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Rb-Sr DATING OF METASEDIMENTARY, METAVOLCANIC, AND METAPLUTONIC IGNEOUS ROCKS FROM THE NASON AND MAD RIVER TERRANES, NORTH CASCADE MOUNTAINS, WASHINGTON

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The purpose of this study was to perform reconnaissance whole rock and whole rock–mineral Rb-Sr dating on a variety of rock types from the Nason terrane (Tabor and others, 1987) in the North Cascade Mountains of Washington. Previous geochronologic work in this region consisted mostly of K-Ar dates on hornblende, biotite, and muscovite (Yeats and McLaughlin, 1968; Engels and Crowder, 1971; Yeats and Engels, 1971; Tabor and others, 1982, 1987, 1988, 1993), a few U-Pb zircon dates (Tabor and others, 1987, 1993; Walker and Brown, 1991), and fission track dates on the Mt. Stuart batholith (Engels and Crowder, 1971; Yeats and Engels, 1971; Erikson and Williams, 1976). It was hoped that this study would help to refine the timing of regional metamorphism through the mineral dates; to search for evidence on the age of the Nason terrane, which lacks fossil control or pre-Late Cretaceous intrusive rocks; and to shed light on the nature and age of a major suite of metatonalite gneisses which make up a large percentage of the northern half of the terrane. A small suite of samples of schist from the adjacent Mad River terrane, located just north of the Nason terrane, were also analyzed for comparison. A zircon fission-track date from a key locality is also presented.

GEOLOGIC SETTING

The Nason terrane is one of five tectonostratigraphic terranes comprising the crystalline basement of the North Cascade Mountains, a Cretaceous orogenic core uparched and exposed in the Cascade volcanic arc of Washington state (fig. 1). The main unit in the Nason terrane is the Chiwaukum Schist, which consists mostly of pelitic to semipelitic schist, with much less abundant amphibolite and amphibolitic schist, and rare marble, calc-silicate, ironstone, and ultrabasic layers (Van Diver, 1964; Plummer, 1969; Getsinger, 1978; Kaneda, 1980; Magloughlin, 1986, 1993; Tabor and others, 1982, 1987, 1988, 1993). Much of the pelitic schist is graphitic and derived from mudstones or fine-grained graywackes. In the north, the terrane is heterogeneously intruded across a wide area by plutonic rock mostly of tonalitic composition, which has been metamorphosed and deformed to orthogneiss. Largest of the discrete late Cretaceous plutons is the Mount Stuart batholith, a generally tonalitic calc-alkaline body composed of two parts,

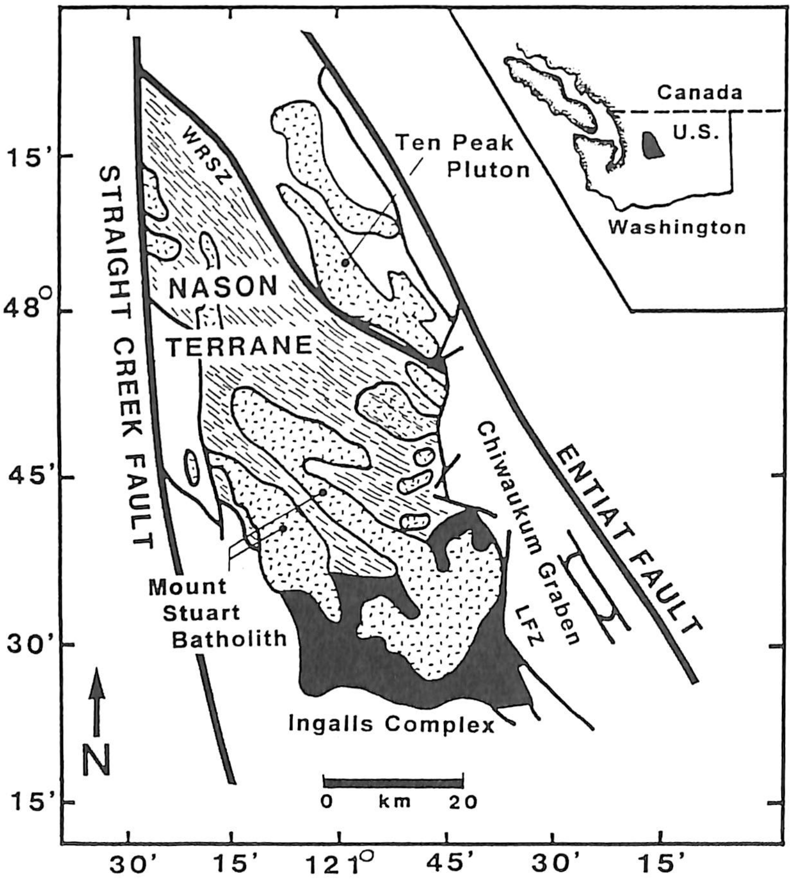

FIGURE 1. Geologic map of the Nason terrane, North Cascade Mountains, Washington. The Nason terrane is bounded by the Straight Creek Fault to the west, the Leavenworth Fault Zone (LFZ) to the east, the Ingalls Complex to the south, and the Mad River terrane to the north, from which it is separated by the White River Shear Zone (WRSZ, Magloughlin, 1986). The location relative to the northwestern U.S. and adjoining Canada is shown by the inset.

a northern and a southern unit, which are separated by a narrow screen of Chiwaukum Schist (fig. 1). The Chiwaukum displays amphibolite facies metamorphic assemblages, possibly low amphibolite facies in the south, and locally hornblende hornfels or pyroxene hornfels adjacent to the Mount Stuart batholith.

