



The Eocene Southern Vancouver Island Orocline — a response to seamount accretion and the cause of fold-and-thrust belt and extensional basin formation

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Abstract

A deflection of the fault controlled southwestern coastline of Vancouver Island suggests the presence of a minor orocline, with a Southern Crustal Block (south of Barkley Sound–Alberni Inlet) rotated 20° counterclockwise relative to a Northern Fixed Crustal Block about a pole of rotation located northeast of Port Alberni. In this paper two models of orocline development, one of pure block rotation and one of pure bending, are proposed. The predictions of these models are tested against available geological maps, structural orientation data, identified regions of extension and contraction, and paleomagnetic data. Structural orientation and paleomagnetic data are consistent with 18° of post-Late Cretaceous counter clockwise rotation of the Southern Crustal Block relative to the Northern Fixed Crustal Block. A southward increase in the magnitude of rotation evident in the structural orientation data argues for a model of bending. Both bending and block rotation models predict the development of a zone of contraction along the northeast margin of the Southern Crustal Block, coincident with the location of the Eocene Cowichan fold-and-thrust belt, that diminishes northward toward the pole of rotation. As predicted, the fold-and-thrust belt is characterized by a northerly decrease in the amount of shortening, from $>30\%$ at the south end of the thrust belt, to 0% shortening north of Port Alberni. The northerly decrease in shortening is complemented by a north to south change in structural style from cylindrical to conical folds, and finally to planar, undeformed strata. The model of block rotation predicts the presence of a zone of extension extending southwest from the zone of rotation, coincident with the location of Eocene extensional structures within Barkley Sound and with horst and graben structures in the offshore Eocene to Miocene Tofino basin. Extension is less than predicted by a model of pure block rotation and suggests that much of the oroclinal rotation was accommodated by bending. Timing constraints indicate that orocline development was coeval with, and resulted from, the Eocene accretion of seamounts of the Crescent terrane. These findings demonstrate that oroclinal orogeny, the buckling of a linear crustal beam about vertical axes of rotation, can significantly impact the geometry, structure and character of an orogenic belt, even where the buckles are minor ($<20^\circ$ of rotation).

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1. Introduction

Oroclines, as defined by Carey (1955), are orogenic belts which have been flexed or bent in plan into

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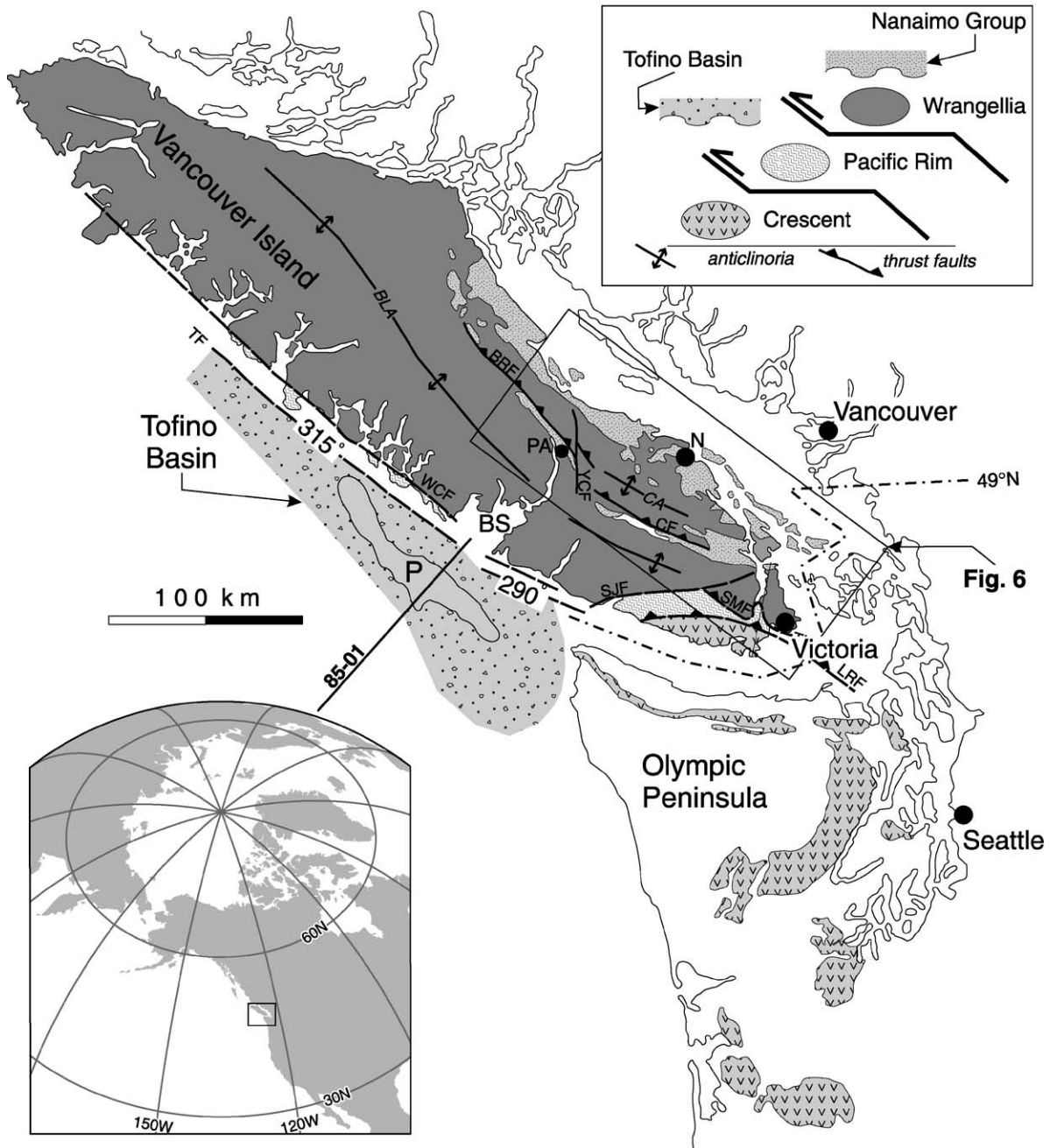


Fig. 1. Regional geology of Vancouver Island. Faults include the West Coast (WCF), and Tofino (TF), San Juan (SJF), Survey Mountain (SMF), Trial Island (TIF), Beaufort Range (BRF), Yellows Creek (YCF), Cowichan (CF), and Leech River (LRF) faults. 315° and 290° indicates the average orientations of the coastline and WCF north and south of Barkley Sound (BS), respectively. Two anticlinoria, the Buttle Lake (BLA), and the Cowichan (CA) are indicated. The central portion of the Eocene–Miocene Tofino Basin is characterized by the Prometheus (P) magnetic anomaly, a basement high underlain by basalt of the Crescent terrane. The line labeled 85-10 crossing the Tofino basin shows the location of a seismic line discussed in the text. Cities indicated include Port Alberni (PA) on Alberni Inlet and Nanaimo (N). The location of the study area is indicated in the inset map at lower left.

a horse-shoe or elbow shape. Oroclines are common features of orogens of all ages, and vary from minor ($<10^\circ$) deflections of tectonic grain, to $>90^\circ$ deviations of structural domains and lithotectonic belts. Despite the abundance of oroclines they remain enigmatic features with little consensus regarding the processes involved in orocline formation, or the crustal-scale geometry of oroclines (for reviews of oroclines see Carey, 1955; Eldredge et al., 1985; Marshak, 1988). Recent papers have demonstrated that orocline formation may be an important process in the evolution of convergent margins, and provide a means for resolving conflicting paleogeographic interpretations (Johnston, 2001; Mihalynuk et al., 1994; Weil et al., 2001). In addition, oroclinal orogeny, the buckling of an originally linear crustal strip, such as a ribbon continent or seamount chain, recently has been identified as an important process in the construction of continents (Johnston, 2001). Here we review geological observations and paleomagnetic data from southern Vancouver Island, within the Cordillera of western North America. These data indicate the presence of a minor orocline, hereafter referred to as the Southern Vancouver Island Orocline (SVIO) (Fig. 1). We speculate on the processes involved in its formation, and discuss the implications of SVIO for the role of oroclines in orogenic belts.

