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Formation of new continental crust in Western British Columbia during transpression and transtension

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Abstract

Crustal growth in the Coast Mountains, along the leading edge of the Canadian Cordillera, was the result of processes associated with horizontal flow of material during transpression and subsequent transtension, and the vertical accretion of mantle derived melts. From 85 to 58 Ma, as exotic terranes were translated northward during transpression, the crust was thickened to about 55 km, and melt that originated from a mix of mantle-derived basalt with partial melt of the thickened crust intruded into crustal scale transpressive shear zones. When the orogen extended, between 58 and 50 Ma, there was large-scale decompression melting in the mantle and dehydration melting in the lower crust. Voluminous emplacement of sub horizontal sills facilitated by ductile flow of the gneissic country rocks partially filled space created as the crust was pulled apart and as 15 to 20 km of tectonic exhumation occurred across low angle normal ductile shear zones. By 50 Ma, the final crustal thickness of the new continental crust was about 34 km. Comparison of seismic data with other crustal sections suggests that the crust-forming processes identified in western British Columbia have general applicability to models for the formation of continental crust.

Keywords: composition of continental crust; transpression; crustal extension; magmatic flare-up; seismic velocities; crustal flow

1. Introduction

Current models for the origin of continental crust include near orthogonal accretion of island arcs [1]. In these models, the basaltic composition of the arcs is modified to that of continents by the addition of silicic melt that was extracted during dehydration melting in the lower arc crust or that came from crystal fractionation of hydrous mafic melt at the base of the arc crust [2,3]. However, the mafic to ultramafic residue formed by the extraction of silicic melt from gabbro is not recognized in most crustal sections. Because the residue is as dense or denser than the peridotite of the mantle, this component is inferred to founder into the mantle or to be masked below the Moho by its nearly identical seismic properties to peridotite.

In this paper, we provide a geologic perspective on the basic model for formation of continental crust. It is based on data from the 7-year multidisciplinary project ACCRETE (1993–2000) [4] that was focused on the largest fossil continental arc in the world, the Coast Mountains batholith of western British Columbia

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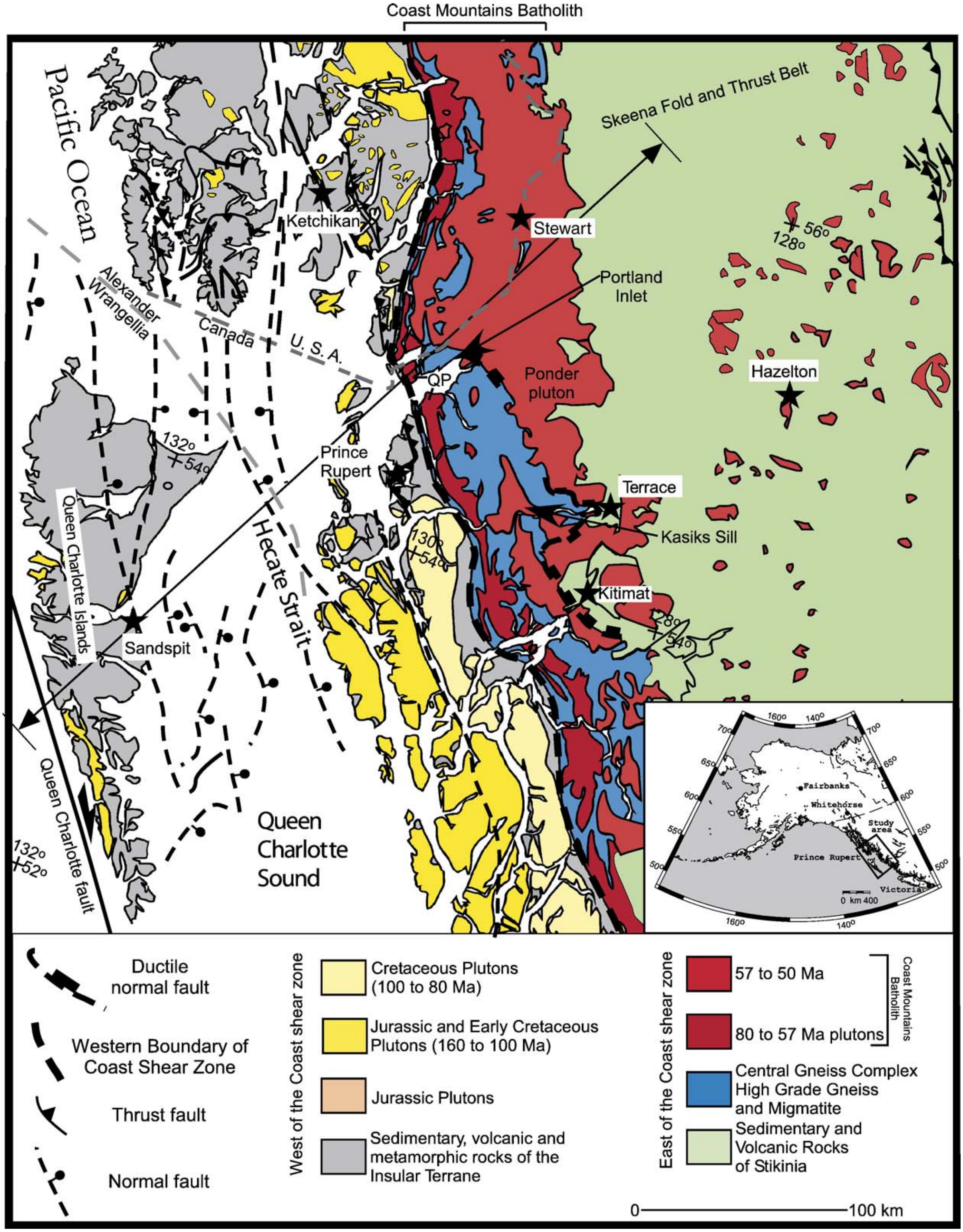

