Recent Revisions to the Early Mesozoic Stratigraphy of Northern Vancouver Island (NTS 102I; 092L) and Metallogenic Implications, British Columbia

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INTRODUCTION

In order to improve our understanding of the mineral potential of northern Vancouver Island beyond the well-known intrusion-related Cu-Au-Ag(-Mo) porphyry deposits (*e.g.,* Hushamu, MINFILE 092L 240 and the former Island Copper mine, MINFILE 092L 158) and base and precious-metal skarns (*e.g.,* Merry Widow, MINFILE 092L 044), we need a better understanding of the stratigraphy of the Bonanza island arc so as to apply predictive models for mineral exploration that target specific stratigraphic metallotects. Epithermal precious-metal prospects are known (*e.g.*, Mount McIntosh – Hushamu, MINFILE 092L 240), but many more opportunities exist in the world-class, metallogenic supra-subduction zone and flood basalt environments presented on Vancouver Island.

A new stratigraphic framework for the Early Mesozoic stratigraphy of northern Vancouver Island was recently published in a series of Geoscience Maps (1:50 000 scale; Nixon *et al*., 2006c–e). This paper provides a brief synopsis of our current view of the regional stratigraphy and attempts to highlight intervals in the stratigraphic column that are prospective for some important deposit types, not all of which are presently known on Vancouver Island.

REGIONAL GEOLOGY

The geology of Vancouver Island is characterized principally by Late Paleozoic to Early Mesozoic rocks belonging to the tectonostratigraphic terrane of Wrangellia (Jones *et al*., 1977), which extends north through the Queen Charlotte Islands into southern Alaska (Wheeler and McFeely, 1991; Fig 1). Wrangellia was amalgamated with the Alexander Terrane in the Alaska panhandle to form the Insular Belt as early as the Late Carboniferous (Gardner *et al*., 1988) and was accreted to inboard terranes of the Coast and Intermontane Belts as late as mid-Cretaceous (Monger *et al*., 1982) or as early as Middle Jurassic time (van der Heyden, 1991; Monger and Journeay, 1994).

At the latitude of northern Vancouver Island, Wrangellia is intruded to the east by granitoid rocks of the Coast Plutonic Complex and fault-bounded to the west by the Pacific Rim Terrane and metamorphosed rocks of the Westcoast Crystalline Complex (Wheeler and McFeely, 1991). Devonian to Early Permian island-arc volcanic, volcaniclastic and sedimentary rocks that form the basement of Wrangellia (Sicker and Buttle Lake groups; Massey, 1995a–c) are not exposed on northernmost Vancouver Island. The bedrock stratigraphy is dominated by the Triassic tripartite succession of Karmutsen flood basalt, Quatsino limestone and Parson Bay mixed carbonate-clastic (volcanic) sequence, which is diagnostic of Wrangellia (Jones *et al*., 1977). The overlying Jurassic volcanic and sedimentary strata, together with coeval granitoid intrusions of the Island Plutonic Suite, comprise the main phase of magmatism of the Bonanza island arc (Northcote and Muller, 1972; DeBari *et al*., 1999).

A major contractional event is marked by an angular unconformity underlying Jura-Cretaceous clastic sequences deposited on the eroded surface of the Bonanza Group. This episode of deformation is constrained by strata of Late Jurassic age (Oxfordian to Tithonian), locally underlying more widespread Cretaceous sedimentary rocks in the northern Vancouver Island – Queen Charlotte Islands region (Gamba, 1993; Haggart and Carter, 1993; Haggart, 1993).

The history of faulting on northern Vancouver Island is complex and embodies Cretaceous transpression and Tertiary extension. Major northwesterly trending, high-angle faults right-laterally displace (where possible to determine), downdrop and fold Jura-Cretaceous to early Late Cretaceous clastic rocks exposed in the Quatsino Sound area (Muller *et al*., 1974; Nixon *et al*., 1993a, 1994a, 1995a). These sequences are preserved as disparate fault-bounded remnants of the Cretaceous basins (Muller *et al.*, 1974; Jeletzky, 1976; Haggart, 1993). The relatively low relief and high heat flow of northernmost Vancouver Island reflect tectonism associated with the development of the Queen Charlotte Basin, a Tertiary transtensional province related to oblique convergence of the Pacific and Juan de Fuca plates with the North American Plate (Riddihough and Hyndman, 1991; Lewis *et al*., 1997).

The present crustal architecture exhibits a dominant northwesterly trending structural grain manifested by the distribution of major lithostratigraphic units and granitoid plutons (Fig 1). Numerous fault-bounded blocks of homoclinal, Early Mesozoic strata generally dip westward

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(Muller *et al*., 1974). The northeasterly trending Brooks Peninsula fault zone appears to coincide with the southern limit of Neogene volcanism in the region and delineate the southern boundary of the Tertiary extensional regime in the Queen Charlotte Basin (Armstrong *et al*., 1985; Lewis *et al*., 1997).

PREVIOUS STRATIGRAPHIC NOMENCLATURE

The evolution of stratigraphic nomenclature for northern Vancouver Island is shown in Figure 2. The earliest recorded geological investigations were made by G.M. Dawson, who introduced the name 'Vancouver Series' for all the volcanic and sedimentary rocks underlying the unconformity at the base of the Cretaceous succession (Dawson, 1887). Subsequently, Gunning (1930) adopted the term Vancouver Group to describe the conformable succession of Lower Mesozoic volcanic and sedimentary rocks in the Quatsino-Nimpkish area. He later subdivided the stratigraphy into three distinct units: the Quatsino limestone (Dolmage, 1919); the underlying Karmutsen volcanics named for extensive exposures overlooking the western shore of Nimpkish Lake in the Karmutsen Range; and the overlying sedimentary-volcanic succession of the Bonanza Group exposed on the upper slopes west of Bo-

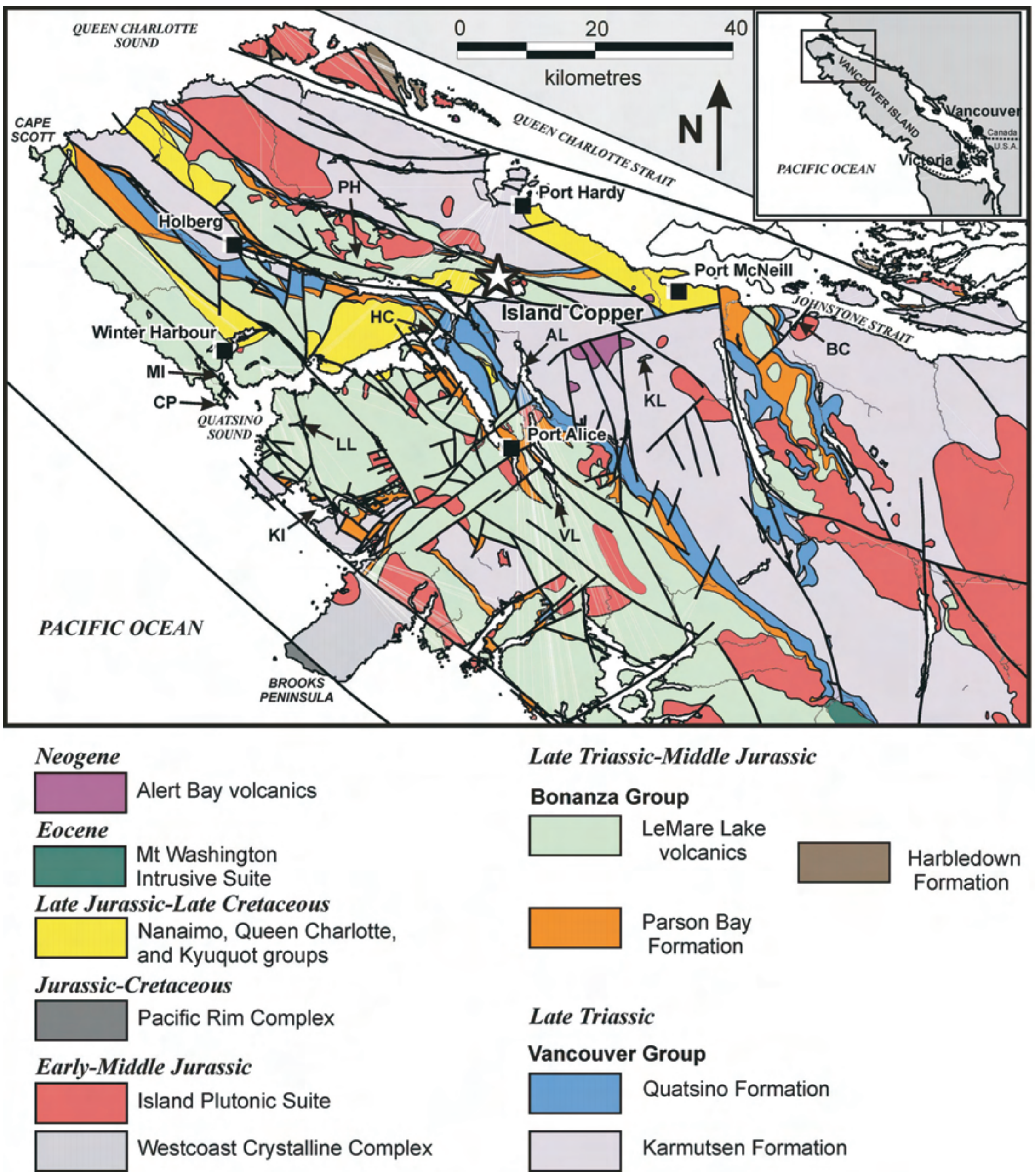

Figure 1. Regional geology of northern Vancouver Island (*after* Massey *et al*., 2005). Abbreviations for localities mentioned in text: AL, Alice Lake; BC, Beaver Cove; CP, Cape Parkins; HC, Hecate Cove; KI, Klaskino Inlet; KL, Keogh Lake; LL, Le Mare Lake; MI, Mathews Island; PH, Pemberton Hills; VL, Victoria Lake.