2. Regional geological setting

The North American Cordillera consists of a collage of terranes accreted to one another and to the North American margin between Permian and Miocene time. Vancouver Island is located within the westernmost portion of this orogen, and is divisible into three terranes: Wrangellia, Pacific Rim and Crescent (Figs. 1 and 2). Wrangellia, one of the largest of the accreted terranes within the Cordillera, underlies $\sim 90\%$ of Vancouver island, includes rocks of Devonian to Jurassic age, and has experienced five pre-Tertiary regional deformation events: Late Devonian, post-Lower Permian–pre-Middle Triassic, Late Triassic, post-middle Jurassic–pre Late Cretaceous and Late Cretaceous (Massey and Friday, 1988; Muller, 1977). Post Middle Jurassic–pre-Late Cretaceous deformation, including the development of northwest–southeast trending anticlinoria (Buttle Lake

and Cowichan; Fig. 1) provide a record of the mid-Cretaceous accretion of Wrangellia to the autochthon. Marine conglomerate, sandstone and shale of the Nanaimo Group underlie southeastern Vancouver Island and much of the adjacent Gulf Islands, and were deposited unconformably on Wrangellia in the Late Cretaceous (Muller and Jeletzky, 1970). North northwest-trending, west-verging folds and faults, collectively referred to as the Cowichan fold-and-thrust belt (England and Calon, 1991), have shortened and thickened the Nanaimo Group strata and the underlying basement. Normal faults in the Port Alberni region, such as the Yellow Creek fault (Fig. 1) cut Nanaimo Group strata and offset older thrust faults, and are interpreted to be coeval with minor Eocene felsic magmatism (Yorath et al., 1999). Northeast-verging thrusts appear to cut older west-verging thrusts of the Cowichan fold and thrust belt and may be the result of younger Neogene crustal shortening (Journey and Morrison, 1999).

The south and southwest coastal regions of Vancouver Island are underlain by rocks of the Pacific Rim and Crescent terranes. The Pacific Rim terrane occurs west and south of Wrangellia and consists of Triassic–Jurassic arc volcanics and Jurassic–Cretaceous melange (Brandon, 1989) and, between the Leech River and San Juan faults, marine sedimentary rocks, pillow basalts and amphibolite (C. Yorath, written communication, 2002; Figs. 1 and 2). The Crescent terrane, a Paleocene to Early Eocene oceanic assemblage of basalt flows, breccia, tuff and volcanic sandstones cut by gabbro and diabase intrusions, lies outboard (southwest) of the Pacific Rim terrane (Massey, 1986). Several lines of evidence suggest that the Crescent terrane originated as a series of seamounts formed above a hotspot (Duncan, 1982; Johnston and Thorkelson, 2000). These include the presence of subaerial flows (Massey, 1986), the occurrence in the Olympic peninsula to the south of Vancouver Island of 12–16 km thick sequences of basalt, and geochemical studies indicating derivation in part from an enriched mantle source (Babcock et al., 1992). Accretion of the Crescent terrane pre-dates or is coeval with the deposition of undeformed sandstone and conglomerate of the latest Early Eocene to Oligocene Carmanah Group that unconformably overlies and stitches the Crescent, Pacific Rim and Wrangellia terranes. The Pacific Rim and Crescent terranes

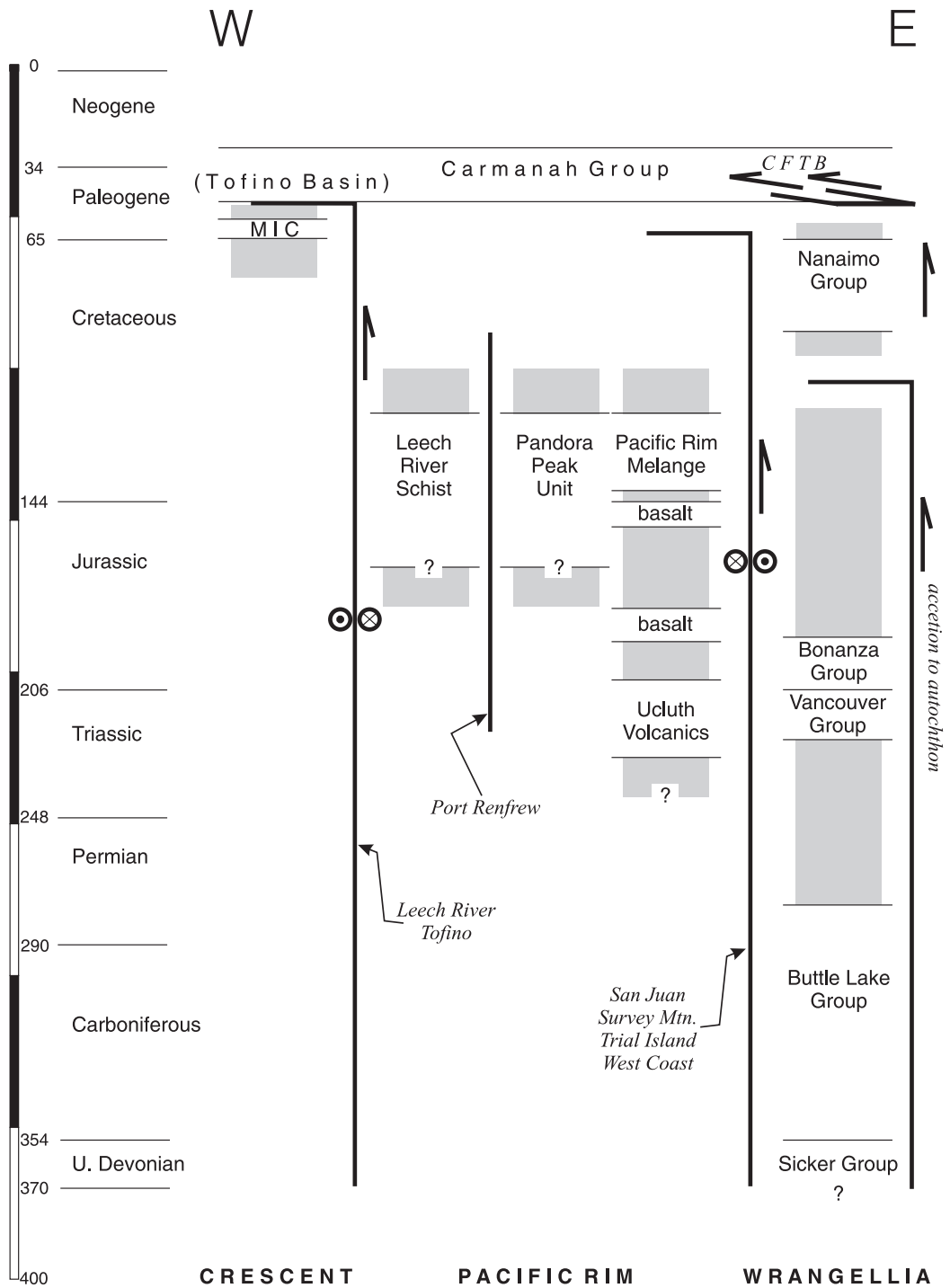


Fig. 2. Stratigraphic columns for Wrangellia, and the Pacific Rim and Crescent terranes of Vancouver Island. Shown schematically are the faults along which the terranes are juxtaposed, and the timing of terrane juxtaposition. CFTB—Cowichan fold-and-thrust belt; MIC—Metchoing Igneous Complex.

are interpreted as thin east-tapering thrust sheets 7 km thick for the Crescent terrane, and 10 km thick for the Pacific Rim terrane, that were offscraped from a subducting slab and now structurally underplate Wrangellia (Hyndman, 1995; Calvert, 1996; C. Yorath, written communication, 2002). Basaltic rocks that form the floor of the Eocene Tofino basin west of southern Vancouver Island are responsible for the prominent Prometheus magnetic anomaly (Fig. 1) and are correlated with the Crescent terrane (Hyndman, 1995). Accretion must therefore have predated or have been coeval with the Eocene initiation of basin formation.

3. Southern Vancouver Island Orocline—a model

A notable feature of the southwest coast of Vancouver Island is the remarkable linearity of the coastline. This linearity, and the location of the coastline is attributable to the presence of the planar West Coast fault (Brandon, 1989), along which resistant crystalline rocks of Wrangellia, east of the fault, are juxtaposed against friable and easily eroded melange of the Pacific Rim terrane (Fig. 1). Consequently, the coastline tends to lie close to the outcrop trace of the West Coast fault, near the southwestern most extent of crystalline rocks of Wrangellia.

For much of the length of Vancouver Island, the southwest coastline, and the West Coast fault, trend $\sim 315^\circ$. South of Barkley Sound–Alberni Inlet, the largest of the fjords and inlets that characterize the

southwest coast, the coastline trends $\sim 290^\circ$ (Fig. 1). This $>20^\circ$ deflection of the coastline, and of the structures controlling the location of the coastline, indicates the presence of an orocline—the Southern Vancouver Island Orocline. C. Yorath first recognized this orocline and suggested it resulted from tectonic bending of Vancouver Island (R. Hyndman, personal communication, 2001).