Fig. 1. Geologic map encompassing ACCRETE study area, showing location of cross section of Fig. 3. Compiled from many sources, including [15,31,35–38]. QP, Quottoon pluton.

(Fig. 1). Our model has two distinct tectonic phases. The first occurred during a period of transpression (oblique plate convergence resulting in concurrent translation and shortening and thickening) from 85 to 58 Ma (Fig. 2a). The continental crust was thickened to about 55 km, and mafic lower crust of the oceanic plateau Wrangellia was pushed under the thickened crust where basalt from the mantle heated it to temperatures hot enough for melting. The basalt and this melt mixed and mingled and rose into the arc along transpressional shear zones [5,6], forming calc–alkaline plutons. The second phase occurred as the arc collapsed when a change of relative plate motions resulted in transtension (oblique plate convergence resulting in extension and thinning) (Fig. 2b). The transtension accompanied intrusion of voluminous calc–alkaline plutons and the exhumation of the core of the Coast Mountains Batholith (CMB) as some 15 km of the upper crust was tectonically omitted across a 5 km thick northeast dipping mylonite zone (Shames River mylonite zone).

The multidisciplinary results from ACCRETE integrate geologic observations with controlled-source seismic data [7]. The seismic data included a surprisingly rich shear wave data set [8], as well as an excellent compressional wave data set [9]. The properties of the new crust resemble those of many crustal sections, showing that our model has general applicability towards understanding how continental crust forms.

