Coherent French Range blueschist: Subduction to exhumation in <2.5 m.y.?

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ABSTRACT

Coherent oceanic strata in the French Range belong to the exotic Cache Creek terrane of the Canadian Cordillera. They were metamorphosed to blueschist grade, tectonically extruded, eroded, and intruded by plutons—perhaps in <2.5 m.y. Sodic amphibole overprint chert as young as late Pliensbachian to Toarcian age (ca. 191 to ca. 177 Ma). Blueschist mineral assemblages define the early metamorphic fabric along with phengite dated by ^{40}Ar/^{39}Ar as 173.7 ± 0.8 Ma. Lack of evidence for phengite recrystallization, secondary muscovite growth, local plutonism, or overprinting of regional prehnite-pumpellyite metamorphic facies limits the possibility of Ar loss subsequent to formation of the blueschist in a subduction zone that had formed >150 m.y. earlier. Southwest-verging folds and northeast-dipping thrust faults along which the blueschist was emplaced affected the width of the northern Cache Creek terrane and the adjacent Whitehorse Trough. Exhumation is recorded by eclogite clasts and by early Bajocian chert granule deposition in Whitehorse Trough before ca. 171 Ma. Oldest postkinematic plutons require that emplacement-related regional deformation, pluton crystallization, and cooling was complete by ca. 172 Ma.

Exhumation may have accelerated upon rupture of Cache Creek oceanic crust as it subducted between two conjoined arc segments (Stikine and Quesnel) that were rotating into parallelism. Paleogeographic changes are recorded by dramatic arc uplift, paleoflow reversal, and changes in ammonite zonation as the last vestiges of Cache Creek ocean crust became isolated. Blueschist was tectonically extruded over the colliding Stikine arc segment from beneath a backstop of Quesnel arc, which had been accreted to the continental margin by ca. 180 Ma.

Keywords: blueschist, Cache Creek, geochronology, structure, radiolarians, microfossils, obduction, exhumation, tectonics.

INTRODUCTION

Preservation of high-pressure–low-temperature metamorphic rocks in orogenic belts requires rapid exhumation in order to prevent thermal overprinting outside of a subduction-zone setting. Numerous mechanisms have been proposed. Some of these, such as diapiric ascent (e.g., England and Holland, 1979) and subduction-zone backflow (Cloos, 1982), include entrainment of high-pressure–low-temperature blocks, up to tens of meters across, in a "flowing" matrix. Neither diapirism nor subduction-zone backflow, however, is a viable mechanism for emplacement of large, coherent blueschist terranes that cover tens or hundreds of square kilometers, such as parts of the Franciscan subduction complex, or the French Range of British Columbia, discussed here. To explain emplacement of these and other coherent blueschists, most workers have invoked extensional exhumation. During growth of the accretionary prism, extension is thought to have been important in maintaining critical wedge taper (e.g., Platt, 1986). After cessation of subduction, exhumation may be driven by convective instability of the thickened lithosphere (e.g., England and Houseman, 1989).

Even in parts of the well-studied Franciscan, however, the role of extensional exhumation is debated. For example, detailed structural study of the Yolla Bolly terrane (Bolhar and Ring, 2001) failed to find evidence of extensional deformation, prompting the authors to attribute exhumation to "vertical ductile shortening" related to domal uplift. Maruyama et al. (1996)

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reviewed worldwide blueschist occurrences and concluded that the exhumation of most blueschists could be attributed to tectonic extrusion of a wedge-shaped "subducted orogen," followed by domal uplift. Wedge extrusion can be caused (1) by a shallowing of the subduction zone owing to collision with a buoyant crustal fragment of arc, microcontinent, continent, juvenile oceanic crust, or ridge segment, or (2) by an increase in the subduction rate.

In the French Range, tectonic exhumation of blueschist may have been due to wedge-like extrusion that was enhanced by rupture of the subducting slab and was accompanied by rapid erosion.

Mihalynuk et al. (1994) suggested that emplacement of the Cache Creek belt, including the French Range blueschist, was a consequence of an unusual subduction-zone configuration during arc-arc collision in Middle Jurassic time at the margin of ancestral North America. The belt, referred to as the Cache Creek Group in the Canadian Cordillera, has been interpreted as a fossil accretion and subduction zone (Monger, 1969) and is known to contain a significant proportion of tholeiitic arc rocks (English et al., 2003). It occupies a central position between the Quesnel and Stikine assemblages, which are interpreted as ancestral arcs (Fig. 1; see Coney et al., 1980) produced by subduction of the ancient Panthalassa Ocean crust (including the Cache Creek oceanic crust) beginning in Devonian time (e.g., Mihalynuk, 1999). Such long-lived subduction produced voluminous arc assemblages, Stikine and Quesnel, which constitute the largest lithotectonic terranes in the Canadian Cordillera. Local blueschist metamorphism and exotic fossil fauna in the Cache Creek Group contrast with the pressure-temperature (*P-T*) histories and faunas of the adjacent arc assemblages (Monger and Ross, 1971). Quesnel is the most inboard (eastern) of these assemblages. It was juxtaposed with the ancestral North American miogeocline during an apparently short-lived event, between 186 and 180 Ma, as recorded in north-central British Columbia (Nixon et al., 1993). The timing and nature of the Quesnel–Cache Creek amalgamation is not well established; however, relatively continuous subduction-related magmatism that began in the Late Triassic ceased abruptly near the close of the Early Jurassic (Nelson and Bellefontaine, 1996).

The demise of subduction beneath the northern Quesnel and Stikine arcs was synchronous with emplacement of Quesnel atop the ancestral continental margin and probably marked collision of the nonsubductable Cache Creek arc at ca. 186 Ma. If so, the Quesnel, Cache Creek, and Stikine arcs were loosely amalgamated at that time. Continentward advance of the Stikine arc resulted in southwestward extrusion of the Cache Creek rocks against a backstop of the Quesnel arc newly welded to the continental margin.

Estimates of the timing of extrusion of Cache Creek oceanic rocks over the Stikine arc have been presented by several workers. In southern Cache Creek terrane, Cordey et al. (1987) presented microfossil age data that support a Middle Jurassic amalgamation. In the north, Ricketts et al. (1992) suggested that overthrusting produced a condensed section of black shales in the late Toarcian and Aalenian (for age calibration of stage boundaries, see Fig. 2). Similar time constraints had been suggested by Gabrielse et al. (1980) on the basis of K-Ar determinations from the Tachilta Lakes plutons (Figs. 1 and 2) that cut deformed strata as young as Aalenian. Gordey et al. (1998) used U-Pb data from zircon in postdeformational plutons near the Yukon–British Columbia boundary to establish a minimum emplacement age of ca. 172 Ma. The initiation of wedge extrusion, however, has been more difficult to constrain.

As part of a continuing study of arc-ocean interaction in the northern Canadian Cordillera, we address the age of initial emplacement of the Cache Creek rocks where they are well exposed in the French Range (Figs. 1 and 3). Isolated blueschist mineral occurrences were known in the area (Monger, 1969), providing the opportunity to date the metamorphism and thereby placing a minimum age on the initiation of wedge extrusion.

This paper summarizes the results of regional geologic mapping and analytical results from the most extensive part of the Cache Creek terrane that straddles the Yukon–British Columbia boundary (Fig. 1). On geologic maps, the northern Cache Creek terrane outline is shaped like a southeastward-tapering wedge. Prior to accretion, it was probably also wedge-shaped in cross section, and we informally refer to it as the "Cache Creek wedge." Herein we present data from the French Range as well as from areas to the north, where plutons cut the inboard edge of the Cache Creek wedge, and to the west, where exhumation of Cache Creek rocks is recorded in well-dated Middle Jurassic clastic strata. We provide new ^{40}Ar/^{39}Ar age data from blueschist in the French Range suggesting an age of 173.7 ± 0.8 Ma, the youngest known blueschists in Cache Creek rocks (Fig. 1). We show that blueschist mineral assemblages extensively overprint primary fabrics in coherent units that can be traced locally for ~12 km along strike. We show how folds and fabrics related to blueschist emplacement are cut by nearly coeval (ca. 172 Ma) plutons, constraining the minimum age of Cache Creek extrusion to ca. 174.5–172 Ma. We suggest that emplacement of the French Range blueschist involved rapid southwestward wedge extrusion of a cold nappe from between a backstop of Quesnel arc and the colliding Stikine arc.

STRATIGRAPHY OF THE FRENCH RANGE

Blueschist mineral assemblages overprinting a stratigraphic sequence in the French Range were first reported by Monger (1969). The sequence was subdivided on the basis of lithology and biogeochronology (Monger 1969, 1975; Monger and Ross, 1971). Gabrielse (1994, 1998) presented a summary of geologic work conducted between 1956 and 1991. Regional map units recognized included Permian mafic volcanic flows and tuff and undivided tuff of the French Range Formation (Fig. DR1),[1] Permian limestone of the Teslin Formation (Fig. DR2 [see footnote 1]), and hemipelagic rocks of the Kedahda Formation (Figs. 3 and 4; details of the stratigraphy are available [see footnote 1]). The age of the Kedahda Formation was thought to range from Carboniferous to Triassic (Gabrielse, 1994; Monger, 1975). Early Jurassic radiolarians, however, occur in chert mapped as Kedahda Formation near the Yukon–British Columbia boundary, and parts of the unit in the French Range are as young as late Pliensbachian and, possibly, Toarcian (Cordey et al., 1991; Fig. 2).