This orocline can be modeled (Fig. 3) as the result of a block rotation of the crustal block south of Barkley Sound–Alberni Inlet, hereafter referred to as the Southern Crustal Block, about a vertical pole

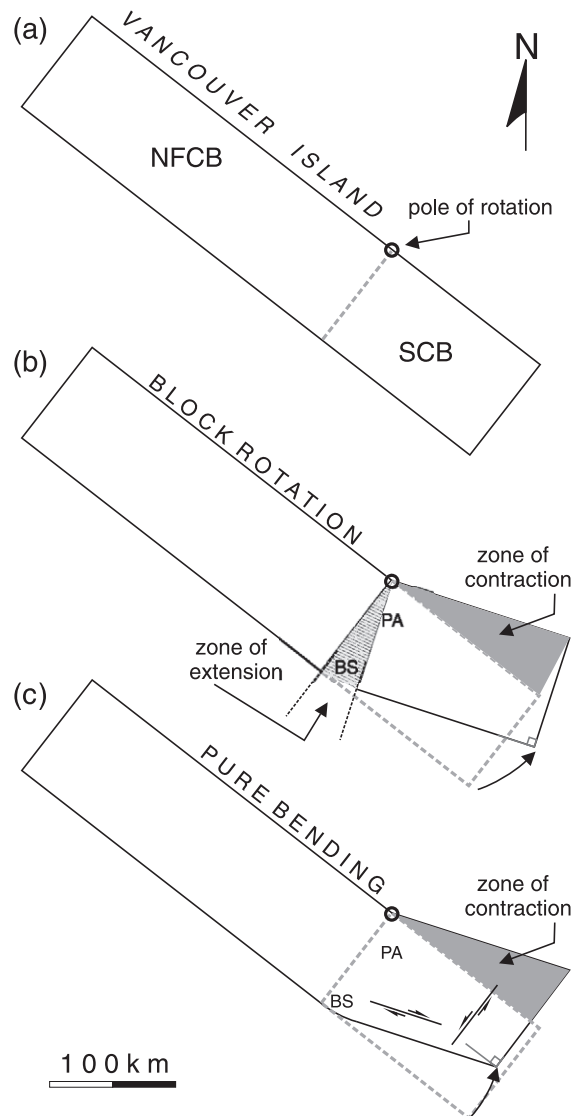


Fig. 3. Oroclinal rotation models for southern Vancouver Island. (a) Vancouver Island depicted as a rectangular crustal block (approximately correct scale), prior to orocline development. The dashed line separates the island into a northerly 'fixed' region, referred to in the text as the Northern Fixed Crustal Block, and a southern rotatable region, referred to in the text as the Southern Crustal Block. (b) Orocline development modeled as a block rotation of the Southern Crustal Block about a pole of rotation located along the northeast coast of Vancouver Island. Note the predicted zone of extension extending southwest from the pole of rotation through the Port Alberni (PA) inlet–Barkley Sound (BS), and the predicted zone of contraction. (c) Orocline development modeled as a response to bending. Shear strain associated with bending is indicated by the change of original right angles. Dextral northeast-trending and sinistral northwest-trending shears that would be expected to have developed during shearing are schematically indicated.

of rotation located along the northeast coast of the island, relative to the crustal block north of Barkley Sound, hereafter referred to as the Northern Fixed Crustal Block (Fig. 3b). Alternatively, the deflection can be modeled as having resulted from pure bending about a similarly located pole of rotation (Fig. 3c). The block rotation model predicts: (a) a uniform counterclockwise rotation of structures within the Southern Crustal Block relative to structures of the Northern Fixed Crustal Block; (b) the presence of a southeast extending zone of overlap or contraction along the northeast coast of the Southern Crustal Block within which shortening increases from zero at the pole of rotation to >50 km at the south end of Vancouver Island; and (c) the occurrence of a zone of extension extending southwest from the pole of rotation, characterized by a southwestward increase in the amount of extension from 0 km at the pole of rotation to >30 km along the southwest coast of Vancouver Island. A model of pure bending predicts: (a) the gradual counterclockwise deflection of structures of the Southern Crustal Block relative to those of the Northern Fixed Crustal Block; (b) a zone of contraction similar to that developed in the block rotation model; and (c) internal shear strain of >0.3 of the Southern Crustal Block—note the distortion of the original right angle at the south of the model Vancouver Island (Fig. 3c). Ductile flow or fault development, either by northeast-trending sinistral faults, or northwest trending dextral faults, are expected manifestations of such shear strain (Fig. 3c).

4. Geology of Southern Vancouver Island—testing the orocline model

To test the model of orocline development, and to distinguish between block rotation and pure bending, we (1) review and analyze structural orientation data; (2) summarize available paleomagnetic data; (3) evaluate evidence for the presence of a southeast extending zone of contraction along the northeastern margin of the Southern Crustal Block, (4) assess evidence for a southwest extending zone of extension lying along the boundary of the Southern Crustal Block and the Northern Fixed Crustal Block, and (5) appraise evidence for shear strain of the Southern Crustal Block.

4.1. Structural orientation data

Structural orientation data was compiled from available regional geological maps and reports for Wrangellia strata, including the Nanaimo Group (data sources are compiled in Appendix A). To facilitate structural analysis, the region was divided into northeastern and southwestern belts divided by the Fulford–Cameron River–Beaufort Range thrust faults (Fig. 4). The belts were further divided into northern, central and southern domains. The northern domains are located within the Northern Fixed Crustal Block, while the central and southern domains are within the Southern Crustal Block (Fig. 4). To distinguish rotations and changes in trend attributable to previous deformation events, strata were further divided by age into Paleozoic Sicker and Buttle Lake groups, Early Mesozoic Vancouver and Bonanza groups, and Late Cretaceous Nanaimo Group (Fig. 2).

Strata in all three stratigraphic packages in the southwestern belt (Figs. 4 and 5; Table 1) are folded. Near parallelism of fold axes in each domain for Paleozoic through Cretaceous strata indicates that much of the folding post-dates deposition of the Nanaimo Group. Fold axes from the central and southern domains, both within the Southern Crustal Block, are rotated with respect to the northern domain. Paleozoic strata from the central domain define a fold axis that is rotated 21° counter clockwise with respect to the fold axis defined by equivalent strata in the northern domain. Early Mesozoic strata yield a broad scatter of orientations, in part because they record multiple deformation events and in part due to the presence of poorly layered volcanic rocks. Despite this, these strata, like the Paleozoic strata, yield similarly rotated fold axes; strata of the central domain yield a fold axis rotated 18° counterclockwise with respect to the northern domain. Nanaimo Group strata show less rotation; fold axes of the central domain are rotated 10° with respect to the northern domain. Because fold axes in all domains are sub-horizontal to shallowly plunging, rotations between domains are best explained as having occurred about steeply plunging poles of rotations, oriented perpendicular to the plane defined by the fold axes (Table 1).

The orientation of folds of strata in the southern domain, though more complicated, are consistent with strata in this domain having undergone an even

