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New Geochronological Evidence for the Timing of Early Tertiary Ridge Subduction in Southern Alaska

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Abstract

We present new U/Pb (monazite, zircon) and $^{40}Ar/^{39}Ar$ (biotite, amphibole) ages for 10 Tertiary plutons and dikes that intrude the Chugach–Prince William accretionary complex of southern Alaska. The Sanak pluton of Sanak Island yielded ages of 61.1±0.5 Ma (zircon) and 62.7±0.35 (biotite). The Shumagin pluton of Big Koniuji Island yielded a U/Pb zircon age of 61.1±0.3 Ma. Two biotite ages from the Kodiak batholith of Kodiak Island are nearly identical at 58.3±0.2 and 57.3±2.5 Ma. Amphibole from a dike at Malina Bay, Afognak Island, is 59.3±2.2 Ma; amphibole from a dike in Seldovia Bay, Kenai Peninsula, is 57.0±0.2 Ma. The Nuka pluton, Kenai Peninsula, yielded ages of 56.0±0.5 Ma (monazite) and 54.2±0.1 (biotite). Biotite plateau ages are reported for the Aialik (52.2±0.9 Ma), Tustumena (53.2±1.1 Ma), Chernof (54.2±1.1 Ma), and Hive Island (53.4±0.4 Ma) plutons of the Kenai Peninsula. Together, these new results confirm, but refine, the previously documented along-strike diachronous age trend of near-trench magmatism during the early Tertiary. We suggest that this event began at 61 Ma at Sanak Island, 2-4 m.y. later than previously supposed. An intermediate dike near Tutka Bay, Kenai Peninsula, yielded a hornblende age of 115±2 Ma. This represents a near-trench magmatic event that had heretofore gone unrecognized on the Kenai Peninsula; correlative Early Cretaceous near-trench plutons are known from the western Chugach Mountains near Palmer.

Introduction

Early Tertiary near-trench plutons of the Sanak-Baranof belt in southern Alaska (fig. 1) have been widely interpreted as the product of ridge subduction (Hill and others, 1981; Helwig and Emmet, 1981; Moore and others, 1983; Bradley and others, 1993; Sisson and Pavlis, 1993; Haeussler and others, 1995). Bradley and others (1993) showed that magmatism was a time-transgressive event, beginning at 66–63 Ma at the western end of the belt (an age that we revise herein), and ending around 50 Ma at the eastern end. On this basis, Bradley and others (1993) inferred that a trench-ridge-trench triple junction, which marked the site of ridge subduction, migrated 2,200 km in 13–16 m.y. In the past few years, several new $^{40}Ar/^{39}Ar$ and U/Pb ages from near-trench intrusions in south-central Alaska have been published (Taylor and others, 1994; Haeussler and others, 1995; Poole, 1996) that confirm, but refine, this age progression. Here we report and document 3 U/Pb and 10 $^{40}Ar/^{39}Ar$ ages from the western half of the Sanak-Baranof belt. Eight of these ages are entirely new. One was previously published in a dissertation (Clendenen, 1991). The rest were cited by Bradley and others (1993) in their compilation, but the analytical data and supporting diagrams have never been published.

The present paper reports results from three somewhat interrelated research efforts involving five different geochronology labs. As a graduate student at Brown University in the late 1980's, William Clendenen began geochronological and thermochronological studies of several near-trench plutons along the Gulf of Alaska margin. Samples for dating were provided by Timothy Byrne, Malcolm Hill, Peter Vrolijk, and Dwight Bradley. Clendenen obtained six of the $^{40}Ar/^{39}Ar$ dates reported herein, in cooperation with Matthew Heizler at the State University of New York at Albany. As part of this effort, Randall Parrish, then at the Geological Survey of Canada, obtained U/Pb ages on zircon and monazite separates from two of Clendenen's samples. A third U/Pb age was obtained recently by Parrish, now at the British Geological Survey, in connection with the present paper. From 1988 to 1993, Bradley and coworkers mapped the Seldovia quadrangle (fig. 2) under the Alaska Mineral Resource Assessment Program of the U.S. Geological Survey (Bradley and others, 1999). Two intrusive-rock samples from the Seldovia quadrangle were among those dated by Clendenen; one sample was dated and published by Hauessler and others (1995); and four other samples, ages of which are reported herein, were dated by Dan Lux at the University of Maine. Tom Donley, meanwhile, was studying emplacement mechanisms of near-trench plutons in south-central Alaska as part of a graduate research project under Timothy Kusky at Boston University. Part of this work involved new $^{40}Ar/^{39}Ar$ geochronology, which is reported herein, by Paul

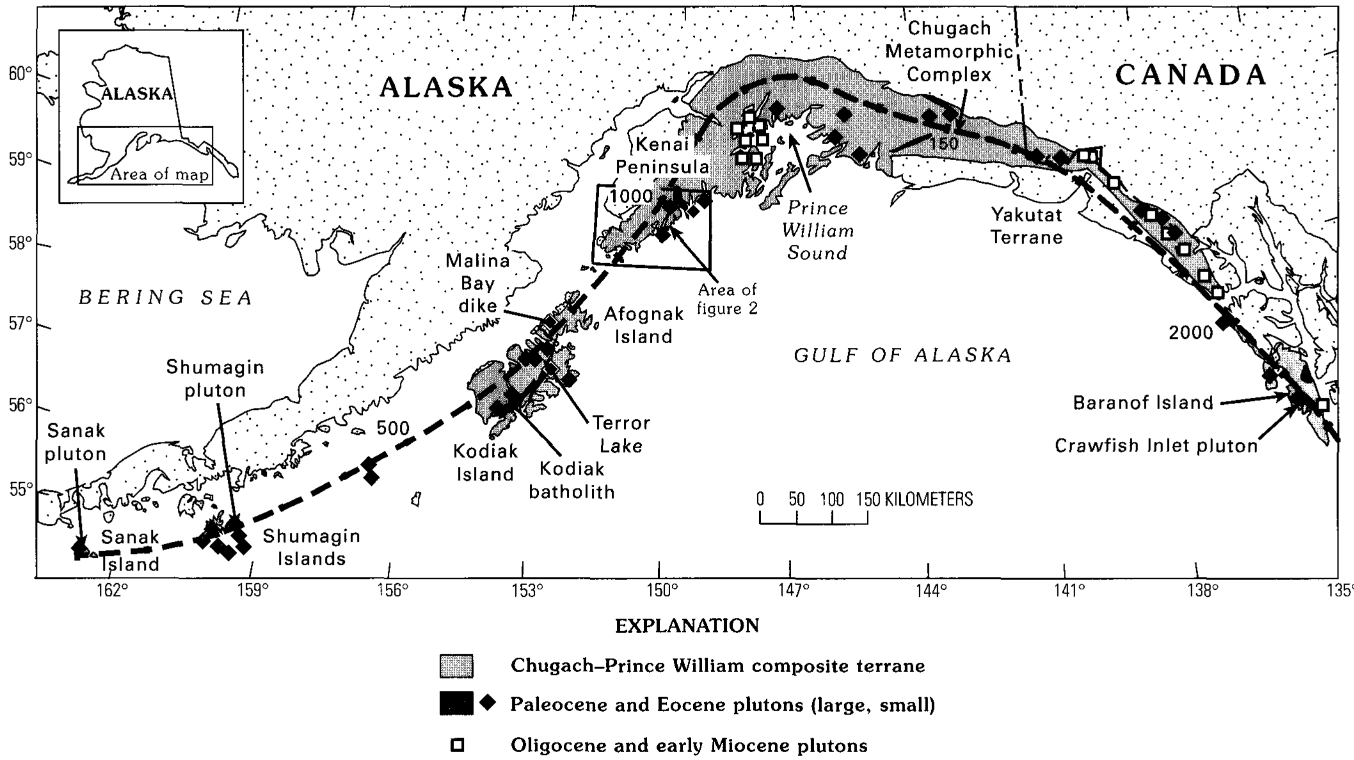

Figure 1. Generalized geologic map of southern Alaska showing plutons of Sanak-Baranof plutonic belt, Chugach-Prince William composite terrane, and localities mentioned in text. Numbers along dashed reference line show distance in kilometers from southern tip of Sanak Island to Baranof Island.

Layer at University of Alaska, Fairbanks. The aim of the present paper is to document the ages of these tectonically significant intrusive rocks—hard-won results from inaccessible places that might not otherwise have been published.

Regional Geology

Plutons of the Sanak-Baranof belt intrude a complexly deformed Mesozoic and Cenozoic accretionary prism known as the Chugach–Prince William composite terrane (the term "composite" is omitted below for brevity) (fig.1). Plafker and others (1994) provided a thorough review and comprehensive bibliography of the regional geology; in this paper we will discuss only the western half of the belt. The inboard part of the Chugach–Prince William terrane is mostly underlain by a melange of relatively competent blocks and fault slices of basalt, chert, and graywacke, surrounded by a phacoidally cleaved argillaceous matrix (Uyak and McHugh Complexes; Connelly, 1978; Bradley and Kusky, 1992). Outboard of the melange is a belt of Upper Cretaceous flysch, assigned to the Shumagin Formation, Kodiak Formation, and Valdez Group (Moore, 1973; Nilsen and Moore, 1979; Nilsen and Zuffa, 1982). Still farther outboard lie belts of flysch assigned to the Ghost Rocks Formation and Orca Group (Moore and others, 1983; Moore and Allwardt, 1980; Helwig and Emmet, 1981). The Ghost Rocks Formation and Orca Group contain mafic volcanic rocks that evidently were erupted in or near a trench and have been cited as one line of evidence for ridge subduction (Moore and others, 1983; Bradley and others, 1993; Lytwyn and others, 1997). Penetrative deformation in the accretionary prism (thrust imbrication, folding, melange formation) and regional metamorphism (typically prehnite-pumpelleyite to greenschist facies) occurred during and shortly after subduction-accretion during the Cretaceous and early Tertiary (Kusky and others, 1997). Near-trench plutons of the Sanak-Baranof belt were emplaced into the accretionary prism after most of this deformation. Another tract of accreted deep-sea turbidites (Eocene Sitkalidak Formation and the outboard part of the Orca Group; Moore and Allwardt, 1980; Helwig and Emmet, 1981) lies outboard of the Sanak-Baranof belt; these younger turbidites are not cut by the plutons and, hence, are probably younger.

