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ABSTRACT

The Great Valley Sequence of Upper Jurassic to Upper Cretaceous strata is composed of clastic detritus eroded from the Sierran-Klamath belt, which was the site of a late Mesozoic magmatic arc. The sequence accumulated mainly as a prismatic wedge of turbidites in an asymmetric trough within the arc-trench gap. Stratigraphic variations in detrital sandstone mineralogy define five petrologic intervals, or nearly synchronous petrofacies, useful for regional correlation. By contrast, local lithofacies are markedly lenticular. The clastic debris in the sequence was derived mainly from volcanic and plutonic rocks in varying proportions. The parameters used to define the petrofacies include: (a) content of quartzose grains (Q), feldspar grains (F), and unstable lithic fragments (L) expressed as volumetric percentages of the Q-F-L population; (b) ratios of plagioclase to total feldspar (P/F) and volcanic rock fragments to total unstable lithic fragments (V/L), and (c) content of mica (M) expressed as volumetric percentage of framework sand grains. The most distinctive characteristics of the petrofacies recognized, and their approximate time-stratigraphic spans, are as follows: (1) Stony Creek (Tithonian-Neocomian): quartz-poor and feldspatholithic sandstones with high P/F, high V/L, low M; (2) Lodoga (Aptian-Albian): quartz-rich sandstones with high P/F; (3) Boxer (Cenomanian): two distinct variants with moderate P/F, one quartz-rich and the other quartz-poor and feldspatholithic; (4) Cortina (Turonian-Coniacian): two similar variants with moderate P/F, one with Q-F-L proportions nearly equal and the other quartz-poor and feldspatholithic; (5) Rumsey (Santonian-Campanian): quartz-rich lithofeldspathic with low P/F and high M. The nature of the petrofacies and their age can be related to the petrology and timing of dated intrusive episodes with inferred volcanic accompaniments in the Sierra Nevada. The Stony Creek petrofacies contains mainly volcanic debris erupted during the Yosemite magmatic epoch, and the overlying Lodoga petrofacies contains mainly plutonic debris emplaced during the same epoch, but only exposed to erosion by subsequent dissection. The Boxer and Cortina petrofacies contain mixed and intercalated volcanic and plutonic debris derived mainly from rocks erupted or emplaced during the Huntington Lake magmatic epoch. The slight differences between the Boxer and Cortina petrofacies may indicate that plutonic contributions were partly from older rocks for the Boxer, but volcanic contributions were essentially the same for both. The Rumsey facies contains mainly plutonic debris, with subordinate volcanic debris, derived from igneous rocks of the Cathedral Range magmatic epoch. Except locally or slightly, petrofacies boundaries do not transgress time-stratigraphic boundaries in the region. A close linkage among major magmatic, tectonic, and depositional events in arc-trench systems is implied.

INTRODUCTION

The Great Valley Sequence (Bailey and others, 1964, p. 123) includes 12 to 15 km of clastic sedimentary strata, ranging in age from Late Jurassic to Late Cretaceous, that crop out mainly in a complex homocline flanking the Coast Ranges along the western side of the Great Valley of California (Fig. 1). Strongly folded and faulted exposures of the Great Valley Sequence within the Coast Ranges to the west structurally overlie coeval rocks of the Franciscan Assemblage along a complex regional thrust fault. The Franciscan rocks were thrust beneath the Great Valley strata in a subduction zone associated with a late Mesozoic trench (Ernst, 1970). The Franciscan Assemblage is partly metamorphosed to

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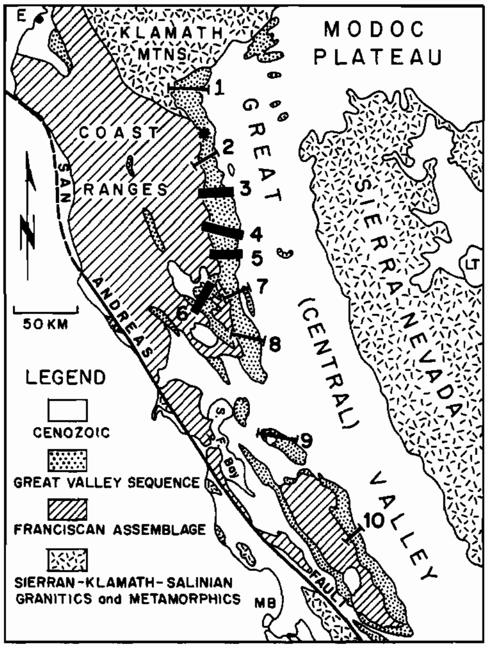