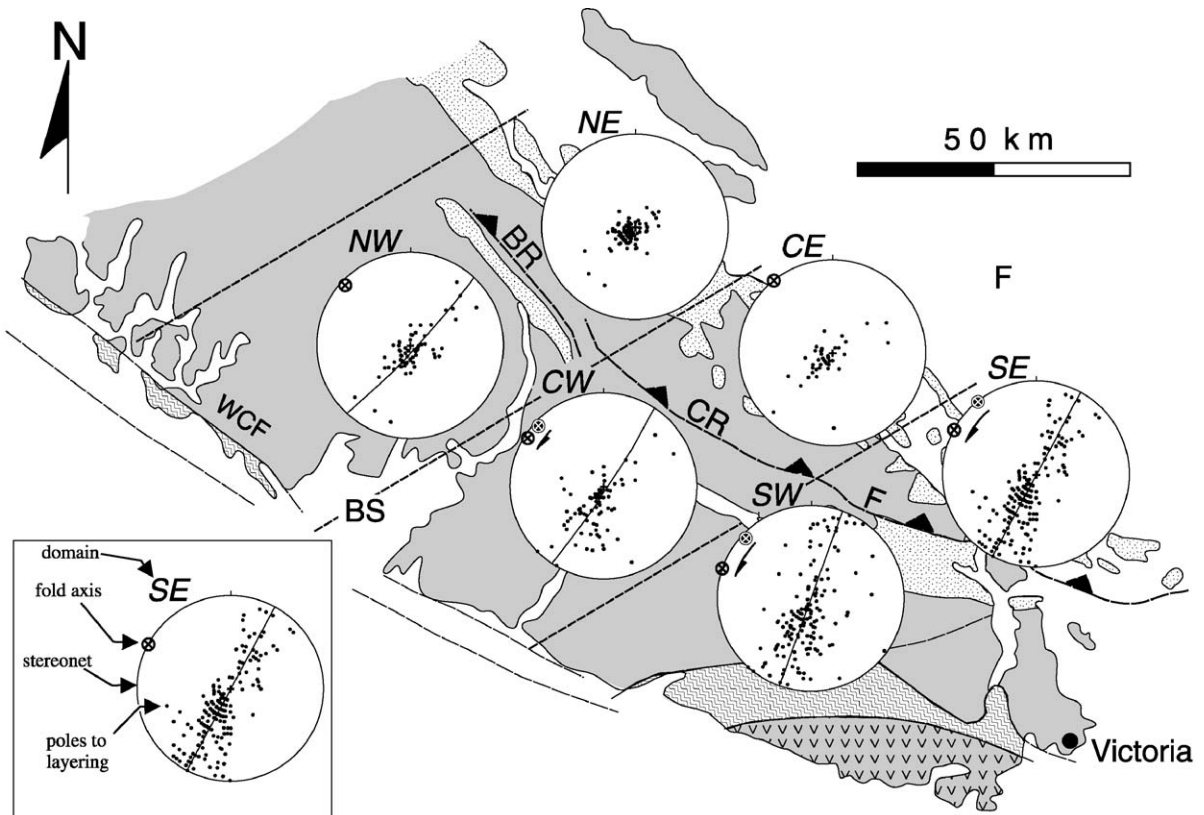


Fig. 4. Geological map of southern Vancouver Island. Stipples and abbreviations as in Fig. 1. The region is divided into northeastern and southwestern belts by the Fulford (F)–Cameron River (CR)–Beaufort Range (BR) thrust faults. Each belt is further divided into domains including the Northwest (NW), Central West (CW), Southwest (SW), Northeast (NE), Central East (CE) and Southeast (SE) domains—dashed lines trending east northeast indicate approximate domain boundaries. Poles to bedding for Late Cretaceous Nanaimo Group strata are plotted on stereonets for each domain, together with a best fit great circle and a corresponding fold axis (black cross). No fold axis is indicated for the NE domain as strata are essentially planar. The pole to a small circle is indicated for the conically folded strata of the CE domain. The calculated fold axis for the NW domain is plotted on the stereonets for each of the CW and SW domains (white cross on black background), with an arrow indicating the relative rotation. Similarly, the fold axis for the CE domain is plotted on the stereonet for the SE domain, with an arrow indicating the relative rotation.

greater relative counterclockwise rotation (Figs. 4 and 5). The fold axes defined by Early Mesozoic and Nanaimo Group strata of the southern domain are rotated 29° and 23° , respectively, relative to folds of equivalent strata in the northern domain. Calculated poles about which the rotation occurred are near vertical. Paleozoic strata of the southern domain were significantly deformed during the Early Mesozoic development of the West Coast Crystalline complex (DeBari et al., 1999), and cannot be reliably used to test for rotation of southern Vancouver Island. Structural data from the southwestern belt are consistent with counterclockwise oroclinal rotation of the South-

ern Crustal Block relative to the Northern Fixed Crustal Block. The southerly increase in the magnitude of rotation is consistent with a model of bending, as opposed to block rotation, during orocline formation.

Poles to bedding for for Nanaimo Group strata underlying the northeastern belt (Fig. 4) define a cluster, and are consistent with planar, little-deformed layering. Detailed 1:20 000 scale geological mapping of coal bearing Nanaimo Group strata (Cathyl-Bickford and Hoffman, 1998) show large areas of flat-lying strata and open folds separated by discontinuous low angle and steep extensional faults. These data

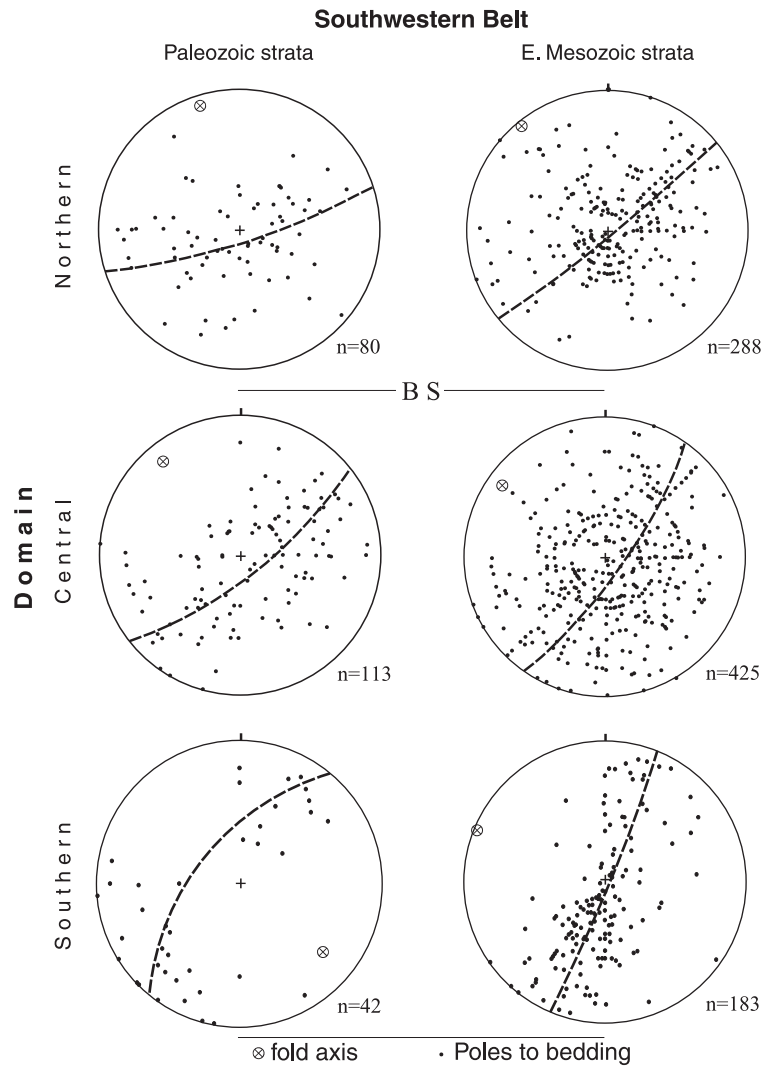


Fig. 5. Poles to bedding for Paleozoic and Early Mesozoic strata for each of the northern domains (north of Barkley Sound (BS) and part of the Northern Fixed Crustal Block), and central and southern domains (south of BS and part of the Southern Crustal Block) of the southwestern belt plotted on stereonets. Also shown are best-fit great circles and corresponding fold axes.

imply that Nanaimo Group strata within this domain have not been tectonically shortened. Poles to bedding for strata in the central domain form a small circle distribution indicating conical folds that plunge toward 318° . Poles to bedding for strata in the southern domain define a well-developed girdle pattern indicating cylindrical folding. Fold axes trend toward 298° , consistent with 21° counterclockwise rotation relative to the central domain. Rotation of the southern domain relative to the northern domain,

measured relative to the strike of northern domain strata, is 25° .

Structural data from the northeastern belt are, like the southwestern belt, consistent with counter clockwise oroclinal rotation of the Southern Crustal Block relative to the Northern Fixed Crustal Block. Implied rotations are of the same order of magnitude as those recorded in the southwestern belt. Because strata in the northern domain of the northeastern belt are planar and unfolded, it is not possible to say if the southern

Table 1

Mean fold axes calculated for the North (N), Central (C) and South (S) sections of the southwest and northeast structural belts (see Fig. 4), with the exception of NE domain for which no folding is evident and the pole to planar bedding is reported

Domain ^a	SW Belt						NE Belt	
	Paleozoic	R&P	E Mesozoic	R&P	Nanaimo	R&P	Nanaimo	R&P
N	343/08 $n=80$		321/02 $n=288$		313/04 $n=68$		233/82 ^b $n=137$	
C	322/13 $n=113$	21 (100/73)	305/10 $n=425$	18 (055/63)	303/04 $n=88$	10 (128/86)	318/01 ^c $n=50$	
S	129/25 ^d $n=42$	34 ^e	292/02 $n=183$	29 (216/88)	290/01 $n=167$	23 (193/82)	298/01 $n=200$	21 ^f (128/89)

Paleozoic—strata of the Sicker and Buttle Lake groups of Wrangellia. E Mesozoic—strata of the Vancouver and Bonanza groups of Wrangellia. R&P—counterclockwise rotation and Pole of rotation (in brackets) given relative to equivalent strata in the northern sections of each domain. n —indicates the number of structural measurements.