In the part of the French Range covered by the present study, coherent stratigraphy is exposed along northwest-trending ridges that are underlain primarily by French Range Formation mafic volcanic strata and overlying or interbedded Teslin Formation limestone (Fig. 3). Relatively recessive Kedahda Formation ribbon chert is exposed at lower structural and stratigraphic levels. The sharp contacts between the volcanic units and limestone, and between tuffaceous units and ribbon chert, are depositional and are exposed in many outcrops. The contact of Kedahda Formation ribbon chert with overlying volcanic strata of the French Range Formation is apparently gradational over 8–15 m. However, rocks within this contact zone are highly folded, and the existence of cryptic faults cannot be ruled out.

Beds above the contact are thicker (typically 5–20 cm) and more heterolithic than the underlying ribbon chert of the Kedahda Formation. Chert layers within the heterolithic beds display tuff,

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[1] GSA Data Repository item 2004105, Figures DR1–DR4 and Tables DR1–DR4, stratigraphic descriptions and photos, ^{40}Ar/^{39}Ar correlation plots and geologic map (Figs. DR1–DR4); fossil identifications and isotopic data (Tables DR1–DR4), is available on the Web at http://www.geosociety.org/pubs/ft2004.htm. Requests may also be sent to editing@geosociety.org.

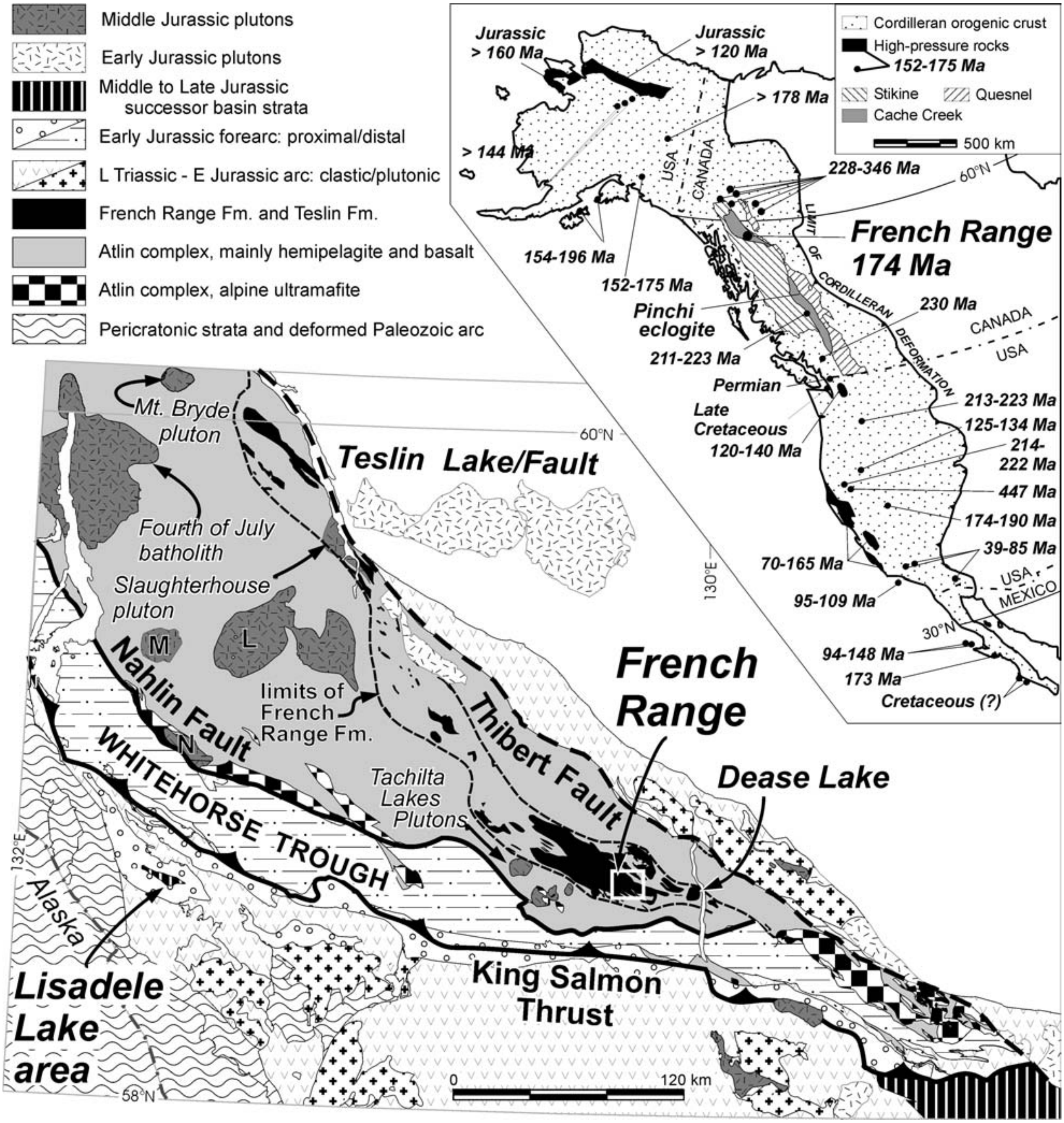

Figure 1. (A) North American blueschist localities (modified after Erdmer et al., 1998) and extent of the Cache Creek terrane and adjacent Stikine and Quesnel terranes, which together compose most of the Intermontane superterrane. L—Llangorse Mountain batholith. M—McMaster pluton. (B) Generalized geology of the wedge-shaped northern Cache Creek terrane and forearc and younger successor-basin strata of the Whitehorse Trough. Cretaceous and younger intrusive rocks are not shown (there are none in the French Range). Geology in British Columbia is after Mihalynuk et al. (1996), and geology in Alaska is after Brew et al. (1991). Location of Figure 3 is shown by the boxed outline.

argillite, and iron contents that vary along strike. Tuffaceous layers with high pelite content have been the most extensively overprinted by sodic amphibole, particularly where they are interbedded with meter-thick layers of ferruginous chert. Together, these bright blue and red rocks produce striking outcrops. Adjacent pelite layers with low tuff content are gun-steel blue, up to 15 cm thick, and are composed of quartz, white mica, ferroan clinochlore, and abundant blue amphibole as fine-grained needles (Fig. 5E), or locally, as prisms up to 3 mm long.

We consider the heterolithic beds as a unit separate from the Kedahda Formation. This distinction is made not only on the basis of lithology, but also on the basis of age. Constraints on the age of Kedahda Formation hemipelagite are provided by Guadalupian (middle Permian) radiolarians

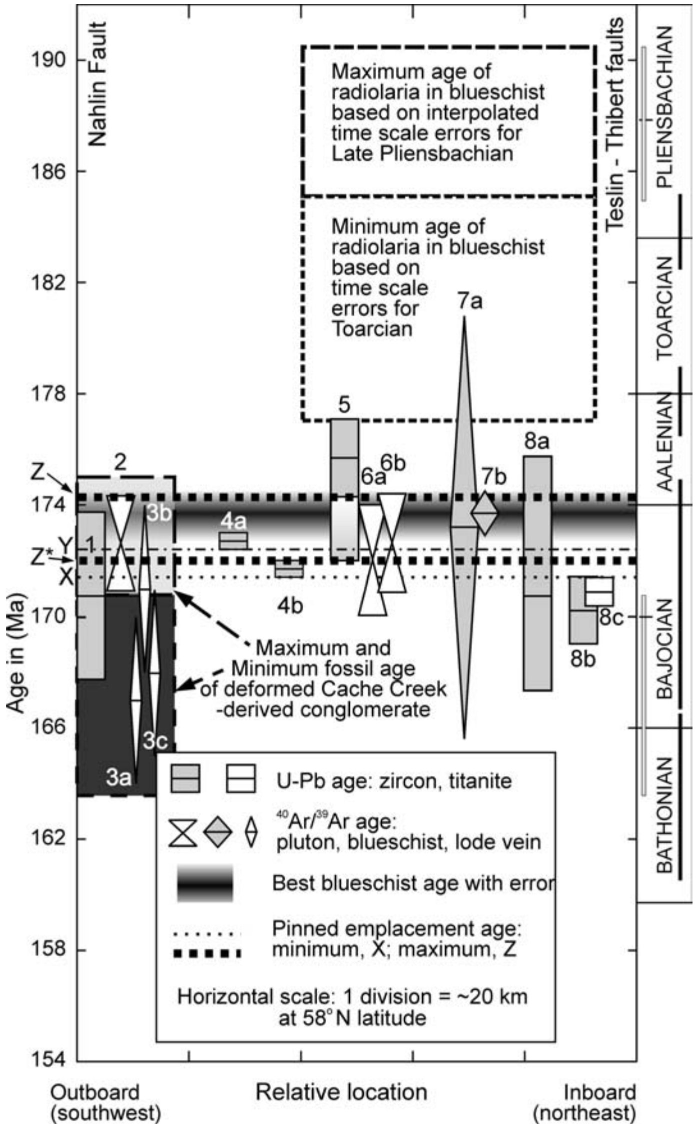

Figure 2. Graphical summary of age data constraining emplacement of the French Range blueschist. Pluton and blueschist ages are plotted schematically to show their position relative to the margins of the northern Cache Creek rocks; data points are projected along strike to lat ~58°N. Symbol size graphically depicts the error envelopes about the best-interpreted age. Sources of isotopic age data: 1, 2—Fourth of July batholith as determined by (1) Mihalynuk et al. (1992), and (2) Harris et al. (2003). 3a, 3b, 3c—Mariposite ages reported by Ash (2001) from lode gold veins, generally >4 km south of the Fourth of July batholith. 4a, 4b—Mihalynuk et al. (2003) for (4a) McMaster stock and (4b) Llangorse batholith. 5—Gordey et al. (1998) for Mount Bryde pluton (the gradational fill box shows the minimum ^{206}Pb/^{238}U age). 6a, 6b—Hunt and Roddick (1994) for Mount Bryde: (6a) hornblende (99% gas plateau) and (6b) biotite (97% gas plateau). 7a, 7b—Blueschist ages presented here. 8a, 8b, 8c—Ages of the Slaughterhouse pluton presented here. Fossil age ranges are based upon stage-boundary error limits from the Jurassic time scale of Pálfy et al. (2000). Dotted lines representing the pinning ages are discussed in the text.