nanza Lake (Gunning, 1932; Fig. 2). Based on sparse fossil evidence, the age of the Vancouver Group was considered to be Late Triassic to Early Jurassic. This tripartite succession was traced southward into the Zeballos region by Gunning (1933) and later by Hoadley (1953), who incorporated much of Gunning's earlier work in the Nimpkish and Woss areas (Gunning, 1938a–d). Hoadley (1953) more formally designated the Karmutsen volcanic rocks as the Karmutsen Group and was able to systematically map a lower sedimentary and upper volcanic division within the Bonanza Group, as previously recognized by Gunning (1932, 1933). This stratigraphic framework for the Vancouver Group was adopted by Muller and Carson (1969), who designated the Bonanza as a subgroup and the Karmutsen as a formation.

Between 1949 and the early 1970s, detailed geological investigations of coastal exposures in Quatsino Sound were conducted by J.A. Jeletzky, who established the basis for Mesozoic stratigraphy in the region from fossil collections (Jeletzky, 1950, 1954, 1969, 1970a, b, 1973, 1976). Following Gunning (1932) and Hoadley (1953), Jeletzky subdivided the Vancouver Group into the Karmutsen and Bonanza subgroups and divided the Bonanza into an upper volcanic and lower sedimentary division, which included the Quatsino Formation at its base (Fig 2). Above the Quatsino limestone, he recognized three mappable sedimentary units, from oldest to youngest: the informally named 'thinly bedded' and 'arenaceous' members, and the Sutton limestone situated at the top of the sedimentary division (where present) and correlative with the Sutton Formation at the type locality on Cowichan Lake (Tozer, 1967; Stanley, 1988). The overlying volcanic division of the Bonanza subgroup contained nine mappable units, only two of which were given formal status: the mixed volcanic-sedimentary succession of the Hecate Cove Formation at the base, named for the cove near Quatsino Narrows at the eastern end of Quatsino Sound; and the younger, predominantly argillaceous Mathews Island Formation near the entrance to the sound in Forward Inlet (Fig 1, 2).

Integrated lithostratigraphic, biostratigraphic and mineral deposit studies of the Alert Bay – Cape Scott map area (NTS 092L; 102I) by Muller and coworkers provided the first regional geological synthesis for northern Vancouver Island (Muller *et al*. 1974; Muller and Roddick, 1983). The entire Lower Mesozoic stratigraphy was referred to as the Vancouver Group and two new formations were introduced: the Late Triassic Parson Bay and Lower Jurassic Harbledown formations, as first distinguished by Crickmay (1928) on Harbledown Island, the type locality, in Queen Charlotte Strait (Fig 2). As used by Muller *et al*. (1974), the Parson Bay Formation is equivalent to the 'sedimentary division of the Bonanza subgroup' of Jeletzky (1973, 1976), but includes his Hecate Cove Formation and excludes the Quatsino limestone (Fig 2). The argillite-greywacke sequence of the Harbledown Formation is correlative with Bonanza volcanics of western Vancouver Island but in the Alert Bay – Cape Scott region has only been distinguished as a map unit at the type locality and on islands in Queen Charlotte Sound (Fig 1, 2). Muller *et al*. (1974) abandoned

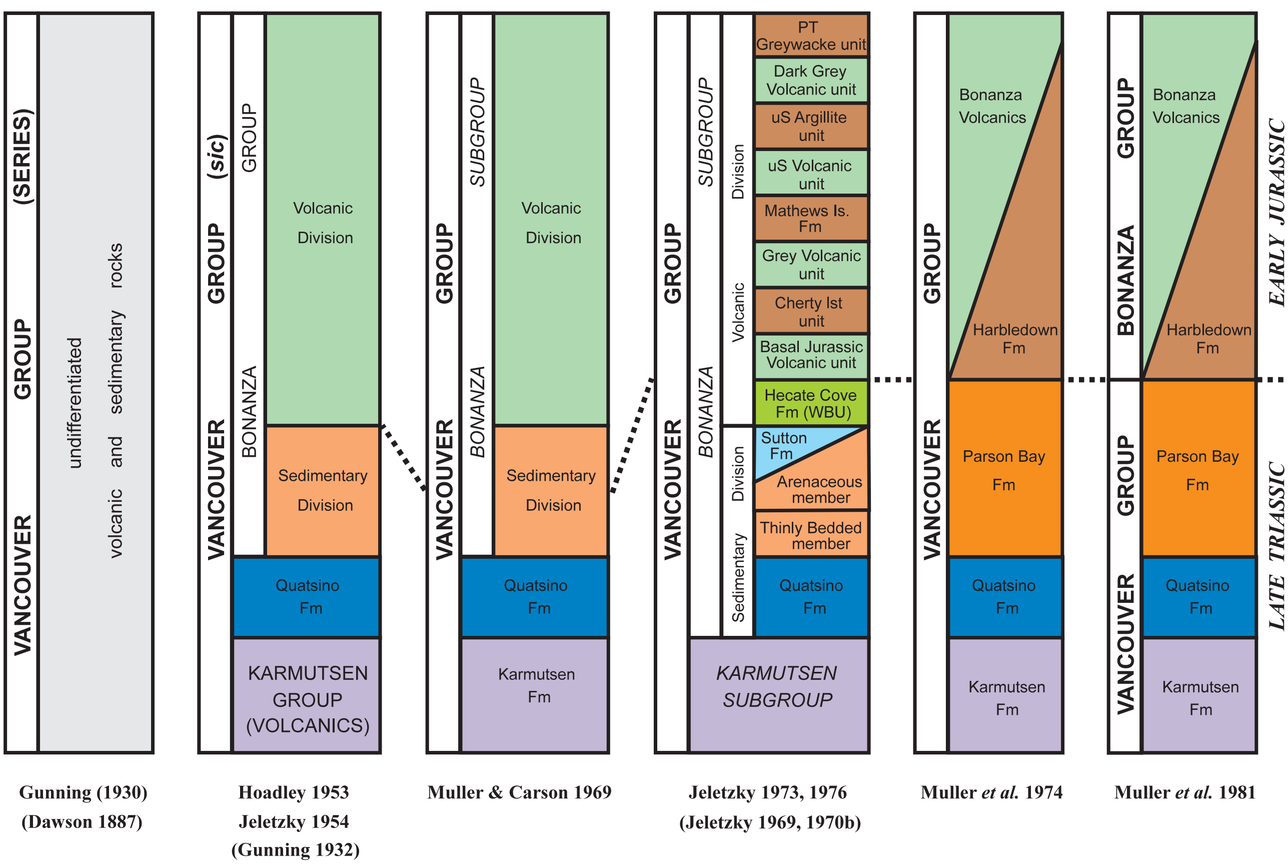

Figure 2. Evolution of Lower Mesozoic stratigraphic nomenclature for northern Vancouver Island. Alternative nomenclature and corresponding references shown in brackets. Abbreviations for Jeletzky's stratigraphy are as follows: WBU, water-laid breccia unit; uS, uppermost Sinemurian (early Early Jurassic); PT, Pliensbachian–Toarcian (late Early Jurassic).

the 'subgroup' and 'division' terminology and defined the 'Bonanza volcanics' as a single map unit comprising diverse volcanic rocks with minor intercalated sedimentary rocks, essentially equivalent to the 'Bonanza subgroup' and replacing the more complex stratigraphy erected by Jeletzky (1976). The base of the 'Bonanza volcanics' was taken as the lowest andesitic lava or volcanic breccia overlying sedimentary strata of the Late Triassic Parson Bay Formation in the west or the Early Jurassic Harbledown Formation in the east; and locally, this contact lies above the Sutton limestone. Subsequently, Muller *et al*. (1981), working in the Nootka Sound area, made revisions to the stratigraphy by restricting the Vancouver Group to the Karmutsen, Quatsino and Parson Bay formations, and reinstating the Bonanza Group, which now comprises the Harbledown Formation and the partly coeval 'Bonanza volcanics' (Fig 2).

REVISED LITHOSTRATIGRAPHY

Revisions to the Early Mesozoic lithostratigraphic nomenclature adopted in this report are shown in Figure 3 and are based on previously published and unpublished mapping, and geochronological and biostratigraphic data for the Quatsino Sound area (Nixon *et al.,* 1993a, b; 1994a, b; 1995a, b; 2000, 2006a–e; Friedman and Nixon, 1995; Archibald and Nixon, 1995). Absolute ages for stage boundaries are based on recent revisions to the geological time scale (Gradstein *et al*., 2004; Furin *et al*., 2006).