Paleocene to Eocene plutons of the Sanak-Baranof belt are mainly granodiorite, granite, and tonalite (Hudson, 1983). Some of the plutons are elongate parallel to structural grain of the accretionary prism; others are transverse. Some are enormous—the Kodiak batholith, for example, is more than 100 km long and as wide as 10 km. In the eastern Chugach Mountains, magmatism was accompanied by high-grade regional metamorphism and anatectic melting of flysch (Hudson and Plafker, 1982; Sisson and others, 1989; Barker and others, 1992; Pavlis and Sisson, 1995). Paleocene to Eocene intermediate to silicic dikes are plentiful in some regions, such as the Kenai Peninsula. Oligocene to early Miocene plutons intruded the Chugach–Prince William terrane in southeastern Alaska and Prince William Sound; post-Eocene plutons have not been recognized from the Kenai Peninsula to Sanak Island.

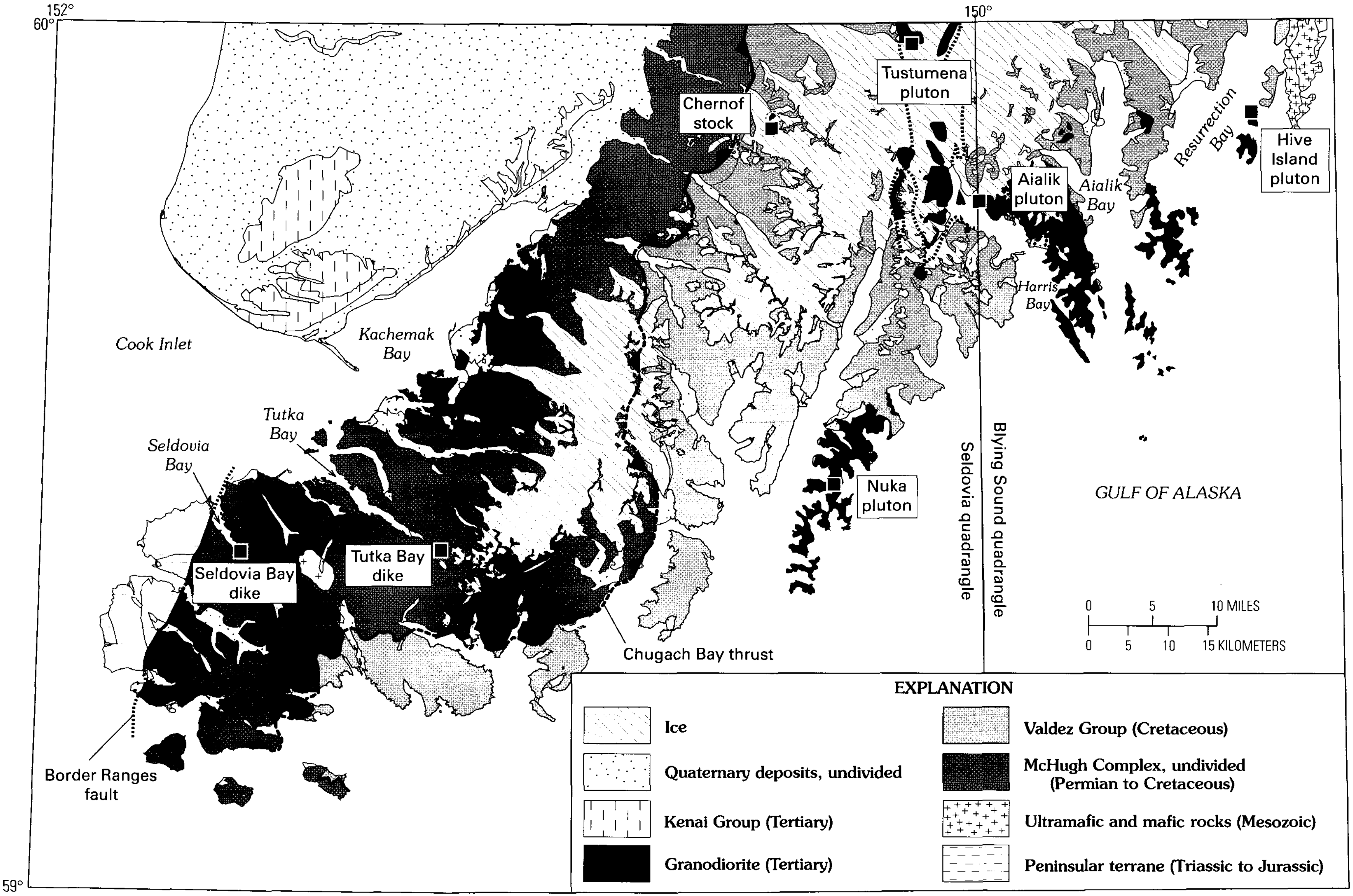

Figure 2. Geologic map of parts of the Seldovia and Blying Sound quadrangles showing locations of newly dated intrusive rocks (black squares). Geology from Bradley and others (1999) and Tysdal and Case (1979).

Analytical Methods

U-Pb analyses

U-Pb analyses were done at the Geological Survey of Canada, Ottawa, and the British Geological Survey, Keyworth. Analytical methods follow procedures outlined by Parrish and others (1987) and utilize zircon abrasion (Krogh, 1982), teflon microcapsule dissolution (Parrish, 1987), a mixed ^{205}Pb-^{233}U-^{235}U tracer (Parrish and Krogh, 1987), multicollector mass spectrometry, and numerical error propagation (Roddick, 1987). Analyses at the Geological Survey of Canada were done on a MAT 261 mass spectrometer; those at the British Geological Survey were done on a VG 354 mass spectrometer using a Daly ion counter in peak switching mode for both U and Pb. Analytical blanks for U and Pb are 3 and 10 picograms, respectively. Regression of the two analyses of sample S-70 used a York (1969) regression. Correction for common lead followed the model of Stacey and Kramers (1975) using ca. 60-Ma Pb. U-Pb results are presented in figure 3 and table 1. Errors on concordia diagrams are shown at the 2σ level.

$^{40}Ar/^{39}Ar$ analyses

$^{40}Ar/^{39}Ar$ analyses were performed at three geochronology laboratories: University of Maine at Orono, State University of New York at Albany, and University of Alaska at Fairbanks. Analytical methods are described below for each lab, and data are presented separately in tables 2, 3, and 4. At all three laboratories, the decay constants recommended by Steiger and Jäger (1977) were used to calculate ages. Methods of data acquisition and analysis differ in detail between the laboratories, and no attempt was made to report the results according a uniform scheme. The argon laboratories at University of Maine and University of Alaska quote results as plateau ages, and, although the two labs use slightly different definitions as to what constitutes a "plateau," this makes no practical difference with any of the data in question. Similarly, argon results from the State University of New York are quoted as isochron ages; these would barely change if recalculated as plateau ages. The incremental heating steps used in the age calculations are indicated in figure 4.

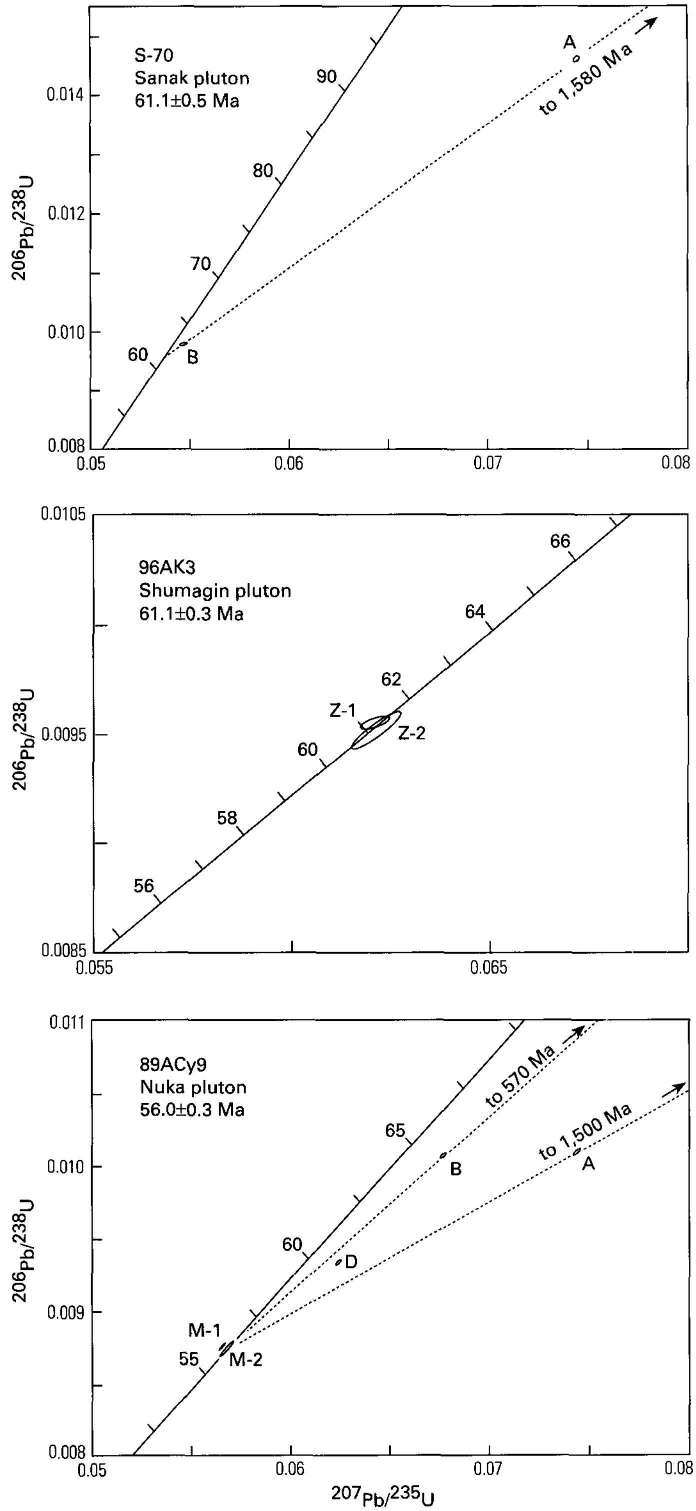

Figure 3. Concordia diagrams for Sanak, Shumagin, and Nuka plutons. Because each fraction consisted of multiple grains, upper intercepts at 1,580 Ma (Sanak pluton) and 570 Ma (Nuka pluton) likely represent averages of inherited ages. See table 1 for explanation of A, B, D, M-1, M-2, Z-1, and Z-2. Errors are shown at 2σ level.

