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ABSTRACT The >1800 km long Coast Mountains–North Cascades orogen of the Canadian Cordillera and north-western US developed as a continental magmatic arc. Metamorphic rocks in the orogen contain widespread evidence for burial of supracrustal rocks to depths of c. 40 km, followed by nearly isothermal decompression to depths of <10 km. Near many shallowly-emplaced, mid-Cretaceous plutons, low-pressure contact metamorphic effects were overprinted by high-pressure regional metamorphic minerals and textures, as evidenced by kyanite ± staurolite pseudomorphs after andalusite in metapelitic rocks. Therefore, near-pluton rocks record the loading history of the orogen. Metapelitic rocks not associated with plutons only preserve evidence for high-pressure conditions and/or high-temperature decompression, as indicated, for example, by sillimanite and cordierite after kyanite and garnet, respectively. Petrological evidence for burial and decompression is therefore recorded in different rocks. Various regions of the orogen differ in timing of metamorphism, the overall shape of P–T paths and the relative timing and regional extent of the high-pressure event, but most of these data and observations are consistent with thrusting and/or pure shear thickening as primary loading mechanisms throughout the orogen, as opposed to magma-dominated loading. This interpretation is further supported by comparison with thermal models, which demonstrate that the P–T paths are consistent with simultaneous thrusting and folding at a high initial geothermal gradient (35–40 °C km⁻¹) in much of the orogen. A high geothermal gradient supports tectonic models invoking intra-arc contraction and suggests that magmatism played an important role in regional temperature-time paths. This tectonic-thermal history may be typical of other contractional orogens and illustrates the importance of large vertical displacement of crust in magmatic arcs.

INTRODUCTION Although most plate tectonic models for the development of contractional orogens emphasize the importance of large lateral motions, the final configuration of these orogens (e.g., topography, distribution of metamorphic rocks and structures) is strongly affected by vertical motions (burial and exhumation). Deciphering the mechanisms responsible for vertical motion requires examining rocks and structures representing a range of crustal depths. The north-western Cordilleran mountain system extending from Washington (North Cascades) to south-east Alaska (Coast Mountains) represents one of the best exposed examples of an ancient continental magmatic arc and contains rocks and structures reflecting processes that occurred in the mid-Cretaceous arc at depths ranging from near-surface to c. 40 km.

This paper contains a survey of thermobarometric data from the Coast Mountains–North Cascades system, with an emphasis on the North Cascades. Data from geographically disparate sites are used to compare metamorphic P–T paths, construct thermal models, and interpret the relation between tectonic processes responsible for low-pressure contact metamorphism and subsequent high-pressure Barrovian metamorphism, both of which accompanied construction of the orogen. The metamorphic history is viewed in the context of existing tectonic models based on the interpretation that the entire mid-Cretaceous orogen, from south-east Alaska to central Washington, is characterized by thrusting (e.g., Rubin et al., 1990; Journeay & Friedman, 1993; Umhoefer & Miller, 1996). We integrate structural and petrological evidence from these rocks to provide a model for the thermal and mechanical behaviour of continental crust in a contractional arc setting. In particular, P–T–t paths constructed from mineral assemblages and reaction textures in metamorphosed supracrustal rocks show that the structural and metamorphic evolution of this and other arcs was greatly influenced by major vertical motion. Comparison with P–T–t paths predicted by finite element and finite difference models suggests that these vertical motions reflect burial during crustal thickening caused by simultaneous thrusting and folding, exhumation, and advection of mass and...
thermal energy by magmatism. Although we discuss the metamorphic history of much of the orogen, we focus on the North Cascades because it is the region with which we are most familiar.

**COAST MOUNTAINS–NORTH CASCADES GEOLOGY**

The Coast Mountains–North Cascades orogen developed during the final stage of accretion of the Insular superterrane to the Intermontane superterrane in the mid-Cretaceous (e.g., Monger et al., 1982; Rubin et al., 1990). The central, crystalline part of the North Cascades (Misch, 1966, 1988) represents the offset, south-eastern extension of the >1800 km long Coast Mountains in British Columbia and Alaska (Figs 1 & 2). Restoring c. 90–190 km of mid-Tertiary offset on the Straight Creek–Fraser River fault places the North Cascades on strike with the Coast Mountains belt. Both northern and southern elements of the orogen contain Cretaceous and Paleogene (<100–45 Ma) plutons and metamorphic rocks ranging in grade from greenschist to upper amphibolite facies (with rare exposures of granulite facies rocks), and widespread evidence for Cretaceous to Paleocene (?) high-pressure metamorphism (e.g., Crawford et al., 1987; Whitney, 1992).

Magmatism in the Cascades core occurred sporadically from 96 to 45 Ma, with the earliest (mid-Cretaceous) plutons widely distributed throughout the core region, and later intrusions occurring in fairly well-defined belts, namely a 78–72 Ma central zone and a 68–48 Ma north-eastern zone (Miller et al., 1989) (Fig. 3). This trend of decreasing pluton ages from west to east is replicated in the southern (Friedman & Armstrong, 1995) and northern Coast Mountains (Armstrong & Ward, 1991) and is similar to that reported for the Sierra Nevada and Peninsular Range batholiths (Silver et al., 1979; Chen & Moore, 1982).

Metamorphosed supracrustal units and many spatially and temporally associated orthogneisses are typically intensely foliated and lineated. In the Cascades core, the foliation has been folded, generally coaxially, a minimum of two times around gently plunging, NNW–SSE-trending axes (e.g., Miller & Paterson, 1992). In the North Cascades, early tight to isoclinal folds of foliation, which have gently to moderately dipping axial planes, have been refolded by gentle to tight upright folds. Kinematic indicators are typically scarce, but imply complex flow, including: sinistral and dextral strike slip (Miller et al., 1994; Moreno, 1996); N-vergent shear on gently dipping surfaces; and SW-vergent reverse slip (e.g., Journeay & Friedman, 1993; Miller & Paterson, 1992). These structures range from ~96 to 45 Ma in age. The early structures are probably coincident with major mid-Cretaceous, SW-directed thrusting recorded in weakly metamorphosed rocks west of the US part of the belt and in

![Fig. 1. Map of western North America showing the location of major Cretaceous magmatic-metamorphic complexes (Coast Mountains-North Cascades; Idaho; Sierra Nevada; Peninsular) and northern Cordilleran tectonic belts (Insular, Coast Mountains, Intermontane, Omineca, foreland). J = Juneau, Alaska; PR = Prince Rupert, British Columbia; S = Seattle, Washington; V = Vancouver, British Columbia. The North Cascades is offset from the Coast Mountains by strike-slip faults. Box shows area of Fig. 2.](image)
both low- and high-grade rocks farther north-west in the Coast Belt (e.g., Crawford et al., 1987; Rusmore & Woodsworth, 1991; Journeay & Friedman, 1993). Subsidiary north-east-directed mid-Cretaceous thrusting occurred on the north-east side of the Coast belt (McGroder, 1991; Rusmore & Woodsworth, 1994), and Journeay & Friedman (1993) proposed that the opposing vergence directions reflect large-scale tectonic wedging. We interpret the overall pattern in the Cascades core as recording complexly partitioned coaxial flow resulting from NE-SW contraction.

**P–T CONDITIONS**

The following sections summarize quantitative P–T information for Coast Mountains–North Cascades metamorphic rocks from the southern end of the Cascades core to south-east Alaska. For consistency, only those results determined for metapelitic rocks using the well-calibrated garnet-plagioclase-aluminoisilicate-quartz (GPAQ, also known as GASP) geobarometer are given here, and most were calculated using the calibration of Koziol & Newton (1988).

