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Mafic meta-igneous arc rocks of apparent komatiitic affinities, Sawyers Bar area, central Klamath Mountains, northern California*

W. G. ERNST

Department of Earth and Space Sciences, Institute of Geophysics and Planetary Physics,
University of California, Los Angeles, California 90024, U.S.A.

Abstract—Metamorphosed mafic igneous rocks of probable Permo–Triassic age, informally designated the Yellow Dog metavolcanics, apparently overly fine-grained metasedimentary strata in the eastern portion of the Western Paleozoic and Triassic Belt. These rocks have been recrystallized under biotite zone greenschist facies pressure-temperature conditions. Bulk-rock XRF analyses of the metavolcanics document the existence of a mafic-ultramafic trend. Fourteen of 55 analyzed protoliths appear to have been komatiitic or picritic basalts. The mean bulk-rock chemistry of these 14 specimens in oxide weight percent is: 49.0 SiO_2; 10.8 Al_2O_3; 14.8 MgO; 10.0 CaO; 1.4 Na_2O; 0.7 K_2O; 11.3 $Fe_2O_3^*$; 1.2 TiO_2; 0.2 MnO; and 0.2 P_2O_5. Cr and Ni contents average 660 and 280 ppm respectively. Most Yellow Dog greenstones represent magnesian tholeiites, but, for the chemical parameters plotted, appear to be chemically intergradational with the consanguineous, apparently aphanitic, komatiitic(?) units. Associated coarser grained hypabyssal dikes and sills tend to be more evolved as a group, and exhibit transitions towards calc–alkaline basalts; evidently more leisurely ascent towards the surface allowed shallow-level crystal fractionation of the intrusive units. All analyzed rocks interpreted as komatiitic display hypersthene in the norm, and only one of the non–komatiitic samples carries significant normative nepheline (4 weight percent). Electron microprobe analyses of relict clinopyroxene phenocrysts from three mafic meta–igneous but non–komatiitic Yellow Dog rocks document a tholeiitic rather than an alkalic trend.

Twelve bulk–rock INAA demonstrate that, unlike most Archean ultramafic lavas, komatiitic(?) members of the Yellow Dog suite are strongly fractionated in rare earth elements and are LREE enriched, whereas some of the more normal mafic units display nearly flat, less evolved patterns; two magma series may therefore be present in the Yellow Dog metavolcanics. Six bulk–rock oxygen analyses show that the metavolcanics ($\delta^{18}O = 9.6–15.3$) are substantially enriched in ^{18}O relative to Archean komatiites and Phanerozoic MORBs, probably as a consequence of partial re–equilibration with large quantities of magmatic water or seawater; isotopic fractionation is thought to have occurred at temperatures on the order of 100°C. However, major element + REE chemistries and mineralogies of the greenstones do not reflect metasomatism comparable to the extent of oxygen isotopic exchange.

Lack of an alkali basalt suite, occurrence of distal metaclastic sedimentary units intricately interlayered with the Yellow Dog metavolcanics and apparently conformably underlying them, and ultramafic affinities of some of the greenstones argue for an origin by partial melting of relatively undepleted mantle ± eclogite at depths approaching 200 km and high temperatures beneath a primitive continental margin, or island arc. Eliminated by the petrochemistry are back–arc basin, intraplate, and rifted plate tectonic settings. Partial fusion of deep–seated portions of a garnet-bearing (REE–enriched?) protolith beneath this sector of the Californian convergent margin evidently was attended by abnormally elevated temperatures during Permo–Triassic subduction, volcanism and accretion, possibly due to oceanic-ridge or hot–spot descent. Subsequent interaction with magmatic water (or seawater) disturbed $^{18}O/^{16}O$ ratios in the analyzed rocks, but seems not to have involved widespread major element migration within the volcanic arc during regional metamorphism.

INTRODUCTION

THE SO-CALLED Western Paleozoic and Triassic belt (WTrPz) of the Klamath Mountains consists of four major lithotectonic units, serially juxtaposed along east-dipping thrust faults, and variably intruded by calc-alkaline plutons of approximately Nevadan age (IRWIN, 1960, 1966, 1985). Regional relationships in northern and central California, after JENNINGS (1977), are illustrated in Figure 1. The lithotectonic units contain fossils of late Paleozoic and early Mesozoic age; some, especially the older macrofossils, appear to occur in olistolithic blocks (IRWIN *et al.*, 1978). The structurally highest unit, on the east, is the Stuart Fork terrane, which bears the effects of a Late Triassic blueschist-type metamorphism (HOTZ, 1973; HOTZ *et al.*, 1977; BORNS, 1984; GOODGE, 1985). The three successively more oceanward units are the North Fork, Hayfork, and Rattlesnake Creek terranes, respectively (IRWIN, 1972). Similar to the inboard Stuart Fork, all were pervasively deformed and overprinted by a greenschist facies metamorphism during final assembly

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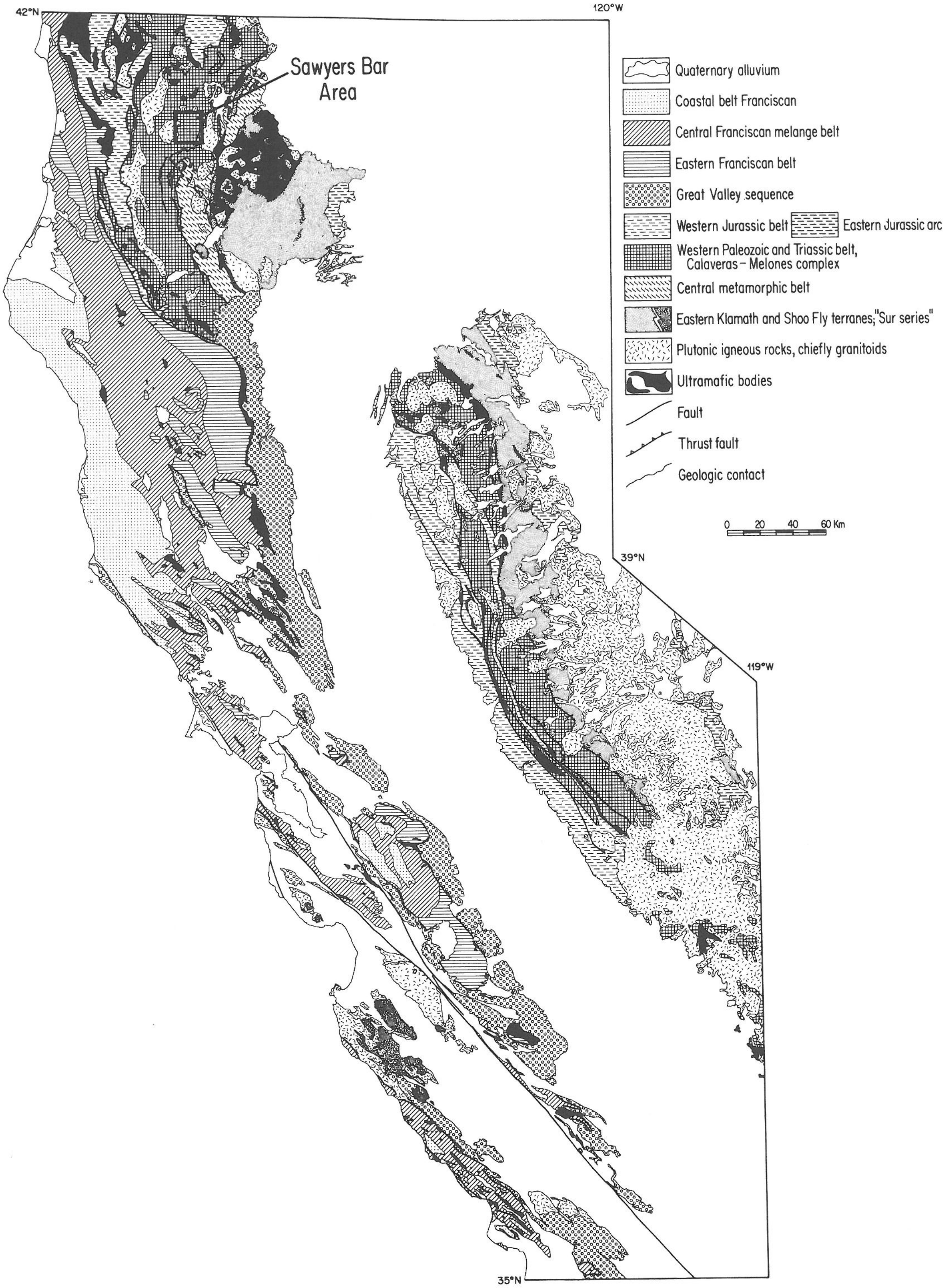

FIG. 1. Geologic setting and lithotectonic belts of northern and central California (JENNINGS, 1977; ERNST, 1983). Note the apparent extension of Klamath terranes into the northern Sierra Nevada foothills (DAVIS, 1969; HIETANEN, 1981). Location of the Sawyers Bar area (Figure 2) is also indicated.

of these units (the Siskiyou event of COLEMAN *et al.*, 1987; see also BARNES *et al.*, 1986), probably preceeding and accompanying emplacement of the Nevadan and slightly older granitoids (LANPHERE *et al.*, 1968; WRIGHT, 1982; HARPER and WRIGHT, 1984; HILL, 1985; COTKIN *et al.*, 1985).