$^{40}Ar/^{39}Ar$ Analytical Methods — State University of New York, Albany

Samples were wrapped in tin foil and irradiated in the H-75 position at the University of Michigan Ford Reactor. Neutron flux was monitored with Fe-mica biotite (age=307.3 Ma), and correction factors for interfering reactions were determined with K_2SO_4 glass and CaF_2. Mass spectrometry and argon extraction line information follows the procedures detailed in Harrison and Fitz Gerald (1986). Analytical results are presented in table 2.

$^{40}Ar/^{39}Ar$ Analytical Methods—University of Maine, Orono

Samples, flux monitors (SBG-7 inter-lab standard), and K and Ca salts were encapsulated in aluminum foil and

Table 1. Uranium-lead data for intrusive rocks from southern Alaska.

[Mineral fraction: l, elongate; e, equant; a, air-abraded in laboratory. *, radiogenic Pb, corrected for spike, fractionation, blank, and common Pb; #, measured ratio, corrected only for spike and fractionation; @, total common Pb in analysis; **, radiogenic ^{208}Pb, expressed as percent of total radiogenic Pb; ^, uncertainties are 1 sigma (percent); ^^, uncertainties are 2 sigma (Ma). Analyses of samples S-70 and 88ACy9 done at Geological Survey of Canada, Ottawa. Analysis of sample 96AK3 done at British Geological Survey]

Mineral fraction	Wt. (mg)	U (ppm)	Pb* (ppm)	^{206}Pb#/^{204}Pb	Pb_c@ (pg)	^{208}Pb** (%)	^{206}Pb^/^{238}U	± (%)	^{207}Pb^/^{235}U	± (%)	Corr. coeff.	^{207}Pb^/^{206}Pb	± (%)	207/206 age (Ma)	Error (Ma)
Sample S-70 (Sanak pluton)															
A, zircon, a, e	0.05	288	4.13	479	28	6.7	0.014609	0.14	0.13165	0.18	0.65	0.06536	0.14	785.8	5.8
B, zircon, a, l	0.03	308	2.9	254	28	6.4	0.009784	0.13	0.06563	0.50	0.55	0.04865	0.44	131.0	20
Sample 88ACy9 (Nuka pluton)															
A, zircon, a,e	0.17	727	6.89	6511	12	3.7	0.010087	0.10	0.07443	0.11	0.94	0.05351	0.04	350.6	1.7
B, zircon, a, e	0.17	841	7.86	4130	22	3.0	0.010065	0.10	0.06774	0.11	0.93	0.04881	0.04	138.9	1.9
D, zircon, a, l	0.08	861	7.47	3670	11	3.1	0.009330	0.09	0.06239	0.11	0.91	0.04850	0.04	123.7	2.0
M-1, monazite	0.19	5489	56.8	20908	28	23.7	0.008746	0.26	0.05678	0.27	0.99	0.04708	0.03	53.5	1.4
M-2, monazite	0.26	5150	93.5	10808	70	56.3	0.008762	0.11	0.05658	0.12	0.96	0.04683	0.03	40.8	1.5

[*Z, zircon; **, atomic ratio of Th to U; ^, measured ratio, corrected for spike and Pb fractionation (0.13%/amu); ^^, total common Pb in analysis, corrected for fractionation and spike; *^, corrected for blank Pb and U, and common Pb (Stacey-Kramers model) Pb equivalent to interpreted age of mineral]

Sample 96AK3 (Shumagin pluton)

Analysis*	Weight (mg)	U (ppm)	Pb** (ppm)	^{206}Pb^/^{204}Pb	Pb_c^^ (pg)	Th**/U	^{206}Pb*^/^{238}U	1 std err (%)	^{207}Pb*^/^{235}U	1 std err (%)	^{207}Pb*^/^{206}Pb	1 std err (%)	^{206}Pb*^/^{238}U (Ma)	2 std err (Ma)	^{207}Pb*^/^{235}U (Ma)	2 std err (Ma)	^{207}Pb*^/^{206}Pb (Ma)	2 std err (Ma)
Z-1	0.162	293.9	2.659	1041	28	0.17	0.009557	0.16	0.06209	0.3	0.04712	0.22	61.3	0.2	61.2	0.4	55.4	10.5
Z-2	0.128	270.2	2.464	1582	13	0.21	0.009521	0.45	0.06212	0.51	0.04732	0.21	61.1	0.5	61.2	0.6	65.5	9.9

Table 2. $^{40}Ar/^{39}Ar$ data for intrusive rocks from southern Alaska.

[Analyses done at State University of New York, Albany]

Temp (°C)	$^{40}Ar/^{39}Ar$	$^{37}Ar/^{39}Ar$	$^{36}Ar/^{39}Ar$	Moles ^{39}Ar	% total ^{39}Ar	% $^{40}Ar^*$	$^{40}Ar^*/^{39}Ar_K$	Age (Ma)	1 sigma error (Ma)
Sample 88ADw230, Seldovia Bay dike, amphibole, J = 0.004546									
850	79.84	2.728	257.8	0.479	3.20	4.85	3.891	31.6	11.7
950	12.96	7.067	19.89	0.39	5.81	57.0	7.539	60.8	6.1
1,000	9.374	9.752	10.97	1.08	13.0	71.1	6.764	54.6	2.0
1,020	8.206	10.61	6.616	1.27	21.5	83.3	6.943	56.1	2.1
1,040	7.950	10.78	6.876	1.06	28.6	81.8	6.619	53.5	3.1
1,050	7.639	11.09	4.156	1.37	37.8	91.9	7.137	57.6	1.2
1,060	7.631	11.23	5.192	1.23	46.0	88.0	6.830	55.2	1.9
1,100	7.795	11.29	4.936	3.89	72.0	89.8	7.075	57.1	0.8
1,150	7.903	11.04	6.041	1.71	83.4	85.3	6.838	55.2	2.0
1,450	7.785	11.30	4.827	2.49	100	90.0	7.098	57.3	1.1
							Total gas age =	**55.6 Ma**	
							K_2O =	**0.40 percent**	
Sample M-19-88, Malina Bay dike, amphibole, J = 0.004531									
750	64.71	0.8520	183.8	0.555	6.65	16.1	10.43	83.3	15.6
850	18.93	2.478	35.16	0.168	8.67	44.7	8.684	69.6	10.1
900	12.76	6.692	11.70	0.100	9.87	71.5	9.744	77.9	12.8
930	11.11	5.154	4.710	0.063	10.6	81.0	10.05	80.4	13.1
960	11.51	7.385	37.84	0.072	11.5	6.07	0.7694	6.3	26.1
990	11.71	12.28	16.15	0.147	13.3	62.7	7.753	62.3	17.1
1,020	10.64	18.16	20.28	0.659	21.2	53.5	5.834	47.1	2.8
1,040	9.475	20.30	12.58	1.67	41.2	73.5	7.104	57.2	1.0
1,070	8.761	20.32	9.965	2.81	75.0	80.3	7.165	57.6	0.6
1,110	10.02	20.11	15.46	0.765	84.2	66.0	6.786	54.6	2.4
1,140	8.781	19.64	11.05	1.03	96.5	75.8	6.814	54.9	2.5
1,200	7.728	10.46	24.33	0.053	97.1	12.7	1.175	9.6	48.2
1,450	9.506	17.17	4.559	0.241	100	93.6	9.323	74.6	7.7
							Total gas age =	**58.3 Ma**	
							K_2O =	**0.23 percent**	
Sample 88ACy9, Nuka pluton, biotite, J = 0.002943									
600	66.65	0.0798	200.7	0.930	1.59	11.0	7.338	38.5	2.6
650	12.42	0.0187	7.402	7.56	14.6	82.2	10.22	53.5	0.3
700	10.71	0.0072	1.266	12.2	35.5	96.4	10.33	54.0	0.2
800	10.66	0.0078	0.9271	9.15	51.2	97.3	10.37	54.2	0.2
870	10.83	0.0082	1.201	4.78	59.4	96.5	10.46	54.7	0.3
950	10.89	0.0086	1.080	6.07	69.8	96.9	10.56	55.2	0.3
1,050	10.65	0.0095	1.161	13.6	93.1	96.6	10.30	53.9	0.1
1,150	10.55	0.0558	0.7973	3.10	98.4	97.4	10.31	53.9	0.2
1,350	10.65	0.0306	2.856	0.952	100	91.3	9.793	51.3	1.0
							Total gas age =	**53.8 Ma**	
							K_2O =	**7.38 percent**	

sealed in silica glass vials. These were irradiated in the L67 position of the Ford Nuclear Reactor at the University of Michigan. Micas and flux monitors weighed approximately 35 mg. Samples were heated in a molybdenum crucible within the ultra-high-vacuum system on line to the mass spectrometer using radio-frequency induction. Temperature estimates have an estimated uncertainty of ± 50°C. Inert gases were purified using standard gettering techniques. The isotopic composition of Ar was measured digitally using a Nuclide 6-60-SGA 1.25 mass spectrometer. All data were corrected for mass discrimination and interfering argon isotopes produced during irradiation (Dalrymple and others, 1981). Error calculations included both the uncertainty in the analytical measurement and the uncertainty in the J-value and are reported at the 2σ level. A plateau age represents the mean of ages in consecutive increments that are not different based on 2σ analytical uncertainties. Analytical results are presented in table 3.