^a Including the Northern (N), Central (C) and Southern (S) domains.

^b The mean pole to planar bedding, as the strata are planar and unfolded within this region.

^c A small circle distribution indicating that folding was conical.

^d The significant variation in fold axis orientation relative to the central and northern sectors of the west domain for Paleozoic strata of Wrangellia is attributed to the significant pre-Cretaceous deformation of these strata, including ductile deformation and foliation development, evident within this region.

^e The calculated rotation is of the strike of the strata, relative to the strike of equivalent strata within the northwest domain.

^f Rotation of the southern domain relative to the northern domain of the eastern belt, measured relative to the strike of the northern domain, is 25°.

domain records greater relative rotation than the central domain.

4.2. Paleomagnetic data

The results of a recent paleomagnetic study of Nanaimo Group strata were reported by Enkin et al. (2001). The magnetic declination of sites characterized by a primary remanent magnetization can be used to test for post-depositional crustal rotations (Fig. 6, Table 2). Sites within the Northern Fixed Crustal Block are restricted to Hornby Island; sites within the Southern Crustal Block are clustered around Nanaimo and Gabriola Island. Three additional data points from the southern Gulf Islands, two on Mayne Island and one on Pender Island, do not together provide a statistically valid average declination and are not further considered. Acceptable sites, defined by Enkin et al. (2001) as those characterized by statistically valid amounts of dispersion ($\alpha_{95} < 15$), include five on Hornby Island, which together yield an average declination of 359.5°; and 10 in the Nanaimo–Gabriola Island area, which yield an average declination of 360.9°. These data are strongly influenced by two (one in each region) spurious results, both of which are characterized by high degrees of scatter ($\alpha_{95} \geq 10$) (Fig. 6, Table 2). By rejecting these two sites the average declinations are

011.7° for Hornby Island, and 354.0° for the Gabriola Island–Nanaimo area. These data imply 18° of counter clockwise rotation of the Southern Crustal Block relative to the Northern Fixed Crustal Block. Rotation has to have postdated deposition of the Nanaimo Group.

4.3. Evidence for a zone of contraction

The development of the west-verging Cowichan fold-and-thrust belt (England and Calon, 1991) along the northeast margin of the Southern Crustal Block involved significant crustal shortening. Deformation was thick-skinned, involving Nanaimo Group and older strata, including the Paleozoic Sicker Group. Structural orientation data and detailed balanced cross-sections constructed across the fold-and-thrust belt indicate that shortening decreases from south to north. Minor shortening present north of Barkley Sound–Port Alberni within the Northern Fixed Block includes 1 km of Late Cretaceous offset along the Beaufort Range thrust fault, based on offset of lower Nanaimo Group strata (Yorath et al., 1999). Nanaimo Group strata north of Port Alberni are, however, flat lying with little evidence of any significant shortening (Cathyl-Bickford and Hoffman, 1998).

Structural orientation data (Fig. 4) define a south to north change in structural style from cylindrical to

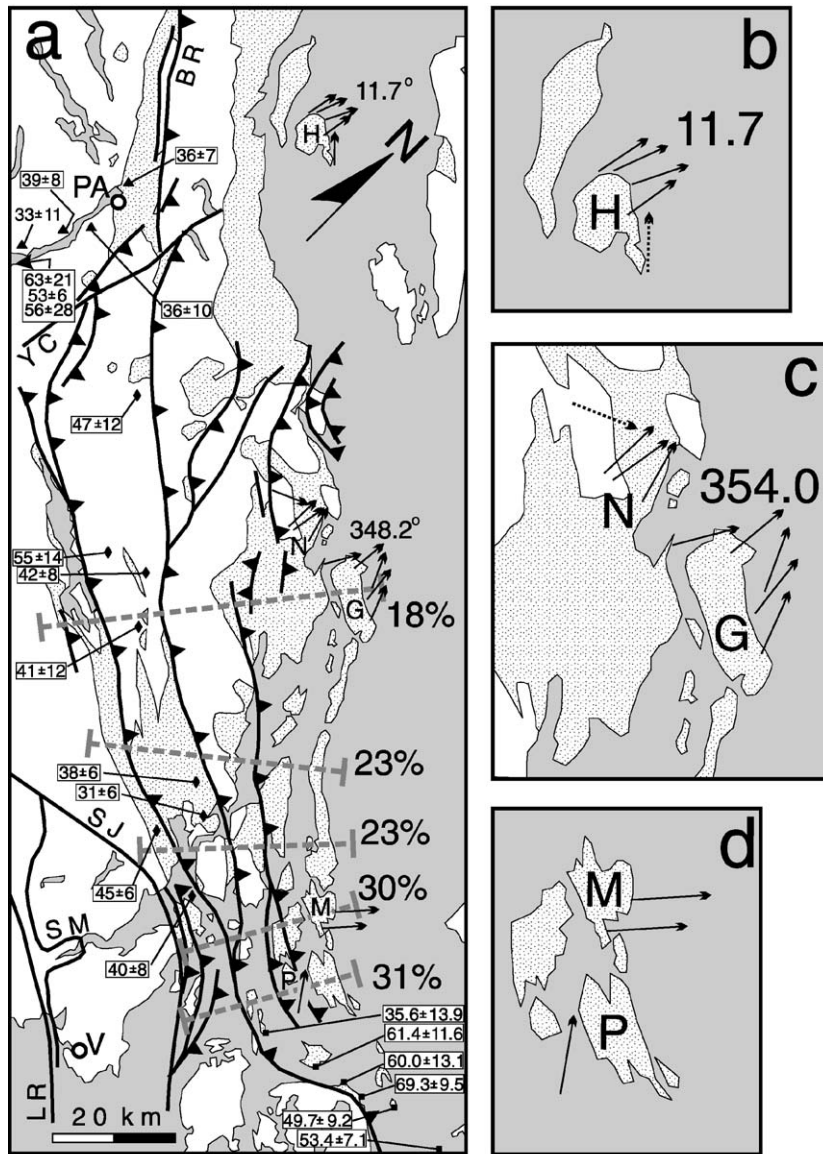


Fig. 6. (a) Geology of the Eocene Cowichan fold-and-thrust belt of northeastern southern Vancouver Island and the Gulf Islands, modified from England and Calon (1991). Only the main thrust faults are indicated here, including the Beaufort Range (BR) thrust. The extensional Yellow Creek (YC) fault is indicated. Faults to the west of the fold-and-thrust belt are the San Juan (SJ), Survey Mountain (SM) and Leech River (LR) faults. Port Alberni (PA), on the Alberni inlet–Barkley Sound, and Victoria (V) are indicated for reference. Grey dashed lines indicate the location of cross-sections constructed by England and Calon (1991); the amount of shortening calculated along each section, is indicated to the right of each section. Arrows show the magnetic declination of paleomagnetic sites in the Nanaimo Group reported by Enkin et al. (2001). Numbers indicated in rectangles are apatite fission track ages from Johnson et al. (1986) (squares, southern most Gulf Islands), England et al. (1997) (diamonds, Cowichan fold-and-thrust belt) and Currie and Grist (1996) (triangles, Alberni Inlet region). Three ages grouped together in a square are from sample locations along the south shore of Barkley Sound west of area shown in the figure. (b–d) Blow ups showing in detail the paleomagnetic data for each of the Hornby Island (H), Nanaimo (N)–Gabriola Island (G), and Mayne (M)–Pender (P) Island areas, respectively. The average declination for each of the Hornby Island and Nanaimo–Gabriola Island sites, calculated without using two spurious data points (dashed arrows) is indicated in degrees relative to present day geographic north pole.

Table 2
Paleomagnetic data

Site	Declination	α_{95}
<i>North of Port Alberni</i>		
HOR28	310.8	13.4
HOR16	006.5	6.6
HOR17	015.0	4.4
HOR18	021.2	4.9
HOR19	004.1	5.4
All data	359.5	
HOR28 rejected	011.7	
<i>South of Port Alberni</i>		
Van 03	339.6	5.4
Van04	062.2	9.9
Van01	357.1	7.7
Van02	004.7	7.7
Van60	002.5	12
GAB05	001.2	6.4
GAB04	026.3	10.7
GAB02	331.0	9.1
GAB01a	349.0	8.1
GAB01b	334.9	6.8
All data	360.9	
Van04 rejected	354.0	

Site designations and data are from [Enkin et al. \(2001\)](#). Data in bold indicate rejected (spurious) sites.

conical folding and then to planar bedding and open folds. This change is consistent with there being a northward decrease in the amount of shortening accommodated during deformation ([Fig. 7](#)). Strata

within the northern domain appear to have remained ‘pinned’ to their underlying basement, having experienced little shortening, and remain, for the most part, planar. The distribution of poles to bedding from the central and southern domains indicate that these strata are folded, likely in response to displacement over flats and ramps along thrust faults ([England and Calon, 1991](#)). Conical folding within the central domain, indicated by the small circle distribution of poles to bedding, gives way in the south to cylindrical folding, consistent with a southerly increase in the amount of shortening ([Fig. 7](#)).