Premetamorphic lithologies of the WTrPz apparently included widespread ophiolitic lenses + associated cherts, as well as abundant, locally melanged argillites, minor limestones and interlayered mafic volcanics. Although ophiolitic metagabbros, metabasalts, serpentinized peridotites and metacherts are of oceanic origin (IRWIN, 1985), the provenance of voluminous terrigineous debris was more probably a nearby calc–alkaline arc (WRIGHT, 1982). The Stuart Fork terrane is interpreted as a section of oceanic crust and distal fan deposits carried down a subduction zone in the vicinity of the eastern Klamath region approximately 220 m.y. (BORNS, 1980; ERNST, 1984; GOODGE, 1985). Its juxtaposition with—and the origins of—the North Fork, Hayfork, and Rattlesnake Creek terranes are less clear, however (*e.g.*, BURCHFIEL and DAVIS, 1981; IRWIN, 1981; WRIGHT, 1982; ANDO *et al.*, 1983; MORTIMER, 1985).

Do these WTrPz terranes constitute a single, evolving, imbricated lithotectonic unit, or several unrelated, far-travelled entities? Are the original rocks parts of a landward arc, a continental margin, or portions of an oceanic plateau? Is the metamorphism coeval throughout the three western units, and is it characteristic of an island arc, a transpression boundary, a subduction zone, a back–arc basin, or yet another plate tectonic environment? In an attempt to address some of these questions, the author has been conducting field, petrographic, and geochemical investigations in the Sawyers Bar area of the central Klamath Mountains since 1979.

GENERAL GEOLOGY OF THE SAWYERS BAR AREA

The mapped area includes small portions of the Stuart Fork and possibly Hayfork terranes, but evidently consists chiefly of North Fork rocks. Local geologic relationships are shown in Figure 2. A small segment of the Stuart Fork thrust sheet, intruded by the Russian Peak pluton, is situated in the southeast corner of the map area (GOODGE, 1986); the English Peak Granodiorite crops out along the western margin of the studied area and appears to have intruded chiefly the eastern portion of the Hayfork belt (WRIGHT, 1982; IRWIN, 1985; COLEMAN *et al.*, 1987). Both granitoids were emplaced during mid Jurassic time subsequent to, or at the terminal stages of, the WTrPz regional dynamothermal event.

The major portion of the mapped region, however, consists of massive to weakly foliated greenstones (mafic metavolcanics), and less voluminous interlayered metaclastic schists; the metavolcanics lie on strike with, and directly north of North Fork rocks termed ophiolitic by ANDO *et al.* (1983); the formational age of this suite is apparently Permo–Triassic. SNOKE *et al.* (1982) drew attention to a widely distributed group of basalts, basaltic andesites, and andesites of the western Klamaths and western Sierra Nevada, and correlated these volcanics (of which the Sawyers Bar greenstones represent a small part) with a series of coextensive ultramafic to dioritic intrusive complexes. BLAKE *et al.* (1982) recognized the North Fork metavolcanics as a separate exotic unit—the so-called Salmon River terrane; others (MORTIMER, 1985; DONATO, 1987) have included mafic meta–igneous rocks directly north of the Sawyers Bar area in the eastern Hayfork subterrane. Recognizing their on–strike correlation with ophiolitic rocks mapped by ANDO *et al.* (1983), the present author tentatively assigns the Sawyers Bar greenstones to the North Fork terrane of IRWIN (1972).

Primary(?) compositional layering and indistinct foliation in the greenstones and better layering in the metaclastics coincide in attitude, strike NS to N30E, and dip steeply, mostly to the east. Although the greenstones are relatively massive, rare pillows, providing unequivocal top indicators, were recognized in the northeastern part of the map area near locality 127M (Figure 2). Based on this occurrence and the stratigraphic coherence displayed by the several mapped lithologies, the region is provisionally interpreted as consisting of a major greenstone synform on the east, and progressively westward, very gently south–plunging, overturned, west–verging metasediment-cored antiforms and greenstone-cored synforms. Tectonic discontinuities between metasedimentary and metavolcanic lithologic packages were not recognized, although a few small lenses of serpentinite are present in the northern part of the mapped area. Protoliths for the metasedimentary rocks consist of pelitic units, argillites, micrograywackes, calcareous quartzofeldspathics, rare limey units, and minor cherty layers—in aggregate probably representing distal turbiditic (continental rise?) deposits.

In general, the greenstone units appear stratigraphically to overlie the fine–grained metaclastics, and dominate the exposed section in the Sawyers Bar area. Depositional interlayering and tight folding are evident from the intricately interdigitated

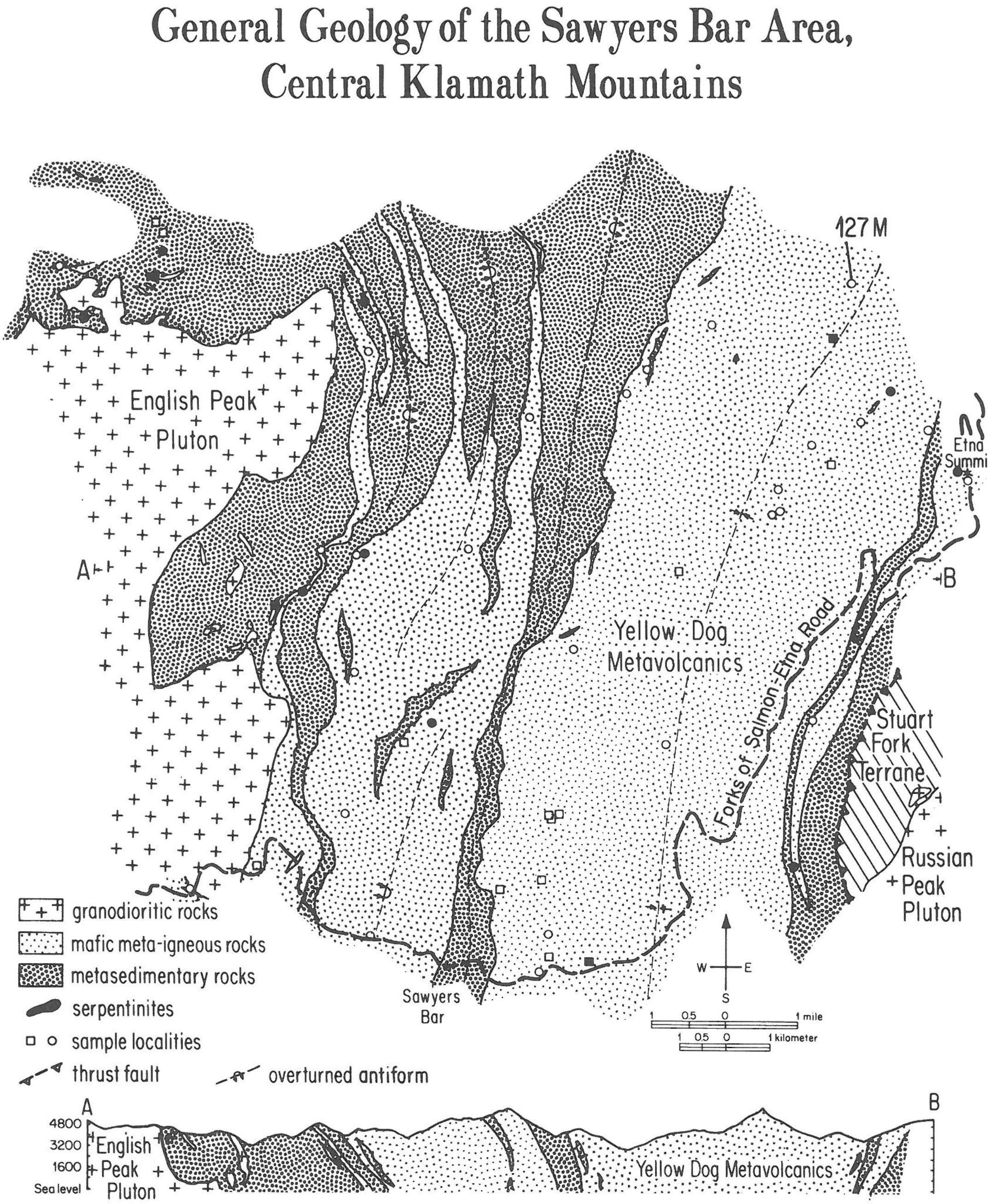

FIG. 2. Provisional, interpretive structure and general geology of the Sawyers Bar area, showing sample localities for metamorphosed mafic igneous rocks. Coarser grained hypabyssal rocks are indicated by square symbols; fine-grained, massive extrusives by circles. Filled symbols denote ultramafic bulk-rock compositions, open symbols mafic bulk-rock chemistry. Locality 127M is the site of unambiguous pillows, with tops facing east.

outcrop patterns of the metasedimentary and mafic meta-igneous units (Figure 2). Although the metavolcanic units comprise chiefly massive flows, minor cross-cutting and concordant tabular bodies—most of which display coarser grained, relict diabasic texture—attest to the presence of hypabyssal metamorphosed mafic intrusives and slowly-cooled flows distributed within the volcanic pile. The entire greenstone assemblage, including the associated dikes and sills, is here referred to informally as the Yellow Dog metavolcanics, after the prominent peak northeast of Sawyers Bar. The association with distal turbidites, and the fact that the extrusive section apparently overlies the sediments argue for construction in an island–arc setting. As will be shown later, the predominantly basaltic volcanics also include more evolved, calc–alkaline type units, supporting the hypothesis of formation in a primitive arc.