For this study, samples of Chiwaukum Schist and amphibolite, metatonalite gneiss, and pegmatite were collected mostly from the northeastern and central Nason terrane. The sample of pegmatite from the Mount Stuart batholith was collected from the southern part of the terrane along Icicle Creek, and the samples of Napeequa Schist were collected near Napeequa Creek, just north of the Nason terrane.

ANALYTICAL PROCEDURES

Rock samples of 1-2 kg were crushed using a jaw crusher and coarse ground using a disk mill, and then several grams were powdered using a motorized agate mortar. Mineral separates were obtained by sieving the coarse ground material to obtain the desired size fraction, and passing the size fraction across a vibration table, which resulted in fairly high purity mica separates. For a few samples, further separation was accomplished using either bromoform or methylene iodide.

Rb and Sr concentrations were determined by replicate analyses of pressed powder pellets using x-ray fluorescence. U.S. Geological Survey rock standards were used for calibration; mass absorption coefficients were obtained from Mo Kα Compton scattering measurements. Rb/Sr ratios have a precision of 2% (1σ) and precision concentrations of 5% (1σ). The Sr isotopic composition was measured on unspiked samples prepared using standard ion exchange techniques. The mass spectrometer, Vacuum Generators Isomass 54R, has data acquisition digitized and automated using a Hewlett-Packard HP-85 computer. Experimental data have been normalized to a $^{86}Sr/^{88}Sr$ ratio of 0.1194 and adjusted so that the NBS standard $SrCO_3$ (SRM987) gives a $^{87}Sr/^{86}Sr$ ratio of 0.71022 ± .00002 and the Eimer and Amend Sr a ratio of 0.70800 ± .00002.

A York regression (York, 1969) was used to calculate dates on the isochrons. To obtain the 2σ error on the dates, 4% of the Rb/Sr value was used along with the 2σ error on the $^{87}Sr/^{86}Sr$ ratio. For some of the samples, the 2σ error on the $^{87}Sr/^{86}Sr$ ratio was not recorded, and the 'standard error' of 0.0001, customarily used at the UBC lab, was used instead.

SAMPLE DESCRIPTIONS

The details of the suites, lithologies, and sample locations are given in table 1.

CHIWAUKUM SCHIST

Pelitic and semipelitic schist

Pelitic Chiwaukum Schist has been thoroughly described by previous workers in the Nason terrane (Van Diver, 1964; Plummer, 1969; Getsinger, 1978; Kaneda, 1980). The rock is typically dark bluish-gray, with a well-developed schistosity formed by aligned biotite and by thin, alternating biotite-rich and quartz-rich laminae. It is typically very fine-grained, and foliation surfaces have a knobby appearance due to the foliation wrapped around 1-5 mm garnet porphyroblasts. Highly deformed quartz veins are striking and ubiquitous. The Chiwaukum is graphitic, and pure graphite occurs locally in patches as large as 1 cm. Quartz, biotite, and garnet are essentially ubiquitous. Pelitic schist also contains staurolite, ilmenite and/or rutile, plagioclase, and commonly minor muscovite and chlorite. In the north, kyanite is the aluminosilicate, while andalusite is common in the south and sillimanite is more common in the west and near the plutons. The semipelitic schist and metagraywacke lack the aluminum excess minerals and muscovite, contain much less graphite, and may contain hornblende. Pyrite, chalcopyrite, and tourmaline are additional accessory minerals.

The schist collected for this study were mostly pelitic and semipelitic schist, along with a few hornblende-bearing schists.

Amphibolite

Amphibolite occurs in layers ranging from a meter to approximately 30 meters thick. Most of these are probably orthoamphibolites, either derived from ocean floor basalts or from basaltic sills (Magloughlin, 1993; Magloughlin and Edwards, in prep.). The layers are oriented parallel to the regional foliation, and some have been traced for up to about 5 km in length (Van Diver, 1964).

Mineralogically, the amphibolites consist of hornblende, plagioclase, and quartz, with varying amounts of garnet, zoisite, epidote, and biotite, along with one or more of titanite, ilmenite, and rutile.

The amphibolites collected for this study are from a single outcrop in the central Nason terrane. They are nearly black, hornblende-rich amphibolites with thin laminations up to a few mm thick of green epidote-rich and white quartz/plagioclase-rich layers.

Metatonalite gneiss

Much of the northern Nason terrane is heavily intruded by felsic rocks, mostly tonalite in composition.

TABLE 1. Sample locations and lithologies.