Pressures were recalculated with this calibration for those references that did not originally determine pressure with this calibration but that contained complete mineral analyses. Recalculation did not result in

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**Fig. 2.** Simplified geological map of the North Cascades and the southern end of the Coast Mountains belt (Coast Plutonic Complex). CCB = Chilliwack composite batholith; FF = Fraser fault; HZ = Hozomeen terrane; RLFZ = Ross Lake fault zone; SCF = Straight Creek fault. Stippled pattern indicates early Tertiary and older plutons. Inverted V pattern indicates later Tertiary intrusive and volcanic rocks (e.g., Glacier Peak volcanic deposits and Chilliwack batholith).

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**Fig. 3.** (A) Major geological features in the crystalline core of the North Cascades and southern Coast Mountains. Key to abbreviations and symbols not defined in Fig. 2: BP = Black Peak batholith; CH = Chiwaukum Schist; CR = Cascade River unit; EL = Eldorado Orthogneiss; EN = Entiat pluton; EO = Excelsior Mountain orthogneiss; FDFZ = Foggy Dew Fault Zone; GH = Golden Horn batholith; GPTB = Gabriel Peak Tectonic Belt; IC = Ingalls Complex; LJ = Little Jack terrane; MSB = Mount Stuart batholith; NC = North Creek volcanic unit; NP = Napeequa unit; OP = Oval Peak batholith; SC = Scuzzy pluton; SG = Skagit Gneiss (orthogneiss 75–50 Ma); SKY = Skymo Complex; SL = Sloan Creek plutons; SP = Spuzzum pluton; SW = Swakane Gneiss; TG = Tonga Formation; TP = Tenpeak pluton; TVS = Twisp Valley schist; WPT = Windy Pass thrust; WRSZ = White River shear zone. Numbers in circles are maximum recorded pressure (kbar). Solid squares = andalusite; open squares = pseudomorphed andalusite. (B) Simplified version of Fig. 3a showing ranges of pressures (kbar).
in significant changes in published results, as pressures determined with the Koziol & Newton (1988) calibration are within 1 kbar of those calculated with the models of Ghent et al. (1979) and Hodges & Crowley (1985). Temperatures on which the pressure calculations are based were determined by garnet–biotite geothermometry, most using the garnet model of Berman (1990) and assuming an ideal solution model for biotite. Mineral compositions used in P–T determinations can be found in most of the original publications. Cited pressures (Fig. 3) are the maximum conditions recorded, and are inferred to represent the thermal maximum (peak) of metamorphism, although it should be noted that disequilibrium textures and evidence for preservation of multiple P–T path segments are common. The maximum recorded pressure for each region discussed in this paper (see below) is given in Table 1. Table 1 also contains estimates for the timing of loading, peak of metamorphism, and cooling through the \( { }^{40}\text{Ar}/^{39}\text{Ar} \) closure temperature for biotite for each region. These age constraints are described in more detail in the following sections.

Previous compilations of North Cascades pressure conditions (e.g., Brown & Walker, 1993) have relied in part on other geobarometers, such as the crossite content of Ca-amphibole (Brown, 1977), garnet-muscovite-biotite-plagioclase, and Al-in-hornblende (for plutonic rocks) for recognizing regional baric patterns. Many of these barometers give significantly lower pressures than GPAQ (see Fig. 3b in Brown & Walker, 1993).

**Chiwaukum Schist and the southern end of the Cascades core (Nason terrane)**

The dominantly metapelitic and metapsammitic Chiwaukum Schist is located at the southern end of the North Cascades core (Fig. 3), and is the country rock for the northern and eastern margins of the 96–93 Ma Mount Stuart batholith. Pressures calculated for Chiwaukum metapelitic schist range from 3 to 9 kbar, and temperatures range from 540 to 700 °C over a distance of 10 km from the north-east margin of the batholith (Evans & Berti, 1986; Bendixen et al., 1991; Brown & Walker, 1993).

The Mount Stuart batholith, which consists of an early (96 Ma) mafic phase (Big Jim Complex) and a later (93 Ma) much more voluminous tonalitic phase, is elongate parallel to the NW–SE structural fabric of the Chiwaukum Schist and intruded across a boundary between the Cascades core and the north-west Cascades–San Juan Islands thrust system (Windy Pass thrust, Fig. 3; Miller, 1985). Miller & Paterson (1992; 1994) documented pre-, syn- and post-intrusion south-west-vergent thrusting and folding that affected the north-east margin of the batholith and its country rocks, and correlated these structures with those in the Coast Mountains thrust system c. 175 km to the north that involve the Settler Schist (Fig. 2) (Journeyay & Friedman, 1993), a unit that has been correlated with the Chiwaukum Schist (e.g., Misch, 1977; Monger, 1985; Evans & Berti, 1986; Magloughlin, 1986).

Textural relations among aluminosilicate poly-morphs provide information about the metamorphic history of the Chiwaukum Schist, as well as about the emplacement conditions of the Mount Stuart batholith (Evans & Berti, 1986; Paterson et al., 1994), because at least part of the metamorphic history of this multiply-deformed schist was synchronous with intrusion of the batholith (Miller & Paterson, 1992). Early low-pressure metamorphism probably occurred in the contact aureole of the batholith, as indicated by a 2 km wide zone of andalusite-bearing rocks around the intrusion (Fig. 3). Cordierite is also widespread near the batholith (Plummer, 1980; Evans & Berti, 1986; Paterson et al., 1994; Davidson & Evans, 1995), and probably formed during this early contact metamorphism. Andalusite growth was syn-kinematic (e.g., Plummer, 1980), suggesting that intrusion occurred during a regional metamorphic event, although some of this deformation has also been attributed to pluton emplacement (e.g., Paterson et al., 1994). Truncation of a regional axial-planar foliation in the Chiwaukum Schist by the Mount Stuart batholith indicates that regional metamorphism occurred before as well as during batholith emplacement (Miller & Paterson, 1992). Later, higher pressure conditions, indicated by kyanite after andalusite, reflect subsequent crustal loading. In some places (Fig. 3), andalusite has been completely replaced by sillimanite or kyanite, staurolite, and plagioclase, but the outline of the original crystals and in some grains, the chiastolite inclusion pattern is preserved. In addition to replacing andalusite in the contact aureole, sillimanite formed north-east of the aureole and post-dated kyanite (Paterson et al., 1994; see also Hollister, 1969).

Within a few hundred metres of the batholith, fibrous sillimanite nucleated on biotite crystals adjacent to andalusite. In other samples, prismatic sillimanite directly replaced andalusite, and these same andalusite grains are rimmed by plagioclase. Sillimanite also connects pull-apart zones between extended andalusite grains. Thermobarometric results for rocks containing zoned garnet suggest that sillimanite–garnet–biotite schists had counter-clockwise paths, assuming that the protoliths started out at low-pressure conditions (i.e., during emplacement of the batholith) and attained higher pressure near the kyanite–sillimanite transition (Bendixen et al., 1991). The retrograde path for these rocks went from c. 680 °C at 4.5 kbar to 570 °C at 3.2 kbar (Bendixen et al., 1991).