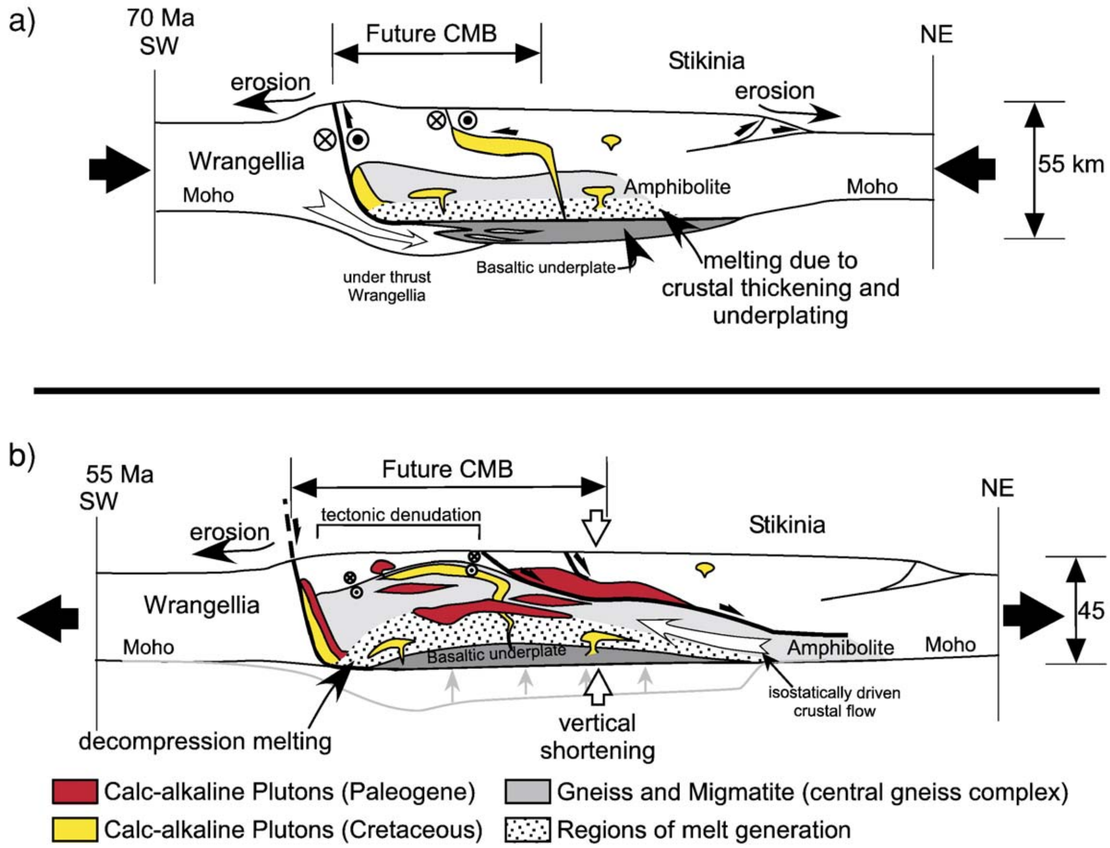

Fig. 2. Cartoon sketches illustrating two time slices for the ACCRETE model for growth of continental crust. Large arrows show bulk strain. East dipping subducting oceanic crust (not shown) underlies both cross sections, with trench to west of Wrangellia. Arrows show displacement direction across shear zones that occurred during each time slice. ⊗ indicates movement away from viewer; ⊙ indicates movement toward viewer. (a) The transpressional regime in the Coast Mountains between 80 and 58 Ma. Shows mingling of basalt from the mantle wedge with melt generated in the lower crust of the converging Wrangellia. A component of northward translation of terranes west of the CSZ is occurring at this time [26–28]. As Wrangellia underthrusts the CMB (convergent component of transpression), it is fed into a melting zone from which diorite melt rises along the transpressional shear zones and a mafic residue founders into the mantle and/or is swept north with the terranes west of the CSZ. (b) Collapse of the orogen between 58 and 48 Ma. As crust underlying the future CMB extended, it underwent lower crustal flow, and material moved parallel and across the strike of the orogen. Crustal flow was synchronous with basaltic underplating and plutonism, and it helped facilitate pluton emplacement. Extension of the orogen occurs as oblique subduction continued. Decompression enhanced the production of melt in the crust and mantle. The present level of erosion under the CMB is at a depth that has gneiss and migmatite exposed at the surface.

2. The continental crust of western British Columbia

2.1. Geologic constraints

Fig. 1 is a geologic map across the Coast Mountains of northern British Columbia, and Fig. 3 shows a SW–NE cross-section from the Pacific plate to the interior of British Columbia. Major batholiths and crustal scale shear zones separate three northwest trending crustal panels. From NE to SW the geologically and geophysically distinct terranes are called Stikinia (a part of the Intermontane superterrane), the Coast Mountains batholith (CMB), and Wrangellia (a part of the Insular superterrane). Stikinia is separated from the CMB by a thick (about 5 km thick) ductile shear zone (Shames River mylonite zone) that dips east to northeast [10] (Fig. 3). Across this zone, Stikinia is displaced down to the northeast relative to the CMB. The age of the last motion along this shear zone (48 Ma) is at the end of the range of ages (85–50 Ma) of most of the plutons that intruded into the CMB.

The history of terrane accretion prior to 85 Ma is not considered in this paper because we focus on formation of continental crust between 85 and 50 Ma. Notable terranes and tectonostratigraphic sequences not included in Figs. 1–3 include the Alexander and Yukon–Tanana Terranes and the Gravina belt.

Along and to the south of Portland Inlet (Fig. 1), foliations within the CMB define an asymmetric gneiss dome (Fig. 3). These foliations at the surface and seismic reflection horizons in the middle crust image the dome from the surface to the middle crust [10]. In the core of the dome, the Kasiks sill complex intruded during orogen parallel extension and top to the north–northwest normal shearing [10]. The foliations at the eastern limb of the dome (defined by the Shames River mylonite zone) are continuous with seismic reflection horizons that were imaged at wide angle and are traced from outcrop down dip to the northeast to a depth of about 18 km on Fig. 3 [11]. This reflecting package can be traced farther to the northeast to where it merges into lower crustal reflectors at a depth of about 25 km [11]. Field observations demonstrate that the Shames river mylonite deformed during northeast directed extensional shearing [10]. High precision U/Pb dating show that the Shames river mylonite deformed as the underlying Kasiks sill complex intruded [10]. The difference in extension direction between the sill complex and extensional shear zones (Fig. 2b) requires crustal flow in two nearly orthogonal directions as the middle crust was being uplifted and exhumed, with one component of flow from the base of Stikinia toward the southwest and a second component parallel to the axis of the arc [10].

Based on their low grade of metamorphism, rocks at the surface today within Stikinia were never at pressures greater than about 3 kbar [10], whereas the metamorphic rocks within the CMB decompressed from 8 to 3 kbar between 60 and 52 Ma while remaining at temperatures near 750 °C [12]. The metamorphic contrast from footwall to hanging wall across the Shames River mylonite zone indicates that the total amount of tectonic exhumation of the CMB relative to Stikinia was about 15 km, and that a portion of Stikinia was above the CMB prior to extension [10].

