and field interference features indicate that the aureole developed during sinistral slip along the shear zone and that sinistral shearing lasted until after aureole tectonics ceased (90–87 Ma).

6.3. Synthesis

The structural, petrological and geochronological data point to the synchronism between plutonism on the one hand and deformation and metamorphism within the batholith's aureole on the other hand. Overall horizontal NNW-directed expansion of the batholith produced the westward extrusion of country rocks associated with radial shortening and horizontal concentric stretching and accommodated by concentric strike-slip shearing. The data argue for the syntectonic emplacement and crystallization of the Ecstall batholith (93–91 Ma) during sinistral slip along the orogen-parallel, crustal-scale Grenville Channel shear zone. Those combined processes interfered with the strain field developed until 92 ± 2 Ma by orogen-perpendicular thrusting and crustal thickening in the Western thrust belt. Therefore, the finite structural pattern is interpreted as resulting from batholith emplacement during strike-slip partitioned transpression, orogen-perpendicular contractional component of transpression being recorded in the Western thrust belt whilst orogen-parallel sinistral slip component of transpression is recorded in the Grenville Channel shear zone.

The present analysis suggests forceful emplacement of the batholith with a horizontal principal direction of expansion that paralleled the incremental maximum stretching direction (Brun and Pons, 1981), oblique on the shear zone's strike. In strike-slip partitioned transpression zones, the incremental and finite maximum stretching axes are highly oblique with respect to the regional strike-slip shear zones (Fossen and Tikoff, 1998) that parallel the magmatic arc trend (i.e. orogenic trend) (Teyssier et al., 1995; de Saint Blanquat et al., 1998). The overall expansion direction of the Ecstall batholith (+20° with respect to the shear zone strike) is rather compatible with left-oblique convergence. Nevertheless, the angle between the map-view long axis of the batholith and the shear zone does not allow inferring the angle between the plate motion vector and the plate margin during batholith emplacement.

The geometry of the structural aureole and the displacement field it implies (Figs. 11 and 12) also suggest that expansion of the batholith has been partly or fully accommodated by the three components of strain in the country rocks (Tikoff et al., 1999). These are radial translation (that is accommodated at least as far as 16 km from the batholith), extrusion-related rotation and radial and concentric elongation (i.e. distortion).

7. Discussion

7.1. Relations to plate kinematics

During the Early Cretaceous, increasingly high-angle left-oblique convergence between the Farallon oceanic plate and North America should be recorded by the Coast Plutonic Complex and a shift from straight-on to right-oblique convergence is expected around 95 Ma (Kelley and Engebretson, 1994). The kinematic history of the Grenville Channel shear zone indicating that sinistral strike-slip shearing took place in the Coast plutonic complex until 87 Ma is therefore apparently in conflict with the plate reconstruction. Given the large uncertainty on the chronology of plate reconstruction (±5–10 Ma), an explanation could be that extreme strike-slip transpressional partitioning accommodated almost straight-on convergence until 87 Ma. Another possibility would be that left-oblique convergence actually lasted until 87 Ma (Chardon et al., 1999).

7.2. Pluton emplacement processes

For Crawford et al. (2000), what is described here as the Prince Rupert shear-lenses system is a stretching lineation-free shear zone (i.e. the Prince Rupert shear zone) that records flattening strain. This shear zone is interpreted to have accommodated loading by westward thrusting of the high-grade country rocks envelope of the batholith after its emplacement (Crawford et al., 2000). The present systematic fabric mapping and kinematic analysis reveal that this arcuate feature cannot accommodate orogen-perpendicular thrusting but rather horizontal, concentric, bulk coaxial stretching during buckling of the foliation trajectories of the structural aureole. For the same reasons, the above analysis does not favor the syn-thrusting emplacement hypothesis for the Ecstall batholith. One should add that the Ecstall batholith does not display the distinctive deformation patterns expected for plutons intruding during thrusting as established by Brun and Pons (1981). Our interpretation is closer to the view of Hutchison (1970, 1982), who interpreted the interference zone as resulting from the forceful emplacement of the Ecstall batholith during NW-directed expansion. Nevertheless, based on the sub-horizontal concentric lineation pattern in the aureole, we do not emphasize northwestward overriding of the interference zone by the batholith as suggested by this author. Indeed, such an interpretation would require that lineations dominantly plunge to the SW in the structural aureole of the batholith.