Pseudomorphs also occur in the Chiwaukum Schist near the 90 Ma Sloan Creek plutons (Fig. 3) and Excelsior Mountain Orthogneiss where andalusite has been locally replaced by sillimanite and staurolite+muscovite, respectively (Heath, 1971; Duggan & Brown, 1994). Kyanite is also a late-forming mineral near these intrusions (Heath, 1971).
Chiwaukum Schist near the Windy Pass thrust (Fig. 3) locally contains cordierite ± sillimanite. Coexisting garnet and biotite from schists directly below the Windy Pass thrust record temperatures of c. 580–700 °C (Whitney & Miller, unpublished data) and pressures of c. 3–4 kbar. Within the Mount Stuart batholith, a large metasedimentary xenolith (Pioneer Creek domain of Miller & Paterson, 1992), which lies a short distance below the projection of the thrust, records similar temperatures. Cordierite in a garnet ± sillimanite-bearing sample from this domain contains abundant inclusions of hercynitic spinel. Cordierite and spinel may have grown during decompression by the equilibrium sillimanite + almandine = cordierite + hercynite, which has a relatively flat slope in $P$–$T$ space and occurs at c. 3 kbar for the mineral compositions in this rock.

K–Ar and $^{40}$Ar–$^{39}$Ar biotite cooling dates for the Mount Stuart batholith and southern part of the Chiwaukum Schist range from 90 to 81 Ma (Engels et al., 1976; Tabor et al., 1982, 1987). Hornblende and biotite dates decrease by c. 10 Ma to the north-east away from the batholith. These dates suggest that the southern end of the Cascades underwent moderate to rapid cooling, owing to cooling of the pluton and exhumation. Biotite dates are slightly younger (c. 76 Ma) near the Sloan Creek plutons (Fig. 3), but still indicate that the Chiwaukum Schist did not experience Late Cretaceous and Paleogene amphibolite facies metamorphism and associated ductile deformation as did core rocks to the north.

**Swakane Gneiss (SE Cascades core)**

The Swakane Gneiss is a largely homogeneous biotite–plagioclase–quartz gneiss in the south-eastern part of the crystalline core (Fig. 3), but it contains rare metapelitic lenses. The homogeneity of the Swakane Gneiss and the lack of a regionally extensive stratigraphy has been interpreted to indicate a volcanic protolith (e.g., Mattinson, 1972; Sawyko, 1994). Our field work (Miller & Paterson, unpublished observations), however, suggests that layering is much more common than previously described and a metasedimentary (dominantly arkosic) protolith is plausible, as originally suggested by Waters (1932).

The Eocene Entiat fault (Fig. 3) separates the Swakane Gneiss into two blocks. Thermobarometric results from Swakane metasedimentary rocks indicate that these blocks record different metamorphic histories. North-east of the Entiat fault (Fig. 3) kyanite–staurolite (+ late sillimanite) schists record pressures of c. 8 kbar (garnet core) and 10–12 kbar (garnet rim) at 580–625 °C (Sawyko, 1994). The higher pressures recorded by garnet rims reflect the presence of grossular-rich, petrographically distinct garnet rim overgrowths (Sawyko, 1994), similar to those reported by Miller et al. (1993b) for metasedimentary rocks elsewhere in the crystalline core (see below). The age of this metamorphism is poorly known. A single K–Ar hornblende date of 51 Ma and eight fission track zircon dates averaging 43 Ma, suggest that the Swakane cooled rapidly in the Eocene (Engels et al., 1976; Tabor et al., 1987). K–Ar hornblende dates of 67–72 Ma, however, have been reported for amphibolites in the structurally overlying Napeequa unit close to the Swakane contact (Tabor et al., 1987; Table 1).

Garnet–kyanite–sillimanite gneiss within the structural block south-west of the Entiat fault and north-east of the White River shear zone (Tenpeak block; Fig. 3, Table 1) have staurolite inclusions in garnet but no staurolite in the matrix. These rocks record $P$–$T$ conditions of 650–700 °C and 8–9 kbar (Sawyko, 1994). These results are consistent with $P$–$T$ conditions calculated by Whitney (1992) for metapelitic rocks elsewhere in this western belt of Swakane Gneiss, in which kyanite–staurolite schists record maximum pressures of 8–8.5 kbar. All rock units within this structural block appear to have had a different history from that of neighbouring regions of the North Cascades. For example, the 91 Ma magmatic epidote-bearing Tenpeak pluton (Fig. 3) is estimated to have been emplaced at 7–9 kbar (Zen & Hammarstrom, 1984), and therefore intruded at much greater depths than most other plutons of similar age in this region. The absence of andalusite in neighbouring country rock is consistent with the deep emplacement of this intrusion. Thus, the metamorphosed supracrustal rocks in this structural block were buried before emplacement of the 96–90 Ma plutons and may have followed a different $P$–$T$ path or may record a different part of a path from that of other structural blocks. The exhumation history of this block is poorly known. Biotite $^{40}$Ar–$^{39}$Ar and K–Ar dates are mostly between 70 and 55 Ma (Engels et al., 1976; Tabor et al. in press), suggesting that unroofing occurred slightly later than in the Chiwaukum Schist, which is compatible with the interpretation of Haugerud (1987) that much of the region south-west of the Entiat fault underwent about 15° of Eocene south-west-side-down tilt.

**Twisp Valley Schist and neighbouring correlative units (NE Cascades core)**

The Twisp Valley Schist (TVS) is a largely supracrustal unit located in the north-east part of the Cascades core (Figs 2 & 3), near where Whitney & McGroder (1989) placed the Insular–Intermontane superradial suture. The TVS and related rocks are in tectonic contact with Skagit orthogneiss (Cretaceous–Paleocene; Miller & Bowring, 1990) on the south-west along the Gabriel Peak tectonic belt (Miller, 1987) of the Ross Lake fault system, and are on strike with the western metapelitic rocks of the Skagit Gneiss–Napeequa schist (see next sections). Possible correlative units occur in the Foggy Dew fault zone (FDFZ; Fig. 3) of the Ross Lake fault system, which truncates the TVS and the 65 Ma Oval Peak batholith. The
protophite age of the TVS is only constrained by the 90 Ma Black Peak batholith, which intruded the west-north-west end of the TVS, but the unit has been correlated with Mississippian to Jurassic strata of the Bridge River-Hozomeen terrane (e.g., Miller et al., 1993b). Metamorphic grade ranges from greenschist to amphibolite facies, based on mineral assemblages and thermobarometric results for garnet + Al$_2$SiO$_3$-bearing rocks (Miller et al., 1993b).

Metapelitic rocks in the TVS and nearby Rainbow Lake Schist contain andalusite, garnet and staurolite. Late prismatic and fibrous sillimanite lie in a foliation that wraps around andalusite porphyroblasts and has locally replaced andalusite. Miller et al. (1993b) also reported randomly-oriented kyanite replacing andalusite in the TVS. Although all three aluminosilicate polymorphs are present in some samples, there is no evidence that they were in equilibrium with each other. Andalusite was the earliest of these minerals, but the relative timing of kyanite and sillimanite growth is unclear. Evidence from garnet zoning in the TVS, combined with observed textural relations described herein from other areas in the North Cascades suggests the growth of andalusite, kyanite and sillimanite in succession, indicating loading followed by heating and/or decompression along a clockwise path (Miller et al., 1993a,b). This interpretation is consistent with inferences based on an increase in grossular from garnet core to rim (Miller et al., 1993b).

Maximum $P$–$T$ conditions recorded by aluminosilicate-bearing rocks are: 2.5–5.5 kbar, 550 °C (TVS sample); 5.4 kbar, c. 600 °C (FDFZ); and 7 kbar, c. 680 °C (Rainbow Lake Schist). The Foggy Dew fault zone sample, which contains sillimanite as its only Al$_2$SiO$_3$ minerals, is juxtaposed across the Foggy Dew fault with the low-grade rocks of the Methow basin (Fig. 3).