(Mihalynuk and Cordey, 1997). Tuffaceous chert layers of the heterolithic beds contain Middle Triassic and Early Jurassic radiolarians (samples FC99-1004 and MMI99-34-12, Figs. 5A–5D, Table DR1 [see footnote 1]). Radiolaria of the same age are found in correlative rocks west of Teslin Lake, ~200 km to the north (Cordey et al., 1991). The youngest radiolarians in the French Range, of late Pliensbachian to Toarcian age (ca. 191 Ma to ca. 177 Ma), are from blueschist and therefore place a maximum age limit on blueschist mineral formation.

REGIONAL AND LOCAL STRUCTURES

At its inboard margin near the Yukon, the Cache Creek wedge is separated from polydeformed, greenschist to amphibolite facies arc-type volcanic rocks and intercalated quartz-rich miogeoclinal strata by the Teslin fault (Mihalynuk et al., 2000) and the Thibert fault farther south (Fig. 1). Deformed volcanic strata inboard of the Teslin fault are correlated with the Quesnel arc (Harms and Stevens, 1996). Exposures of inboard strata east of Teslin Lake (Fig. 1) show a strong, regionally pervasive schistosity that also affects crosscutting plutons as young as 196 Ma. In contrast, ca. 185 Ma plutons appear to be undeformed except for their earliest intrusive phases (Mihalynuk et al., 1998). These younger intrusions are interpreted to have coincided with waning regional deformation related to accretion of the Quesnel arc. Fabrics developed along the Teslin fault overprint regional schistosity. Steeply dipping (75°–85°) zones of ultramylonite record dominantly transcurrent (but also transpressive) sinistral shear and subsequent brittle dextral transpressive shear (de Keijzer et al., 2000). The same shear fabrics are also developed in meter-thick zones in adjacent Cache Creek ribbon chert and wacke. An undeformed Middle Jurassic pluton, the Slaughterhouse pluton (see Fig. 1), intrudes the Cache Creek rocks along southern Teslin Lake, but it is not observed within or east of the Teslin fault zone.

On its outboard edge, the western limit of the Cache Creek wedge is the Nahlin fault (e.g., Souther, 1971). This nearly vertical structure is most conspicuous where it juxtaposes serpentinized harzburgite against vertical to steeply overturned fault panels of Lower Jurassic Laberge Group strata of the Whitehorse Trough. Thrust faults within the Cache Creek rocks northeast of the Nahlin fault and within the Laberge Group to the southwest are dominantly northeast dipping (Mihalynuk et al., 2002, and English et al., 2003). A regional positive aeromagnetic anomaly extends northeast of harzburgite exposed along the southwest margin of the Cache Creek wedge, suggesting that the ultramafic rocks are present in the subsurface as a moderately northeast-dipping fault panel (Lowe and Anderson, 2002). Thrust faults are the dominant late structures within the wedge. They are cut by Middle Jurassic plutons with well-developed thermal aureoles. Contact metamorphic zones are commonly tens to hundreds of meters wide. In immature clastic sedimentary or tuffaceous rocks, the contact metamorphic mineral assemblage commonly includes biotite, actinolite, chlorite, pyrite, magnetite, quartz, plagioclase, epidote, and, rarely, garnet. Contact aureoles typically produce a strong magnetic response in the regional aeromagnetic data (Lowe and Anderson, 2002), and none appears to be deformed.

Emplacement of the Cache Creek wedge above the Stikine arc by low-angle south- or southwest-directed thrust faults is consistent with seismic reflection geometries. Evenchick et al. (2001) have suggested that Cache Creek rocks form a relatively thin flap or nappe above Stikine arc rocks. They were carried southwest in the hanging wall of the King Salmon thrust, which was active between early Toarcian and middle Bajocian time (Tipper, 1978).

In the French Range, a subparallel orientation of bedding and a schistosity defined by metamorphic minerals including white mica, chlorite, and sodic amphibole indicates that the earliest folds developed under blueschist-facies conditions. Schistosity is locally deformed by large-amplitude upright isoclinal folds of wavelengths of up to 1 km. Folds of this type are well displayed on the ridge immediately south of Slate Creek (Figs. 3A and 3B), where a sequence of tuffaceous red and blue, sodic amphibole-bearing chert is repeated four times by isoclinal folds with a wavelength of tens of meters. In the cores of some of these folds are well-developed crenulations that lack an associated, pervasive axial-planar fabric. The isoclinal fold set is pervasively overprinted by a later set of open, asymmetric folds with northeast-dipping axial surfaces (Figs. 3C and 3D). In the northeastern French Range, these late folds verge southwest, consistent with the regional vergence of Cache Creek emplacement-related folds and thrust faults.

No map-scale thrust faults have been observed to crop out in the French Range. However, at the headwaters of Slate Creek, a low-angle thrust fault is interpreted to juxtapose blueschist-grade Early Jurassic radiolarian–bearing argillaceous chert and structurally overlying Permian tuffaceous rocks (Figs. 3 and 4). At some point within a covered interval extending several tens of meters below the Jurassic chert, the blueschist-bearing section passes into much more highly strained ribbon chert and argillite in which blueschist-facies minerals are not developed. This strain transition also occurs below the blueschist-grade basalt and tuffaceous chert south of Slate Creek (Fig. 3). We interpret it as the expression of a folded regional thrust that soles the blueschist nappe. Absent from the French Range is any low-angle extensional fault that should juxtapose the blueschist with overlying lower-pressure rocks. Blueschists, however, occur at the highest elevations in the French Range, and evidence of a structure that bounded their upper surface has likely been removed by erosion.

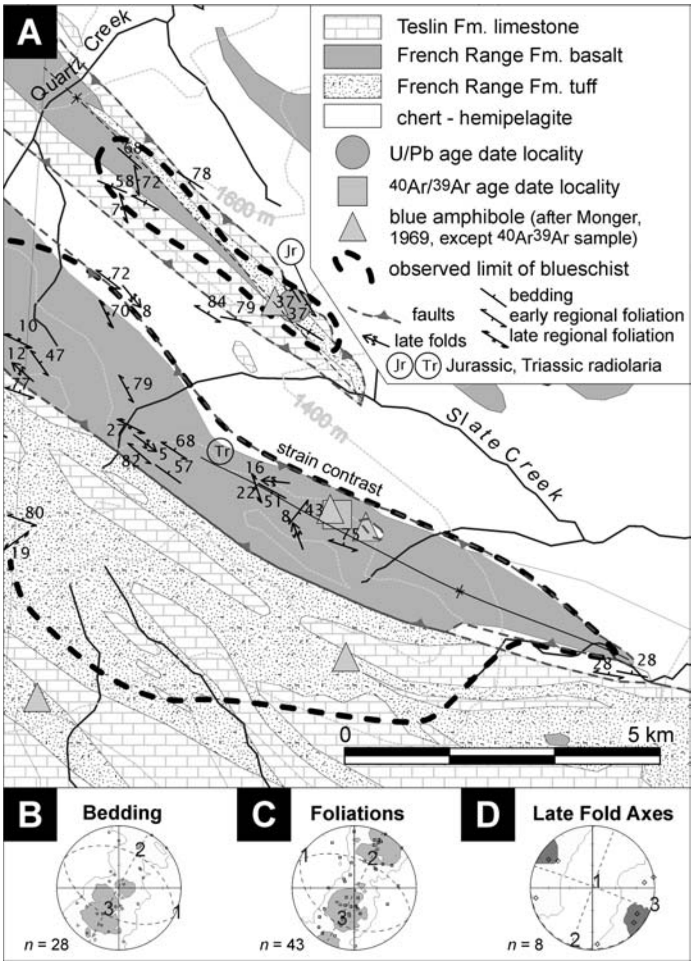

Figure 3. (A) Geologic map of the headwaters of Quartz and Slate Creeks in the French Range. Sources of information are Monger (1969) and our previously unpublished mapping in 1996, 1999, and 2000. (B, C, D) Schmidt equal-area lower-hemisphere plots showing structural data collected during field studies in 1996. Data are contoured by Gaussian counting function with contour intervals of 2σ, 4σ, and 6σ. Contoured poles to early, folded foliation in C show maxima corresponding to steep southwest-dipping and shallow northeast-dipping limbs of southwest-verging, emplacement-related folds. Fold axis orientations shown in D are representative of the late emplacement-related folds.

METAMORPHISM

Mineral assemblages of the prehnite-pumpellyite metamorphic facies are characteristic of Cache Creek rocks for >300 km along strike and up to 100 km across strike, except where they are overprinted by thermal aureoles around plutons (typically <2 km wide) and in the French Range, where blueschist minerals are preserved. Rocks in the French Range are typically very fine grained and contain relict igneous and clastic minerals, e.g., augite, plagioclase, and K-feldspar phenocrysts. We used a combination of microscopic petrography, X-ray diffraction, and electron-microprobe analyses to identify and characterize the minerals. It was difficult to obtain reliable electron-microprobe analyses of authigenic minerals because of their fine grain size.