Except for the preservation of diabasic texture in some of the coarser grained intrusives, pillows in a few of the flows, and rare relict cpx in several of the Yellow Dog (chiefly hypabyssal) rocks, recrystallization has obliterated most original features in both meta-igneous and metasedimentary units. Petrographic studies demonstrate that the investigated rocks have been recrystallized under physical conditions of the upper greenschist facies (Donato *et al.*, 1982; Mortimer, 1985; Coleman *et al.*, 1987). Biotite is an important phase in metasedimentary (especially pelitic and quartzofeldspathic) units, and is a widespread accessory in the mafic metavolcanics. The typical assemblage of the latter is albite + chlorite + actinolitic hornblende + epidote + sphene. Average modes for 297 pre-Nevadan metamorphic rocks examined petrographically are listed in Table 1. Low-variance, pressure-temperature diagnostic assemblages are rare in the studied area and geothermometric/geobarometric investigations are not yet completed. Judging from the experimental pressure-temperature location of the greenschist–epidote amphibolite facies boundary (Liou *et al.*, 1974; Apted and Liou, 1983), and occurrences of andalusite directly to the north (Donato, 1987), provisional estimated physical conditions for greenschist facies metamorphism in the Sawyers Bar area are 400° ± 75°C, 3 ± 1 kbar.

Megascopically, a few of the metavolcanic rocks which are situated adjacent to the English Peak and Russian Peak plutons are dark green, and were

Table 1. Average modes of pre-Nevadan North Fork/Hayfork metamorphic lithologies, Sawyers Bar area*

Mineral \ Rock type (no. of samples)	Siliceous (22)	Pelitic (33)	Carbonaceous (18)	Quartzo-feldspathic (44)	Serpentinite (6)	Mafic volcanic (21)	More felsic volcanic (118)	Hypabyssal (35)
Quartz	79	57	54	38	—	2	2	5
Plagioclase	1	2	2	17	—	17	26	34
Pyroxene	—	—	—	1[a]	1[b]	—	2[b]	3[b]
Amphibole	—	—	1	12	14	43	36	31
Biotite	4	13	2	6	—	3	1	2
White mica	7	14	14	9	—	2	1	2
Chlorite	2	8	2	5	3	16	9	8
Talc	—	—	—	—	31	—	—	tr
Serpentine	—	—	—	—	40	—	—	—
Epidote	tr	tr	1	1	—	6	16[c]	8
Garnet	tr	tr	—	tr	—	—	—	—
Carbonate	tr	tr	—	5	6	3	2	2
Carbonaceous matter	3	2	19	2	—	—	—	—
Opaques	4	4	5	3	5	4	2	2
Sphene ± rutile	—	tr	—	1	—	4	3	3

a = diopside in marble layers; b = relict igneous pyroxene; c = tr prehnite, stilbite.
* Modes visually estimated.

mapped in the field as mafic metavolcanics. Most of the greenstones possess pale, apple-green or light-gray colors, however, and were originally regarded as more felsic metavolcanics and intrusive equivalents. Modes presented in Table 1 demonstrate that both rock types are, in fact, quite mafic in composition, although the lighter-colored metavolcanics and meta-hypabyssals contain greater proportions of albite + epidote and less amphibole + chlorite than the darker metavolcanics. The conclusion that all the metavolcanics are mafic is supported by chemical analyses now to be discussed.

MAJOR ELEMENT CHEMISTRY OF MAFIC META-IGNEOUS ROCKS

X-ray fluorescence (XRF) bulk-rock analyses of 17 hypabyssal and 38 extrusive mafic metavolcanics from the Sawyers Bar area are presented in Table 2. Analytical methods were described by CORTESOGNO *et al.* (1977). Locations of analyzed Sawyers Bar samples are indicated on Figure 2. Only samples which appeared fresh and generally free from veining were collected in the field. After petrographic examination, the least altered of these were chosen for bulk-rock and mineral analyses. CIPW normative minerals were computed for the rock analyses listed in Table 2, assuming a $Fe^{2+}/(Fe^{3+} + Fe^{2+})$ ratio of 0.80, as is reasonable for fresh basalts. Only one rock (sample no. 1M) contains normative nepheline—4 weight percent; two others, 288M and 372M, are critically undersaturated. The remaining 52 specimens are hypersthene normative.

Bulk XRF data indicate that the darker metavolcanics (Table 2a) in general are slightly more titaniferous than the lighter green units (Table 2b) with which they are regionally associated. The modal abundance of Ti-rich oxides + sphene, and slightly more voluminous hornblende evidently account for the more ferromagnesian aspect of the dark green units. However, the latter do not occur as stratigraphically distinct flows. Accordingly, they are not distinguished from the lighter-colored mafic metavolcanics in Figures 2–9. Most of the coarser grained, recystallized hypabyssal rocks appear to be slightly more silicic and alkalic and lower in iron + magnesium than the meta-extrusives (compare Table 2c with 2a,b). Bulk chemical variations are plotted for all the Yellow Dog meta-igneous rocks in Figures 3–8. Intrusive and extrusive protoliths are shown separately. As will now be discussed, fourteen of the analyzed rocks—eleven extrusives and three hypabyssals—possess compositional affinities with picritic or komatiitic basalts. Several others (*e.g.*, sample 81M) are transitional in chemical properties between those exhibiting ultramafic affinities and the more normal basaltic meta-igneous rocks. The highly magnesian character of the komatiitic(?) rocks was only recognized after XRF analyses, hence field collection and petrographic

Table 2a. Bulk-rock major element chemistry, mafic metavolcanics, Sawyers Bar area

Weight percent	1M	11M†	38M†	46M	67M†	89M†	91M†	92M†	153M	170M	174M†	201M	207M	Ave$_{13}$
SiO_2	43.75	46.40	49.70	51.90	52.00	46.80	45.20	48.80	51.40	51.80	50.15	49.35	48.35	48.89 ± 2.69
Al_2O_3	14.30	12.40	10.50	14.60	10.70	10.00	10.60	10.80	11.10	13.95	10.30	13.70	13.84	12.06 ± 1.76
MgO	10.30	14.10	14.30	10.70	14.10	12.25	14.00	15.00	9.60	9.40	16.10	9.20	7.40	12.03 ± 2.74
CaO	6.10	10.25	7.50	11.20	9.60	13.25	12.70	13.40	6.40	6.40	9.20	6.30	10.80	9.47 ± 2.73
Na_2O	3.40	1.70	2.00	2.30	1.35	0.91	0.91	1.20	3.50	2.00	1.50	2.90	1.12	1.91 ± 0.89
K_2O	1.45	0.52	0.90	0.32	1.02	0.34	0.70	0.10	0.36	0.71	0.58	0.16	1.50	0.67 ± 0.45
$Fe_2O_3^*$	15.90	11.70	12.30	8.30	10.00	13.50	12.30	9.00	14.70	13.10	11.20	14.60	13.30	12.30 ± 2.25
TiO_2	4.00	2.20	2.17	0.20	0.65	2.38	2.64	0.11	2.20	2.20	0.50	3.10	2.80	1.93 ± 1.20
MnO	0.22	0.17	0.19	0.17	0.18	0.15	0.18	0.18	0.17	0.15	0.18	0.18	0.17	0.18 ± 0.02
P_2O_5	0.28	0.32	0.28	0.09	0.14	0.29	0.43	0.01	0.15	0.30	0.15	0.38	0.32	0.24 ± 0.12
Total	99.90	99.97	99.99	99.85	99.91	100.02	99.89	99.71	99.63	99.96	99.98	99.96	99.70	
ppm														
Cr	60	485	425	75	981	403	549	644	97	136	642	113	176	368 ± 287
Cu	94	97	48	55	80	33	26	24	42	22	31	74	89	55 ± 28
Ni	43	374	299	83	219	310	359	131	42	66	153	46	68	169 ± 127
Rb	14	5	28	10	34	2	17	1	0	21	10	1	27	13 ± 12
Sr	508	635	326	450	261	421	954	202	100	360	216	379	440	404 ± 218
Zn	113	274	111	42	81	133	114	44	77	79	61	77	81	99 ± 59
Zr	148	217	254	0	73	242	271	0	116	206	87	245	208	159 ± 95

† Indicates komatiitic meta-igneous rock.
Analyst: G. Stummer, UCLA.