Loading of the TVS and Rainbow Lake Schist must have occurred after crystallization of the 90 Ma shallow level (1–3 kbar) Black Peak batholith, which intruded the TVS, and probably occurred by 75 Ma (K–Ar biotite date for Black Peak) and certainly by 65 Ma when the 5–7 kbar Oval Peak batholith was emplaced (Miller et al., 1993b). Relatively rapid cooling of the TVS took place from c. 58–56 Ma (K–Ar and 40Ar/39Ar hornblende dates for three samples) to c. 50–48 Ma (K–Ar biotite and fission track titanite sphene dates for Oval Peak batholith) during dextral-normal slip in the Foggy Dew fault zone (Miller & Bowring, 1990).

Cascade River unit (NW Cascades core)

The Cascade River (CR) unit crops out in the west-north-west part of the Cascades core (Fig. 3) and was considered by Misch (1966, 1968) to be a lower grade part of the Skagit suite (=Skagit Gneiss + Cascade River Schist). Dragovich et al. (1989) and Brown et al. (1994) interpreted the CR unit as consisting of Triassic and younger (?) arc-related sedimentary and volcanic rocks that were metamorphosed at conditions ranging from 500 °C, 3 to 4 kbar to 650 °C, 8–9 kbar. These $P$–$T$ conditions are recorded by rocks collected from a 10 km across-strike section. Rare metamorphic rocks contain kyanite and staurolite. In the vicinity of the Eldorado orthogneiss (Fig. 3), andalusite has been replaced by kyanite, and garnet is strongly zoned, with grossular content increasing from core to rim (Miller et al., 1993a; Brown et al., 1994). Loading of up to 6 kbar has been inferred (Brown & Walker, 1993; Miller et al., 1993a; Brown et al., 1994).

Loading of the Cascade River unit near the Eldorado Orthogneiss occurred after crystallization of this 91–88 Ma pluton, and before c. 76 Ma, the crystallization age of the nearby deep (8–9 kbar) Marble Creek pluton, which intruded the high-pressure schists (Brown & Walker, 1993). These rocks may have remained at elevated temperatures for 30 Ma or more before possible rapid cooling, as a K–Ar hornblende date of 42 Ma has been reported from the Eldorado Orthogneiss and K–Ar biotite dates in the area are all <50 Ma (Engels et al., 1976; Tabor et al. in press).

Skagit Gneiss (N and NE Cascades core)

The Skagit Gneiss consists predominantly of orthogneiss with subordinate meta-supracrustal rocks and amphibolite that probably have both Napeequa and Cascade River unit protoliths (Tabor et al., 1989). In the central part of the unit, all Skagit rocks are migmatitic. The migmatites formed by a variety of processes, including in situ partial melting, subsolidus differentiation + metasomatism, and magmatic injection (Misch, 1968; Babcock & Misch, 1989; Whitney & Irving, 1994). Dated (U–Pb zircon) Skagit orthogneisses range in age from c. 100–50 Ma (Mattinson, 1972; Miller et al., 1989; Haugerud et al., 1991).

Four known garnet + Al$_2$SiO$_3$-bearing metapelitic outcrops occur in the Skagit Gneiss, two containing kyanite and two containing sillimanite (Misch, 1966; Whitney, 1992) (Fig. 3). Whitney et al. (1995) were unable to identify chemical mass balance relations between kyanite-staurolite schist and sillimanite gneiss, and suggested that the two formed from different protoliths. The kyanite schists may be part of the Napeequa unit, but are described here because published thermobarometric studies have considered them with the Skagit Gneiss (Whitney & McGroder, 1989; Whitney, 1992).

The kyanite-staurolite schists record maximum conditions of 8–9 kbar, c. 650 °C, and contain cordierite that rims garnet. In a sample from the Ross Lake fault zone (Fig. 3), andalusite and cordierite rim garnet and staurolite in rocks containing skeletal kyanite. These textures are interpreted to imply a relatively steep decompression path (Whitney, 1992). Garnet in sillimanite gneiss contains armoured relics
of kyanite, staurolite and rutile. Thermobarometric results give maximum pressures of 9–10 kbar at >700 °C. These rocks also contain late cordierite (rimming and filling fractures in garnet) that formed during high-temperature, nearly isothermal decompression (Whitney, 1992). Garnet-cordierite thermobarometry indicates final equilibration conditions of 3–5 kbar at T > 650 °C.

Crustal thickening of the Skagit Gneiss occurred prior to intrusion of epidote-bearing orthogneiss, the oldest of which are 74 Ma and 68 Ma (Haugerud et al., 1991; Wernicke & Getty, 1997), that probably crystallized at ≤ 6 kbar. 40Ar–39Ar and K–Ar hornblende dates are younger than in the rest of the Cascades core, namely 57–43 Ma (Engels et al., 1976; Tabor et al., 1994; Wernicke & Getty, 1997) and some are nearly concordant with biotite ages. Thus, the Skagit Gneiss remained at amphibolite facies conditions for a prolonged period and then cooled rapidly from 50–45 Ma (e.g., Tabor et al., 1989; Haugerud et al., 1991; Wernicke & Getty, 1997).

Other metamorphic rocks in the Ross Lake fault zone (North Cascades)

The metamorphic grade of metasedimentary rocks in the RLFZ decreases from west to east. Most sedimentary and volcanic rocks in and immediately east of the RLFZ are only slightly metamorphosed and therefore do not contain mineral assemblages suitable for thermobarometry. For example, the fault-bound North Creek volcanic unit, which lies within the RLFZ between the Twisp Valley Schist of the Cascades core and unmetamorphosed strata of the Methow basin (Fig. 2), consists mainly of andesitic and arkosic rocks (Misch, 1966) with a maximum metamorphic grade of greenschist facies.

In the northern part of the RLFZ in Washington state, the Little Jack terrane (Tabor et al., 1989) is in fault contact with deformed Hozomeen terrane greenstone and ribbon chert to the north-east, and the Skymo complex (Wallace, 1976; Whitney & Hirschmann, 1994, 1996) to the south-west (Fig. 3). In addition to primitive mafic intrusive rocks, the Skymo complex contains a fault-bound sliver of low-pressure/high-temperature granulite facies metasedimentary rocks that is interpreted to represent the contact aureole of the intrusion and may be correlative with the Little Jack terrane (Baldwin et al., 1997). Low-pressure contact metamorphism followed earlier, higher pressure (6–7 kbar) regional metamorphism (Baldwin et al., 1997).

The Little Jack terrane consists primarily of graphitic phyllite and fine-grained schist that contain metamorphic biotite and less commonly, garnet, staurolite or chloritoid, andalusite, and late sillimanite and cordierite. Metamorphic grade decreases from lower amphibolite facies along the south-west margin of the terrane to subgreenschist facies in the north-east. Graphitic phyllite along the western margin of the Little Jack terrane, in the vicinity of the fault contact with the Skymo complex, contains garnet and ductilely deformed andalusite. Andalusite-bearing rocks record P–T conditions of 3.5 kbar, 475–500 °C (Baldwin et al., 1997). Andalusite in rocks closest to the fault contact has been partially replaced by prismatic and fibrous sillimanite and cordierite ± hercynitic spinel. These samples record similar pressures but higher temperatures (> 600 °C) than those lacking sillimanite and/or cordierite and may have equilibrated during contact metamorphism associated with intrusion of the Skymo gabbro (Baldwin et al., 1997). These rocks are part of the ‘Buchan’ style metamorphism described by Misch (1966) in the ‘eastern metamorphic belt’. This belt also includes rocks from the Elijah Ridge area, described above as Skagit Gneiss, containing late cordierite ± andalusite.

Skymo mafic magmatism and accompanying low-pressure/high-temperature metamorphism occurred c. 50 Ma (Baldwin et al., 1997). Therefore, these events post-date the loading history of the rest of the North Cascades and indicate that rocks on the east side of the metamorphic core were at depths of < 10 km by the Middle Eocene.