[England and Calon \(1991\)](#) documented a progressive southerly increase in shortening across the Cowichan fold-and-thrust belt. Based on a series of balanced cross-sections constructed across the belt, and assuming that all shortening was taken up along thrust faults, they demonstrated that the amount of shortening decreased from >30% near the south end of the thrust belt to <20% just south of Nanaimo ([Fig. 6](#)), and into little deformed strata with no evidence for shortening further to the north ([England and Calon, 1991](#)). These findings are consistent with detailed 1:20 000 scale geological mapping of Nanaimo Group ([Cathyl-Bickford and Hoffman, 1998](#)) that show significant imbrication and tectonic thickening of the Nanaimo Group in the vicinity of Nanaimo, and no evidence of thrust imbrication or tectonic thickening north of Port Alberni.

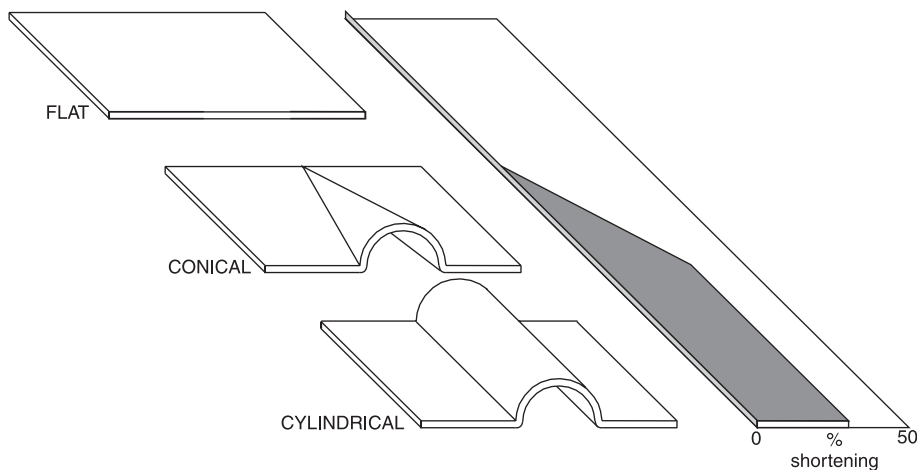


Fig. 7. Schematic figure showing the structural style of Nanaimo Group strata in the northeastern belt. Cylindrical folding in the southern domain accommodates more shortening (shown at right), than cylindrical folding of the central domain. Northern domain strata appear to have accommodated no significant shortening.

The age of fold and thrust belt formation is constrained by stratigraphic relationships, by cross-cutting intrusions, and by apatite fission track ages. Paleocene to Lower Eocene fluvial strata exposed on the southernmost Gulf Islands are folded and faulted, restricting fold-and-thrust belt formation to Eocene or younger time (England and Calon, 1991). Undeformed porphyritic dacite dykes intrude fault zones in the northern part of the fold-and-thrust belt, and are interpreted to post-date thrust imbrication (Massey, 1995). K–Ar age determinations limit crystallization of the dykes to pre-45 Ma, providing a lower limit to the age of deformation (Massey, 1995). Apatite fission track age determinations on samples of Jurassic plutons and Nanaimo Group strata from within the Cowichan fold-and-thrust belt (Fig. 6) yield ages of mostly 50 to 40 Ma. Slightly older ages (~ 60 Ma) are reported for the southernmost Cowichan fold-and-thrust belt (Johnson et al., 1986). These ages constrain the timing of cooling of these rocks to temperatures of less than 100 °C, and are interpreted to record the timing of uplift and exhumation during fold-and-thrust belt formation (England et al., 1997). Together these data limit fold-and-thrust belt formation to about 45 Ma.

4.4. Evidence for a zone of extension

Three lines of evidence point to extension in and west of the Port Alberni Inlet–Barkley Sound area; (1) the presence of the Eocene and younger Tofino basin, (2) reflection seismic data showing deep Eocene basins extending into the mouth of Barkley Sound; and (3) fission track cooling ages recording Eocene cooling and exhumation along the length of Barkley Sound coeval with basin formation.

Fine grained sands and shales, interpreted as distal Carmanah Group (Yorath, 1991) are preserved in, and form the basal units of the Tofino Basin (Fig. 1). The Tofino basin, which is centered west of Barkley Sound off the west coast of southern Vancouver Island, contains up to 6 km of Eocene to Oligocene clastic sediment. A prominent magnetic anomaly, the Prometheus anomaly, central to the basin is coincident with a pronounced basement high across which Eocene strata are not preserved (Fig. 1). The basin has previously been interpreted, and may have originated as a forearc basin related to

underplating along the Cascadia subduction zone (Hyndman, 1995). The presence of a prominent central basement high of restricted geographic extent is however consistent with a horst and graben geometry and points to extensional modification of the basin.

A marine multichannel reflection seismic line (85-01) shot along a line extending southwest from the mouth of Barkley sound (Fig. 1) (Hyndman, 1995; Yorath et al., 1987), provides further evidence of Eocene basin development within and adjacent to Barkley Sound. The two main geological features evident on this and several more recent seismic lines (Calvert, 1996) that may be attributable to extension are (1) thick Eocene and younger clastic sedimentary rocks extending to the east end of the seismic line, into Barkley Sound, and (2) the deep (locally 3-s two-way travel time to the base of the basin) and irregular Tofino Basin. A narrow, deep structural trough (>3 s two-way travel time to the base of the trough) imaged along the eastern side of the basin, just off of Barkley sound, is filled with Eocene and younger sediment (Hyndman, 1995). This trough coincides with the submarine boundary between the Pacific Rim terrane to the east, and the Crescent terrane and has been previously interpreted as a fossil trench marking the relic subduction zone along which these two terranes were juxtaposed (Hyndman, 1995). The Pacific Rim–Crescent terrane boundary south of Barkley sound lacks a coincident trough, suggesting that trough is not attributable to a relic trench. We interpret the trough as a half-graben developed during extension within and west of Barkley Sound.

There is little geological data from within Barkley Sound. The presence of Eocene strata immediately west of Barkley Sound contrasts with the lack of preserved Eocene strata on the flanks of Barkley Sound. Rocks along the margins of Alberni Inlet, north and west of the northwestern most portions of the Cowichan fold-and-thrust belt, are characterized by apatite fission track ages are similar to those reported for the Cowichan fold-and-thrust belt (~ 60 to 40) and appear to young to the east (Currie and Grist, 1996). We interpret these cooling ages as recording exhumation during extension along the Alberni Inlet–Barkley Sound region. Younging of the apatite fission track ages to the east may indicate that extension propagated from west to east over time.

Perhaps the strongest evidence of extension in the Barkley Sound–Alberni Inlet areas is the extensional Yellow Creek fault (C. Yorath, written communication, 2002). The Yellow Creek fault trends north–south through the region, disrupts the Beaufort Range and Cowichan Lake fault systems, and lies close to outcrops of Tertiary hypabyssal quartz diorite intrusions (Figs. 1 and 6). Similar intrusive rocks were intersected in drill holes in nearby Nanaimo Group strata, forming sills. Magmatism and faulting are interpreted to have resulted from extension coeval with, or slightly post-dating shortening in the Cowichan fold-and-thrust belt (Yorath et al., 1999).

4.5. Shear strain: sinistral and dextral shears

There are no documented northwest trending dextral shears from southern Vancouver Island. Evidence for sinistral shear is restricted to the Leech River and San Juan faults (Fig. 1). The east trending, terrane-bounding Leech River fault juxtaposes the Pacific Rim terrane, to the north, against the Crescent terrane (Fig. 1). Seismic data show that the fault dips north beneath the Pacific Rim terrane. Based on its geometry, the fault has been interpreted as a thrust fault that accommodated accretion, via underplating, of the Crescent terrane (Clowes et al., 1987). Rocks within the fault zone and in the immediate hanging and footwall are, however, characterized by subhorizontal mineral and stretching lineations and associated kinematic indicators consistent with sinistral shear (Groome et al., *in press*; C. Yorath, unpublished data, 2002; S. Johnston, unpublished data, 2001; M. Journeay, personal communication, 2001). These include extensional shears, asymmetric folds, crenulation cleavage geometry, tension gash geometry, and rare C–S fabrics. These data suggest that sinistral shear was accommodated along the fault, possibly after or coincident with its initial development as a terrane bounding thrust fault.

