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Petrofacies and Provenance of Late Mesozoic Forearc Basin, Northern and Central California[1]

RAYMOND V. INGERSOLL[2]

ABSTRACT

Data from the Great Valley Group (sequence) represent the most complete information regarding sandstone petrology of sediment derived from a magmatic arc. This information is useful in documenting tectonic and magmatic events within the arc and related terranes, and forms the basis for the establishment of petrostratigraphic units for mapping and correlation. Sandstone and conglomerate compositions are controlled by changes in provenance, many of which were basinwide and synchronous. Clay-mineral composition is controlled primarily by burial metamorphism. Careful attention to sample collection, sample preparation, and petrographic techniques is essential for uniform results. Seven petrographic parameters (P/F, Lv/L, M, Qp/Q, Q, F, and L—listed in decreasing importance to petrofacies discrimination) define eight petrofacies (Stony Creek, Platina, Lodoga, Grabast, Boxer, Cortina, Los Gatos and Rumsey—listed in approximate order of decreasing age).

The Upper Jurassic–Lower Cretaceous petrofacies (Stony Creek, Platina, and Lodoga) contain higher lithic contents (supracrustal sources), whereas the Upper Cretaceous petrofacies (especially the Rumsey) contain higher proportions of plutoniclastic components (quartz, feldspar, and micas). The proportion of potassium-feldspar increases from near zero in the Upper Jurassic to nearly 50% of all feldspars in the uppermost Cretaceous.

The lower part of the Great Valley Group (Upper Jurassic and Lower Cretaceous) contains significant quantities of sedimentaclastic and metamorphiclastic material eroded from accreted and deformed terranes ("tectonic highlands") formed by the arc-arc collision (Nevadan orogeny) that occurred prior to initiation of the Franciscan–Great Valley–Sierra Nevada arc-trench system. The Klamath Mountains area provided a major proportion of this detritus. Ophiolite and serpentinite detritus was deposited locally near the base of the Great Valley Group as a result of deformation along the east side of the growing Franciscan subduction complex. Volcaniclastic detritus was fed into the entire forearc basin as magmatism increased in the Sierra Nevada area during the Cretaceous. As the volcanic cover was stripped off, plutoniclastic and metamorphiclastic detritus from the underlying batholithic terranes was provided in abundance to the forearc basin. Crustal components were more "continental" in the southern Sierra Nevada and more "oceanic" in the northern Sierra Nevada, as demonstrated by the higher proportions of metamorphiclastic detritus and by the more felsic nature of volcaniclastic detritus to the south. By the middle of the Late Cretaceous, extensive batholithic terranes provided potassium-feldspar-rich arkosic detritus to the entire forearc basin. By the Paleogene, arc magmatism had migrated eastward sufficiently that deeper levels of the California part of the arc were exposed by erosion, tectonic activity decreased in the forearc basin, and the basin was filled to sea level in most parts.

INTRODUCTION

The late Mesozoic and Paleogene history of the forearc basin of northern and central California (Fig. 1) has been reconstructed using stratigraphic, structural, petrologic, sedimentologic, and tectonic data in combination with actualistic models for arc-trench systems (e.g., Ingersoll, 1978a, 1979a, 1982; Dickinson and Seely, 1979; Ingersoll and Dickinson, 1981). Subduction-accretion, arc magmatism and forearc sedimentation initiated in the Late Jurassic (Tithonian, Fig. 2), following arc-arc collision (Schweickert and Cowan, 1975). During the latest Jurassic and all of the Cretaceous, the Great Valley was the site of a deep forearc basin, within which the Great Valley Group accumulated (Great Valley sequence of Bailey et al, 1964; Ingersoll and Dickinson, 1981; Ingersoll, 1982). By the Paleogene, the forearc basin had filled to near sea level throughout most of the Great Valley area (Dickinson et al, 1979b) and subduction had been terminated sequentially by the northward movement of the Mendocino triple junction during the Neogene (Atwater, 1970). The upper Mesozoic strata filling the forearc basin record the history of the magmatic arc (Dickinson and Rich, 1972; Ingersoll, 1978b; Mansfield, 1979), as well as the history of erosion of the crust on top of which and within which the arc formed. Sandstone petrology, in combination with conglomerate petrology and clay mineralogy, provides the primary method of determining the provenance of the Great Valley Group, and hence the history of the magmatic arc and related features.

This paper is the product of years of work on the petrology of the Great Valley Group. This is the first study that has involved the application of uniform methods by a sin-

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[2] Department of Geology, University of New Mexico, Albuquerque, New Mexico 87131; present address, Department of Earth and Space Sciences, University of California, Los Angeles, California 90024.

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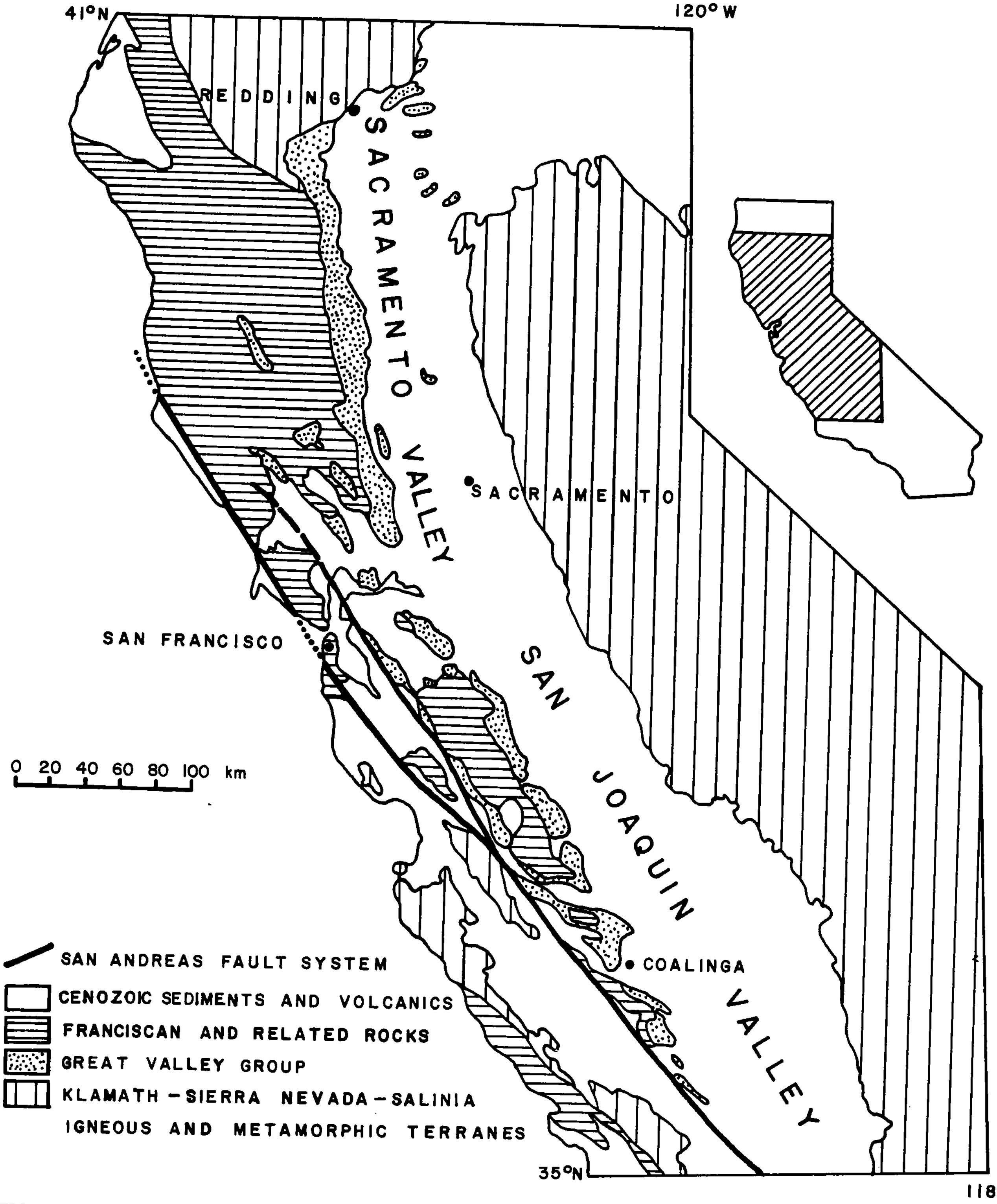

FIG. 1—Location map of northern and central California, showing principal components of late Mesozoic arc-trench system and geographic locations. Great Valley includes both Sacramento and San Joaquin Valleys. Sierra Nevada igneous and metamorphic terranes represent roots of magmatic arc, and Franciscan Complex represents highly deformed subduction complex formed landward of trench. Great Valley Group is primarily Upper Cretaceous in San Joaquin Valley and is Upper Jurassic through Upper Cretaceous in Sacramento Valley. Exposures of Lower Cretaceous and Upper Jurassic along west side of San Joaquin Valley are not discussed in this paper (see Mansfield, 1979). Small outcrops of uppermost Cretaceous that nonconformably overlie Sierra Nevada basement along east side of Sacramento Valley are too small to show at this scale. Great Valley Group lies nonconformably on Klamath basement near Redding. Coast Range ophiolite underlies Great Valley Group at other surface locations along west side of Great Valley (after Ingersoll, 1978a)

gle operator to rocks encompassing the entire age span (Tithonian through Maestrichtian) and the entire length of the Great Valley (Sacramento and San Joaquin Valleys). It is both a refinement of previous work, especially that of Dickinson and Rich (1972), Ingersoll (1978b), and Mansfield (1979), and a contribution of new data and insights from areas not previously studied in detail. The petrologic data represent the most complete information available on sandstone petrology from any forearc basin. In addition, the present study demonstrates the usefulness of the petrofacies concept both for provenance-tectonic reconstructions and for stratigraphic-correlation studies.

PREVIOUS WORK

Vertical stratigraphic variations in sandstone composition within the Great Valley Group have formed the basis for stratigraphic mapping, provenance inferences, and paleotectonic reconstructions for several years (e.g., Schilling, 1962; Ojakangas, 1968; Gilbert and Dickinson, 1970; Swe and Dickinson, 1970; Rich, 1971; Dickinson and Rich, 1972; Perkins, 1974; Ingersoll, 1978a, b, 1979b; Mansfield, 1979). Stratigraphically extensive petrofacies based on inferred original sandstone composition may be used to define petrologic intervals equivalent to formations (Dickinson and Rich, 1972). "Petrofacies" is used here in the more restricted sense expressed first by Mansfield (1971), based on detailed sandstone composition, rather than in the broader sense of Weller (1958), which is synonymous with "lithofacies," as most commonly used today. In my usage, petrofacies is one type of lithofacies, and petrostratigraphy is one type of lithostratigraphy.

In general, sandstone composition is controlled by the following factors: provenance, transportation, depositional environment, and diagenesis (Suttner, 1974). However, sandstone composition of the Great Valley Group is controlled primarily by provenance, as demonstrated by the immaturity of the detritus (both compositionally and texturally), the close linkage between source areas and basin, the lack of correlation between composition and depositional environment, and the lack of destruction by diagenesis of the key components (Ingersoll, 1978b). Thus, in the Great Valley Group, transportation and depositional environment appear to have been unimportant in determining sandstone composition. The effects of diagenesis may be removed mentally by careful petrographic work based on an understanding of the types of alterations (Dickinson et al, 1969; Ingersoll, 1978b).

good is [illegible] while [illegible]?