The geometry of the batholith's structural aureole (Fig. 12) and its metamorphic pattern require the applicability of the magma-loading model to be evaluated for the present case. Brown and Walker (1993) and Brown and McClelland (2000) proposed this model for increasing pressure record of the metamorphic aureoles of mid-Cretaceous plutons in the Southernmost CPC. Several lines of evidence may argue against the magma-loading model for the Prince Rupert area. As stated above (Section 6.1), the high-pressure inverted metamorphic pattern had already been achieved by thrusting on a regional scale at the time the batholith intruded as the regional isograds are deformed during batholith emplacement. In other words, the inverted metamorphic gradient is not restricted to the batholith's structural aureole and is not systematically directed toward the batholith (e.g. thrust belt-related, orogen-normal gradient in the vicinity of Port Simpson). Furthermore, the increasing pressure record across the aureole toward the batholith, from location 2 to location 1 (Fig. 5a), is rather small (from 7–8 to 8–9 kbar). However, Pluton emplacement rotated thrust belt-related foliation into shallower dips within the aureole (Fig. 6a). This could suggest that the country rocks have been pushed downward underneath the head of the batholith. Such geometry would be compatible with the magma-loading hypothesis. But the structural evidence for dominantly horizontal shearing and stretching in the batholith's structural aureole argues against down-warping of the wall rocks. However, the magma-loading model cannot be definitely ruled out until detailed geobarometry is performed along an E–W transect across the batholith's aureole and along a NW-directed transect in the high-grade rocks unit (Fig. 5).

Paterson and Miller (1998) invoke the downward return flow of a narrow wall rock aureole to partly accommodate space creation for batholiths during their ascent in contractional arcs. Their hypothesis is based on the observation of the downward deflection of foliations and pre-emplacement rock markers in the aureoles. Those relations would suggest apparent downward displacement of the batholith relative to its wall rocks. In the present case, pre-emplacement thrust belt-related foliations were moderately to steeply dipping before they acquire shallower dips in the batholith's aureole. Close to the batholith, country rock foliations parallel the batholith's contact that is the locus of syn-plutonic, dip-slip, reverse shearing (area of triple point *A*, Fig. 11), indicating apparent upward displacement of the batholith with respect to its country rocks. Elsewhere at the batholith's contact, bulk coaxial shortening prevails across contact-parallel foliations in the country rocks (Fig. 11). Those relations around the Ecstall batholith suggest that the downward return flow of country rocks did not operate during its emplacement.

7.3. Transpression, magmatism and exhumation

The cessation of thrusting in the Western thrust belt (92 ± 2 Ma) coincides with the emplacement of the Ecstall batholith (93.5 ± 1 to 91 ± 1 Ma). This could suggest that batholith emplacement favored the strike-slip component of transpression over contractional deformation in the Prince Rupert area. Given their geometry, strike-slip systems tend to favor plutonic activity as they provide steep crustal-scale vertical pressure gradients (de Saint Blanquat et al., 1998). For very high-angle oblique- and even almost straight-on convergence, magma-assisted strike-slip partitioning can also be enabled by the intrusion of batholiths (de Saint Blanquat et al., 1998). In the present case, slip along the Grenville Channel shear zone was likely to be active before batholith emplacement, suggesting that strike-slip partitioning facilitated magma ascent. In addition, lower crustal melting and batholith emplacement probably led to significant weakening of the lower crust that could not sustain ongoing thickening anymore and developed extreme strike-slip partitioning.

The geometry and metamorphic pattern of the thrust belt, the low ambient geothermal gradient at the time the batholith intruded and the preservation of intermediate- to high-pressure metamorphic assemblages suggest that the thrust belt was a crustal scale wedge (Davy and Gillet, 1986). Metamorphic relations and the crystallization depth of the batholith further imply that the orogenic wedge produced an almost doubly thickened crust in a cold thermal environment (<20°/km) (Zen, 1985) and that the crustal thermal structure was not substantially perturbed by plutonism. Those considerations imply rapid exhumation of the crustal panel intruded by the batholith. Simple thermal calculations on three-dimensional particle paths within model transpressional orogens (Thompson et al., 1997) suggest that extrusional exhumation can be efficient for high-angle to straight-on convergence and brings rocks that exhibit low thermal gradient to upper crustal levels within 10–20 Ma. This is compatible with the metamorphic and deformational history of the Prince Rupert crustal panel and its plate tectonics setting between 92 and ~80 Ma. Knowing that plutonism is not required in such models to produce fast exhumation, one may expect even faster extrusional exhumation rates for the Prince Rupert crustal panel as batholith emplacement took place during this period.