Figure 1. Sketch map showing location of traverses and mapped belts of exposure along which petrologic intervals in the Great Valley Sequence have been keyed in the field to stratigraphy mapped locally (*see* Fig. 2). Single and multiple traverses along roads and streams are shown schematically by lines. Mapped belts are indicated schematically by heavy bars, and nos. 3 to 5 adjoin to provide locally continuous control along strike (*see* Fig. 2). Eureka (E), San Francisco (S.F.) Bay, Monterey Bay (MB), and Lake Tahoe (LT) are indicated for orientation. Large asterisk (*) between traverses 1 and 2 denotes position of the Paskenta–Elder Creek–Cold Fork system of prominent transverse faults. Salinian block lies west of San Andreas fault.

tectonites, and is in the exceptional structural disorder of mélange over wide areas. The Great Valley Sequence, however, is involved only in simple folds, except for local imbricated belts in the overthrust terrane (Swe and Dickinson, 1970; Rich, 1970). Much of the Franciscan Assemblage is in the blueschist facies, but the Great Valley Sequence generally is not metamorphosed beyond zeolitic grade (Dickinson and others, 1969).

Most of the Great Valley strata seen on the outcrop are turbidites, and the base of the sequence in the Coast Ranges may lie depositionally on an ophiolitic slab of uplifted oceanic crust (Bailey and others, 1970). Shallower Upper Cretaceous facies occur to the east in the subsurface of the Great Valley, and locally in the foothills of the Sierra Nevada. These beds rest unconformably on granitic and metamorphic basement rocks of continental aspect. Paleocurrents in the turbidites are mainly longitudinal, parallel to the regional grain, and west of the Sacramento Valley indicate flow dominantly from north to south (Ojakangas, 1968). Subordinate plaeocurrents indicating transverse flow from east to west are most commonly associated with coarser sequences, and probably indicate the presence of subsea fans built into a deep trough from a source region to the east.

As discussed below, the source terranes were mainly igneous rocks, both volcanic and plutonic, in the region of the present Sierra Nevada batholith and similar ground in the Klamath Mountains to the north. During deposition of the Great Valley Sequence in the late Mesozoic, the Sierran-Klamath region was a magmatic arc along the continental margin of Mesozoic North America, much as the Andes now lie along the continental margin of Cenozoic South America (Hamilton, 1969). The site of deposition of the Great Valley Sequence was evidently a deep trough that lay within an arc-trench gap spanning the continent-ocean interface between the Sierran arc and the Franciscan trench (Dickinson, 1971). On the side bounded by the Sierran arc, the Great Valley trough had a shelving flank that was probably modified progressively by faulting during deposition (Brown and Rich, 1967). The Great Valley trough was probably separated from the Franciscan trench by a submerged bathymetric barrier similar to the outer acoustic basement ridges in many modern arc-trench systems (Karig, 1970). Such barriers are likely formed by the isostatic uplift of mélanges and other crustal rocks stacked tectonically within subduction zones. We interpret all the contacts known to us between the Franciscan Assemblage and the Great Valley Sequence within the Coast Ranges as faults. However, submarine unconformities that are as yet undescribed may well occur locally between Great Valley strata and Franciscan mélanges, if the hypothesis of the bathymetric barrier during deposition is valid. Assumption of its presence now seems the most logical way to account for the dominance of longitudinal paleocurrents in the Great Valley Sequence (Ojakangas, 1968).