Studies of conglomerate petrology (e.g., Perkins, 1974; Bertucci, 1980; Seiders, 1983) contribute additional data, and broadly confirm petrofacies and provenance interpretations based on sandstones. Such studies are especially useful for correlating petrographic parameters to source rock types. However, conglomerates are not ubiquitous within the Great Valley Group, and they are much more time-consuming to study in detail than are related sandstones (Dickinson and Rich, 1972).

Studies of clay mineralogy within the Great Valley Group (e.g., Ojakangas, 1968; Clark and Bond, 1978) indicate that burial depth and depositional facies control clay-mineral types; therefore, clays are not useful as provenance-determined petrofacies indicators. However, the roughly equal amounts of illite, chlorite, and montmorillonite are consistent with mid-latitude deposition and volcanic provenance (Clark and Bond, 1978).

is it mid-lat in K?

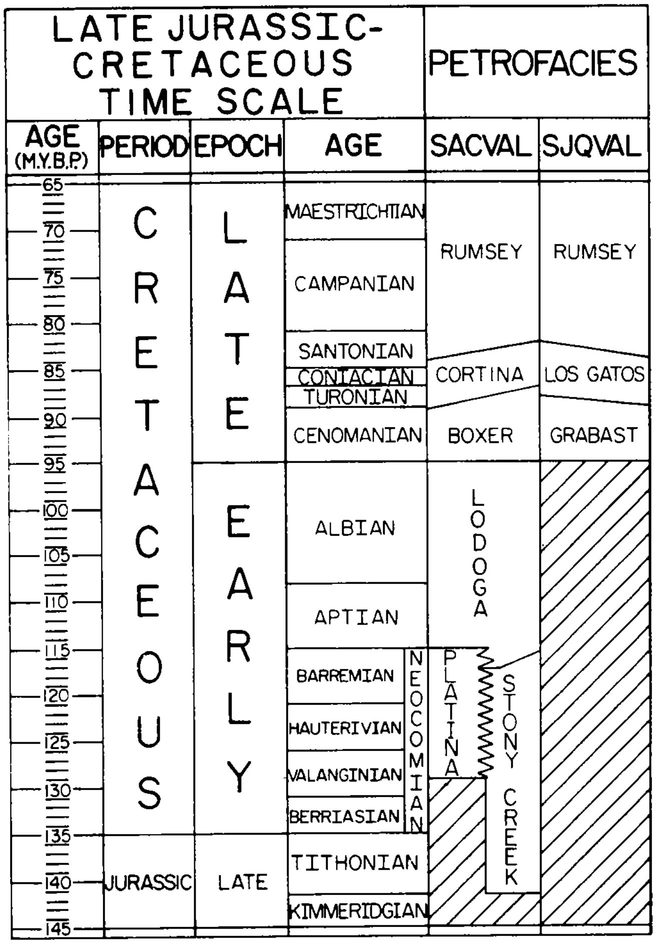

FIG. 2—Radiometric time scale used in present study, and stratigraphic relations of eight petrofacies. Diagonal lines denote general absence or paucity of strata. After Ingersoll (1979a); van Hinte (1976a, b).

Techniques of detailed petrographic work on graywackes and arkoses (terms used in the broadest sense) were outlined first by Dickinson (1970). Subsequently, several studies have expanded on this work, and modified nomenclature and procedures (e.g., Graham et al, 1976; Stewart, 1976, 1977, 1978; Ingersoll, 1978b; Dickinson and Suczek, 1979; Dickinson et al, 1979a; Ingersoll and Suczek, 1979; Mansfield, 1979; Moore, 1979). These studies involve sand and sandstone from a wide variety of tectonic settings, but all of the studied areas have in common rapid deposition in tectonically active basins, resulting in thick accumulations of compositionally and texturally immature sandstones.

SAMPLING

The Upper Cretaceous part of the Great Valley Group was sampled extensively and studied petrographically by Ingersoll (1976, 1978b). Sample locations can be found in

Table 1. Data Used in Present Study

Sample Number	QFL%					FRMW%						QpLvmLsm%			LmLvLs%		
	Q	Qm	F	L	Lt	M	P/F	Lv/L	Qp/Q	MYBP	D	Qp	Lvm	Lsm	Lm	Lv	Ls
RUMSEY																	
75-37	36	35	42	22	23	6	41	56	3	84	360	4	54	42	38	56	6
75-38	45	42	32	23	26	11	48	60	6	82	360	11	53	36	33	60	7
75-41	35	34	43	22	23	11	46	79	1	74	365	2	77	21	19	79	2
75-60	45	44	43	13	13	20	52	84	1	74	515	2	82	16	14	84	2
75-65	47	46	36	17	19	8	49	78	3	73	495	6	73	20	18	78	4
75-103	39	38	42	19	20	11	52	79	3	82	180	6	74	19	13	79	8
75-104	41	41	42	18	18	19	73	87	0	82	180	0	87	13	8	87	5
75-112	33	31	23	44	46	10	70	55	7	76	105	5	53	43	35	55	10
75-114	37	35	26	37	39	4	59	42	7	76	105	6	39	55	48	42	10
75-116	37	34	19	44	47	7	71	38	9	80	110	7	36	57	54	38	7
75-119	39	37	23	38	40	17	67	51	6	77	125	6	48	46	40	51	9
75-120	39	38	20	41	43	12	58	45	4	77	125	4	43	53	48	45	8
75-121	32	31	18	50	51	15	52	32	4	77	125	2	32	66	61	32	7
75-125	43	41	36	21	22	12	64	48	3	77	130	5	46	49	41	48	11
75-129	35	34	21	44	45	21	93	47	3	75	240	3	45	52	44	47	9
75-131	30	29	26	44	46	4	50	45	5	74	325	4	44	53	35	45	20
75-132	33	33	40	27	27	22	52	61	0	74	325	0	61	39	24	61	16
75-157	42	42	40	18	18	6	62	79	1	72	485	3	77	20	15	79	5
75-163	44	43	40	16	17	10	56	78	2	76	555	5	74	21	13	78	10
75-177	43	42	47	10	11	13	46	57	2	73	415	8	53	40	35	57	8
75-179	46	45	37	17	18	8	41	40	2	70	415	5	38	58	44	40	16
75-181	38	38	42	20	20	13	43	53	0	77	425	0	53	47	36	53	11
75-185	39	39	38	23	23	6	45	67	1	71	430	2	66	32	29	67	4
75-187	40	39	45	16	16	12	51	60	1	73	445	3	58	38	28	60	12
75-188	39	38	36	25	25	7	47	61	1	73	445	2	60	38	29	61	10
784-27	48	47	43	10	11	8	52	56	2	82	290	9	51	40	34	56	10
784-29	41	40	51	8	9	7	59	49	2	82	280	10	44	46	40	49	11
MC-10	34	32	49	17	19	11	51	69	5	84	290	9	63	28	22	69	9
DPC-6	37	37	43	19	20	7	42	59	1	75	360	1	58	41	29	59	13
DPC-7	46	44	33	21	22	6	41	72	4	76	360	7	67	26	8	72	20
DPC-9	48	44	30	22	26	3	59	58	8	80	360	15	50	35	25	58	17
AP-26-7	47	44	33	20	23	8	62	61	7	73	165	14	53	33	33	61	6
J-22-3	39	38	42	20	21	8	59	65	3	78	165	5	62	33	32	65	3
JA-10-6	46	43	33	20	24	8	61	80	8	84	165	15	68	17	15	80	5
LOS GATOS																	
75-51	33	32	36	31	32	9	63	44	5	88	575	5	42	53	55	44	1
75-59	31	29	34	35	37	7	79	53	6	82	525	5	50	45	43	53	5
75-141	37	35	37	26	28	10	54	37	5	86	385	6	35	59	55	37	8
75-143	38	37	39	22	24	11	56	51	5	86	385	8	46	45	48	51	1
75-144	35	34	39	26	27	8	54	49	3	85	385	4	47	50	47	49	5
75-164	44	43	37	20	21	10	70	39	2	83	555	4	38	58	53	39	8
75-174	43	40	37	20	23	6	54	38	6	86	410	11	33	55	53	38	9
75-180	40	37	33	28	30	9	50	32	6	87	420	7	30	63	62	32	6
75-182	43	41	42	15	17	8	50	41	3	85	435	8	38	55	51	41	8
75-184	32	31	53	15	16	8	81	35	3	89	430	6	33	61	57	35	8
75-191	40	39	41	19	20	11	61	44	2	83	460	4	42	54	54	44	1
75-192	45	44	43	12	14	17	73	46	3	85	460	10	41	49	50	46	4
75-194	39	39	40	21	21	14	77	25	0	88	450	0	25	75	69	25	6
75-195	30	29	42	28	29	11	75	31	1	89	450	1	31	68	57	31	12
CORTINA																	
74-35	38	37	42	21	22	6	72	69	3	88	150	5	65	30	26	69	6
74-36	22	21	39	39	40	3	71	73	6	87	150	3	71	26	23	73	4
74-39	26	24	27	47	50	7	68	74	9	86	150	5	71	24	22	74	4
74-41	52	51	30	18	19	9	73	66	1	88	145	3	64	33	21	66	13
74-70	35	34	35	30	31	7	60	74	1	85	115	2	73	26	20	74	6

Table 1 (Continued)