As shown in Figure 3, the Vancouver Group on northern Vancouver Island includes two lithostratigraphic units, the Late Triassic Quatsino and mid to Late Triassic Karmutsen formations. The basal unit of the Vancouver Group, the Middle (late Ladinian) to Late Triassic 'sediment-sill unit' of Muller *et al*. (1974), comprising siliceous black shale and siltstone (including the pelecypod-rich 'Daonella beds') intruded by super-abundant basaltic sills considered coeval with Karmutsen lava, is not exposed on this part of Vancouver Island. The overlying Bonanza Group now includes the Late Triassic Parson Bay Formation and two informal units of latest Triassic to Middle Jurassic (Bajocian) age: a mixed volcaniclastic-sedimentary rock sequence resting conformably on Parson Bay strata; and the overlying LeMare Lake volcanics. The latter unit is named for Le Mare Lake on the west coast near the entrance to Quatsino Sound (Mahatta Creek map sheet NTS 092L/05), where basaltic to rhyolitic lava, ash flow tuff and interbedded epiclastic deposits of the Bonanza Group are well exposed. The informal term 'LeMare Lake volcanics' replaces the 'Bonanza volcanics' of Muller *et al*. (1974, 1981; Fig 2) in order to potentially avoid confusion with the Bonanza Group as a whole and to conform to naming conventions specified in the North American Stratigraphic Code. Since the term 'Bonanza volcanics' is so well established in the literature, it may be usefully retained to describe all volcanic rocks within the Bonanza Group, including those within the Parson Bay Formation (described below).

The unnamed, latest Triassic – earliest Jurassic volcaniclastic-sedimentary unit of the Bonanza Group occupies a transition between predominantly marine deposition in the Parson Bay and widespread subaerial volcanism in LeMare Lake time, and appears to be partially correlative with the Early Jurassic Harbledown Formation (Muller *et al*., 1974, 1981; Fig 2, 3). Following the early work of Crickmay (1928) at the type locality in Parson Bay, Harbledown Island, Tipper (1977) found that ammonite zonation in the Harbledown Formation could only confirm late–early to latest Sinemurian strata, and noted that the Jurassic rocks were separated by a fault from the Late Triassic Parson Bay Formation. However, working farther south in the Bute Inlet area, Carlisle (1972) established a conformable contact between the Parson Bay and Harbledown formations. Based on ammonite fauna collected from an argillite-greywacke succession on Balaclava Island in the Queen Charlotte Sound, Muller *et al*. (1974) extended the Harbledown Formation into the Early Pliensbachian (Frebold and Tipper, 1970). Thus, these data indicate that the Harbledown Formation, as currently defined, is correlative with much of the lower part of the LeMare Lake volcanics and practically the entire stratigraphic succession erected by Jeletzky (1976; Fig 2).

STRATIGRAPHY

The principal mappable units of the Vancouver and Bonanza groups presently comprise both formal lithostratigraphic units and informal subunits, which require further investigation before their status can be determined. The latter units occur within the Karmutsen and Parson Bay formations and LeMare Lake volcanics, and are lithologically distinct from their hostrocks, except for picritic lava within the Karmutsen (Fig 3). Some of these subunits are regionally significant and may serve as local stratigraphic markers once confirmed by isotopic dating studies currently in progress. The main lithological and textural characteristics of the map units and their stratigraphic relationships, are summarized below.

Vancouver Group

The Vancouver Group in the Quatsino Sound area is represented by the mid to Late Triassic Karmutsen and overlying Quatsino formations.

KARMUTSEN FORMATION

Previous work by Carlisle (1972) in the Bute Inlet – Schoen Lake area established three subdivisions of regional significance within the Karmutsen flood basalt: a lower pillow lava sequence overlain by locally well-bedded pillow breccia, hyaloclastite ('aquagene' tuff) and reworked equivalents; in turn overlain by a succession of subaerial flows. In the Quatsino Sound area, layered flow sequences of the youngest Karmutsen subdivision predominate and the intermediate clastic division appears to be only weakly developed. The uppermost part of the basal pillow lava sequence underlies ground south of Port McNeill between the northern tips of Alice and Nimpkish lakes and toward the east coast in the poorly accessible, northeastern part of the Nimpkish map sheet (Nixon *et al*., 2006a, b). The minimum true thickness of the entire basalt succession is estimated to exceed 6000 m (Muller *et al*., 1974); evidence of low-grade metamorphism in the Karmutsen Formation, ranging from zeolite to prehnite-pumpellyite facies, is well documented (*e.g*., Surdam, 1973; Kuniyoshi and Liou, 1976; Greenwood *et al*., 1991).

Typical Karmutsen basalt is black to dark grey-green, commonly aphanitic or more rarely plagioclase-phyric, and generally amygdaloidal in some part of the flow unit. Contacts between individual flows are usually sharp and planar to undulatory, and typically lack flow breccia or any evidence for significant erosion or paleosol development. Flow thicknesses are usually on the order of several metres, but range from 1 m or less to over 12 m where clearly discernible; flows up to 30 m thick were recorded by Muller *et al*. (1974). Primary columnar jointing, a characteristic feature of many continental flood basalt provinces, is notably lacking. Rarely, bulbous flow lobes, toes and ropy crusts of pahoehoe lava are well preserved. Certain lava exhibits pronounced flow foliations defined by zones of vesicle enrichment ranging from a few centimetres to >50 cm. These zones are almost invariably parallel to flow contacts and provide reliable structural markers in the absence of bedding. Locally conspicuous pipe vesicles are oriented perpendicular to flow contacts and vesicle layering, except where plastically deformed during the final stages of flow emplacement. Amygdules are commonly filled with quartz, potassium feldspar, epidote, chlorite, carbonate, zeolite and clay minerals.

Pillow lava sequences are generally closely packed and locally contain interpillow hyaloclastite and interstitial quartz, zeolite, carbonate, epidote and chlorite. Rarely, near the top of the pillow basalt subdivision, compound flow units are exposed, comprising several metres of massive lava passing into pillowed flows directly below. Such features may represent an emergent event or simply reflect an increase in the rate of extrusion or local flow emplacement.

The pillow breccia is generally massive or indistinctly bedded and some contain dispersed whole pillows. Hyaloclastite deposits incorporate curvilinear, spalled pillow rinds, dispersed pillow fragments locally preserving

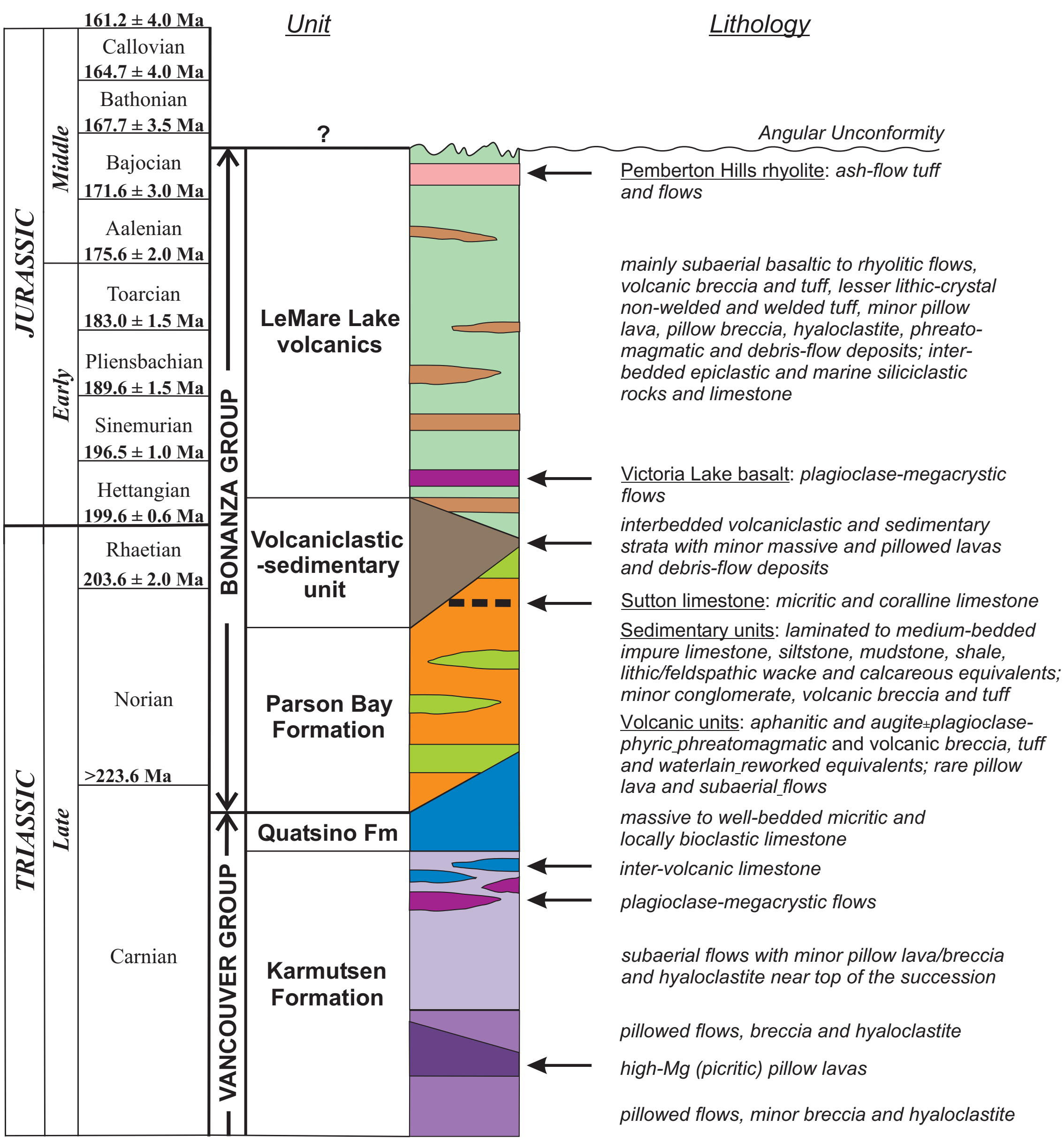

Figure 3. Schematic stratigraphy of northern Vancouver Island and revised nomenclature for Triassic-Jurassic lithostratigraphic units described in this report. The geological time scale is that of Gradstein *et al*. (2004), except for the Carnian-Norian Stage boundary, which is taken from Furin *et al*. (2006).

