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Formation of the Shuswap metamorphic core complex during late-orogenic collapse of the Canadian Cordillera: Role of ductile thinning and partial melting of the mid- to lower crust

Formation du complexe métamorphique du Shuswap lors de l'effondrement tardi-orogénique de la Cordillère Canadienne : Rôle de l'amincissement ductile et de la fusion partielle de la croûte

O. VANDERHAEGHE and C. TEYSSIER

ABSTRACT. – The early Tertiary evolution of the Shuswap metamorphic core complex is characterised by low-angle crustal detachments and nearly isothermal decompression followed by rapid cooling of rocks in the footwall of the detachments. Previous work as well as our own observations suggest that Paleogene late-orogenic extension produced the main tectonic features of the region. Furthermore, structural analysis of the migmatites and published geochronological data indicate that partial melting of the mid- to lower crust was coeval with extension in the upper crustal levels, suggesting that these two processes are linked genetically. Consequently, we propose that the formation of the Shuswap metamorphic core complex corresponds to late-orogenic gravitational collapse of the Canadian Cordillera accommodated by normal faulting of the brittle upper crust and by ductile thinning of the mid- to lower crust. The initiation and amplification of extension during the Paleocene in the Shuswap metamorphic core complex are tentatively related to partial melting of the thickened crust which caused drastic mechanical weakening of the crust.

Key-words : Late-orogenic collapse, metamorphic core complex, Shuswap, partial melting, migmatites, tectonics, Canadian Cordillera, Omineca belt, British Columbia.

RÉSUMÉ. – L'évolution durant le Tertiaire du complexe métamorphique du Shuswap est marquée par la formation de détachements crustaux subhorizontaux au-dessous desquels les roches ont subi une décompression quasi-isothermique, suivie d'un refroidissement très rapide. L'étude des travaux publiés sur le complexe métamorphique du Shuswap, ainsi que nos observations de terrain, montrent que l'extension tardi-orogénique paléogène est à l'origine des structures majeures de cette région. L'analyse structurale des migmatites et les données géochronologiques indiquent que la fusion crustale fut synchrone de l'extension de la croûte supérieure, ce qui suggère que ces deux processus sont liés génétiquement. En conséquence, nous proposons que la formation du complexe métamorphique du Shuswap corresponde à l'effondrement gravitaire de la Cordillère canadienne accommodé par extension fragile de la croûte supérieure et par l'amincissement ductile de la croûte médiane à inférieure. Nous proposons également que l'initiation et l'amplification de l'extension orogénique durant le Paléocène dans le complexe du Shuswap sont liées à la fusion de cette croûte épaissie qui entraîne un amollissement catastrophique de la croûte.

Mots clés : Effondrement tardi-orogénique, metamorphic core complex, Shuswap, fusion partielle, migmatites, Cordillère canadienne, Colombie Britannique.

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INTRODUCTION

Late-orogenic collapse has been recognised as an important stage affecting the evolution of thickened continental crust (Coney & Harms, 1984; Dewey, 1988; Molnar *et al.*, 1993). In areas of active tectonics such as the Himalaya, the Alps, and the Andes, orogenic collapse is characterised by extension and normal faulting of the brittle, upper crust while the plates are still converging (e.g. Molnar & Tapponnier, 1975; 1978; Dalmayrac & Molnar, 1981; Burg *et al.*, 1984). In older orogenic belts such as the North American Cordillera or the Hercynian belt, which expose deeper crustal levels, lower crustal units are exhumed and brought in contact with upper crustal units along low-angle detachment faults forming metamorphic core complexes (Coney & Harms, 1984; Coney, 1987; Ménard & Molnar, 1988). The processes of exhumation of the metamorphic core complexes and the mechanisms controlling late-orogenic collapse remain controversial.

Three major processes can explain a change from crustal shortening and thickening to late-orogenic extension (Molnar *et al.*, 1993): (1) Sudden increase of relief as an isostatic response to removal of the lithospheric root of the orogen; (2) reduction of the compressive forces applied to the margins of the mountain range, for instance due to a change in plate motion; and (3) a change in the rheology of the lithosphere leading to mechanical weakening and gravitational collapse. The latter has often been discarded on the basis that a weaker lithosphere would be likely to favour an increase in the convergence rate and contraction. However, the India-Asia collision, which occurred at a constant rate for the last 50 My (Molnar & Tapponnier, 1975; Patriat & Achache, 1984; Dewey *et al.*, 1989), indicates that thickening of the continental crust does not have a strong influence on the rate of lithospheric plate convergence. Initiation of normal faulting in the Tibetan plateau started during the Miocene (Burg *et al.*, 1984; Burchfiel *et al.*, 1992) long before the onset of mantle delamination inferred from rapid uplift of the plateau (Molnar *et al.*, 1993), and concurrent with the emplacement of leucogranites (Burg *et al.*, 1984; Mattauer & Brunel, 1989; Guillot *et al.*, 1994). In addition, recent seismic refraction profiles on a N-S section of the Tibetan plateau indicate the presence of a partially molten layer at mid-crustal depth (Ross *et al.*, 1995). Therefore, we propose that following crustal thickening, thermal relaxation and especially partial melting cause weakening of the crust, and hence play a significant role in controlling the initiation and localisation of late-orogenic collapse. In this paper we document the spatial and temporal relationships between partial melting and late-orogenic collapse of the hinterland of the Canadian Cordillera in the Shuswap metamorphic core complex.

The Cordilleran metamorphic core complexes (hereafter called the Shuswap MCC) form a sinuous belt of high-grade metamorphic rocks extending from Canada to Mexico and exhumed during the Paleogene (fig. 1; Crittenden *et al.*, 1980). Palinspastic reconstruction indicate that the MCC developed at the expense of a thickened crustal welt formed as a result of terranes accretion on the western margin of North America during Mesozoic time (Monger *et al.*, 1982; Coney & Harms, 1984). In Eocene time, plate motion reorganisation, related to the complete subduction of the Kula plate, caused significant decrease in the convergence rate at the latitude of the Southern Canadian Cordillera (Engebretson *et al.*, 1985). On the other hand, the current high heat flow over the hinterland of the Canadian Cordillera has been associated with mantle delamination that occurred approximately 50 Ma ago, at a time of voluminous basaltic volcanism (Bardoux & Mareshal, 1994). These two mechanisms provide a plausible explanation for the Tertiary regional extension that affected the Canadian Cordillera.

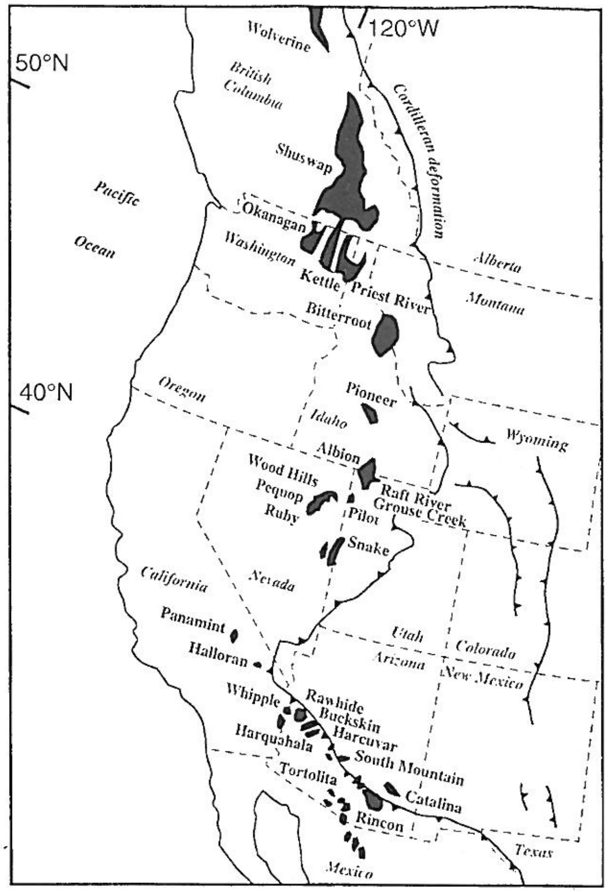


Fig. 1. – **The Cordilleran metamorphic core complexes (After Crittenden *et al.*, 1980; Armstrong, 1982;).** The narrow and sinuous belt of metamorphic core complexes, represented in black, delineates the North American paleomargin. The thick black line with chevrons represents the limit of Cordilleran deformation.

Fig. 1. – ***Complexes métamorphiques de la Cordillère nord-américaine (d'après Crittenden* et al.*, 1980; Armstrong, 1982).*** *Ces complexes, en noir, forment une ceinture étroite et sinueuse soulignant la paléomarge nord-américaine. Le trait avec chevrons marque la limite orientale de la déformation de la Cordillère.*

Alternatively, this paper focuses on the potential role of crustal anatexis during late-orogenic collapse. In the northern part of the Cordillera, most authors attributed the ductile fabric and the formation of the Cordilleran metamorphic core complexes to Mesozoic to Paleogene contraction associated with crustal thickening (Brown & Read, 1983; Mattauer *et al.*, 1983; Okulitch, 1984; Brown & Journeay, 1987) whereas the importance of Tertiary extension overprint was emphasised in the southern part (Armstrong, 1972; Davis & Coney, 1979; Wernicke, 1985). We review the existing data on the geology of the Shuswap MCC, and illustrate the relationship between partial melting and deformation at the latitude of the Thor-Odin dome. We propose a model for the formation of the Shuswap MCC, where late-orogenic gravitational collapse of the Canadian Cordillera is accommodated by normal faulting of the brittle upper crust and ductile thinning of the mid- to lower crust coeval with partial melting and the formation of migmatite domes (fig. 2). Based on our structural analysis and on the fact that crustal anatexis apparently slightly predated mantle delamination and the decrease in convergence rate, we suggest that crustal anatexis played a major role in weakening the crust and controlling the initiation of collapse in the Shuswap MCC.