Table 2b. Bulk–rock major element chemistry, more felsic metavolcanics, Sawyers Bar area

Weight percent	5M	6M	9M†	80M	84M	85M	86M	103M	115M	117M	127M	146M
SiO_2	50.10	52.50	48.00	51.50	51.50	49.80	50.60	50.20	51.20	51.35	53.90	51.80
Al_2O_3	12.80	11.50	12.77	11.60	12.60	12.90	12.00	12.65	12.60	13.30	11.80	12.60
MgO	9.77	9.23	14.90	11.56	10.50	11.15	12.10	10.85	10.50	9.30	10.70	11.70
CaO	9.97	11.50	9.40	9.90	10.20	11.15	8.20	11.50	7.94	10.10	9.45	9.30
Na_2O	2.75	2.70	1.70	2.90	2.75	1.90	2.90	2.40	3.20	3.02	2.60	2.60
K_2O	0.69	0.15	1.06	0.30	0.21	1.00	0.42	0.11	0.34	0.08	0.14	0.15
$Fe_2O_3^*$	12.10	10.75	10.80	10.70	10.70	10.80	12.10	10.75	12.45	11.35	10.10	10.40
TiO_2	1.22	1.17	0.82	1.00	1.02	0.75	1.13	1.00	1.09	0.97	0.76	0.93
MnO	0.18	0.18	0.17	0.17	0.16	0.17	0.19	0.17	0.24	0.14	0.14	0.14
P_2O_5	0.10	0.09	0.09	0.08	0.09	0.08	0.10	0.11	0.08	0.07	0.07	0.07
Total	99.76	99.84	99.83	99.78	99.79	99.79	99.83	99.81	99.70	99.73	99.71	99.75
ppm												
Cr	224	169	506	212	209	367	318	231	138	129	230	245
Cu	70	79	68	121	86	115	113	56	55	45	83	35
Ni	100	133	269	105	97	181	173	67	55	41	84	99
Rb	13	2	20	7	6	28	15	5	13	3	4	2
Sr	265	169	109	139	85	101	66	274	135	90	76	183
Zn	91	79	197	76	70	72	93	38	110	54	46	40
Zr	73	60	68	59	86	69	93	83	70	74	59	80

Weight percent	161M	215M	237M	245M	249M	272M	288M	312M	320M†	354M†	372M
SiO_2	50.75	51.00	48.30	52.30	55.30	50.20	50.50	50.20	49.20	46.05	48.55
Al_2O_3	13.25	14.20	14.30	14.20	13.00	14.80	15.80	13.45	9.50	11.83	13.40
MgO	11.30	9.15	10.30	8.50	8.50	10.60	6.25	10.60	18.60	13.12	7.10
CaO	8.96	9.40	12.00	10.50	8.00	7.60	13.10	8.32	8.10	9.33	12.10
Na_2O	3.00	2.90	2.60	2.80	2.50	3.40	3.10	2.80	1.50	1.54	3.20
K_2O	0.23	0.35	0.11	0.59	2.10	0.15	0.60	0.30	0.62	0.42	0.20
$Fe_2O_3^*$	11.00	11.60	10.70	9.80	9.00	12.00	9.00	12.50	11.00	14.80	12.85
TiO_2	0.88	1.06	1.12	0.89	0.75	1.01	1.16	1.24	0.79	2.07	1.95
MnO	0.17	0.17	0.16	0.16	0.14	0.18	0.27	0.15	0.18	0.17	0.14
P_2O_5	0.08	0.08	0.10	0.07	0.24	0.07	0.21	0.11	0.16	0.36	0.25
Total	99.67	99.96	99.79	98.29	99.53	100.01	100.03	99.73	99.68	99.82	99.81
ppm											
Cr	178	118	270	185	240	300	53	117	1000	445	118
Cu	54	59	75	105	63	95	20	62	64	38	30
Ni	66	48	135	75	40	110	40	55	400	345	53
Rb	2	6	13	8	40	10	0	6	6	10	0
Sr	113	206	110	110	340	160	150	200	115	200	290
Zn	45	54	70	66	68	80	81	85	88	105	84
Zr	66	87	60	38	90	52	92	95	80	160	140

Weight percent	374M	375M†	Ave (25 analyses)
SiO_2	51.20	48.30	50.57 ± 1.93
Al_2O_3	14.00	9.00	12.79 ± 1.49
MgO	8.80	18.18	10.93 ± 2.88
CaO	9.30	10.00	9.82 ± 1.46
Na_2O	2.60	1.35	2.59 ± 0.56
K_2O	0.67	0.39	0.46 ± 0.44
$Fe_2O_3^*$	11.75	11.11	11.20 ± 1.24
TiO_2	1.08	0.75	1.06 ± 0.32
MnO	0.14	0.18	0.17 ± 0.03
P_2O_5	0.10	0.20	0.12 ± 0.07
Total	99.72	99.65	
ppm			
Cr	205	1000	288 ± 238
Cu	70	22	67 ± 28
Ni	72	500	134 ± 120
Rb	0	0	9 ± 9
Sr	190	150	161 ± 72
Zn	77	86	78 ± 31
Zr	114	105	82 ± 27

Table 2c. Bulk-rock major element chemistry, hypabyssal meta-igneous rocks, Sawyers Bar area

Weight percent	54M	57M	65M	69M	81M	124M†	212M†	220M	221M	222M	235M
SiO_2	54.40	52.50	54.00	56.20	49.10	52.30	48.80	51.80	58.70	55.90	49.55
Al_2O_3	13.35	14.50	13.25	14.25	12.30	11.00	10.90	16.95	15.90	13.80	15.30
MgO	8.50	11.50	9.40	7.30	12.15	14.00	16.40	7.30	5.00	7.20	9.50
CaO	8.10	8.95	9.40	6.70	9.60	8.75	8.50	9.00	5.30	5.80	10.20
Na_2O	1.75	2.00	2.12	2.70	2.90	2.00	1.60	2.80	3.20	3.50	2.90
K_2O	1.92	1.40	1.72	1.73	0.76	1.15	1.10	1.00	2.80	1.35	0.20
$Fe_2O_3^{\ddagger}$	10.30	8.25	8.60	9.57	11.40	9.60	11.10	9.60	7.65	10.90	10.90
TiO_2	1.10	0.53	0.85	1.02	1.22	0.68	0.85	0.82	0.65	0.86	1.07
MnO	0.18	0.14	0.17	0.17	0.18	0.15	0.17	0.19	0.13	0.16	0.16
P_2O_5	0.26	0.08	0.21	0.25	0.22	0.13	0.17	0.29	0.25	0.23	0.10
Total	99.96	99.95	99.81	99.98	99.97	99.87	99.73	99.86	99.69	99.78	99.88
ppm											
Cr	126	232	227	265	641	715	696	56	36	115	260
Cu	37	49	85	50	88	26	41	35	74	29	80
Ni	22	169	60	50	208	206	242	21	21	10	108
Rb	86	55	35	50	10	27	26	22	72	36	14
Sr	500	327	330	380	306	93	222	768	660	404	100
Zn	108	81	86	90	76	56	57	69	68	77	76
Zr	165	49	80	85	71	75	90	120	235	130	45

Weight percent	241M	285M	321M	329M	347M	351M†	Ave (17 analyses)
SiO_2	53.90	56.40	55.50	54.46	53.47	54.10	53.59 ± 2.71
Al_2O_3	15.90	15.40	15.25	13.90	14.35	11.20	13.97 ± 1.80
MgO	5.30	5.90	5.50	7.77	9.52	12.56	9.11 ± 3.27
CaO	6.20	8.30	7.55	8.35	8.32	9.88	8.17 ± 1.43
Na_2O	2.70	3.15	2.80	2.73	2.22	0.58	2.45 ± 0.72
K_2O	2.10	1.05	2.42	1.53	0.97	1.05	1.43 ± 0.64
$Fe_2O_3^{\ddagger}$	12.20	8.50	9.50	10.11	9.95	9.52	9.86 ± 1.20
TiO_2	1.03	0.85	0.87	0.78	0.76	0.78	0.87 ± 0.18
MnO	0.18	0.15	0.15	0.18	0.17	0.18	0.17 ± 0.02
P_2O_5	0.41	0.27	0.28	0.26	0.13	0.25	0.22 ± 0.08
Total	99.92	100.12	99.91	100.20	99.95	100.23	
ppm							
Cr	50	134	75	170	325	680	283 ± 236
Cu	70	570	55	70	65	50	87 ± 126
Ni	19	70	35	65	60	160	90 ± 77
Rb	40	40	35	27	16	28	36 ± 20
Sr	540	490	450	760	245	210	399 ± 204
Zn	105	75	90	90	85	82	81 ± 14
Zr	150	160	160	145	92	130	117 ± 50

selection for detailed chemical investigation, based on freshness of specimens, is not regarded as having introduced a sample bias. Collecting in the northeastern corner of the mapped area, DONATO (1985) also reported the presence of several dikes and sills characterized by high MgO contents.

Although alkali metasomatism may have affected these units during metamorphism, Figure 3 demonstrates that protoliths of analyzed metavolcanic rocks from the Sawyers Bar area belong chiefly to tholeiitic and high–alumina basalt suites. Of the 55 analyses, only one (non–komatiitic sample 1M) appears to be distinctly alkalic, as is also clear from the presence of four weight percent normative nepheline required by this bulk composition. The nearly complete absence of alkali basaltic protoliths is also supported by clinopyroxene analyses to be presented farther on. The specimens regarded as possibly komatiitic have low total alkalis and moderate silica contents. Clearly, Si–, Na–, K–metasomatism have not strongly modified the rock bulk compositions during metamorphism, except probably that of sample 1M.