Southern British Columbia (Coast Mountains)

The Settler Schist of the southern Coast Mountains (Fig. 2) is correlated with the Chiwaukum Schist in the southern Cascades core. Both schists have similar metamorphic ages, isotopic signatures, P–T histories, and other metamorphic features (e.g., kyanite after andalusite; common increase in garnet grossular content from core to rim) near Cretaceous intrusions – the Chiwaukum Schist in the contact aureole of the 96–93 Ma Mount Stuart batholith, and the Settler Schist near the 96 Ma Spuzzum pluton (Misch, 1977; Evans & Berti, 1986; Brown & Burmester, 1991; Magloughlin & Edwards, 1992; Brown & Walker, 1993).

Metamorphic conditions in the Settler Schist range from garnet to sillimanite zones, with grade increasing towards the magmatic epidote-bearing Scuzzy pluton (Figs 2 & 3). Lower grade terranes crop out to the west. Maximum pressures recorded in the Settler Schist are 4–8 kbar (Figs 3 & 4) and loading of up to 4 kbar was inferred by Brown & Walker (1993).

Loading of the Settler Schist occurred after crystallization of the Spuzzum pluton (96 Ma) and is inferred by Brown & Walker (1993) to have taken place during intrusion of the 91–84 Ma Scuzzy pluton (Fig. 3). Monazite U–Pb dates of 91–88 Ma in the Settler Schist may date peak metamorphism (Brown & Walker, 1993). Relatively rapid cooling is implied by the K–Ar biotite dates, which are mostly older than 80 Ma (Monger, 1991; Brown & Walker, 1993), mimicking the history of the Chiwaukum Schist and Mount Stuart batholith.
Central British Columbia (Coast Mountains)

One of the few thermobarometric studies of the central Coast belt focused on a sequence of low-pressure (<5 kbar) and low- to high-temperature (480–645 °C) metasedimentary rocks exposed in the Waddington thrust belt, at the eastern margin of the Coast belt in British Columbia (Rusmore & Woodsworth, 1994). Rusmore & Woodsworth (1994) identified andalusite (+ staurolite), sillimanite/fibrous sillimanite, and sillimanite + K-feldspar isogrades. Based on field relations (including an inverted thermal gradient and the correspondence of the Al$_2$SiO$_5$ isogrades to mapped plutons) and mineral textures, they concluded that metamorphism was driven by contractional deformation and that peak metamorphic conditions were attained soon after thrusting.

Thrusting occurred later than in much of the rest of the Coast belt – between 87 and 84 Ma – and the metamorphic peak is inferred to have occurred slightly later than the thrusting, 84–82 Ma (Rusmore & Woodsworth, 1994; Table 1). The thrust belt was intruded by 68 and 58 Ma plutons, by which time thrusting and metamorphism had ceased (Rusmore & Woodsworth, 1994).

Northern British Columbia and SE Alaska (Coast Mountains)

Stowell & Crawford (personal communication), in the most recent synthesis of metamorphism and deformation in the Coast Mountains of western British Columbia and south-east Alaska, reported six related and sequential metamorphic events: (1) an early (c.101 Ma) regional event, accompanied or followed by; (2) contact metamorphism (101–90 Ma); (3) regional metamorphism related to thrusting (90–85 Ma); (4) contact metamorphism associated with intrusion of sill complexes (72–58 Ma); (5) high grade regional metamorphism (55 Ma); and (6) a very late contact metamorphic event (c. 20 Ma). Near shallowly emplaced plutons (101–90 Ma), randomly oriented andalusite was replaced by kyanite, and presumably records tectonic burial to > 8 kbar during the 90–85 Ma thrusting.

Brew et al. (1992) noted the presence of kyanite after andalusite in the inner zones of contact aureoles (their M4 metamorphism, c. 95 Ma) in the western metamorphic belt of the Coast Mountains, and reported M4 metamorphic conditions of c. 6–9.5 kbar at 500–644 °C. Himmelberg et al. (1991) described an inverted metamorphic gradient in the western metamorphic belt near Juneau, Alaska (Fig. 1), with peak pressures of 9–11 kbar at c. 700 °C in kyanite-bearing rocks.

Clockwise metamorphic $P$–$T$ paths with maximum pressures of c. 8–10 kbar and maximum temperatures of 600–650 °C are reported from the western Coast Mountains (Hollister, 1982; Crawford et al., 1987; Stowell, 1989). As in the Skagit Gneiss, garnet in sillimanite schist contains armoured relics of kyanite and staurolite, and sillimanite pseudomorphs after kyanite and staurolite are observed.

The Coast Belt experienced Eocene regional granulite facies metamorphism (725–775 °C, 4.2–5.5 kbar) in the Prince Rupert area (Hollister, 1975; Selverstone & Hollister, 1980) (Fig. 1) that has no known equivalent in the North Cascades or elsewhere in the southern Coast Belt, the granulite facies metamorphism in the Skymo complex, North Cascades, being a local, contact metamorphic event. Hollister (1982) proposed rapid uplift (2 mmyr$^{-1}$) of the Coast belt granulites from

Fig. 4. $P$–$T$ paths for North Cascade Range and Coast Mountains metapelitic rocks. Key to numbers: 1a,b = Skagit sillimanite gneiss garnet core, rim (Whitney, 1992); 2a,b = Skagit kyanite–staurolite schist garnet core, rim (Whitney, 1992); 3 a,b = Eldorado orthogneiss contact zone garnet core, rim (Miller et al., 1993a); 4a,b = Settler Schist (southern Coast Mountains), garnet core, rim (Brown & Walker, 1993; Miller et al., 1993a); 5a,b = Chiwaukum Schist (near Mount Stuart batholith) garnet core, rim (Evans & Berti, 1986; Magloughlin, 1986; Bendixen et al., 1991; Miller et al., 1993a); 6a–d = western metamorphic belt, Coast Mountains, Canada and SE Alaska (Himmelberg et al., 1991; Stowell & Crawford, personal communication); 7a,b = Swakane Gneiss (average values) (Whitney, 1992; Sawyko, 1994); 8 = Prince Rupert area, British Columbia, Canada (Crawford et al., 1987); FDFZ = Foggy Dew fault zone (Miller et al., 1993b); OP = Oval Peak batholith contact zone (Miller et al., 1993b); RLS = Rainbow Lake schist (Miller et al., 1993b). $P$–$T$ paths determined from thermal modelling for 12 km (gray lines) and 18 km-thick pressures of 9–11 kbar at 700 °C in kyanite-bearing rocks.
Table 1. Summary of age and pressure data*.