Ojakangas (1968) first showed that stratigraphic variations in the detrital mineralogy of sandstones in the Great Valley Sequence correlate well in detail with radiometrically dated magmatic episodes that affected the Sierra Nevada batholith. His petrologic data were based on a detailed traverse through the section exposed at Cache Creek. Our purpose in this paper is to show that the same variations occur at roughly the same time-stratigraphic horizons for most of the length of the Great Valley. We recognize five petrologic intervals, or "petrofacies" units (Mansfield, 1971a). The value of the petrofacies for correlation is far superior to local lithofacies, which are markedly lenticular. Where fossils are scarce, as is commonly the case in exposures of complexly deformed Great Valley strata in the Coast Ranges, diagnostic petrologic intervals are an effective aid to structural mapping (Swe and Dickinson, 1970; Rich, 1970; Gilbert and Dickinson, 1970; *also* Schilling, 1962a). The nature of each petrofacies can be interpreted in terms of the timing and characteristic petrology of correlative magmatic epochs and intrusive series in the Sierra Nevada. The source terrane for graywackes in the coeval Franciscan Assemblage is thought to have been the same Sierran arc region. We hope, therefore, that the petrologic intervals established within the Great Valley Sequence can be used to help determine large-scale structural relations within the largely unfossiliferous Franciscan rocks.

The stratigraphic relations used here as a basis for the presentation of the petrologic data are taken mainly from a recent compilation by Rich (1971, in press). Previously unreported point counts of sandstones were performed by Dickinson. Field reconnaissance of petrologic intervals in all traverses noted was done jointly. Strata along the west side of the Great Valley south of the Sacramento–San Joaquin drainage divide are not discussed, but are treated by Mansfield (1971b). His detailed work near Coalinga shows that the same general petrofacies can be recognized there, but with distinctive local variants whose possible significance he discusses.

METHODS

The median grain size of clastic rocks in the the Great Valley Sequence spans the full range from clay to gravel, but sandstones and silty mudstones are most common. In most sections, the proportion of rock types present is approximately as follows: (1) 55 to 75 percent sequences of thin-bedded (1 to 5 cm) gray to green lutite (mudstone-siltstone), with intercalated thin beds (1 to 20 cm) of graded or laminated fine-grained sandstone. (2) 25 to 40 percent sequences of medium- to coarse-grained, massive or graded sandstones in beds typically 25 cm to 1 m thick, with intercalated layers of thin-bedded mudstone-siltstone between sandstone beds. (3) 0 to 10 percent sequences of pebble and cobble conglomerate, locally bouldery, in massive or imbricated thick beds (1 to 15 m), with intercalated layers and lenses of sandstone.

All the figures quoted are generalizations, and exceptions exist to each statement given; nevertheless, the three lithofacies described are representative, and field mapping to date has relied principally upon recognition of these three main types of sequences for the designation of packets of strata as formations or informal map units. The approach is satisfactory for establishing detailed stratigraphic relations locally, but is not particularly useful for a regional view. The local representatives of each type of lithofacies are packets of strata that range from a few tens of feet to thousands of feet in thickness, and are markedly variable and lenticular along strike. Gradational and intertonguing relations abound both vertically and laterally within the stratigraphic sequence. Unless each lithofacies is mapped continuously along the outcrop, correlations cannot be defended well. In the field, many structural complications and areas of poor exposure break the continuity of outcrops.

Stratigraphic variations in detrital mineralogy offer the means of establishing petrologic intervals, or petrofacies units, that can be recognized in all exposures despite local variations in lithofacies. This approach is not intended to wholly replace the mapping of lithofacies, for accurate data on local lithofacies commonly may be the most important information for purposes of economic and environmental geology. Nor are the petrologic correlations intended to supplant paleontological correlations, for the petrologic intervals are a type of rock-stratigraphic unit, and are not time-stratigraphic in a rigorous sense. If the petrologic intervals prove to be slightly time-transgressive in a regional view, they may provide important insight into the over-all pattern of sediment delivery into the Great Valley trough. Meanwhile, where fossils are rare, the petrofacies provide a rough key to approximate time-stratigraphic relations.

We have used the detrital mineralogy or petrology of medium- to coarse-grained sandstones to define the petrofacies. Finer grained rocks are unsuitable for detailed optical work, but nearly all mudstone-siltstone sequences locally contain enough interbeds of sandstone to be included in our work. Conglomeratic sequences also contain suitable sandstone interbeds in most instances.

