10-1991

Metamorphic Evidence for Tilt of the Spuzzum Pluton – Diminished Basis for the Baja British-Columbia Concept

E. H. Brown
Western Washington University, ned.brown@wwu.edu

Russ R. Burmester
Western Washington University, russ.burmester@wwu.edu

Recommended Citation

Brown, E. H. and Burmester, Russ R., "Metamorphic Evidence for Tilt of the Spuzzum Pluton – Diminished Basis for the Baja British-Columbia Concept" (1991). *Geology Faculty Publications*. 23.
https://cedar.wwu.edu/geology_facpubs/23

TECTONICS, VOL. 10, NO. 5, PAGES 978-985, OCTOBER 1991

METAMORPHIC EVIDENCE FOR TILT OF THE SPUZZUM PLUTON: DIMINISHED BASIS FOR THE "BAJA BRITISH COLUMBIA" CONCEPT

E. H. Brown and R. F. Burmester
Department of Geology, Western Washington University

Abstract. To address the question of tilt versus translation as the mechanism responsible for discordance between paleomagnetic directions of Cretaceous plutons in the British Columbia Coast Plutonic Complex and the North American reference direction, metamorphic pressures around the margin of the Spuzzum pluton have been determined. Pressures are derived from microprobe analyses and evaluation of exchange equilibria in the assemblage garnet-biotite-plagioclase-aluminum silicate-quartz. Samples studied come from eight localities in the contact aureole around the pluton and encompass the area of a previous paleomagnetic study. The analyzed samples are coarse grained and exhibit textural features indicative of equilibrium crystallization following emplacement of the Spuzzum pluton. Results of this study indicate a complicated tilt history for the Spuzzum pluton, with tilt first to the northeast then to the southwest. The southwest tilt can fully explain the discordance of the paleomagnetic direction in the Spuzzum but does not preclude translation. However, in view of the tilt history of this pluton, the paleomagnetic data derived from it should not be used in an analysis of north-south translation.

INTRODUCTION

A major problem in addressing processes of orogeny in the North American Cordillera is the unsettled question of how to interpret discordant paleomagnetic directions from Cretaceous plutons in the British Columbia Coast Plutonic Complex. The discordance is broadly systematic: relative to North American reference directions, the paleomagnetic directions from the plutons show flatter inclinations and more easterly declinations [e.g. Beck et al. 1981; Irving et al., 1985; Irving and Wynne, 1990]. Two mechanisms have been considered to explain this phenomenon [Symons, 1977; Beck et al., 1981; Irving et al., 1985]: (1) tilt on the order of 20°-35° about a northwest trending axis or (2) northward translation on the order of 2000-3000 km coupled with clockwise rotation of up to 65° around a vertical axis. This second hypothesis has been popularized as the "Baja British Columbia" concept [Umhoefer, 1987]. Scant direct geologic evidence has been mustered in support of either of the two models. Arguments for the tilt model are based on: (1) lack of evidence for faults of great enough offset to accommodate the large translation required by the second model [Price and Carmichael, 1986], (2) northeast-southwest variations in depth of metamorphism and K-Ar ages across the plutons and their host schists [Butler et al., 1989], and (3) southwest tilt of Tertiary strata inferred to be unconformable on the Mount Stuart pluton [Butler et al., 1989]. This evidence is questioned on the basis that the major faults could be hidden or obscured by younger geology and that the Tertiary strata on the Mount Stuart pluton may be faulted against the pluton [Miller et al., 1990]. The metamorphic and K-Ar evidence has not been seriously considered by critics of the tilt model, perhaps because it has not been fully developed.

Virtually no geologic evidence has been discovered in support of the "Baja British Columbia" model. Acceptance of this concept, which is wide, derives primarily from the systematic nature of the discordance and difficulty in understanding the seemingly necessary alternative tectonic process of regular block tilting across the British Columbia Cordillera [e.g. Oldow et al., 1989], and the attractiveness of driving the northward translation by oblique Farallon and/or Kula plate convergence against North America [Beck, 1986; Umhoefer et al., 1989].

Until this problem is resolved, many fundamental aspects of Cordilleran tectonic/petrologic evolution remain unapproachable. Particularly problematic is understanding the relation of structural and petrologic patterns (e.g., orientations of stretching lineations, magmatic belts, isotopic patterns, metamorphic zones) to inferred plate interactions and the continental margin of North America. Also critical to Cordilleran geology is the mechanism of either orogen-wide block tilting or large-scale translation, both processes possibly coupled with coeval foreland contraction [considered recently by Oldow et al., 1989].

The Spuzzum pluton is a mainstay of the "Baja British Columbia" concept but also has been suspected of being tilted [Bartholomew, 1979]. Our study is a quantitative analysis of metamorphic P-T conditions around this pluton and as such is a follow-up to the metamorphic evidence for southwest tilt presented by Bartholomew [1979].