$^{40}Ar/^{39}Ar$ Analytical Methods—University of Alaska, Fairbanks

Samples were wrapped in aluminum foil and arranged in one of two levels, labeled top and bottom, within aluminum cans of 2.5-cm diameter and 4.5-cm height. Samples of hornblende

Table 2. $^{40}Ar/^{39}Ar$ data for intrusive rocks from southern Alaska—*Continued.*

Temp (°C)	$^{40}Ar/^{39}Ar$	$^{37}Ar/^{39}Ar$	$^{36}Ar/^{39}Ar$	Moles ^{39}Ar	% total ^{39}Ar	% $^{40}Ar^*$	$^{40}Ar^*/^{39}Ar_K$	Age (Ma)	1 sigma error (Ma)
				Sample TLP-95, Kodiak batholith, biotite, J = 0.005599					
600	44.11	0.2723	142.0	1.21	1.10	4.59	2.033	20.4	2.3
670	6.817	0.0611	6.413	7.16	7.64	70.0	4.793	47.8	0.4
740	6.533	0.0180	2.090	14.1	20.5	88.3	5.783	57.5	0.2
800	6.424	0.0522	1.625	8.86	28.6	90.2	5.814	57.8	0.3
850	6.865	0.0720	2.767	5.15	33.3	85.7	5.918	58.8	0.4
930	6.841	0.0437	2.021	7.63	40.3	89.0	6.113	60.7	0.1
1,020	6.539	0.0264	1.247	27.5	65.5	92.2	6.039	60.0	0.1
1,100	6.351	0.0220	1.163	32.0	94.6	92.4	5.875	58.4	0.1
1,200	6.949	0.1372	3.116	5.41	99.6	84.5	5.903	58.7	0.6
1,350	16.20	0.3129	30.03	0.469	100	43.4	7.210	71.4	5.2
							Total gas age =	**57.8 Ma**	
							K_20 =	**7.15 percent**	
				Sample TL-2-87, Kodiak batholith, biotite, J = 0.005580					
600	28.46	0.1567	87.91	1.59	3.00	8.27	2.361	23.6	1.0
670	6.775	0.0241	3.978	6.33	14.9	80.5	5.467	54.2	0.5
720	6.298	0.0087	1.104	11.7	37.0	92.6	5.839	57.8	0.2
790	6.282	0.0184	0.5791	10.3	56.4	95.0	5.979	59.2	0.3
850	6.512	0.0432	1.193	2.68	61.4	92.1	6.029	59.7	0.6
920	9.745	0.0301	11.12	2.81	66.8	64.7	6.326	62.6	0.7
1,020	11.53	0.0190	15.71	1.34	69.3	58.2	6.753	66.7	1.5
1,060	6.516	0.0138	1.351	7.15	82.8	91.6	5.984	59.3	0.3
1,130	6.261	0.0213	0.5614	7.61	97.1	95.0	5.963	59.1	0.3
1,200	6.355	0.1312	1.082	0.943	98.9	91.5	5.910	58.5	2.0
1,350	6.417	0.0894	1.682	0.590	100	87.9	5.792	57.4	2.1
							Total gas age =	**57.6 Ma**	
							K_20 =	**3.99 percent**	
				Sample S-70, Sanak pluton, biotite, J = 0.002981					
600	21.25	0.1554	45.82	2.37	3.82	36.2	7.713	41.0	0.9
650	14.87	0.0270	10.44	3.28	9.11	79.1	11.78	62.3	0.3
700	12.75	0.0109	2.712	7.05	20.5	93.6	11.94	63.1	0.3
750	12.23	0.0274	2.282	3.86	26.7	94.2	11.54	61.0	0.4
800	12.10	0.0219	0.9366	7.90	39.5	97.6	11.82	62.5	0.3
870	12.20	0.0329	0.9448	3.66	45.4	97.5	11.92	63.0	0.5
950	12.82	0.0747	1.226	4.03	51.9	97.0	12.45	65.7	0.3
1,050	12.22	0.0386	0.9487	17.4	80.0	97.6	11.93	63.1	0.1
1,150	11.96	0.0791	0.9172	11.3	98.3	97.6	11.68	61.7	0.2
1,350	12.27	0.1108	3.253	1.07	100	91.6	11.30	59.8	1.4
							Total gas age =	**61.8 Ma**	
							K_20 =	**7.76 percent**	

Hb3gr (with an age of 1,071 Ma) and MMHb-1 (with an age of 513.9 Ma) were used to monitor the neutron flux. The samples were irradiated for 70 MWh in position 5c of the uranium-enriched research reactor of McMaster University in Hamilton, Ontario. Upon their return from the reactor, the samples and monitors were loaded into 2-mm-diameter holes in a copper tray that was then loaded in a ultra-high-vacuum extraction line. The monitors were fused, and samples step-heated using a 6-watt argon-ion laser using the technique described in York and others (1981) and Layer and others (1987). Argon purification was achieved using a liquid nitrogen cold trap and a SAES Zr-Al getter at 400°C. The samples were then analyzed in a VG-3600 mass spectrometer at the Geophysical Institute, University of Alaska, Fairbanks. The argon isotopes measured were corrected for system blank and mass discrimination, as well as calcium, potassium, and chlorine interference reactions following procedures outlined in McDougall and Harrison (1988). For each sample, a plateau age was determined from three or more consecutive fractions whose ages are within 2σ of each other and total more than 50 percent of gas release. Three samples of each mineral were dated, yielding three plateau ages. These were averaged together for a weighted mean plateau age; the weighting is the inverse of the variance (square of the standard deviation). The error associated with the mean age takes into account the individual errors on each sample (weighted error). The detailed analyses are given in table 4, with all ages quoted to the $\pm 1\sigma$ level).

Table 3. $^{40}Ar/^{39}Ar$ data for intrusive rocks from southern Alaska.

[Analyses done at University of Maine, Orono. rad, radiogenic]

Temp (°C)	$^{40}Ar/^{39}Ar$	$^{37}Ar/^{39}Ar$	$^{36}Ar/^{39}Ar$	Moles ^{39}Ar	% total ^{39}Ar	% rad ^{40}Ar	K/Ca	Age (Ma)	1 sigma error (Ma)
Sample 91ADW55g, Chernof pluton, biotite, J = 0.006255, plateau age = 54.2±1.1 Ma									
775	5.491	0.006	0.0022	189.0	21.3	88.1	86.6	53.8	0.6
860	5.502	0.011	0.0023	120.0	13.5	87.2	42.9	53.3	0.7
910	5.539	0.013	0.0021	82.9	9.3	88.2	36.3	54.3	0.8
980	5.516	0.042	0.0023	67.1	7.5	87.6	11.7	53.7	1.3
1,060	5.405	0.017	0.0017	206.1	23.2	90.2	28.9	54.2	0.9
1,180	5.143	0.083	0.0009	95.7	10.8	94.6	5.9	54.1	0.8
Fuse	7.104	0.068	0.0073	128.3	14.4	69.4	7.2	54.8	0.8
Totals				**889.2**	**100.0**			**54.0**	**0.8**
Sample 93ASB66, Tutka dike, hornblende, J = 0.006268, plateau age = 115.0±1.7 Ma									
930	160.30	0.979	0.4568	2.9	0.2	15.8	0.50	266.6	41.8
930	153.76	4.626	0.4594	3.7	0.3	11.9	0.11	197.1	26.6
1,070	27.01	5.247	0.0544	35.8	2.6	41.9	0.09	124.2	4.6
1,070	12.43	4.610	0.0078	875.8	63.8	84.4	0.11	115.2	1.4
1,120	12.80	4.705	0.0093	168.9	12.3	81.2	0.10	114.2	1.6
1,155	13.35	4.634	0.0109	69.1	5.0	78.5	0.11	115.1	2.1
1,190	15.66	4.729	0.0186	38.0	2.8	67.2	0.10	115.6	3.8
1,250	22.59	5.180	0.0377	3.5	0.3	52.4	0.09	129.6	38.3
1,310	13.26	5.256	0.0115	30.4	2.2	77.3	0.09	112.8	4.4
Fuse	12.49	4.733	0.0072	144.1	10.5	85.8	0.10	117.7	1.3
Totals				**1,372.2**	**100.0**			**116.1**	**1.9**
Sample 92AKu71b, Tustumena pluton, biotite, J = 0.006578, plateau age = 53.2±1.1 Ma									
675	14.718	0.306	0.0350	13.2	1.3	29.7	1.6	51.1	3.0
775	8.062	0.017	0.0118	42.2	4.2	56.6	28.7	53.3	1.5
845	6.061	0.069	0.0050	90.0	9.0	75.6	7.1	53.6	1.4
940	5.430	0.006	0.0028	194.7	19.4	84.5	89.1	53.7	0.8
1,030	5.291	0.032	0.0026	206.9	20.6	85.0	15.5	52.6	0.6
1,130	4.947	0.026	0.0014	260.4	25.9	91.6	18.9	53.0	0.6
Fuse	4.913	0.026	0.0015	197.2	19.6	90.9	18.7	52.3	0.7
Totals				**1,004.6**	**100.0**			**52.9**	**0.8**

Geochronological Results

Sanak Pluton

The Sanak pluton crops out on a remote island at the extreme southwestern end of the Sanak-Baranof plutonic belt. The sample for age determination was originally collected by Casey Moore and was acquired by Clendenen from Malcolm Hill. The same sample previously yielded a K/Ar biotite age of 61.4±1.8 Ma (Moore, 1974a) and an Rb/Sr isochron age of 62.7±1.2 Ma (Hill and others, 1981). Hill and others (1981) reported the following mineral assemblage: 26 percent quartz, 44 percent plagioclase, 7 percent potassium feldspar, 21 percent biotite, 1 percent oxides, 2 percent muscovite, and trace amounts of apatite, zircon, and kyanite. Two fractions of euhedral clear magmatic zircons were analyzed (table 1, fig. 3). For reasons outlined below, the results suggest a crystallization age of 61.1±0.5 Ma. Fraction A was composed of relatively equant multifaceted crystals, whereas fraction B was composed of needle-shaped elongate crystals. Fraction A contained some faint older xenocrystic cores, and this was borne out by significant zircon inheritance in the analyses. $^{207}Pb/^{206}Pb$ ages are 786 and 131 Ma for fractions A and B, respectively. The zircons were strongly abraded and were low in uranium (288-308 ppm); these two factors together suggest that there would have been minimal secondary Pb loss from the zircons reflected in the analyses. The regression of the two points (fractions A and B) yields an upper intercept of about 1,580 Ma, suggesting this as the average age of the inherited component. The lower intercept, 61.1± 0.5 Ma, is interpreted as the age of magmatic crystallization. Fraction B is not concordant, and 61.1 Ma represents a minimum age due to the possibility of minor Pb loss. The $^{206}Pb/^{238}U$ age of fraction B is 62.7 Ma, which, given its strong abrasion and low U concentration, is an absolute maximum age for the magmatic component. A biotite separate from sample S70, dated by the $^{40}Ar/^{39}Ar$ method, yielded a slightly irregular age spectrum (table 2, fig. 4). The corresponding isochron age is 62.7±0.38 Ma, in agreement with the other results.

