Early Jurassic intrusion and deformation in the Wark-Colquitz complex, Victoria, British Columbia

JoAnne Nelson[1, a]

[1] Emeritus Scientist, British Columbia Geological Survey, Ministry of Mining and Critical Minerals, Victoria, BC, V8W 9N3
[a] corresponding author: JoAnne.Nelson@gov.bc.ca

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Abstract

Precise U-Pb zircon ages from deformed and crosscutting, post-kinematic intrusive phases of the Wark-Colquitz plutonic-metamorphic complex in downtown Victoria are ca. 193 Ma and agree within error, indicating a short-lived episode of intrusion accompanied by ductile deformation. This age coincides with Early Jurassic volcanism in the Bonanza Group (LeMare Lake volcanic unit) and emplacement of the oldest intrusions of the Island Plutonic Suite, considered to have fed the Bonanza arc. In agreement with previous workers, we consider the Wark-Colquitz complex to be an exhumed deep-crustal portion of Wrangellia that exposes the roots of the Triassic-Jurassic Bonanza magmatic arc. Episodic syn-plutonic ductile deformation may be the result of subduction-related strain due to coupling with the down-going plate.

Keywords: Wark-Colquitz, Bonanza arc, Island Plutonic Suite, Wrangellia, Westcoast complex, Victoria

1. Introduction

The Wark-Colquitz plutonic-metamorphic complex is exposed on southernmost Vancouver Island (Fig. 1), in the traditional territory of the lək̓ʷəŋən-speaking (Lekwungen; Songhees and Xʷsepsəm (Ko-sap-sum)/Esquimalt) peoples. It forms an isolated, west-northwesterly trending, fault-bounded belt that extends westward from Victoria (Fig. 2). It represents the southernmost extent of Wrangellia and is distinct from the Paleozoic to Jurassic supracrustal section that characterizes most of this accreted terrane. On its southwest border, the complex lies in the hanging wall of the Survey Mountain thrust fault, above metamorphosed siliciclastic rocks of the Leech River complex, which forms part of the subduction-related Pacific Rim terrane. Its northeastern limit is an unnamed, steeply dipping fault that juxtaposes the complex with Mesozoic Wrangellia supracrustal strata, cut by Jurassic plutons of the Island Plutonic Suite. All of these units and structures are truncated by the northeast-striking San Juan fault (Fig. 2). Restoration of 25 kilometres of sinistral displacement on this fault aligns the Wark-Colquitz complex with the equivalent Westcoast complex farther west near Port Renfrew, which forms the outermost unit of Wrangellia along the west coast of Vancouver Island (Isachsen, 1984; Canil et al., 2010).

Original work on the Wark-Colquitz complex subdivided it into mafic and felsic units: Wark gneiss, consisting of massive to gneissic metadiorite, metagabbro, and amphibolite; and Colquitz quartz-feldspar gneiss, both considered to be Paleozoic (Muller, 1983). More recent studies have shown that the Wark-Colquitz and Westcoast complexes (193-174 Ma) represent a single highly variable, syntectonic intrusive entity containing minor remnant pre-plutonic protoliths (Isachsen, 1984; Canil et al., 2010, 2013). On outcrop scale, unfoliated, generally more felsic phases intrude older mafic and felsic phases that have undergone ductile strain, locally forming protomylonites. These rocks are considered to represent the deep-crustal infrastructure of the Jurassic Bonanza magmatic arc (deBari et al., 1999; Larocque, 2008), which elsewhere on Vancouver Island includes the predominantly volcanic Bonanza Group and Island Plutonic Suite. The Bonanza arc was active between 202 and 169 Ma, based on U-Pb zircon dating of volcanic rocks (Nixon and Orr, 2007).

Given its urban location, remarkably little is known about the Wark-Colquitz complex. Prior to this study, very few reliable U-Pb zircon dates were available. In particular, ages of coexisting foliated and unfoliated phases were not known, which left unconstrained the timing and duration of high strain in the complex. In 2007-2008, excavation for a building foundation adjacent to the Jack Davis Building on Blanshard Street offered a unique opportunity to study and sample freshly blasted outcrops of Wark-Colquitz intrusive bodies. This paper presents field and U-Pb zircon geochronology results from these outcrops.