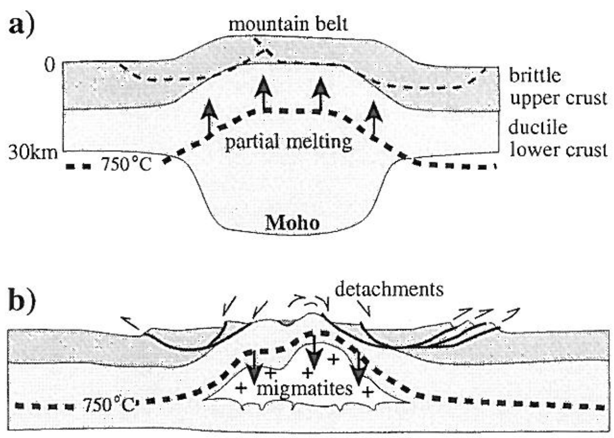


Fig. 2. – **Conceptual model of late-orogenic collapse; a) Crustal thickening is followed by thermal relaxation and partial melting of the fertile middle crust; b) late-orogenic collapse is accommodated by brittle extension of the upper crust and ductile thinning of the mid-to lower crust with formation of migmatite domes.** Exhumation of the high-grade rocks is associated with rapid cooling.

Fig. 2. – ***Modèle d'effondrement gravitaire tardi-orogénique; a) épaississement crustal suivi par relaxation thermique et fusion partielle de la croûte médiane fertile; b) effondrement gravitaire accommodé par l'extension fragile de la croûte supérieure et amincissement ductile de la croûte médiane à inférieure accompagné de la formation de dômes migmatitiques.*** *L'exhumation des roches métamorphiques est associée à un refroidissement rapide.*

PREVIOUS WORK

The Shuswap MCC, the largest Cordilleran MCC, straddles the NW-SE trending suture between the most inboard Intermontane superterrane and the paleocontinental margin of Ancestral North America (fig. 3). The Shuswap MCC displays the juxtaposition, across N-S trending normal faults, of upper crustal levels that have preserved Mid-Cretaceous and older cooling ages, and high-grade rocks of the middle and lower crust, characterised by Paleocene-Eocene K-Ar ages (Ewing, 1981; Mathews, 1981; Parrish *et al.*, 1988). During Mesozoic and early Tertiary time, subduction and accretion of terranes on the western margin of ancient North America resulted in contraction and crustal thickening, strike-slip faulting, and extension (Monger & Price, 1979; Monger *et al.*, 1982; Gabrielse, 1985; Price & Carmichael, 1986; Parrish *et al.*, 1988; Gabrielse *et al.*, 1991; Struik, 1993). The amount of Paleogene extension, crustal anatexis, and granite intrusion that followed Mesozoic contraction is debated, and the age and significance of the ductile fabric in the hanging wall of the major detachment faults is controversial (Price, 1986; Brown & Read, 1983; Brown & Journeay, 1987; Carr *et al.*, 1987; Parrish *et al.*, 1988; Carr, 1992). In contrast to most Cordilleran MCC, which show either a shallower structural level or a severe mylonitic overprint under low-grade conditions, the Shuswap MCC has preserved high-grade fabrics.

Lithologic units

Based on stratigraphic correlation and recognition of major tectonic contacts, the Shuswap MCC has been divided into three crustal units (Reesor & Moore, 1971; Okulitch, 1984; Brown & Journeay, 1987; Carr, 1991b, 1992). The high-grade metamorphic core of the complex comprises parautochthonous basement gneisses overlain by allochthonous amphibolite-facies units above the Monashee décollement. The allochthon is in turn overlain by upper crustal cover units and Paleogene sedimentary basins along large-scale outward dipping detachment faults (fig. 3).

Parautochthonous basement gneisses

The lower structural unit, referred to as the basement gneisses, is exposed in dome-shaped culminations aligned along the strike of the belt, comprising from north to south, the Malton complex, the Monashee complex (Frenchman Cap and Thor-Odin domes), and the Valhalla complex (fig. 3). These complexes display Paleoproterozoic cratonic basement, or core gneisses, composed of metapelites and migmatitic gneisses attributed to the Windermere Supergroup intruded by Proterozoic granodioritic gneisses (Wanless & Reesor, 1975; Armstrong *et al.*, 1991; Parkinson, 1991). Partial melting and granite emplacement is mostly Early Tertiary in the Valhalla complex (Carr *et al.*, 1987) but the extent to which Tertiary high-temperature metamorphism has overprinted the Paleoproterozoic rocks is not well constrained in the other complexes (Parkinson, 1991, 1992; Carr, 1992). The core gneisses are unconformably overlain by a thick quartzite horizon and alternating pelitic and psammitic gneisses containing fairly continuous marble and quartzite strata (fig. 4). This sequence, referred to as the mantling or cover gneisses, has been interpreted as a shelf or platform sedimentary sequence correlated with either Lower Paleozoic or Lower Mesozoic formations (Reesor & Moore, 1971; Read, 1980; Brown, 1980; Read & Brown, 1981; Okulitch, 1984; Scammel & Brown, 1990; Carr, 1991b, 1992). The polyphased

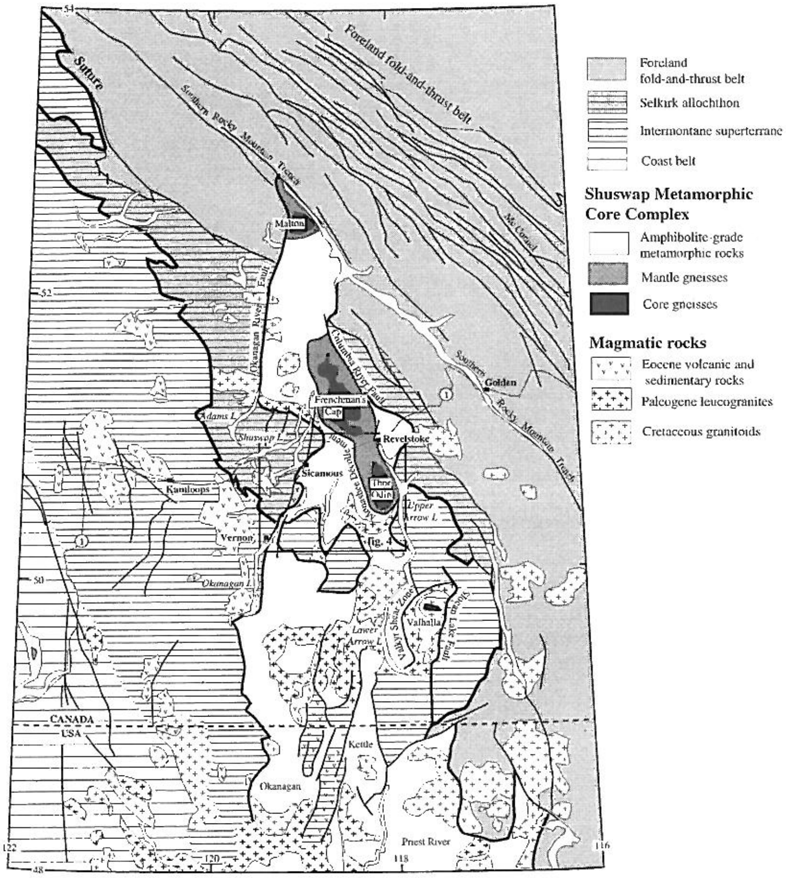


Fig. 3. – **Geologic map of the Shuswap metamorphic core complex (After Wheeler & McFeely, 1991).** East of the suture, the North American craton is overthrusted by sedimentary sequences deposited on the paleomargin and forming the foreland belt and the Selkirk allochthon. West of the suture, the Intermontane superterrane is composed of amalgamated units of oceanic and magmatic arc affinities. The high-grade rocks of the Shuswap metamorphic core complex are exhumed below outward dipping detachments.

Fig. 3. – ***Carte géologique du complexe métamorphique du Shuswap (d'après Wheeler & McFeely, 1991).*** *A l'est de la suture, le craton nord-américain est chevauché par les séries sédimentaires de la paléomarge qui constituent la chaîne d'avant-pays ainsi que les unités allochtones du Selkirk. A l'ouest de la suture, le "Superterrane Intermontane" est composé d'unités à affinités océaniques ou d'arcs magmatiques. Les roches métamorphiques du Shuswap sont exhumées sous les détachements délimitant le complexe métamorphique.*

deformation affecting the basement gneisses and resulting in overturning of the cover gneisses has been described has mantled-gneiss domes related to the buoyant rise of the core gneisses (Reesor & Moore, 1971). In contrast, the formation of dome-shaped culminations has been attributed to fold interferences following an episode of large-scale nappe formation (Read, 1980; Raeside & Simony, 1983; Duncan, 1984).