Table 4. $^{40}Ar/^{39}Ar$ data for intrusive rocks from southern Alaska.

[Analyses done at University of Alaska, Fairbanks. atmos., atmospheric]

Laser power (mW)	Cumulative ^{39}Ar	$^{40}Ar/^{39}Ar$ measured	±	$^{37}Ar/^{39}Ar$ measured	±	$^{36}Ar/^{39}Ar$ measured	±	% atmos. ^{40}Ar	±	Ca/K	±	$^{40}Ar^{*}/^{39}Ar_K$	±	Age (Ma)	± (Ma)
95TD002b, Hive Island pluton, biotite #1 — Weighted average of J from standards = 0.006450±0.000028															
50	0.0268	8.587	0.160	0.014	0.007	0.017	0.005	59.61	16.27	0.026	0.013	3.457	1.396	39.8	15.9
100	0.0548	6.175	0.065	0.017	0.013	0.005	0.003	24.42	13.79	0.031	0.024	4.645	0.849	53.3	9.6
150	0.0832	5.184	0.063	–0.007	–0.011	0.003	0.002	19.49	13.24	–0.013	0.019	4.151	0.685	47.7	7.8
200	0.0990	5.260	0.104	0.014	0.022	0.008	0.005	44.05	28.11	0.025	0.040	2.927	1.472	33.7	16.8
300	0.1288	5.909	0.078	0.012	0.010	0.006	0.003	32.63	16.88	0.021	0.019	3.962	0.995	45.5	11.3
500	0.2992	5.325	0.034	0.002	0.002	0.002	0.000	11.10	2.67	0.004	0.003	4.709	0.145	54.0	1.6
700	0.3171	6.069	0.119	–0.026	–0.012	0.007	0.002	32.01	9.55	–0.048	0.022	4.107	0.584	47.2	6.6
1,000	0.3689	5.475	0.034	–0.006	–0.004	0.003	0.001	16.33	4.56	–0.011	0.007	4.557	0.250	52.3	2.8
1,500	0.5768	5.009	0.024	0.001	0.001	0.001	0.000	6.89	1.13	0.002	0.003	4.638	0.061	53.2	0.7
2,000	0.7230	5.007	0.035	0.002	0.002	0.001	0.000	4.40	1.88	0.003	0.004	4.759	0.099	54.5	1.1
4,000	1.0000	4.946	0.022	0.003	0.001	0.001	0.000	6.22	1.78	0.006	0.002	4.612	0.090	52.9	1.0
Integrated		5.253	0.013	0.002	0.001	0.002	0.000	12.83	1.42	0.004	0.002	4.554	0.075	52.2	0.9
95TD002b, Hive Island pluton, biotite #2 — Weighted average of J from standards = 0.006450±0.000028															
100	0.0321	7.125	0.118	–0.007	–0.021	0.009	0.004	35.61	16.02	–0.012	0.038	4.569	1.141	52.4	12.9
300	0.3282	5.266	0.027	–0.001	–0.001	0.002	0.000	9.52	1.63	–0.002	0.003	4.739	0.089	54.3	1.0
600	0.6352	4.956	0.015	0.001	0.001	0.001	0.000	6.51	1.96	0.002	0.002	4.606	0.098	52.8	1.1
900	0.8927	4.896	0.038	–0.001	–0.001	0.001	0.001	5.14	3.38	–0.001	0.002	4.618	0.168	52.9	1.9
1,200	0.9543	5.058	0.064	0.014	0.018	0.000	–0.002	–0.07	14.63	0.026	0.033	5.033	0.738	57.6	8.3
1,500	0.9716	4.966	0.101	0.045	0.045	0.002	0.009	13.50	52.61	0.083	0.082	4.271	2.599	49.0	29.4
2,000	0.9833	4.903	0.174	–0.015	–0.071	0.011	0.007	69.00	45.24	–0.028	0.130	1.511	2.206	17.5	25.4
5,000	0.9977	5.153	0.151	–0.014	–0.065	0.007	0.007	42.69	38.54	–0.025	0.119	2.936	1.977	33.9	22.6
9,000	1.0000	4.242	0.796	0.123	0.300	–0.003	–0.052	–17.76	421.28	0.225	0.550	4.962	15.482	56.8	174.6
Integrated		5.109	0.015	0.001	0.002	0.002	0.000	9.29	2.10	0.002	0.004	4.608	0.108	52.8	1.2
95TD002b, Hive Island pluton, biotite #3 — Weighted average of J from standards = 0.006450±0.000028															
100	0.0409	6.991	0.091	–0.011	–0.006	0.010	0.001	40.79	4.29	–0.020	0.012	4.122	0.305	47.3	3.5
300	0.1615	5.549	0.035	0.001	0.002	0.003	0.000	15.11	1.51	0.001	0.004	4.686	0.089	53.7	1.0
900	0.3638	5.302	0.020	–0.001	–0.001	0.002	0.000	12.23	1.25	–0.002	0.002	4.628	0.068	53.1	0.8
1,200	0.7757	5.702	0.030	0.001	0.001	0.004	0.000	18.27	0.80	0.001	0.001	4.637	0.053	53.2	0.6
1,500	0.8074	5.115	0.046	–0.013	–0.009	0.001	0.001	5.64	6.07	–0.025	0.017	4.799	0.312	55.0	3.5
2,000	0.8360	5.140	0.057	–0.011	–0.013	0.001	0.001	5.17	6.80	–0.021	0.024	4.847	0.352	55.5	4.0
5,000	0.9223	4.892	0.030	–0.002	–0.004	0.000	0.001	2.63	3.52	–0.004	0.007	4.735	0.174	54.3	2.0
9,000	1.0000	4.964	0.033	–0.007	–0.004	0.000	–0.001	–0.98	3.30	–0.013	0.008	4.983	0.166	57.1	1.9
Integrated		5.493	0.015	–0.002	–0.001	0.003	0.000	14.61	0.67	–0.003	0.002	4.666	0.039	53.5	0.5

Table 4. $^{40}Ar/^{39}Ar$ data for intrusive rocks from southern Alaska—*Continued.*