Sample Number	QFL%					FRMW%						QpLvmLsm%			LmLvLs%		
	Q	Qm	F	L	Lt	M	P/F	Lv/L	Qp/Q	MYBP	D	Qp	Lvm	Lsm	Lm	Lv	Ls
74-71	30	29	50	20	21	6	61	83	4	87	110	6	78	16	16	83	1
74-74	34	33	50	16	16	6	68	76	1	86	135	3	74	24	20	76	5
74-76	28	28	53	19	20	4	62	79	2	87	130	4	76	20	16	79	5
74-103	27	24	42	31	34	4	58	84	11	88	35	9	77	14	12	84	4
74-105	34	33	27	39	40	5	58	77	4	86	40	3	74	22	17	77	7
74-106	25	23	42	33	36	3	51	86	11	88	30	8	80	13	5	86	9
75-8	34	31	40	26	29	6	64	70	7	86	220	8	64	27	25	70	5
75-11	41	38	39	20	23	4	58	71	8	84	220	14	61	25	23	71	6
75-36	43	42	38	19	20	4	46	60	3	86	360	6	56	38	23	60	17
75-84	29	28	46	25	27	2	58	76	6	88	0	6	72	22	14	76	9
75-85	26	24	49	25	27	3	51	81	6	88	0	6	76	18	7	81	12
75-87	31	29	38	32	33	3	56	80	4	88	0	4	77	19	12	80	8
75-90	28	26	43	29	31	3	50	73	8	88	5	7	68	25	18	73	9
75-93	28	25	40	32	35	4	52	77	9	84	15	7	71	21	6	77	17
75-95	22	19	37	41	44	2	48	76	11	82	15	6	72	23	12	76	12
75-97A	28	25	29	43	46	3	47	72	11	82	25	7	67	27	18	72	11
75-97B	21	18	31	48	51	2	46	71	13	82	25	5	67	27	15	71	14
75-99	25	23	35	40	43	4	62	70	10	82	25	6	65	28	10	70	20
75-102	40	39	39	21	22	9	68	92	2	83	180	4	89	7	5	92	3
75-135	35	33	39	26	27	5	69	50	3	85	230	4	48	47	39	50	11
75-137	36	34	40	24	26	7	66	50	6	83	230	8	46	46	34	50	15
784-18	49	44	32	20	24	4	60	57	9	84	300	18	47	36	27	57	17
784-19	45	42	31	25	28	4	55	54	7	84	305	11	48	41	35	54	11
MC-4	27	26	41	32	33	6	69	81	5	89	290	4	78	18	13	81	6
MC-8	46	45	37	17	17	7	56	73	1	86	290	1	72	27	23	73	4
NC-1	35	33	40	26	27	5	84	61	3	86	315	4	58	37	27	61	12
NC-2	34	33	41	25	27	4	63	53	4	86	315	5	51	44	38	53	9
NC-3	30	29	44	26	27	5	65	62	3	86	315	3	60	37	23	62	15
NC-4	35	34	39	26	27	5	65	66	3	86	315	4	63	33	28	66	6
NC-6	39	38	40	21	22	6	68	61	1	87	315	1	61	38	26	61	13
NC-7	41	40	35	24	25	6	63	48	4	88	315	6	44	49	38	48	15
NC-8	35	34	37	28	29	7	64	47	3	88	315	3	45	52	47	47	7
NC-9	37	36	39	24	25	4	62	51	3	88	315	5	48	47	36	51	14
NC-15	36	34	37	27	29	5	66	61	7	89	310	9	56	35	28	61	11
D-18-6	35	34	51	15	15	10	69	76	2	82	165	5	72	23	22	76	2
F-18-3	39	38	38	23	25	8	63	85	4	86	165	6	79	14	13	85	2
J-22-20	29	27	46	25	27	6	65	73	6	88	160	6	68	25	23	73	4
								BOXER									
74-1	26	22	28	46	50	1	64	84	16	95	165	8	77	15	7	84	9
74-4	21	17	30	49	53	1	68	79	16	93	170	6	74	20	14	79	7
74-25	42	42	37	21	21	8	82	84	0	90	215	0	84	16	10	84	6
74-27	21	19	45	34	36	4	79	90	10	95	165	6	85	9	5	90	5
74-28	36	35	30	34	35	4	77	88	3	95	165	3	86	12	5	88	7
74-30	33	30	32	35	38	6	69	76	8	90	150	7	71	22	19	76	5
74-33	35	32	31	35	38	7	88	72	9	89	150	8	66	25	22	72	6
74-44	35	33	29	36	38	6	71	74	7	90	145	6	69	25	23	74	3
74-45	33	31	29	38	40	4	78	64	6	89	145	5	60	35	31	64	5
74-46	40	38	25	35	37	5	80	80	5	95	145	5	75	19	15	80	6
74-50	25	23	29	46	48	4	65	91	9	94	145	5	87	9	6	91	3
74-54	26	26	32	43	43	4	62	91	0	94	135	0	91	9	6	91	2
74-56	37	35	27	37	39	2	57	87	6	90	130	6	81	13	11	87	3
74-59	26	24	26	49	51	4	79	71	7	89	100	4	69	28	22	71	7
74-62	20	16	34	46	50	5	65	87	19	93	100	8	81	12	9	87	3
74-64	31	28	29	40	42	4	92	78	10	89	100	7	73	20	14	78	8
74-66	30	28	27	43	46	2	78	70	9	89	100	6	66	28	22	70	8
74-68	31	29	32	37	40	5	82	81	8	89	115	6	76	18	14	81	5
74-69	29	26	38	32	35	3	68	77	10	89	115	9	70	21	19	77	5
74-72	31	28	30	39	42	4	80	74	10	89	120	7	69	23	22	74	4
74-77	38	38	36	25	26	6	87	47	2	88	130	4	45	51	42	47	11

Table 1 (Continued)

Sample Number	QFL%					FRMW%						QpLvmLsm%			LmLvLs%		
	Q	Qm	F	L	Lt	M	P/F	Lv/L	Qp/Q	MYBP	D	Qp	Lvm	Lsm	Lm	Lv	Ls
74-84	31	27	35	34	38	4	58	85	12	95	55	9	77	13	9	85	6
74-89	36	33	30	34	37	1	76	90	8	92	50	8	82	10	9	90	1
74-92	39	33	30	31	37	7	84	50	14	87	50	15	42	43	38	50	13
74-93	38	34	29	33	37	3	61	82	11	91	45	12	72	16	13	82	5
74-95	34	31	36	30	33	2	65	74	9	88	45	9	67	24	13	74	13
74-100	29	27	41	30	32	3	64	80	5	92	35	4	76	19	12	80	9
75-1	37	36	42	21	22	5	86	60	4	88	215	6	56	38	29	60	11
75-17	29	27	32	38	41	2	53	85	10	93	155	7	79	14	5	85	10
75-18	26	23	32	42	45	1	77	88	13	93	155	8	82	11	4	88	8
75-35A	32	29	33	35	38	3	68	58	8	87	360	7	54	39	39	58	3
75-35B	43	41	35	23	24	5	92	66	4	87	360	7	62	32	23	66	11
75-78A	20	18	40	40	42	2	68	78	10	94	25	5	74	21	14	78	8
75-78B	19	17	42	39	41	1	72	77	10	94	25	5	73	22	12	77	11
75-82	46	44	30	24	26	6	75	62	4	88	10	8	57	35	24	62	14
77-76	39	32	30	32	39	3	81	62	18	98	25	18	51	31	8	62	30
784-6	34	28	32	34	40	4	77	55	18	95	310	15	47	38	32	55	13
784-7	26	23	28	46	49	4	79	51	12	92	315	6	48	46	42	51	7
784-8	32	29	30	38	41	3	86	65	8	92	315	6	61	32	21	65	14
784-12	30	27	35	34	38	4	67	51	12	92	310	9	46	44	38	51	11
NC-10	34	32	31	35	37	4	84	61	7	95	310	6	57	37	27	61	13
NC-12	24	20	27	48	52	1	85	49	16	92	315	7	46	47	38	49	13
NC-14	31	27	36	33	37	4	88	55	11	91	310	9	50	41	33	55	12
GRABAST																	
75-46	28	25	28	44	47	7	81	24	11	95	570	7	22	71	75	24	1
75-49	26	25	32	42	42	11	70	39	2	89	575	1	38	61	60	39	1
75-50	42	40	37	21	23	4	88	58	4	91	575	8	53	39	29	58	13
75-52	30	26	23	47	51	5	66	51	15	94	520	9	47	44	46	51	2
75-53	33	29	22	45	49	9	69	41	12	94	525	8	38	54	51	41	7
75-55	25	20	33	42	47	7	70	33	19	92	525	10	30	60	59	33	8
75-57	35	34	28	37	39	10	65	32	4	89	525	4	31	65	67	32	1
75-140	32	30	30	39	40	7	60	26	5	89	385	4	25	71	69	26	4
75-149	28	26	33	39	40	7	60	49	6	88	390	4	47	49	44	49	7
75-152	26	24	30	43	46	4	59	40	9	88	395	5	38	57	55	40	5
75-159	38	34	39	23	27	11	82	27	9	94	560	13	24	63	62	27	11
75-166	23	22	29	47	49	6	79	18	5	94	555	2	18	80	77	18	4
75-168	28	25	22	51	53	6	72	36	9	90	400	5	34	61	57	36	8
75-169	31	29	31	38	40	6	63	39	8	89	405	6	36	57	50	39	11
75-170	27	25	31	42	44	5	61	34	7	89	405	4	33	63	60	34	6
75-172	28	25	35	37	40	7	65	33	10	89	405	7	30	63	66	33	1
SL-3	24	21	22	54	56	2	51	48	11	89	405	5	46	50	40	48	12
PLATINA																	
77-77	53	33	13	34	54	2	78	45	38	117	25	37	28	34	22	45	33
77-78	33	28	23	44	49	2	89	33	15	123	20	10	29	60	48	33	20
77-79	31	20	19	50	61	2	89	35	35	124	20	18	29	53	13	35	51
77-81	29	11	8	64	82	0	97	44	62	125	15	22	35	44	43	44	12
77-82	29	24	38	33	38	6	83	24	17	125	15	13	21	67	73	24	3
77-84	40	34	33	27	32	7	84	32	14	125	10	18	27	55	33	32	34
77-85	48	20	9	42	71	0	93	63	60	126	10	41	37	22	9	63	28
77-86	40	23	8	52	69	2	47	2	43	126	5	25	2	73	95	2	3
77-87	43	27	18	39	55	2	84	53	38	126	5	30	37	33	40	53	7
77-89C	46	19	8	46	74	2	71	14	60	128	-5	37	9	54	44	14	42
77-89F	30	18	8	62	74	4	85	6	40	128	-5	16	5	79	75	6	19
77-90	46	37	28	25	35	5	78	18	20	125	-15	27	13	60	38	18	44
77-91	30	13	10	61	77	0	95	39	56	126	5	22	31	48	49	39	11
77-92	42	32	34	24	35	9	83	27	25	125	10	31	19	50	41	27	32
77-93	38	30	22	40	48	5	82	18	21	125	10	17	15	68	27	18	55
77-94	41	38	37	21	25	1	84	38	8	124	10	13	33	54	32	38	30
77-95	59	57	34	7	8	9	86	10	2	123	10	17	9	74	76	10	14

Table 1 (Continued)