2. Local geology

The Wark-Colquitz complex, well-exposed on rocky hilltops and beaches in the Victoria area, shows great variety of intrusive phases that range in composition from mafic to felsic. In a given outcrop, the degree of deformation varies markedly between and, in some cases, within intrusive phases. In some areas, remnants of pre-intrusive metamorphosed supracrustal units – meta-tuffs, metaclastics, and calc-silicates – are preserved; notably at Cattle Point (Fig. 2). The age and affinity

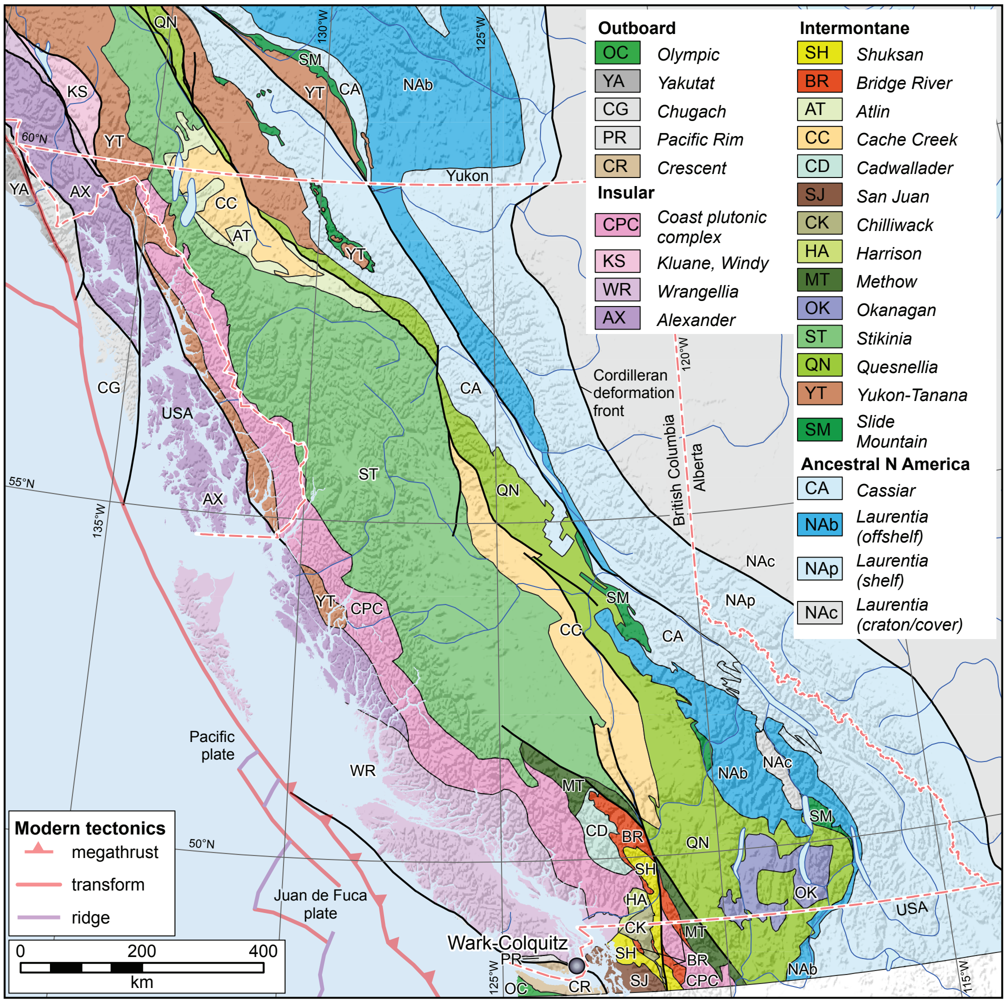

Fig. 1. Tectonic elements of the Canadian Cordillera in British Columbia and location of study site in Victoria. Terrane boundaries after Colpron (2020).

of their protoliths are unknown. Muller (1983) suggested they are correlative with the Sicker Group, but supporting geochronological data are currently lacking; conceivably, they could be derived from pre-Sicker units in the basement of Wrangellia.