8. Conclusion

The present work allows the evaluation of three-dimensional interaction patterns of transpression and pluton emplacement at deep crustal levels within a magmatic arc. The main results are summarized as follows:

1. The emplacement of the Ecstall batholith was driven by strike-slip-partitioned sinistral transpression. The batholith expanded horizontally and obliquely with respect to the shear zone strike, in a direction that is compatible with a high-angle left oblique convergence.
2. Space for the batholith was generated by syn-emplacement strain partitioning resulting in horizontal extrusion of country rocks in a direction normal to the expansion direction of the batholith. Strain partitioning combined far-field batholith boundary-normal translation, extrusion-related rotation, radial shortening, concentric elongation and strike-slip shearing in its structural aureole.
3. The example of the Ecstall batholith illustrates the orogen-parallel growth of a magmatic arc during oblique plate convergence, the direction and sense of growth being determined by the direction of plate motion relative to the magmatic arc and the degree of strike slip partitioning of transpression.

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References

Andronicos, C.L., Hollister, L.S., Davidson, C., Chardon, D., 1999. Kinematics and tectonic significance of transpressive structures within the Central Gneiss Complex, British Columbia. Journal of Structural Geology 21, 229–243.

Balé, P., Brun, J.-P., 1989. Late Precambrian thrust and wrench zones in Northern Brittany (France). Journal of Structural Geology 11, 391–405.

Bouhallier, H., Chardon, D., Choukroune, P., 1995. Strain patterns in Archaean dome-and-basin structures: the Dharwar craton (Karnataka, South India). Earth and Planetary Science Letters 135, 57–75.

Brown, E.H., Walker, N.W., 1993. A magma-loading model for Barrovian metamorphism in the Southeast Coast Plutonic Complex, British Columbia and Washington. Geological Society of America Bulletin 105, 479–500.

Brown, E.H., McClelland, W.C., 2000. Pluton emplacement by sheeting and vertical ballooning in part of the southeast Coast Plutonic Complex, British Columbia. Geological Society of America Bulletin 112, 708–719.

Brun, J.-P., Pons, J., 1981. Strain patterns of pluton emplacement in a crust undergoing non-coaxial deformation, Sierra Morena, Southern Spain. Journal of Structural Geology 3, 219–229.

Brun, J.-P., Gapais, D., Cogné, J.-P., Ledru, P., Vigneresse, J.L., 1990. The Flamanville Granite (Northwest France): an uniquivocal example of a syntectonically expanding pluton. Geological Journal 25, 271–286.

Chardon, D., Andronicos, C.L., Hollister, L.S., 1999. Large-scale transpressive shear zone patterns and displacements within magmatic arcs: the Coast Plutonic Complex, British Columbia. Tectonics 18, 278–292.

Choukroune, P., Gapais, D., 1983. Strain pattern in the Aar granite (Central Alps): orthogneiss developed by bulk inhomogeneous shortening. Journal of Structural Geology 5, 411–418.

Cook, R.D., Crawford, M.L., 1994. Exhumation and tilting of the western metamorphic belt of the Coast orogen in southern southeastern Alaska. Tectonics 13, 528–537.

Crawford, M.L., Hollister, L.S., 1982. Contrast of metamorphic and structural histories across the Work channel lineament, Coast Plutonic Complex, British Columbia. Journal of Geophysical Research 87, 3849–3860.

Crawford, M.L., Crawford, W.A., 1991. Magma emplacement in a convergent tectonic orogen, southern Revillagigedo Island, southeastern Alaska. Canadian Journal of Earth Sciences 28, 929–938.

Crawford, M.L., Kraus, D.W., Hollister, L.S., 1979. Petrologic and fluid inclusion study of calc–silicate rocks, Prince Rupert, British Columbia. American Journal of Science 9, 1135–1159.