Sample Number	QFL%					FRMW%						QpLvmLsm%			LmLvLs%		
	Q	Qm	F	L	Lt	M	P/F	Lv/L	Qp/Q	MYBP	D	Qp	Lvm	Lsm	Lm	Lv	Ls
LODOGA																	
75-107	37	36	**26**	36	38	6	83	45	5	95	125	5	43	52	40	45	15
75-110	37	32	**26**	37	42	6	86	53	12	95	125	11	48	41	38	53	9
75-111	47	41	**19**	34	39	3	68	46	12	95	125	14	40	46	44	46	10
77-1	38	34	**40**	22	26	4	62	54	11	112	240	16	46	39	26	54	20
77-7	28	22	**16**	56	61	5	98	24	20	98	195	9	22	69	65	24	11
77-15	33	29	**28**	39	43	6	71	70	12	112	170	9	63	28	6	70	24
77-16	27	19	**11**	62	70	2	91	13	29	110	170	11	11	78	82	13	5
77-17	36	27	**26**	38	47	3	75	54	24	98	175	18	44	38	20	54	26
77-22	46	44	**25**	29	32	3	95	15	6	115	155	8	13	78	21	15	64
77-23	39	30	**17**	44	53	3	87	45	23	106	160	17	37	46	30	45	25
77-24	48	46	**32**	20	22	6	91	41	5	104	160	10	37	54	51	41	8
77-26	39	25	**13**	48	63	5	91	22	38	106	150	24	17	59	50	22	28
77-27	35	28	**14**	51	58	4	98	21	21	104	150	12	18	69	38	21	42
77-30	25	17	**12**	63	71	8	89	22	31	106	125	11	20	69	64	22	14
77-31	29	22	**11**	60	67	3	90	28	25	105	130	11	25	64	61	28	11
77-32	30	19	**14**	56	67	3	90	31	36	104	130	16	26	58	23	31	46
77-34	33	24	**13**	54	63	4	98	26	28	105	115	14	23	63	43	26	31
77-40	39	38	**31**	30	31	9	71	61	2	114	100	3	59	38	6	61	33
77-48	36	25	**18**	46	57	5	90	37	31	103	85	19	30	51	36	37	27
77-55	41	33	**17**	42	50	9	100	55	20	103	70	17	46	37	39	55	6
77-60	44	40	**19**	36	41	5	96	45	11	101	60	12	39	49	26	45	29
77-61	38	29	**17**	45	53	4	93	56	23	111	55	16	47	37	17	56	27
77-65	34	24	**24**	42	53	1	73	61	30	112	50	20	49	31	17	61	22
77-66	32	26	**17**	51	57	4	87	39	19	96	40	11	35	54	55	39	6
77-67	37	28	**27**	36	45	3	58	62	23	117	40	19	50	31	8	62	31
77-68	44	33	**22**	34	45	3	89	59	26	102	40	25	44	31	20	59	21
77-69	39	27	**14**	47	59	7	96	30	30	98	35	20	24	56	33	30	38
77-70	36	26	**15**	48	59	3	95	16	29	105	35	18	14	69	17	16	66
77-72	45	36	**31**	24	33	2	68	78	19	116	35	26	58	16	7	78	14
77-97	40	37	**24**	36	39	4	93	38	8	115	170	8	35	57	23	38	39
77-99	48	46	**27**	25	27	5	86	33	5	114	170	9	30	61	45	33	22
77-100	22	7	**12**	67	81	3	89	55	67	112	170	18	45	37	11	55	34
STONY CREEK																	
77-2	1	1	14	85	86	0	100	96	25	138	230	0	96	4	0	96	4
77-8C	37	32	30	33	38	3	80	90	14	131	205	14	77	9	2	90	8
77-8F	35	31	45	20	24	3	64	68	10	131	205	15	58	27	3	68	29
77-9	31	26	35	33	38	3	96	55	17	135	205	14	48	39	41	55	4
77-10	19	11	14	67	75	4	98	48	44	140	205	11	43	46	8	48	44
77-11	60	56	26	14	18	2	79	63	6	134	215	21	50	29	5	63	32
77-12	14	7	18	68	75	0	100	70	48	138	220	9	64	27	1	70	28
77-13	12	6	21	67	73	1	89	73	51	136	230	8	67	25	6	73	20
77-18	24	23	41	35	36	5	96	44	2	134	165	1	44	55	22	44	33
77-20	11	4	17	72	78	2	94	75	60	139	160	8	69	23	1	75	23
77-21	52	48	30	18	22	3	99	74	8	131	160	18	61	21	4	74	22
77-25	35	10	10	55	80	1	88	18	73	131	145	32	12	56	21	18	61
77-33	8	4	23	69	73	1	100	67	47	130	120	5	63	32	2	67	32
77-35	14	7	18	68	74	1	94	60	47	139	120	9	55	36	4	60	36
77-38	26	4	7	68	89	1	93	76	83	138	120	24	58	18	1	76	23
77-39	14	12	20	66	68	3	96	76	17	131	100	4	74	23	9	76	14
77-41	14	12	26	60	62	1	98	72	12	130	100	3	70	28	4	72	24
77-42	16	9	35	50	56	4	96	62	40	140	95	11	55	34	2	62	36
77-44	26	15	14	59	71	2	98	55	43	139	95	16	46	38	3	55	42
77-45	15	12	28	56	60	1	96	80	23	130	95	6	75	19	1	80	19
77-46	15	9	15	70	76	3	100	61	40	138	90	8	57	36	12	61	27
77-47	26	5	14	60	82	2	98	67	82	135	85	26	49	24	15	67	18
77-49	20	9	21	59	71	3	99	68	57	135	80	17	57	26	19	68	13
77-53	24	9	19	57	72	0	100	42	64	140	70	21	33	45	2	42	56
77-56	34	19	18	48	63	4	79	29	43	124	60	23	23	54	24	29	47

Table 1 (Continued)

Sample Number	QFL%					FRMW%						QpLvmLsm%			LmLvLs%		
	Q	Qm	F	L	Lt	M	P/F	Lv/L	Qp/Q	MYBP	D	Qp	Lvm	Lsm	Lm	Lv	Ls
77-57	25	9	14	61	78	1	97	30	66	138	60	21	24	55	15	30	54
77-58	35	22	16	49	61	4	87	62	35	136	60	20	50	30	2	62	36
77-59	18	11	9	73	81	1	85	31	42	134	60	10	28	62	57	31	12
77-63	34	24	14	52	62	2	100	43	29	138	55	16	36	48	18	43	39
77-64	30	23	22	48	55	4	99	65	24	128	55	13	57	30	13	65	22
77-74	12	8	31	56	61	2	65	42	33	118	30	7	42	52	42	45	12
77-75	30	22	25	45	53	2	89	42	28	115	25	16	35	49	27	42	31
77-96	47	45	45	8	9	3	92	82	4	116	170	18	68	15	3	82	15

Plate 17 of Ingersoll (1976). Subsequently, the Lower Cretaceous and Upper Jurassic parts of the section were collected and studied, and the preliminary results have been presented in an abstract (Ingersoll, 1979b). Table 1 contains all of the recalculated data used in the present study, both new data and data previously reported (in modified form) for the Upper Cretaceous petrofacies. Figure 3 is a map showing locations of all new sample sites. Only point counts by the writer were used in the present compilation to assure uniformity of technique and because most previous workers' results did not include all of the writer's parameters. Nonetheless, most previous studies agree with the present results, as discussed by Ingersoll (1978b).

Sampling was of a reconnaissance nature. Fairly uniform stratigraphic and geographic distribution of sites was achieved by sampling along all easily accessible roads, as well as some areas accessible only on foot. Samples were collected, wherever possible, from massive, medium-grained, unweathered sandstones lacking calcite replacement. Two samples of pebbly sandstone (77-81 and 77-91) were collected because finer grained material was not available. Oversized thin sections approximately 45 by 60 mm were made for these samples, so that 500 points could be counted on each slide with grid spacing greater than grain size. Outcrop and road-cut sampling cannot be considered random in a rigorous sense. However, the broad conclusions reached by this study are valid, based on the consistency of results and the agreement with other types of data. Local variations in sandstone petrology may have escaped notice owing to lack of sampling. However, definition of the petrofacies is broad enough so that significant local variation is accommodated within each group.

PETROGRAPHIC METHODS

All samples were cut perpendicular to bedding, and impregnated; half of each section was stained for both plagioclase and potassium-feldspar. Point counts were performed with sample locations and ages unknown to avoid bias. The maximum possible grid spacing was chosen that allowed 500 points to be counted on each slide. In almost all cases, grid spacing exceeded grain size, so that individual grains were not counted more than once (see Van der Plas and Tobi, 1965). Use of Dickinson's (1970) method of counting all crystals greater than 0.0625 mm within lithic fragments as monocrystalline grains (a method independently proposed by Gazzi, 1966, and discussed by Zuffa, 1980) further reduces compositional variation with grain size because effective grain size is reduced to 0.0625 mm for most microphaneritic and microphenocrystic grains. All parameters counted and calculated are explained in Table 2.

Counting methods, criteria for distinguishing components, and problems in mentally removing diagenetic alterations to reconstruct original compositions are discussed thoroughly by Dickinson (1970), Graham et al (1976), Ingersoll (1978b), and Ingersoll and Suczek (1979). All procedures used in the present study were those of Ingersoll (1978b), with the exception that miscellaneous grains (dense minerals, carbonates, unidentified, etc) were included as a category of framework grains. Only the M parameter (framework-percent of phyllosilicates) involves miscellaneous grains, and inclusion or exclusion of miscellaneous grains has an insignificant effect on the calculations.

Upper Jurassic and Lower Cretaceous sandstones from the Great Valley Group have experienced significant burial metamorphism in many locations (Dickinson et al, 1969). As a result, determining original detrital modes is more difficult than for Upper Cretaceous sandstones. Albitization of plagioclase, chloritization of biotite, crushing of lithic grains and phyllosilicates to form pseudomatrix, destruction of dense minerals, and replacement and cementation by calcite and other minerals are ubiquitous in the more deeply buried sandstones. All of these alterations must be mentally removed in order to reconstruct original detrital compositions. Application of these methods to more highly deformed sandstones (e.g., Franciscan Complex) probably will lead to the determination of similar petrofacies in such related terranes (e.g., Dickinson et al, 1982).

really?

PETROGRAPHIC RESULTS

Point-count results were tabulated and recalculated as shown in Table 2. All information listed in Table 1 was put on punch cards for later analysis, but only seven parameters were used in the stepwise discriminant analysis (UCLA BMDO7M, revised 12/24/75). These parameters, from most important to least important, are P/F, Lv/L, Framework% M, Qp/Q, QFL% Q, QFL% F, and QFL% L. Control groups were established on the basis of preexisting groupings (especially, those of Dickinson and Rich, 1972; Ingersoll, 1978b; Mansfield, 1979), but the group-