An AFM diagram is illustrated in Figure 4. Analyzed Yellow Dog greenstones in general plot along the Skaergaard trend, but do not exhibit marked

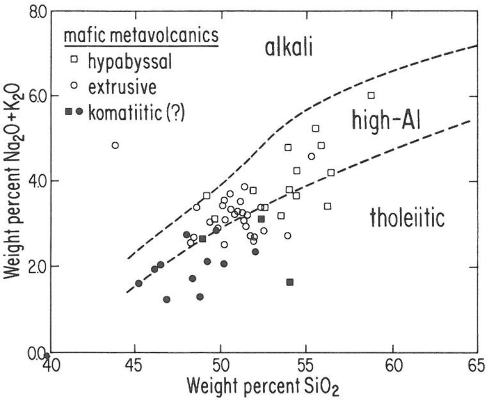

FIG. 3. Total alkalis versus silica variations for mafic meta-igneous bulk-rock analyses, Sawyers Bar area (data of Table 2). The tholeiitic, high-alumina and alkali basalt fields for unaltered volcanics are shown after KUNO (1960, 1966). As with Figures 4 and 8, field boundaries are valid only if oxides plotted have not been remobilized subsequent to igneous solidification.

iron enrichment. Most hypabyssal units are alkali enriched, and show chemical characteristics transitional between tholeiitic and calc-alkaline differentiation trends. In contrast, the komatiitic(?) basalts and a few hypabyssal rocks are impoverished in alkalis, and tend towards more magnesian compositions compared to the rest of the extrusive greenstones.

Komatiitic lavas are characterized by high CaO/Al_2O_3 weight percent ratios, as well as by elevated MgO contents. VILJOEN and VILJOEN (1969) defined komatiites as having CaO/Al_2O_3 ratios exceeding unit value, although others (*e.g.*, ARNDT and NISBET, 1982; XU and CHEN, 1984) have indicated that slightly lower ratios, 0.8 or even 0.7, may still qualify highly magnesian aphyric lavas as komatiitic. High MgO contents are diagnostic of ultramafic lavas. Hybrid picritic rocks (*i.e.*, the solidification products of mafic melts + cumulate olivine crystals) and boninites are also characterized by high magnesia, although the CaO/Al_2O_3 values for such crystal + liquid assemblages are much lower than unity. (However, as will be shown in Table 6, some island-arc picrites appear to be chemically rather similar to komatiites.) The ratio of CaO/Al_2O_3 is plotted against MgO in Figure 5 for the Yellow Dog metavolcanics. Clearly, the fourteen analyzed magnesian samples as a group have komatiitic(?) chemistries. The lack of pseudomorphs after olivine and the probable aphanitic nature of the precursor lavas (as indicated by a lack of textural relics) also suggest a komatiitic rather than a picritic protolith.

Elevated nickel and chromium contents typify olivine-, chrome diopside- and spinel-rich rocks. Liquids derived through high degrees of partial fusion of such solid precursor assemblages, therefore, tend to be enriched in these transition elements, whereas olivine-cumulate basalts should exhibit high Ni but more nearly normal Cr contents relative to MORB. (Of course, olivine + chrome-diopside cumulate hybrids, ankaramites, would also exhibit high Cr and Ni values, but ankaramites are typically alkalic and titaniferous.) The Yellow Dog magnesian metabasalts shown in Figure 6, a Ni–Cr plot, are compositionally distinct from—but transitional with—the associated mafic metavolcanics of more normal chemistry.

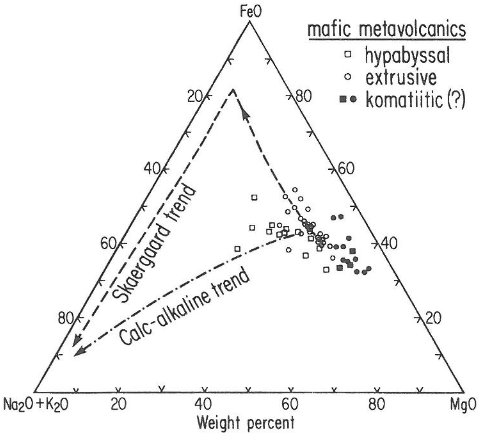

FIG. 4. AFM diagram for mafic meta-igneous bulk-rock analyses, Sawyers Bar area (data of Table 2). The Skaergaard and calc-alkaline trends of igneous differentiation are shown after WAGER and DEER (1939) and DALY (1933), respectively.

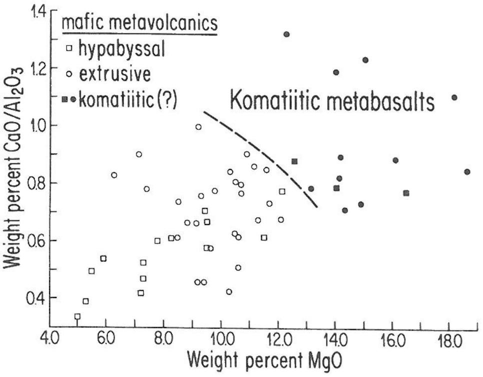

FIG. 5. Ratio of lime/alumina versus magnesia for mafic meta-igneous bulk-rock analyses, Sawyers Bar area (data of Table 2). The dashed line separating metamafics of komatiitic(?) affinities from more normal meta-igneous rocks is arbitrary.

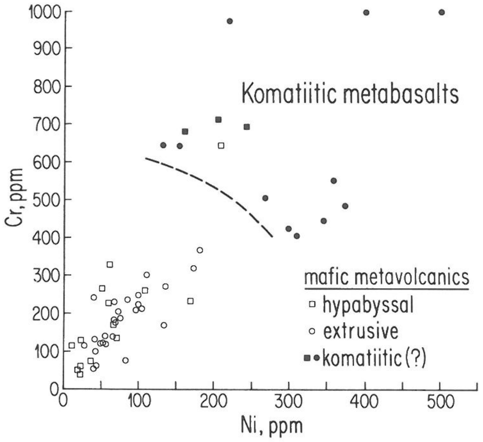

FIG. 6. Proportions of chromium versus nickel for mafic meta-igneous bulk-rock analyses, Sawyers Bar area (data of Table 2). The dashed line separating metamafics of komatiitic(?) affinities (+ hypabyssal sample 81M) from more normal meta-igneous rocks is arbitrary.

More evolved melts in general have higher titanium contents, and display notable iron enrichment. The Yellow Dog greenstone bulk-rock analyses are chemographically portrayed in Figure 7 in terms of weight percent TiO_2 versus mol fraction Fe (*i.e.*, Fe*/(Mg + Fe*), or X_{Fe}). The metamorphosed hypabyssal rocks show nearly constant TiO_2 contents, regardless of X_{Fe}. Among the metamorphosed extrusives, for any given X_{Fe}, rocks of presumed komatiitic affinity are slightly more titaniferous than the associated normal greenstones; in general, although a range in X_{Fe} exists, the former are less fractionated than the latter. If the analyzed non-alkalic komatiitic(?) lavas were cumulate (olivine + clinopyroxene)-enriched hybrids, the titania contents would be expected to be lower than parental basalts rather than higher, as is observed.

For metamorphosed rocks—and in particular, for mafic metavolcanics—metasomatism may alter the chemical proportions of the more mobile constituents. JENSEN (1976) pointed out that the most stable, inert components (*e.g.*, KORZHINSKII, 1959) should provide the best indication of original lithologies, and on this basis instituted a triangular diagram, the apices of which are the cations Mg, (Fe* + Ti), and Al. Jensen subdivided this ternary to provide separate fields for the well-recognized calc-alkaline, tholeiitic and komatiitic magma types. According to this diagram, presented as Figure 8, the Yellow Dog metavolcanics are komatiitic

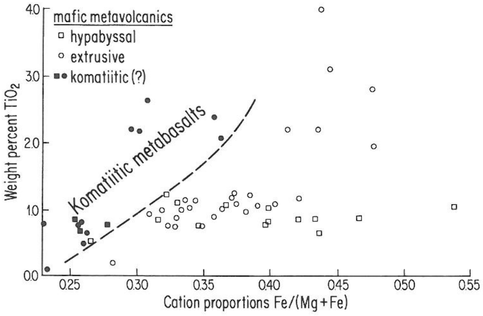

FIG. 7. Proportions of titania versus X_{Fe} for mafic meta-igneous bulk-rock analyses, Sawyers Bar area (data of Table 2). The dashed line separating metamafics of komatiitic(?) affinities + hypabyssal specimen 57M (and hypabyssal sample 81M situated on the line) from more normal meta-igneous rocks is arbitrary.