The Monashee décollement and the Selkirk allochthon

The parautochthonous basement is truncated by the Monashee décollement which wraps around the Monashee complex (fig. 3). The Monashee décollement has been interpreted as a thrust responsible for the displacement of the Selkirk allochthon, also referred to as the Kootenay terrane, towards the NE over the Monashee complex (e.g. Brown, 1980; Duncan, 1984; Brown *et al.*, 1986; Price, 1986). The Selkirk allochthon is composed of an overturned sedimentary sequence comprising discontinuous layers of an amphibolite-facies assemblage of pelite, psammite, calc-silicate, marble, amphibolite, and quartzite, which are part of a large scale east-verging nappe structure (Reesor & Moore, 1971; Raeside & Simony, 1983; Duncan, 1984; Scammel & Brown, 1991; Crowley & Brown, 1994; McNicoll & Brown, 1995). At the latitude of the Thor-Odin dome, the Monashee décollement corresponds to a diffuse shear zone and the stratigraphic correlation between the Selkirk allochthon and the basement gneisses are not well constrained.

The major detachments, the upper crustal units, and Paleogene sedimentary basins

The basement gneisses and the Selkirk allochthon appear in a tectonic window delineated by outward dipping detachment faults at the contact with upper crustal units. The major detachments are oblique to the suture between ancient North America and accreted terranes (figs. 3 & 4). The west-dipping Okanagan fault system comprises high-angle normal faults merging into a major low-angle detachment (Tempelman-Kluit & Parkinson, 1986). To the east, the significance of the major shear zones is more controversial. At the latitude of the Monashee complex, the high-angle Columbia River fault truncates the major fabric of the high-grade metamorphic rocks and a mylonitic shear zone attributed to the Monashee décollement (Lane, 1984; Brown & Jour-

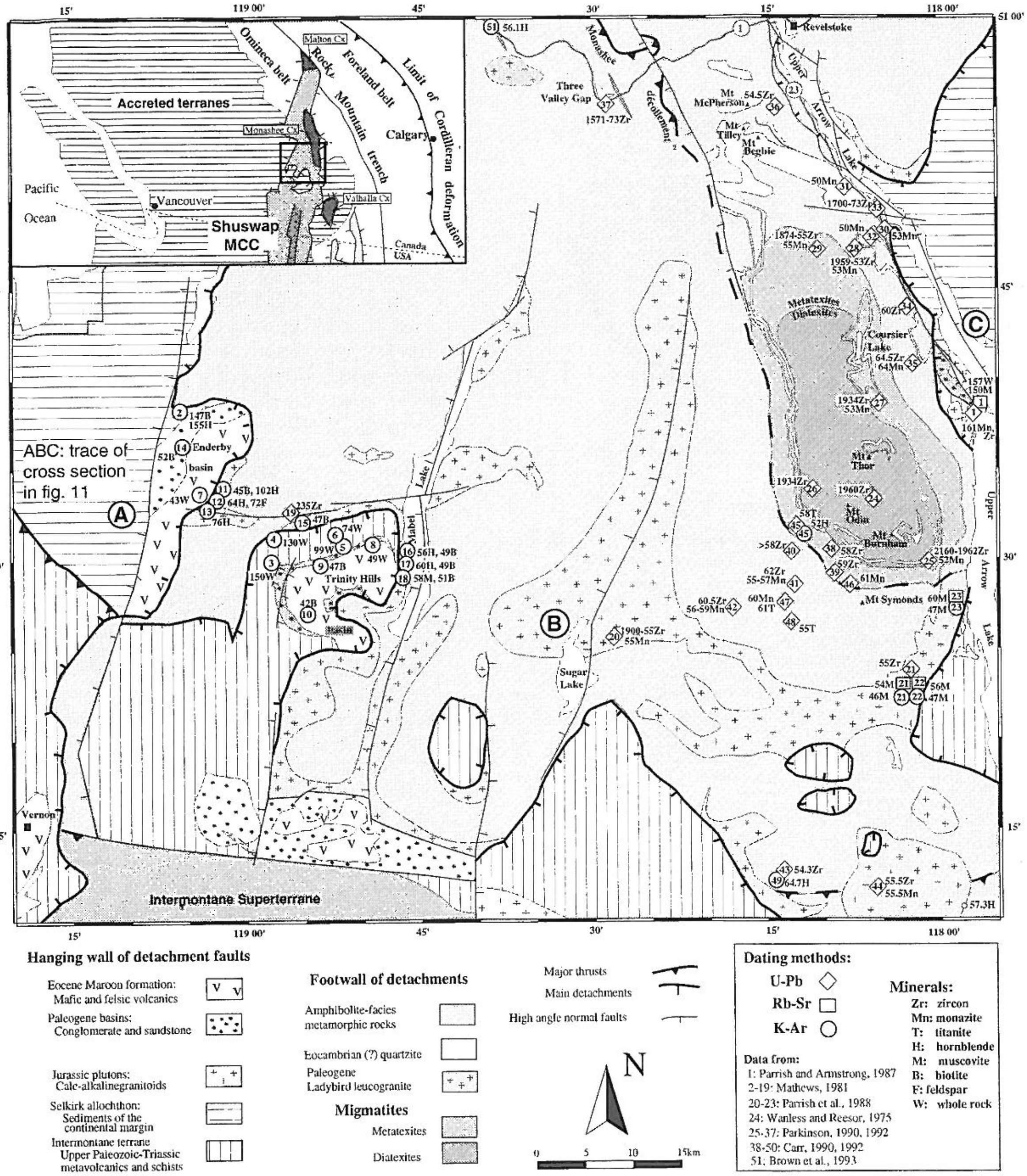


Fig. 4. – **Geologic map of the Shuswap metamorphic core complex at the latitude of the Thor-Odin dome, and summary of published geochronological data (Carr, 1990, 1992; Mathews, 1981; Parkinson, 1991, 1992; Parrish *et al.*, 1988, Parrish & Armstrong, 1987; Wanless & Reesor, 1975).** Circles represent sample locations and the numbers in the circle refer to the corresponding publication. A, B and C on section of figure 11.

Fig. 4. – ***Carte géologique du complexe métamorphique du Shuswap à la latitude du dôme de Thor-Odin avec les données géochronologiques existantes.*** *Les cercles représentent la localisation des échantillons et les nombres à l'intérieur renvoient aux publications correspondantes. A, B et C sont les repères de la coupe, figure 11.*

neay, 1987). In contrast, at the latitude of the Valhalla complex, the high-angle Slocan Lake fault truncates the Valkyr shear zone (fig. 3), which is in a similar structural position to the Monashee décollement, but is interpreted as an extensional detachment (Carr *et al.*, 1987; Parrish *et al.*, 1988). In addition to the normal component, some high-angle faults, such as the Rocky Mountain Trench, recorded dextral strike-slip motion during

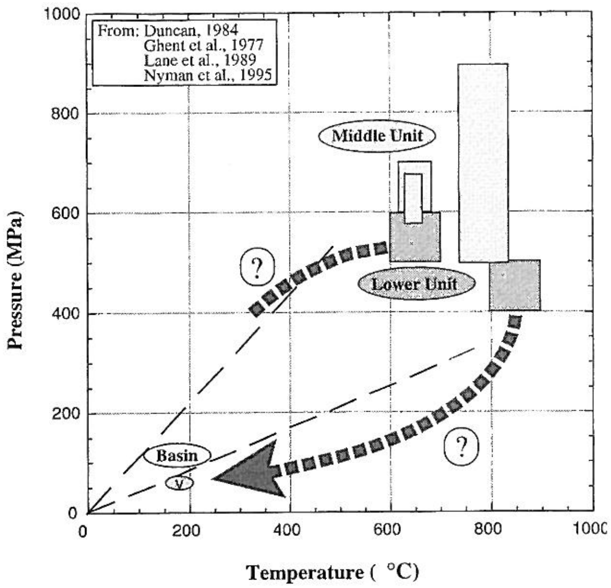


Fig. 5. – **Pressure and Temperature evolution of the Shuswap metamorphic core complex.** Metamorphic assemblages preserved in the high-grade rocks (middle and lower units), at the latitude of the Thor-Odin dome, indicate a high thermal peak (each box represents one pressure and temperature estimate and the size of the box corresponds to the uncertainty). The pressure and temperature at the base of the Trinity Hills basin is constrained by the vitrinite reflectance of coal-bearing sediments, that were buried at depth of about 2-3 km and indicate a temperature of about 175°C; see text for original references.

Fig. 5. – ***Évolution pression-température du complexe métamorphique du Shuswap.*** *Les assemblages métamorphiques, à la latitude du dôme de Thor-Odin, indiquent un pic à haute température (chaque rectangle correspond à une estimation avec sa marge d'approximation). Le coefficient de réflectance de la vitrinite obtenu sur des sédiments enfouis à approximativement 2-3 km, indique une température de 175°C à la base du bassin à Trinity Hills (voir texte pour les références.*

Cretaceous and early Tertiary time (Ewing, 1981; Van den Driessche & Maluski, 1986; Struik, 1993).

The upper crustal units are overlain by early Tertiary sedimentary basins filled with several hundred to thousand meters-thick immature, coarse, and volcaniclastic fanglomerates, and slide blocks of the metamorphic basement including quartzite and granite-gneisses. The basin fill is capped by early Eocene volcanics of the Maroon Formation (Mathews, 1981; Tempelman-Kluit & Parkinson, 1986).