The faulted northern margin of the Wark-Colquitz complex demarcates different depths of crustal exposure. To the south, Al-in-hornblende barometry indicates that Wark-Colquitz complex plutons were emplaced in the middle to lower crust, at depths of 10-18 km (Canil et al., 2010). North of the fault, weakly metamorphosed upper crustal strata of the Karmutsen and Bonanza groups are intruded by unfoliated plutons of the Island Plutonic Suite, which have yielded local U-Pb dates of 167-173 Ma (Fig. 2; Breitsprecher and Mortensen, 2004). The current trace of the fault is consistent with a near-vertical dip (Fig. 2; Harrichhausen et al., 2023). A trench excavated in 2023 on the eastern shore of Elk Lake exposed a fault-propagation fold within deformed Quaternary sediments above the southwest-dipping fault. Using the WSÁNEĆ peoples' name for Elk Lake in the SENĆOTEN language (pronounced hul-lakl-lik), Harrichhausen et al. (2023) applied the local name X̱EOLX̱ELEꝀ-Elk Lake fault. The fold indicates reverse motion of the southern (Wark-Colquitz) block on top of the upper crustal strata to the north. The larger-scale structural relationship between mid-crustal rocks of the Wark-Colquitz complex and Mesozoic strata to the north is unknown. Was the original intervening fault a top-to-the-north reverse fault, or is recent motion superimposed on a north-dipping denudation fault?

The intricate geology of the Wark-Colquitz complex is evident in its many outcrops. Instead of true orthogneisses, the complex consists of a wide range of plutonic and meta-plutonic bodies. Degree of deformation varies widely, from large areas of weakly deformed diorite to local zones of protomylonite. Multiple crosscutting phases are common at outcrop scale. Foliations are folded, and in general ductile deformation was succeeded by ductile-brittle shearing.