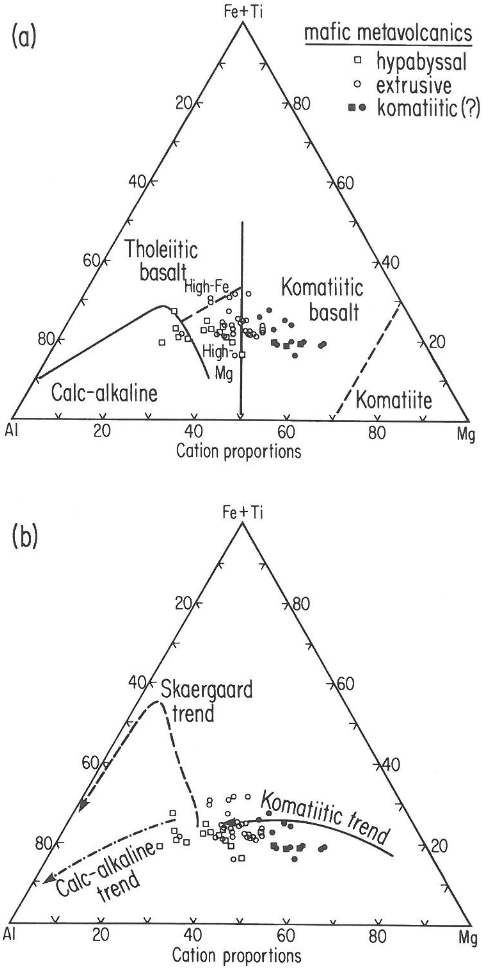

FIG. 8. Metal proportions of Mg, (Fe* + Ti) and Al for mafic meta-igneous bulk-rock analyses, Sawyers Bar area (data of Table 2). The fields for the various magma types (a), and crystal-fractionation trends (b) are illustrated after JENSEN (1976).

basalts and high–Mg tholeiites, with an important portion of the hypabyssals exhibiting chemical tendencies transitional towards calc–alkaline basalts. They appear to represent an intergradational, consanguineous suite. The relatively high proportion of komatiitic samples (14 of 55 analyzed specimens) supports the contention that these rocks are products of a widely operating process, and may represent true liquids rather than crystal + melt hybrids.

The low–alkali, low–silica nature of the Sawyers Bar mafic meta–igneous suite, as well as systematic magmatic chemical differentiation trends, leads to the suggestion that major element metasomatism played only a minor role during the subsequent metamorphism.

RARE EARTH ELEMENT CHEMISTRY OF MAFIC META–IGNEOUS ROCKS

Bulk–rock instrumental neutron activation analyses (INAA) of rare earth elements (REE) for twelve Yellow Dog metavolcanics are presented in Table 3, along with chondrite normalizing values. Analytical data were provided employing routine techniques (*e.g.*, Baedecker, 1976; Kallemeyn and Wasson, 1981). Rare earth patterns are plotted in Figure 9.

The six komatiitic(?) greenstones form a very well–defined group characterized by marked REE enrichments relative to chondrites, and high values of the LREE/HREE ratio (Figure 9a). In contrast, although two of the six Yellow Dog greenstones of more basaltic major element chemistry (sample numbers 207M and 32IM) exhibit patterns quite similar to the units of ultramafic affinity, the other four possess somewhat variable but unfractionated patterns, much less enriched in rare earths (Figure 9b). One of the latter (sample number 46M) possesses a distinct positive Eu anomaly, suggesting the possibility of cumulate plagioclase in this protolith.

Uniformity of the komatiitic(?) metavolcanic REE compositions (and two of six analyzed metabasaltic units) indicates the crustal introduction of a chemically homogeneous magma type. Elevated LREE concentrations and fractionated rare earth element patterns suggest the likelihood of derivation from a garnet-bearing mantle protolith, but argue against high degrees of partial fusion of the source rock. Strong REE enrichment relative to chondrites allows the conjecture that, at depths within the stable non-subducted lithosphere, the postulated garnet lherzolite source had been previously enriched in REE, especially LREE, possibly by mantle metasomatism associated with descent of the downgoing, devolatilizing slab (*e.g.*, Mysen, 1979). Alternatively, small amounts of strongly LREE–enriched, siliceous liquid produced by partial fusion of eclogitic material within the subducted plate (see Apted, 1981), when mixed with mantle–derived subsiliceous melt containing near-chondritic REE concentrations, might account for the observed major element and REE chemistry of the Yellow Dog komatiitic metavolcanics. Yet another possibility might involve reaction with crustal materials, but it is hard to imagine how the ultramafic affinities of the Yellow Dog metakomatiites could be retained during assimilation of sialic components. However, Late Archean magnesian metabasalts from western Australia have been shown to contain older zircon populations, and bulk–rock chemistries are strongly LREE enriched, indicating that contamination of felsic crust has played a role in the petrogenesis of some greenstone belts (Compston *et al.*, 1986; Arndt and Jenner, 1986).

The diverse REE patterns which characterize the more normal basaltic metavolcanics may be a consequence of: (1) two or more mafic magma types present in the terrane; (2) exchange with mantle wall rocks accompanying melt ascent and emplacement; (3) variable degrees of crustal contamination;

Table 3. Bulk–rock rare earth element chemistry, mafic metavolcanics, Sawyers Bar area

ppm	Normalizing values	11M*	46M	57M	89M*	117M	207M	212M*	215M	320M*	321M	351M*	375M*
La	0.315	25.9	0.3	3.9	25.7	3.7	28.0	11.0	3.5	10.2	20.0	15.5	14.8
Ce	0.813	55	2	11	56	14	60	25	10	23	41	32	35
Nd	0.597	27	<3	6	27	7	29	12	7	12	22	15	17
Sm	0.192	6.05	0.42	1.53	6.38	2.23	5.40	2.91	2.35	2.98	5.08	3.93	3.48
Eu	0.0722	2.01	0.43	0.60	2.77	0.90	1.78	0.95	0.90	0.93	1.38	1.13	1.04
Tb	0.049	0.8	0.1	0.2	1.0	0.5	0.9	0.6	0.5	0.3	0.6	0.7	0.4
Yb	0.209	1.78	0.60	1.27	1.31	2.63	1.95	1.75	2.55	1.60	2.10	1.85	1.37
Lu	0.0323	0.28	0.10	0.21	0.18	0.39	0.27	0.26	0.40	0.25	0.35	0.27	0.19

* Indicates komatiitic meta–igneous rock.
Analyst: X-ray Assay Laboratories, Ltd., Don Mills, Ontario.

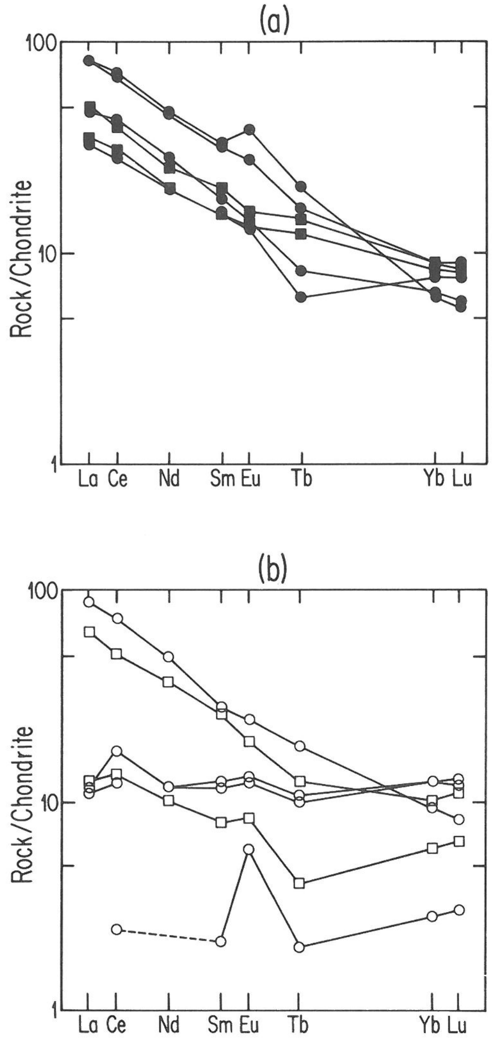

FIG. 9. Chondrite-normalized bulk-rock rare earth patterns for mafic meta-igneous rocks, Sawyers Bar area (data of Table 3): (a) rocks of komatiitic(?) affinity; (b) rocks of basaltic affinity. Symbols conform to usage of Figures 2–8.

and/or (4) metasomatic alteration during WTrPz regional dynamothermal metamorphism. Too few data are available to allow the erection of a compelling hypothesis.

RELICT CLINOPYROXENE COMPOSITIONS OF MAFIC META-IGNEOUS ROCKS

Subcalcic augites are present as relict, stumpy igneous phenocrysts in a few of the Yellow Dog hypabyssals and the more felsic greenstones (Table 1), but are totally lacking in the 14 analyzed rocks which display ultramafic characteristics. Evidently protoliths of the komatiitic extrusives were aphyric, judging by this negative textural evidence. For the porphyritic mafic meta-igneous rocks, clinopyroxenes enriched in Al, Cr, Na and Ti would be expected in rocks of ankaramitic—and other alkali basaltic—bulk compositions (*e.g.*, HUCKENHOLZ, 1965, 1966; HAWKINS and NATLAND, 1975; IMSLAND, 1984).