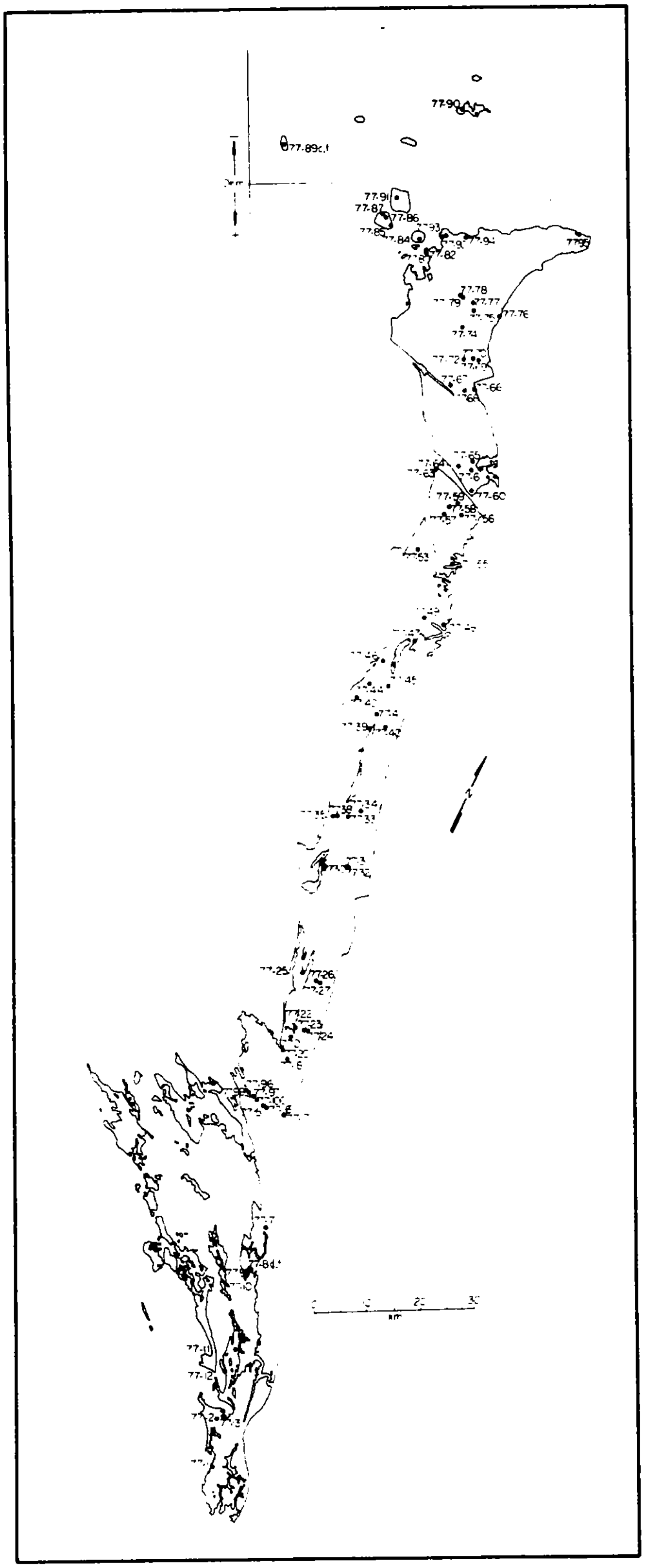

FIG. 3—Sample locations for lower Great Valley Group, Sacramento Valley. Solid line outlines Upper Jurassic-Lower Cretaceous outcrops, as shown on California Division of Mines and Geology state map sheets. Lines on left and top show arbitrary base line and direction along which distances were measured. A few samples in north have negative distances. Sample locations for Upper Cretaceous outcrops are given by Ingersoll (1976).

ings remained flexible as successive groupings were run. Stratigraphic and geographic positions were used loosely to constrain the movement of samples between groups (i.e., samples were moved freely to stratigraphically and geographically neighboring groups, but were not moved to distant groups). Previous petrofacies groups were combined (e.g., Grabast and Studhorse of Ingersoll, 1978b, and Mansfield, 1979, were combined into one petrofacies, the Grabast of the present study), and a new petrofacies group was defined (Platina). High-lithic and low-lithic variants (e.g., Dickinson and Rich, 1972; Ingersoll, 1978b) were combined into single groups, thus decreasing the importance of QFL percentages in petrofacies discrimination and increasing the importance of the other parameters. Interestingly, but not surprisingly, the ratio of plagioclase to total feldspar (P/F) is the most important factor in discriminating the petrofacies. Bailey and Irwin (1959) first noted the stratigraphic significance of potassium-feldspar content in their pioneering study of the Franciscan Complex and the Great Valley Group in northern California. The ratio of volcanic lithics to total unstable lithics (Lv/L) is the second most important discriminating parameter.

Several other parameters were tried before choosing these seven. Of most interest, polycrystalline quartz (Qp) was added to the unstable lithics to form a total-lithics category, and QmFLt (Table 2) percentages were calculated. No significant change in petrofacies discrimination resulted; therefore, QFL percentages were retained as defining parameters. The ratio of polycrystalline quartz to total quartz (Qp/Q) was added as a seventh parameter (Dickinson and Rich, 1972, and Ingersoll, 1978b, used only six parameters) because of the high polycrystalline-quartz content of the lower Sacramento Valley petrofacies. Previous work (Dickinson and Rich, 1972) had misidentified much of this fine-grained material as felsic volcanics, a distinction that is difficult to make without properly stained thin sections (W. R. Dickinson, personal commun., 1979).

Once the petrofacies groupings had been established, means, standard deviations, and correlation coefficients were calculated from all the data using a stepwise-regression-analysis program (UCLA BMDO2R, revised 12/24/75). In addition, super petrofacies were constructed for the Sacramento Valley, San Joaquin Valley, lower petrofacies (Upper Jurassic and Lower Cretaceous), and upper petrofacies (Upper Cretaceous). These four groups, along with the Total group (all samples) were analyzed in the same manner as the petrofacies.

The stratigraphic and geographic distributions of the eight petrofacies are shown in Figures 2 and 4. Some of the boundaries are time-transgressive and interfingering in detail, but the broad correspondence between stratigraphic position and petrofacies is clear. The southern boundary of the Platina petrofacies is not controlled by stratigraphic position, but apparently represents a lateral change in source terranes from primarily Klamath provenance (Platina) to primarily northern Sierra Nevada provenance (Stony Creek and Lodoga). Undoubtedly, this petrofacies boundary is gradational and is not precisely defined locally. The lateral boundaries between the Upper Cretaceous Sacramento Valley (Boxer and Cortina) and

Table 2. Explanation of Petrographic and Other Parameters (after Ingersoll and Suczek, 1979)

Q = Qm + Qp	where	Q	= total quartzose grains
		Qm	= monocrystalline quartz grains
		Qp	= polycrystalline quartz grains
F = P + K	where	F	= total feldspar grains
		P	= plagioclase feldspar grains
		K	= potassium feldspar grains
Lt = L + Qp	where	Lt	= total aphanitic lithic grains
		L	= total unstable aphanitic lithic grains
L = Lm + Lv + Ls	where	Lm	= metamorphic aphanitic lithic grains
		Lv	= volcanic-hypabyssal aphanitic lithic grains
		Ls	= sedimentary aphanitic lithic grains
L = Lvm + Lsm	where	Lvm	= volcanic-hypabyssal and metavolcanic aphanitic lithic grains
		Lsm	= sedimentary and metasedimentary aphanitic lithic grains
Framework = Q + F + L + M + Mc	where	M	= monocrystalline phyllosilicate grains
		Mc	= miscellaneous and unidentified framework grains
M.Y.B.P. = age in millions of years before present			
D = distance in kilometers south of arbitrary line near Redding (see Fig. 3)			

the San Joaquin Valley (Grabast and Los Gatos) petrofacies similarly are gradational, although at the scale of Figure 4, the boundaries are well defined.

PETROFACIES CHARACTERISTICS

Means and standard deviations (see Ingersoll, 1978b, and Ingersoll and Suczek, 1979, for discussion of the statistical significance of such constrained data) for the seven parameters that define the eight petrofacies are given in Table 3. These data form the basis for Figures 5, 6, and 7a, b, c. Similar information for the four super petrofacies and the Total Great Valley group are given in Table 4 and Figure 7 (d, e, f, g, h, i). It should be apparent from this maze of data, that one parameter or one type of display (e.g., QFL triangle) by itself is insufficient to distinguish all of the petrofacies. Multivariate analysis using computer programs is the recommended method of analyzing such data. However, certain key parameters may be used to distinguish various groupings of petrofacies with a minimum of effort. P/F is the single most important discriminating parameter. Figure 6 demonstrates that there is no overlap in standard-deviation intervals of P/F values for the Stony Creek petrofacies and four of the five Upper Cretaceous petrofacies. Thus, determination of P/F alone clearly differentiates some of the petrofacies. Values of M, Lv/L, and Qp/Q for several of the petrofacies similarly do not overlap, and key distinctions can be made quickly based on only one or two parameters (see Figs. 5, 6). With experience, a skilled petrographer can determine quickly whether an unknown sandstone is from the Sacramento or San Joaquin Valleys and whether it is from the lower or upper part of the Great Valley Group. Distinction of all of the individual petrofacies requires more careful work and multivariate analysis.

The following discussion summarizes the salient features of each petrofacies (see Table 3 and Figs. 5 through 7 for details).

The Stony Creek petrofacies (Tithonian and Neocomian) is distinctive for the combination of low Q, low F, high L, low M, high P/F, high Lv/L, and high Qp/Q. The lowest stratigraphic zones contain sandstones rich in basaltic and andesitic detritus, with a gradual decrease in L with time. Conglomerates are rich in volcanic, chert, and shale-argillite clasts (Bertucci, 1980; Seiders, 1983). The volcanic cover formed during the Yosemite intrusive epoch (Evernden and Kistler, 1970) was presumably the source for most of the volcanic detritus. Uplifted "tectonic highlands" (accreted arc terranes of Schweickert and Cowan, 1975; Ingersoll, 1982) provided the abundant chert and shale-argillite to this petrofacies.

The Platina petrofacies (Neocomian) has similar characteristics to both the Stony Creek and the Lodoga. However, it has the lowest Lv/L ratio of any of the petrofacies and occurs only at the extreme northern end of the Sacramento Valley. It apparently was derived directly from underlying metamorphic terranes of the southern Klamath province (primarily accreted-arc and related deformed terranes). The low volcanic content probably indicates that this petrofacies is a local variant formed directly from metamorphic rocks exposed away from the volcanic parts of the accreted arcs.

The Lodoga petrofacies (Aptian and Albian) is distinguished by the combination of high Q, low F, variable L, low M, high P/F, low Lv/L, and high Qp/Q. The sandstones probably were derived from a combination of plutonic and metamorphic sources (intruded and deformed during the Yosemite intrusive epoch), and reworked sedimentary sequences, possibly coupled with low relief and deep weathering in the source terranes (Ojakangas, 1968).