3. This study

In 2008, two samples were collected from a pit being blasted

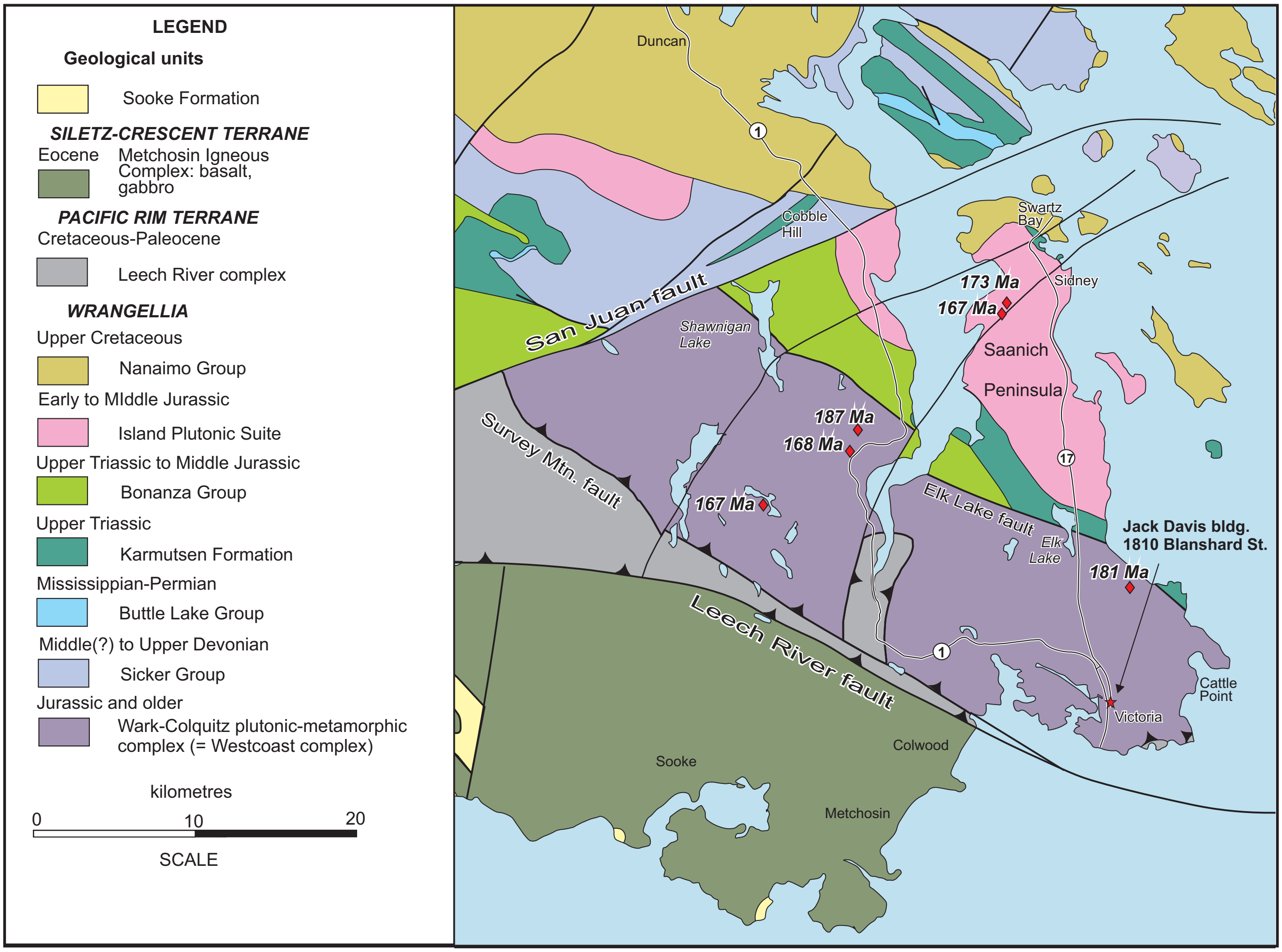

Fig. 2. Geology of the Victoria area, southern Vancouver Island. From British Columbia Geological Survey (2019) with modifications from Harrichhausen et al. (2023). Uranium-lead zircon ages from Isachsen (1984); Breitsprecher and Mortenson (2004); Canil et al. (2013).

for the foundation of a condominium development adjacent to 1810 Blanshard Street, the home of the British Columbia Geological Survey. The data presented here are the sole record of the geology of the 'Jack Davis pit'.

The eastern wall of the pit exposed microporphyritic diorite with a steeply dipping S_1 foliation parallel to contacts with metabasalts that likely originated as sills (Fig. 3). The main foliation is truncated by a gently north-dipping zone of brittle shearing (S_2, Fig. 3). Top-to-the-south, reverse motion is suggested by a set of steeper splays. The foliation is defined by wispy trains of fine-grained matrix minerals albite+actinolite+chlorite (Figs. 4a, b). A finer-grained, unfoliated leucotonalite cuts the foliated diorite, and contains xenoliths of foliated diorite and metabasalt (Figs. 4c, d).

3.1. Geochronology

Samples of the foliated diorite (JDP-5) and crosscutting unfoliated tonalite (JDP-6) were taken for U-Pb zircon geochronology. CA-TIMS analyses were performed by Richard Friedman at the Pacific Centre for Isotopic and Geochemical Research at The University of British Columbia (PCIGR) in 2009.

3.1.1. Methods

Zircon was separated from rock samples using conventional crushing, grinding and Wilfley table techniques, followed by final concentration using heavy liquids and magnetic separations. Mineral fractions for analysis were selected based on grain morphology, quality, size and magnetic susceptibility. Except where noted, all zircon fractions were abraded before dissolution to minimize the effects of post-crystallization Pb-loss (Krogh, 1982). Samples were dissolved in concentrated hydrofluoric acid (HF) and nitric acid (HNO_3) in the presence of a mixed $^{233\text{-}235}$U-^{205}Pb tracer. Separation and purification of Pb and U employed ion exchange column techniques modified slightly from those described by Parrish et al. (1987). Pb and U were eluted separately and loaded together on a single Re filament using a phosphoric acid-silica gel emitter. Isotopic ratios were measured using a modified single collector VG-54R thermal ionization mass spectrometer equipped with