<table>
<thead>
<tr>
<th>Region</th>
<th>Initiation of loading (Ma)</th>
<th>Peak of metamorphism</th>
<th>Biotite cooling</th>
<th>Max. P (kbar)</th>
</tr>
</thead>
<tbody>
<tr>
<td>North Cascades</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Chiwaukum Schist</td>
<td>93–90</td>
<td>88</td>
<td>75</td>
<td>9</td>
</tr>
<tr>
<td>Tenpeak block</td>
<td>&gt;92 (if loaded)</td>
<td>?</td>
<td>65–55</td>
<td>9</td>
</tr>
<tr>
<td>Swakane Gneiss</td>
<td>&gt; 51</td>
<td>&gt;51</td>
<td>55–45</td>
<td>10–12</td>
</tr>
<tr>
<td>Napeequa Unit</td>
<td>90–76</td>
<td>?</td>
<td>70–50</td>
<td>7?</td>
</tr>
<tr>
<td>Twisp Valley Schist</td>
<td>90–75</td>
<td>90–60</td>
<td>55–50</td>
<td>10–12</td>
</tr>
<tr>
<td>Skagit Gneiss</td>
<td>&gt; 75</td>
<td>75–50</td>
<td>50–45</td>
<td>10</td>
</tr>
<tr>
<td>Cascade River Unit</td>
<td>89–72</td>
<td>89</td>
<td>72–46</td>
<td>9</td>
</tr>
<tr>
<td>Ross Lake fault zone</td>
<td>&gt; 50</td>
<td>&gt;50</td>
<td>?</td>
<td>&gt;6</td>
</tr>
<tr>
<td>Southern Coast Mountains</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Settler Schist</td>
<td>96–84</td>
<td>91–88</td>
<td>80</td>
<td>8</td>
</tr>
<tr>
<td>Central Coast Mountains</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Waddington area</td>
<td>87–84</td>
<td>84–82</td>
<td>55</td>
<td>&lt;5</td>
</tr>
<tr>
<td>Northern Coast Mountains</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Western belt</td>
<td>101–80</td>
<td>80–55</td>
<td>55</td>
<td>10–11</td>
</tr>
<tr>
<td>General Model</td>
<td>95–75</td>
<td>90–60</td>
<td>60–45</td>
<td>9</td>
</tr>
</tbody>
</table>

* References and explanation of age constraints given in the text.

35–5 km, based on the presence of low density fluid inclusions, decrepitated fluid inclusions, and andalusite in late veins, all of which indicate moderate temperatures at relatively shallow depths.

Summary of burial and cooling histories

Tectonic models for the orogen must account for the following: (1) major crustal loading occurred after emplacement of most terrane-stitching, mid-Cretaceous plutons at depths of <10–12 km (Miller et al., 1993a); (2) loading was at least in part synchronous with contraction of deep levels of the arc; and (3) supracrustal rocks record pressures of up to 10–12 kbar, followed by nearly isothermal decompression to 3–5 kbar (Whitney, 1992).

Above we summarized evidence for the following generalized history for the orogen: (1) widespread thrusting and magmatism throughout the orogen prior to 85 Ma (Rubin et al., 1990; Rusmore & Woodsworth, 1991; Journeay & Friedman, 1993; Umhoefer & Miller, 1996); (2) regional but somewhat diachronous loading not necessarily associated with magmatism (Miller et al., 1993a; Wernicke & Getty, 1997) and typically associated with local thrusting and widespread folding that deformed the earlier thrusts and; (3) resumption of more localized magmatism (c. 70–45 Ma), which, at least from 50 to 45 Ma, was associated with unroofing of the orogen.

Information is only available locally for P–T paths during early thrusting and magmatism. For example, Paterson et al. (1994) noted that regional metamorphism was at lower amphibolite facies conditions before the 93 Ma Mt Stuart batholith was emplaced, at which time andalusite and then sillimanite grew in the contact aureole at pressures of 3–4 kbar (see also Brew et al., 1992; Stowell & Crawford (personal communication); for Coast belt examples). Throughout the orogen, the second and third events are associated with a pressure increase of 3–5 kbar along a clockwise P–T path followed by nearly isothermal decompression of up to 5 kbar (e.g., Whitney, 1992). The data in Fig. 3 show that high-pressures are recorded in rocks both near and relatively far from exposed plutons, suggesting that a regional burial mechanism was important.

In summary, the relative timing, style, and P–T conditions of deformation, plutonism, and metamorphism were broadly similar along much of the length of the orogen, from the southern Cascades core to south-east Alaska. In both the north and south, the main stage of orogenic activity occurred between c. 100 Ma and c. 48–45 Ma, with rapid Eocene uplift (1 mm yr⁻¹) indicated in at least parts of the belt by similarities in biotite and hornblende K–Ar cooling ages (e.g., Crawford et al., 1987; Miller et al., 1989; Hollister et al., 1993). Though loading and cooling histories were diachronous across parts of the orogen, we have shown that the P–T paths (which form the basis for tectonothermal models) are strikingly similar, as discussed in more detail below.

In the following sections we use the data and observations presented above to construct models that describe vertical motions (burial, exhumation) in the Coast Mountains–North Cascades belt and other continental magmatic arcs.

THERMAL MODELS AND PREDICTED P–T PATHS

Thermal-mechanical modelling provides constraints on likely mechanism(s) of loading and exhumation because
P–T paths inferred from thermobarometric results can be compared with paths predicted by models calculated from heat flow equations for different crustal thickening and exhumation histories (e.g., England & Thompson, 1984; Koons, 1987; Ruppel & Hodges, 1994; Jamieson et al., 1998). For example, crustal thickening accomplished by thrusting or pure shear thickening results in different P–T paths from those predicted by magma loading models. Magmatism plays a particularly sensitive role in these models because of the higher heat content of magma relative to the base of a thrust sheet and the significant thermal contribution of the heat of crystallization of magma (typical values for latent heat are orders of magnitude larger than heat production owing to radioactive decay). In addition, depending on intrusion rates and volume, advective heating by magmatism is one to several orders of magnitude faster than advective heating by thrusting; e.g., compare rates in Ruppel & Hodges (1994) to Paterson & Tobisch (1992). This contrast would be accentuated for regions in which long-lived magmatism is the rule, such as in the Coast Mountains–North Cascades orogen. Unfortunately, no thermal-mechanical models exist that examine simultaneous crustal thickening, exhumation, and magmatism, particularly using the elevated geotherms more typical of arcs. Therefore, we first examine results from thrust loading models, present new 1-D thrust loading models using elevated geotherms, and then compare these to P–T paths predicted during magmatism, particularly magma loading.

Early 1-D models of thrusts (e.g., Oxburgh & Turcotte, 1974; England & Thompson, 1984) assumed instantaneous thrust emplacement and produced inverted (‘sawtooth’) geotherms. Later 2-D models with transient thrusts (e.g., Shi & Wang, 1987; Willet et al., 1993) only produced inverted geotherms at extreme thrusting rates and emphasized that after initial depression of geotherms, the advection of heat by thrusting, by exhumation, and by increasing the thickness of the radiogenic crust, raised geotherms significantly. The P–T paths in these models are clockwise.

The 2-D modelling of Ruppel & Hodges (1994) incorporated the effects of radiogenic heat and isostasy, and these authors examined the effects of transient thrusting with variable thrust rates (typically 0.5–5 mm yr$^{-1}$), thrust dips, rates of symmetrical pure shear thickening or exhumation, and exhumation rates (typically 1–5 mm yr$^{-1}$) on P–T paths. Most predicted P–T paths were clockwise, but varied in shape both vertically and laterally. Fault dip and burial rate had little effect on the prograde parts of these paths, whereas pure shear thickening reduced lateral variation in P–T paths, but otherwise produced similar paths to thrusting. Erosional and pure-shear extensional unroofing resulted in nearly isothermal decompression paths, particularly from 8 to 4 kbar pressures, whereas unroofing by normal faults did not. With increasing rate of unroofing, the length of the isothermal decompression curve increased and maximum metamorphic temperatures tended to be lower, were reached earlier, and at shallower depths. Geotherms returned to pre-deformation configurations 10–20 Ma after thickening ceased.

Jamieson et al. (1998) used thermal-mechanical models to examine the effects of tectonic redistribution of crust rich in heat-producing elements on the thermal and deformation history of convergent orogens. Their models, which do not quantitatively include the effects of magmatism, showed that clockwise P–T paths in the field of typical regional (Barrovian) metamorphism result from the large-scale tectonic thickening of radiogenic crustal material such as an accretionary wedge or continental margin sediments.