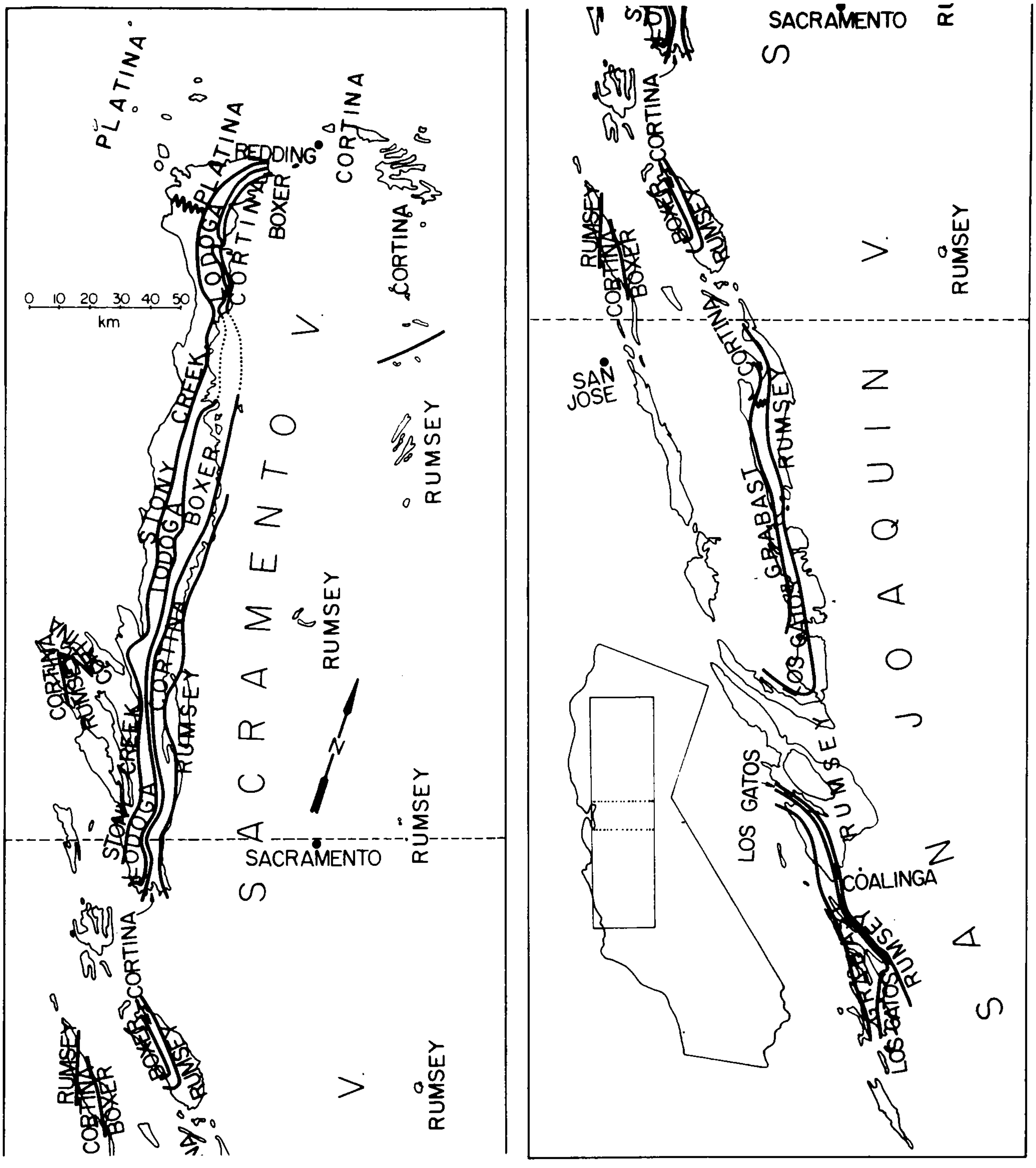

FIG. 4—Generalized map showing geographic locations of outcrops of eight petrofacies. Fine lines denote outcrops; heavy lines show petrofacies boundaries. Base map from Jennings (1977). Dashed horizontal lines indicate area of overlap between north part of map (left) and south part of map (right).

A possible regional unconformity (Peterson, 1967) and general quiescence of plutonism in the Sierra Nevada during much of Lodoga deposition (Evernden and Kistler, 1970) support this contention. The Huntington Lake intrusive epoch (Early Cretaceous) affected sandstone compositions more in the San Joaquin Valley than in the Sacramento Valley (Ingersoll, 1978b; Mansfield, 1979).

The Boxer petrofacies (Cenomanian and Turonian) includes two contrasting types (quartzose and lithic variants) that fall into discrete fields on a QFL plot, but which

Table 3. Means and Standard Deviations for Seven Parameters of Eight Great Valley Petrofacies (Numbers of Samples Shown in Parentheses)

Parameter	Stony Creek (33)	Lodoga (32)	Platina (17)	Boxer (43)	Cortina (42)	Grabast (17)	Los Gatos (14)	Rumsey (34)
QFL% Q	25±13	37±7	40±9	32±7	34±7	30±5	38±5	40±5
QFL% F	22±10	21±7	21±11	32±5	39±6	30±5	40±5	36±9
QFL% L	53±19	42±12	39±16	36±7	27±8	41±8	23±7	24±11
FRMW% M	2±1	4±2	3±3	4±2	5±2	7±2	10±3	10±5
P/F	0.92±0.10	0.86±0.11	0.83±0.11	0.75±0.10	0.61±0.08	0.68±0.10	0.64±0.11	0.55±0.11
Lv/L	0.60±0.18	0.42±0.17	0.29±0.17	0.73±0.13	0.70±0.11	0.37±0.10	0.40±0.08	0.60±0.14
Qp/Q	0.37±0.22	0.21±0.13	0.33±0.19	0.09±0.05	0.05±0.03	0.09±0.04	0.04±0.02	0.03±0.03

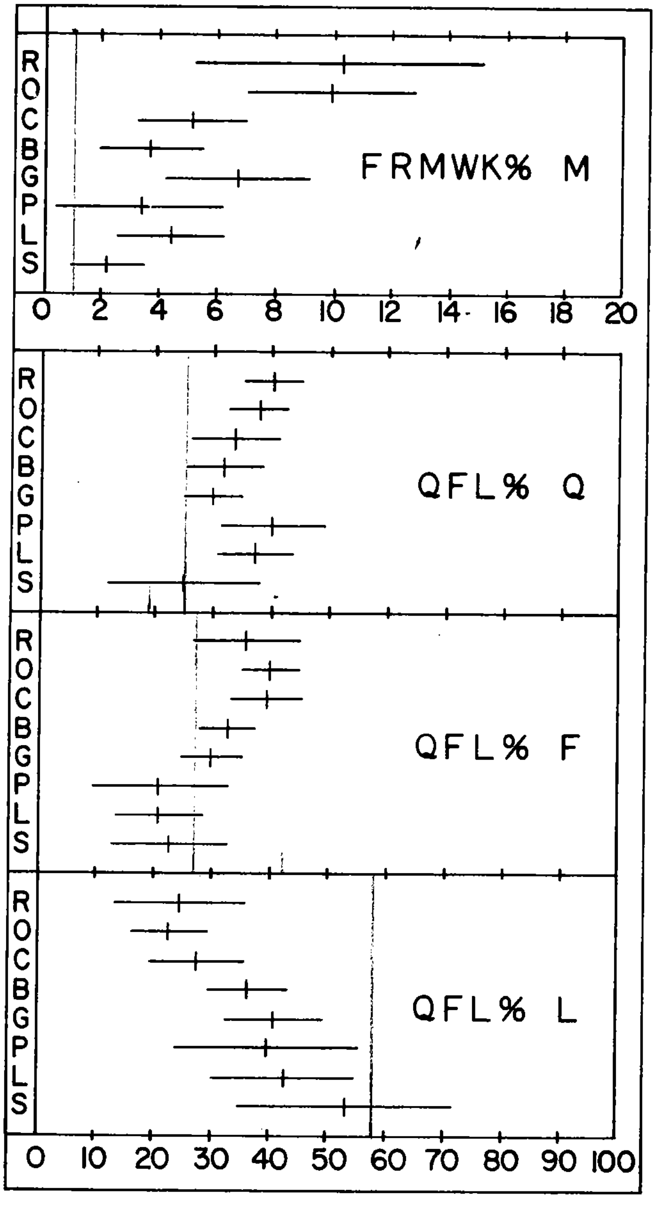

FIG. 5—Means and standard deviations of four percentage parameters for eight petrofacies. Petrofacies are abbreviated on left side for each parameter as follows: R = Rumsey, O = Los Gatos, C = Cortina, B = Boxer, G = Grabast, P = Platina, L = Lodoga, S = Stony Creek. See text for discussion.

intertongue in the field. Both variants are characterized by moderate F, low M, moderate P/F, high Lv/L, and low Qp/Q. Boxer conglomerates are rich in volcanic, hypabyssal, and plutonic clasts. Extensive felsic volcanics and potassium-feldspar (both volcanic and plutonic) first occurred during deposition of the Boxer petrofacies. The high-L Boxer variant was derived from volcanic cover associated with the early stages of the Cathedral Range intrusive epoch (Evernden and Kistler, 1970), whereas the low-L Boxer variant was derived from older plutons exposed by erosion during Lodoga deposition.

The Cortina petrofacies (Turonian, Coniacian, and Santonian) also includes intertonguing high-L and low-L variants. Both variants are similar to the corresponding Boxer variants, and it is difficult to differentiate the two petrofacies. However, the Cortina variants tend to have higher F and M, and lower P/F, than their corresponding Boxer variants. Source terranes for the Cortina petrofacies were similar to those for the Boxer petrofacies, with the possible addition of more felsic plutonic and volcanic terranes by the time of Cortina deposition.

The Grabast and Los Gatos petrofacies occur only in the San Joaquin Valley, where they were first recognized in modified form by Mansfield (1979). They correspond in age to the Boxer and Cortina petrofacies (Cenomanian through Santonian), and differ from them in having higher M and lower Lv/L owing to their derivation in large part from metamorphic terranes in the southern Sierra Nevada (Ingersoll, 1978b; Mansfield, 1979). Aside from the higher metamorphic contents of the Grabast and the Los Gatos, the former is similar to the Boxer and the latter is similar to the Cortina (see Figs. 5 to 7).

The Rumsey petrofacies (Santonian, Campanian, and Maestrichtian) is characterized by high Q, high F, low L, high M, low P/F, moderate Lv/L, and low Qp/Q. Sandstone compositions usually can be classified as arkosic with approximately equal amounts of plagioclase and potassium-feldspar, and represent derivation from primarily felsic plutonic rocks. Paleogene sandstones have similar compositions in much of California. Rumsey sandstones were derived primarily from the vast quartz-monzonite plutons formed during the Cathedral Range intrusive epoch (Evernden and Kistler, 1970), whose volcanic cover had been eroded by the time of Rumsey deposition. Widely spaced outcrops of shallow-marine Campanian sandstones along the east side of the Sacramento Valley form a high-L variant of the Rumsey (Inger-

Table 4. Means and Standard Deviations for Seven Parameters of Four Super Petrofacies and TOTAL Group (Numbers of Samples Shown in Parentheses)

Parameter	SACVAL (191)	SJQVAL (41)	UPRGVG (150)	LOWGVG (82)	TOTAL (232)
QFL% Q	33 ± 10	36 ± 7	34 ± 7	33 ± 12	34 ± 9
QFL% F	29 ± 11	36 ± 7	35 ± 7	21 ± 9	30 ± 10
QFL% L	37 ± 15	29 ± 12	30 ± 11	46 ± 17	36 ± 15
FRMW% M	5 ± 3	9 ± 3	7 ± 4	3 ± 2	5 ± 4
P/F	0.75 ± 00.16	0.62 ± 0.12	0.65 ± 0.12	0.88 ± 0.11	0.73 ± 0.16
Lv/L	0.59 ± 0.20	0.45 ± 0.16	0.62 ± 0.18	0.47 ± 0.21	0.57 ± 0.20
Qp/Q	0.17 ± 0.18	0.05 ± 0.04	0.06 ± 0.04	0.30 ± 0.20	0.15 ± 0.17

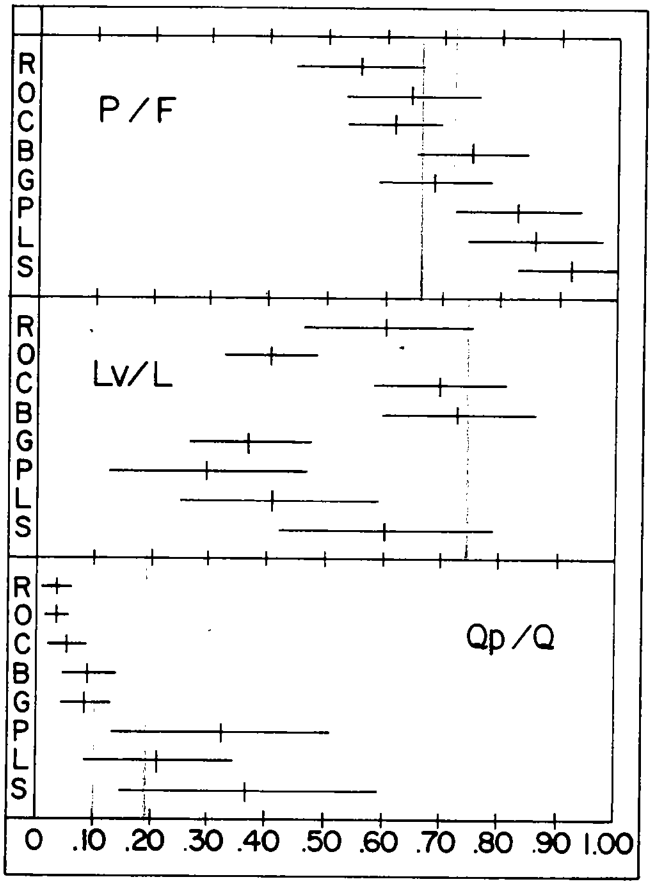

FIG. 6—Means and standard deviations of three ratio parameters for eight petrofacies. Petrofacies abbreviations on left side same as for Figure 5. See text for discussion.

soll, 1978b). This variant may represent the erosion of local exposures of metamorphic terranes. Average Lv/L values are lower and average M values are higher within this variant than within the much more common low-L Rumsey variant. The Rumsey petrofacies occurs throughout the Great Valley area.