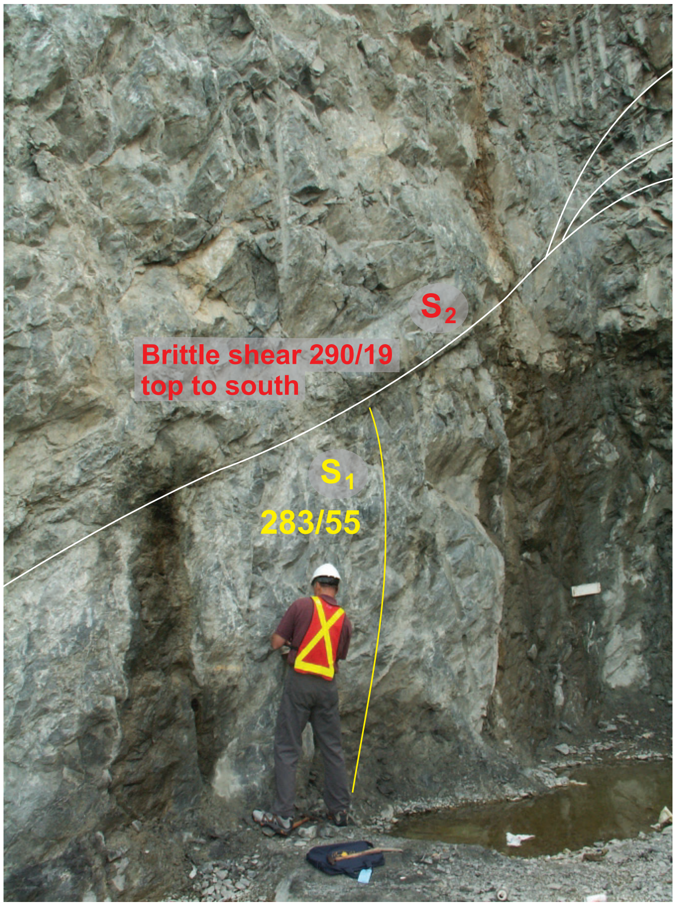

Fig. 3. East wall of the 'Jack Davis pit'. Main foliation (S_1) is parallel to contacts of metadiorite and metabasalt. Cut by brittle shear (290/19); UTM 473129E, 5364229N.

a Daly photomultiplier. Measurements were done in peak-switching mode on the Daly detector. U and Pb total procedural blanks were in the range of 1 pg and 3 to 5 pg, respectively, during this study. U fractionation was determined directly on individual runs using the $^{233-235}U$ tracer, and Pb isotopic ratios were corrected for a fractionation of 0.37%/amu for Faraday and Daly runs, respectively, based on replicate analyses of the NBS-981 Pb standard and the values recommended by Thirlwall et al. (2000). All analytical errors were numerically propagated through the entire age calculation using the technique of Roddick (1987). Concordia intercept ages and associated errors were calculated using a modified version of the York-II regression model (wherein the York-II errors are multiplied by the mean square of weighted deviates (MSWD) and the algorithm of Ludwig (1980). All errors are quoted at the two-sigma level. Results are plotted on standard concordia diagrams (Fig. 5) and listed in Table 1.

3.1.2. Results

Sample 08JDP-5 yielded five concordant zircon fractions. A weighted mean of the three younger fractions is 192.5 ±0.24 Ma (Fig. 5). The two older fractions are ca. 195 Ma and probably represent xenocrysts or antecrysts. Sample 08JDP-6 yielded four concordant fractions. A weighted mean of the three younger fractions is 192.66 ±0.59 Ma (Fig. 5), with a single ca. 195 Ma fraction representing xenocrysts or antecrysts. The two dates agree within analytical error (±0.6 Ma 2σ). The two populations of xenocrysts/antecrysts are remnants of a slightly older zircon crystallization.

4. Discussion

With dates of 192.59 ±0.24 Ma and 192.6 ±0.6 Ma, the two plutonic phases at the 'Jack Davis pit' were emplaced during a <1 Ma time interval, between 193 and 192 Ma. This age corresponds to the oldest intrusive ages reported elsewhere in the Westcoast complex (Canil et al., 2012), and to the Early Jurassic (Hettangian-Sinemurian) LeMare Lake volcanic unit, the older of the two predominantly volcanic units in the Bonanza Group on northern Vancouver Island (Nixon et al., 2011). It may coincide with the earliest stages of Jurassic magmatism in the Bonanza arc on southern Vancouver Island.

The contrast in foliation development in the two phases, from early foliated diorite to later unfoliated leucotonalite, demonstrates that this brief intrusive episode was accompanied by ductile deformation that waned before emplacement of the leucotonalite. Coexisting ca. 192-194 Ma foliated and unfoliated phases also occur in the Westcoast complex near Port Renfrew (Canil et al., 2012), indicating a similar short-lived episode of localized strain accompanying plutonic emplacement. A significantly younger foliated phase (ca. 183 Ma) has also been identified, a banded meta-quartz diorite from Meares Island near Tofino (Isachsen, 1984). Episodic, localized deformation may have accompanied intrusion at various times throughout the development of the Bonanza arc infrastructure.