Though less sophisticated than 2-D models, 1-D thermal models provide some information about P–T paths for regions with high geothermal gradients and serve as a useful step to evaluating the relation between observed P–T–t paths and mechanisms of loading and heating. More detailed models (e.g., those involving magmatism) affect the slope of the P–T path and predict longer times for re-equilibration to regional temperatures. We modelled crustal thickening as the instantaneous emplacement of a single thrust sheet, recognizing that this is a great simplification. A value for maximum load thickness was determined from the P–T paths plotted in Fig. 4. For rocks near plutons, post-intrusion loading of c. 12–18 km of burial is indicated. Although the initial P–T conditions calculated for near-plutons rocks have been reset during burial and heating subsequent to contact metamorphism, maximum pressure during contact metamorphism is indicated to have been < 3.9 kbar by the presence of andalusite. Furthermore, although temperatures determined from garnet–biotite geothermometry for andalusite-bearing rocks cannot be taken as representing contact metamorphic conditions because of the effects of resetting during burial and subsequent heating, the occurrence of andalusite in a 2–3 km wide zone and narrower zones of sillimanite around some North Cascades plutons suggests that the country rock was already at moderate (greenschist to lower amphibolite facies) temperatures at the time of intrusion and contact metamorphism. Moderate initial country rock temperature is supported by the petrographic observation that andalusite crystals enclose a crenulated graphitic schistosity that must have developed before contact metamorphism and growth of andalusite (Evans & Berti, 1986), and by the presence of tight to isoclinal folds of schistosity defined by biotite, and locally hornblende and plagioclase, that are cut by plutons (e.g., Miller & Paterson, 1992; Paterson et al., 1994). Therefore values adopted for the thermal models are likely to be reasonable.

The temperature at the base of the thrust sheet is not known and could vary from relatively cool (300–450 °C, geotherm of 25 °C km$^{-1}$) if the thrust sheet
were composed of Methow-Hozomeen rock types (Whitney & McGroder, 1989), to much hotter (up to 720 °C; geotherm of 40 °C km \(^{-1}\)) if the thrust sheet(s) comprised of hot arc material (Miller et al., 1993a). In these models, rocks below the thrust fault follow clockwise \(P-T\) paths (Fig. 4). The original steady-state geotherm is re-established throughout the thickened crust c. 13–12 Ma after thrusting. The models shown in Fig. 4 account for 1 mm yr \(^{-1}\) of erosion following thrusting. Model paths calculated for higher rates of unroofing (up to 5 mm yr \(^{-1}\)) also approximate the paths inferred from thermobarometry. Detailed information about the thermal modelling, including input parameters, is given in the Appendix.

Figure 4 compares several model \(P-T\) paths for rocks below 12 and 18 km-thick thrust sheets for an initial geothermal gradient of 40 °C km \(^{-1}\). Models for lower geothermal gradients (e.g., 25–35 °C km \(^{-1}\); not shown) predict similar paths at lower temperature.

These thermal models for thrust loading correspond well to peak metamorphic conditions and nearly isothermal decompression paths (large arrows in Fig. 4). In particular, models for an 18 km-thick thrust sheet and an elevated geotherm (35–40 °C km \(^{-1}\)) predict similar conditions to those recorded in the rocks (Fig. 4). Discrepancies between model results and inferred \(P-T\) paths/conditions may be partially reconciled by consideration of additional thrust sheets or the effects of tectonic exhumation.

According to proposed magma loading models, diapiric emplacement and ballooning of magma chambers or formation of numerous sub-horizontal sills are the principal mechanisms of crustal loading in orogens (Brown & Walker, 1993; Brown, 1996). Warren & Ellis (1996) considered qualitative \(P-T\) paths near Ramberg-like diapirs (Ramberg, 1981) during which return flow transports host rock downwards adjacent to the diapir.

Host rocks adjacent to the diapir follow counter-clockwise \(P-T\) paths as they are rapidly heated (by the passing diapir) then loaded (due to return flow), except for those immediately at the contact which are dragged upward with the diapir. Mid-crustal host rocks start at moderate pressure and temperature, undergo some heating (owing to the diapir) and pressure increase (owing to crustal thickening during return flow) but along paths with steeper \(dP/dT\) slopes than the rocks at shallower levels.

During ballooning or emplacement of sub-horizontal sheets, rocks immediately below the pluton are rapidly heated during gradual burial, but high temperatures due to magmatism are unlikely to be sustained for long (<10 Ma) compared to heating during thrust thickening (>10 Ma). Rocks below but greater than a few kilometres from the intrusive contact experience loading and less extreme amounts of heating than rocks near the contact, and may record clockwise \(P-T\) paths similar to those predicted for crustal thickening by thrust loading, but with more gradual \(dP/dT\) slopes.

In a mixed model involving simultaneous magma intrusion and thrust loading, rocks are predicted to follow counter-clockwise \(P-T\) paths if the magma intruded at relatively shallow crustal levels (England & Richardson, 1977; Spear, 1993). Such paths do not characterize the metamorphism of the Coast Mountains–North Cascades belt.

In summary, 2-D models incorporating simultaneous crustal thickening, magmatism, and exhumation are not yet available, making it difficult to fully evaluate \(P-T\) paths in orogens such as the Coast Mountains–North Cascades belt. The clockwise paths recorded in the orogen, however, are best described by thrust or pure shear thickening of hot crust rather than the more variable but typically counter-clockwise paths associated with magmatism. Furthermore, the widespread evidence of isothermal decompression over a pressure range of 5 kbar strongly supports rapid unroofing by erosional processes or pure shear extension. The latter conclusion is supported by old cooling ages, which are recorded over a wide area (including regions with no evidence for magmatism) and a lack of any recognized normal faults active during the time of unroofing.

**\(P-T\) Evidence for Tectonic Mechanisms**

Observations and interpretations of the metamorphic history of the Coast Mountains–North Cascades belt are: (1) metamorphic histories of widely separated parts of the orogen are similar in terms of maximum \(P-T\) conditions and relative timing of metamorphism, deformation, and magmatism; (2) metapelitic rocks in contact aureoles of many mid-Cretaceous plutons contain andalusite, some of which has been partially replaced by kyanite ± sillimanite, indicating an increase in pressure following low-pressure conditions; and (3) metapelitic rocks not associated with plutons record moderate- to high-pressure metamorphism (7–10 kbar) and nearly isothermal decompression with rare late andalusite (+ cordierite), i.e., kyanite → sillimanite → andalusite.

Two possible explanations for the latter two observations are: (1) contact zone and non-contact zone rocks preserve different segments of different metamorphic episodes (perhaps involving different loading mechanisms); or (2) contact and non-contact zone rocks preserve different segments of the same \(P-T\) path. We prefer the latter interpretation and propose that near-pluton rocks preserve the loading (prograde) part of the \(P-T\) path because they contain a kinetically-sluggish, Al-rich domain (andalusite) which persisted metastably during the increase in \(P-T\). Rocks not near plutons experienced only regional metamorphism and therefore never contained andalusite. These rocks preserve evidence for peak conditions and/or part of the decompression path. Different rocks therefore preserve different segments of the generalized \(P-T\) path.

Although burial and unroofing occurred at various
times in different parts of the orogen, rocks from most parts of the orogen followed similar $P$–$T$ trajectories. The regional extent of high-pressure rocks and the similarity of $P$–$T$ histories along the length of the Coast Mountains–North Cascades belt suggest a similar burial mechanism occurred over much of the orogen. Local variations in mineralogy, metamorphic textures, structures, and maximum pressures and temperature recorded likely reflect differences in protolith bulk composition, deformational regimes, and position (depth) in the contractional orogen. For example, the highest pressures recorded in the North Cascades are in a N-S trending zone along the central part of the crystalline core, with lower pressures to the east and west near the bounding faults and at the extreme southern end where the core is structurally overlain by low-grade rocks. This pattern appears to reflect the overall antiformal structure of the northeastern part of the crystalline core (Tabor et al., 1989; Kriens & Wernicke, 1990).