IMPLICATIONS

In the following discussion of geologic implications of the Great Valley petrofacies, new terminology is introduced to facilitate discussion. I propose that the following terms be used where source rocks of sediments are known: plutoniclastic, metamorphiclastic, and sedimentaclastic, in addition to the widely used volcaniclastic. These terms are genetic and interpretive, as opposed to descriptive terms such as arkose and graywacke, although the latter terms commonly have been used incorrectly to imply specific provenance or tectonic significance. The new terms are needed because there are presently no comparable terms that are based on source rocks alone. Naturally, the terms must be applied carefully and they represent end-member sediments. For example, the Great Valley Group contains mixtures of all four types of sediments, although volcaniclastic and sedimentaclastic sandstones dominate the lower part of the section, and plutoniclastic sandstones dominate the upper part of the section. Specific terms such as phyllarenite, low-rank graywacke and schist wacke (summarized and discussed in Chapter 5 of Pettijohn et al, 1972) are based on both composition and texture; they do not directly reflect source rocks, although these sandstones generally are metamorphiclastic. The terms proposed here may be applied equally well to sand and sandstone, mud and mudrock, and gravel and conglomerate. The scheme is used most successfully in describing immature sediments in tectonically active settings where source rocks determine detrital composition (e.g., Great Valley Group).

Dickinson and Rich (1972), Ingersoll (1978b), Mansfield (1979), and others have discussed the general and specific implications of the Great Valley petrofacies. The following discussion is restricted to modifications necessitated by the new data as well as new insights.

Figure 7d illustrates the temporal change from more lithic to more feldspathic sandstones. This change reflects the dominance of both volcanic and sedimentary supracrustal components early in the arc history, and the later dominance of exposed plutons (unroofed batholith) in the Late Cretaceous. Figures 7 (e and f) illustrates that polycrystalline quartz (mostly chert) and sedimentary-metasedimentary lithics (mostly shale-argillite) constituted most of the lithic fragments early, and that volcanic lithics, and to a lesser degree, metamorphic lithics were more important later, relative to other lithic fragments. This conclusion agrees with the observation that M increases with time (Fig. 5), suggesting increasing depth of erosion of the magmatic arc. Decreasing P/F through time is explained readily by the increasing potassium-feldspar content of modern arcs away from their trenches (Dickin-

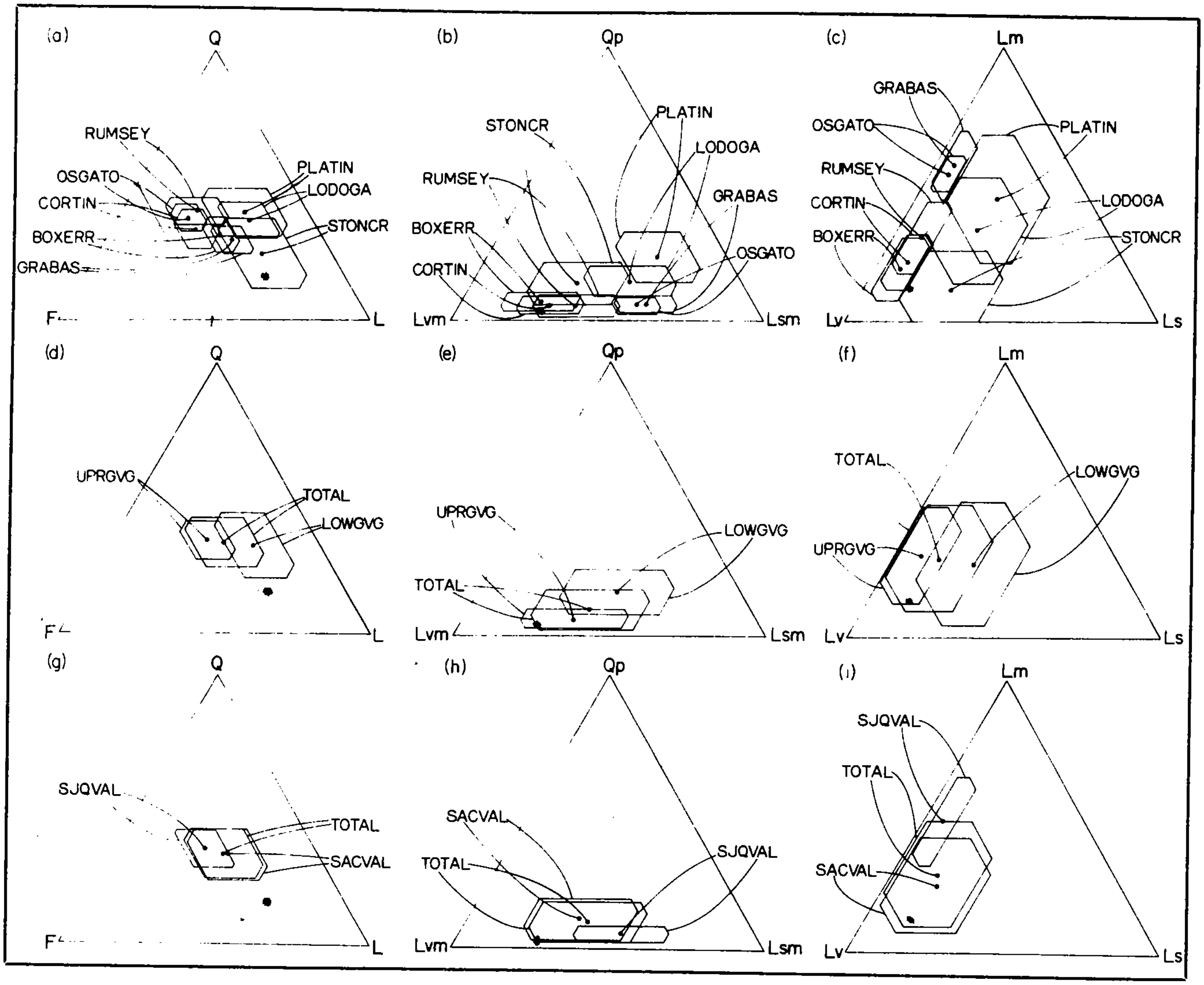

FIG. 7—Triangular plots of QFL (left), QpLvmLsm (center), and LmLvLs (right) for eight petrofacies (top row), TOTAL, upper (UPRGVG), and lower (LOWGVG) super petrofacies (middle row), and TOTAL, Sacramento (SACVAL), and San Joaquin (SJQVAL) super petrofacies (bottom row). See Table 2 for explanation of terminology. See Ingersoll and Suczek (1979) for discussion of statistical significance of fields of variation determined by standard deviations. See text for discussion of plots.

son, 1975), coupled with the eastward migration of the Sierra Nevada arc during the Cretaceous (Evernden and Kistler, 1970; Dickinson, 1973; Ingersoll, 1978a, b, 1979a). The lowest occurrence of significant amounts of potassium-feldspar in the Great Valley Group is within the Lodoga petrofacies, which also contains the lowest occurrence of significant quantities of monocrystalline quartz and increased phyllosilicates (increased plutoniclastic detritus).

North-south variations of petrofacies are illustrated in Figure 7 (g, h, i). These plots primarily reflect the contrast in crust ("continental" to the south and "oceanic" to the north), within which and on top of which the late Mesozoic magmatic arc was constructed (Burchfiel and Davis, 1972; Kistler and Peterman, 1973; Ingersoll, 1978b). The San Joaquin petrofacies contain higher percentages of plutoniclastic and metamorphiclastic detritus, whereas the Sacramento petrofacies contain more volcaniclastic and sedimentaclastic (supracrustal) detritus. These conclusions are supported by the positive correlation coefficients relating southerly distance to Qm, M, and Lm (Table 5) for the upper part of the sequence, and by the increasingly felsic nature of volcanic lithic fragments to the south (Ingersoll, 1978b). Correlations among most of these components for the lower petrofacies are insignificant, but correlation between Lv and distance is positive, reflecting distance from nonvolcanic sources in the Klamaths. Sub-Upper Cretaceous petrofacies are mostly absent in the San Joaquin Valley (see Mansfield, 1979, for summary of the few data that exist), so that comparison of the San Joaquin and Sacramento petrofacies is affected by age differences.

In summary, prior to the Late Cretaceous, primarily sedimentaclastic and metamorphiclastic detritus was derived from the Klamath area, whereas primarily volcaniclastic detritus was derived from the Sierra Nevada east of

Table 5. Correlation Coefficients Between Distance and Age, and the Petrographic Parameters for Four Super Petrofacies and TOTAL Group*

Petrofacies**	Dist. Age+		QFL%					FRMW%				QpLvmLsm%			LmLvLs%		
			Q	Qm	F	L	Lt	M	P/F	Lv/L	Qp/Q	Qp	Lvm	Lsm	Lm	Lv	Ls
SACVAL	−0.37	D	0.12	0.30	0.33	−0.31	−0.38	0.27	−0.24	0.14	−0.35	−0.39	0.19	−0.05	0.03	0.14	−0.27
		MYBP	−0.27	−0.53	−0.55	0.56	0.64	−0.50	0.68	−0.31	0.73	0.55	−0.38	0.21	−0.12	−0.31	0.54
SJQVAL	0.18	D	0.02	0.01	−0.11	0.05	0.06	0.12	0.53	0.07	0.10	0.08	0.07	−0.09	−0.02	0.07	−0.19
		MYBP	−0.67	−0.72	−0.51	0.66	0.69	−0.29	0.69	−0.75	0.65	0.35	−0.77	0.71	0.77	−0.75	−0.21
UPRGVG	−0.16	D	0.27	0.28	0.05	−0.22	−0.23	0.38	−0.06	−0.62	−0.26	−0.12	−0.59	0.62	0.65	−0.62	−0.17
		MYBP	−0.47	−0.52	−0.15	0.42	0.45	−0.52	0.53	0.09	0.52	0.21	0.06	−0.10	−0.06	0.09	−0.04
LOWGVG	−0.01	D	−0.22	−0.02	0.18	0.06	−0.08	−0.05	0.15	0.38	−0.17	−0.46	0.45	−0.27	−0.29	0.38	−0.10
		MYBP	−0.42	−0.47	0.01	0.30	0.31	−0.46	0.20	0.32	0.43	0.04	0.31	−0.36	−0.42	0.32	0.17
TOTAL	−0.46	D	0.14	0.32	0.36	−0.34	−0.40	0.46	−0.34	−0.12	−0.41	−0.43	−0.05	0.24	0.38	−0.12	−0.38
		MYBP	−0.30	−0.56	−0.58	0.58	0.66	−0.53	0.71	−0.21	0.75	0.59	−0.30	0.10	−0.20	−0.21	0.56

*Correlation coefficients are underlined if absolute value is greater than cutoff ($2/\sqrt{n}$).