Metamorphism

Petrographic analysis of the high-grade rocks of the Shuswap MCC indicates widespread occurrence of synkinematic sillimanite after kyanite and roughly concentric distribution of isograds around the domes cored by the basement gneisses (Reesor & Moore, 1971; Read & Brown, 1981; Okulitch, 1984; Carr, 1992). In the northern part of the Monashee complex (Frenchman's cap dome) Journeay and Brown (1986) described leucosomes derived from partial melting, in the kyanite-garnet-biotite zone just below the Monashee décollement indicating a pressure of 6.4-7.1 kbar, and temperature of 640-680°C. In the Thor-Odin dome, Duncan (1984) described a first metamorphic event defined by the reactions (1) kyanite + gedrite + quartz = cordierite; and (2) gedrite + kyanite = cordierite + corundum, corresponding to pressures of 5-6 kbar and temperatures of 600°-700°C, followed by decompression to 4-5 kbar at a temperature of 700°C inferred from the absence of staurolite and the reaction sillimanite + biotite = garnet + cordierite + alkali feldspar (fig. 5).

At Three Valley Gap, to the west of the Monashee complex, a boudin of garnet-plagioclase-hornblende amphibolite within a sillimanite-biotite pelitic gneiss indicates metamorphic conditions of 620-685°C and 6-7 kbar (fig. 5) (Ghent *et al.*, 1977). In the vicinity of this locality, pelitic gneisses yield another estimate of 720-820°C and 7.5-9 kbar (fig. 5) (Nyman *et al.*, 1994). Similar metamorphic conditions are inferred for the region north of the Frenchman's cap dome, with 700°C and 7.5 kbar (Sevigny *et al.*, 1989), and near Revelstoke, with about 700°C and 6 kbar (fig. 5) (Lane *et al.*, 1989). This metamorphic event has been related to the Late Cretaceous early Tertiary evolution of the Cordillera based on geochronologic studies (Parkinson, 1991; Carr, 1992).

Metamorphism of the hanging wall in the detachments is commonly in the greenschist facies and reaches the amphibolite facies around Jurassic plutons (Carr, 1991b, 1992). These features are interpreted in terms of burial and contact metamorphism during the Jurassic history of the Cordillera (Monger *et al.*, 1982; Brown & Journeay, 1987; Carr, 1992). The early Tertiary sedimentary basins do not show any trace of metamorphism besides the high thermal gradient reflected by elevated vitrinite reflectance values in coal-bearing sediments (Ro = 1.16; Mathews, 1981). This value indicates that the temperature at the base of the basin was 150°C for a duration of 45 Ma, or reached 200°C for a few million years (fig. 5) (Mathews, 1981), suggesting an elevated geothermal gradient.

In summary, the Shuswap MCC comprises a zone of high-grade synkinematic regional metamorphism overlain above the major detachments by a zone of pre-kinematic low-grade metamorphism. The metamorphic assemblages of the high-grade rocks indicate a high-temperature metamorphism followed by decompression.

Isotopic data

Magmatic events

Previous geochronologic studies on the Shuswap MCC indicate a wide range of ages (fig. 4). The age of the basement gneisses has been debated and it is not clear how far the Precambrian basement extends to the west underneath the Cordilleran region. A Precambrian basement in the Shuswap MCC is demonstrated by U-Pb analysis on zircon and Rb-Sr isochrons, indicating detrital zircons of ca 2.2 Ga in paragneisses (Parkinson, 1991), and yielding ages from 1.87 Ga to 2.10 Ga for orthogneisses (Wanless & Reesor, 1975; Parkinson, 1991; Armstrong *et al.*, 1991). However, the zircons show discordant ages with lower intercepts ranging from 175 Ma to 49 Ma indicating one or more events of lead loss during Mesozoic or Paleogene time.

The hanging wall of the major detachments contains Jurassic, mantle-derived batholiths intrusive in the Slide Mountain terrane (Woodsworth *et al.*, 1991; Roback *et al.*, 1994). These batholiths mark the period of subduction and building of a magmatic arc off-shore of the North-American continent. At the latitude of the Thor-Odin dome it is represented by the Kuskanax and Spruce Groove batholiths dated by U-Pb on zircon at 173-174 Ma (Parrish & Wheeler, 1983; Carr, 1991a) and by the Galena Bay stock dated by U-Pb on zircon and monazite at 161 Ma (Parrish & Armstrong, 1987).

Two periods of crustal anatexis followed the accretion of allochthonous terranes. The first one occurred during Cretaceous time and is characterised by the intrusion of peraluminous granites in the different units of the Shuswap MCC. To the east of the Monashee complex, the Selkirk allochthon is intruded by several plutons yielding Rb-Sr isochrons ranging from 115 to 106 Ma (Brandon & Lambert, 1993). To the north of the Monashee complex, synkinematic granitic sheets yield an U-Pb age of 100.4+/-0.3 Ma on zircon, and 99+/-1.0 Ma on monazite (Sevigny *et al.*, 1990).

The second period of anatexis is marked by emplacement of leucogranites of the Ladybird suite and associated pegmatites. On the southern flank of the Thor-Odin dome leucogranites yield U-Pb ages on zircons from 60.5 to 55 Ma, and slightly younger ages on monazites (Carr, 1992). The same leucogranite deformed in the Columbia River fault has zircon ages of 55 Ma, Rb-Sr cooling ages on muscovite-K-feldspar of 54-56 Ma, and K-Ar cooling ages on muscovite of 46-47 Ma (Parrish *et al.*, 1988). Pegmatites intrusive in the amphibolite-facies Selkirk allochthon yield U-Pb ages between 62-55 Ma on zircons and 61-51 Ma on monazites (fig. 4). Dating of pegmatite bodies intrusive on the west side of the Monashee complex indicates that the Monashee décollement was still active at 62 Ma, but motion ended before 58 Ma (Carr, 1992). This range of ages encompasses the age of zircons from a leucosome of the southern flank of the Thor-Odin dome of 59+/-0.3 Ma (Carr, 1992). The migmatitic basement gneisses contain significantly younger pegmatites than the overlying amphibolite-facies units, with U-Pb ages ranging from 52 Ma to 50 Ma on zircons and from 55 Ma to 49.8 Ma on monazite (Parkinson, 1992).

These two periods of crustal anatexis are associated with the regional high-temperature metamorphism affecting the Shuswap MCC. To the north of the Monashee complex, high initial $^{87}Sr/^{86}Sr$ ratios (0.71492-0.74181) and evidence of Precambrian Pb inheritance indicates a crustal source (Sevigny *et al.*, 1989). Furthermore, REE patterns of the peraluminous granites suggest that they could have been generated by partial melting of the metapelites found in the Selkirk allochthon and in the basement gneisses (Sevigny *et al.*, 1989).

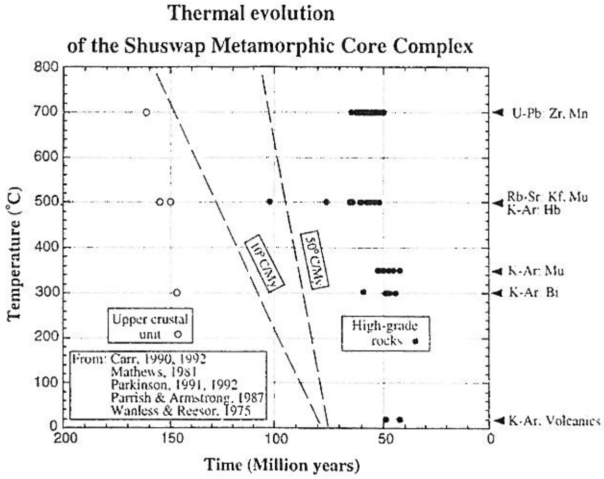


Fig. 6. – **Temperature-time paths of the Shuswap metamorphic core complex.** The thermal evolution at the latitude of the Thor-Odin dome is determined from the closure temperature of the U-Pb system in zircon (Zr) and monazite (Mn), the Rb-Sr system on white mica (Mu), and the K-Ar system in hornblende (H), white mica (Mu), and biotite (BI). The ages of the basins is constrained by the age of the volcanics that are capping the sediments. The lines corresponding to cooling rates of 10°C/My and 50°C/My are given for comparison.

Fig. 6. – ***Évolution température-temps du complexe métamorphique du Shuswap.*** *A la latitude de Thor-Odin, l'évolution thermique est contrainte par les températures de fermeture des systèmes U-Pb sur zircon (Zr) et monazite (Mn), Rb-Sr sur mica blanc (Mu), et K-Ar sur hornblende (H), mica blanc (Mu) et biotite (BI). L'âge des bassins Tertiaires est contraint par l'âge des roches volcaniques qui les recoupent et recouvrent les sédiments. Pour référence, les droites indiquant les taux de refroidissement de 10°C/My et 50°C/My sont représentées.*

Cooling ages

Cooling ages obtained from K-Ar dating of hornblende, white mica, and biotite distinguish the thermal evolution of rocks above and below the detachments (figs. 4 & 6). Phyllitic rocks in the hanging wall show cooling ages of 155 Ma on hornblende and 147 Ma on biotite (Mathews, 1981), similar to the 161 Ma age on zircon and monazite of the Galena Bay stock (Parrish & Armstrong, 1987) and the 173-174 Ma age on zircon of the Kuskanax and Spruce Groove batholiths (Parrish & Wheeler, 1983; Carr, 1991a). Below the detachment, in the western part of the MCC, K-Ar cooling ages in gneisses of the amphibolite-facies unit range from 102 Ma to 52 Ma on hornblende, and 52 Ma to 44 Ma on biotite (Mathews, 1981). Volcanics that are capping the Paleogene sediments deposited on the hanging wall of the detachments yield 42-47 Ma (K-Ar on biotite) and 49 Ma ages (whole rock K-Ar, Mathews, 1981). For instance, the Trinity Hills basin lies directly above amphibolite-grade gneisses that yield K-Ar hornblende ages of 56-60 Ma, biotite ages of 49-57 Ma, and a muscovite age of 58 Ma. The volcanics that crosscut and overlie this basin indicate K-Ar ages of 47-49 Ma (Mathews, 1981), a minimum age at which the metamorphic rocks were at, or near, the surface. These data indicate high cooling rates, on the order of 30-50°C/Ma, for the footwall of the detachments at the Paleocene-Eocene transition.