In developing magmatic arcs, both orogen-normal and strike-slip episodic deformation occur (de Saint Blanquat et al., 1998; Buritica et al., 2019; Gehrels et al., 2025), as well as less common episodes of orogen-normal extension linked to megathrust events (Acocella, 2014). The extensive exposures of the Wark-Colquitz and Westcoast complexes present an opportunity for detailed study of linked deformation and plutonism in the mid-crustal region of an active magmatic arc. Future work should focus on geochronology of coexisting deformed and undeformed intrusive phases as well as kinematic observations to establish prevailing strain regimes.

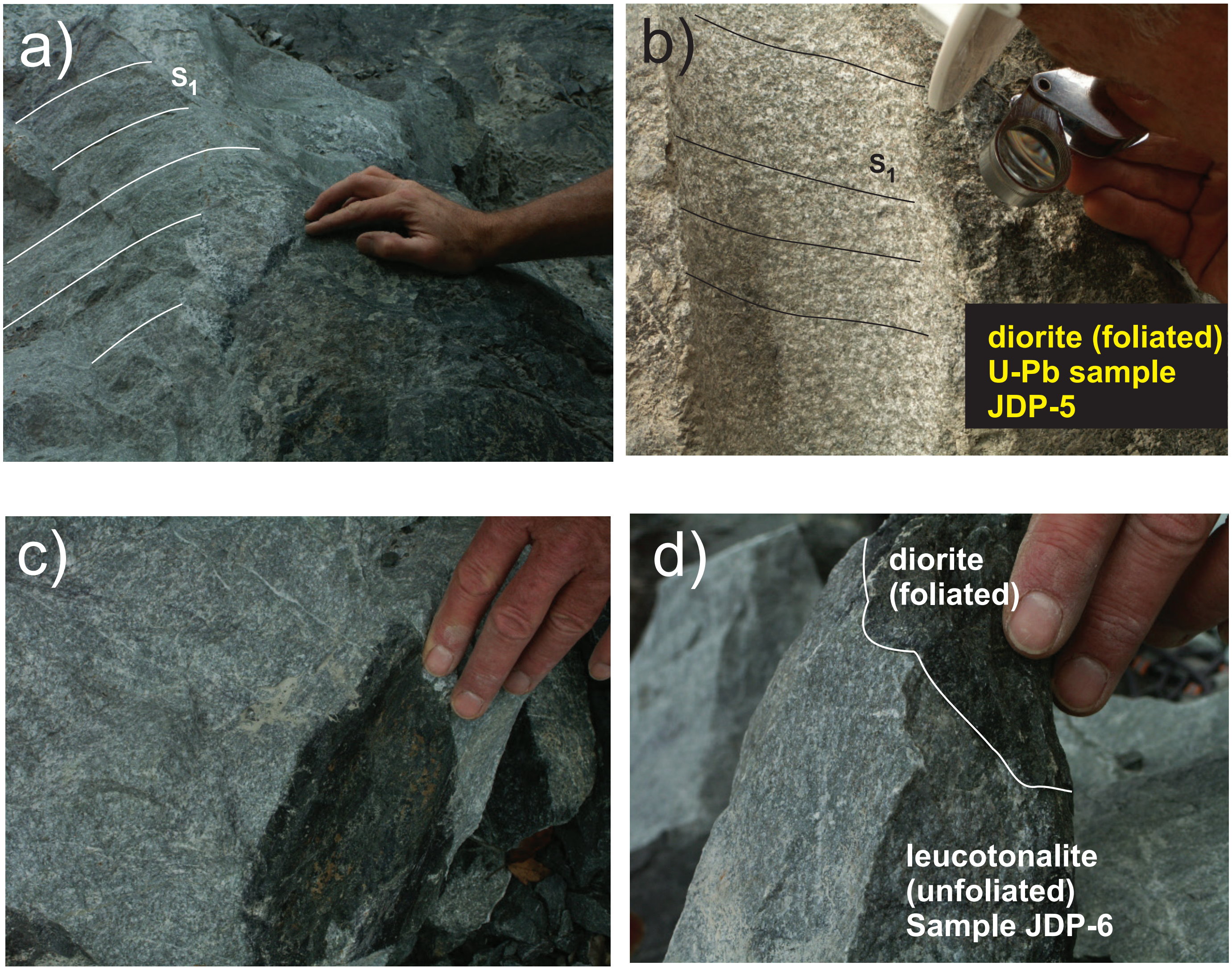

Fig. 4. Intrusive phases in the 'Jack Davis pit'. **a)** Ductile fabrics in metadiorite-metabasalt; UTM 473111E, 5364229N. **b)** Foliated diorite, U-Pb sample 08JDP-5, UTM 473111E, 5364229N. **c)** Pale green leucotonalite, unfoliated but with discrete brittle shears and well-foliated metabasalt inclusion, UTM 473190E, 5364262N; **d)** Unfoliated leucotonalite, U-Pb sample 08JDP-6 cutting foliated diorite, UTM 473190E, 5364262N.