Suite	Sample	Type	Location	Latitude	Longitude
Chiwaukum pelitic and semipelitic schist	WR 157-2	1	Dirty Face Ridge	47° 54.2′	120° 52.15′
	WR 157-3	1	"	"	"
	WR 157-4	1	"	"	"
	WR 388-6	2	"	"	"
	WR 394-1	1	"	"	"
	NOC-1	3	Nason Ridge, US #2	47° 48.05′	120° 53.62′
	NOC-2	3	"	"	"
	NOC-3	3	"	"	"
	WR 126-3	3	White River	47° 53.68′	120° 53.44′
	WR 261-5	1	"	47° 53.81′	120° 53.74′
	WR 261-6	2	"	"	"
	WR 261-7	2	"	"	"
	TC-1	4	Tunnel Creek	47° 42.99′	121° 6.99′
	TC-2	4	"	"	"
	TC-3	4	"	"	"
	N105-1a, 1b	3,1	Chiwaukum Creek	47° 41.25′	120° 45.00′
	N100-8	1	Nason Ridge, US #2	47° 48.05′	120° 53.62′
	N109-2	3	Icicle Creek	47° 36.50′	120° 55.14′
	N116-3	1	White Pine Creek	47° 47.83′	120° 52.45′
	WR 181-1	3	Lake Wenatchee	47° 52.26′	120° 51.60′
	WR 306-1	1	Lake Wenatchee	47° 54.30′	120° 56.70′
	WR 337-2	5	Little Wenatchee River	47° 52.59′	120° 59.75′
Chiwaukum amphibolite	N100-9	6	Nason Ridge, US #2	47° 48.05′	120° 53.62′
	N100-10	6	"	"	"
	N100-11	6	"	"	"
	N100-12	6	"	"	"
	N100-13	6	"	"	"
Metatonalite gneiss	N100-7	7	Nason Ridge, US #2	47° 48.05′	120° 53.62′
	WR 102-3	8	White River	47° 51.49′	120° 50.40′
	WR 102-5	8	"	"	"
	WR 102-6	8	"	"	"
	WR 105-15	8	Wenatchee Ridge	47° 50.34′	120° 50.50′
	WR 105-16	8	"	"	"
	WR 105-17	8	"	"	"
	WR 106-5	9	"	47° 50.23′	120° 47.50′
	WR 140-8	10	White River Road	47° 52.47′	120° 52.01′
	WR 140-9	10	"	"	"
	WR 140-10	10	"	"	"
Pegmatite	N100-14	11	Nason Ridge, US #2	47° 48.05′	120° 53.62′
	N100-2	11	"	"	"
	N116-2	11	White Pine Creek	47° 47.83′	120° 52.45′
	PEG-3	12	Wenatchee Ridge	47° 50.78′	120° 52.70′
Mount Stuart batholith	N106-1	13	Icicle Creek	47° 35.40′	120° 47.10′
Napeequa Schist	A34A	5	Headwaters, Napeequa River	48° 4.88′	120° 59.52′
	A34B	3	"	"	"
	A34C	3	"	"	"
	A36	14	Base of Lewis Creek falls, Napeequa R. trail	48° 4.33′	120° 56.31′
	A39A	15	Boulder Pass trail	48° 2.67′	120° 55.10′
	A41-D	1	Near Boulder Pass	48° 2.67′	120° 55.68′
	A41-E	16	"	"	"

1) pelitic schist
2) hornblende-bearing schist
3) semipelitic garnet-biotite schist
4) andalusite-bearing pelitic schist
5) kyanite-bearing pelitic schist
6) epidote amphibolite
7) biotite metatonalite gneiss
8) muscovite metatonalite gneiss
9) quartz-rich bi-mu-epi metatonalite gneiss
10) muscovite-biotite metatonalite gneiss
11) garnet-muscovite tonalite pegmatite
12) epidote-muscovite tonalite pegmatite
13) biotite tonalite pegmatite
14) fine-grained bi-mu quartz schist
15) garnet-bi-mu pelitic schist
16) garnet-hornblende-biotite schist

This metatonalite is typically well foliated, and while it displays relict igneous textures, it is mostly mineralogically adjusted to the amphibolite facies. The lithologically layered appearance of these rocks is what characterizes the so-called 'banded gneiss' unit of Tabor and others, (1987, 1988, 1993). Areas comprised almost exclusively of tonalite have been mapped and given separate names, such as the Wenatchee Ridge Gneiss of Van Diver (1964) and the Excelsior Mountain Orthogneiss (Tabor and others, 1993). The metatonalite gneiss is extremely lithologically varied, with ten or more distinct intrusive phases present in single exposures (Magloughlin, 1994). The age constraints on these rocks are poor, although U-Pb zircon dates on the Excelsior Mountain Orthogneiss from the Skykomish Quadrangle are approximately 90 Ma although the ^{207}Pb-^{206}Pb range from 115-120 Ma (Tabor and others, 1993). It is also possible that the Excelsior Mountain Orthogneiss is more closely related to the Mount Stuart batholith and associated plutons than with the widespread gneissic tonalite.

The metatonalites collected for this study are from four locations near the southern end of Wenatchee Ridge in the northeastern Nason terrane, and one location in the central part of the terrane. All are medium-grained, moderately to well foliated, and all contain muscovite, while one sample, N100-7, contains more biotite than muscovite. The WR102 samples are from an outcrop which shows considerable evidence for incorporation of ultrabasic rock, in the form of small pods of serpentinite and common blackwall assemblages involving serpentine, chlorite, talc, tremolite, and phlogopite. The WR140 samples are muscovite poor, while sample WR106-5 is biotite rich and also contains minor epidote and garnet. The WR105 samples are muscovite rich but lack garnet.

Pegmatite

In decreasing order of abundance, muscovite tonalite, mica-poor tonalite, and biotite tonalite pegmatite are common throughout the northern Nason terrane. They are normally but not exclusively associated with the metatonalites. The pegmatite is most commonly concordant, but less commonly crosscuts both the Chiwaukum Schist and the metatonalites. Grain size is typically one to several cm. The majority of the pegmatite contains several percent muscovite that reaches 1-2 cm in diameter. It typically displays a random orientation, and is normally either undeformed or shows kinks or crenulations. The only xenoliths occurring in the pegmatite are slightly displaced metatonalite, and these locally attain 5 meters in diameter. Locally the pegmatite forms large concentrations of nearly mappable size. Isolated boudins up to 2 meters in length are developed especially where the pegmatite intrudes the Chiwaukum Schist. Magmatic epidote-bearing pegmatites occur at two localities and one of these has also been analyzed (sample PEG-3). Pegmatite from Wenatchee Ridge has yielded K-Ar biotite and muscovite dates of 81-84 Ma (Tabor and others, 1987). These rocks are described further by Van Diver (1964) and Magloughlin (1986).