The western border of the CMB contains the 58 Ma Quottoon pluton and the near vertical 1200 km long Coast Shear zone [13] (Fig. 3). The Quottoon pluton is a

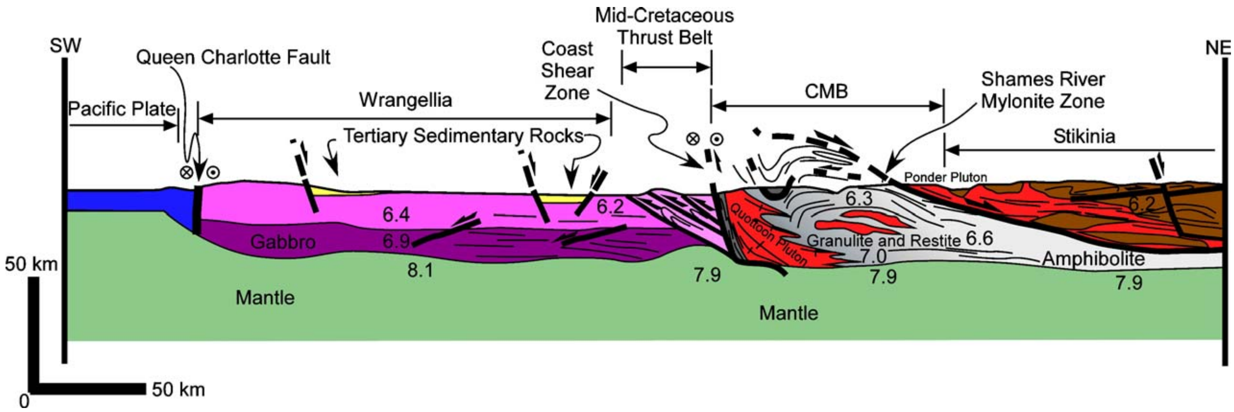

Fig. 3. Simplified SW–NE cross-section from the Pacific plate to the interior of BC; the location of cross section is shown on Fig. 1. Shows present-day distribution of lithologies, location of Moho, compressional wave velocities (V_p, km/s), and displacement directions across major shear and fault zones. Compiled from [8,11,15,31,35–37,39].

segment of the 700 km long string of Cretaceous and Paleocene tonalite bodies that average about 10 km in width and have southwestern contacts that are nearly vertical. About half of this string of plutons is shown in Fig. 1, and their proximity to the Coast shear zone (CSZ) implies that their emplacement was facilitated by the CSZ [14,15].

The CSZ marks a magmatic front between the CMB and Insular superterrane. The thermal contrast at this front is a first order constraint on our model for crust formation. Plutons between 85 and 50 Ma make up most of the CMB, whereas no plutons younger than 80 Ma occur within the Insular superterrane [16]. Additionally, there are profound breaks in metamorphic grade across the Coast shear zone [17]. The central gneiss complex (Fig. 1), which forms the country rocks to the batholith, is made of sedimentary and volcanic rocks that were at temperatures of 750 °C at about 5 kbar at about 55 Ma [17] whereas across the CSZ the Insular superterrane underwent peak metamorphism at 90 Ma. Within the Insular superterrane, metamorphic grade increases toward the CSZ from greenschist facies to 600 °C at 8 kbar [17]. At the present level of exposure, temperatures within the Insular superterrane were between 400 and 250 °C at the time (58 Ma) that the CMB was still at 750 °C [18].

Mafic magma intruded throughout the evolution of the CMB [19]. Hornblendite, gabbro and fine-grained amphibolite dikes cut migmatite and are co-magmatic with plutons of the CMB. Within plutons, synplutonic dikes, pillows of amphibolite with cuspate–lobate boundaries, and mafic schlieren are ubiquitous. These textures show that basalt liquid was present at the same time and place as the granitoid melts and likely was a heat source for melting the crustal rocks. Additionally, cumulate textures in the plutons indicate high temperatures (about 1000 °C) of intrusion and therefore high temperatures at their source.

Based on geochemical and isotopic evidence [20], the Quottoon pluton intruded in at least two phases. The earlier, at about 65 Ma, was generated by partial melting of an amphibolite source reservoir at pressures of about 14 kbar (or 45 km) and by mixing of that melt with a mantle-derived magma. The later phase, at about 55 Ma, was the result of assimilation and fractional crystallization processes of a magma that was derived by partial melting of amphibolite without mixing with mantle-derived basalt. Sm/Nd isotope and trace element geochemistry studies are also consistent with pre 65 Ma magmas having been derived from mantle sources whereas younger magmas appear to have mainly a crustal component [21]. These geochemical trends for