REGIONAL SETTING

The Spuzzum pluton lies at the southeast end of the British Columbia Coast Plutonic Complex (Figure 1), a predominantly Late Jurassic and Cretaceous assemblage of plutons emplaced in largely primitive arc and ocean floor metasedimentary and metavolcanic rocks. In the vicinity of the Spuzzum pluton, three mappable host metamorphic units, in mutual fault contact, are recognized: the Settler schist, the Cogburn Creek unit, and the Slollicum unit [Monger, 1986]. The Spuzzum intrudes across parts of all three units but is in most part hosted by the Settler schist. Many other plutonic bodies ranging in age from Triassic to Tertiary [Monger, 1989] occur in the area. Most notable is the large Scuzzy plutonic complex lying north of the Spuzzum body (Figure 1).

The timing and delineation of intrusive phases that make up the Spuzzum and Scuzzy plutons are poorly known. Although K-Ar mineral ages are relatively abundant for the region (Figure 2), the range of ages and complexity of their distribution preclude a simple interpretation, except a reasonable inference that Cretaceous plutonism had ceased and all systems were locked in by 75-80 Ma. U-Pb ages are scant. Figure 2 shows two concordant 96 Ma ages on parts of the Spuzzum-Mount Breckenridge plutonic suite and one 84 Ma concordant age for the Scuzzy pluton. Discordant zircon ages also have been obtained but are not easily interpreted [Gabites, 1985]. Pending further geochronologic results, we accept 96 and 84 Ma, respectively, as the ages of the

Paper number 91TC00978
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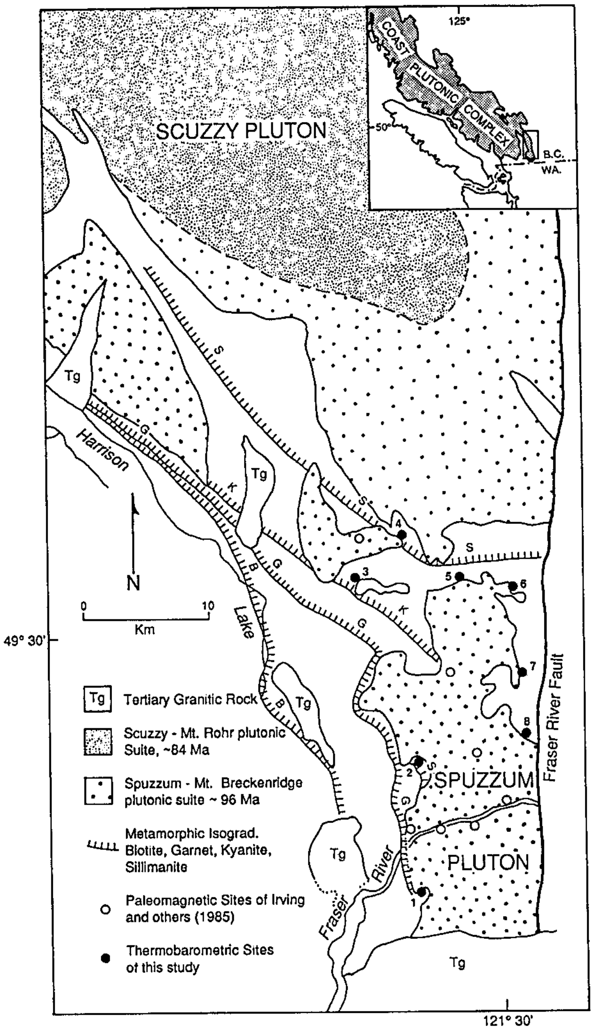

Fig. 1. Geologic setting of the Spuzzum pluton, with locations of metamorphic samples of this study (solid dots) and A1 paleomagnetic sites of Irving et al. [1985] (open circles). Also shown are the Scuzzy pluton, whose axis trends across the northeast side of the Spuzzum, and metamorphic isograds that portray an increase in grade to the northeast. Geology from Pigage [1973], Reamsbottom [1974], Bartholomew [1979], Gabites [1985], Bennett [1989], Hettinga [1989], and Monger [1989].

Spuzzum and Scuzzy plutons but note that precise ages are not critical to the conclusions of this study.

The Spuzzum pluton consists of a number of intrusive bodies of dominantly diorite and tonalite [Richards and McTaggart, 1976]. An intrusive relation of the plutonic bodies to the host schists is indicated by crosscutting contact features and development of a contact metamorphic aureole around the bodies [Lowes, 1972; Pigage, 1973; Bartholomew, 1979; Bennett, 1989; Hettinga, 1989]. Fabric in the plutonic rock, defined by alignment of mineral grains, is mostly igneous [following criteria of Patterson et al., 1989]. Locally foliation in the host schist passes into the pluton, indicating subsolidus deformation and thus overlap of intrusive and dynamic metamorphic events.