Mount Stuart batholith

The Mount Stuart batholith is the largest of the Cretaceous plutons in the Nason terrane. U-Pb zircon dates on the Big Jim Complex, an early mafic phase of the batholith, yielded dates in the range of 95-97 Ma (Tabor and others, 1987). A U-Pb zircon date on diorite from the batholith was concordant at 93 Ma (Walker and Brown, 1991). In this study, a biotite tonalite pegmatite cross-cutting the dioritic phase from the southern part of the batholith has been dated. The sample comes from a dike approximately 30 cm thick, and is composed of minor biotite and magnetite, abundant plagioclase and quartz, with plagioclase and biotite crystals up to about 3 cm across.

Napeequa Schist

The Napeequa Schist of the Mad River terrane is lithologically heterogeneous, consisting of pelitic schist, micaceous quartzite, mafic breccia, fine-grained amphibolite, and marble (Tabor and others, 1987). The samples analyzed in this study include pelitic, quartz-rich, and amphibole-bearing schists.

RESULTS

The analytical data are given in table 2, and the mineral dates are presented in table 3.

Whole Rock Analyses

Chiwaukum pelitic and semipelitic schist

The whole rock analyses on the Chiwaukum Schist yield a diffuse isochron (or 'scatterchron') corresponding to a date of 212 ± 17 Ma (fig. 2a). The geological significance of this is uncertain; this could represent the time of deposition, diagenesis, or simply result from mixing of two or more sources (for discussion, see Magloughlin, 1993 and Magloughlin and Edwards, in prep.). If mixing can be discounted as an origin for the 'scatterchron,' then the date may yield a minimum age

TABLE 2. Rb-Sr analytical data. Data refer to whole rock analyses except where noted.

(mu = muscovite, bi = biotite, pl = plagioclase, ep = epidote)

Suite	Sample	Sr, ppm	Rb, ppm	$^{87}Rb/^{86}Sr$	$^{87}Sr/^{86}Sr$	2σ
Chiwaukum pelitic and semipelitic schist	WR 157-2	258	94.7	1.063	0.70765	0.00004
	WR 157-3	207	72.5	1.014	0.70728	0.00004
	WR 157-4	248	62.8	0.734	0.7071	0.0001
	WR 157-4, bi	31.5	238	26.1	0.7307	0.0001
	WR 388-6	401	26.9	0.195	0.70462	0.00003
	WR 394-1	117	59.5	1.476	0.70780	0.00004
	NOC-1	221	95.4	1.251	0.70760	0.00005
	NOC-1, bi	100.9	310	8.89	0.7180	0.0001
	NOC-2	280	86.1	0.890	0.7074	0.0002
	NOC-3	211	89.2	1.221	0.70806	0.00005
	WR 126-3	320	72.9	0.659	0.70688	0.00006
	WR 261-5	385	52.7	0.396	0.70578	0.00005
	WR 261-5, bi	27.7	304	31.9	0.7401	0.0001
	WR 261-6	457	18.7	0.119	0.70415	0.00008
	WR 261-7	298	74.0	0.720	0.70683	0.00009
	TC-1	181	70.7	1.128	0.7074	0.00010
	TC-1, bi	42.0	233	16.11	0.7274	0.0001
	TC-2	218	77.0	1.025	0.70743	0.00011
	TC-3	164	72.5	1.281	0.70829	0.00006
	N105-1a	99.8	34.4	0.997	0.70818	0.00012
	N105-1a, bi	86.3	193	6.469	0.71473	0.00008
	N105-1b	232	95.5	1.190	0.70843	0.00008
	N100-8	168	88.2	1.517	0.70833	0.00010
	N109-2	273	52.7	0.559	0.70603	0.00014
	N109-2, bi	44.7	167	10.848	0.71564	0.00016
	N116-3	264	38.3	0.420	0.70591	0.00012
	WR 181-1	102.6	16.7	0.471	0.70562	0.00018
	WR 306-1	300	51.1	0.492	0.70614	0.00008
	WR 337-2	204	79.3	1.123	0.70813	0.00020
Chiwaukum amphibolite	N100-9	176	4.5	0.074	0.70345	0.00014
	N100-10	148	4.8	0.094	0.70402	0.00012
	N100-11	154	4.8	0.091	0.70413	0.00014
	N100-12	200	2.5	0.036	0.70387	0.00014
	N100-13	203	11	0.159	0.70448	0.00012
Metatonalite gneiss	N100-7	660	31.6	0.139	0.70427	0.00018
	N100-7, bi	148	202.5	3.969	0.70834	0.00008
	WR 102-3	650	44.2	0.197	0.7046	0.0001
	WR 102-3, mu	117	206	5.12	0.7111	0.0001
	WR 102-5	574	37.1	0.187	0.7047	0.0001
	WR 102-5, mu	116	197	4.90	0.7099	0.0001
	WR 102-6	615	13.5	0.063	0.7046	0.0001
	WR 105-15	507	51.7	0.295	0.7052	0.0001
	WR 105-15, mu	113	246	6.29	0.7113	0.0001
	WR 105-16	555	9.5	0.049	0.7051	0.0001
	WR 105-17	575	15.8	0.079	0.7050	0.0001
	WR 106-5	94.2	21.7	0.666	0.7066	0.0001
	WR 140-8	723	19.8	0.079	0.7053	0.0001
	WR 140-8, mu	168	193	3.32	0.7092	0.0001
	WR 140-9	535	12.4	0.067	0.7054	0.0001
	WR 140-10	573	7.8	0.039	0.7053	0.0001

TABLE 2. Rb-Sr analytical data. Data refer to whole rock analyses except where noted (continued).