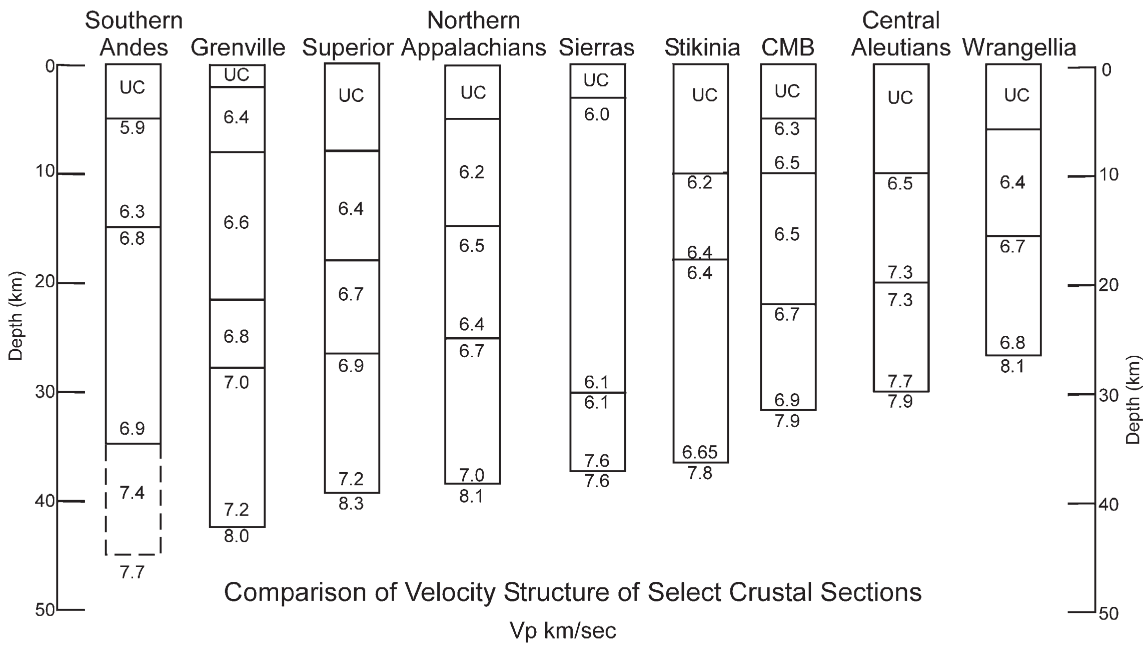

Fig. 4. Comparison of compressional wave velocities (V_p, km/s) and thickness for several crustal sections, arranged by thickness, with those for the three crustal panels of Fig. 3: Wrangellia, the CMB, and Stikinia. V_p for upper crust (UC) not shown. Values of V_p are shown above and below depth markers, or between them if variation is minimal. All data are from controlled source seismic refraction experiments except those for below 35 km of the southern Andes, which are based on a receiver function study [40]. Sources: southern Andes [40], Grenville province [25], Superior province [41], northern Appalachians [25], southern Sierra Nevada batholith [42], Stikinia [11], Coast Mountains batholith [8], central Aleutians [43], Wrangellia [39].

the Quottoon pluton indicate a change from a dominance of juvenile sources prior to ~65 Ma to a dominance of recycled melts between 60 and 50 Ma.

The CMB was uplifted and exhumed in response to erosion and the tectonic removal of the upper 15 km of the crustal section. As it rose, it was inflated by intrusion of sills of diorite and tonalite. These melts were largely recycled crustal materials mixed with basalt from the mantle. The amount of both melts was enhanced by decompression melting due to the exhumation. These magmas, which intruded between 65 and 50 Ma, compose about one third of the volume of the CMB within the ACCRETE study area (Figs. 1 and 3). The 7 km thick Kasiks sill complex (Fig. 1) is one example of this inflation of the crust. The intrusion of these sills was facilitated in the middle and lower crust by ductile flow of the country rocks, including orogen perpendicular flow from the base of Stikinia and orogen parallel flow during north–northwest directed extension [10,22] (Fig. 2b). The presence of mafic garnet granulite (metamorphosed basalt), imaged in the seismic profiles of ACCRETE [8], implies basalt also underplated the lower crust. By the end of this phase, at about 52 Ma, a new piece of continental crust, the CMB (Fig. 3), had been stabilized.

2.2. Seismic constraints

Fig. 4 compares compressional wave velocities (V_p, km/s) and thickness for several crustal sections with those for the three ACCRETE crustal panels: Stikinia, the CMB, and Wrangellia. Three sections are of stable continental crust (Grenville, Superior, northern Appalachians), one is an intra oceanic arc (central Aleutians), one is a continental margin arc (southern Andes), and one, the Sierras, shows the crust of the Sierra Nevada batholith where a strong case has been made for distillation of granitic rocks from a mafic residue [23]. Besides having good active source seismic V_p refraction data available, two sections also have shear wave (V_s) data sets (Grenville, northern Appalachians). We use the shear wave data to compare V_p/V_s with the three ACCRETE panels in Fig. 5, and to refine inferences for present-day lithologies of the three crustal panels.