We have not worked systematically with the conglomerates themselves for three reasons. First, they are too rare in many areas—and at many horizons—to offer the possibility of systematic sampling. Second, many are rich in intrabasinal and reworked clasts. Third, the task of developing a statistically valid expression for the volumetric composition of a conglomerate bed has proved to be too challenging and tedious for routine application on a regional basis. The traditional count of 100 random or adjoining clasts leaves room for obvious bias, unless beds do not vary much in composition internally, and results in percentage figures for clast types that are little better than gross estimates under the most favorable circumstances. With C. F. Mansfield, we tried making point counts of 400 to 600 clasts exposed on the faces of clean outcrops using a ruled stick to establish a grid. Conditions of weathering required us to break nearly every clast in order to complete the operation. Even so, the identification of clasts of fine-grained igneous and metamorphic rocks proved to be partly impossible without individual thin sections of each of a number of types of clasts that looked similar through the hand lens.

For the sandstones, a single thin section permits point counts of 400 to 600 grains. A count of 500 points provides estimates of the volumetric percentage of major grain types that are probably within 2.5 percentage points of the true values. Consistent differences on the order of 2.5 to 5 percentage points are then significant. To achieve a similar result for conglomerates would be much more costly and time consuming. We recognize that our restricted use of the sandstones requires a level of interpretation, from type of sand grain to inferred source rock, that would not be required for conglomerates whose clasts are pieces of bedrock. In practice, this potential difficulty has not been a major problem, and we show below that the compositions of the conglomerates that have been studied in the section are in general agreement with our results for the sandstones.

Our petrographic work with the sandstones has been within the framework outlined elsewhere by Dickinson (1970a), to whom the reader is referred for details of procedure and the recognition of salient grain types in thin section.

Clast Types and Source Rocks

The sandstones in the Great Valley Sequence are all texturally immature rocks with subangular to subrounded grains, and a matrix that ranges in amount from a few percent to as much as one-fifth to one-quarter of the rock. Calcareous cement is common, but we have avoided rocks with large amounts, for where the calcite is abundant, it partly replaces detrital grains as well as matrix. Grain populations are unstable chemically, and all the sandstones would fall within the fields of graywacke and arkose in most classifications. Quartzose grains are consistently less than two-thirds of the detrital sand framework, and commonly are less than half the framework.

We divide the framework initially into quartzose grains (Q), feldspar crystals (F), and lithic fragments (L) of unstable, aphanitic rocks (Dickinson, 1970a). Rock compositions can than be expressed in the simplified form $Q_xF_yL_z$ where the subscripts are volumetric percentages.

Quartzose grains are mainly common plutonic quartz crystals with curvilinear trains of vacuoles and wavy extinction. Clear, unstrained volcanic quartz crystals, some still bipyramidal, also occur in varying but lesser proportions, except in the most lithic sandstones where they may locally dominate the quartzose grain population. Chert and metachert are ubiquitous in small amounts, consistently less than 10 percent of the total quartzose grains. We count as chert or metachert only those aphanitic grains that are essentially pure silica. Siliceous argillite and felsite grains are counted as lithic fragments. No orthoquartzite fragments or overgrown quartz crystals indicative of second-cycle quartzose detritus have been observed in any of the sandstones.

Fesldpar grains include both plagioclase and potash feldspar types, whose relative proportions were recognized early as an important key to different compositions of source rocks (Bailey and Irwin, 1959). Volcanic and plutonic varieties of both feldspar types are present, but we have gathered no systematic data on their relative abundances at different horizons. Much of the plagioclase in the sequence is partly or wholly albitized (Dickinson and others, 1969), and this alteration to an essentially metamorphic composition and structural state largely spoils the chance to gauge whether any plagioclase grains present were originally volcanic or plutonic. The presence of altered, rounded glass inclusions is an indicator, but not an infallible one, of volcanic plagioclase in some cases. Structural states of the potash feldspar, which is largely unaltered, offer a potential means for identifying plutonic and volcanic crystals. Although we have noted the presence of sanidine in some rocks, mainly from lithic sandstones in the Upper Cretaceous, we have not undertaken a systematic survey of the structural state of the potash feldspar in the section. Statistically valid results would require an extensive program of work, and their interpretation would remain uncertain in view of the present incomplete knowledge about the structural state of feldspars in Sierran granitic rocks.