(mu = muscovite, bi = biotite, pl = plagioclase, ep = epidote)

Suite	Sample	Sr, ppm	Rb, ppm	$^{87}Rb/^{86}Sr$	$^{87}Sr/^{86}Sr$	2σ
Pegmatite	N100-14	102	130	3.704	0.70961	0.00010
	N100-14, mu	45.2	292	18.75	0.72525	0.00010
	N100-2	77.9	86.6	3.215	0.70942	0.00016
	N100-2, mu	36.8	262	20.640	0.73006	0.00016
	N116-2, pl	71.0	19.5	0.800	0.70590	0.00006
	N116-2	71.0	37.4	1.525	0.70670	0.00012
	N116-2, mu	43.9	178	11.706	0.71899	0.00016
	PEG-3, pl	515	9.28	0.052	0.70477	0.00004
	PEG-3, ep	2409	61.4	0.074	0.70491	0.00008
	PEG-3, mu	274	136	1.431	0.70653	0.00006
Mount Stuart batholith	N106-1	486	1.6	0.010	0.70387	0.00014
	N106-1, bi	85.2	72.8	2.471	0.70718	0.00016
Napeequa Schist	A34A	36.8	36.6	2.883	0.71176	0.00006
	A34B	52.1	43.9	2.437	0.70837	0.00026
	A34C	460	39.3	0.247	0.70610	0.00008
	A36	41.2	7.47	0.524	0.70706	0.00030
	A39A	113	109.4	2.814	0.70846	0.00018
	A41-D	179	36.3	0.586	0.70699	0.00012
	A41-E	216	26.4	1.026	0.70658	0.00038

TABLE 3. Rb-Sr mineral dates.

Suite	Sample	Isochron	Date (Ma) & error, 2σ	$^{87}Sr/^{86}Sr_i$ & error, 2σ
Chiwaukum Schist	WR 157-4	whole rock - biotite	65 ± 3	0.7064 ± .0007
	NOC-1	whole rock - biotite	96 ± 5	0.7059 ± .0004
	WR 261-5	whole rock - biotite	77 ± 3	0.7054 ± .0010
	TC-1	whole rock - biotite	94 ± 4	0.7059 ± .0006
	N105-1a	whole rock - biotite	84 ± 4	0.7070 ± .0003
	N109-2	whole rock - biotite	66 ± 3	0.7055 ± .0003
Metatonalite gneiss	N100-7	whole rock - biotite	75 ± 5	0.7041 ± .0002
	WR 102-3	whole rock - muscovite	93 ± 4	0.7043 ± .0002
	WR 102-5	whole rock - muscovite	77 ± 4	0.7045 ± .0002
	WR 105-15	whole rock - muscovite	72 ± 3	0.7049 ± .0002
	WR 140-8	whole rock - muscovite	85 ± 5	0.7052 ± .0002
Mount Stuart batholith	N106-1	whole rock - biotite	95 ± 7	0.7039 ± .0002
Pegmatite	N100-14	whole rock - muscovite	73 ± 4	0.7058 ± .0006
	N100-2	whole rock - muscovite	83 ± 4	0.7056 ± .0008
	N116-2	whole rock - plagioclase -muscovite	84 ± 4	0.7049 ± .0001
	PEG-3	plagioclase - epidote - muscovite	89 ± 6	0.7047 ± .0001