Sodic amphibole is widespread but does not coexist with lawsonite in any sample that we examined. A typical sodic amphibole contains the following cations (normalized to 15 cations minus K): Si = 7.98; Al^{vi} = 0.70; Fe^{3+} = 0.61; Mg = 1.217; Fe^{2+} (octahedral) = 2.472; Ca = 0.33; Na (M_4) = 1.523. Some very fine-grained sodic amphibole coexisting with quartz has very strong pleochroism and is probably riebeckite rich. Albite (An = ~0) is widespread and coexists

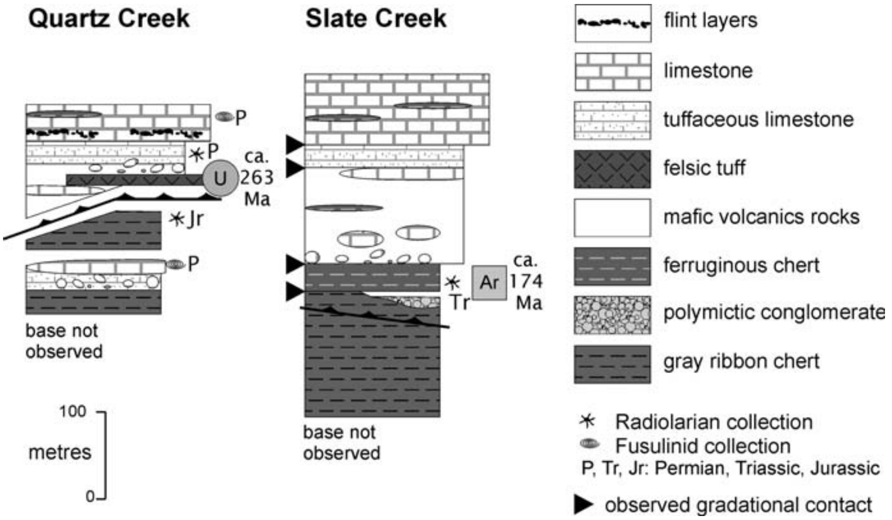

Figure 4. Generalized stratigraphic column, showing stylized facies relationships and age control in the French Range.

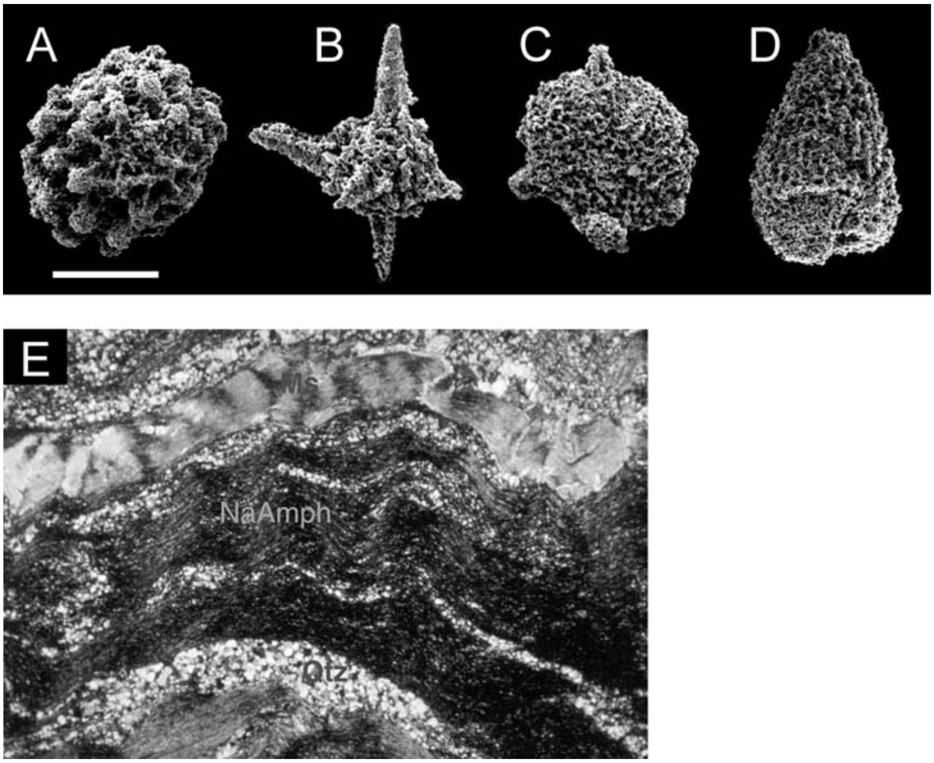

Figure 5. (A to D) SEM photomicrographs of Early Jurassic radiolaria (sample MMI99-34-12). Scale bar is 100 µm. (A) *Orbiculiforma* sp. cf. *silicatilis* Cordey (Early Jurassic). (B) *Thurstonia* sp. (Hettangian–Aalenian). (C) *Praeconocaryomma* sp. aff. *media* Pessagno and Poisson (Pliensbachian–Toarcian). (D) ?*Canutus izeensis* Pessagno and Whalen (Pliensbachian). Pliensbachian to Toarcian is the age range based on the occurrence of *Praeconocaryomma* sp. aff. *media* (C). Specimens A and D strengthen an Early Jurassic affinity. Specimen D lacks sufficient preservation to enable a confident Pliensbachian assignment. (E) Photomicrograph of argillaceous partings in ribbon chert, showing the development of white mica (Ms) and sodic amphibole (NaAmph) layers with polygonal quartz (Qtz). A weak crenulation folds, but does not recrystallize, the authigenic minerals. The sample is number MMI97-17-4, view is under cross-polarized light. Long dimension of the photograph represents ~2.5 mm.

with sodic amphibole and chlorite. Aegirine-rich clinopyroxene (jadeite = 20 mol%) occurs in veins with quartz. Veins of epidote crosscutting the schistosity are present in the western part of the map area, and small amounts of granular epidote occur with riebeckitic amphibole in metachert. We identified calcite from X-ray diffraction analysis of carbonate matrix in bioclastic limestone and massive marble, but no aragonite was detected.

Few direct estimates of metamorphic temperatures have been made for blueschist-facies rocks. Exceptions include $^{18}O/^{16}O$ thermometry using coexisting quartz + muscovite, quartz + carbonate, and quartz + iron oxides, e.g., Brown and O'Neil (1982). Aside from these approximations, only rather broad temperature limits have been estimated. These are typically 150–350 °C for lawsonite-albite–bearing blueschist (see, e.g., Evans, 1990); whereas the prehnite-pumpellyite facies is estimated at <~275 °C (Digel and Gordon, 1995; Fig. 6). If aragonite is present, temperature limits can be based on the rapid kinetics of the aragonite → calcite reaction, i.e., temperature not higher than ~200–250 °C (Carlson and Rosenfeld, 1981). The lack of aragonite suggests either higher temperatures or *P-T* conditions outside of the aragonite stability field. Using thermodynamic data (from Berman 1988) to calculate the lower *P-T* limits of lawsonite-albite stability requires using poorly constrained data for analcime and Ca-zeolites. The minimum pressure for $P_{H_2O} = P_{solid}$ is ~3 kbar, and the maximum pressure, based upon the jadeite component of the sodic clinopyroxene + quartz and stable albite, is ~5 kbar at 200 °C (Fig. 6).

^{40}Ar/^{39}Ar DATING OF BLUESCHIST

Two samples of phyllitic to schistose tuffaceous pelite composed of quartz, primary white mica (phengite), Fe-rich blue amphibole, and Fe-rich chlorite were collected at the contact between the Kedahda and French Range Formations for $^{40}Ar/^{39}Ar$ isotopic analysis (samples MMI96-17-4 and MMI96-17-4B, location shown in Figs. 3 and 4). Layer-parallel schistosity in the metapelite is weakly crenulated, and both white mica and sodic amphibole display undulatory extinction (Fig. 5E). Typical crystals in cross section are <75 µm long and 5–8 µm thick. Some mica domains are 2.5 mm thick and are optically continuous for >12 mm.

Following irradiation for 29 h at the McMaster Reactor, splits of the sample were analyzed at Queen's University using a Mass Analyzer Products 216 (MAP216) mass spectrometer and continuous-Ar laser. The irradiation standard was Hb3Gr hornblende for which an age of 1071 Ma is assumed. From semiquantitative X-ray analysis, the fraction of sample MMI96-17-4 with a specific gravity of >2.85 is composed of 34% quartz, 28% phengite, 28% crossite, and 9% clinochlore. The nonmagnetic fraction of sample MMI96-17-4b is composed of 71% quartz, 28% phengite, and 2% crossite. These results and microprobe data show that the primary source of K and radiogenic Ar in both fractions is phengite.

Sample MMI96-17-4 with a specific gravity of >2.85 yielded a spectrum with a pronounced “hump shape” (i.e., low dates for low- and high-temperature steps). The spectrum (Fig. 7A, Table DR2a [see footnote 1]) yields a plateau-segment date at 173.7 ± 0.8 Ma (2σ, 59% of ^{39}Ar released; MSWD [mean square of weighted deviates] = 1.4), and the integrated age is 164.4 ± 0.7 Ma (2σ). This sample is too radiogenic to yield a meaningful isotope correlation date.