chilled margins and angular, lapilli-sized clasts set in a finely comminuted, grey-green to orange-brown (formerly palagonitized?) basaltic matrix.

Intra-Karmutsen Limestone

Discontinuous beds and lenses of grey limestone, and more rarely, fine-grained siliciclastic sedimentary rocks, occur near the top of the Karmutsen succession, not far below the base of the overlying Quatsino Formation. The intra-Karmutsen limestone is typically micritic, massive or poorly bedded, and generally does not exceed about 8 m in thickness. Rarely, this limestone contains oolitic beds and exhibits cross-stratification, providing clear evidence of intertidal and shallow marine deposition. Locally, the limestone is associated with thin units of pillow basalt. Other rare intervolcanic deposits include thin, laminated to medium-bedded, variably calcareous, intercalated sequences of mudstone, shale, siltstone and limestone. Similar, stratigraphically equivalent rock types, including *Halobia*-bearing shale, were described in detail by Carlisle and Suzuki (1974).

It is clear from their stratigraphic position that these intervolcanic sedimentary deposits were formed during the waning stages of Karmutsen volcanism. The limestone essentially represents the initial phase of deposition of Quatsino limestone prior to the cessation of volcanic activity, and the fine-grained clastic rocks are vestiges of erosive products deposited in low-energy environments. Thus, erosion, carbonate-clastic sedimentation and effusive volcanism were occurring concurrently, through to the initial stages of deposition of Quatsino limestone.

Plagioclase-Megacrystic Flows

Near the top of the subaerial succession, lava distinguished by its plagioclase megacrysts is locally intercalated with aphanitic and sparse porphyritic flows carrying plagioclase phenocrysts (<5 m). The plagioclase megacrysts (1–2 cm) form euhedral to subhedral laths and blocky grains, occupy 20 to 40 vol% of the rock, and are set in a compact to strongly amygdaloidal groundmass carrying smaller feldspar crystals. Locally, these lavas display trachytoid textures and zones of megacryst concentration oriented parallel to the flow fabric. It is important to note that these megacrystic flows are confined to the uppermost part of the Karmutsen Formation, and as such, serve as stratigraphic markers where outcrops of intra-Karmutsen or Quatsino limestone are sparse or absent altogether (Nixon *et al*., 2006b).

Picritic Lavas

The first occurrence of picritic lava with high MgO content (up to ~20 wt%) in the Karmutsen Formation was recently reported by Greene *et al*. (2006). Currently known occurrences of picrite is confined to the uppermost part of the basal pillow basalt division (Fig 3). At Keogh Lake, the type locality situated 12 km south of Port McNeill, oblate to subrounded pillows measuring between about 0.25 and 1 m across form closely packed pillow sequences with virtually no interstitial clastic or mineral infillings. In other exposures, individual pillows may be much larger (up to 5 m), and secondary quartz, epidote and carbonate commonly occupy interstices between pillows and rarely infill semi-circular to oblate intrapillow cavities formed by partial lava drainage.

Macroscopically, the picrite is indistinguishable from normal Karmutsen basalt; they are slightly denser and characteristically non-magnetic, in contrast to the strongly magnetic character of the least-altered basalt. Chemical analysis and petrographic identification of olivine phenocrysts, which have been completely replaced by serpentine, talc, chlorite, opaque oxide and clay minerals, are the only true discriminants. Aside from their potential importance with respect to the petrogenesis of the Karmutsen flood basalt province, the picrite may have metallogenic significance with regard to the potential for Ni-Cu-PGE (platinum group element) mineralization in this part of Wrangellia (discussed below).

QUATSINO FORMATION

The contact between the Quatsino and Karmutsen formations has been described by Muller *et al*. (1974) as a paraconformity (*i.e*., an uncertain unconformity in which no erosion surface is clearly discernible). The examination of this contact at various localities reveals either massive Quatsino limestone in sharp contact with basaltic flows, or a thin (<25 cm) intervening layer of black to orange-brown weathering, basaltic sandstone and siltstone, which is variably calcareous and clay altered. These clastic deposits are commonly discontinuous along strike, but provide clear evidence for a brief period of erosion of the lava shield prior to, and probably during, the primary stages of deposition of the Quatsino limestone. Thus, these initial carbonate-clastic deposits at the base of the Quatsino mirror those that formed prior to the cessation of volcanism as more restricted deposits of intra-Karmutsen limestone and marine siliciclastic material.

The lower part of the Quatsino Formation is typically a pale grey weathering, dark to medium grey, predominantly massive micritic limestone. Fossils are generally rare, although poorly preserved ammonites have been noted at several localities. The uppermost part of the Quatsino limestone is typically composed of thinly laminated to medium or thickly bedded micrite and rarely calcarenite, which locally contain laminae enriched in bioclastic debris. Dark grey to black chert concretions, layers and irregular replacements are locally conspicuous. Normally graded beds and rare crosslaminations in some sequences attest to deposition by turbidity currents. Transported shell fragments of note include gastropods up to 1 cm across, and thin-shelled pelecypods (mainly *Halobia* sp.) up to several centimetres in width. The top-most beds of the Quatsino Formation locally contain a diverse fossil assemblage, including both single and colonial corals, nautiloids and ammonites (Muller *et al*., 1974; Jeletzky, 1976).

Previous workers noted that the thickness of Quatsino limestone varies from west to east across northern Vancouver Island: the unit is <40 m thick in Klaskino Inlet on the west coast, reaches a maximum thickness of almost 500 m in the central Alice Lake area and thins eastward to about 75 m in the vicinity of Beaver Cove (Muller and Rahmani, 1970). This variation in thickness corresponds to a difference in age. Based on ammonite and conodont faunas, the top of the Quatsino limestone in the thickest section near Alice Lake is late Early Norian in age, but on the east and west coasts, the limestone is entirely restricted to the Carnian (Muller *et al*., 1974; Jeletzky, 1976; Nixon *et al*., 2000; 2006a, b). Given the subaerial nature of the final phase of Karmutsen volcanism and the existence of a discontinuous veneer of basaltic detritus at the base of the

Quatsino limestone, it seems probable that the base of the Quatsino Formation is also diachronous.

Bonanza Group

The Late Triassic to Middle Jurassic Bonanza Group comprises the Parson Bay Formation at its base, an intermediate unnamed unit of interbedded volcaniclastic and sedimentary rocks, and the overlying LeMare Lake volcanics (Fig 3). As redefined herein, therefore, the Bonanza Group reverts to the original definition of Gunning (1932; Fig 2) and embodies a diverse assemblage of volcanic and epiclastic products related to the development and demise of the Bonanza island arc.

PARSON BAY FORMATION

The Parson Bay Formation may be described in terms of two mappable units: sedimentary units typically comprising fine-grained siliciclastic-carbonate sequences, which are usually predominant; and subordinate volcanic units, which includes flows and volcaniclastic deposits (*i.e.*, fragmental rocks of volcanic parentage, irrespective of origin). The volcanic units are restricted in lateral extent and occupy more than one stratigraphic position within the Parson Bay Formation (Fig 3). Their precise stratigraphic relationships are currently being investigated using conodont biostratigraphy and geochronology.

The contact between the Parson Bay Formation and underlying Quatsino limestone is conformable and typically gradational over widths of about 0.5 to 5 m. This thin to medium-bedded interval is generally marked by intercalations of pale grey-weathering Quatsino limestone and dark grey, impure (siliceous to sandy) limestone, calcareous mudstone and siltstone and minor, locally fossiliferous (*Halobia* sp.) black shale of the Parson Bay succession. The contact is placed at the first appearance of siliciclastic beds.

The thickness of the Parson Bay Formation is difficult to estimate due to its generally poor exposure, localized structural disruption by low-angle faults subparallel to bedding and intrusion by numerous dikes and sills coeval with the LeMare Lake volcanics. In measured sections presented by Muller and Rahmani (1970), the true thickness of the Parson Bay is estimated to be on the order of 300 m in the Klaskino section on the west coast, and 600 m in the central Alice Lake area. These thicknesses, however, include, in part or in whole, the Triassic-Jurassic volcaniclastic-sedimentary unit of this report (described below).