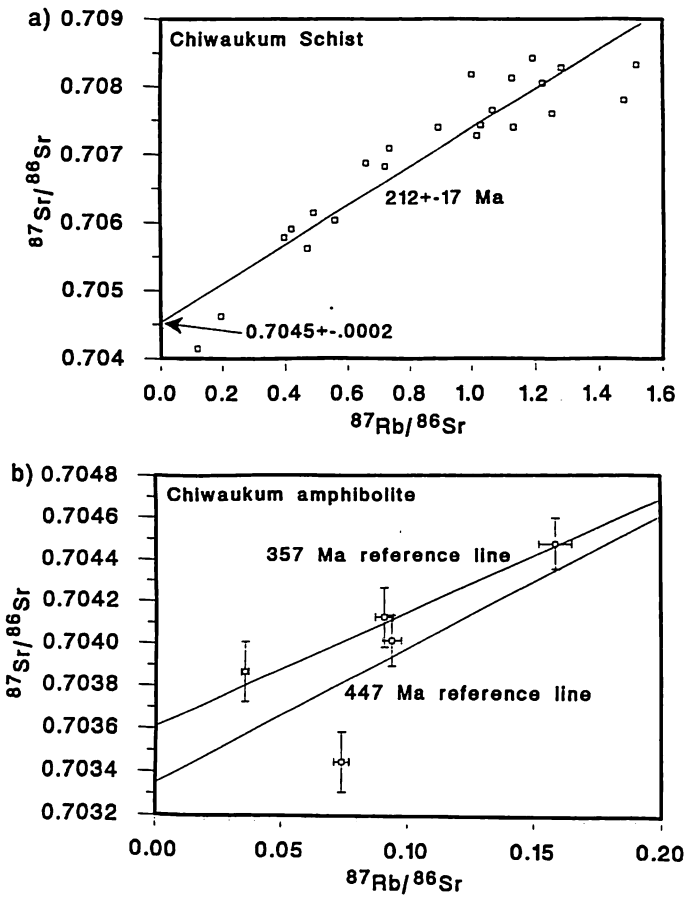

FIGURE 2. *a:* **Rb-Sr isochron diagram for Chiwaukum pelitic and semipelitic schist. The data yield a best fit 'scatterchron', using a York regression, of 212 ± 17 Ma.** *b:* **Rb-Sr isochron diagram for Chiwaukum amphibolites from the central Nason terrane. Reference lines based upon regressions for the four upper samples (357 Ma) and for all five samples (447 Ma) are shown.**

for the Chiwaukum Schist. The importance of this date, regardless of its interpretation, is that it provides an isotopic fingerprint of the terrane allowing comparison and correlation to other units. The date and the $^{87}Sr/^{86}Sr_i$ are very similar to those of the Settler Schist (210 ± 10 Ma, $^{87}Sr/^{86}Sr_i$ = 0.7043, Gabites, 1985), and the Tonga Formation ($^{87}Sr/^{86}Sr_i$ = 0.7042, 193 ± 11 Ma, Duggan, 1992), which along with lithologic and other information, provide strong evidence for the correlation of these units.

Chiwaukum amphibolite

The amphibolites yield $^{87}Sr/^{86}Sr$ ratios below almost all of the Chiwaukum Schist samples, and have very low $^{87}Rb/^{86}Sr$ ratios. Four of the five samples are colinear within error and a regression through these yields an apparent date of 357 Ma (fig. 2b). Regression through all five yields an older apparent date with a very large error. It is possible these data hint at a Paleozoic age for the amphibolites, but mixing with an external Sr reservoir could have dispersed an originally tight cluster of points into the pattern observed. The small spread of both $^{87}Rb/^{86}Sr$ and $^{87}Sr/^{86}Sr$ ratios precludes extensive interpretation of these data.

Metatonalite gneiss

Most of the gneiss samples yield low $^{87}Rb/^{86}Sr$ ratios. There is a cluster of points near $^{87}Rb/^{86}Sr$ ratios of 0.05, and a possible dispersal of points to higher $^{87}Sr/^{86}Sr$ ratios (fig. 3a). Clearly no age interpretation can be drawn from these data, and thus the age of the metatonalites remain bracketed only by the age of the Chiwaukum Schist and the cooling dates (below). However, the metatonalites display many characteristics of S-type granitoids (Magloughlin, 1986), and the scattering in Rb-Sr isotopic data could support variable incorporation of metasedimentary rocks into the melts.

There is a correlation between mineralogy and $^{87}Sr/^{86}Sr$. The WR102 samples, which show evidence for ultrabasic contamination, have three of the four lowest $^{87}Sr/^{86}Sr$ ratios, while the garnet-bearing (most sediment-contaminated?) sample (WR106-5) has the highest. The remaining samples display intermediate $^{87}Sr/^{86}Sr$ ratios.

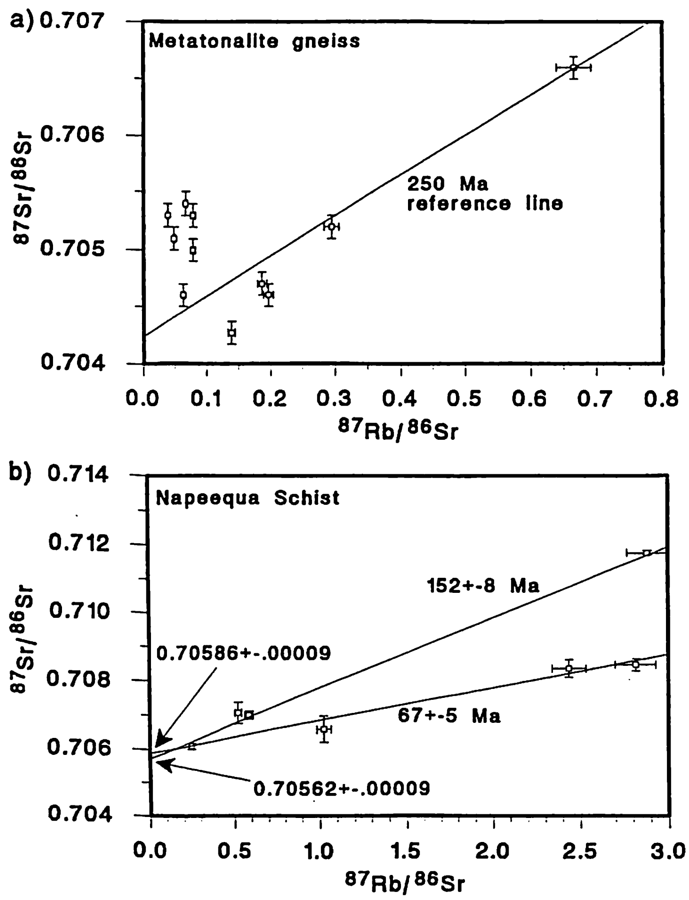

FIGURE 3. *a:* **Rb-Sr isochron diagram for the metatonalite gneiss. A 250 Ma reference line is shown.** *b:* **Rb-Sr isochron diagram for the Napeequa Schist. Two possible isochrons and their $^{87}Sr/^{86}Sr$ initial ratios are shown.**