Lithic fragments are mainly volcanic and metavolcanic types. In view of the albitic and chloritic alteration within the Great Valley Sequence, no useful distinction can be drawn between volcanic rock fragments with fresh mineralogy and those with unaltered volcanic textures but greenschist or subgreenschist mineralogy. Schistose and granoblastic metavolcanic rock fragments are rare, and were counted as a variety of metamorphic rock fragments. Volcaniclastic rock fragments are probably common, but were counted with other clastic types as a variety of sedimentary rock fragments. Small amounts of clearly hypabyssal igneous rock fragments with hypidiomorphic microgranular textures were counted as a variety of volcanic rock fragments. The volcanic rock fragments are mainly fine-grained microlitic types suggestive of intermediate compositions, but felsitic types of more silicic composition are also common. Many felsite grains may be devitrified. Vitric types and clearly mafic, intergranular-intersertal types are rare throughout the section. No systematic variations in the proportion of "microlitic" and "felsitic" types could be detected with confidence, partly because the actual variation in groundmass textures is so difficult to categorize. The ratio of felsitic types to microlitic types is probably higher over-all in the Upper Cretaceous rocks than in older parts of the sequence.

Nonvolcanic lithic fragments are mainly argillitic sedimentary rocks and metasedimentary rocks of slaty to phyllitic, or of hornfelsic, character. No independent trends of relative proportions could be established for either, largely because their variability is great, yet their abundance is low.

Heavy minerals were not separated, because earlier studies had indicated that inferences about the nature of the source terranes for unstable sandstones can be made directly from the light mineral fraction. In thin section, epidotes, amphiboles, pyroxenes, sphene, garnets, and zircon are occasionally seen, but only micas are volumetrically significant. The content of mica, mainly biotite, is a diagnostic supplementary parameter, M, for the recognition of petrologic intervals in conjunction with aspects of the Q-F-L population.

From the grain populations in the sandstones, we infer that the source rocks were mainly cogenetic suites of volcanic, hypabyssal, and plutonic igneous rocks with which were associated adjoining metamorphic terranes of low-grade metasedimentary and metavolcanic rocks. This description would appear to apply well to the Sierran-Klamath region in the late Mesozoic, as implied above. Reported clast types in conglomerates support the inference of the nature of the source. A compositional range representative of many conglomerates is: 40 to 60 percent volcanic and metavolcanic rocks, mainly intermediate types with lesser felsite; 15 to 35 percent granitic and other plutonic rocks; 10 to 30 percent chert and quartzitic metachert; 5 to 15 percent clastic sedimentary rocks, and 5 to 15 percent metamorphic rocks. Porphyritic andesitic to dacitic volcanic rocks and hypabyssal porphyries of similar petrology are everywhere abundant. Welded rhyolitic tuffs are rare but striking locally. Granitic and subordinate dioritic-gabbroic plutonic rocks are common but rarely dominant. The tendency for granitic rocks to disintegrate to sandy grus upon weathering, whereas dense joint blocks of aphanitic volcanics are persistent, may account partly for the high ratio of volcanic to plutonic clasts in most conglomerates. Resistant chert is common in conglomerates, and locally dominant in some older ones. The chert is almost wholly some shade of gray, and doubtless came from chert-argillite sequences like those now exposed in the Sierran foothills and the Klamath Mountains, rather than from the Franciscan Assemblage, in which red and green cherts are widespread. Metamorphic rocks include gneisses, schists, slates, phyllites, quartzites, and hornfelses like those common as wall rocks around the Sierran-Klamath batholiths. Blueschists are not represented.

DIAGENETIC ALTERATIONS

Valid detrital modes can be determined for sandstones only where diagenetic or metamorphic modifications of the original mineralogy and texture have not been severe enough to obscure the initial grain population (Dickinson, 1970a, p. 703). Most of the rocks we have studied have undergone mild burial metamorphism in the zeolite facies, but there are no tectonites (Dickinson and others, 1969).