Sedimentary Rock Types

Typical Parson Bay sedimentary rock types include grey to black, thinly laminated to medium-bedded, impure micritic limestone and calcareous to non-calcareous mudstone, siltstone and shale. Minor interbeds include grey-brown to pale buff, fine to coarse-grained feldspathic sandstone, locally pebbly; grey-green lithic volcanic wacke; rare pebble to cobble conglomerate rich in volcanic clasts; and thin volcaniclastic breccia and debris-flow deposits. Rare ochre to pale grey weathering, clay-rich beds (<5 cm thick) may reflect degraded tuffaceous layers; black shale may be distinctly carbonaceous; and wavy laminations in certain limestone probably represent algal mats. Sedimentary structures observed in the sandy layers include normal, and rarely reverse, grading and rare bedding plane scours and dewatering features (load and flame structures). Debris flow deposits commonly occupy erosional channels, and structures resembling desiccation cracks were noted in mudstone at a single locality. Fissile black shale horizons may contain bedding planes crowded with thin-shelled pelecypods: *Halobia* sp. (Carnian to Middle Norian) in the lower part of the succession and *Monotis* sp. (Late Norian) in the upper part.

From the variety and distribution of sedimentary rock types forming the Parson Bay Formation, it is clear that depositional environments extended from predominantly shallow or moderate-depth marine to locally higher-energy intertidal and beach.

Volcanic Rock Types

The volcanic rock types of the Parson Bay Formation comprise mappable units of volcaniclastic breccia, massive flows and rare pillow lava. These volcanic rocks are particularly abundant and best exposed in the Quatsino – Port Alice area along Neroutsos Inlet and in Quatsino Sound, and have been traced south to the southern limit of the Alice Lake map sheet (Nixon *et al.*, 2006c–e). Although regionally significant, individual units have a limited lateral extent and thus stratigraphic correlation is hampered without adequate age control. Also, it is evident from field relationships that similar volcanic units occupy different stratigraphic positions within the Parson Bay Formation: some lie virtually on the contact with Quatsino limestone, whereas others occur near the top of the succession (Fig 3). Where contacts between volcanic and sedimentary rocks are exposed, they are generally conformable, or locally disconformable due to erosion, with little evidence for a significant hiatus in sedimentation.

The main characteristics and stratigraphic relationships among the volcanic and sedimentary components of the Parson Bay Formation may be best described with reference to the detailed work of Jeletzky (1976), who recognized Late Triassic (?Rhaetian) volcanism in the 'Hecate Cove Formation' (Fig 2). The diverse rock types comprising this formation were divided into three intercalated facies: 1) a characteristic assemblage of limestone breccia, water-laid volcanic breccia and mixed volcanic-sedimentary breccia (and associated volcanic conglomerate), in which clasts are supported by a fine-grained, impure limestone to calcareous mudstone-siltstone matrix; 2) well-bedded sequences of locally fossiliferous, variably tuffaceous limestone, calcareous argillite, wacke and water-laid tuff; and 3) coarse volcanic breccia, augite-porphyritic lava and volcanic conglomerate. He regarded the first two facies as predominantly marine and the third facies as nonmarine and resting with the regional unconformity on the deeply eroded remnants of the underlying sedimentary succession. The origin of the distinctive volcanic and sedimentary breccia in facies 1 were ascribed to explosive volcanism and concomitant syntectonic slumping accompanying the 'Rhaetian Orogeny'.

Some of the best exposures of the Hecate Cove Formation were examined at the type locality just west of Hecate Cove and along the coast beyond (Jeletzky, 1976, sections 4 and 8; Fig 1). Dark reddish grey to greenish grey limestone sequences enclose breccia containing both lithified (angular to subrounded) and semi-consolidated (plastically deformed) clasts (most <15 cm across) of pale grey limestone dispersed in a dark grey-green, impure limestone matrix. Thin interbeds of volcanic breccia generally comprise angular to subangular, poorly sorted clasts (<2 cm) of aphanitic to augite±plagioclase-phyric basalt set in a fine-grained limy matrix. Hybrids of these two end-member breccia types also exist in this section. It is evident from the scattered occurrence of slump folds and the locally erosive base of these breccia units that they were emplaced as submarine debris flows, as inferred by Jeletzky (1976). As discussed below, these deposits were formed during the growth and emergence of small volcanic centres, and there is no evidence in the stratigraphic record for a major tectonic or erosional event in the latest Triassic, as previously contended by Muller *et al* (1974).

Volcanic breccia of a different type is found in the middle to lower parts of the type section. These units form massive beds of dark grey-green, angular to subangular clasts (up to 20 cm across) of dense to amygdaloidal, aphanitic to porphyritic basalt set in a comminuted basaltic matrix rich in lapilli-sized fragments. The virtually monolithic, closed-framework textures, apparent lack of pillow fragments and hyaloclastite debris, presence of dense and vesicular, poorly sorted clasts and paucity of fine-grained constituents in the matrix implies either a direct pyroclastic airfall origin or limited epiclastic redistribution by near-vent mass wastage of basaltic ejecta and/or fragmented flow material. The textural features and close association of flows and breccia emplaced at the air-sea interface strongly suggest that phreatomagmatic activity was responsible for much of the fragmentation.

The lava flows associated with the latter deposits are generally massive and locally exhibit conspicuous flow breccia. Five types of basaltic lava have been recognized based on mineralogy and textures: augite-porphyritic, plagioclase-porphyritic, augite-plagioclase-porphyritic (the most common variety), augite-megacrystic and aphanitic (also common). The porphyritic lava carries euhedral to subhedral, blocky phenocrysts (<5 mm) that grade serially into an amygdaloidal, aphanitic groundmass. Euhedral augite megacrysts in hiatal-textured basalt flows reach up to 1.5 cm in length. The massive and locally oxidized nature of the flows, together with autobrecciated textures and lack of pillow lava/breccia, are consistent with subaerial emplacement, as suggested by Jeletzky (1976). Similar lava and associated breccia are found stratigraphically below the type section at the head of Hecate Cove and also occur above this section to the west (Berg Cove area) within the basal part of the overlying LeMare Lake volcanics (section 8, 'Basal Jurassic Volcanic Unit' of Jeletzky, 1976; Fig 2, 3).

Lithologically, the thinly bedded limestone and fine-grained siliciclastic rocks within the Hecate Cove succession belong to the Parson Bay Formation and were treated as such by Muller *et al*. (1974; Fig 2). Correlative sedimentary successions enclosing aphanitic to augite-plagioclase-phyric flows and water-laid volcanic-sedimentary breccia have been mapped across the inlet on the southern shores of Quatsino Sound and Drake Island where Early Norian to Rhaetian conodonts and bivalves have been recovered (Nixon *et al*., 2006d). These sections also contain a pale grey weathering, micritic to locally coralline limestone near the top of the Parson Bay succession, which has been correlated with the Late Norian Sutton limestone of Cowichan Lake (Jeletzky, 1976; Muller *et al*., 1974; Fig 3). This limestone has been identified farther south in slopes west of Neroutsos Inlet and possibly extends south beyond Alice Lake (*e.g.*, the coralline limestone unit at the top of the Alice Lake section; Muller and Rahmani, 1970), but exposures are sparse and it does not form a regionally mappable unit.

Restricted occurrences of augite±plagioclase-phyric flows, volcanic breccia and related intrusions, and rare sequences of aphanitic pillow basalt, have been mapped locally around Neroutsos Inlet and south of Alice Lake (Nixon *et al*., 2006c). In the latter area, local sequences of clast to matrix-supported aphanitic basaltic breccia, situated at or near the top of the Quatsino Formation, contain abundant, angular lapilli-sized fragments of limestone and appear to represent the variably remobilized products of vent-clearing, phreatomagmatic eruptions.

VOLCANICLASTIC-SEDIMENTARY UNIT

The volcaniclastic-sedimentary rock unit is transitional between the predominantly marine succession of the Parson Bay Formation and regionally extensive, subaerial volcanic sequences at the base of the LeMare Lake volcanics. A heterogeneous assemblage of laminated to thickly bedded sedimentary and volcaniclastic deposits are incorporated, but the unit is dominated by water-laid epiclastic detritus. The principal rock types are: dark grey to grey-green or buff, fine to coarse-grained lithic and feldspathic wacke locally exhibiting graded bedding, and rarely crosslaminations and channel features; finer-grained siliciclastic rocks including siltstone, mudstone and minor shale; impure limestone and calcareous equivalents of the clastic rocks described above; heterolithic and monolithic, clast and matrix-supported volcanic breccia, including rhyolitic to basaltic lapilli tuff, tuff breccia and reworked equivalents. Minor rock types include feldspathic arenite; heterolithic, and rarely monolithic, volcanic conglomerate and debris-flow breccia; and rare crystal-vitric airfall tuff and remobilized equivalents. Thin massive flows and pillow lava may occur locally, and the succession is cut by abundant dikes and sills related to the overlying volcanic rocks.