METAMORPHIC SETTING

The metamorphic history of the region may be quite complicated; however, for this study, only two events need be considered. They are detailed separately but are likely aspects of a continuous process. First, an early Barrovian event ranging from subgreenschist to upper amphibolite facies was at least in part coincident in space and time with intrusion of the Spuzzum and related plutons (M1 of Journeay [1990]). During this event the Spuzzum pluton produced a shallow andalusite-sillimanite contact aureole, which is still preserved in spite of a subsequent metamorphic overprint. Therefore the present attitude of the pluton is approximately the same as that immediately following intrusion. Second, a later Barrovian event is spatially associated with the Scuzzy pluton (M2 of Journeay [1990]). This caused a penetrative fabric in schists along the northeast margin of the Spuzzum pluton. It overprinted andalusite of the Spuzzum contact aureole, producing high-pressure coarse garnet-kyanite-staurolite assemblages in schists around the northern and eastern sides of the Spuzzum pluton. The present-day exposure of the pressure gradient preserved from the second event indicates that the Spuzzum was uplifted and tilted to the southwest after metamorphism. It is this tilt that we quantify below and that we infer compensated for an earlier northeast tilt to restore the pluton to more nearly its original attitude.

QUANTITATIVE EVALUATION OF SOUTHWEST TILT

Geobarometry and Geothermometry

Metamorphic features described in this section indicate southwest tilt of the Spuzzum pluton since the time of recrystallization, i.e., the time when mineral compositions

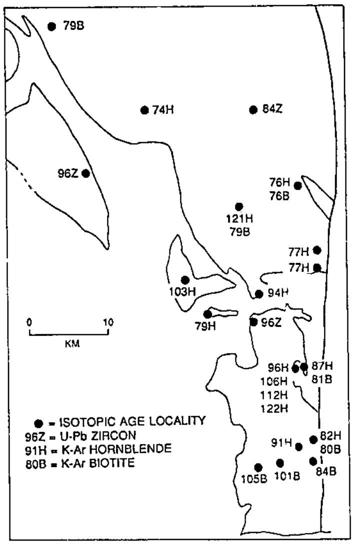

Fig. 2. Isotopic ages available for the study area. Most ages are from the compilation of Monger [1989]; these are supplemented with information by McLeod et al. [1976], Bartholomew [1979], Gabites [1985], and an unpublished U-Pb zircon age for the Spuzzum pluton from N. Walker (personal communication, 1990).

were locked in. Fundamental to this argument is evidence that the assemblages studied represent P-T conditions attained at the time of, or after, intrusion of the pluton; this point is of particular concern where pre-Spuzzum assemblages may be present in the country rock. The studied samples all come from the Spuzzum contact aureole. One sample (P-3; Table 1) is from Bartholomew [1979]; the others are newly collected. All samples but one contain andalusite porphyroblasts, or relict porphyroblasts; the exception (163-241, Table 1) contains primary sillimanite. The andalusite is developed in and restricted to a narrow (less than 100 m wide) zone along the perimeter of the pluton. This contact zone, well described by Lowes [1972], Pigage [1973] and Bartholomew [1979], represents an upgrade of the regional rocks on the southwest side of the pluton. On the northeast side, the andalusite-bearing contact metamorphic assemblage possibly overprints earlier high-grade minerals; it is in turn clearly overprinted by kyanite-grade metamorphism (see Pigage [1973] and Bartholomew [1979] for good descriptions).

The present study is based on thermobarometric analysis of minerals in the assemblage garnet-biotite-plagioclase-aluminum silicate-quartz in rocks where these minerals are in close mutual proximity (a few millimeters) and show textural evidence of equilibrium (i.e., coarse grains, straight grain boundaries, and absence of reaction textures). Along the northeast side of the pluton, where a pre-Spuzzum mineralogy in the host schists may exist, the study was focused on mineral grains within or next to pseudomorphed andalusite porphyroblasts. Commonly, the entire assemblage can be found within the outlines of a pseudomorphed andalusite. Garnets in the studied specimens are mildly zoned, and care has been taken to obtain compositions of growth rims, avoiding resorption edges. Straight grain edges, dodecahedral crystal form, and consistency of rim compositions are criteria used for recognizing growth rims.