Several models have been proposed to account for the metamorphism, intrusion, and structural evolution of the Coast Mountains–North Cascades system: (1) high-pressure Barrovian-style metamorphism related to mid-Cretaceous intra-arc contraction (Rubin et al., 1990) or collision of the Insular and Intermontane superterranes (Monger et al., 1982; Whitney & McGroder, 1989; McGroder, 1991); (2) orogen-parallel (dextral) shearing during mid-Cretaceous to Paleogene transpression (Brown, 1987; Brown & Talbot, 1989), accompanied by magmatic loading-induced metamorphism (Brown & Walker, 1993) and; (3) tilting, but no major deformation, resulting in an essentially intact 30 km thick crustal section of a mid-Cretaceous arc (Kriens & Wernicke, 1990).

The latter two models are inconsistent with petrological evidence. The model of Kriens & Wernicke (1990) is problematic because it is inconsistent with evidence for loading, late magmatism, and widespread deformation. The magma loading model of Brown & Walker (1993) is based in part on their suggestion that recorded pressures in metasedimentary rocks in the contact aureoles of a number of North Cascade intrusions decrease away from the plutons. As noted above, however, high-pressures are recorded in rocks both near and not associated with plutons. In addition, the timing of deep burial of rocks typically post-dates the ages of volumetrically large magmatism (Wernicke & Getty, 1997). $P$–$T$ paths, rather than maximum recorded pressure, provide the information necessary to evaluate mechanisms of crustal thickening. In this orogen paths are consistent with metamorphism driven by thrust loading or pure shear thickening partly driven by folding in a contractional setting. The model presented here, which is based largely on $P$–$T$–t information from the North Cascades, is generally consistent with the conclusions of studies of the Coast Mountains to the north (e.g., Crawford et al., 1987; Rusmore & Woodsworth, 1994).

**Comparison with other continental magmatic arcs**

Several other ancient magmatic arcs preserve evidence that plutonism and metamorphism occurred during sub-horizontal arc contraction, which resulted in thickening of the arc and may have been associated with $P$–$T$–t paths similar to those of the Coast Mountains–North Cascades belt. The best examples are those that form the roots of other Mesozoic arc(s) in the North American Cordillera, including the Early Cretaceous arc plutons in the western margin of the Idaho batholith (e.g., Manduca et al., 1993) and Jurassic arc plutons in the Klamath Mountains (Wright & Fahan, 1988), Black Rock Desert of north-western Nevada (Wyld, 1996), Sierra Nevada foothills (e.g., Paterson et al., 1991), and Mojave Desert (Howard et al., 1995). The amount of crustal thickening in these arcs may be large. For example, thickening in the Sierra foothills during Late Jurassic and Early Cretaceous plutonism was on the order of 125% (Paterson et al., 1991).

The Cretaceous Sierra Nevada batholith may also be somewhat analogous to the Coast Belt in that recent work on lower crustal xenoliths suggests the crust may have been extremely thick, perhaps 75–80 km, much like the present Andean arc (Dueea & Saleeby, 1996). Saleeby (1990) contends that parts of the volcanic cover of the Sierra Nevada batholith were rapidly displaced downward by as much as 10 km during return flow of country rock during pluton emplacement, a process somewhat resembling the magma loading model of Brown & Walker (1993). Furthermore, kyanite is present in selvages of schist between Cretaceous plutons in the deep southern part of the batholith (Saleeby, 1990). Thus, there are similarities to the Coast Mountains–North Cascades belt, but we caution that to our knowledge clockwise $P$–$T$–t paths resembling those we have documented for the northern Cordillera have not been demonstrated for the Sierra Nevada or for other parts of the Jurassic and Cretaceous Cordilleran arcs.

Several workers (Bradshaw, 1989; Miller et al., 1993a; Brown, 1996) have noted similarities in the metamorphic histories of the Fiordland Complex, New Zealand, and the Coast Mountains–North Cascades belt. The metasedimentary country rocks to the Fiordland magmatic arc preserve a history of relatively low-pressure metamorphism followed by a nearly isothermal $P$ increase of 6 kbar, with maximum $P$ c. 12 kbar (Bradshaw, 1989). Metamorphism therefore followed a clockwise $P$–$T$ path, with evidence for c.20 km of vertical movement of supraarc crustal rocks. Cooling of at least parts of this arc was rapid, as intrusion, loading, and final cooling all happened within 20 Myr (Bradshaw, 1989).

(1996) assumed that both metamorphism and magmatism occurred in the Early Cretaceous, but in a recent paper, Ireland & Gibson (1998) described a previously unrecognized Palaeozoic regional metamorphic event in Fiordland, and noted that the presence of regional isoclinal, recumbent folds suggested that tectonic loading was perhaps the more likely mechanism of burial of metasedimentary rocks.

Cretaceous arc construction in Japan was also accompanied by high-grade metamorphism, and burial followed the initiation of arc magmatism. Metasedimentary rocks record a clockwise \( P-T \) path with burial followed by c. 6 kbar of decompression at high temperatures (>700 °C), with the pressure changes occurring within 10 Ma. (Hiroi et al., 1998). Hiroi et al. (1998) attributed the burial event to tectonic loading of the metasedimentary rocks by oceanic and other terranes.

In conclusion, we suspect that \( P-T-t \) paths similar to those in the Coast Mountains–North Cascades orogen occur in other belts of arc metamatism that experienced significant crustal thickening. Such paths are similar to those documented for metamorphism in collisional orogens that were not accompanied by voluminous magmatism (e.g., Alpine-Himalayan belt), although these orogens are typically characterized by lower geothermal gradients.

**CONCLUSIONS**

Our results show that despite diachronous loading and unroofing involving numerous structures along the length of the orogen, maximum depth of burial (up to c. 40 km), peak metamorphic temperature (650–700 °C), and \( P-T \) paths (clockwise with isothermal decompression) are similar in many parts of the mountain belt, likely indicating a similar mechanism for burial and unroofing. \( P-T \) paths and the timing of metamorphism in relation to magmatism are most consistent with thrust loading or pure shear thickening partly driven by folding as the dominant mechanism, and indicate significant vertical motion during contraction and decompression. The results of thermal modeling support this conclusion and further suggest that much of the region had a relatively high geothermal gradient at the time of thrusting, consistent with contraction in an intra-arc setting.

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**APPENDIX**

**Modelling parameters**

The following parameters were used to calculate model \( P-T \) paths: heat capacity 1000 J kg\(^{-1}\) K\(^{-1}\), density 3000 g m\(^{-3}\), surface temperature 0 °C, thermal conductivity 2.25 W m\(^{-1}\) K\(^{-1}\), heat production 2.10\(^{-6}\) W m\(^{-3}\), mantle heat flow 0.03 W m\(^{-2}\). Mantle heat flow values were varied slightly to produce different geothermal gradients. Other input parameters include the thickness of the thrust sheet and the position of the sample of interest in relation to the thrust sheet (see text and Fig. 4 for model values). The time required to re-establish a steady-state geotherm was determined using an erosion rate of 1 mm yr\(^{-1}\). Overall crustal thickness was assumed to be two times the thrust sheet thickness. The program employs an explicit finite difference algorithm with a grid spacing of 1000 m (see Spear et al., 1991).

**REFERENCES**


Umhoefer, P. J. & Miller, R. B., 1996. Mid-Cretaceous thrusting

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