The basal contact with the Parson Bay Formation is conformable and arbitrarily placed, where clastic rocks, typically wacke, siltstone and fine volcanic breccia, first become dominant over carbonate rocks in the stratigraphy. It is a transitional contact which, because of the generally poor exposure of Parson Bay strata, is especially sensitive to the amount of outcrop. As such, this map unit may locally include typical Parson Bay rock types stratigraphically above the first significant interval of epiclastic material. The upper contact of this unit is more sharply defined and occurs where the predominantly epiclastic succession first passes into the thick sequence of lava flows and their associated breccia at the base of the LeMare Lake volcanics. Although poorly constrained by radiometric dates, both contacts appear to be diachronous (Fig 3).

LEMARE LAKE VOLCANICS

The LeMare Lake volcanics constitute thick sequences of intercalated volcanic and marine sedimentary strata and mark an episode of regionally extensive subaerial volcanism in the Bonanza Group. In fact, most of the western half of northern Vancouver Island is underlain by these rocks (Fig 1). As noted above, volcanic rocks at the base of the unit conformably overlie the shallow marine strata of the volcaniclastic-sedimentary unit, and the eroded top of the succession is marked by an angular unconformity overlain by Cretaceous clastic rocks. The thickness of the unit is difficult to estimate due to the faulting and the paucity of internal stratigraphic markers, except for two thin subunits (described below). A measured section presented by Muller *et al*. (1974), near Cape Parkins at the entrance to Quatsino Sound, gave an estimated thickness of some 2500 m, which is probably a minimum.

The age of the LeMare Lake volcanics is constrained by extensive fossil collections and, to a much lesser degree, geochronology, but is still inadequately known. The fragmentary fossil record indicates that, since the latest Triassic, marine sedimentation occurred intermittently between the mid-Hettangian and mid-Aalenian (*see* Nixon *et al*., 2006c–e). The youngest U-Pb isotopic dates for the volcanic rocks are *ca*. 169 Ma (mid-Bajocian) obtained on the Pemberton Hills rhyolite and the oldest dates are approximately 199 to 202 Ma (Rhaetian-Hettangian) from rhyolite on the west coast and near Le Mare Lake (Friedman and Nixon, 1995; Fig 3). Volcanic stratigraphy lying between these extremes has not been dated, thus the interplay of arc volcanism and marine transgression through the Jurassic remains obscure. Therefore, the position of volcanic and sedimentary units within this part of the stratigraphic column shown in Figure 3 is somewhat conjectural.

The wide variety of rock types that characterize the LeMare Lake volcanics may be summarized as follows: black to grey-green or reddish grey, aphanitic to plagioclase-phyric, amygdaloidal flows of basaltic to andesitic composition; grey to pink and pale buff, dacitic to rhyolitic flows and flow-dome complexes with aphanitic to feldspar-phyric, flow-laminated textures, and localized, well-developed spherulitic devitrification; rhyodacitic to rhyolitic, welded to non-welded, lithic-crystal ash-flow tuff with angular to subrounded lapilli-sized volcanic and sedimentary clasts, strongly welded zones defined by collapsed eutaxitic pumice, and rare carbonized wood fragments; and basaltic to rhyolitic volcanic breccia of pyroclastic and autoclastic origin. Notable minor components are rhyolitic and basaltic airfall tuff; pyroclastic surge and explosion breccia of basaltic composition; and thin sequences of basaltic pillow lava, breccia and hyaloclastite.

The common non-marine to marine, generally well-bedded sedimentary rock types are: black to grey-green or reddish brown, variably calcareous siltstone, mudstone and shale, impure limestone (rarely oolitic), and epiclastic volcanic wacke and breccia. Heterolithic to monolithic conglomerate and debris-flow breccia, including lahars, are comparatively rare.

Victoria Lake Basalt

The Victoria Lake basalt is a distinctive plagioclase-megacrystic flow or multiple flow unit(s) found at or near the base of the LeMare Lake volcanics. It is named for Victoria Lake, where these flows are well exposed in roadcuts and along the shoreline. Although this lava is restricted in extent within any one area, it is a recurrent and widespread feature of the volcanic stratigraphy (Nixon *et al*., 2006c–e).

The occurrence of ‘coarsely porphyritic’ flows in the LeMare Lake volcanics has been noted by previous workers. On the north shore of Quatsino Sound west of Hecate Cove (near Sherbourg Islands), Jeletzky (1976, section 8, unit 3) encountered these flows within a sequence of amygdaloidal lava and breccia that strongly resembles Karmutsen basalt, and assigned it to his ‘Basal Jurassic Volcanic Unit’ (Fig 2). At this locality, Victoria Lake megacrystic basalt is associated with aphanitic, amygdaloidal flows and flow breccia that rest on a densely welded, lithic-crystal rhyolitic ash-flow tuff, in turn resting (contact not exposed) on pebble to cobble conglomerate (Jeletzky, 1976, section 8, near top of unit 4). These units lie near the base of the LeMare Lake volcanics, which is represented in Jeletzky’s type section by the contact between the ‘Basal Jurassic Volcanic Unit’ and his underlying ‘Hecate Cove Formation’, represented herein by a locally thick volcanic unit lying at the top of the Parson Bay Formation (Fig 3).

The Victoria Lake basalt is typically intercalated within the basal part of a much thicker sequence of aphanitic, variably amygdaloidal basaltic to andesitic lava, many of which are moderately to strongly magnetic, including the megacrystic member. The megacrystic flows may form a single unit or several distinct units within the local stratigraphic succession. The Karmutsen-like nature of this lavas is striking, even to the point of replication of its plagioclase-megacrystic textures.

The black to dark grey-green or reddish grey megacrystic lava is characterized by euhedral to subhedral, lath-shaped to blocky plagioclase crystals, commonly reaching 1 cm, and locally 2 cm, in length. Some megacrysts exhibit a pronounced flow orientation, which is useful as a structural indicator. The aphanitic to finely crystalline groundmass is dense to strongly amygdaloidal and the plagioclase population displays either hiatal or seriate textures. Locally, at the base of the LeMare Lake succession, these flows are pillowed or fragmented and incorporated in laharic breccia. Rare intrusive equivalents may exhibit notably coarser groundmass textures involving subophitic intergrowths of plagioclase and pyroxene.

The age of the Victoria Lake basalt is currently not well constrained. It is shown schematically in Figure 3 as Hettangian, but could range in age across the map area from Rhaetian to (Early?) Sinemurian. In the Cape Parkins section described by Muller *et al*. (1974), the Victoria Lake basalt appears to be correlative with plagioclase-megacrystic flows in unit 8, which is bracketed (assuming no fault disruption) by other units in the section containing ammonite fauna identified as Sinemurian.

Pemberton Hills Rhyolite

The Pemberton Hills rhyolite unit is situated north of Holberg Inlet and forms a southeasterly trending series of resistant knobs and ridges trending subparallel to the coastline from Mount McIntosh in the north through the Pemberton Hills. As noted above, this unit lies near the top of the LeMare Lake volcanics and is the youngest dated member of the Bonanza Group (mid-Bajocian). At its northern extremity, the unit is intruded by dioritic rocks of the Island Plutonic Suite, and to the south it disappears beneath the waters of Holberg Inlet about 15 km due west of the former Island Copper mine. The Pemberton Hills rhyolite is underlain by a succession of dark reddish grey to green-grey, aphanitic to pyroxene-plagioclase-phyric andesitic flows with minor interbeds of crystal-lithic and lapilli tuff, volcanic sandstone and epiclastic breccia. It is overlain by similar rock types, including hornblende-bearing andesite. Contacts between these map units are generally not exposed; however, at one locality, the lower contact of the rhyolite overlies an erosion surface.

Lithologically, the unit comprises mainly pale grey to buff or white-weathering, rhyolitic to rhyodacitic, crystal-lithic ash-flow tuff and viscous aphanitic lava that form the remnants of flow-dome complexes. Interbedded porphyritic andesite flows, heterolithic volcanic breccia and vitric tuff are minor constituents. Textural features such as welding, flow laminations, flow folds and flow breccia are only rarely preserved due to regionally intense acid-sulphate leaching and silicification accompanying epithermal mineralization (described below).

MINERAL POTENTIAL

The mineral potential of stratigraphic metallotects on northern Vancouver Island does not appear to have attracted the same attention as the well-known base and precious-metal environments of the calcalkaline porphyry and skarn systems such as Island Copper (MINFILE 092L 158) and Merry Widow (MINFILE 092L 044), respectively, yet world-class metallogenic environments clearly exist in the Karmutsen flood basalt province and supra-subduction setting of the Bonanza volcanic arc. Recent advances in our understanding of the stratigraphy, as revealed by ongoing regional mapping and complementary biostratigraphic and geochronological studies, allow for a preliminary reconstruction of the Early Mesozoic evolution of this part of Wrangellia so as to bring into focus favourable stratigraphy in the search for new mineral deposits. The importance of stratigraphic controls on mineralization is perhaps best exemplified by intrusion-related deposits, where the prime environment for skarn mineralization occurs at the contact of Quatsino (and to a lesser extent intra-Karmutsen) limestone with granitoid of the Island Plutonic Suite (*e.g.*, Nixon *et al*., 2006a, b).