TABLE 1. Mineral Compositions

	Site and Sample Numbers											
	1			2	3	4		5	6		7	8
	164-191A	164-191B	164-191C	163-241	162-192	162-186	JT-88-05	P-3*	164-233D	164-233F	164-195E	164-193B
Garnet (calculation based on 24 O)												
Si	5.97	5.95	6.03	5.99	5.92	6.04	5.94	5.90	5.99	5.96	5.98	5.93
Al	4.02	4.00	3.96	4.02	4.01	3.94	4.01	4.08	3.95	3.97	4.00	4.00
Mg	0.802	0.789	0.811	1.22	0.829	0.956	1.03	0.850	0.952	0.927	0.910	0.891
Fe	4.42	4.66	4.41	4.37	4.39	4.28	4.38	4.48	4.43	4.40	4.36	4.69
Mn	0.550	0.386	0.537	0.165	0.410	0.480	0.420	0.270	0.263	0.220	0.163	0.063
Ca	0.243	0.234	0.244	0.232	0.529	0.262	0.277	0.460	0.439	0.569	0.637	0.471
Biotite (calculation based on 20 O and 4 H)												
Si	5.81	5.83	5.86	5.37	5.70	5.52	5.66	5.44	5.86	5.89	5.95	5.91
Al^{4+}	2.19	2.17	2.14	2.63	2.30	2.48	2.34	2.56	2.14	2.11	2.05	2.09
Al^{6+}	1.74	1.71	1.92	0.89	1.22	0.93	1.06	0.92	1.73	1.74	1.70	1.61
Ti	0.21	0.21	0.21	0.24	0.24	0.21	0.28	0.20	0.25	0.22	0.20	0.28
Fe	2.72	2.69	2.55	1.99	2.25	2.31	2.48	2.15	2.27	2.31	2.23	2.35
Mg	2.40	2.43	2.32	2.61	2.70	2.23	2.58	2.50	2.77	2.81	2.97	2.78
Mn	0.01	0.00	0.01	0.00	0.01	0.01	0.01	0.00	0.01	0.01	0.00	0.00
Na	0.02	0.03	0.02	0.12	0.06	0.14	0.05	0.07	0.10	0.08	0.08	0.09
K	1.85	1.88	1.77	1.68	1.69	1.53	1.85	1.67	1.77	1.70	1.70	1.78
Plagioclase												
Xan	0.300	0.317	0.293	0.307	0.385	0.340	0.330	0.314	0.300	0.331	0.330	0.270
Mineral Assemblage												
Qtz	x	x	x	x	x	x	x	x	x	x	x	x
Plg	x	x	x	x	x	x	x	x	x	x	x	x
Mu	x	x	x		x			x	x	x	x	x
Bi	x	x	x	x	x	x	x	x	x	x	x	x
Ga	x	x	x	x	x	x	x	x	x	x	x	x
Ky					x			x	x	x	x	x
Si				x		x	x					
And	x	x	x									
St	x	x	x		x			x	x	x	x	x
Rut								x	x	x		
Ilm	x	x	x	x		x	x	x	x	x	x	x

Site locations shown on Figure 1 and Table 3. Cross indicates mineral is present: Qtz, quartz; Plg, plagioclase; Mu, muscovite; Bi, biotite; Ga, garnet; Ky, kyanite; Si, sillimanite; And, andalusite; St, staurolite; Rut, rutile; Ilm, ilmenite.

* Mineral data from Bartholomew [1979]

Compositions of the minerals were derived by electron probe microanalysis, averaging three to ten spots for a small area on a thin section, the number depending on uniformity of grain composition. Mineral compositions vary within normal ranges observed in rocks interpreted to represent equilibrium crystallization. These compositions are presented in Table 1 in sufficient detail that others may experiment with alternative calculations. (Analyses of muscovite and ilmenite for some samples are available from the authors upon request.) For two localities, results from two separate hand samples were obtained and averaged; for another, results from three hand samples were averaged.

Two mineral equilibria pertinent to all rocks sampled were used in thermobarometric analysis:

almandine + phlogopite = pyrope + annite (GABI)

grossularite + aluminum silicate + quartz = anorthite (GASP)

The GABI equilibrium is strongly temperature dependent, while the GASP is more pressure dependent (Figure 3). A unique solution of pressure and temperature is obtained by evaluation of the two equilibria. A number of calibrations have been proposed for these equilibria. For GASP we applied the calibrations of: (1) Ghent [1976] with modifications from Ghent et al. [1979] and (2) Berman [1991]. Results are given in Table 2; an example from one sample is shown in Figure 3. The two calibrations of GASP agree fairly closely (compare A and B, Table 2 and Figure 3). The Berman GASP calibration is based on experimental data and thermodynamic relationships derived in large part within the last 10 years. The Ghent calibration is in part based on 1970s thermodynamic data and is in part empirical, derived from fitting samples to the kyanite-sillimanite stability fields.

For GABI we have used the calibrations of Ferry and Spear [1978] and Berman [1991]. These two GABI solutions agree for most samples (Table 2), but the Berman calibration, which includes corrections for nonideal solution, produces systematically higher temperatures in the higher-pressure samples, i.e., those with higher calcium in garnet. The difference from the Ferry and Spear result for these samples is only 30°-40°C, but this yields significantly higher pressures (0.6-0.7 kbar) than obtained with the Ferry and Spear calibration (B versus C, Figure 3).