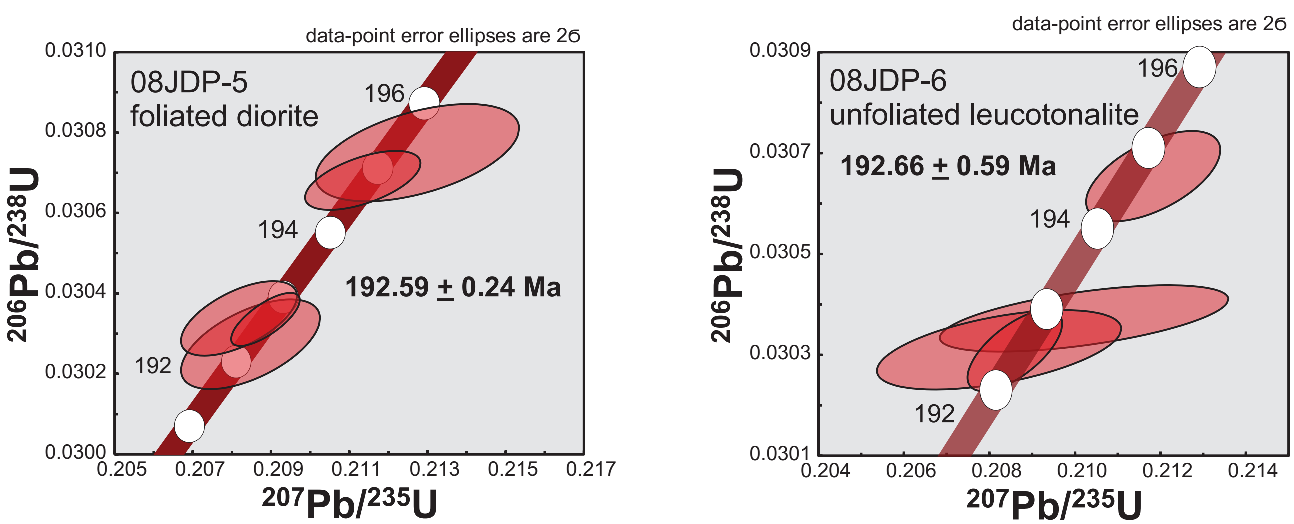

Fig. 5. U-Pb concordia plots for Wark-Colquitz complex intrusive phases.

Table 1. U-Pb zircon geochronological results for samples 08JDP-5 and 08JDP-6.