Summary

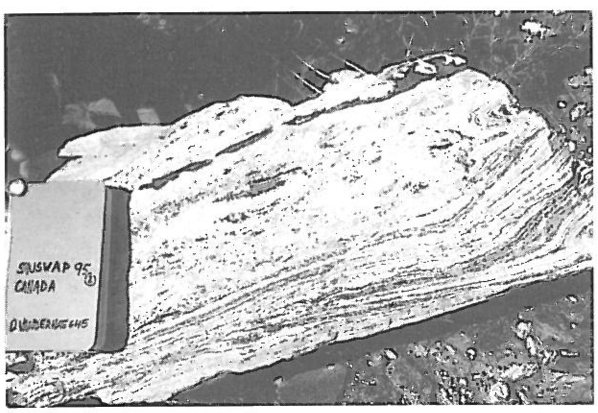
Crustal thickening of the Canadian Cordillera is inferred from the metamorphic conditions recorded in the high-grade rocks of the Shuswap MCC, which indicate a minimum burial of ~ 20-30 km. Crustal shortening was achieved by the formation of nappes and large-scale thrusting. The high-grade rocks of the Shuswap MCC are affected by widespread high-temperature/low-pressure metamorphism, and partial melting of the fertile Paleoproterozoic and Paleozoic metapelites, which provides a source for the leucogranites and pegmatites intruding the sequence at about 115 Ma and during the early Tertiary from 60 to 50 Ma. Metamorphic assemblages of the high-grade rocks indicate that the thermal peak was followed by decompression. Thermochronologic data suggest subsequent fast cooling rates at the Paleocene-Eocene boundary (on the order of 30-50°C/Ma).

STRUCTURAL ANALYSIS

Previous structural analysis in the Shuswap MCC has focused on the description of different generations of folds and shear zones attributed to the contractional event. Alternatively, although crustal shortening certainly occurred, our structural analysis from the migmatitic core to the detachments suggests that the major fabric of the high-grade rocks formed during collapse of the orogen while the middle crust was partially molten.

In the Shuswap MCC the transition from ductile foliation in the migmatites to ductile-brittle structures in the detachments is exposed within a few kilometres of

A



B

C

Fig. 7. – **Migmatites of the Thor-Odin dome.** A) metatexite, from the eastern flank of the Thor-Odin dome along Pingston Creek, exhibit a synmigmatitic layering delineated by the alternations of continuous melanosomes and leucosomes. Leucosomes are localised in inter-boudins and shear zones. B) Outcrop-scale metatexite-diatexite transition along Odin road on the eastern flank of the Thor-Odin dome. The synmigmatitic layering is marked by continuous alternations of melanosomes and leucosomes in metatexites, and by discontinuous schlieren in diatexites. C) diatexite with a contorted fabric marked by the alignments of biotite and xenoliths.

Fig. 7. – ***Migmatites du dôme de Thor-Odin.*** *A) Les métatexites du flanc est, le long de Pingston Creek, sont caractérisées par un litage syn-migmatitique souligné par l'alternance régulière de niveaux continus de mélanosomes et de leucosomes. Les leucosomes se localisent également dans les inter-boudins et zones de cisaillement; B) transition métatexite-diatexite à l'échelle de l'affleurement sur le flanc est du dôme; le litage syn-migmatitique est marqué par des schlieren discontinus dans les diatexites; C) diatexite avec une fabrique plissée, marquée par des alignements de biotite et des xénolites étirés.*

structural section. We distinguish three superposed structural units that reflect the tectonic history during late-orogenic collapse, based on structural analysis at the latitude of the Thor-Odin dome (fig. 4, 10 &11). The lower unit is composed of migmatitic gneisses whose protolith corresponds to both core and cover of the so-called "parautochthonous basement gneisses" described above. The middle unit comprises rocks of the previously described cover gneisses and of the Selkirk allochthon and is characterised by widespread intrusion of pegmatites and leucogranites. The migmatites of the lower unit are intrusive in the middle unit, forming domes delineated by the general foliation pattern. The upper crustal unit corresponds to the hanging wall of the major detachments.

Migmatitic lower unit

Diatexite-metatexite transition

The lower structural level of the Shuswap MCC appears in dome-shaped culminations composed of migmatized Paleoproterozoic protolith. Structural analysis of the Thor-Odin dome reveals that migmatites are composed of diatexites surrounded by metatexites. Metatexites (fig. 7A) are characterised by a continuous solid framework containing leucosomes, whereas diatexites (fig. 7B & C) are dominated by the granitic melt fraction (>50%) in which the solid is represented by discontinuous schlieren, restites, and xenoliths (Mehnert, 1968; Burg & Vanderhaeghe, 1993). The mapped diatexite-metatexite transition crosscuts the stratigraphic sequence as illustrated by its relationship with the basal quartzite (fig. 4, 10 &11) . Therefore, we consider that the diatexites of the Shuswap MCC moved "en masse" with respect to metatexites, leading to the upwelling of the diatexites and the formation of domes.

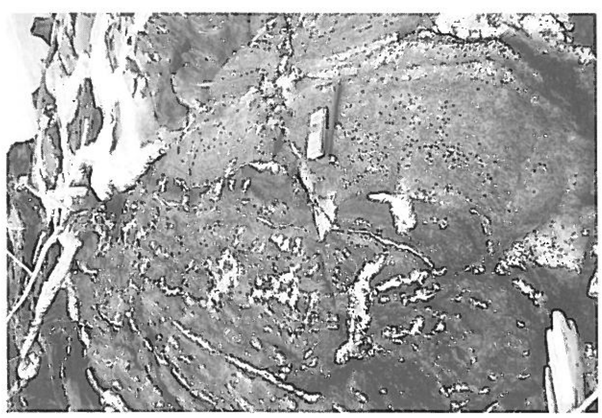
Syn-migmatitic layering: melt migration and deformation

The major fabric in the diatexites is defined by the orientation of schlieren and xenoliths and by the alignment of biotite grains. The granitic fraction shows only weak overprinting by plastic deformation of individual grains, suggesting that the layering of the diatexites records dominantly a "magmatic" fabric (fig. 7 B & C).

The metatexites lying directly above the diatexites of the Thor-Odin dome are characterised by a sequence of regularly spaced leucosomes surrounded by melanosomes and mesosomes (fig. 7A & B). We interpret these alternations to represent "in situ" melt segregation. The leucosomes commonly exhibit an igneous texture characterised by interlocked grain boundaries, untwinned euhedral K-feldspar phenocrysts, sub-idioblastic biotite and white mica grains, and myrmekitic intergrowth of quartz and feldspar. This texture is only weakly overprinted by plastic deformation and recrystallisation of individual grains.

The major foliation of the diatexites and metatexites, which we refer to as syn-migmatitic layering, is a combination of deformation at the magmatic stage, melt segregation and sub-solidus overprinting. At higher crustal level, migmatitic metapelites preserved a compositional foliation representing a transposed sedimentary bedding. In this unit the abundance and distribution of quartzo-feldspathic pods, veins, and layers (leucosomes) is directly related to the fertility of the protolith.

A



B

Fig. 8. – **Synmigmatitic way-up criteria along the Columbia River.** A) cauliflowers (incipient diapiric structures) developed on a centimetre scale at the top of leucosome layers (arrow), indicating right way up. The criteria indicate a right way-up in the eastern flank of the dome. B) asymmetric vein clusters interpreted as trapping of melt at the base of an impermeable amphibolite layer, indicating way up (arrow).