The east-trending, San Juan fault locally juxtaposes Wrangellia, to the north, against the Pacific Rim terrane (Fig. 1). Seismic data indicate that the fault is a steep structure (Clowes et al., 1987). No detailed kinematic data are available for the fault. Sinistral offset of the West Coast Crystalline complex, a gneissic metaplutonic complex that is interpreted as the basement of the Jurassic Bonanza arc of Wrangellia

(DeBari et al., 1999) is consistent with 30–40 km of sinistral strike–slip along the fault.

5. Discussion

Structural orientation data, paleomagnetic data, the distribution of zones of contraction and extension, folding style, and the geometry of the Cowichan fold-and-thrust belt are all consistent with a model of oroclinal rotation of southern Vancouver Island with a pole of rotation in the vicinity of Port Alberni. Paleomagnetic data indicate counterclockwise rotation of the Southern Crustal Block by 18° relative to the Northern Fixed Crustal Block. Structural orientation data are consistent with 20–30° of counterclockwise oroclinal rotation of the Southern Crustal Block. A southerly increase in the amount of rotation argues against pure block rotation of the Southern Crustal Block and indicates that a component of oroclinal rotation was accommodated by bending.

A model of 20° of oroclinal rotation (Fig. 3) suggests that the amount of shortening accommodated across the southern portion of the fold-and-thrust belt should be >40 km. This assumes a distance of 120 km from the pole of rotation to the southern Cowichan fold-and-thrust belt. Palinspastic restoration of balanced cross-sections across the fold-and-thrust belt (England and Calon, 1991) are consistent with their being little more than 15 km of shortening. Possible explanations of this discrepancy include (1) the pole of rotation lies further south than modeled; (2) less than 20° of rotation has occurred; (3) a large amount of shortening being taken up at depth along blind thrusts; or (4) the amount of shortening accommodated by the fold-and-thrust belt is significantly greater than previously estimated. If the pole of rotation was located just north of Nanaimo, 20° of oroclinal rotation would require 27.4 km of shortening across the southern portion of the fold-and-thrust belt, still more than has been observed. Paleomagnetic data indicate 18° of rotation. Using a model with 15° of rotation, which is within error of the structural and paleomagnetic data, results in 31 km of shortening, and only 20.7 km if the pole of rotation was just north of Nanaimo. Thrust faults observed at the surface locally carry Paleozoic Sicker Group strata in their hangingwalls, indicating that the stratigraphically

deepest and oldest portions of Wrangellia are carried on thrust faults. Consequently, it seems unlikely that any significant shortening has been accommodated by blind thrusts at depth. The accommodation of 15–40 km of blind shortening would have resulted in significant (50–150%) sub-surface thickening of Wrangellia. Such crustal thickening should have resulted in a 5 to >10 km of uplift of overlying strata, for which there is no evidence; Nanaimo Group strata exposed at the surface are not metamorphosed, and are characterized by vitrinite reflectance values of 0.4–1.3, indicating removal of 3.7–6.6 km of overburden, much of which can be attributed to uplift along mapped faults cutting the Nanaimo Group (England and Calon, 1991; England and Bustin in Yorath et al., 1999).

Conversely, the amount of shortening across the fold-and-thrust belt may have been underestimated. On the cross-sections utilized by England and Calon (1991) to estimate the amount of shortening, thrust faults are depicted cutting steeply up-section at angles of 45–90° with respect to bedding, with rare, short flats. Thrust faults are, however, typically characterized by much shallower (5–30°) dips relative to bedding (Boyer and Elliott, 1982). Reinterpretation of the Cowichan fold-and-thrust belt utilizing thrust faults that cut upsection at angles of 20–30° relative to bedding and which are consistent with the mapped geology, yield estimates of shortening that are three to five times that proposed by England and Calon (1991). Supporting evidence for this comes from recent mapping (S. Johnston, unpublished data, 2000, 2001) indicating that layer parallel thrust faults are common in the southern Cowichan fold-and-thrust belt. It seems likely that a combination of a pole of rotation slightly south of that used in the model (Fig. 3), a rotation of slightly less than 20°, and a reinterpretation of the structure of the Cowichan fold-and-thrust belt in which shallow angle thrust faults are utilized, adequately resolves the apparent discrepancy between the predicted and observed amount of crustal shortening in the Cowichan fold-and-thrust belt.

The amount of extension within the zone trending southwest along Alberni Inlet out through Barkley Sound and into Tofino basin is less than the 30 km predicted by the block rotation model, as such significant extension would have resulted in complete rupture of the crust. The more modest amounts of

extension argued for here are inconsistent with a model of pure block rotation of the crustal block south of Barkley Sound, and require that a significant portion of the oroclinal rotation be accommodated by bending. The southerly increase in the extent to which structures are rotated are consistent with much of the oroclinal rotation of southernmost Vancouver Island having been accomplished by bending. Pure bending should have resulted in shear strain of the rotating crustal block. Aside from sinistral shearing localized along the Leech River and San Juan faults, there remains little evidence of penetrative shear strain of the Southern Crustal Block. Further research is required to test for the presence of such strain.

Truncation of thrust faults by the extensional Yellows Creek fault near Port Alberni indicates that extension post-dated the of fold-and-thrust belt formation. This suggests that initial oroclinal rotation was accomplished by pure bending, and that the final stages of orocline formation involved block rotation of the Southern Crustal Block and related extension through Barkley Sound and the Tofino Basin.

Orocline formation was coeval with, and likely resulted from the Early Eocene accretion of the Paleocene Crescent terrane along the south and west side of southern Vancouver Island (Fig. 8). Plate motion models for the Paleocene to Eocene place constraints on a model of orocline formation in response to terrane accretion (Fig. 8). Two oceanic plates, the Kula and the more southerly Farallon plates, both of which were characterized by a significant component of convergence with the North America plate, lay west of North America at this time. The location of the spreading center that separated the Kula and Farallon plates is unknown but is believed to have been located close by, and probably to the south of Vancouver Island (Duncan, 1982; Engebretson et al., 1985). We assume that the Kula plate lay west of Vancouver Island and that the Crescent terrane originated as a linear, plate motion parallel seamount chain generated on the Kula plate during passage over a hotspot. The Yellowstone hotspot is thought to have been located southwest of Vancouver Island at this time and was the likely source of Crescent terrane magmatism (Duncan, 1982; Johnston and Thorkelson, 2000; Johnston et al., 1996). Convergence between southern Vancouver Island and the Crescent seamounts may have resulted from either the removal