U-Th-Pb isotopic data

	Compositional Parameters									Radiogenic Isotope Ratios								Isotopic Ages					
Sample	Wt. mg	U ppm	Th/U	Pb ppm	$^{206}Pb^*$ x10^{-13} mol	mol % $^{206}Pb^*$	Pb^*/Pb_c	Pb_c (pg)	$^{206}Pb/^{204}Pb$	$^{208}Pb/^{206}Pb$	$^{207}Pb/^{206}Pb$	% err	$^{207}Pb/^{235}U$	% err	$^{206}Pb/^{238}U$	% err	corr. coef.	$^{207}Pb/^{206}Pb$	±	$^{207}Pb/^{235}U$	±	$^{206}Pb/^{238}U$	±
(a)	(b)	(c)	(d)	(c)	(e)	(e)	(e)	(e)	(f)	(g)	(g)	(h)	(g)	(h)	(g)	(h)		(i)	(h)	(i)	(h)	(i)	(h)
08JDP-5																							
A	0.005	192	0.286	5.8	1.2140	99.43%	50	0.57	3263	0.091	0.049941	0.245	0.208895	0.342	0.030337	0.177	0.730	192.26	5.69	192.62	0.60	192.65	0.34
B	0.005	263	0.415	8.7	1.6831	98.20%	16	2.53	1030	0.132	0.050181	0.876	0.212753	0.990	0.030749	0.320	0.498	203.39	20.32	195.86	1.76	195.24	0.61
C	0.005	188	0.340	5.9	1.1893	98.78%	23	1.21	1514	0.108	0.049775	0.470	0.208215	0.573	0.030339	0.249	0.596	184.51	10.94	192.05	1.00	192.67	0.47
D	0.005	377	0.291	11.5	2.3786	99.16%	34	1.65	2215	0.093	0.049953	0.573	0.208517	0.692	0.030275	0.301	0.579	192.80	13.32	192.31	1.21	192.27	0.57
E	0.005	364	0.317	11.5	2.3280	98.74%	23	2.44	1469	0.101	0.049966	0.482	0.211367	0.567	0.030681	0.194	0.575	193.40	11.20	194.70	1.00	194.81	0.37
08JDP-6																							
A	0.005	419	0.275	12.8	2.6526	99.26%	38.03	1.64	2483	0.088	0.050196	1.219	0.210217	1.313	0.030374	0.177	0.580	204.08	28.28	193.73	2.32	192.89	0.34
B	0.005	666	0.355	20.5	4.2055	99.48%	55.72	1.81	3553	0.113	0.049913	0.331	0.208590	0.433	0.030310	0.216	0.667	190.93	7.70	192.37	0.76	192.49	0.41
D	0.005	954	0.355	30.5	6.0987	98.76%	23.23	6.30	1490	0.113	0.050117	0.509	0.211832	0.607	0.030656	0.237	0.577	200.40	11.81	195.09	1.08	194.65	0.45
E	0.005	423	0.383	14.7	2.6736	96.07%	7.17	9.01	470	0.121	0.049822	1.028	0.208224	1.124	0.030312	0.212	0.527	186.70	23.92	192.06	1.97	192.50	0.40

(a) A, B, etc. are labels for fractions composed of single zircon grains or fragments; all fractions annealed and chemically abraded after Mattinson (2005).

(b) Nominal fraction weights estimated from photomicrographic grain dimensions, adjusted for partial dissolution during chemical abrasion.

(c) Nominal U and total Pb concentrations subject to uncertainty in photomicrographic estimation of weight and partial dissolution during chemical abrasion.

(d) Model Th/U ratio calculated from radiogenic $^{208}Pb/^{206}Pb$ ratio and $^{207}Pb/^{235}U$ age.

(e) Pb* and Pbc represent radiogenic and common Pb, respectively; mol % $^{206}Pb^*$ with respect to radiogenic, blank and initial common Pb.

(f) Measured ratio corrected for spike and fractionation only. Daly analyses, based on analysis of NBS-982.

(g) Corrected for fractionation, spike, and common Pb; up to 3 pg of common Pb was assumed to be procedural blank: $^{206}Pb/^{204}Pb$ = 18.50 ±1.0%; $^{207}Pb/^{204}Pb$ = 15.50 ±1.0%; $^{208}Pb/^{204}Pb$ = 38.40 ±1.0% (all uncertainties 1-sigma). Excess over blank was assigned to initial common Pb employing Stacey and Kramers model Pb at 195 Ma.

(h) Errors are 2-sigma, propagated using the algorithms of Schmitz and Schoene (2007) and Crowley et al. (2007).

(i) Calculations are based on the decay constants of Jaffey et al. (1971). $^{206}Pb/^{238}U$ and $^{207}Pb/^{206}Pb$ ages corrected for initial disequilibrium in $^{230}Th/^{238}U$ using Th/U [magma] = 3

(j) Corrected for fractionation, spike, and blank Pb only.

5. Conclusion

Precise 192.6 ±0.6 Ma U-Pb TIMS zircon dates from coexisting synkinematic and post-kinematic intrusive phases of the Wark-Colquitz complex in downtown Victoria document a brief deformation episode within the much longer, ca. 25 Ma history of the complex as the roots of the Triassic-Jurassic Bonanza magmatic arc. Given abundant outcrops in Victoria, oopportunities to unravel the history of the complex abound, and it is hoped that this very limited study will be succeeded by more thorough work to investigate of the magmatic and structural evolution of the complex, which will provide insight into subduction dynamics along the developing Cordilleran plate margin.

Acknowledgments

Philippe Erdmer instigated and led the field foray into the pit. Richard Friedman conducted the U-Pb zircon geochronology at Pacific Centre for Isotopic and Geochemical Research, University of British Columbia (Vancouver).

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