Fig. 8. – ***Critères de polarité syn-migmatitiques le long de la Columbia River.*** *Le haut est indiqué par les flèches; A) choux-fleurs correspondant à du micro-diapirisme à l'interface supérieure des niveaux de leucosomes. Ces critères indiquent que les migmatites sont en position normale ; B) distribution asymétrique des veines granitiques interprétées comme des accumulations de magma à la base de niveaux imperméables d'amphibolite.*

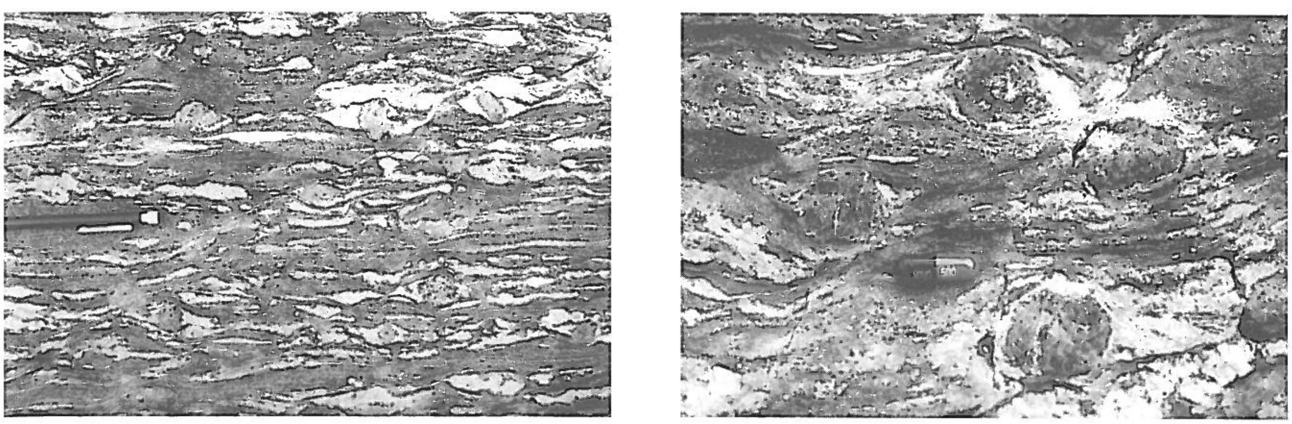
Within the migmatite, the melt fraction is concentrated in low-pressure zones provided by dilatant structures affecting the syn-migmatitic layering, such as inter-boudins, indicating dilation along two conjugate directions with respect to the lineation (fig. 7A, 8A & 9; chocolate tablet structure, Ramsay & Huber, 1983). Asymmetry of the boudins indicates a normal sense of shear. These relations indicate that partial melting was coeval with the acquisition of the major fabric.

Synmigmatitic way-up criteria

The metatexites surrounding the dome show syn-migmatitic way-up criteria, which are based upon the asymmetric distribution of leucosomes, assuming that the less dense and less viscous melt tends, on average, to migrate upward (Burg, 1991; Burg & Vanderhaeghe, 1993). The criteria include (1) cauliflowers that represent incipient diapirism on a centimetre to meter scale; (2) asymmetric vein clusters that are due to the trapping of melt at the base of an impermeable layer; and (3) branching fractures, filled with granitic material, that tend to propagate upward. Asymmetric vein clusters (fig. 8B) are common beneath amphibolite layers, and cauliflowers (fig. 8A) are observed even in the high-grade, mylonitic gneisses along the eastern side of the Monashee complex (fig. 4). These criteria all indicate a right way-up sequence on the eastern side of the Thor-Odin dome and an outward tilting of the flanks of the dome. Since the Thor-Odin dome has been described as an overturned sequence (Reesor & Moore, 1971; Duncan, 1984), the synmigmatitic way-up criteria suggest that partial melting and doming post-dated the formation of large-scale fold nappes.

The ductile fabric of the amphibolite-facies middle unit

Above the migmatites of the basement gneisses, isoclinal folding and transposition of the sedimentary bedding of amphibolite-facies metasedimentary units resulted in the formation of a major flat-lying foliation (fig. 10; Reesor & Moore, 1971; Raeside & Simony, 1983; Duncan, 1984). Most of the folds appear to be sheath folds with curvilinear axes. The major foliation carries a NE to E trending lineation defined by the alignment of biotite, the preferred orientation of fibrous and prismatic sillimanite, and quartz ribbons. Kinematic criteria, such as delta and sigma crystallisation tails (Passchier & Simpson, 1986), C/S structures (Berthé et al., 1979), shear bands, and asymmetric boudinage (Hanmer, 1990) indicate variable sense of shear throughout the MCC. The eastern side of the MCC is marked by east-side-down sense of shear, whereas the western side is marked by west-side-down sense of shear. In metapelites, garnet porphyroblasts are commonly transected by fractures oriented perpendicular to the foliation (fig. 9). These fractures and pressure shadows around garnets are filled by quartzo-feldspathic granitic material, indicating that melt migration occurred during bulk coaxial deformation. In general, the proportion of criteria representing non-coaxial deformation decreases down section. This crustal level is also characterised by widespread intrusion of foliation-parallel granitic sheets connected by cross-cutting dikes. Map-scale relations



A **B**

Fig. 9. – **Metapelites from the amphibolite-grade cover to the south of the migmatite Thor-Odin dome (Mt. Symonds).** The foliation is delineated by preferred orientation of biotite and large acicular sillimanite crystals. Leucosomes with magmatic textures are preserved in pressure shadows around garnets. Garnets are fractured perpendicular to the foliation, and the fractures contain granitic material and sillimanite. A) Normal shear zone affecting the foliation and causing rotation of the garnets. B) Close view of the fractured garnets with sillimanite in the foliation and within the fractures.

Fig. 9. – ***Métapélites de la couverture en faciès amphibolite au sud du dôme de Thor-Odin (Mt Symonds).*** *La foliation et la linéation sont soulignées par l'allongement de biotite et sillimanite. Des leucosomes à texture magmatique sont préservés dans les ombres de pression autour des grenats. Les grenats sont affectés par des fractures subperpendiculaires à la foliation, et contenant des veines granitiques et de la sillimanite. A) zone de cisaillement normale affectant la foliation et causant la rotation des grenats; B) grenat fracturé, avec de la sillimanite dans la foliation et les fractures.*

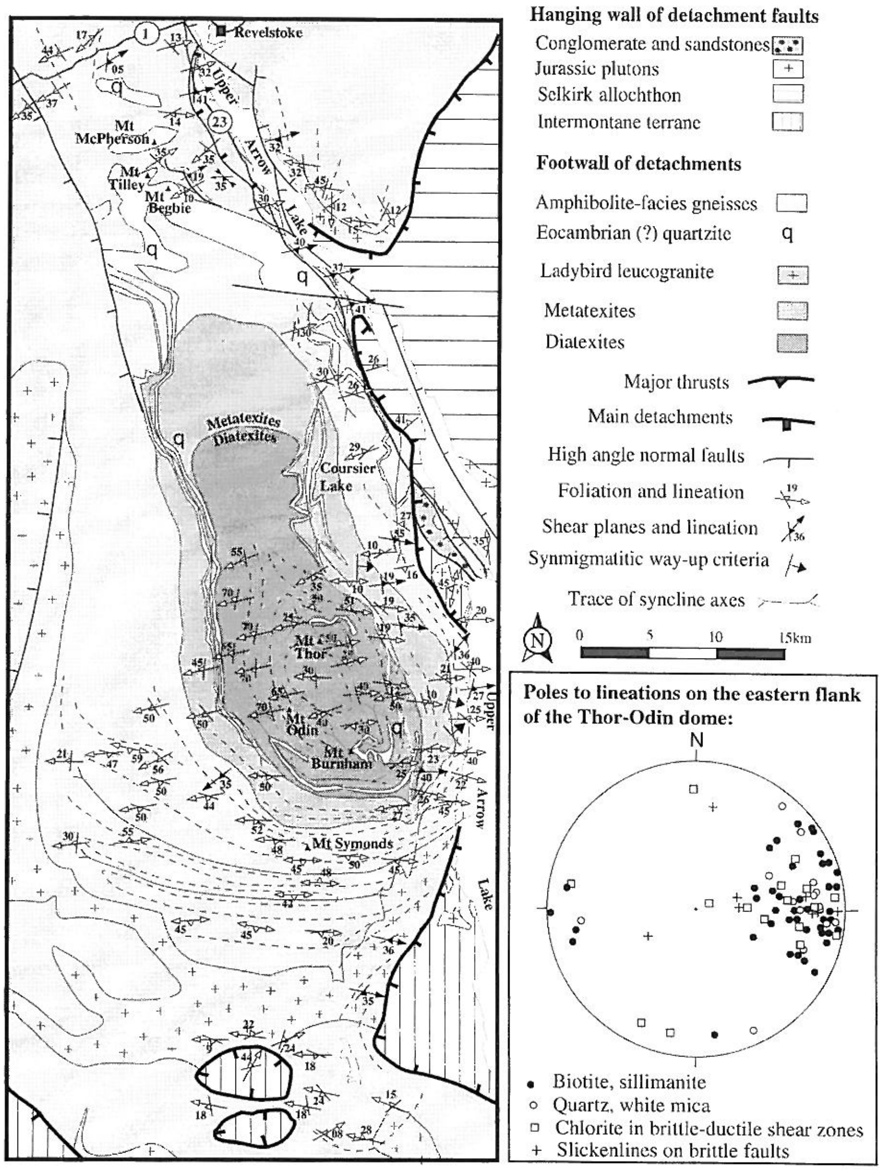


Fig. 10. – **Structural map of the Thor-Odin dome (based partly on previous work by Carr, 1991b, 1992; Duncan, 1984; Read, 1980; and Reesor and Moore, 1971).** The dome is delineated by the foliation pattern and the curvilinear shape of fold axes and of the Ladybird leucogranite. Note the E-W attitude of lineations throughout the dome. An equal area, lower hemisphere stereogram of lineations in the eastern flank of the Thor-Odin dome shows the consistency in orientation of lineations defined by (1) biotite-sillimanite; (2) quartz-white mica; (3) chlorite in brittle-ductile shear zones; (4) slickenlines on brittle faults. Sense of shear associated with these lineations is consistently outward (normal) relative to the Thor-Odin dome.