The Moho depth for Stikinia of 37 km is similar to that of the northern Appalachians, Sierras, and Superior Province. The crust of the CMB has a maximum thickness of only 32 km and is similar to that of the central Aleutians. Neglecting the uppermost crust, the CMB has higher velocities at all depths compared to Stikinia, and the lower half of the CMB has markedly lower V_p than that of the central Aleutians. The Grenville and Superior sections have middle crustal velocities similar to the CMB but differ from the CMB by having a lower crustal layer with V_p of 6.9 to 7.2 km/s. If about half of this layer was added to the base of the CMB, the crustal section of the CMB would be nearly identical in velocity and thickness to those of the Grenville and Superior sections. On the other hand, Stikinia has a velocity structure similar to the northern Appalachians except at the base where V_p of the northern Appalachians is higher. The velocity structure of the Sierras throughout most of the crust is markedly lower than that of any of the other sections.

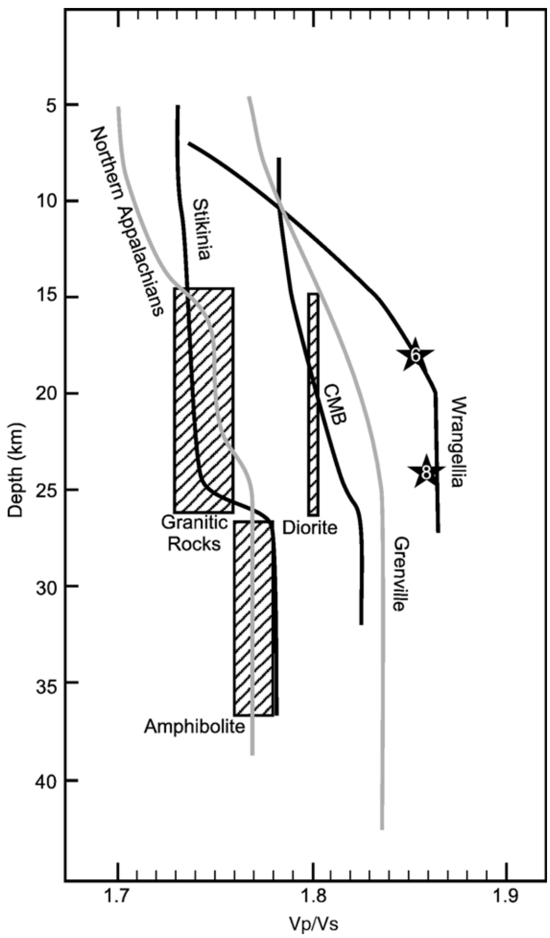

Fig. 5. The seismic property V_p/V_s of three intervals along the section shown in Fig. 3, compared with V_p/V_s from the Grenville province [25], the northern Appalachians [25], and V_p/V_s for gabbro (stars labeled 6 and 8, for 6 and 8 kbar [24]). V_p/V_s of CMB and Wrangellia from [7], that of Stikinia from [11] and [44]. Shows striking difference of crustal lithology between the three ACCRETE panels, and similarities to the other crustal sections. The approximate uncertainty for the three ACCRETE crustal sections and for the Grenville and Appalachian sections is ±0.02 [7,25]; that for gabbro is ±0.03 [24]. V_p/V_s for diorite and granitic rocks were taken from rock measurements [7] and the values for amphibolite are based on data in [24] and [25].

Fig. 5 shows the seismic property V_p/V_s of the three ACCRETE panels [7] compared with gabbro (stars), the Grenville section, and the northern Appalachians section. Where available, V_p/V_s is the preferred property to correlate with rock type at depth because V_p/V_s is independent of temperature [24] and is only slightly dependent on pressure, whereas V_p is dependent on temperature and pressure. To partially compensate for the small pressure effect on V_p/V_s, we compare V_p/V_s to experimental values for common minerals and rocks at 6 kbar: gabbro [24] is 1.85 (Fig. 5); granodiorite, representative of felsic crust, has V_p/V_s of 1.76 or less [7,24]; amphibolite, which we interpret to be at the base of Stikinia and the northern Appalachians, has V_p/V_s of 1.78 or less [7,24,25]; diorite averages 1.80 [7,24]. Amongst minerals [24], calcic plagioclase and hornblende have V_p/V_s over 1.83; quartz is 1.48. In general, the more quartz there is in a rock, the lower the V_p/V_s; the more plagioclase and/or hornblende, the higher the V_p/V_s.