Crawford, M.L., Hollister, L.S., Woodsworth, G.J., 1987. Crustal deformation and regional metamorphism across a terrain boundary, Coast Plutonic Complex, British Columbia. Tectonics 6, 343–361.

Crawford, M.L., Crawford, W.A., Gehrels, G.E., 2000. Terrane assembly and structural relationships in the eastern Prince Rupert quadrangle, British Columbia. In: Stowell, H.H., McClelland, W.C. (Eds.), Tectonics of the Coast Moutains, Southeastern Alaska and British Columbia. Geological Society of America, Special Paper 343, pp. 1–21.

Davy, P., Gillet, P., 1986. The stacking of thrust slices in collision zones and its thermal consequences. Tectonics 5, 913–929.

Fossen, H., Tikoff, B., 1998. Extended models of transpression and transtension, and application to tectonic setting. In: Holdsworth, R.E., Strachan, R.A., Dewey, J.F. (Eds.), Continental Transpressional and Transtensional Tectonics. Geological Society Special Publication 135, pp. 15–33.

Gapais, D., Balé, P., Choukroune, P., Cobbold, P., Mahjoub, Y., Marquer, D., 1987. Bulk kinematics from shear zone patterns: some field examples. Journal of Structural Geology 9, 635–646.

Gareau, S.A., 1989. Metamorphism, deformation and geochronology of the Ecstall–Quaal rivers area, Coast Plutonic Complex, British Columbia. Geological Survey of Canada Paper 89-1E, 155–162.

Gareau, S.A., 1990. Geology of the Scotia–Quaal metamorphic Belt, Coast Plutonic Complex, British Columbia. Geological Survey of Canada Open File Report 2327.

Gareau, S.A., Woodsworth, G.J., 2000. Yukon–Tanana terrane in the Scotia–Quaal belt, Coast Plutonic Complex, central-western British Columbia. In: Stowell, H.H., McClelland, W.C. (Eds.), Tectonics of the Coast Moutains, Southeastern Alaska and British Columbia. Geological Society of America, Special Paper 343, pp. 23–43.

Gehrels, G.E., McClelland, W.C., Samson, S.D., Patchett, P.J., 1991. U–Pb geochronology of Late Cretaceous and Early Tertiary plutons on the northern Coast Mountains Batholith. Canadian Journal of Earth Sciences 28, 899–911.

Harland, W.B., 1971. Tectonic transpression in Caledonian Spitsbergen. American Association of Petroleum Geologists Bulletin 108, 27–42.

Holdsworth, R.E., Strachan, R.A., Dewey, J.F. (Eds.), 1998. Continental Transpressional and Transtensional Tectonics. Geological Society Special Publication 135.

Hollister, L.S., Andronicos, C.L., 1997. A candidate for the Baja–British Columbia fault system in the Coast Plutonic Complex. GSA Today 7, 1–7.

Hollister, L.S., Grissom, G.C., Peters, E.K., Stowell, H.H., Sisson, V.B., 1987. Confirmation of the empirical correlation of Al in hornblende with pressure of solidification of calc–alkaline plutons. American Mineralogist 72, 231–239.

Hutchison, W.W., 1970. Metamorphic framework and plutonic styles in the Prince Rupert region of the Central Coast Mountains, British Columbia. Canadian Journal of Earth Sciences 7, 376–405.

Hutchison, W.W., 1982. Geology of the Prince Rupert–Skeena map area, British Columbia. Geological Survey of Canada Memoir 394, 1–116.

Hutton, D.H., 1988. Granite emplacement mechanisms and tectonic controls: inferences from deformation studies. Transactions of the Royal Society of Edinburgh: Earth Sciences 79, 245–255.

Hutton, D.H.W., Reavy, R.J., 1992. Strike-slip tectonics and granite petrogenesis. Tectonics 11, 960–967.

Ingram, G.M., Hutton, D.H.W., 1994. The Great Tonalite Sill: emplacement into a contractional shear zone and implications for late Cretaceous to early Eocene tectonics in southeastern Alaska and British Columbia. Geological Society of America Bulletin 106, 715–728.