Electron microprobe analyses of Sawyers Bar mineral assemblages were obtained on a Cameca automated electron microprobe, employing analytical and data-reduction techniques described previously (ERNST, 1976). Core and rim values were obtained for two or three clinopyroxene in each of three non-komatiitic rocks; in all cases, compositional zoning was searched for but not detected. As shown in Table 4, averaged relict clinopyroxene compositions from three specimens, metavolcanic 215M, and hypabyssals 221M and 321M, exhibiting X_{Fe} values of 0.174, 0.297 and 0.303 respectively, appear to conform to a tholeiitic trend (CARMICHAEL, 1967; GARCIA, 1978). The subcalcic augites are uniformly low in aluminum, titanium, chromium and sodium. Rock sample no. 321M, although not highly magnesian, does exhibit strong LREE enrichment, like the analyzed komatiitic(?)

Table 4. Major element mineral chemistry of relict clinopyroxenes from mafic metavolcanics, Sawyers Bar area

Weight percent	215M	221M	321M
SiO_2	52.54	51.34	51.52
Al_2O_3	2.23	2.30	2.07
Cr_2O_3	0.09	0.01	0.04
TiO_2	0.38	0.50	0.62
FeO	6.58	10.53	11.36
MgO	17.57	13.96	14.67
MnO	0.18	0.31	0.34
CaO	19.45	20.11	19.17
Na_2O	0.17	0.39	0.27
K_2O	0.00	0.00	0.01
Total	99.20	99.44	100.05
cations/ 6 oxygens			
Si	1.939	1.934	1.931
Al^{IV}	0.061	0.066	0.069
Al^{VI}	0.036	0.036	0.022
Cr	0.003	0.000	0.001
Ti	0.011	0.014	0.017
Fe^{2+}	0.203	0.332	0.356
Mg	0.967	0.783	0.819
Mn	0.006	0.010	0.011
Ca	0.769	0.812	0.770
Na	0.012	0.029	0.019
K	0.000	0.000	0.000
Total	4.006	4.015	4.016

Analyst: W. G. Ernst, UCLA.

metavolcanics. These data reinforce the conclusion that the Yellow Dog metavolcanics are not of alkaline affinities, and therefore do not represent alkali basaltic or ankaramitic lavas. Except for somewhat lower Al contents, the analyzed Sawyers Bar relict clinopyroxene phenocrysts are virtually indistinguishable from subcalcic augites of Archean komatiitic flows from northeastern Ontario (ARNDT *et al.*, 1977).

OXYGEN ISOTOPE CHEMISTRY OF MAFIC META-IGNEOUS ROCKS

Bulk-rock mass spectrometric analyses of ^{16}O and ^{18}O were obtained for six Yellow Dog metavolcanic specimens, employing routine techniques. Data are presented in Table 5.

The investigated samples, four metakomatiitic and two of more normal chemistry, are all ^{18}O-enriched ($\delta^{18}O = 9.6$–15.3) relative to Phanerozoic MORBs as well as Archean komatiites ($\delta^{18}O = 6$; TAYLOR, 1968; LONGSTAFFE *et al.*, 1977; HOEFS and BINNS, 1978; BEATY and TAYLOR, 1982). Limited isotopic analyses of the Sawyers Bar greenstones prevent the demonstration of detailed relationships, but several observations, nevertheless, can be made: (1) All analyzed rocks have exchanged isotopically with large quantities of oxygen-bearing fluid under low-grade metamorphic conditions. Employing the method of ELTHON *et al.* (1984), which involves weighting fractionation factors for the silicates present and assumes equilibrium between aqueous fluid and the condensed assemblage, it appears that isotopic exchange took place with magmatic water (or seawater) at low temperatures, on the order of 100°C; nominal water/rock ratios indicated for this isotherm range from 0.4 (or 1.0) to 3 (or 20). (2) There is no systematic isotopic contrast between rocks of mafic versus ultramafic affinity, or between extrusives (sample numbers 11M, 89M, 215M, 375M) versus hypabyssals (sample nos. 321M, 351M). (3) An inverse correlation between chromium–, nickel– or magnesium–contents on the one hand, and $\delta^{18}O$ enhancement on the other is not evident, nor are the rare earth element–, SiO_2–, Na_2O– or K_2O–contents, or modes of minerals such as alkali feldspars and/or micas proportional to $\delta^{18}O$—as might be expected if metasomatism had modified bulk-rock concentrations in these units.

Therefore, although the Yellow Dog metavolcanics have been subjected to the throughput of large volumes of an oxygen-bearing fluid during recrystallization, and have at least partially re-equilibrated isotopically, the major element and REE chemistries of these greenstones are not principally metasomatic in origin.

Table 5. Bulk-rock oxygen isotope chemistry, mafic metavolcanics, Sawyers Bar area

Sample no.	$\delta^{18}O$
11M*	9.6†
89M*	13.2†
215M	10.0
321M	11.4
351M*	15.3†
375M*	11.1

* Indicates komatiitic meta-igneous rock.

† Indicates duplicate analyses on separate portions of sample analyst: Geochron Laboratories, Cambridge, Massachusetts.

PETROCHEMICAL DISCUSSION

Bulk-rock major element chemical data have been presented which demonstrate that, among the investigated mafic metavolcanic rocks of the Sawyers Bar area, fourteen are strongly magnesian, possess high CaO/Al_2O_3 ratios, and elevated concentrations of Cr and Ni; they are not notably titaniferous or iron-enriched, and are neither alkalic nor, apparently, the result of olivine ± clinopyroxene accumulation. Employing a variety of major element discrimination diagrams, these fourteen greenstones (three of which are hypabyssal) appear to represent recrystallized komatiitic(?) basalts. Unlike Archean komatiitic basalts, they are neither associated with true komatiites, nor display spinifex texture. The remaining 27 analyzed meta-extrusives are chiefly magnesian metabasalts, although a few display modest iron-enrichment. With several exceptions, the associated coarser grained dikes and sills are more evolved and are enriched in Na_2O, K_2O and SiO_2; most possess bulk chemistries gradational to calc-alkaline basalt/andesite. Some of the meta-extrusives and metahypabyssals exhibit compositions transitional between the more normal recrystallized mafic igneous rocks and the picritic/komatiitic types.

Approximately a quarter of the analyzed Yellow Dog metavolcanics are highly magnesian [MgO (average of 14 analyses) = 14.83 ± 1.90 weight percent] in their bulk-rock chemistries. Nevertheless, lacking diagnostic textural criteria, ambiguities exist in the distinction of former komatiitic liquids from hybrid basaltic melts containing cumulate olivine ± clinopyroxene (picrites ± ankaramites), as discussed by many authors (*e.g.*, ARNDT *et al.*, 1977; ARNDT and NISBET, 1982; NESBITT *et al.*, 1982).

The Sawyers Bar mafic meta–igneous rocks of komatiitic affinities contrast markedly with average calc–alkaline island–arc volcanic rocks (*e.g.*, Ewart, 1976; Taylor, 1977) which are much higher in silica, alumina and alkalis, and substantially lower in magnesia and lime. Oceanic and abyssal tholeiites from the North Atlantic (*e.g.*, Jakobsson, 1972; Wood, 1976; Sigurdsson *et al.*, 1978; Irvine, 1979) and plateau basalts from peninsular India (*e.g.*, Ghose, 1976) all possess low CaO/Al_2O_3 ratios, low MgO, and generally high TiO_2 contents compared with the Sawyers Bar komatiitic(?) greenstones.

The latter are compared in Table 6 with modern boninites and a Cenozoic picrite from the South Pacific, a mean of picrites from the circum–Atlantic, Phanerozoic ankaramites from southernmost British Columbia and from the Atlantic realm, and Archean komatiites from Ontario and South Africa. All rock types listed are characterized by high concentrations of Cr and Ni. The average for fourteen Yellow Dog komatiitic(?) greenstones most closely corresponds to the Ontario olivine–rich pyroxenitic komatiite, except that the TiO_2 and K_2O contents of the Sawyers Bar lithology are slightly higher. The Barberton komatiite is a good match too, although it is somewhat more siliceous. The southwest Pacific picritic basalt, surprisingly, has a CaO/Al_2O_3 ratio of unity, and a very high MgO content. Perhaps two different kinds of rock have been termed "picrite" in the literature, olivine–cumulate occurrences, such as have been described from the British Isles, and more nearly primitive Pacific arc lavas. Lavas of the former do not represent true melts, but the latter possibly might, and appear to be chemically indistinguishable from komatiitic basalts. It is to this second category that the Sawyers Bar metavolcanics evidently belong. Boninites (Crawford *et al.*, 1981; Hawkins *et al.*, 1984) are too rich in SiO_2 and impoverished in CaO (also probably they are too poor in TiO_2, MgO and Fe_2O_3*) to compare satisfactorily with the Yellow Dog ultramafic rocks. Ankaramites possess bulk chemistries rather similar to picrites and komatiites, but most are markedly enriched in alkalis and iron plus titania relative to the Sawyers Bar and Archean metakomatiites (Sorenson, 1974; Imsland, 1984); so, too, are nephelinites and basanites (Hawkins and Natland, 1975). Thus, komatiitic and (non-cumulate?) picritic basalt seems to best describe the