The data plotted in Fig. 5 show that the three panels of the cross section of Fig. 3 are distinct in lithology throughout the whole crust. Wrangellia is underlain by rock with the seismic properties of gabbro (Fig. 5; [24]). Stikinia has seismic properties that indicate it is mainly underlain by quartzofeldspathic rocks such as granite and granodiorite, with a zone at the base of the crust of somewhat higher V_p/V_s that, when V_p is taken into account [7], is consistent with the presence of amphibolite. The V_p/V_s profile for the CMB (Fig. 5) is remarkably similar to the section under the granulite facies metamorphic rocks exposed in the Grenville province, and the V_p/V_s profile of Stikinia (Fig. 5) is similar to that for the northern Appalachians. According to our model (see below), dehydration melting of this amphibolite during decompression from 8 to 5 kbar played a role in generating granitic liquid that was added to the crust of the CMB during extension. The upper two-thirds of the CMB has V_p/V_s consistent with granodiorite to diorite, which are exposed at the surface along the line of seismic section. The increase of V_p/V_s with depth was attributed by [7] to an increase in the proportion of sills of diorite relative to granodiorite. The lower third of the CMB has a V_p/V_s of 1.82. Based on this V_p/V_s and its V_p of 6.9 km/s [7–9] concluded that the lower crust of the CMB contains a mixture of mafic garnet granulite and of quartz and sillimanite-bearing restite.

The major insight to be taken from the comparisons of crustal sections in Figs. 4 and 5 is that the processes that led to the formation of the crust of the CMB are reasonably inferred to have also led to formation of stable continental crust similar to the Grenville and Superior provinces.

3. Model for formation of the continental crust

3.1. Phase 1: Transpression

Simultaneous translation and thickening between 85 and 60 Ma imply a transpressive tectonic regime. The main arguments for translation are based on paleomagnetic data, plate movement reconstructions, geologic discontinuities, and kinematics of shear zones. The paleomagnetic data require a minimum of ~1000 km of northward displacement of the Insular superterrane (including Wrangellia) relative to terranes east of the CSZ between 85 and 50 Ma [26,27]. This overlaps the time interval for rapid northward translation of the Kula plate relative to the North American plate [28]. Evidence that the Insular superterrane is far traveled includes the anomalously shallow inclinations of magnetic remanence directions that were recorded in mid-Cretaceous plutonic rocks [29]. The shallow inclinations imply that the plutons of the Insular superterrane cooled closer to the magnetic equator than their present latitude. A modern analogue for transpression across an arc is Sumatra [30].

Several lines of evidence point to a thick crust under the CMB that was generated by dextral transpression between 85 and 60 Ma. Peak metamorphic pressures of supracrustal rocks of the Central Gneiss Complex were ~8 kbar, requiring ~24 km of tectonic burial [10,15]. The northeast verging Skeena fold and thrust belt (Fig. 2a) led to west-derived clastic sediment that began to be accumulated in the Late Cretaceous and continued into the Paleocene [31]. Also, a thick sequence of Late Cretaceous to Tertiary clastic sediment that accreted to southern Alaska originated from a source likely to be the Late Cretaceous Coast Mountains [32]. Within the CMB, tight northwest trending isoclinal folds with steep axial planes attest to SW/NE shortening and thickening prior to intrusion of the abundant Eocene (58–50 Ma) plutons [19].

Kinematic evidence for transpression between 85 and 58 Ma is found throughout the CMB. The migmatite of the CMB contains abundant top to southwest, syn-migmatite (75–60 Ma) contractional thrust shear zones [10,19]. Reverse shear along the eastern side of the Quottoon pluton and dextral shear across near vertical shear zones found along the northeastern side of the pluton [10] indicate transpression. Much of this transpression must have ended by 58 Ma because the 58 Ma Quottoon pluton crosscuts kilometer-scale folds that formed during the transpression, and Quottoon pluton intruded into the actively deforming Coast shear zone [10]. The buoyancy of the magmas overcame the compressional force across the interface, and the transpression led to strain partitioning which in part facilitated the emplacement of Quottoon pluton [5,6].

The Coast Mountains thus were high standing from roughly 85 to 58 Ma as a result of crustal thickening during dextral transpression. During this time interval, the Insular superterrane was moving NW relative to the terranes to the northeast (Fig. 1). A nearly vertical shear zone, the Coast shear zone, bounds the western side of the CMB and truncates a major mid Cretaceous west vergent thrust belt [9,17] (Fig. 3). These geometries are consistent with this structure being the locus of dextral transcurrent displacement of the Insular superterrane relative to the interior of North America. During transpression, the cool Insular superterrane was sheared into and past the hot continental arc. This led to a contrast in geothermal gradient across the CSZ during Late Cretaceous and early Paleocene [18].

During the period of transpression, the CMB was underlain by an east-dipping subduction zone, with the trench located to the west of Wrangellia. We do not have direct evidence for the processes of interaction of this subduction zone with the lithosphere under the CMB. We assume here that these processes were similar to those now occurring above active subduction zones, which include asthenosphere upwelling and mantle metasomatism from fluids driven off the subducting plate. The asthenosphere upwelling provides heat for melting of the mantle lithosphere and the metasomatism lowers the melting temperature of the mantle lithosphere.