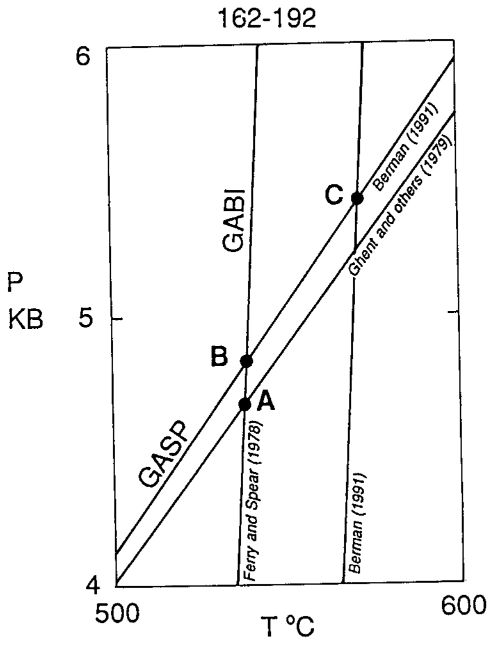

Fig. 3. P-T graph showing an example of results obtained with application of two calibration schemes each for GASP and GABI equilibria. See text for other details. A, B, and C represent the three results adopted for each sample (Tables 2 and 3; Figures 4 and 5).

Calculation of Tilt

The fundamental assumptions in the following analysis are (1) the rocks sampled represent points within a rigid body that has behaved as a coherent block since culmination of metamorphism; (2) the pressures deduced existed simultaneously across the block, or if not, the block did not move during metamorphism; (3) paleodepths of those points beneath a horizontal surface can be calculated from geobarometry assuming 3.58 km/kbar, which is based on an overburden density of 2.85 (average crustal density [Verhoogen et al., 1970]); and (4) errors in estimations of

TABLE 2. Pressures and Temperatures Calculated From Mineral Compositions of Table 1

	Site and Sample Numbers											
	1			2	3	4		5	6		7	8
Method	164-191A	164-191B	164-191C	163-241	162-192	162-186	JT-88-05	P-3*	1641-233D	164-233F	164-195E	164-193B
	Pressure, kbar											
A	4.39	3.30	4.40	4.13	4.68	4.77	4.89	5.15	5.58	6.02	5.80	5.59
B	4.28	3.17	4.34	4.52	4.82	5.45	5.09	5.22	5.77	6.20	5.98	5.59
C	4.09	3.08	4.17	4.45	5.41	5.41	4.97	5.85	6.03	6.81	6.77	6.22
	Temperature, °C											
A	627	590	621	642	538	677	670	551	577	573	542	547
B	628	590	622	642	539	680	671	551	578	575	542	547
C	617	585	609	637	572	679	665	584	591	604	581	572

Method A, GASP: Ghent [1976], Ghent et al., [1979]; GABI: Ferry and Spear [1978].
Method B, GASP: Berman [1991]; GABI: Ferry and Spear [1978].
Method C, GASP: Berman [1991]; GABI: Berman [1991].
* Mineral data from Bartholomew [1979].

Table 3. Depths Calculated from Pressures of Table 2 and Rotated Points

	Site							
	1	2	3	4	5	6	7	8
Coordinates								
North	0.00	9.64	25.31	28.08	25.01	24.70	17.64	12.26
East	5.10	5.26	0.00	3.40	7.86	12.03	13.25	14.39
Vertical	0.17	0.20	0.92	0.68	1.11	1.26	0.62	0.55
Method A								
Depth	14.43	14.79	16.75	17.29	18.44	20.76	20.76	20.01
Tilt	14.02	15.81	15.72	17.91	18.92	20.54	20.36	19.94
Method B								
Depth	14.07	16.18	17.26	18.87	18.69	21.43	21.41	20.01
Tilt	14.15	16.22	16.76	18.93	19.71	21.20	20.78	20.17
Method C								
Depth	13.53	15.93	19.37	18.58	20.94	22.98	24.24	22.27
Tilt	13.83	16.54	17.34	20.17	21.48	23.59	22.84	22.06

Coordinates are rectangular coordinates of the points from an arbitrary origin at sea level.
Method A, tilt azimuth 337.4, angle 28.1;
Method B, tilt azimuth 332.5, angle 27.2;
Method C, tilt azimuth 333.8, angle 38.3. All measures in kilometers. Depths calculated as P x 3.58 km/kbar.

paleodepths are normally distributed. Table 3 presents rectangular coordinates of the points from an arbitrary origin, and the paleodepths calculated from A, B, and C methods (Table 2).