**SACVAL = Sacramento Valley; SJQVAL = San Joaquin Valley; UPRGVG = upper Great Valley Group; LOWGVG = lower Great Valley Group; TOTAL = all samples.

+Correlations between distance and age for each group.

the Sacramento Valley. During the Late Cretaceous, volcaniclastic detritus was contributed by the entire Sierra Nevada arc, with greater amounts of metamorphiclastic detritus in the south; plutoniclastic detritus increased with time.

There are other interesting correlations demonstrated in Table 5. However, interpretation of many of these correlations is complicated by the fact that many of the variables are linked either mathematically or geologically. Of special concern is the fact that distance (increasing southward) and age (m.y. before present) are negatively correlated for the SACVAL and TOTAL groups. This correlation is due to the lack of sub-Upper Cretaceous petrofacies in the San Joaquin Valley as well as to better exposure of Upper Cretaceous petrofacies at the south end of the Sacramento Valley than at the north end. Therefore, some correlations in these two groups are artifacts of this sampling bias rather than being geologically significant. This problem does not exist for the other three groups in Table 5, as demonstrated by the lack of significant correlation between distance and age.

The primary way in which the present petrofacies differ from those of Dickinson and Rich (1972) is in the recognition that the lower petrofacies (Stony Creek, Platina, and Lodoga) contain significant proportions of nonvolcanic detritus (Ingersoll, 1979b). In addition, the Platina petrofacies is newly defined as a separate entity. Dickinson and Rich (1972) mentioned that petrologic characteristics at the north end of the Sacramento Valley did not fit easily into the petrofacies subdivisions to the south. They included all of the sediments at the north end of the valley in their Lodoga petrofacies, even though the bottom of the section is significantly older than the lower Lodoga to the south. Discriminant analysis suggests that the northern sandstones (primarily locally derived from underlying metamorphic terranes) are distinct enough from both the Stony Creek and Lodoga petrofacies to warrant establishment of a new petrofacies. The Platina differs from the other two petrofacies in having higher Qp and Lm (primarily metasedimentary; Fig. 7b, c). However, as mentioned, the boundary between the Platina and the other two petrofacies is gradational and possibly intertonguing (Fig. 4). The Stony Creek and Lodoga become more volcaniclastic in nature to the south (Table 5).

Recognition of significant quantities of Qp, Ls, and Lsm (sedimentaclastic and metamorphiclastic detritus) within the three lower petrofacies is supported by studies of Upper Jurassic and Lower Cretaceous conglomerates (e.g., Bertucci, 1980; Seiders, 1983). Dickinson and Rich (1972) noted that chert was the predominant clast type in these conglomerates, without explaining the apparent lack of voluminous chert in their sandstones. Detailed study of the paleontology of some of the chert clasts in the conglomerates confirms that source areas included both Klamath and northern Sierra Nevada Triassic-Jurassic terranes (Bertucci, 1980; Seiders et al, 1979) which consisted of accreted "tectonic highlands" (intraoceanic arcs, subduction complexes, and related features) and locally formed continental-margin arc terranes. These terranes were accreted to North America and/or deformed primarily during the Late Jurassic during arc-arc collision (Schweickert and Cowan, 1975; Irwin, 1981; Schweickert, 1981; Ingersoll, 1982), the classic Nevadan orogeny. Thus, when the late Mesozoic subduction regime was initiated in the Tithonian, significant terranes of nonvolcanic rock provided much of the detritus to the base of the Great Val-

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ley Group. These sedimentaclastic and metamorphiclastic sediments resemble suture-derived detritus more than arc-derived detritus (e.g., Graham et al, 1976; Ingersoll and Suczek, 1979). This is demonstrated best by the fact that the Platina (and to a lesser degree, the Stony Creek and Lodoga) overlaps the "mixed magmatic arcs and subduction complexes" and "suture belts" fields of Figure 6 of Ingersoll and Suczek (1979) (compare to Figure 7b, c of this paper). In contrast, all of the other petrofacies plot within or very close to the "magmatic arc" fields. This observation has fundamental significance regarding paleotectonic reconstructions of California in the Jurassic because the abundance of suture-derived detritus in the lower Great Valley Group is consistent with Schweickert and Cowan's (1975) model. Prior to the identification of this detritus, a major problem with the model of arc-arc collision during the Nevadan orogeny was the scarcity of subduction- and suture-related detritus in the Sierran foothills, where it "should" be (R. A. Schweickert, personal commun., 1981). The present results suggest instead that most of this detritus accumulated in the newly formed forearc basin (Great Valley) west and south of the suture belts.

Bertucci (1980) has suggested that Tithonian and Valanginian conglomerates within the Stony Creek Formation are fundamentally different, with the former primarily consisting of chert-argillite assemblages and the latter primarily consisting of volcaniclastic detritus. My point counts agree with his cobble counts wherever we collected the same units. However, Bertucci studied only one Valanginian conglomerate (Bidwell Point lens), whereas I point-counted several Valanginian sandstones. The Bidwell Point lens apparently is unique within the Stony Creek Formation, representing an unusually pure volcanic provenance. Sandstones both above and below this unit consist of the more common mixtures of volcanic, sedimentary, and metamorphic provenances. My point counts delineate other sandstone and conglomerate units with volcaniclastic components as significant as the Bidwell Point lens, but they are minor in volume. None of the counted parameters shows a systematic difference between Tithonian and Valanginian, and all fall within the Stony Creek petrofacies, even though there are significant local variations in composition.

Local occurrences of "basaltic sandstones," detrital serpentinite, and other ultramafic sediments and volcanics within the base of the Great Valley Group (Dickinson and Rich, 1972) probably were derived locally from the underlying Coast Range ophiolite (Bailey et al, 1970; Hopson et al, 1981). Some of the "basaltic sandstones" were counted during the present study and were found to consist of mixtures of probably locally derived basaltic detritus with probably distantly derived "normal" Stony Creek detritus. Even where mafic volcanics are the dominant clast type, the sandstones have Stony Creek characteristics. Bertucci (1980) demonstrated that Kimmeridgian(?) breccias at the base of the Great Valley Group consist of ophiolite detritus. Also, McLaughlin and Pessagno (1978) suggested that the "basaltic sandstone," pillow lavas, diabase, and breccias within the Great Valley Group and the Coast Range ophiolite all had common sources.

Also of local significance are detrital and protrusive serpentinites within the Stony Creek Formation (e.g., Carlson, 1981a, b). Some Stony Creek sandstones near these protrusions (of Late Jurassic through Early Cretaceous age?) contain significant proportions of detrital serpentinite mixed with the dominant distantly derived "typical" Stony Creek detritus. It can be difficult to recognize this serpentinite detritus, especially with the high degree of burial metamorphism that the Stony Creek has experienced. Most of the serpentinite clasts were counted as Lv and/or Lvm because they are altered ultramafic or mafic igneous rocks. Some were counted as M if they consist of coarse-grained single serpentine crystals or flakes. Extrabasinal ophiolite detritus (primarily from the Klamaths and northern Sierra Nevada) shows up mostly as Lv, Qp, P, and Ls. Presumably, serpentinite weathered rapidly and could not be transported very far, so that Klamath-derived serpentinite probably is rare in the Great Valley Group. This conclusion is supported by the fact that significant quantities of identifiable detrital serpentinite have been recognized only in locations near known local serpentinite protusions.

Significant correlation coefficients were used to separate (negative) or group together (positive) various parameters (Table 6). The resulting groupings delineate the dominant source rock types for the Great Valley Group. Other groupings are possible and some parameters may stand alone in certain provenance settings (e.g., Lv may be the only significant parameter contributed by certain volcanic provinces). However, the groupings in Table 6 are suggested as the primary source types for the Great Valley Group as a whole. Potassium-feldspar probably was derived from both plutonic and volcanic settings, whereas plagioclase does not show up in any of the groups, probably because it was ubiquitous in all source areas at all times. However, interpretation of correlation coefficients between ratios, such as P/F and Qp/Q, is tentative, as discussed by Ingersoll (1978b). The associations in Table 6 seem to be the best estimates for major source rock types based on statistically determined correlations and geologic reasoning.

Table 6. Parameter Associations for TOTAL Group

Qm-F-K-M-Lm	(plutoniclastic-metamorphiclastic)
F-K-Lv-Lvm	(volcaniclastic)
Lt-Q-Qp-Lsm-Ls	(sedimentaclastic)
M-Lm-Lsm	(metamorphiclastic)

CONCLUSIONS

The present study demonstrates the usefulness of detailed sandstone petrography in stratigraphic, provenance, and paleotectonic studies. The late Mesozoic and Paleogene magmatic-arc history is preserved within the Great Valley Group and related strata, and magmatic-tectonic events (many of which are basinwide) control petrostratigraphic characteristics.

The lower part of the Great Valley Group (Upper Jurassic and Lower Cretaceous) contains significant quantities of sedimentaclastic and metamorphiclastic material eroded from accreted and deformed terranes ("tectonic highlands") formed by arc-arc collision (Nevadan orogeny) that occurred prior to initiation of the Franciscan-Great Valley-Sierra Nevada arc-trench system. The Klamath Mountains area provided a major proportion of this detritus. Ophiolite and serpentinite detritus was deposited locally near the base of the Great Valley Group as a result of deformation along the east side of the growing Franciscan subduction complex. Volcaniclastic detritus was fed into the entire forearc basin as magmatism increased in the Sierra Nevada area during the Early Cretaceous. As the volcanic cover was stripped off, plutoniclastic and metamorphiclastic detritus from the underlying batholithic terranes was provided in abundance to the forearc basin. Crustal components were more "continental" in the southern Sierra Nevada and more "oceanic" in the northern Sierra Nevada, as demonstrated by the higher proportions of metamorphiclastic detritus and by the more felsic nature of volcaniclastic detritus to the south. By the middle of the Late Cretaceous, extensive batholithic terranes provided K-feldspar-rich arkosic detritus to the entire forearc basin. By the Paleogene, arc magmatism had migrated eastward sufficiently that the California part of the arc was eroded to deep levels, tectonic activity was lessened in the forearc basin, and the basin filled to sea level in most parts.

The data presented here represent the most complete documentation of the history and erosion of any magmatic arc. The late Mesozoic arc-trench system of California may be used as a norm for comparison with other systems because it is so thoroughly studied. However, the local history of any basin and related source areas must be understood on its own terms also, as demonstrated by the present study. Speculations concerning magmatic-arc evolution in general must await additional detailed analysis of other arc-derived sediments.

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