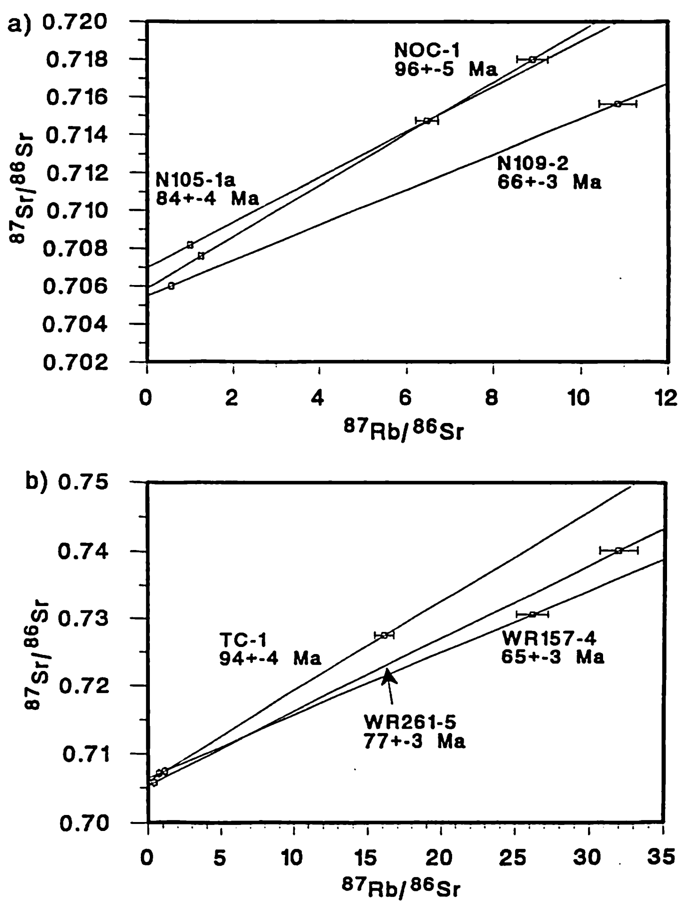

FIGURE 4. ***a and b:*** **Rb-Sr isochron diagram showing whole rock-biotite isochrons for the Chiwaukum Schist.**

Napeequa Schist

The Napeequa Schist data (fig. 3b) do not fall along a single isochron, but may be interpreted using 2 isochrons, which, within error, may both be drawn through the sample with the lowest $^{87}Rb/^{86}Sr$ ratio, sample A34C. The $^{87}Sr/^{86}Sr_i$ ratios nearly overlap, within error, but the fitting of the upper (older) isochron is dependent on the sample with the highest $^{87}Rb/^{86}Sr$ ratio, sample A34A. The two most likely scenarios are as follows:

1) The data may actually be fit by two isochrons, corresponding to an earlier event (diagenesis?) at 152 ± 5 Ma and local isotopic homogenization on the whole-rock scale at 67 ± 5 Ma. Both dates are geologically reasonable; the former corresponds closely to the age of the Ingalls Complex to the south of the Nason terrane (Late Jurassic, Tabor and others, 1982) while the latter falls within the range of K-Ar dates (50-68 Ma, Tabor and others, 1987) on micas and hornblende from the Mad River terrane.
2) If sample A34A is discounted, then the remaining data may be fairly well fit by a single scatterchron yielding an early Tertiary apparent date. This could suggest fairly thorough isotopic homogenization on the whole rock scale at this time.

Mineral dates

Chiwaukum Schist

The whole rock-biotite data yield dates from 66 to 96 Ma (figs. 4a,b). The three oldest dates are from near the center of the terrane, while the three youngest are from the most northerly and southerly samples. Broadly, these dates represent cooling ages through the ca. 300°C closure temperature of biotite, but there is definitely late, generally non-penetrative deformation in the terrane that could have partially reset some of the dates to anomalously young values. The 94 ± 4 Ma date is from a rock contact metamorphosed by the Mount Stuart batholith within the narrow septum between the two parts of the batholith mentioned above, and this date is very close to the age of the batholith. This would suggest very rapid cooling of the pluton and the central Nason following emplacement. Such a date is supported by a ca. 95 Ma zircon fission track (J. Vance, personal communication), and K-Ar hornblende dates as old as 95 Ma on the Mount Stuart batholith (Engels and Crowder, 1971). The 96 ± 5 Ma date is from about 3 km northeast of the margin of the batholith, and while the sample does not display evidence for contact metamorphism, it similarly suggests rapid cooling of this part of the terrane at about this time. However, the younger dates are similar to K-Ar dates in the Nason terrane, and even the youngest is supported by a zircon fission-track date (below). At face value, these dates suggest the present erosion surface did not uniformly cool below ca. 300°C at the same time, but possibly somewhat sooner in the central part of the terrane than in the north or south.

Metatonalite gneiss

The whole rock-mica dates show considerable spread, from about 72 to 93 Ma (fig. 5a). Even two samples from the same location, WR102-3 and WR102-5, give dates 16 Ma apart. One possible explanation for the spread is contamination or resetting by the tonalite pegmatite, which is abundantly present in this locality. Variable uplift rates could also be a factor, but the four samples are from a fairly small area, and the considerable disagreement between two samples from the same outcrop suggests uplift may not be the most important factor. The degree of deformation and grain size could also be factors contributing to the spread in dates. However, in general, these dates likely indicate cooling through the closure temperature of muscovite, possibly with some resetting to younger dates.