Table 6. Bulk–rock major element chemistry, mafic–igneous rocks of ultramafic affinities

Weight percent	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
SiO_2	48.99 ± 2.54	57.1 ± 1.7	48.08 ± 1.35	40.93 ± 2.65	44.99	42.18 ± 2.53	48.30	52.92
Al_2O_3	10.82 ± 1.03	9.8 ± 1.6	12.24 ± 1.58	9.94 ± 2.11	6.54	8.27 ± 3.20	10.80	8.14
MgO	14.83 ± 1.90	12.5 ± 2.6	12.45 ± 1.13	15.05 ± 3.05	28.10	23.29 ± 4.96	13.90	11.81
CaO	9.99 ± 1.86	5.41 ± 1.64	9.36 ± 1.68	12.87 ± 1.28	6.56	5.99 ± 2.28	10.00	11.53
Na_2O	1.42 ± 0.41	1.70 ± 0.75	1.97 ± 0.24	2.43 ± 0.93	0.92	1.56 ± 0.89	2.24	2.29
K_2O	0.71 ± 0.34	0.60 ± 0.29	1.66 ± 0.53	0.86 ± 0.49	0.57	0.53 ± 0.35	0.00	0.04
$Fe_2O_3^*$	11.28 ± 1.59	9.0 ± 1.0	14.62 ± 3.65	13.53 ± 0.40	10.77	14.42 ± 1.43	10.61	12.00
TiO_2	1.24 ± 0.84	0.20 ± 0.08	0.81 ± 0.07	3.29 ± 0.59	0.33	1.19 ± 0.54	0.62	0.50
MnO	0.17 ± 0.01	0.17 ± 0.02	0.19 ± 0.01	0.16 ± 0.06	0.19	0.22 ± 0.06	0.18	0.19
P_2O_5	0.21 ± 0.11	0.03 ± 0.01	0.35 ± 0.15	0.65 ± 0.41	0.08	0.20 ± 0.11	—	0.67
ppm								
Cr	655 ± 210	1061 ± 641	664 ± 106	—	1152	—	1460	904
Cu	46 ± 23	—	118 ± 47	—	—	—	—	—
Ni	283 ± 106	231 ± 134	212 ± 67	—	590	—	647	138
Rb	14 ± 12	—	39 ± 12	—	—	—	1	1
Sr	294 ± 237	99 ± 36	542 ± 79	—	—	—	41	33
Zn	106 ± 62	—	97 ± 15	—	—	—	—	—
Zr	132 ± 83	39 ± 26	62 ± 11	—	—	—	—	44

(1) Sawyers Bar area, average of 14 samples: 9M, 11M, 38M, 67M, 89M, 91M, 92M, 124M, 174M, 212M, 320M, 351M, 354M and 375M (Table 2).

(2) Average of four representative aphyric modern boninites from Papua New Guinea, Mariana Trench, Bonin Islands and New Caledonia (Crawford and Cameron, 1985, Table 3).

(3) Average of four ankaramites, Ominica Crystalline Belt, southern British Columbia (Beddoe-Stephens, 1982, Table 1).

(4) Average of four ankaramites, Atlantic Ocean Islands (Borley, 1974, Table 3A, B).

(5) Picritic basalt no. NG 143/2, from Solomon Islands (Stanton and Bell, 1969).

(6) Average of nine picritic lavas and sills, mostly from the British Isles (Drever and Johnston, 1967, Table 3.1).

(7) Olivine-rich pyroxenitic komatiite lava no. P9-132, northeastern Ontario (Arndt *et al.*, 1977).

(8) Komatiitic basalt no. 331/780 from Barberton, South Africa (Nesbitt, *et al.*, 1979).

protolith for the now-metamorphosed Yellow Dog mafic igneous series. The average Al_2O_3/TiO_2 value for 14 Sawyers Bar metakomatiites(?), 8.7, likewise, compares favorably with Barberton analogues (SUN and NESBITT, 1978). The clinopyroxene analyses presented in Table 4 are also in accord with this comparison.

It is of interest to note that analyses of a picritic flow and a dike in the Lower Devonian Copley Greenstone from the Redding section of the Eastern Klamath plate (Figure 1), presented by LAPIERRE *et al.* (1985), have somewhat lower CaO/Al_2O_3 ratios than the Yellow Dog metavolcanics; the Copley picrites also possess much higher Al_2O_3/TiO_2 ratios, 23 ± 5. As described by LAPIERRE *et al.*, these metamorphosed, immature arc volcanics evidently represent low–K tholeiitic melts enriched by cumulate olivine, and are not chemically analogous to the Sawyers Bar greenstones.

The marked LREE enrichment of Yellow Dog metavolcanics of ultramafic affinities does not compare favorably with typical Archean komatiites (*e.g.*, see Basaltic Volcanism Study Project, 1981, pages 21–23; ARNDT and NESBITT, 1982; ARNDT, 1986) or with Phanerozoic ridge basalts such as the Oman Ophiolite (PALLISTER and KNIGHT, 1981) inasmuch as both komatiites and MORBs are characterized by flat or LREE–depleted patterns.* The REE enrichments and high LREE/HREE ratios of the Sawyers Bar magnesian greenstones also exceed those of modern back–arc basin basalts (HAWKINS and MELCHIOR, 1985). Yellow Dog REE patterns are rather comparable, however, to some mid–plate alkali basalts (CHEN and FREY, 1985) and the more potassic rifted oceanic ankaramites (MAALOE *et al.*, 1986) and island–arc lavas (GILL, 1981; POLI *et al.*, 1984); none of these series appears to be closely related genetically to the Yellow Dog greenstones, however. Perhaps, as stated previously, partial fusion of previously REE–enriched garnitiferous protolith (lherzolite ± eclogite) was responsible for the generation of the Sawyers Bar komatiitic(?) suite.

TECTONIC SPECULATIONS

In what sort of geologic environment was this mafic to komatiitic complex formed? SNOKE *et al.* (1982) suggested that petrogenesis of such volcanics and related peridotitic to dioritic plutonic suites in the western Klamaths and western Sierra Nevada was related to repeated fracturing and magmatism in a rifted oceanic arc. Absence of an alkali basalt suite, however, seems to preclude a rifted plate tectonic setting. The occurrence of distal clastic metasediments, apparently lying conformably beneath the greenstone pile, argues for a convergent plate tectonic environment, and against a mid-oceanic ridge origin for the mafic–komatiitic protolith. Transitions of the slower cooled, more chemically fractionated hypabyssals towards calc–alkaline compositions suggest that the Sawyers Bar greenstones were produced during the early stages of construction of a continental margin or an island arc, with the dikes and sills reflecting low–pressure crystal fractionation attending later injection into the volcanic pile. This origin is rather similar to that proposed for many boninites (KUSHIRO, 1972; HAWKINS *et al.*, 1984).

Major element bulk-rock chemistry is compatible with the idea that the Yellow Dog suite is komatiitic in its affinities. However, this hypothesis is at variance with the REE bulk-rock chemistry unless the preexisting mantle source had been a rare earth–enriched garnet lherzolite, or a mixture of peridotite and eclogite, and was subjected to only low degrees of partial melting. How REE enrichment of the mantle lithosphere beneath the arc took place is unclear, but could have been a manifestation of metasomatism involving aqueous fluids or eclogitic partial melting and invasion during Permo–Triassic underflow of the paleopacific plate.

The high degrees of partial fusion required to produce komatiitic melts at moderate mantle depths involve unusually high temperatures (GREEN, 1975, 1981). TAKAHASHI (1986) and HERZBERG *et al.* (1986) have recently demonstrated, however, that only very small degrees of partial melting would be necessary to generate picritic, komatiitic and lherzolitic liquids from mantle peridotite at pressures approaching 60 kbar—thus somewhat easing the problem of obtaining LREE–enriched komatiitic chemistries. In any case, such pressure-temperature conditions are not characteristic of shallow portions of divergent or transform plate boundaries, but could have attended the generation of magmas at profound depths (*e.g.*, 180–210 km) beneath an evolving continental margin or island arc.

The subduction of a spreading center (*e.g.*, UYEDA and MIYASHIRO, 1974) or hot spot is one way in which a high heat–flow regime could have been emplaced beneath the WTrPz during its constructional stage. Ridge or hot–spot destruction would represent an uncommon but episodic phenomenon in the history of the circum–Pacific, thus

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* An unusual LREE–enriched Archean komatiite from Ontario has recently been reported by STONE (1986), but this flow is iron rich and HREE poor compared to the Sawyers Bar ultramafic greenstones. Some hangingwall basalts from Kambalda, western Australia similarly display LREE–enriched patterns, but these relationships are ascribed to melt contamination by assimilation (CHAUVEL *et al.*, 1985).

explaining the relative rarity of mafic–komatiitic lithologies in the Phanerozoic rock record (for another example, see ECHEVERRIA, 1982). The source of Yellow Dog volcanism thus appears to have been within a convergent plate setting, with low degrees of partial melting of REE-enriched garnetiferous mantle (± eclogite) taking place at depths near 200 km, followed by emplacement into a primitive island arc or continental margin.

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