The nonmagnetic fraction of MMI96-l7-4B was analyzed twice. The spectra are comparable to that of sample MMI96-17-4, but with a lower yield of ^{39}Ar (from a lower potassium content) and a lower analytical uncertainty (Fig. 7D–F, and Table DR2b [see footnote 1]). A detailed spectrum with 10 heating steps has a plateau segment accounting for >50% of the ^{39}Ar released. Although the errors are large (owing to the low percentage of phengite), it appears that the spectrum has a slight “hump-shape.” In contrast, the three-step analysis has a “U shape” (Fig. 7D, Table DR2b [see footnote 1]). Taken together, the two analyses define a plateau date at 170 ± 7 Ma (2σ, 80% of the ^{39}Ar released, MSWD = 0.8). The close correspondence between the plateau date, the integrated date of 177 ± 8 Ma (2σ), and the isotope correlation date of 172 ± 9 Ma (2σ, MSWD = 0.7), as well as an ^{40}Ar/^{36}Ar ratio equal to that of atmospheric Ar within error (309 ± 30), all support the interpretation that the mica in this rock does not contain excess ^{40}Ar and probably closed to Ar diffusion in Jurassic time, by ca. 172 Ma.

The combined data for the three analyses (Table DR2c [see footnote 1]) define an integrated age of 164.7 ± 0.8 Ma (2σ), a plateau date of 173.3 ± 0.9 Ma (2σ; MSWD = 1.4, for 71% of the ^{39}Ar released) and an isotope correlation age of 173.0 ± 1.0 Ma (2σ, MSWD = 1.0; Fig. 7G) for 58% of the ^{39}Ar released (the ^{40}Ar/^{36}Ar ratio is 315 ± 13, only slightly higher than the atmospheric value of 295.5). This plateau date may be the best estimate of the time of white mica growth, but we use the slightly more conservative (older) plateau age (173.7 ± 0.8 Ma; MMI96-17-4, specific gravity of >2.85) in the discussions below. The low- and high-temperature steps are also discussed.

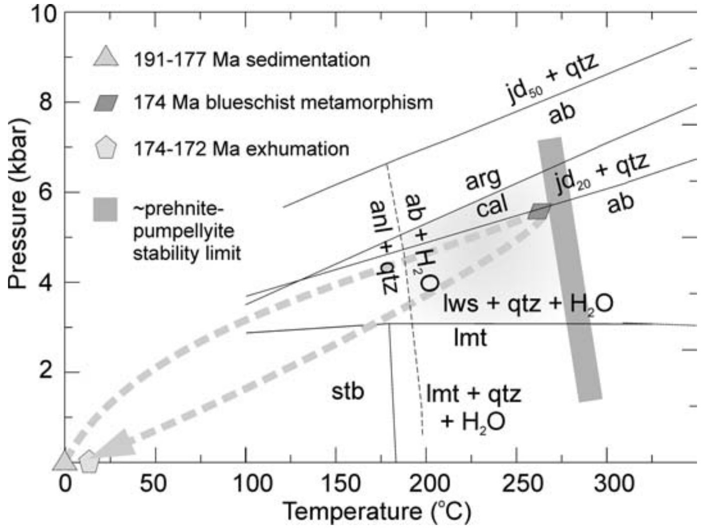

Figure 6. Mineral equilibria that constrain *P-T* conditions for the formation of French Range blueschists, calculated by using Ge0-Calc (Brown et al., 1988). Approximate prehnite-pumpellyite stability limit from Digel and Gordon (1995). Heavy dashed gray arrow shows simplest possible *P-T* path followed by the French Range blueschist. Phases: ab—albite, anl—analcime, cal—calcite, lmt—laumontite, lws—lawsonite, jd—jadeite, qtz—quartz, stb—stilbite.

U-Pb GEOCHRONOLOGY

We selected three samples for U-Pb isotopic analysis. One was from a blueschist-grade, ignimbritic rhyodacite unit selected to demonstrate that blueschist metamorphism affected the Permian volcanic and sedimentary rocks as well as the Lower Jurassic tuffaceous chert. Two other samples were collected from the Slaughterhouse pluton, which cuts all fabrics in the Teslin Formation near the inboard limit of the Cache Creek wedge. The pluton is located ~200 km along strike to the northwest of the French Range blueschist locality. Existing isotopic age data are for postkinematic plutons near the outboard limit of the Cache Creek wedge, and we needed to establish consanguinity between late, southwest-verging folds and northeast-dipping thrusts interpreted as having formed during Cache Creek emplacement, across both the length and breadth of the Cache Creek wedge.

The ignimbritic rhyodacite sample (sample MMI96-17-7) yielded clear, colorless to pale pink, stubby to elongate prismatic zircon. Mineral separation and analytical techniques followed those described by Mortensen et al. (1995). Three analyzed fractions yielded concordant dates in the range 265–260 Ma. By using the average of the ^{206}Pb/^{238}U results for two concordant fractions (Table DR3 [see footnote 1], fractions A and C; Fig. 8A), the interpreted crystallization age of the sample is 263.1 +1.0/–1.4 Ma. The result is consistent with the age of the overlying Teslin Formation limestone at this locality, i.e., late Guadalupian (Monger, 1969; between 264 ± 2 and 256 ± 5 Ma, if the time-scale calibration of Okulitch [1999] is used).

The Slaughterhouse pluton is mainly quartz diorite and is at least 25 km across in its longest exposed dimension along the southern part of Teslin Lake (Fig. 1). Samples of two separate phases were taken ~7.5 km apart: sample MMI96-2-11 from near the pluton margin and sample MMI96-16-3 from near the pluton core. Clear, pale pink, prismatic, and tabular zircons were recovered in abundance from both samples. In addition, sample MMI96-2-11 yielded abundant clear to cloudy, pale yellow titanite. Sample MMI96-16-3 yielded a small quantity of titanite.

U-Pb results for five of six fractions from sample MMI96-16-3 are slightly discordant and plot adjacent to a 2 m.y. segment of the concordia curve near 171 Ma (Fig. 8B). Fraction F is marginally concordant; its error ellipse partly intersects the concordia curve as well as the error ellipses of several other analyses. We infer a crystallization age of 170.7 +5.1/–3.4 Ma by using the ^{207}Pb/^{206}Pb result for fraction F. The ^{206}Pb/^{238}U result for this fraction (167.7 ± 0.4 Ma) is interpreted as a minimum age and is the cause of the reported asymmetric precision. A minimum age of 167.7 ± 0.4 Ma is inferred from the ^{206}Pb/^{238}U result for fraction F.

The results of U-Pb analysis of four zircon fractions and one fraction of titanite from sample MMI96-2-11 are illustrated in Figure 8C (fractions A, B, C, D, and T2). Fractions