The most characteristic alterations are albitization of plagioclase and chloritization of biotite; both alterations increase in intensity with stratigraphic depth in the sequence. Clayey alteration products occur in potash feldspar, but white mica inclusions are not abundant, and those present probably were inherited from source rocks. Both albitization and chloritization were replacement reactions—albite containing inclusions of associated hydrous, lime-bearing phases is pseudomorphous after plagioclase; and chlorite is pseudomorphous after biotite. In grain counting, the replacement pseudomorphs were interpreted as directly representing the original minerals. Potential errors stemming from simple volume changes during alteration are not significant. Similar albitization and chloritization of crystals within unstable rock fragments do not interfere with the identification of original grain types. Where calcareous cement is abundant, partial replacement of detrital grains is widespread, and is preferential for plagioclase (Ojakangas, 1968), but we have avoided calcareous rocks for the grain counts reported here.

Of more concern is the abundance of interstitial phyllosilicate matrix, which includes diagenetic epimatrix grown in pore spaces after deposition, as well as recrystallized detrital lutum, or orthomatrix (Dickinson, 1970a, p. 702). The substance of the epimatrix was probably derived in part from alteration of the detrital framework; unstable lithic fragments and heavy minerals are especially likely contributors of material for the growth of epimatrix during diagenesis. Such a mass transfer process within the rocks may bias our data in ways we cannot detect, but the bias is unlikely to be significant for two reasons: (1) in rocks from comparable horizons in the sequence, no systematic variation was observed in the proportions of grain types in the detrital framework as the matrix content varies from minimal to maximal amounts; and (2) the proportion of unstable lithic fragments does not decrease as alterations increase in intensity with stratigraphic depth in the sequence.

Also of potential concern is the intrastratal solution of detrital grains. Selective removal of hornblende, and probably other pyriboles, has been reported previously for the rocks we have studied (Ojakangas, 1968). Except for micas, however, we do not rely upon any heavy minerals as indicators of changes in detrital composition, and we have excluded them as well as matrix from our recalculated detrital modes. The uniformly fresh appearance of white mica flakes throughout the sequence, and the pronounced tendency for biotite flakes to alter in place to clear chlorite pseudomorphs with crisp outlines, argues against any wholesale removal of mica. Neither micas nor feldspars display etched or serrate grain boundaries that might reflect partial removal. We conclude that none of the grain parameters we emphasize has been affected significantly by diagenetic changes.

PETROLOGIC INTERVALS

Five stratigraphically controlled petrofacies have been recognized in correlative petrologic intervals within the Great Valley Sequence in ten areas between the northern end of the Great Valley and the latitude of Monterey Bay (Figs. 1, 2). We use the term "petrofacies" to imply rocks of similar petrology, and the term "petrologic interval" for the stratigraphic entity within which a petrofacies occurs. The terms are thus analogous to, but not the same as, lithofacies and formation, respectively. The names proposed here for the five petrofacies are taken from local stratigraphic units that are