The actual sequence and mechanisms of tectonic events that brought these points to the present surface may have been quite complicated, but the net effect can be resolved into two components: rotation (tilt) about a local, horizontal axis and uplift (equivalent to rotation about a distant axis). The net uplift is the difference between average elevation of the points today and the average of their paleodepths. The local rotation is the tilt that produces the best match between the depths of the rotated points and their paleodepths. For simplicity, the net uplift was removed from all paleodepths and the origin of the points' coordinate system was transformed to the centroid of the data so the means of the data would be zero.

Judgement of the best tilt parameters and determination of confidence regions followed standard chi-square methods [Press et al., 1986]. Since the data were transformed to have a zero mean, chi-square is merely the sum of squares of each point's deviation (rotated depth less corresponding paleodepth) divided by its standard deviation. Initial calculation of chi-square used an arbitrary standard deviation based loosely on results from replicate samples. Chi-square was repeatedly calculated after incremental changes in rotation axis azimuths and angles. The azimuth and angle combination that produced the minimum chi-square was judged the best; thus it is a least squares best fit. The best rotation and net uplift for each of the thermobarometric

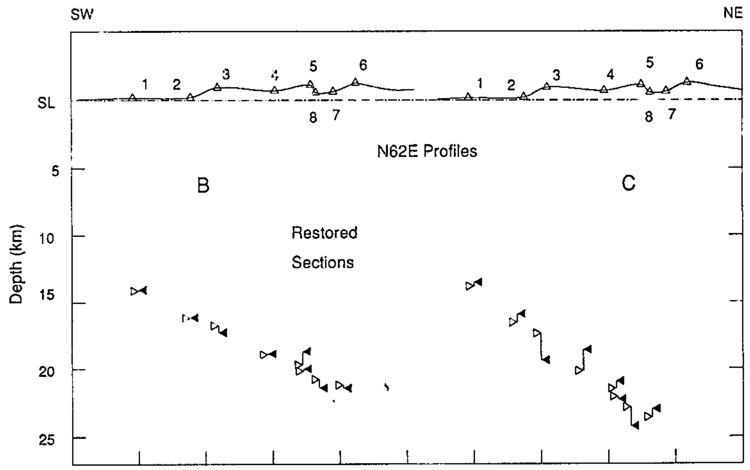

Fig. 4. Cross section oriented N62°E with sampled points projected onto it. Paleodepths derived from B and C calibrations (Tables 2 and 3) are shown. Solid triangles represent paleodepths directly calculated from barometry; open triangles represent paleodepths derived from best fit tilts. Vertical lines between represent deviations of depths derived in the two ways. Horizontal and vertical scales are the same.

calibrations A, B, and C were used to restore the points to their paleolocations (Table 3). Restorations for B and C are shown in Figure 4.

Goodness of fit of these restorations could not be judged by using chi-square because we do not know each point's error independently. Instead, we assumed that the points have a common uncertainty that is approximated by the standard deviation calculated from the differences of the tilt-restored depths and barometrically determined depths. The uncertainties about the best tilt for A, B, and C were estimated by using this standard deviation to recalculate chi-square over a suitable range of tilt azimuth and angle. For two parameters (degrees of freedom in this analysis), the locus of azimuths and angles that increase chi-square by 2.30 defines the one standard deviation or 68% confidence limit; an increase of 6.17 defines the 95% limit [Press et al., 1986; p. 536]. Only the one standard deviation confidence regions are shown in Figure 5 to reduce clutter. One standard deviation is useful in evaluating propagation of errors and adequately reflects the relative uncertainties of the three methods.

No significance should be attached to the apparent linearity of the points in the restored section (Figure 4); it is an artifact of the small relief with respect to horizontal distance across the area. Consider that if the profile were across a Grand Canyon-like abyss, it would look "U" shaped, and its restored section like a tilted "U". What is important is the agreement between depths of the restored points and their paleodepths.

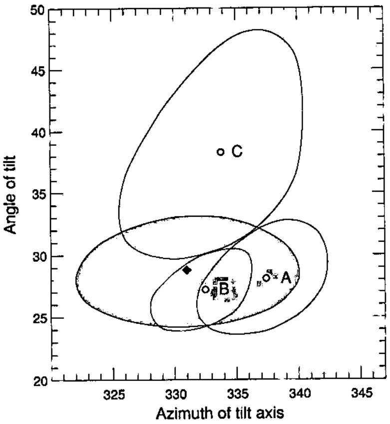

Fig. 5. Best fit rotation parameters (tilt azimuth and angle), shown by circles, and regions of confidence at one standard deviation for A, B, and C calibrations (Tables 2 and 3). Actual tilt may have been about 5° less if the land surface was 1.5 km higher over the northeast side of the Spuzzum pluton than over the southwest during metamorphism. Diamond shows rotation about horizontal axis required to transform a mid-Cretaceous reference direction (calculated from poles given by Globerman and Irving [1988]) into the mean direction of A1 magnetizations from the Spuzzum [Irving et al., 1985]. Its one standard deviation uncertainty region (shaded) was calculated using the test of McFadden and Lowes [1981]. Similarity of tilts deduced from barometry and paleomagnetism suggests that the discordant direction can be completely explained by a single, postmetamorphic tilt.