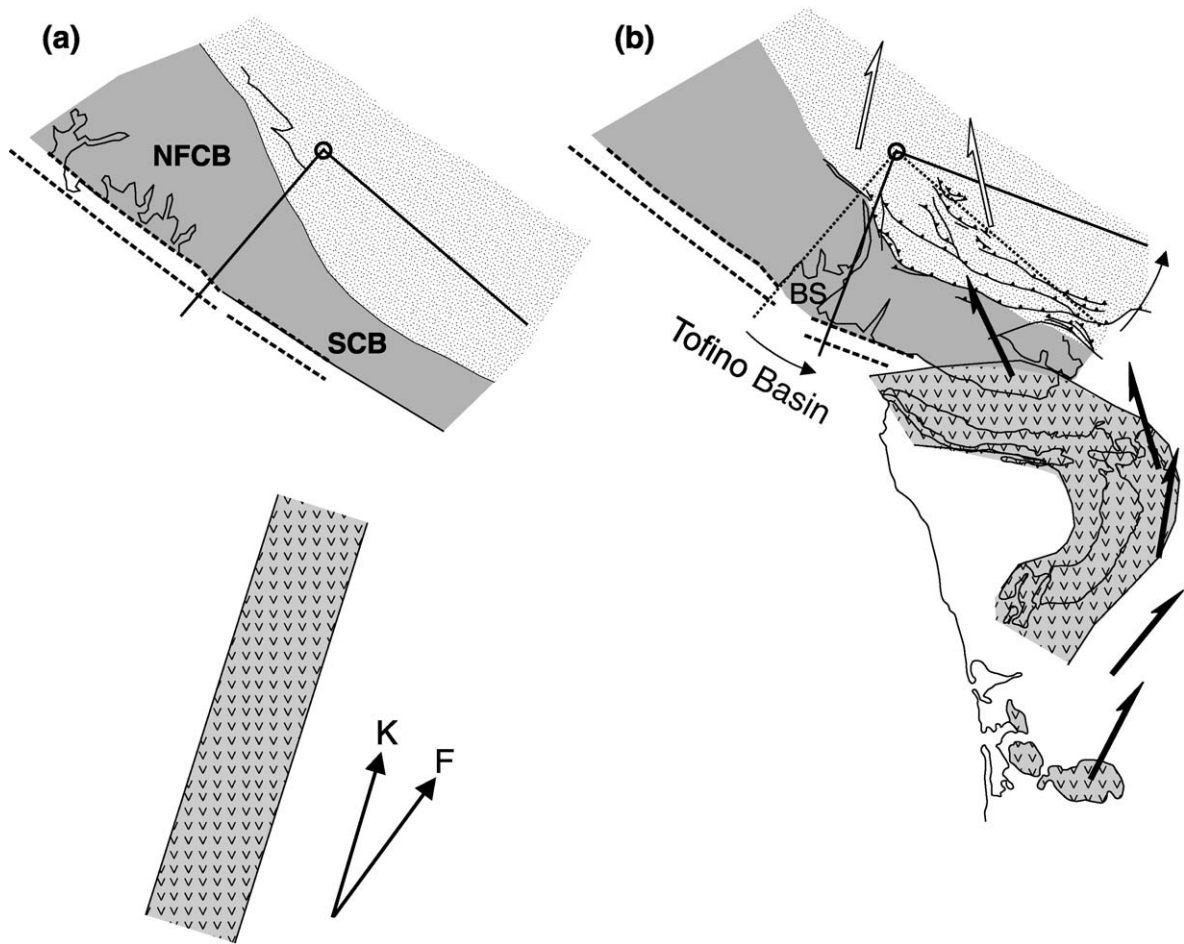


Fig. 8. A tectonic model showing development of the Southern Vancouver Island Orocline in response to collision of the Crescent terrane. Stipples are as in Fig. 1. Note that the Pacific Rim terrane is not shown here and is assumed to have previously accreted to Wrangellia. (a) The pre-collisional paleogeography with the Crescent terrane depicted as a linear seamount chain that parallels motion of, and is interpreted to have been erupted, onto the Kula (K) plate. Convergence between the Kula and North American plates results in encroachment of the seamount chain upon Vancouver Island. The Farallon (F) plate motion vector is also indicated. Rotation of Southern Crustal Block of Vancouver Island relative to the Northern Fixed Crustal Block in response to collision with the seamount chain is predicted to occur about a pole of rotation (indicated as a black circle) along the northeast margin of Vancouver Island. Black lines perpendicular and parallel to the southwest coast of Vancouver Island that meet at the pole of rotation are shown for reference. (b) The paleogeography subsequent to collision and orocline formation. The Southern Crustal Block is rotated 20° counterclockwise relative to the Northern Fixed Crustal Block, shown by rotation of black reference lines (initial location of the lines shown by dashed lines). Orocline formation gives rise to the Cowichan fold-and-thrust belt (thrust faults indicated by lines with east-pointing teeth) that dies out to the north and is absent north of the pole of rotation. Related extension gives rise to the Tofino Basin and Barkley Sound (BS). Collision also results in buckling (orocline orogeny) of the seamount chain, giving rise to the Olympic Orocline documented by Beck and Engebretson (1982). Paleomagnetic declinations, which corroborate both the Southern Vancouver Island and Olympic oroclines, are indicated by black- (Beck and Engebretson, 1982) and white-filled (Enkin et al., 2001) arrows.

of intervening oceanic crust by subduction, for which there is little direct evidence, or motion along a transform fault. Collision of the seamount chain with Vancouver Island caused an oroclinal orogeny—the buckling about vertical axes of rotation of an origi-

nally linear crustal domain, Vancouver Island, giving rise to the Southern Vancouver Island Orocline.

Beck and Engebretson (1982), based on paleomagnetic data that require 65° of counterclockwise rotation, suggested that the southward continuation of the

Crescent terrane in northwestern Washington defines a concave to the west orocline (Fig. 8). The current outcrop pattern of Crescent terrane in the Olympics forms a horseshoe geometry with 135° of curvature, however, much of this curvature is attributable to younger uplift and anticline formation in the core of the Olympic Peninsula (Brandon et al., 1998). In our model, the 65° of rotation observed in paleomagnetic data by Beck and Engebretson (1982) is attributable to buckling (oroclinal orogeny) of the seamount chain after collision of its leading edge with southern Vancouver Island. Buckling results from continued (post-collision) northeastward motion of the trailing portion of the seamount chain, presumably because it remained rooted in the Kula plate. Hence collision appears to have resulted in the formation of two related oroclines; the Southern Vancouver Island Orocline as a response of the upper plate to collision with the Crescent terrane seamount chain; and buckling of the seamount chain itself in response to continued northeastward motion of the trailing portion of the chain after pinning of its leading edge against Vancouver Island.

6. Conclusions

The geometry and character of the Southern Vancouver Island Orocline provides constraints regarding the origin of oroclines, their geometry and the processes involved in their development. The Southern Vancouver Island Orocline developed in response to a collisional event, in this case collision with Crescent terrane seamount chain. Thick-skinned fold and thrust belt formation and the association of magmatism with extension indicates that the formation of the Southern Vancouver Island Orocline involved most, if not all of the crust. Thus, at least in this case, orocline formation cannot be attributed to rotations about a shallow crustal detachment. Paleomagnetic and structural orientation data are consistent with rotation having occurred about a vertical pole of rotation located northeast of Port Alberni. This emphasizes the crustal scale of orocline formation and rules out shallow level rotations about horizontal axes as the process for formation of the Southern Vancouver Island Orocline. Oroclinal rotation was accomplished by initial bending of the Vancouver Island crustal block, with a late

and minor component of block rotation. Collision appears to have given rise to two oroclines, the second being the Olympic Orocline of Western Washington. Formation of the Olympic Orocline appears to have resulted from buckling (oroclinal orogeny) during continued convergence between the seamount chain and Vancouver Island after initial collision.

Despite the small degree of crustal bending involved in the Southern Vancouver Island Orocline (20°), its formation was directly responsible for the development and geometry of the Cowichan fold-and-thrust belt, and the extensional Barkley Sound and Tofino basin. Orocline formation also explains changes in the orientation of structures along the length of Vancouver Island, and may be responsible for sinistral shearing of the southernmost part of the island. Thus, even minor oroclines can account for numerous significant features within an orogenic belt. Significant bends are present in numerous orogenic belts of all ages, many of them involving larger crustal blocks and greater degrees of rotation than that found in the Southern Vancouver Island Orocline. The resolution of puzzling and enigmatic aspects of numerous orogenic belts may lie in understanding these bends and the oroclinal rotations involved in their development.

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Appendix A. Sources of structural orientation data

	Authors	Scale	Map-NTS sheet
1	England and Calon, 1991	1:400 000	92 B/10-B/14, C/16, F/1, F/8, G/4
2	Hoadley, 1954	1:63 360	92 E/15
3	Massey et al., 1988, 1989, 1991a,b,c	1:50 000	92 B/13, C/16, F/7E, F/1W, F/2E
4	Muller, 1965	1:126 720	92 F/11-F/14
5	Muller, 1969	1:250 000	92 F
6	Muller, 1977	1:125 000	92 B, C, E, F, K, L; 102 I/9, 16
7	Muller, 1981	1:250 000	92 E/1NE, E/7NE, E/8NW, E/8NE, E/8SE, E/9-10, E/14NE, E/15-16
8	Muller, 1982	1:125 000	92 C/5-16
9	Muller, 1983	1:100 000	92 B/5-6, B/11-14
10	Muller and Jeletzky, 1970	1:125 000	92 B/11-14, C/16, F/1, F/8, G/4
11	Sutherland Brown et al., 1986	1:50 000	92 C/10, C/14-16, F/1-2, F/7-8
12	Yorath et al., 1999	1:100 000	92 B/05, C/14NE, C/14SE, C/15, F/2, F/7, F/8SE, F/8SW

1—England, T.D.J. and Calon, T.J., 1991. The Cowichan fold and thrust system, Vancouver Island, southwestern British Columbia. *Geological Society of America Bulletin*, 103: 336–362.

2—Hoadley, J.E., 1954. Zeballos, Vancouver Island, British Columbia. Geological Survey of Canada, Ottawa, Ontario.

3—Massey, N.W.D., Friday, S.J., Riddell, J.M. and Dumais, S.E., 1989. Geology of the Port Alberni–Nanaimo Lakes area, NTS 92F/1W, 2E and part of 92F/7E. British Columbia Ministry of Energy, Mines and Petroleum Resources, Geology Survey Branch, Victoria, British Columbia.

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