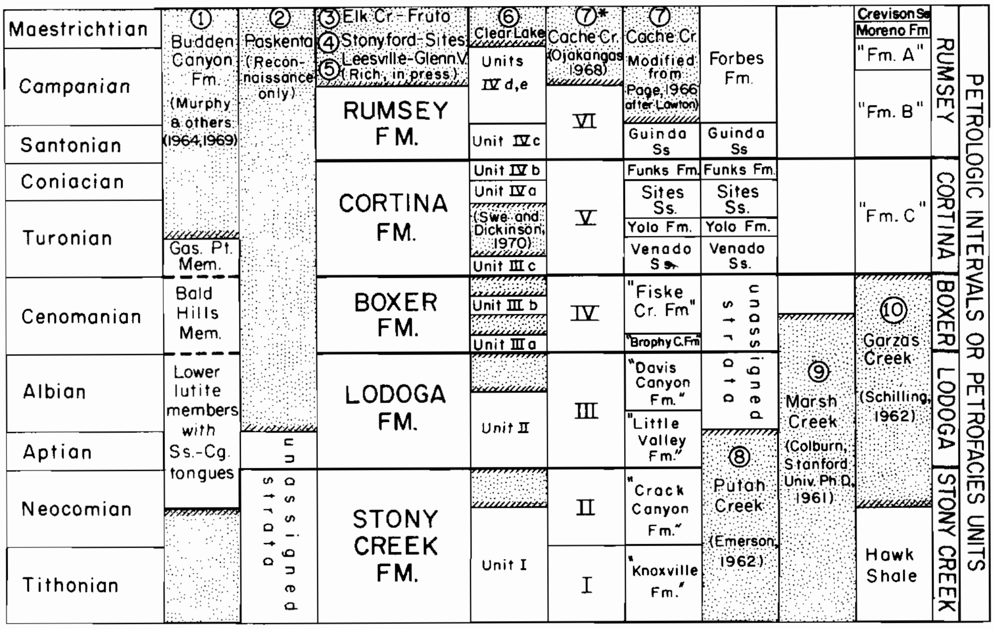

Figure 2. Correlation of petrologic intervals with local stratigraphy in exposures of the Great Valley Sequence mapped in detail (references cited). Columns designated by general geographic location and by numbered traverse (Fig. 1). Petrofacies boundaries (right-hand column) are shown by heavy lines. Approximate time-stratigraphic scale is controlled by radiometric dates (*see* Fig. 9). Shaded bars denote stratigraphic limits of local exposures. Extra column for Cache Creek (*) shows correlation of our petrofacies with petrologic intervals (in Roman numerals) of Ojakangas (1968). Petrofacies names taken from columns 3, 4, 5. The exact coincidence shown between stage boundaries and petrofacies boundaries is only a pictorial device to indicate our best estimates of the mutual relations, and should not be taken as indicative of precise correlations.

coextensive locally with the respective petrofacies in a large area west of the Sacramento Valley described by Rich (1971, in press). The correlation of the regional petrologic intervals with the local compositional intervals of Ojakangas (1968) at Cache Creek is shown in Figure 2. The five named petrofacies units of this paper are the same as the five lettered petrologic "intervals" and "units" of Rich and others (1969), Swe and Dickinson (1970), and Gilbert and Dickinson (1970).

Rigorous definition of the petrologic differences between the petrofacies is based on detailed petrography, but most of the distinctions can be made readily on the outcrop using only a hand lens. In all ten areas used for control, the petrologic intervals have been related directly to local lithostratigraphic units based on detailed geologic mapping (Fig. 2). The older petrofacies are most completely exposed at the surface toward the north, whereas the younger petrofacies crop out mainly toward the south. The correlation with biostratigraphic units (Figs. 2, 9) is approximate only; but it is consistent, with one exception—the Budden Canyon traverse that is discussed later.

We here discuss the petrographic characteristics of each petrofacies with reference to a series of figures showing various aspects of the compositions of sandstones in the five petrofacies. Figure 3 shows proportions of quartzose grains (Q), feldspar grains (F), and unstable lithic fragments (L) expressed as percentages of the Q-F-L population recalculated to 100 percent. Some of the petrofacies can be distinguished on this basis alone. Figure 4 shows two ratios which permit further discrimination: (1) P/F, plagioclase to total feldspar grains, and (2) V/L, volcanic rock fragments to total unstable lithic fragments. Figure 5 shows the mica content, M, expressed as volumetric percentage of the framework, or of total sand

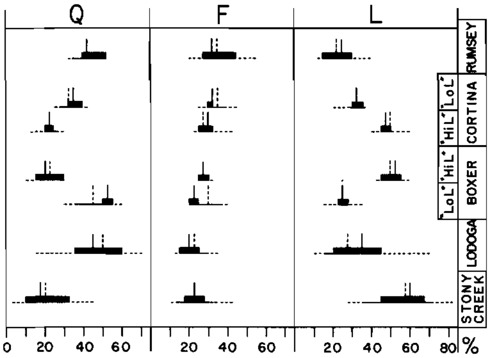

Figure 3. Volumetric Q-F-L percentages of quartzose grains (Q), feldspar grains (F), and unstable lithic fragments (L) in each of the petrologic intervals in the Great Valley Sequence. Different percentages are given for relatively lithic ("hi L") and relatively quartzose ("lo L") variants of two intervals. Heavy bars represent the total range in control specimens counted by one operator (Dickinson), and solid-line ticks indicate the median values for these specimens. Light lines represent the additional variance introduced by including results from specimens counted by additional operators (*see* text): solid lines encompass the central two-thirds of the additional range, if any, and dashed lines encompass the full range of all specimens counted; dashed ticks indicate the median values for all specimens counted where these differ from median values for the control specimens. Note that median F ~ 20 to 35 for all petrofacies, but that Q and L values discriminate two general groups of contrasting petrofacies: (a) quartzose types where Q ~ 30 to 50 and L ~ 20 to 35; and (b) lithic types where Q ~ 20 to 25 and L ~ 50 to 55.