Fig. 10. – ***Carte structurale du dôme de Thor-Odin (en partie basée sur le travail de Carr, 1990, 1991, 1992; Duncan, 1984; Read, 1980; Reesor & Moore, 1971).*** *Le dôme est souligné par les trajectoires de foliation, par des axes de plis courbes et par la virgation du leucogranite Ladybird. La linéation est orientée est-ouest sur l'ensemble du dôme. Un diagramme stéréonet de Schmidt, hémisphère inférieure, montre la cohérence des orientations de linéations développées en conditions ductiles jusqu'à la fracturation. Les critères cinématiques associés à ces linéations indiquent un cisaillement uniformément normal, de part et d'autre du complexe métamorphique.*

suggest that this granitic network originated in the migmatitic unit and fed larger leucogranite laccoliths (several hundred meters thick) that accumulated below the major detachments (fig. 4 & 11).

Transition middle unit - detachments

The syn-migmatitic layering and the foliation of the amphibolite-facies cover are concordant and delineate the shape of the domes. These fabrics grade upward into mylonite and cataclasite zones which define the detachments. Mineral lineations defined by sillimanite and biotite in the gneissic foliation of the basement gneisses, stretching lineations in mylonites, and slickenlines on brittle faults are all collinear and oriented approximately E-W (fig. 10). For example, on the eastern side of the MCC, within a few kilometres, the footwall of the Columbia River fault displays a gradual progression from migmatites with leucosomes localised in east-side-down shear zones, through a sequence of amphibolite facies rocks with a strong foliation and sheath folds, to a few hundred meters thick greenschist-facies mylonites and cataclasites showing east-side-down sense of shear. We interpret these fabrics to have been juxtaposed during the same deformation event, and because

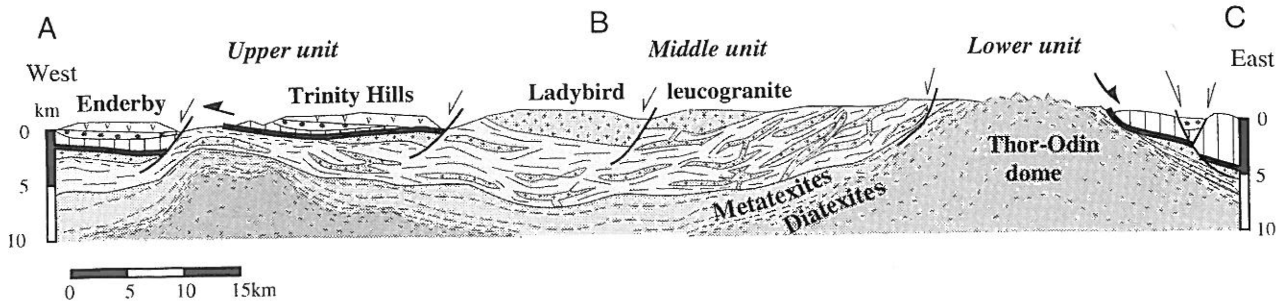


Fig. 11. – **E-W cross section of the Shuswap metamorphic core complex.** The lower migmatitic unit intrudes the amphibolite-grade middle unit. The middle unit is permeated by a network of granitic dikes and sills that are connected to the Ladybird leucogranite localised below the major detachment. The dashed lines represent the attitude of the foliation and of the synmigmatitic layering. Above detachment (thick line), thin plate of allochthonous terrane is overlain by Paleogene sedimentary basins and volcanic rocks. A, B and C located figure 4.

Fig. 11. – ***Coupe est-ouest du complexe métamorphique du Shuswap.*** *L'unité inférieure migmatitique est intrusive dans l'unité médiane de faciès amphibolite. L'unité médiane est traversée par un réseau de filons granitiques connectés au granite Ladybird qui est localisé sous les détachements majeurs. Les tirets représentent les trajectoires de foliation et le litage syn-migmatitique. Au-dessus des détachements (traits épais) une lame fine de terranes allochtones est recouverte de bassins sédimentaires et roches volcaniques paléogènes. A, B et C situés sur figure 4.*

they developed under widely different metamorphic conditions, we propose that they accommodated crustal attenuation. In addition, the detachment exhibits a progressive overprinting of ductile fabrics by brittle structures indicating decreasing metamorphic conditions during deformation. In this region, the major fabric of the Slide mountain (intermontane) terrane, in the hanging wall of the detachment, is discordant with the fabric of the footwall. In particular, the hornblende mineral lineation is N-S trending (fig. 10).

Summary

Based on this structural analysis, we propose that partial melting, upwelling of the Thor-Odin migmatite dome, formation of the major foliation in the migmatites and in the amphibolitic cover, are synchronous and overlap with the early Tertiary extension along the Columbia River fault. This hypothesis is supported by the fact that the Paleocene (~60 Ma) Ladybird leucogranite wraps around the Thor-Odin dome, indicating that the granite was probably deformed during the formation of the dome.

Within this crustal section, melt migrated from the migmatitic core to the detachment through a network of granitic sills and dikes. Diapiric upwelling of the buoyant diatexites was facilitated by extension of the upper crust. However, if the rise of the migmatites was only controlled by the presence of detachments, they should form long anticlines. The domal shape of the migmatites suggests a significant role of diapirism.

DISCUSSION

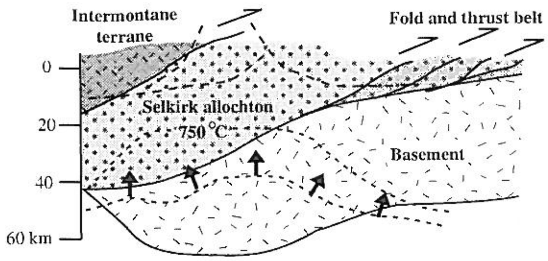
Geologic and tectonic evolution of the Canadian Cordillera

Crustal thickening

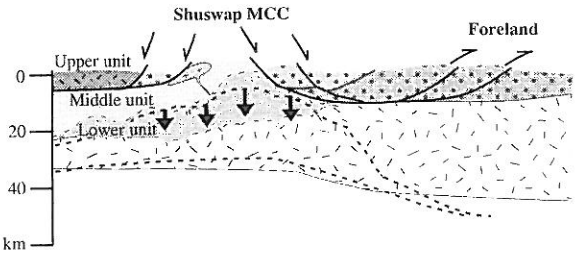
The Canadian Cordillera, and more specifically the Omineca belt, was a zone of thickened crust before the early Tertiary extension as indicated by the metamorphic conditions recorded in the high-grade rocks of the Shuswap MCC (fig. 12). The inferred crustal thickness before extension is on the order of 50-60 km, which is consistent with the palinspastic reconstruction of the Cordillera (Coney & Harms, 1984) and is comparable to the current thickness of modern mountain belts. Crustal thickening occurred in response to accretion of terranes to the margin of ancient North America , and was accommodated by large scale thrusting and nappe structures. The timing of crustal thickening and contraction is indirectly constrained. The deposition of late Early Jurassic marine sediments on the shore of ancient North America gives a limit for the onset of accretion (Monger, 1984).

Thermal relaxation

Thermal relaxation following crustal thickening caused widespread high-temperature/low-pressure metamorphism, and partial melting of the fertile Paleoproterozoic and Paleozoic metapelites (fig. 12; Sevigny *et al.*, 1989, 1990; Brandon & Lambert, 1993), providing a source for the leucogranites and pegmatites, and



a) Mid to late Cretaceous:
Crustal thickening followed by thermal relaxation and partial melting



b) Paleogene:
Late-orogenic collapse: Brittle extension of the upper crust and thrusting in the foreland; ductile thinning of the lower crust and formation of migmatite domes.

Fig. 12. – **Schematic cross sections of the evolution of the internal zones of the Canadian Cordillera which resulted in the development of the Shuswap metamorphic core complex during late-orogenic collapse.** a) During Mid- to late Cretaceous time, the accretion of allochthonous terranes and overthrusting of sediments from the paleomargin causes crustal thickening and the formation of a crustal welt. Crustal thickening is followed by thermal relaxation illustrated by the upwelling o the 750°C isotherm, delineating the onset of partial melting of fertile metapelites. b) Late-orogenic collapse during Paleogene time is accommodated by (1) brittle extension of the upper crust, and lateral sliding of upper crustal units correlated with out-of sequence reactivation of thrusts in the foreland; and by (2) ductile thinning of the mid- to lower crust and formation of migmatite domes. Rapid exhumation of the high-grade rocks is associated with rapid cooling.

Fig.. 12. – ***Coupe schématique montrant l'évolution des zones internes de la Cordillère canadienne dont l'aboutissement correspond à la formation du complexe métamorphique du Shuswap lors de l'effondrement gravitaire tardi-orogénique de la chaîne.*** *a) Au crétacé moyen et supérieur, l'accrétion de terrains allochtones et le chevauchement des séries de la paléomarge causent un épaississement de la croûte, suivi par la relaxation thermique et une remontée de l'isotherme 750°C causant l'initiation de la fusion partielle des métapélites; b) Effondrement gravitaire tardi-orogénique au cours du paléogène accommodé par (1) extension fragile et glissement latéral de la croûte supérieure et réactivation des chevauchements d'avant-pays, et (2) amincissement ductile de la croûte médiane à supérieure accompagné de la formation de dômes migmatitiques. L'exhumation rapide des roches métamorphiques est associée à un refroidissement rapide.*

also explains the formation of migmatites in the lower unit. Crustal anatexis in the Shuswap MCC began at about 115 Ma in the form of peraluminous granites. However, the largest event of crustal anatexis occurred during early Tertiary time from 60 to 50 Ma and was responsible for the Ladybird leucogranite and its pegmatitic equivalents. Our structural analysis suggests that partial melting of the basement gneisses and upwelling of the migmatites are related to this event. Widespread high-temperature/low-pressure metamorphism and partial melting of metapelites are expected after a characteristic time of 30 to 40 My following crustal thickening (England & Thompson, 1984), which is broadly consistent with the time gap observed between the onset of accretion and the inception of crustal anatexis.