DISCUSSION

The field and petrographic data described above evince a series of events related to the emplacement and uplift of the Spuzzum pluton: (1) intrusion of the pluton at approximately its current orientation, which produced the relatively shallow-level contact aureole observed; (2) northeastward tilting and depression of the pluton and surrounding schist, and recrystallization at temperatures in the range 540°-680°C; then (3) uplift and southwest tilting to the current position (Figure 6). Barometric analysis based on mineral equilibria shows pressures attained at the last time of recrystallization, before uplift and southwest tilt. Paleodepths derived from these pressures can be used to calculate southwest tilt and its imprecision implicit in the scatter of the data. We need now to examine other uncertainties in the derived tilt, the implications of that tilt for the paleomagnetism of the Spuzzum pluton, and possible tilt mechanisms.

The largest source of uncertainty in the barometrically derived tilt is in the choice of calibration. In the absence of a clear rationale for chosing one calibration, we accept that the uncertainty of the barometrically determined tilt embraces the uncertainty regions of all calibrations.

Other uncertainties may result from erroneous assumptions used in the tilt calculations. The coherent block assumption appears substantiated by the good agreement between depths calculated from barometry and those calculated from rigid-block rotation. Error in the density used for conversion to depth and the implicit assumption of uniform density would have a small effect, probably negligible here. Of greater concern is the assumption that metamorphism peaked under a horizontal plane. Random topography would manifest itself as scatter in the derived pressures and depths just as the present topography and rotated depths depart from a plane (Figure 4). However, departure of the surface from horizontal would bias the calculated tilt. In fact we suspect this is probable and offer the following scenario.

The inferred sequence of tilts, first northeast then southwest, suggests a process of loading then unloading the northeast side of the pluton. Loading by thrust slices [Journeay, 1990] is one possibility. Another is loading by pluton emplacement. The latter is suggested by the large plutonic complex that lies just north of the Spuzzum pluton proper (Figure 1). This batholith, which includes the Scuzzy pluton, appears to have controlled metamorphic zones that overprint the northeast side of the Spuzzum pluton, and its long axis is parallel to the tilt axis and projects northeast of the tilted area. We envision that this pluton complex was emplaced above and northeast of the Spuzzum pluton, displacing its northeast flank downward while thickening the crust over it (Figure 6). For an addition of 10 km to a 30 km thick crust, and assuming crustal and mantle densities of 2.8 and 3.3, respectively, the isostatically compensated elevation difference across the study area could have been as much as 1.5 km. This reduces the required tilt 5° from that calculated for the horizontal plane. Therefore the uncertainty region should be expanded to include tilt angles a few degrees less than shown in Figure 5.

Next, what are the implications of this tilt to the paleomagnetism of the Spuzzum pluton? The area surrounded by the metamorphic samples includes the sites of the Irving et al.'s [1985] paleomagnetic study (Figure 1) so it is reasonable to assume that they also experienced the tilt

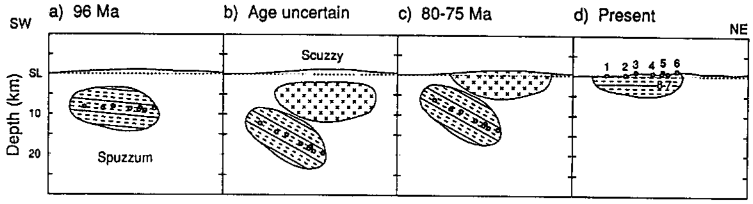

Fig. 6. Inferred history of the Spuzzum pluton and its contact aureole sampled for this study. (a) Emplacement of the Spuzzum pluton at an intermediate depth such that the presently observed contact was entirely within the andalusite stability field. The orientation of the pluton is poorly constrained. (b) Depression of the Spuzzum, especially its northeast side, when loaded by the Scuzzy pluton and metamorphosed under peak conditions. (c) Magnetization of the Spuzzum pluton before the youngest K-Ar ages in the area, perhaps during uplift and cooling. (d) Tilt of about 27° during continued uplift to the present position. Numbers and symbols indicate sample locations projected onto these N62°E cross sections.

derived above. The chief uncertainties are the absolute age of magnetization and its age relative to metamorphism and tilting. The former is important because it determines which paleomagnetic reference is proper. The maximum age cannot be older than the age of emplacement. The best estimate of this is probably 96 Ma as given by the two zircon ages for the Spuzzum suite rather than an older age given by the more highly scattered hornblende ages (Figure 2). The minimum age probably is not less than the youngest biotite age in the area, around 80 Ma. For most of this time span, there was little apparent polar wander [Irving and Irving, 1982; Gordon et al., 1984]. Therefore the mid-Cretaceous reference poles preferred by Globerman and Irving [1988] were used to calculate the reference direction expected for the Spuzzum. Results based on these references may be in slight error if the magnetization is young because of rapid apparent polar wander between 87 Ma and 76 Ma [Gunderson and Sheriff, 1991].