3.2. Transpression and magmatism

Fig. 2a sketches the kinematic model that we propose applies to the transpressional regime in the Coast Mountains between 85 and 58 Ma. The time for the section of Fig. 2a is for before the beginning of intrusion of the two phases of Quottoon pluton. In the sketch, Wrangellia moves toward the north (away from viewer, out of section) as it converges from the west against the proto-CMB. The transpression results in shortening and thickening of the continental crust by folding, by northeast directed structures of the Skeena fold and thrust belt [31], and by southwest directed, synmagmatic thrusting within the CMB [10,15,16]. Translation occurs across dextral shear zones, the biggest of which are the vertical portions of the interface (the CSZ) between the superterranes. The crust under the CMB and under the Skeena fold and thrust belt is taken to be >55 km thick, based on the metamorphic evidence and the geochemistry of the Quottoon pluton. This thickness is also consistent with the thickness the CMB had prior to the Eocene extension, with the restoration of the western portion of Stikinia to above the CMB.

The continued underthrusting of the lower crust of Wrangellia beneath the base of the CMB, along with the translational component, kept the west side of the CMB relatively cool. Heat was only advected where basalts rose from under the thickened continental arc, and these basalts did not leak west of the CSZ because of the refrigeration effect of the convergent component of Wrangellia. However, melting of the underthrusting lower crust of Wrangellia would occur as it came into contact with basalt derived from the mantle wedge (Fig. 2a).

3.3. Phase 2: Extension and magmatism

As the plate tectonic regime of the northeast Pacific changed from dextral transpression to dextral transtension [15], some 15 km of the upper crust of the future CMB was tectonically removed (Fig. 2b), and the core of the orogen began to rise. The decompression due to this unloading led to additional melting in the mantle and lower crust. Underplated basaltic melt advected heat to the lower crust, which resulted in more crustal melting. Melt from vapor absent melting of amphibolite at the base of the crust contributed a felsic component during the decompression. The mix of basalt and felsic melt led to formation of large amounts of granodiorite and diorite, some of which flowed laterally in the lower to middle crust from the north and northeast [15] to the line of section (Fig. 2b). Crustal flow of melt and ductile rock was driven by pressure gradients due to removal of the upper crust [33]. The sills that inflated the middle to lower crust of the CMB in part compensated for the tectonic thinning. The mass of melt produced through these processes resulted in the Eocene magmatic flare up of the CMB, and the final phase of formation of the new continental crust of the CMB.

As a portion of the lower crust under western Stikinia flowed to the CMB, the upper crust of the CMB was translated to the northeast and now in part makes up the upper portion of western Stikinia. This resulted in formation of new continental crust of western Stikinia that differs from that of the CMB; the new crust of Stikinia is also similar to other well-characterized crustal sections (Figs. 4 and 5).

4. Conclusion

New continental crust was made in the CMB in two phases. The first phase was during a period of transpression. As the oceanic plateau Wrangellia was laterally accreted, it was partially melted at the base of the arc (Fig. 2a), forming a felsic melt and a mafic residue. The basalt that came from the mantle wedge above the subduction zone (not shown on Fig. 2a) provided the heat to melt the lower crust of Wrangellia. These two melts mixed and mingled and rose into the arc crust along transpressional shear zones, forming granodiorite, tonalite, and diorite plutons such as the Quottoon pluton (Fig. 3). The new crustal material added to the arc is composed of a mixture of the basalt that was derived from the mantle and the material that was imported with Wrangellia.

The second phase of crust formation accompanied crustal extension (Fig. 2b). The thickened crust that formed during the first phase was extended and thinned to a crust of "normal" thickness. During this thinning, decompression melting in the mantle and lower crust generated additional melts. The magmas of the Eocene magmatic flare up were composed of this mixture of melts [15]. Melt and ductile rock in the middle and lower crust flowed across and along strike in response to the extensional removal of the upper crust. The upper crust of the CMB was transported to the northeast where it forms the present upper crust of western Stikinia.

Our model incorporates the processes of dehydration melting and the addition of mantle-derived basalt into the crust, which are included in the basic model of crust formation, but it shows how non-steady state lateral flow of middle to lower crustal material during transpression and tectonic extension may be essential for forming the compositional and structural characteristics of typical continental crust. Because our model does call for significant basalt contribution to the crustal composition, there must be a mafic residue in order to account for the overall felsic nature of the crust. However, this residue need not be directly below a particular section of crust, as appears to be the case for the Sierras [34] and it may still be present under the CMB. Our results show that deformation during arc construction is a 3-d process involving along and across strike, as well as vertical, movement of melt and ductile crust. The overall similarity of the CMB and Stikinia crustal columns to other crustal columns suggests that processes associated with transpression and extension may be widespread in generating continental crust.

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