Late-orogenic collapse

In the Shuswap MCC, thermochronologic data suggest rapid cooling rates at the Paleocene-Eocene boundary (on the order of 30-50°C/Ma) similar to that documented in other North-American metamorphic core complexes (e.g. Davy *et al.*, 1989; Foster *et al.*, 1993; House & Hodges, 1994; Lee, 1995), in the Aegean region (Gautier *et al.*, 1993; Hetzel *et al.*, 1995), or in Papua New Guinea (Hill *et al.*, 1992; Baldwin *et al.*, 1993). The nearly-isothermal decompression following high-temperature metamorphism and partial melting (fig. 5 & 12) suggests that the exhumation of the high-grade rocks occurred faster than thermal relaxation. Synkinematic assemblages indicate that the major fabric, which we attribute to crustal thinning, formed during the thermal peak. The consistency of kinematic criteria during the evolution of the major detachments from amphibolite- to greenschist-facies, show that deformation was associated with a decrease in the metamorphic conditions and hence probably with exhumation of the high-grade metamorphic rocks. In the Shuswap MCC, exhumation of the high-grade metamorphic rocks occurred in a relatively short time, about 5 My, based on the time gap between the crystallisation of the younger granites in the middle and lower units, and the deposition of similar granite clasts in the basins.

According to these data, collapse of the Canadian Cordillera began in Paleocene time. However, the timing of the transition between contraction and extension is not well constrained. On the scale of the Canadian Cordillera, spatial and temporal relations have recently been established and support a genetic relation between the formation of the Shuswap MCC in the hinterland and the last increments of deformation in the fold and thrust belt. The structural link between the basal detachment of the fold-and-thrust belt and a major shear zone on the eastern side of the Shuswap MCC is apparent on the Lithoprobe seismic reflection lines (Cook *et al.*, 1988; 1992). On the eastern side of the Shuswap MCC the Monashee décollement and the Columbia River detachment are indistinguishable. K-Ar dating of clay minerals grown in fault gouge within the main thrusts of the Canadian fold-and-thrust belt record an early displacement between 96 Ma and 72 Ma, but also support an out-of-sequence reactivation at 53 Ma and 55 Ma (Covey *et al.*, 1994). The latter event correlates with the collapse of the hinterland. Therefore, in contrast to Brown *et al.* (1992), we propose to link the reactivation of the major thrusts of the fold and thrust belt to the late-orogenic extension in the hinterland which provides a solution to the long-standing paradox of simultaneous extension in the hinterland and contraction in the foreland. Accordingly, following the visionary model of Price and Mountjoy (1970), we suggest that the late-stage development of the Canadian Rockies fold-and-thrust belt is related to gravity-driven lateral spreading of the upper crust accommodating the collapse of the internal part of the Canadian Cordillera (fig.1 & 12).

Conceptual kinematic model

In the upper unit, collapse was probably accommodated by brittle normal faults merging in a detachment zone that decoupled the upper crust from the lower crust. At the latitude of the Thor-Odin dome, kinematic analysis indicates that collapse of the belt was essentially symmetrical with two major detachment zones bounding the metamorphic core complex; the Columbia River detachment to the east, and the Okanagan River detachment to the west. Below the detachments, the ductile fabric of the high-grade metamorphic rocks suggests vertical thinning of the lower crust combined with E-W horizontal extension. The formation of migmatite domes during extension was caused by the combined effects of crustal-scale boudinage and diapiric upwelling of the partially molten layer. The detachment zone accommodated partitioning of deformation between the brittle, upper crust and the ductile lower crust, and hence, the detachment zone probably reflects the brittle-ductile transition during late-orogenic collapse.

This geometric and kinematic framework is consistent with physical experiments and analytical studies which show that extension of the brittle upper crust is accommodated by ductile flow of the lower crust (fig. 1, 11 & 12; e.g. Gans, 1987; Block & Royden, 1990; Brun *et al.*,1994). The presence in the lower crust of low-viscosity and buoyant bodies, such as partially molten rocks, generates localisation and amplification of extension on selected normal faults in the upper crust. The low-viscosity and buoyant bodies move upward in order to fill the space created by extension of the brittle crust. Upwelling of the ductile lower crust causes roll-over of the footwall of normal faults and warping of the normal faults. Consequently, the finite structure in the models is asymmetric and displays low-angle normal faults, or even apparent thrusts, which are overlying a high-grade, dome-shape, metamorphic core. Overall, the general characteristics of the models fit well the geometric and kinematic framework presented for the Shuswap MCC, with the exception of the detachment faults which developed more symmetrically in the Shuswap MCC.

Role of partial melting during late-orogenic collapse

Many experimental studies have demonstrated that the strength of crustal rocks decreases with increasing temperature (e.g. Brace & Kohlstedt, 1980). In addition, experimental and theoretical work indicate that a drastic strength decrease occurs during partial melting of rocks for a melt fraction of about 30% (Arzi, 1978; Van der Molen & Paterson, 1979; Wickham, 1987). Consequently, if thermal relaxation following crustal thickening results in partial melting of a significant portion of the continental crust, a drastic decrease in its strength is expected.

Our results suggest that partial melting and deformation are synchronous in the region of the Thor-Odin dome (Proterozoic protolith). A qualitative estimation of the granitic fraction at the outcrop scale indicates that within the lower unit, the diatexite migmatitic core is well above 50% of granite, and the metatexites have about 25-40% of leucosomes. The amphibolite-facies cover unit contains commonly about 30-40% of granite, but it can be argued that all this granitic fraction was not melted simultaneously since they form cross cutting veins. The large migmatite domes are spatially related to the major normal faults (like the Columbia River fault) suggesting that a genetic relation exists between dome formation and extension. Although extension of the upper crust may create the room necessary for buoyant, partially molten rocks to rise, the density and viscosity contrast between migmatites and the upper crust may also drive their ascent. If the geometry was entirely controlled by normal faults, then the migmatites should appear in anticlinal culminations, cylindrical along strike. On the contrary, the migmatites appear in domes aligned along the strike of the belt, which is the typical shape of a gravitational instability, suggesting that the buoyancy of the migmatites played a significant role in determining the geometry of the lower unit upwelling. However, similar geometry can potentially result from opening of pull-apart controlled by strike-slip faulting, although the structural analysis does not favour this interpretation.

In addition, the lithologic units of the Shuswap MCC, dominated by clastic sedimentary sequences deposited on a thinned paleomargin, represent fertile protoliths for partial melting (Vielzeuf & Holloway, 1988; Patino Douce & Johnston, 1991). On a larger scale, the North American metamorphic core complexes form a sinuous belt that is spatially related to the zone of thicker continental crust after the Laramide orogeny (Coney & Harms, 1984), but also with the position of the paleomargin of North America (Price, 1981). Melting potentially enhances strain localisation (Hollister & Crawford, 1986; Dell'Angelo & Tullis, 1988). We offer as a hypothesis that large regions of fertile protoliths controlled the location of metamorphic core complexes. Furthermore, leucogranite sheets emplaced at higher levels of the crust may have controlled the localisation of detachment zones.

CONCLUSIONS

(1) Metamorphic and isotopic data in the Shuswap MCC, indicating a high thermal gradient followed by decompression and rapid cooling, are diagnostic of the collapse of a thickened crust.

(2) Structural analysis suggests that the major fabric of the Shuswap MCC formed during this late-orogenic collapse in Paleogene time.

(3) Partial melting of the thick and fertile metapelites in the core of the Shuswap MCC was coeval with ductile thinning and formation of detachments at higher crustal levels which allowed the exhumation of high-grade metamorphic rocks. This temporal and spatial relationship suggests that partial melting caused mechanical weakening of the crust.

(4) Crustal anatexis generated magmatism expressed as a network of granitic sills and dikes emanating from the migmatitic core and feeding larger leucogranite sheets localised along major detachments. These intrusions may have further weakened the higher levels of the crust, enhancing late-orogenic collapse.

(5) Diapiric upwelling of the migmatitic core is a significant mechanism contributing to the exhumation of high-grade rocks in metamorphic core complexes.

The inferred role of partial melting in controlling the initiation and amplification of collapse rests on the spatial and temporal relationships between deformation and partial melting. This relationship argues against the hypothesis of regional extension controlled solely by a shift in plate motion. Future work should focus on the relative timing of extension and basin development between the Shuswap MCC and the terranes further west. The cause of partial melting (whether it is related to thermal relaxation only or is caused in part by other processes such as mantle delamination) cannot be definitely resolved without a precise determination of the timing of mantle delamination with respect to partial melting and late-orogenic collapse.

If the evolution of crustal strength controls the collapse of over-thickened continental crust, then a fundamental mechanical decoupling must exist between the crust and the lithospheric mantle. The forces driving late-orogenic collapse may not be directly controlled by plate motion. We suggest that late-orogenic collapse is related to the decrease in strength associated with significant partial melting of the crust and propose that, after a few tens of million years following crustal thickening, weakening of the lower crust causes mechanical decoupling between the crust and the mantle.

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