Laser power (mW)	Cumulative ^{39}Ar	$^{40}Ar/^{39}Ar$ measured	±	$^{37}Ar/^{39}Ar$ measured	±	$^{36}Ar/^{39}Ar$ measured	±	% atmos. ^{40}Ar	±	Ca/K	±	$^{40}Ar^{*}/^{39}Ar_K$	±	Age (Ma)	± (Ma)
91AKU003, Harris Bay pluton, biotite #1 Weighted average of J from standards = 0.006450±0.000028															
50	0.0029	9.834	0.366	0.142	0.060	0.023	0.014	68.30	41.57	0.260	0.110	3.109	4.008	35.8	45.7
100	0.0276	6.495	0.056	0.015	0.010	0.007	0.002	31.88	7.77	0.027	0.018	4.405	0.505	50.5	5.7
150	0.1035	5.738	0.035	0.007	0.002	0.005	0.000	23.66	2.41	0.013	0.004	4.358	0.141	50.0	1.6
200	0.1668	5.196	0.037	0.009	0.003	0.002	0.000	12.24	2.57	0.017	0.006	4.535	0.138	52.0	1.6
300	0.2724	4.984	0.042	0.006	0.001	0.002	0.001	10.17	4.31	0.010	0.002	4.451	0.217	51.1	2.5
500	0.4342	4.865	0.023	0.002	0.001	0.001	0.000	6.60	1.54	0.003	0.002	4.517	0.078	51.8	0.9
700	0.5723	4.858	0.024	0.001	0.002	0.001	0.000	7.20	1.71	0.003	0.004	4.482	0.086	51.4	1.0
1,000	0.6972	4.758	0.027	0.003	0.002	0.001	0.000	6.56	2.07	0.006	0.003	4.419	0.101	50.7	1.1
1,500	0.8127	4.778	0.041	–0.002	–0.002	0.001	0.000	7.39	2.54	–0.003	0.003	4.398	0.127	50.5	1.4
2,000	0.8821	4.758	0.035	0.003	0.003	0.001	0.001	8.10	3.56	0.006	0.006	4.346	0.172	49.9	1.9
4,000	1.0000	4.739	0.040	0.004	0.002	0.001	0.000	4.30	2.39	0.007	0.004	4.508	0.120	51.7	1.4
Integrated		4.973	0.011	0.004	0.001	0.002	0.000	10.02	0.88	0.007	0.001	4.449	0.045	51.0	0.6
91AKU003, Harris Bay pluton, biotite #2 Weighted average of J from standards = 0.006450±0.000028															
100	0.0352	7.746	0.117	0.063	0.006	0.011	0.001	42.70	3.63	0.116	0.011	4.422	0.292	50.7	3.3
200	0.1661	5.931	0.032	0.004	0.002	0.004	0.000	18.39	1.80	0.007	0.003	4.817	0.111	55.2	1.2
300	0.3160	5.288	0.026	0.005	0.001	0.002	0.000	10.13	1.62	0.010	0.002	4.727	0.089	54.2	1.0
500	0.5423	5.030	0.017	0.003	0.001	0.001	0.000	7.62	0.73	0.006	0.002	4.620	0.040	53.0	0.5
700	0.7350	4.885	0.014	0.006	0.001	0.001	0.000	4.98	1.09	0.010	0.002	4.614	0.055	52.9	0.6
900	0.8189	4.851	0.042	0.000	–0.002	0.000	0.000	2.25	2.65	0.000	0.004	4.714	0.135	54.0	1.5
1,100	0.8652	4.815	0.030	0.016	0.004	0.001	0.001	6.09	3.97	0.029	0.008	4.495	0.192	51.6	2.2
1,300	0.9176	4.773	0.039	–0.004	–0.003	0.000	0.001	2.64	4.37	–0.008	0.006	4.619	0.211	53.0	2.4
1,500	0.9478	4.688	0.052	–0.021	–0.006	0.000	–0.002	–3.01	10.18	–0.038	0.010	4.799	0.477	55.0	5.4
2,000	1.0003	4.728	0.026	–0.004	–0.003	0.001	0.001	3.29	5.07	–0.008	0.006	4.544	0.240	52.1	2.7
5,000	1.0000	32.834	6.076	1.265	0.595	0.126	0.088	113.40	1010.63	2.323	1.094	–4.400	25.127	–51.9	300.9
Integrated		5.180	0.010	0.005	0.001	0.002	0.000	9.53	0.72	0.008	0.001	4.660	0.038	53.4	0.5
91AKU003, Harris Bay pluton, biotite #3 Weighted average of J from standards = 0.006450±0.000028															
900	0.3417	4.707	0.031	0.013	0.002	0.001	0.001	4.97	3.52	0.024	0.003	4.446	0.168	51.0	1.9
1,100	0.6030	4.840	0.037	0.007	0.004	0.002	0.001	12.60	4.58	0.013	0.007	4.205	0.223	48.2	2.5
1,300	0.8198	4.853	0.037	0.007	0.007	0.002	0.001	11.41	8.52	0.013	0.013	4.274	0.413	49.0	4.6
1,500	0.8659	4.874	0.087	–0.003	–0.023	0.008	0.004	49.05	22.63	–0.006	0.042	2.469	1.098	28.2	12.3
2,000	0.9664	4.728	0.060	0.000	–0.009	0.005	0.002	29.99	14.77	0.000	0.017	3.290	0.695	37.7	7.9
5,000	1.0000	4.632	0.124	0.064	0.030	0.007	0.006	44.99	39.11	0.117	0.056	2.532	1.801	28.8	20.4
Integrated		4.774	0.019	0.006	0.003	0.001	0.001	5.61	4.67	0.011	0.006	4.479	0.223	46.7	1.8

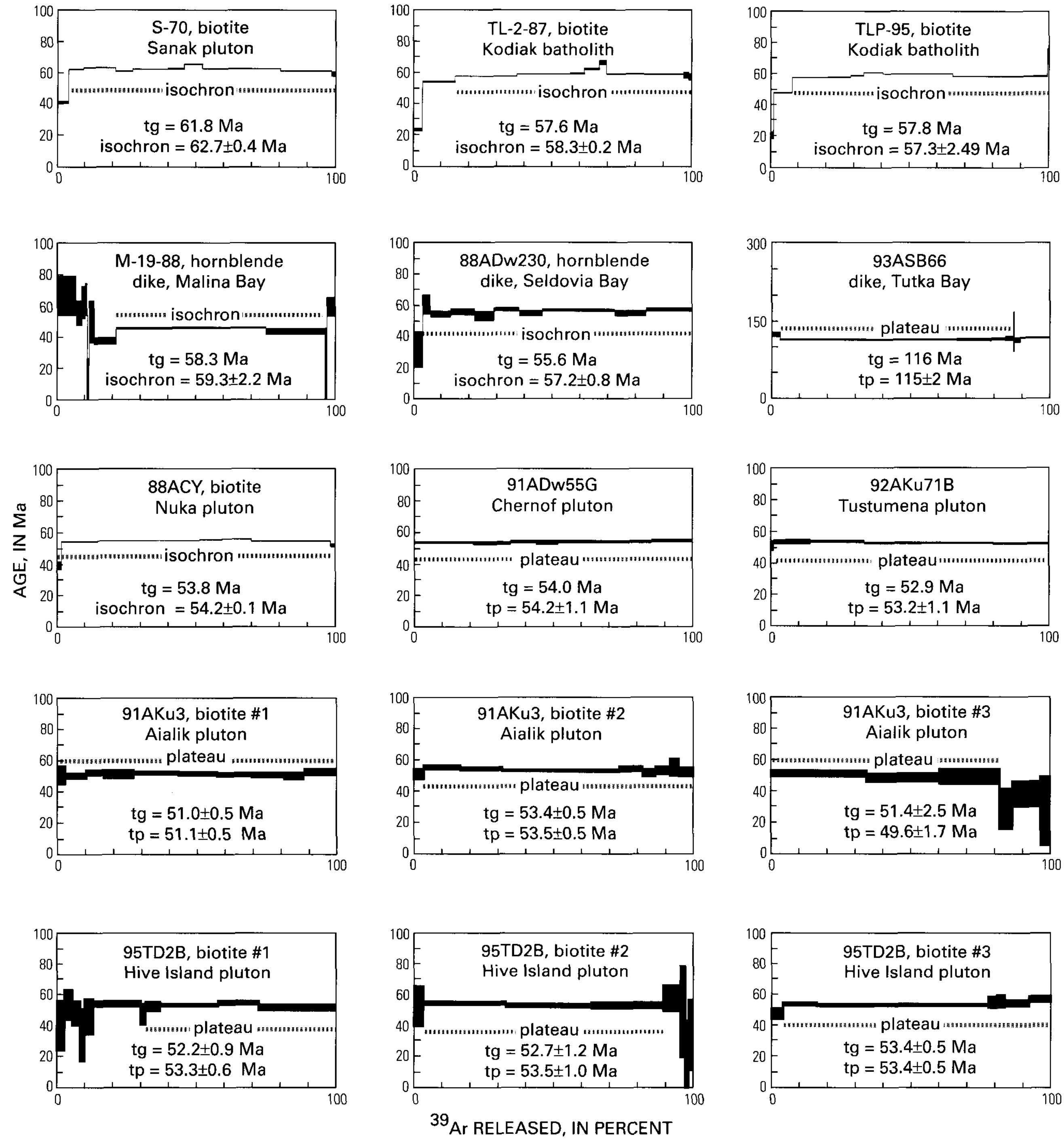

Figure 4. Argon release spectra for plutons dated in this study. Dashed lines indicate steps used to calculate isochron and plateau ages. tg, total gas (integrated) age; tp, plateau age.

Shumagin Pluton

The outer Shumagin Islands, an archipelago located 175–240 km along strike from the southwestern end of the Sanak-Baranof plutonic belt, are underlain by Upper Cretaceous turbidites intruded by early Tertiary granodiorite. It is not known whether the granodiorite exposed on various islands (Moore, 1974b) represents a single, irregularly shaped pluton, or more than one. The sample for age determination was collected on Big Koniuji Island by Maurice Witschard. The dating sample is a medium- to coarse-grained, nonfoliated biotite granodiorite. According to Hill and others (1981), three granodiorite samples from near our dating-sample location average 69 percent SiO_2 and 3.1 percent K_2O. Two fractions of euhedral, clear, magmatic zircons were analyzed (table 1, fig. 3). Both fractions were concordant and unequivocally indicate a crystallization age of 61.1±0.3 Ma (mean of two $^{206}Pb/^{238}U$ ages). As summarized by Bradley and others (1993), eight previously published K/Ar (biotite) and Rb/Sr (mineral/whole-rock isochron) ages from the Shumagin pluton range from 57.4±2.9 to

60.7±1.8 Ma; one K/Ar muscovite age was significantly older at 65.6±3.3 Ma. Our new U/Pb zircon age eclipses these older age determinations.

Kodiak Batholith at Terror Lake

The Kodiak batholith is one of the largest near-trench plutons in the world, more than 100 km long and 5–10 km wide. One of two granodiorite samples was obtained by Peter Vrolik from the hydroelectric tunnel at Terror Lake; the other was collected by Clendenen from the peak above the tunnel. Both samples were analyzed by the $^{40}Ar/^{39}Ar$ method (fig. 4, table 2). Biotite separates from the two samples yielded slightly humped age spectra, giving isochron ages of 58.3±0.2 and 57.8±2.5 Ma.

Malina Bay Dike

A 1-m-thick dike, cutting the Uyak Complex at Malina Bay on Afognak Island, was analyzed by the $^{40}Ar/^{39}Ar$ method. The results were reported by Clendenen (1991) and are repeated here. The age spectrum shows anomalously old ages in the early steps but has a plateau represented by 75 percent of total gas released. Data from these four steps give an isochron age of 59.3±2.2 Ma (fig. 4, table 2).

Seldovia Bay Dike

A dike that cuts the McHugh Complex near the head of Seldovia Bay (fig. 2) was analyzed by the $^{40}Ar/^{39}Ar$ method. The dike, collected by Will White, is a leucocratic porphyry containing feldspar and hornblende phenocrysts. Aside from the sample location, little else is known about this rock; a hand sample and major-element data apparently once existed but could not be located. A hornblende separate yielded a mainly flat, but somewhat irregular, age spectrum corresponding to an isochron age of 57.0±0.2 Ma (fig. 4, table 2).