Metallogenic Environments

The Early Mesozoic evolution of geological environments, as presently gleaned from the stratigraphic record, and a selection of important deposit types in relation to prospective stratigraphy are shown in Figure 4. A very generalized summary of the geological events that shaped northern Vancouver Island is offered below so as to properly place some prospective mineral deposit types described thereafter in their plate tectonic context.

TECTONOMAGMATIC SETTING

The voluminous Triassic flood basalt volcanism that built the Karmutsen oceanic plateau evolved from a wholly submarine phase to the construction of a low-profile lava shield near the end of the Carnian (Carlisle and Suzuki, 1974; Muller *et al.*, 1974; Jones *et al*., 1977). As the plume-related hotspot thermally decayed, this plateau subsided and the ensuing marine transgression deposited, Quatsino limestone (Jones *et al*., 1977; Richards *et al.*, 1991). As subsidence continued, fine siliciclastic detritus, marking the initial influx of Parson Bay sediments, began swamp carbonate deposition, beginning in the Carnian on the west and east coasts of Vancouver Island, and eventually covering the axial high (Alice Lake area) in the late Early Norian, as determined by macrofossils and conodont biostratigraphy (Muller *et al.*, 1974; Jeletzky, 1976; Nixon *et al*., 2000, 2006a, b). The initial stages of deposition of Parson Bay siliciclastic rocks may well reflect distal detritus derived from an encroaching arc, a possibility first raised by Muller *et al*. (1974), but made in the context of an intra-oceanic arc-rift environment for the Karmutsen basalt, as opposed to the open oceanic hotspot setting currently envisaged (Richards *et al*., 1991; Greene *et al.*, 2006). Evidence for proximal volcanic-arc sedimentation in the Middle to Late Norian part of the Parson Bay Formation exists in the form of tuffaceous crystal-rich volcanic wacke and breccia, as well as rare debris-flow deposits with volcanic cobbles (Nixon *et al*., 2000).

Incipient arc volcanism in Parson Bay time may have begun as early as the start of the Middle Norian in the Alice Lake area, judging by deposits of juvenile volcaniclastic breccia close to the Quatsino – Parson Bay contact. Early submarine phreatomagmatic and effusive basaltic volcanism in the Norian to Rhaetian, characterized by aphanitic and augite±plagioclase-phyric volcanic breccia and rare pillow lava, built small, isolated volcanic centres, some of which breached sea level on the emplacement of subaerial flows. Widespread subaerial volcanism commenced around the time of the Triassic-Jurassic boundary (Rhaetian to ?Early Sinemurian) and initiated the main phase of growth of the Bonanza arc. The nature of the volcanic products (LeMare Lake volcanics), which include significant volumes of basaltic to andesitic flows (Victoria Lake member and its associated aphanitic, amygdaloidal lava) and rhyolitic ignimbrite, are consistent with a more advanced stage of arc evolution on relatively mature crust. The Early to Middle Jurassic phase of arc development is poorly known but clearly involved marine transgressions punctuated by volcanic events. The Bonanza arc remained active until at least mid-Bajocian time, when rhyolitic tuff and flow-dome complexes were emplaced (Pemberton Hills rhyolite). The demise of Bonanza volcanic activity finally occurred sometime in the Middle to Late Jurassic and was followed by a significant period of tectonism and erosion prior to the deposition of continentally derived, marine to non-marine Jura-Cretaceous clastic rocks (Haggart, 1993).

Our current state of knowledge of the evolution of the Bonanza Group on northern Vancouver Island places the earliest arc volcanism in the Parson Bay Formation firmly within Late Norian, and probably Middle Norian time (Friedman and Nixon, 1995; Nixon *et al*., 2000); and the cessation of volcanic activity in the Middle Jurassic (mid-Bajocian) at the earliest (Fig 3). The recognition of a nascent volcanic arc in the Late Triassic stratigraphy of the Bonanza Group significantly extends the record of arc magmatism previously documented for lower (Westcoast Crystalline Complex), middle (Island Plutonic Suite) and upper (Bonanza Group) crustal components of the arc (Debari *et al*., 1999). The evolution of the Bonanza arc on northern Vancouver Island is the subject of current geochronological studies, but from the data at hand, arc volcanism on northern Vancouver Island, albeit episodic, spans on the order of 40 to 50 Ma, according to current time scales (Fig 3). The longevity of volcanic activity in the Bonanza Group compares favourably with the magmatic record of some of the best geochronologically calibrated island arcs in the circum-Pacific region, such as the Aleutians (~46 Ma, Jicha *et al*., 2006). This time span is especially significant from a metallogenic perspective, when one considers that the Late Mesozoic to Cenozoic belts of 'giant' porphyry copper deposits and related epithermal systems in the Andes were emplaced during a protracted history of subduction and formed in distinct magmatic cycles lasting no more than ~15 m.y. per event (Camus, 2006).

EPITHERMAL PRECIOUS METALS

Epithermal precious and base-metal systems are an enticing exploration target, but may be difficult to discover and economically evaluate; however, the prospect of finding even one 'Bonanza-type' orebody in this environment can make the search rewarding. One well-known example is El Indio, Chile, where ore reserves in narrow vein systems have been estimated at 140 t Au, 771 t Ag and 0.4 million tonnes Cu (Jannes *et al*., 1990).

Epithermal mineralization on northern Vancouver Island is probably best known as a result of work conducted in the Mount McIntosh – Pemberton Hills area, a high-sulphidation or acid-sulphate base and precious-metal system (Panteleyev and Koyanagi, 1993, 1994; Koyanagi and Panteleyev, 1993; Nixon *et al*., 1994a). Here, zones of advanced argillic and clay-silica alteration are associated with weak Cu-Au-Ag mineralization and enveloped by propylitic alteration. The acid-sulphate alteration is hosted by crystal-lithic ash-flow tuff and flow-dome complexes of the Pemberton Hills rhyolite, and to a minor extent, adjacent andesite of the LeMare Lake volcanics and dioritic intrusions of the Island Plutonic Suite. These rocks have undergone pervasive silicification and localized acid leaching such that original textures may be completely obliterated. Finely crystalline pyrite is locally abundant in these zones. Panteleyev and Koyanagi (1994) describe irregular veins and stockworks of quartz, locally accompanied by alunite, zunyite, dickite, kaolinite, hematite and rutile. They also noted that pyrite occurs both in stockworks and as semi-