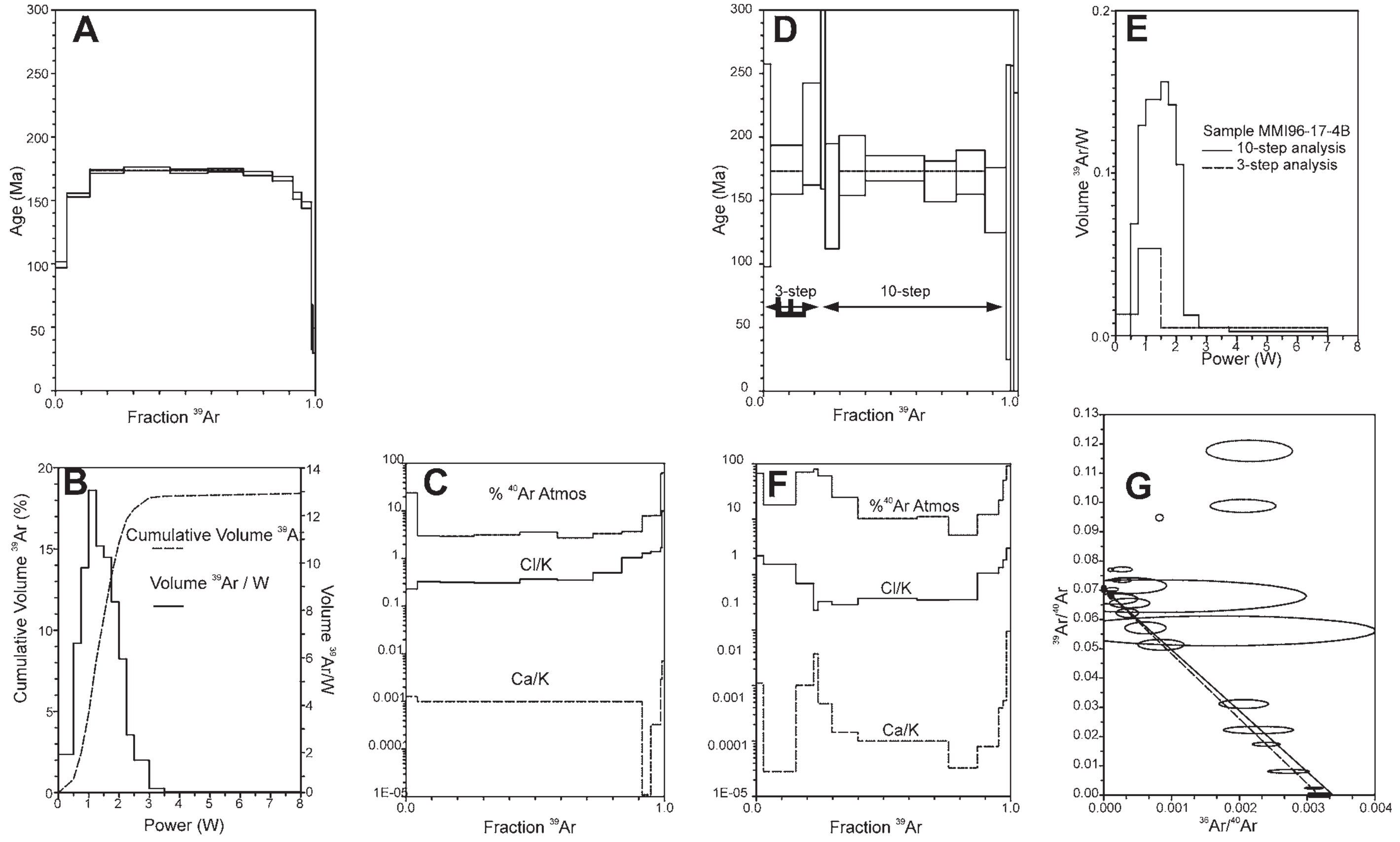

Figure 7. Step-heating ^{40}Ar/^{39}Ar results for two French Range blueschist samples. (A–C) Sample MMI96-17-4, mica-rich whole-rock fraction with a specific gravity of >2.85. (D–F) Two analyses of sample MMI96-17-4B, nonmagnetic fraction, plotted on the same graphs. (G) Isotope correlation plot of data from all three analyses. (A) and (D) are age spectra, (B) and (E) are gas-release spectra, and (C) and (F) are estimates of % atmospheric contamination; Ca/K and Cl/K ratios calculated from the argon isotope volumes released in each step. The data from which these plots are derived are presented in Table DR2 (see footnote 1 in text).

A, B, and C indicate the presence of minor inheritance; fraction C also records Pb loss. A maximum crystallization age of ca. 175 Ma is given by the ^{207}Pb/^{206}Pb age for fraction D. The titanite fraction is concordant at 170.9 ± 0.5 Ma (^{206}Pb/^{238}U age). We regard the titanite result as the minimum crystallization age of the rock and the slightly younger zircon fractions as recording minor Pb loss. Mihalynuk et al. (1998) had previously interpreted the median ^{206}Pb/^{238}U date of 170.2 ± 1.2 Ma for concordant zircon D and titanite T2 as the crystallization age for the sample. Our interpretation of the enhanced U-Pb isotopic age data suggests a minimum age of 170.4 Ma at the limits of error.

RECORD OF UPLIFT IN SUCCESSOR-BASIN STRATA

Clastic strata of the Whitehorse Trough (Wheeler, 1961) are exposed immediately outboard (southwest) of the Cache Creek wedge (Fig. 1), separated from the Cache Creek wedge by the Nahlin fault (Aitken, 1959). They are predominantly coarse tuffaceous wacke and conglomerate (Fig. 9) interpreted to mark an Early Jurassic forearc basin (Fig. 10; Johannson et al., 1997; Mihalynuk, 1999). Lithologic and paleontologic controls are available from the Lisadele Lake area (Fig. DR4 [see footnote 1]), ~80 km east of Juneau, Alaska. In that area, upper Pliensbachian to Toarcian conglomerate records the unroofing of the Stikine magmatic arc, as volcanic, plutonic, and strongly schistose metamorphic clasts characterize progressively younger beds (Fig. 9). In earliest Middle Jurassic time (Aalenian), deep-water mud and distal tuffaceous deposits predominated. They are immediately overlain by lower Bajocian pebble and granule conglomerate containing clasts of hemipelagite and chert, recording a rapid change in sediment provenance (Fig. 9). Ages of radiolaria in chert clasts (Table DR1 [see footnote 1]) largely overlap the ages of Cache Creek chert. Only the oldest radiolarians of the Kedahda Formation (Carboniferous) are not represented in the conglomerate. A minimum age of the chert source is provided by the species *Praeconocaryomma* cf. *immodica* Pessagno and Poisson, *Thurstonia* sp., which ranges from Pliensbachian to Toarcian.

Modification of the Whitehorse Trough is indicated not only by changes in sediment provenance, but also by changes in paleoflow directions as well as the Early Jurassic ammonite distribution. Paleocurrent data from the Lisadele Lake area show a reversal in early Middle Jurassic time, from northeast to southwest directed, consistent with uplift of the Cache Creek rocks and their emergence as the dominant source of coarse clastic material within the basin.

Ammonite populations have been inferred to record variations in water temperature (Table DR4 [see footnote 1]) due to changes in basin restriction and paleolatitude. Late Pliensbachian ammonites include a mixture of warm-water Tethyan taxa (*Arieticeras*, *Leptaleoceras*, *Lioceratoides*, *Protogrammoceras*, *Fontanelliceras*, and *Fieldingiceras*) and Boreal taxa (*Amaltheus* and *Tiltoniceras*), interpreted to indicate a Subboreal paleogeography (Smith and Tipper, 1986). In contrast, Toarcian taxa include the genus *Pseudolioceras*, a Boreal genus common in Arctic North America, Siberia, Japan, and Great Britain (Jakobs, 1997). This genus is interpreted to indicate a high-latitude Boreal position by early to middle Toarcian time.

DISCUSSION

On the basis of blueschist metamorphism of Early Jurassic radiolarian–bearing chert (late Pliensbachian to Toarcian, Fig. 2), the maximum age of blueschist metamorphism in the French Range is constrained to between ca. 191 Ma and ca. 177 Ma (including time-scale error limits). The minimum age is constrained by the 173.7 ± 0.8 Ma $^{40}Ar/^{39}Ar$ cooling age of phengite intergrown with blue amphibole. This cooling age is similar to the age of erosional exhumation of Cache Creek, as recorded by a change in paleoflow, and clastic detritus in the early Bajocian basin, between ca. 171 and ca. 175 Ma (maximum age, including time-scale errors, Fig. 2). Southwest-verging folds and northeast-dipping thrusts deform the lower Bajocian strata, as well as older strata across the Whitehorse Trough and the Cache Creek wedge. The minimum age of the folds and thrusts is constrained by crosscutting plutons, the oldest of which is at least 172 Ma. We interpret these stratigraphic, structural, and isotopic age data as indicating blueschist metamorphism and exhumation that spanned <2.5 m.y. This interpretation assumes that (1) the cooling age is also the age of blueschist formation, (2) blueschist was exhumed during ongoing sedimentation in the Whitehorse Trough, and (3) Middle Jurassic plutons cut fabrics that are related to the emplacement of Cache Creek rocks. We address each of these assumptions below.

Cooling Age Same as Age of Blueschist Formation?

Argon release spectra for two of the French Range fractions are “hump shaped” and might, as a result, be considered suspect. For example, Wijbrans and McDougall (1986) investigated the effect of thermal metamorphic overprinting on $^{40}Ar/^{39}Ar$ release spectra of phengitic mica in early metamorphic (M1) blueschist from Naxos and showed them to be “humped shaped” when two generations of white mica are present (in this case, phengite and late muscovite). Their observations showed that phengitic mica was overprinted when a sufficiently high metamorphic grade was attained (M2, ~420–440 °C, Jansen and Schuiling, 1976); corundum appeared in metabauxite, and biotite grew in metapelite and metabasite. In the Naxos rocks, overprinting is manifested petrographically by the recrystallization of phengite into segmented domains and stubby, variably oriented muscovite. In the French Range, neither authigenic biotite nor recrystallization of phengitic mica occurred, and blueschist-facies rocks are surrounded by rocks of prehnite-pumpellyite facies, indicating peak temperatures of <~275 °C (see Digel and Gordon, 1995). Furthermore, our X-ray and microprobe data show that only phengitic white mica is present in the dated samples and not secondary muscovite. We note that the release of ^{39}Ar is concentrated in the 1–2 W (laser power) range for both fractions (Figs. 7B and 7E). The decreasing dates yielded by higher-temperature steps correlate with an increase in the Ca/K ratio as determined from the measured $^{37}Ar/^{39}Ar$ ratios (Table DR2a [see footnote 1]). Because the Ca/K ratios for these steps are >1, we interpret this result to indicate gas release from sodic amphibole and clinochlore and not from another white mica phase. The young dates in low-temperature steps for the fraction having a specific gravity of >2.85 could be caused by a postcrystallization thermal event. Temperatures required to affect Ar retention in white micas have been estimated to be in the range of 350 ± 50 °C (e.g., Hames and Bowring, 1994). By using the grain size and diffusion parameters for muscovite (not phengite) of Lister and Baldwin (1996), we calculated closure temperatures between 360 and 385 °C, if we assume cooling rates of between 30 and 70 °C/m.y. (based on our estimates of the maximum time interval available and the temperature range for blueschist metamorphism). For cooling rates of >200 °C/m.y., the closure temperature is >400 °C. Such temperatures would have led to greenschist overprinting of prehnite-pumpellyite and blueschist mineral assemblages in the French Range. There is no mineralogical evidence of later metamorphism.

We cannot discount the possibility of minor thermal overprinting and Ar loss; there is no evidence, however, of thermal overprinting due to migration of isotherms in the accretionary wedge or due to late igneous activity. Thermal modeling of subduction zones by Cloos (1985) showed that persistent subduction (>~25 m.y.) produces deep refrigeration, stable isotherms, and cessation of Ar loss by thermal diffusion. Such thermal structure should have been established before the French Range strata were subducted because >150 m.y. of subduction of Panthalassa is recorded by the Cache Creek rocks and the formation of the Devonian to Jurassic Stikine and Quesnel arc complexes.