Tutka Bay Dike

The most surprising age reported herein is from a dike that cuts massive graywacke of the McHugh Complex about 4 km southeast of the head of Tutka Bay (fig. 2). The dike is a hornblende-phyric basaltic andesite (56.6 weight percent SiO_2; D.C. Bradley, unpub. data, 1994). A hornblende separate yielded a $^{40}Ar/^{39}Ar$ method plateau age of 115.0±1.7 Ma (fig. 4, table 3). This unexpected result is the only pre-Tertiary age reported in the present paper; its possible significance is discussed in a later section.

Nuka Pluton

The Nuka pluton crops out along the southern coast of the Kenai Peninsula in the eastern Seldovia quadrangle (fig. 2). The rock is a medium- to coarse-grained granodiorite containing biotite, muscovite, and rare hornblende. Xenocrysts of kyanite have been observed (Donley and others, 1995). Four whole-rock samples from the Nuka pluton vary from 67.3 to 72.4 weight percent SiO_2 and 1.9 to 2.2 weight percent K_2O (D.C. Bradley, unpub. data, 1994). Locally, the plutonic rocks have a weak tectonic foliation; elsewhere they are unfoliated. A sample of granodiorite from the Nuka pluton (88ACy9, collected by Bela Csejtey) yielded equant and elongate crystals of magmatic zircon, some with xenocrystic cores (fig. 3, table 1). All of the zircons contained a significant inherited component, which includes ages as young as 570 Ma and probably older than 1,500 Ma. A precise crystallization age cannot be derived from the zircons because of the significant scatter due to variable age of inheritance and lack of concordant data. Fortunately, igneous monazite is also an accessory mineral in this rock; two analyses yield concordant to slightly reversely discordant ages at 56.0 Ma. The points are slightly above concordia due to the excess ^{206}Pb typical of igneous monazite (see Scharer, 1984, for a more detailed explanation) resulting from excess ^{230}Th upon crystallization. $^{207}Pb/^{235}U$ ages of monazite are unaffected by this problem and have consistent and overlapping ages of 56.0±0.3 Ma, which we regard as the best estimate of the age of crystallization of monazite as well as zircon. A biotite separate from sample 88ACy9 was also analyzed by the $^{40}Ar/^{39}Ar$ method (table 2). The age spectrum is nearly flat but has a slight hump shape; the corresponding isochron age is 54.2±0.1 Ma (fig. 4, table 2).

Chernof Stock

The Chernof stock crops out in nunataks near the confluence of the Chernof Glacier and Harding Icefield (fig. 2). It is a nonfoliated, medium-grained biotite granodiorite. Major-element whole-rock analysis of the dating sample showed 71.4 weight percent SiO_2 and 1.8 weight percent K_2O (D.C. Bradley, unpub. data, 1994). A biotite separate yielded a plateau age of 54.2±1.1 Ma (fig. 4, table 3).

Aialik Pluton

The Aialik pluton crops out along the southern coast of the Kenai Peninsula southwest of Seward, in the Blying Sound and Seldovia quadrangles (fig. 2). Tysdal and Case (1979) informally called it the "granite of Harding Icefield region" and assigned it an Eocene age. The largest contiguous part of the pluton underlies the peninsula between Harris and Aialik Bays; nearby islands of granodiorite to the southeast and nearby nunataks of granodiorite to the northwest are very likely part of the same pluton. The Tustumena and Hive Island plutons are discussed under separate headings below—they are similar in age and lithology and might, in fact, be continuous beneath ice and water with the main part of the Aialik pluton. In the Seldovia quadrangle, the Aialik pluton is a medium- to coarse-grained granodiorite containing biotite, muscovite, rare hornblende, and xenocrystic kyanite (Donley and others, 1995). Tysdal and Case (1979) reported subordinate granitic and tonalitic phases in the Blying Sound quadrangle. Two whole-rock samples from the pluton in Seldovia quadrangle vary from 69.3 to 73.4 weight percent SiO_2 and 2.9 to 3.9 weight percent K_2O (D.C. Bradley, unpub. data, 1994). The pluton locally displays a tectonic foliation that also affects aplitic dikes (T. Kusky, unpub. field notes, 1991). A biotite separate from the pluton at Harris Bay, collected by Tim Kusky and analyzed at University of Alaska, Fairbanks, yielded three plateau ages: 51.1±0.5, 53.5±0.5, and 49.6±1.7 Ma (fig. 4, table 4). The weighted mean age for the sample is 52.2±0.9 Ma, which probably reflects the cooling age of the biotite.

Tustumena Pluton

The Tustumena pluton crops out in remote nunataks in the Seldovia and Kenai quadrangles, around the confluence of the Tustumena Glacier and Harding Icefield (fig. 2). It was not even known to exist until 1992, when the Seldovia D1 and D2 quadrangles were mapped (Bradley and others, 1999). In 1998, Bradley and Wilson (this volume) traced it northward into the Kenai quadrangle. The Harding Icefield obscures its relationship with the Nuka and Aialik plutons, of which it may be a part. Where sampled in reconnaissance, the Tustumena pluton consists of medium-grained, nonfoliated biotite granodiorite. A biotite separate, collected by Tim Kusky, yielded a plateau age of 52.2±1.1 Ma (table 3, fig. 4), which probably reflects the cooling age of the biotite.

Hive Island Pluton

Hive and Rugged Islands, near the mouth of Resurrection Bay, are composed of granodiorite (fig. 2). As noted above, it is not known whether or not these plutonic rocks are continuous with the main body of the Aialik pluton. Biotite from granodiorite at Hive Island, collected by Tom Donley, yielded three plateau ages of 53.3±0.6, 53.5±1.0, and 53.4±0.5 Ma (table 4, fig. 4). The weighted mean age is 53.4±0.4 Ma, which we interpret as the cooling age of the biotite. This result overlaps with the mean age of the Aialik pluton at Harris Bay, permitting correlation.

Discussion

Early Tertiary Near-Trench Magmatism

The new isotopic ages allow some refinements to a plot of age versus distance along strike for intrusive rocks of the Sanak-Baranof belt (fig. 5). Figure 5 and table 5 include the new data from the present study, as well as other pertinent results since the last modifications were made to the age-distance plot published in Bradley and others (1993); these include ages in Hauessler and others (1995) and Poole (1996).

Bradley and others (1993) suggested that magmatism at the Sanak end of the plutonic belt probably began at 66–63 Ma. The value of 63 Ma was based on two conventional K/Ar and two Rb/Sr ages (61.4±1.8 to 63.1±1.2 Ma) of unknown reliablity. We regard the new 61.1±0.5 Ma zircon age for the Sanak pluton as a more reliable estimate of the age of emplacement than any of these earlier findings. The value of 66 Ma for initiation of Sanak-Baranof magmatism made allowance for the conventional K/Ar muscovite age of 65.6±3.3 Ma from the Shumagin pluton, the next pluton in the belt. In light of our new 61.1-Ma U/Pb age of this pluton, we can suggest with confidence that near-trench magmatism commenced at about 61 Ma at the western end of the Sanak-Baranof belt. The west-to-east age progression suggests the migration of a triple junction about 2,200 km along strike in about 11 m.y., at an average rate of about 200 km/m.y. This is somewhat faster than the rate of 140–170 km/m.y. suggested by Bradley and others (1993).

As discussed by Bradley and others (1993), several factors complicate tectonic interpretations based on figure 5. First, the Chugach–Prince William terrane has been displaced some distance northward as a result of Tertiary motion on coast-parallel dextral faults (Coe and others, 1985; Bol and others, 1992). Bol and others (1992) estimated 13±9° of northward motion—equivalent to somewhere between ~400 and ~2,400 km. The position of the triple junction, inferred from near-trench plutons within the Chugach–Prince William terrane, must have been a commensurate distance farther south. Second, paleomagnetic data suggest that the southern Alaska orocline formed sometime during the interval between 65 and 35 Ma (Coe and others, 1985); Alaska's southern margin must have been considerably straighter before than after. The essentially linear trend of ages in figure 5 would be difficult if not impossible to achieve by the migration of a trench-ridge-trench triple junction along the margin in its present, oroclinal configuration. Accordingly, it seems reasonable to conclude that the oroclinal bend could not have been imposed until after the triple junction had migrated past the oroclinal axis in Prince William Sound, around 54 Ma. A third complication relates to the unknown geometry of any transform faults associated with the subducting ridge system: the spacing, length, and sense of motion of such transforms are highly conjectural because the relevant parts of the Kula and Farallon plates have long since been subducted. In the area of figure 1, alternating pluton-rich and pluton-poor sectors of the Chugach terrane might perhaps record the subduction of ridge segments and transform segments, respectively. Poole (1996) invoked a transform offset to explain near-trench intrusive ages that deviate from the broadly linear age trend (fig. 5), east of the present study area. Sisson and Pavlis (1993) and Pavlis and Sisson (1995) explained the lengthy history of near-trench metamorphism and magmatism in the Chugach Metamorphic Complex (fig. 1) in terms of a reorganization of the Pacific-Kula-Farallon system, and a resulting short-term reversal of the migrating trench-ridge-trench triple junction. This corresponds to the "56-Ma plate reorganization" of Engebretson and others (1985). The age of this reorganization, however, is younger than previous accounts (e.g., Sisson and Pavlis, 1993; Pavlis and Sisson, 1995) would suggest. The reorganization occurred during Chron 23R, the age of which is now fixed between 52.35 and 51.75 Ma, based on the most recent compilation of Pacific magnetic anomalies (Atwater and Severinghaus, 1989), coupled with the new magnetic polarity time scale of Berggren and others (1995). Finally, the possibility that the subducting ridge was one other than the Kula-Farallon ridge cannot be ruled out.