The age of magnetization with respect to metamorphism and tilt is more difficult to resolve. One possibility is that the Spuzzum pluton was completely remagnetized during metamorphism. Table 2 shows that sampled points on the periphery of the Spuzzum pluton reached temperatures in the range 540°-680°C. Although we are uncertain as to the relative timing of the peak temperatures for samples 1 and 2, the recorded temperatures correlate with the M2 event for samples 3-8. These temperatures are high with respect to the Curie temperature of magnetite (578°C), which caries the bulk of the A1 magnetization used to calculate the Spuzzum mean direction [Irving et al., 1985]. Ideally, any magnetic minerals with Curie or blocking temperatures lower than peak temperatures reached during metamorphism would be completely remagnetized. Thus if the interior of the Spuzzum were in thermal equilibrium with its margins, the A1 magnetization may represent a remagnetization dating from the peak of metamorphism or subsequent cooling. Based on this possibility that the magnetization postdates metamorphism, a simple hypothesis is that the discordance of the paleomagnetic direction observed in the Spuzzum pluton is due to the same tilt about a horizontal axis that is recorded barometrically. Tilts derived from paleomagnetism and barometry are so similar (Figure 5) that this hypothesis is difficult to reject.

It is of course possible to construct more complicated hypotheses. One such might be that magnetization survived metamorphism and that the discordance of its direction reflects translation as well as tilt. However, to test for significance of translation, the observed direction would first have to be corrected for the effect of tilt. We can correct for the southwest tilt, but with the large uncertainty described above. We can only guess at the inferred earlier tilt to the northeast and would have to assign an additional uncertainty of about 20°-30° to it. The resulting imprecision of the tilt-corrected direction would be so large as nullify the test.

The mechanism and timing of the southwest tilt of the Spuzzum pluton are uncertain. If there were isostatic compensation of a magmatic welt or thrust stack over the northeast side of the Spuzzum, differential isostatic crustal rebound with fastest uplift along the inferred thickest part of the load northeast of the Spuzzum pluton could account for at least part of the southwest tilt. This is possibly dated by the youngest K-Ar ages. However there is accumulating evidence from surrounding regions for Eocene age of similar tilts: to the west, Eocene Tofino and Kennedy Lake stocks of Vancouver Island are tilted about 30° down to the southwest and west [Irving and Brandon, 1990]. To the east, Eocene intrusions above an east dipping extension fault are tilted 37° down to the west [Bardoux and Irving, 1989], and farther east the Eocene Granby pluton and Syringa dikes are tilted oppositely about 40° down to the east and west, respectively [Marquis and Irving, 1990]. Bardoux and Irving [1989], noting the similarity of the magnetic discordances in these bodies to those observed in the western Cordillera, suggested all might have a common cause: regional extension on very large crustal extensional shears, some of which have not yet been recognized. The possibility that southwest tilt of the Spuzzum also is Eocene and due to extension should be considered.

In conclusion, results of this study do not disprove northward translation of western British Columbia, but indicate a complicated tilt history for the Spuzzum pluton that precludes attributing paleomagnetic discordance simply to translation. Thus the Spuzzum pluton should be withdrawn from the body of data upon which the "Baja British Columbia" concept is based.

Acknowledgments. This study was supported by grants from the National Science Foundation (EAR 8720721 and EAR 9004480). Microprobe analysis was carried out at the University of Washington with the able assistance of Scott Keuhner. We are indebted to numerous colleagues, for assistance: discussions with Myrl Beck, Dave Engebretson, and Jim Talbot provided guidance during the research; Jeff Bennett, Mike Hettinga, and Jim Talbot provided samples from their research collections; Ed Ghent contributed useful advice regarding thermobarometry; Steve Fluke developed a computer program at W.W.U. to convert probe data to P and T, and Rob Berman provided us with his latest thermobarometric program; Gene Hoerauf and Lucky Tedrow provided computer expertise in a preliminary regression analysis, and Dave Engebretson encouraged the use of chi-square. The manuscript has benefitted from reviews by Myrl Beck, Rob Berman, Bob Butler, Randy Parrish, Ted Irving, and Scott Babcock.

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E. H. Brown and R. F. Burmester, Department of Geology, Western Washington University, Bellingham, WA 98225.

(Received December 7, 1990;
revised March 27, 1991;
accepted March 27, 1991.)