Thermal overprinting as a result of plutonism is unlikely. The nearest exposed Jurassic pluton is 25 km to the west, and the large Cretaceous Cassiar batholith is ~50 km to the east, across a regional fault system. However, to test the sensitivity of the white mica to a low-temperature event that might have resulted from a buried pluton, we performed some diffusion calculations for a single-stage, episodic-loss model, by using formulae presented in McDougall and Harrison (1988). Under the assumption that the temperature of the event must be less than or equal to the temperature of regional metamorphism (≤275 °C), for a reheating event of 2 m.y. duration, the fraction of ^{40}Ar lost would be only 2%, and the reduction in the ratio corresponding to the original plateau age would be <1% at the end of the heating event. The model age spectrum provides a reasonable fit to the form of the actual age spectra, with a comparable reduction in the integrated date and a comparable plateau segment. An uncertainty affecting our interpretation is the imprecisely known

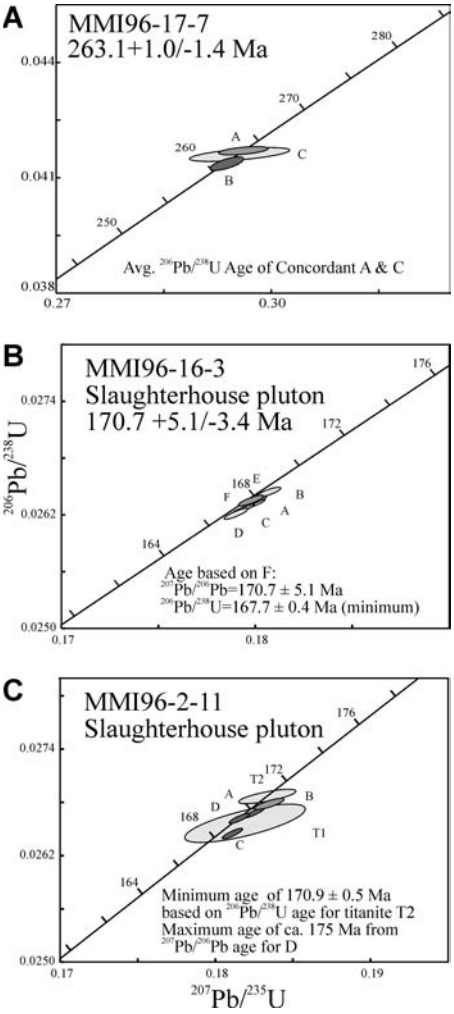

Figure 8. U-Pb concordia diagrams for samples: (A) MMI96-17-7, (B) MMI96-16-3, and (C) MMI96-2-11. See Table DR3 (see footnote 1 in text) for data.

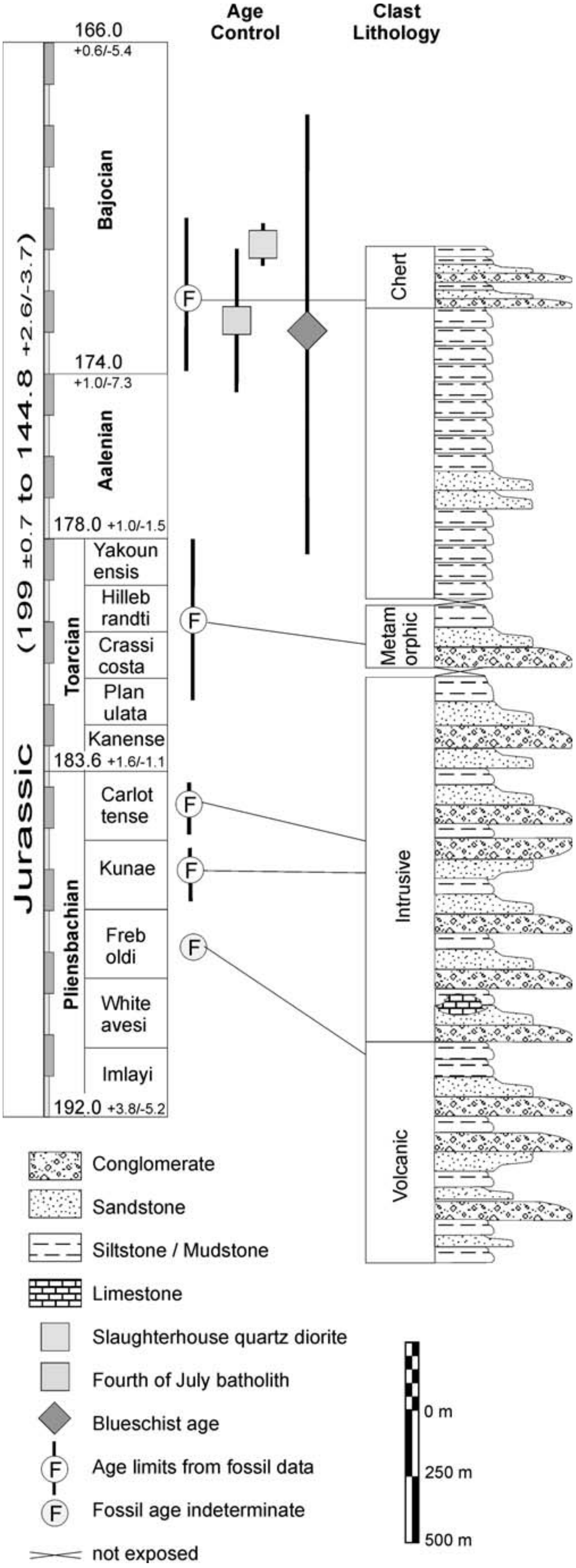

Figure 9. Laberge Group stratigraphy of the northeast Tulsequah area. Conglomerate composition records unroofing of the Stuhini arc. Youngest conglomerates are chert rich and derived from the Cache Creek terrane. The fossil ages are calibrated against the revised Jurassic time scale of Pálfy et al. (2000).

diffusion parameters of phengite and the poor constraint of closure temperature (see Scaillet et al., 1992). Conservative interpretation of the Ar data requires that they provide a minimum age. Because there is no evidence of significant later Ar diffusion, we consider the plateau date of 173.7 ± 0.8 Ma to be a good estimate of blueschist formation age. Folds and thrust faults related to Cache Creek extrusion are nearly coeval with blueschist cooling, lending support to the interpretation.

Blueschist Exhumation Coeval with Whitehorse Trough Strata?

Changes in Whitehorse Trough architecture prior to extrusion of the Cache Creek rocks are reflected by a change in ammonite fauna from a mixed Subboreal realm to a Boreal realm. A regional tectonic model proposed by Mihalynuk et al. (1994) showed Cache Creek ocean crust consumed beneath two converging and oppositely polarized segments of the same subduction zone (Fig. 10A). The convergence of these arcs may have restricted the intervening basin and isolated it from a seaway in which warmer-water ammonites lived. The emplacement of Cache Creek rocks above the Stikine arc is recorded in strata of the Whitehorse Trough by the reversal of paleocurrent directions and the appearance of chert granule conglomerate. Fossils in the transitional strata near Lisadele Lake are early Bajocian (Table DR4 [see footnote 1]); the lower boundary of the Bajocian stage has been estimated at 174 +1.0/–7.3 (Pálfy et al., 2000; Fig. 2). The ages of radiolarians in the youngest chert clasts are Pliensbachian to Toarcian, similar to the youngest radiolarians in chert of the adjacent Cache Creek Group (Table DR1 [see footnote 1]; Cordey et al., 1991). Wacke is interbedded with the Jurassic chert, in contrast to argillite in the underlying Paleozoic chert. Locally, chert sharpstone conglomerate is interbedded with chert layers (see also Gordey, 1991; Gordey and Stevens, 1994), which we interpret to reflect cannibalization during basin collapse, similar to the situation in axial parts of the Molucca Sea (e.g., Bader et al., 1999; Fig. 10D).

Direct evidence of subaerial exposure of French Range blueschist (i.e., blueschist clasts in the Whitehorse Trough) is elusive, although other clast types derived from the Cache Creek rocks are common. Our examination of clasts in ≥100 samples of Whitehorse Trough arkose, sandstone, wacke, and siltstone revealed only one sand-sized grain that may be composed of fine-grained blue amphibole; dozens of eclogitic clasts, however, were recovered. The possible blueschist clast is a composite grain of blue prismatic crystals that are <100 µm in long dimension. Its fine grain size renders petrographic identification equivocal. The clast, as well as the eclogite clasts, is from strata for which biostratigraphic age control is lacking. From their location within the inboard part of the Whitehorse Trough, however, the strata containing the eclogite clasts are probably among the youngest exposed: they are part of a thrust sheet high in the stack, and they occupy the highest stratigraphic level within that sheet (English et al., 2003).

As near Pinchi Lake (Fig. 1), the only other eclogite locality known within Cache Creek rocks in British Columbia, the eclogite clasts are interpreted as derived from high-pressure–low-temperature Cache Creek rocks. Considering the small area of relatively recessive blueschist exposed today, blueschist grains derived from the French Range are expected to be rare. This likelihood is in contrast to abundant exposures of mantle tectonite and vast exposures of chert, which provided durable clasts. Whitehorse Trough strata containing clasts derived from Cache Creek rock types are Middle Jurassic (Bajocian), but fossiliferous strata of this age are uncommon within the Whitehorse Trough. Unfossiliferous strata of possible Middle Jurassic age contain locally abundant chromite, serpentinite, and fresh olivine clasts, suggesting that mantle rocks were subaerially exhumed by ca. 170 Ma.