Early Cretaceous Near-Trench Magmatism

The Early Cretaceous dike from Tutka Bay drainage is the only rock dated in the present paper that does not have an early Tertiary age. Judging from the age spectrum for this sample, there seems no reason to doubt an age of about 115 Ma. During the Seldovia mapping project, more than 200 basalt, andesite, dacite, and rhyolite dikes were sampled and their attitudes and thicknesses measured. Roughly half of the dikes cut the Maastrichtian Valdez Group and hence cannot be as old as 115 Ma. Those that cut only the McHugh Complex are similar to dikes cutting the Valdez Group, and most are probably Tertiary in age; but a few, at least, may be Early Cretaceous. Most dikes in the Seldovia quadrangle strike roughly east-west and are subvertical (Bradley and others, 1995); the Tutka Bay dike strikes northeast-southwest and dips moderately to the northwest. This dike represents a near-trench magmatic event that has gone unrecognized in the Kenai Peninsula. It may be related to leucotonalite to trondhjemite plutons that were emplaced into the McHugh Complex and its backstop in the western Chugach Mountains near Palmer (Pavlis and others, 1988). The plutons near Palmer are not very well dated: the most reliable determination appears to be a $^{40}Ar/^{39}Ar$ plateau age of 118 Ma

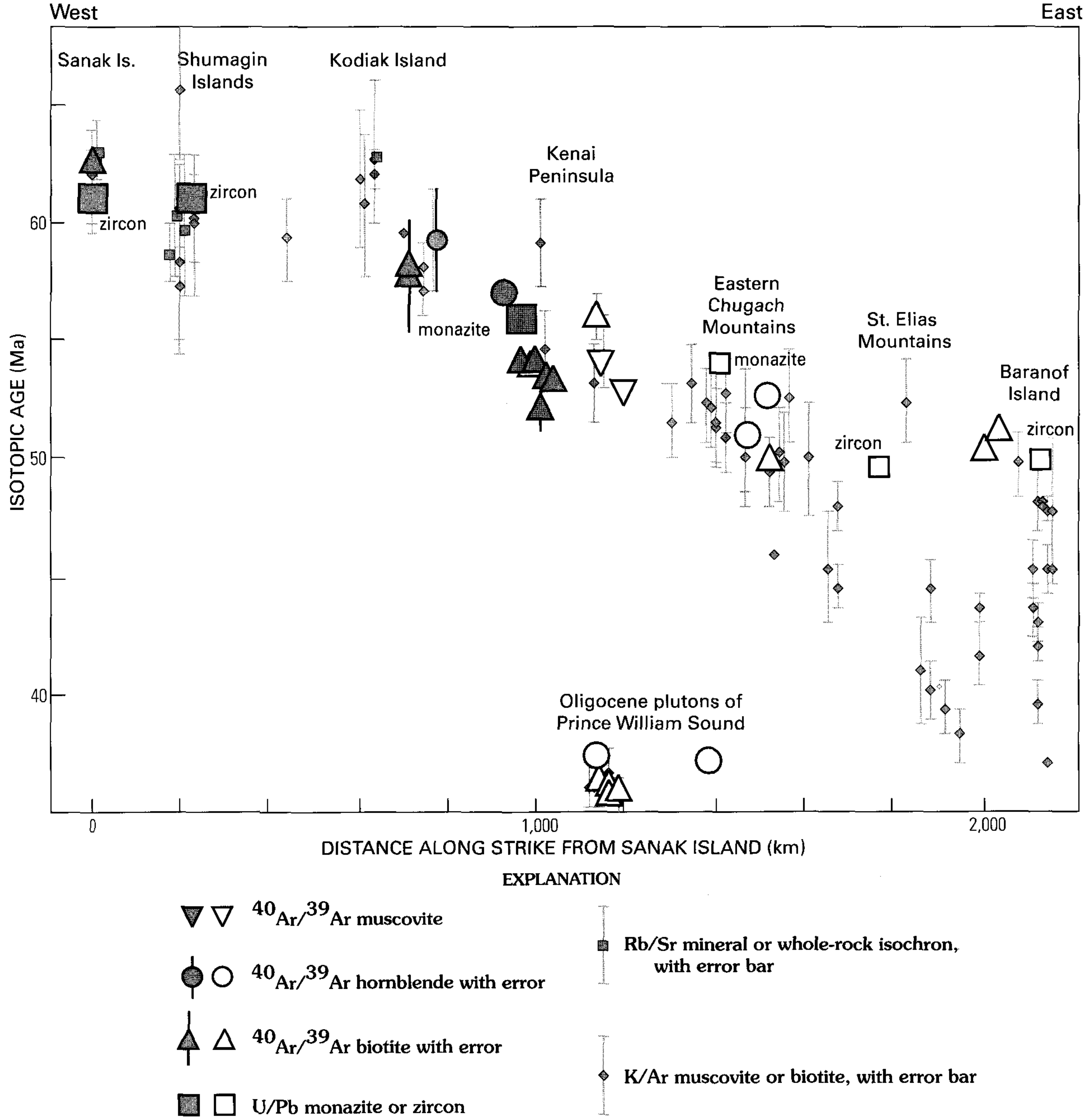

Figure 5. Isotopic age plotted against distance along strike for early Tertiary intrusive rocks of the Sanak-Baranof plutonic belt. See figure 1 for distance from Sanak Island. New and recent data (summarized in table 5) are highlighted by filled symbols; the remaining data are from the compilation by Bradley and others (1993). Most error bars for $^{40}Ar/^{39}Ar$ and U/Pb data are smaller than the symbols; a few error bars are omitted from crowded areas for clarity. Note the diachronous trend in ages of older to the west and younger to the east, indicating a migrating trench-ridge-trench triple junction (Bradley and others, 1993).

Table 5. Summary of new isotopic ages of intrusive rocks from the Sanak-Baranof belt, southern Alaska.

[Abbreviations for 1:250,000-scale quadrangles: AF, Afognak; BS, Blying Sound; CV, Cordovia; FP, False Pass; KD, Kodiak; SB, Stepovak Bay; SR, Seward; SV, Seldovia; YA, Yakutat. Distance along strike was measured from the western tip of Sanak Island on Beikman's (1980) geologic map of Alaska]

Igneous body	Quad	Field number or location	Latitude (N.)	Longitude (W.)	Age (Ma)	Error (m.y.)	Method	Dist. from Sanak Is. (km)	Reference or geochronologist
Sanak pluton	FP	S70	54°29.2'	162°45.8'	61.1	0.5	U/Pb zircon	5	Parrish (this study)
Sanak pluton	FP	S70	54°29.2'	162°45.8'	62.7	1.2	40Ar/39Ar biotite	5	Clendenen & Heizler (this study)
Shumagin pluton	SB	96AK3	55°12'04"	159°32'02"	61.1	0.3	U/Pb zircon	230	Parrish (this study)
Kodiak batholith, Terror Lk.	KD	TLP-95	57°39.44'	152°58.25'	57.3	2.52	$^{40}Ar/^{39}Ar$ biotite	715	Clendenen & Heizler (this study)
Kodiak batholith, Terror Lk.	KD	TL-2-87	57°39.29'	152°58.33'	58.3	0.2	$^{40}Ar/^{39}Ar$ biotite	715	Clendenen & Heizler (this study)
Dike, Malina Bay	AF	M-19-88	58°12.6'	153°00.1'	59.3	2.2	40Ar/39Ar hornblende	765	Clendenen & Heizler (this study)
Dike, Seldovia Bay	SV	88ADw230	59°23.6'	150°39.9'	57.0	0.2	$^{40}Ar/^{39}Ar$ hornblende	920	Clendenen & Heizler (this study)
Dike, Tutka Bay	SV	93ASB66	59°23'38"	151°13'7"	115.0	1.7	$^{40}Ar/^{39}Ar$ hornblende	930	Lux (this study)
Nuka pluton	SV	88ACy9	59°28.4'	150°20.2'	54.2	0.1	$^{40}Ar/^{39}Ar$ biotite	970	Clendenen & Heizler (this study)
Nuka pluton	SV	88ACy9	59°28.4'	150°20.2'	56.0	0.5	U/Pb monazite	970	Parrish (this study)
Chernof stock	SV	91ADw55g	59°52'58"	150°27'23"	54.2	1.1	$^{40}Ar/^{39}Ar$ biotite	1,000	Lux (this study)
Tustumena pluton	SV	92AKu71b	59°58'38"	150°9'40"	53.2	1.1	$^{40}Ar/^{39}Ar$ biotite	1,020	Lux (this study)
Aialik pluton, Harris Bay	SV	91AKu3	59°47'30"	149°59'30"	52.2	0.9	$^{40}Ar/^{39}Ar$ biotite	1,010	Layer (this study)
Hive Island (Aialik?) pluton	BS	95TD3b	59°53'30"	149°22'	53.4	0.4	$^{40}Ar/^{39}Ar$ biotite	1,040	Layer (this study)
Thunder Bay granitic sill	SV	92PH454B	59°32'34"	150°10'50"	53.7	0.1	$^{40}Ar/^{39}Ar$ biotite	990	Haeussler and others (1995)
Granite at Granite mine	SR	92PH216E	60°58'19"	148°12'40"	56	1	$^{40}Ar/^{39}Ar$ biotite	1,170	Haeussler and others (1995)
Crow Pass felsic intrusion	AN	91AKU137	61°02'53"	149°06'28"	54.1	0.1	$^{40}Ar/^{39}Ar$ white mica	1,150	Haeussler and others (1995)
Granite at Homestake mine	AN	92PH215C	61°04'49"	148°16'30"	52.8	0.1	$^{40}Ar/^{39}Ar$ white mica	1,190	Haeussler and others (1995)
Sill, Van Cleve Glacier	CV	94APo36	60°45'49"	144°11'23"	54	not given	U/Pb monazite	1,410	Poole (1996)
Novatak Glacier pluton	YA	95APo13	59°36'02"	138°32'32"	49	not given	U/Pb zircon; lower intercept age	1,770	Poole (1996)

on hornblende; conventional K/Ar, Rb/Sr, and unpublished U/Pb ages range from 135 to 103 Ma. Pavlis and others (1988) offered two possible explanations for the Early Cretaceous near-trench magmatic event. Their preferred model involved shallow melting at a young subduction zone; a viable alternative, however, is that the melts formed during a ridge-trench encounter, much like the widespread early Tertiary near-trench intrusives that we attribute to subduction of the Kula-Farallon ridge.

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