Kelley, K.P., Engebretson, D.C., 1994. Updated relative motions and terrane trajectories for North America and oceanic plates: Cretaceous to present. Geological Society of America Abstracts with Programs 26, A-409.

Klepeis, K.A., Crawford, M.L., Gehrels, G., 1998. Structural history of the crustal-scale coast shear zone north of Portland Canal, southeast Alaska and British Columbia. Journal of Structural Geology 20, 883–904.

Morozov, I.B., Smithson, S.B., Hollister, L.S., Diebold, J.B., 1998. Wide-angle seismic imaging across accreted terranes, southeastern Alaska and western British Columbia. Tectonophysics 299, 281–296.

Oldow, J.S., Bally, A.W., Ave Lallemant, H.G., Leeman, W.P., 1989. Phanerozoic evolution of the North American Cordillera; United States and Canada. In: Bally, A.W., Palmer, A.R. (Eds.). The Geology of North America—an Overview. Geological Society of America, pp. 139–232.

Paterson, S.R., Miller, R.B., 1998. Magma emplacement during arc-perpendicular shortening: an example from the Cascades crystalline core, Washington. Tectonics 17, 571–586.

Roddick, J.A., 1970. Douglas Channel and Hecat strait map-area, British Columbia. Geological Survey of Canada Paper 70-41, 1–56.

Rubin, C.M., Saleeby, J.B., 1992. Tectonic history of the eastern edge of the Alexander terrane, southeast Alaska. Tectonics 11, 586–602.

Runkle, D.E., 1979. Geology and geochronology of the Coast Plutonic Complex adjacent to Douglas, Sue and Loretta channels, British Columbia. Master thesis, Univiversity of British Columbia.

Rusmore, M.E., Woodsworth, G.J., 1991. Coast Plutonic Complex: a mid-Cretaceous contractional orogen. Geology 19, 941–944.

de Saint Blanquat, M., Tikoff, B., Teyssier, C., Vigneresse, J.-L., 1998. Transpressional kinematics and magmatic arcs. In: Holdsworth, R.E., Strachan, R.A., Dewey, J.F. (Eds.), Continental Transpressional and Transtensional Tectonics. Geological Society Special Publication 135, pp. 327–340.

Sanderson, D.J., Marchini, W.R.D., 1984. Transpression. Journal of Structural Geology 6, 449–458.

Sutter, J.F., Crawford, M.L., 1985. Timing of metamorphism and uplift in the vicinity of Prince Rupert, British Columbia and Ketchikan, Alaska. Geological Society of America Abstracts with Programs 17, 411.

Teyssier, C., Tikoff, B., Markley, M., 1995. Oblique plate motion and continental tectonics. Geology 23, 447–450.

Thompson, A.B., Schulmann, K., Jezek, J., 1997. Thermal evolution and exhumation in obliquely convergent (transpressive) orogens. Tectonophysics 280, 171–184.

Tikoff, B., de Saint Blanquat, M., Teyssier, C., 1999. Translation and the resolution of the pluton space problem. Journal of Structural Geology 21, 1109–1117.

van der Heyden, P., 1989. U–Pb and K–Ar geochronometry of the Coast Plutonic Complex, 53°N-54°N, and implication for the Insular–Intermontane superterrane boundary, British columbia. Ph.D. thesis, University of British Columbia.

van der Heyden, P., 1992. A middle Jurassic to Early Tertiary Andean–Sierran arc model for the Coast Belt of British Columbia. Tectonics 11, 82–97.

Woodsworth, G.J., Hill, M.H., van der Heyden, P., 1985. Geology, Terrace, B.C. 1031 east half. Geological Survey of Canada Open File Report 1136.

Woodsworth, G.J., Monger, J.W.H., Gabrielse, H., 1991. Structural style, Coast belt. In: Gabrielse, H., Yorath, C.J. (Eds.), Geology of the Cordilleran orogeny in Canada. Geological Survey of Canada, Geology of Canada 4, pp. 581–591.

Zen, E.-A., 1985. Implications of magmatic epidote-bearing plutons on crustal evolution in the accreted terranes of the northwestern North America. Geology 13, 266–269.

Zen, E.-A., Hammarstrom, J.M., 1984. Magmatic epidote and its petrologic significance. Geology 12, 515–518.