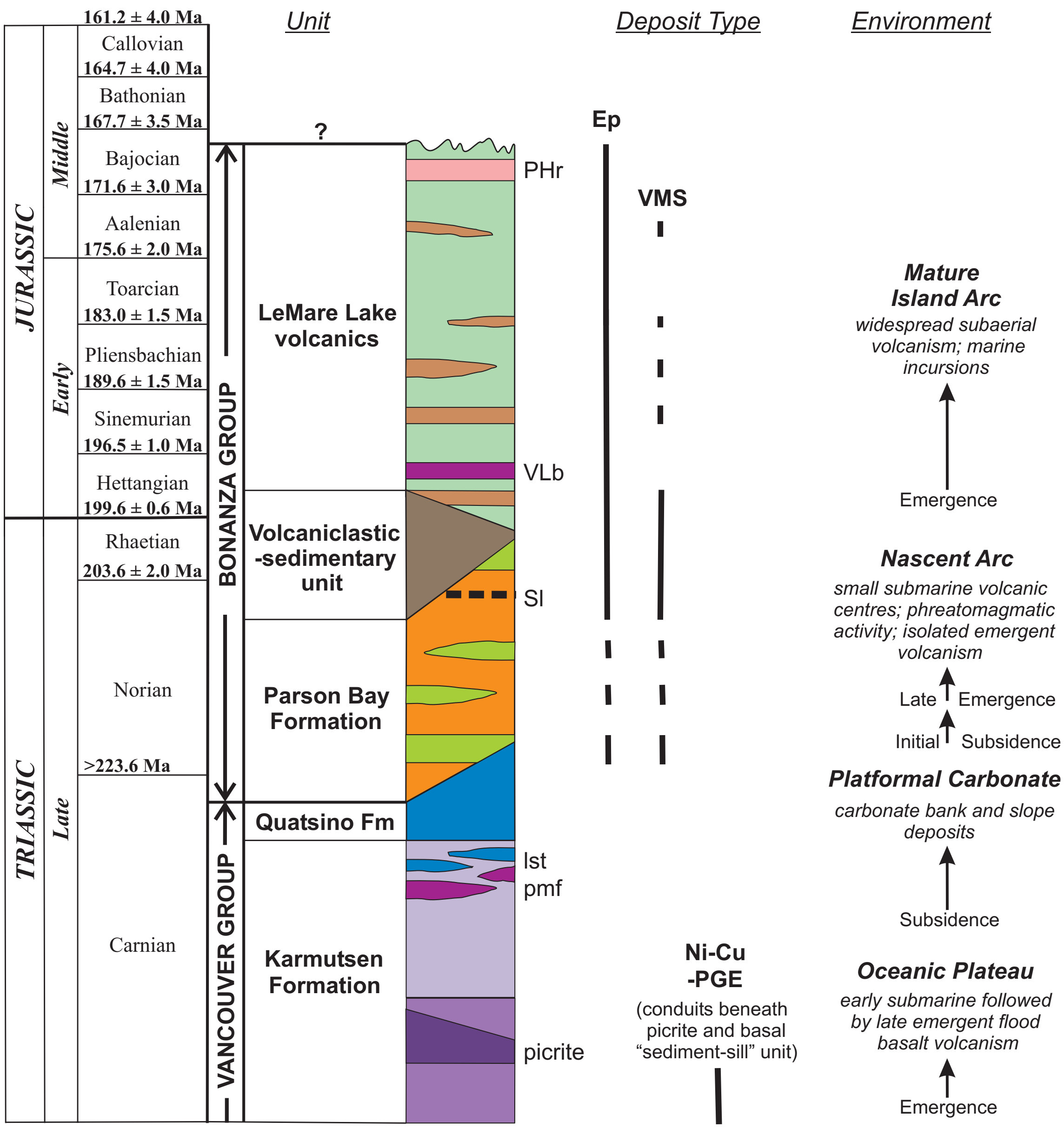

Figure 4. Tectonomagmatic evolution of northern Vancouver Island and environment of mineralization for selected mineral deposit types in relation to prospective stratigraphy as shown in Fig 3. Note that this diagram does not include the important porphyry copper and skarn mineralization. Abbreviations: PHr, Pemberton Hills rhyolite; VLb, Victoria Lake basalt; Sl, Sutton limestone; lst, intra-Karmutsen limestone; pmf, plagioclase-megacrystic flows; Ep, epithermal precious and base-metal deposits; VMS, volcanogenic massive sulphide deposits (Eskay and Kuroko-type); Ni-Cu-PGE, Noril'sk-Talnakh-type nickel-copper – platinum group element deposits.

massive to massive replacements in permeable clastic horizons within the rhyolite; and they discovered veins of pyrite-alunite containing rare native gold. Small amounts of copper minerals were identified as chalcocite, covellite and enargite. The occurrence of clasts of pyrite locally rimmed by marcasite was taken as evidence for repeated, synvolcanic mineralization in a near-surface, subaerial environment, and the source of magmatic-hydrothermal fluids was related to coeval intrusions of the Island Plutonic Suite at depth (Panteleyev and Koyanagi, 1994).

Taking the Mount McIntosh – Pemberton Hills epithermal system as a template for exploration, the most favourable metallotect is rhyolite within the LeMare Lake volcanics. Rhyolitic map units, comprising flows, flow-dome complexes and ash-flow tuff (welded and nonwelded), have been distinguished where possible (Nixon *et al*., 2006c–e). Our current knowledge of stratigraphic relationships would place many of these rhyolite units in the lower part of the LeMare Lake volcanics, below the Victoria Lake basalt. Since pervasive silicification attending acid-sulphate alteration promotes an inherent resistance to erosion and thereby positive relief, this tends to generate relatively large exploration targets for this class of deposit. Other favourable exploration factors include spatially related granitoid/porphyry intrusions and natural acidic drainages due to the high concentration of pyrite (Panteleyev and Koyanagi, 1994; Koyanagi and Panteleyev, 1993).

VOLCANOGENIC MASSIVE SULPHIDES

The Eskay Creek Au-Ag mine in northwestern BC is the world's highest-grade volcanogenic massive sulphide (VMS) deposit (MINFILE, 2006; 104B 008). It belongs to a relatively new class of shallow subaqueous hotspring VMS deposit, transitional toward subaerial epithermal Au-Ag deposits (Poulsen and Hannington, 1996; Barrett and Sherlock, 1996; Alldrick, 1995). The Eskay Creek deposit type is a polymetallic, precious-metal-rich sulphide and sulphosalt deposit with a total resource (past production + reserves + projected resources) of 2.34 million tonnes grading 51.3 g/t Au and 2326 g/t Ag (Roth, 2002).

The deposit is hosted by volcanic and sedimentary rocks of the Hazelton Group that belong to an Early to Middle Jurassic magmatic arc (McDonald *et al*., 1996). The mineralization is hosted by rhyolitic to basaltic flows, volcaniclastic rocks and minor argillite; and ore horizons form laminated stratiform to massive layers and clastic, remobilized sulphide-sulphosalt beds associated with sulphide stockworks and breccia veins in the footwall (Roth, 2002). The geochemical signature of Eskay-type VMS deposits is transitional between typical volcanic-hosted base-metal massive sulphide minerals and precious-metal epithermal deposits (Massey *et al*., 1999).

The most favourable stratigraphy for Eskay-type VMS in the Bonanza Group is where shallow marine sedimentary rocks are interbedded with, or pass laterally into, volcanic rocks, especially those packages containing rhyolitic rocks. Hence, the base of the LeMare Lake volcanic sequence, where marine deposits of the volcaniclastic-sedimentary unit pass upwards into subaerial basaltic to rhyolitic flows and volcaniclastic rocks, present a prime exploration target, as well as any transitions of similar nature within the LeMare Lake succession (Fig 4; *see* Nixon *et al*., 2006c–e). It should be noted that these metallotects are also favourable for Kuroko-type VMS deposits, which appear to have formed in deeper water (*e.g.,* the H-W deposit at the Myra Falls mine hosted by mid-Paleozoic volcanic arc rocks of the Sicker Group on Vancouver Island; MINFILE 092F 330; Massey, 1999). The shallow marine to emergent sequences of volcanic rocks within the Parson Bay Formation likewise present a prospective environment, but appear to have more limited potential due to the general lack of rhyolitic rock types. It is perhaps encouraging that a number of highly anomalous to anomalous RGS samples, screened for epithermal/Eskay-type VMS signatures, have been detected in the Bonanza Group along the northwest coastal regions of Vancouver Island (Massey *et al*., 1999).

NI-CU-PGE

The recognition of picritic pillow basalt with MgO content ranging from 13 to 20 wt% in the Karmutsen Formation (Greene *et al*., 2006) has important implications for the potential for Ni-Cu-PGE (platinum group element) mineralization on northern Vancouver Island.

World-class Ni-Cu-PGE deposits are well known in the Noril'sk-Talnakh region of Siberia where ultramafic-mafic intrusions associated with Permo-Triassic continental flood basalt hosts magmatic sulphide mineralization. The ore-bearing intrusions form transgressive sill-like bodies hosted by Devonian to Late Permian carbonate-clastic sequences, including evaporites and coal measures, directly underlying the flood basalt; and some of these bodies intrude the lower part of the overlying volcanic stratigraphy. As summarized by Naldrett (2004), the main ore horizons are hosted primarily by olivine-enriched, picritic (18–29 wt% MgO) and 'taxitic' (*i.e.,* variably textured; 9–16 wt% MgO) gabbrodolerite with interstitial and blebby disseminated sulphide minerals, mainly pyrrhotite, pentlandite, chalcopyrite and cubanite, and underlain by a layer of massive sulphide at the base of the intrusion. The massive sulphide minerals are somewhat enigmatic in that they commonly form apparently isolated bodies in the wallrocks and veins cutting both the lower intrusive contact and gabbrodolerite. Bulk ore compositions (*i.e*., sulphide plus silicate gangue minerals) in disseminated ores average 2.3 to 3.3 g/t Pd, 0.5 to 1.1 g/t Pt, 0.4 to 0.7 wt% Ni and 0.9 to 1.2 wt% Cu; and in massive ores average 5.9 to 12.2 g/t Pd, 1.4 to 2.8% Pt, 4.6 to 5.2 wt% Ni and 2.9 to 4.8 wt% Cu.

In considering the origin of the Noril'sk-Talnakh deposits, Naldrett emphasized that a fortuitous combination of factors was necessary in order to produce such 'giant' ore deposits. Some critical aspects of his model are 1) an external source of sulphur (in this case, the combined assimilation of evaporites to supply oxidized sulphur and coal to act as a reductant); 2) a supply of hot picritic magma with the potential to thermally erode and assimilate country rocks; 3) arterial conduits that channelled sustained magma flow (recognized by anomalously well-developed peripheral zones of contact metamorphism); and 4) the presence of hydrodynamic traps in locally flared conduits that served to gravitationally concentrate the magmatic sulphide droplets.

The picritic pillow basalt of northern Vancouver Island demonstrates that this part of the Karmutsen flood basalt province received a supply of primitive magma from a mantle plume. Finding an external source of sulphur is more of a challenge, but the Middle Triassic shale and siltstone underlying the Karmutsen Formation may provide a suitable contaminant, especially if ascending magmas are close to saturation in sulphur. The later point is being addressed by J.S. Scoates and coworkers, whose preliminary investigations reveal that certain lava forming a chemical subtype of Karmutsen basalt with typical MgO content (8–10 wt%) and appreciable PGE abundances were erupted close to sulphide saturation (J.S. Scoates, pers comm, 2006). The intriguing observation of small concentrations of disseminated sulphide minerals (mainly pyrrhotite) near the lower contact of some Karmutsen sills intruding the basal 'sediment-sill' unit of Muller *et al*. (1974) is proof that certain magma batches did indeed reach sulphur saturation (Greene *et al*., 2006). This demonstrates the potential for ore-forming processes near the base of the Karmutsen basalt, at least, but whether or not such processes have successfully produced significant Ni-Cu-PGE deposits in the Karmutsen of northern Vancouver island remains to be evaluated.

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