Pegmatite

The Mount Stuart batholith pegmatite (N106-1) yielded the oldest date, 95 ± 7 Ma, which is very close to the U-Pb zircon dates on the batholith. This suggests that the southern part of the batholith cooled through the biotite closure temperature within several million years of emplacement.

The N100 samples yield dates (73 and 83 Ma) that do not quite agree within error. Their $^{87}Sr/^{86}Sr_i$ ratios do, however, agree within error. Sample N116-2 yields a date (84 Ma) in agreement with the older of the two. The younger date agrees well with the whole rock-biotite date on sample N100-7 from the same outcrop, while the older dates agree well with the Nason terrane K-Ar dates (Tabor and others, 1987) and the Rb-Sr biotite date from Chiwaukum Creek (sample N105-1a). The Rb-Sr closure temperatures for these very coarse-grained muscovites (books commonly exceeding 1 cm across) should be very high, probably over 600°C (Cliff, 1985). The pegmatites appear to be the final pulse of magmatic activity in the central and southern Nason terrane, so while the older dates could be cooling dates, and perhaps close to crystallization dates, the younger appear to be reset. One possibility stems from the observation that some of the pegmatites are obviously ductilely deformed, and are also affected by later faulting. It is possible that deformation of the muscovite allowed Sr exchange to continue until, or to occur at, temperatures below the normal closure temperature. This could certainly explain the variation in dates in a single outcrop.

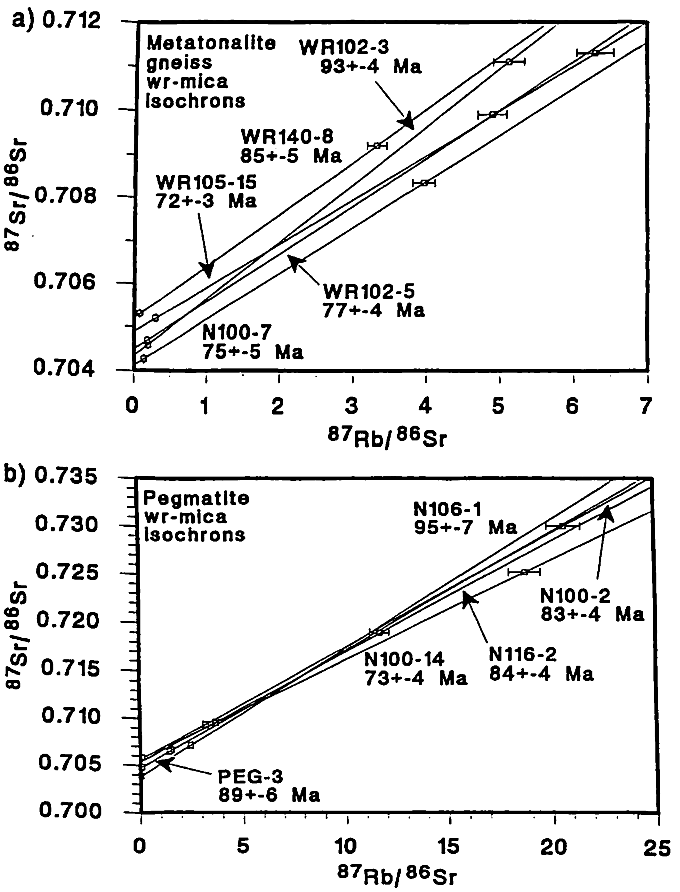

FIGURE 5. *a:* **Rb-Sr isochron diagram showing whole rock-muscovite isochrons for the metatonalite gneiss.** *b:* **Rb-Sr isochron diagram showing whole rock-mineral and multiple mineral isochrons for the pegmatites. A whole rock-biotite isochron is shown for sample N106-1, whole rock-muscovite isochrons f or samples N100- 14 and N100-2, a plagioclase-whole rock-muscovite isochron for sample N100-16, and an epidote-plagioclase-muscovite isochron f or sample PEG-3.**

The epidote muscovite pegmatite yields a date (89 ± 6 Ma) younger than the MSB pegmatite, but which agrees with N100-2 and N116-2 within error. Because of the very coarse grained nature of this rock, with crystals of all three minerals commonly exceeding 1 cm in diameter, this date is likely close to the crystallization age of the pegmatite. As this pegmatite cuts the Wenatchee Ridge Gneiss, it provides a minimum estimate of the age of the metatonalite.

The $^{87}Sr/^{86}Sr_i$ ratios of the muscovite pegmatites, but not the Mount Stuart batholith pegmatite, do overlap with those of the metatonalite gneiss, which in addition to the mineralogical similarities, also suggests the pegmatites are a late phase of the metatonalite intrusives.

Zircon fission track date

Zircons separated from the Dirty Face Pluton were submitted for fission track dating in order to obtain a cooling date on the pluton and its host rocks. The analysis was done by Professor J. Vance of the University of Washington. Eight grains were counted, yielding 1738 fossil tracks and 907 induced tracks, for a date of 60.5 ± 5.0 Ma. For rapid cooling rates, zircon has a closure temperature for the retention of fission tracks of about 300°C, and so this date yields the approximate time at which the Dirty Face pluton and the northern Nason terrane cooled through this temperature. This is in good agreement with the Rb-Sr biotite date from sample WR157-4, collected from within a few hundred meters of the Dirty Face pluton sample, of 65 ± 3 Ma.

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