Plutons Cut Cache Creek Wedge Extrusion Fabrics by 172 Ma?

Emplacement-related folds and faults affect the inboard margin of the Cache Creek wedge from Teslin Lake in the north (Jackson, 1992; Gordey and Stevens, 1994) to the French Range in the south. They also extend across the wedge and into the Whitehorse Trough. The minimum age of these structures is constrained by postkinematic plutons along the inboard central and outboard parts of the Cache Creek wedge for >200 km along strike (Fig. 1) that show crystallization ages of ca. 172 Ma (Fig. 2). The minimum crystallization age of 170.9 ± 0.5 Ma from the Slaughterhouse pluton places a minimum age constraint on structures along the inboard edge. The tightest constraint, however, is provided by age-dated postkinematic plutons closer to the outboard edge (Figs. 1 and 2). Near Atlin, the Fourth of July batholith cut and thermally metamorphosed the structurally thickened Cache Creek wedge at its outboard edge (Aitken, 1959). A sample of the batholith has yielded a U-Pb zircon date of 171.7 ± 3 Ma (Mihalynuk et al., 1992). A hornblende ^{40}Ar/^{39}Ar date of 172.7 ± 1.7 Ma was reported by Harris et al. (2003) and, thus, is identical within error. Other ^{40}Ar/^{39}Ar cooling dates of 167 ± 3 Ma, 168 ± 3 Ma, and 171 ± 3 Ma (Ash, 2001) for chromian mica from the thermal halo of the batholith similarly indicate rapid cooling.

North of the Yukon–British Columbia boundary, near Teslin Lake, the Mount Bryde pluton cuts deformed Cache Creek rocks and yielded a U-Pb zircon date of 175.7 ± 1.4 Ma (provides constraint Z, 174.3 Ma, in Fig. 2), with slight discordance attributed to lead loss, and a minimum possible ^{206}Pb/^{238}U age of 172.0 Ma (Gordey et al., 1998; provides constraint Z* in Fig. 2). Cooling dates from hornblende and biotite (^{40}Ar/^{39}Ar) of 173 ± 3 and 169 ± 2 Ma, respectively, also indicate rapid cooling.

Spanning the central part of the northern Cache Creek wedge are the postkinematic Llangorse Mountain batholith and McMaster pluton (L and M in Fig. 1), which yielded U-Pb zircon dates of 172.7 ± 0.3 Ma (provides constraint Y in Fig. 2) and 171.7 ± 0.3 Ma (provides constraint X in Fig. 2), respectively (Mihalynuk et al., 2003). At the latitude of the French Range, near Tachilta Lakes (see Fig. 1), a postkinematic granite body has yielded a K-Ar date of 173 ± 4 Ma (Stevens et al., 1982).

Broad undeformed metamorphic aureoles have been mapped around most of the Middle Jurassic bodies (Aitken, 1959; Mihalynuk et al., 1998; Bath, 2003). Several are recorded as annular aeromagnetic highs around other intrusive bodies (Lowe and Anderson, 2002); no aureoles appear deformed.

In consideration of the available data, we conclude that the French Range blueschists were emplaced along structures that ceased to be active before ca. 172 Ma, the age of the oldest postkinematic plutons. This time is similar to the time of emplacement of Cache Creek rocks proposed by Tipper (1978) on the basis of middle Bajocian ammonite zones that date the oldest rocks not affected by deformation in the footwall of the King Salmon thrust (see Fig. 2 for stage boundaries). In contrast, Ricketts et al. (1992) suggested an older, late Toarcian to Aalenian age on the basis of a condensed section that they interpreted as recording the onset of emplacement. This age, however, is too old to accommodate the formation of 173.7 ± 0.8 Ma blueschist.

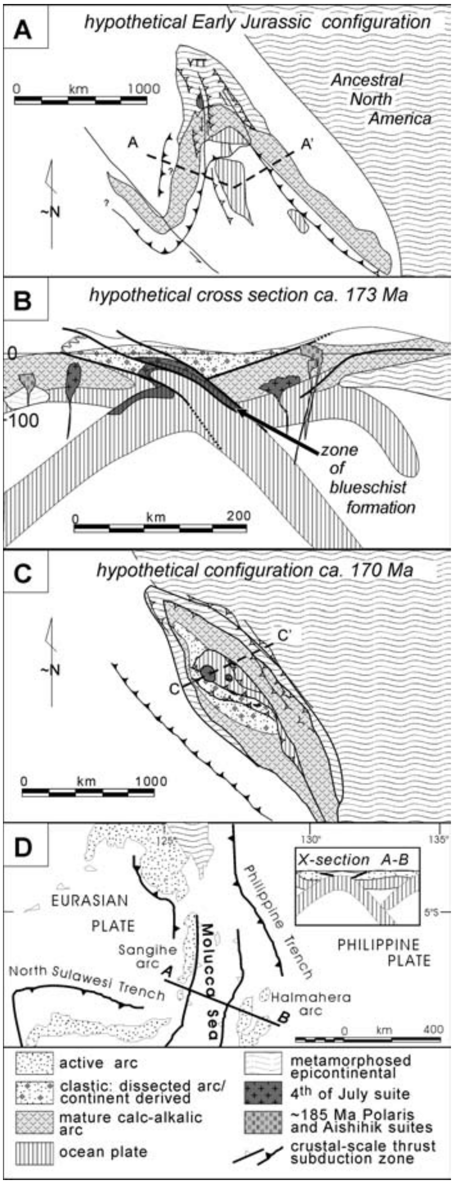

Figure 10. Model for blueschist emplacement, modified after Mihalynuk et al. (1994). (A) Cartoon of arc configuration at ca. 185 Ma when Cache Creek terrane strata deposited included hemipelagite and chert sharpstone conglomerates near fault scarps. (B) Hypothetical cross section at ca. 173 Ma showing rupture of doubly subducting Cache Creek oceanic crust. Location of cross section lines A–A′ (in A) and C–C′ (in C) show past and future locality of cross section. (C) Cartoon of hypothetical configuration ca. 170 Ma. (D) The Molucca Sea region: a modern-day analogue of a double subduction zone with an exposed axial region.

Exhumation Rate

Some blueschists of the North American Cordillera are interpreted as tectonic mélanges developed during subduction-zone backflow (e.g., parts of the Franciscan Complex, see Cloos, 1986). In contrast, stratigraphic units in the French Range are physically coherent over large areas. This coherence limits the amount of tectonic dismemberment attributable to exhumation. Other coherent blueschist terranes are known, for example, in the Villa de Cura belt of Venezuela (Smith et al., 1999), the Mount Olympus area of Greece (Schermer et al., 1990), and, in the Franciscan Complex, the Yolla Bolly terrane (Blake et al., 1988), Black Butte area (Ghent, 1965), Diablo Range (Chatawanich and Cloos, 2000), and Bay areas (Wakabayashi, 1999) of California. For none of these coherent blueschist terranes, however, is the chronology of blueschist uplift and emplacement as precisely constrained as in the French Range (if it can be assumed that our interpretation of geologic and geochronologic data are correct). Combining this chronology with petrographic data permits calculation of a lower limit on the rate of emplacement.

The minimum pressure recorded by French Range blueschists is ~3 kbar for $P_{H_2O} = P_{solid}$ (~11 km depth for a mean density of 2700 kg·m^{-3}). From the aegirine (Jd$_{20}$) + quartz veins, the minimum pressure is constrained to be ~4.8 kbar, at 200 °C (~18 km depth for a density of 2700 kg·m^{-3}). Draper and Bone (1981) suggested that the minimum exhumation rate to preserve blueschists for rocks with normal radioactive heat generation is 1.4 mm·yr^{-1}. For the French Range rocks, this rate yields only 3.5 km of unroofing in 2.5 m.y., if it is assumed that the blueschists reached the surface in this time interval. The time of surface exposure of Kedahda chert is recorded by chert-granule deposition in the lower Bajocian strata of the Whitehorse Trough (ca. 170 Ma). By using these minimum depths, the rates of unroofing would be ~4.4–7.2 mm·yr^{-1}. These rates are higher than those estimated from sediment-discharge rates (<1 mm·yr^{-1}), but are within the range estimated from isotopic ages and used in thermal models proposed for the Alps and the Canadian Cordillera (e.g., Draper and Bone 1981). They are also consistent with the exhumation rates that prevent a higher-temperature overprint in blueschists worldwide (e.g., Ernst, 1988).

SUMMARY

Rapid emplacement of Cache Creek oceanic rocks, including 173.7 ± 0.8 Ma blueschist of the French Range, probably occurred by wedge extrusion during arc collision with ancestral North America (Figs. 10A, 10B). Cache Creek oceanic crust was bowed up between the colliding Stikine and Quesnel arcs and finally ruptured (analogous to the Molucca Sea, Figs. 10B, 10C, 10D), leading to rapid wedge extrusion. Collision produced widespread southwest-verging folds and northeast-dipping thrust faults that deformed Cache Creek and forearc strata as young as early Bajocian (ca. 171–175 Ma). Geologic relationships require that coherent blueschist-grade strata containing late Pliensbachian to Toarcian radiolaria (ca. 177 Ma to ca. 191 Ma) in the French Range were tectonically emplaced together with other oceanic rocks and intruded by postkinematic plutons dated as at least as old as 172 Ma (Fig. 10C). If the cooling age represents the age of peak metamorphism within the subduction zone, <2.5 m.y. elapsed between the initiation of wedge extrusion and exhumation of the French Range blueschist.

ACKNOWLEDGMENTS

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