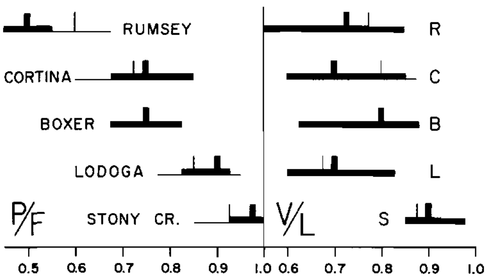

Figure 4. Values of P/F ratio and V/L ratio (*see* text) for each of the petrologic intervals in the Great Valley Sequence. Heavy bars and ticks indicate the total range and median values, respectively, for control specimens counted by one operator (Dickinson). Light lines and ticks indicate corresponding data for all specimens counted by all operators (*see* text) where these exceed the control range or differ from the control median. Note that Cortina and Boxer petrofacies show similar P/F values, and that only Stony Creek petrofacies shows distinctive V/L values.

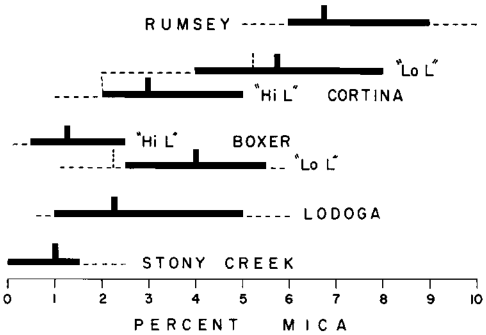

Figure 5. Volumetric framework percentages (*see* text) of mica (M) in each of the petrologic intervals in the Great Valley Sequence. Different percentages are given for relatively lithic ("hi L") and relatively quartzose ("lo L") variants of two intervals. Heavy bars and ticks indicate the total range and median values, respectively, for control specimens counted by one operator (Dickinson). Dashed lines and ticks indicate corresponding data for all specimens counted by all operators (*see* text) where these exceed the control range or differ from the control median. Note complex overlaps in range.

grains. M is diagnostic for certain petrologic intervals. Figure 6 includes triangular Q-F-L plots with points for each rock counted in each petrologic interval. Figure 7 is a comparison of the Q-F-L fields of the dominant types of sandstones in each petrologic interval. Figure 8 displays the median Q-F-L compositions of each petrofacies in comparison with certain selected rocks. As the numerical summaries of Tables 1 and 2 indicate, Figures 4 and 5 must be used in conjunction with Figure 3 or 6 to distinguish between the various petrofacies.

The plots incorporate data of two kinds: (a) the results of modal point counts by Dickinson on a specially collected group of 38 representative control specimens, and (b) the results of modal point counts performed by Ojakangas (1964), Rich (1968), Schilling (1962a), and Swe (1968) on 142 other rocks in local areas, and reported by them in Ph.D. dissertations at Stanford University. Although some operator variance is inevitable, we do not judge it to be significant for the various parameters we have extracted from the data (Table 1). The greater range in the data for all the 180 samples, as opposed to the control group, probably reflects the real presence of slightly anomalous rocks. These were collected deliberately in areas studied by the other operators to provide estimates of the total ranges and minor overlaps in

TABLE 1. NUMERICAL SUMMARY OF RESULTS OF POINT COUNTS ON THIN SECTIONS OF SANDSTONES

Petrofacies		Control group (single operator)				Total samples (multiple operator)		
		N	Mn	SD	CE	N	Mn	SD
Rumsey	Q	7	42	5.7	~2.5	43	42	5.3
	F	7	33	5.2	2.25-2.5	43	36	6.2
	L	7	25	8.1	2.0 -2.25	43	22	4.9
	M	7	7.3	1.4	1.0 -1.25	30	7.0	1.4
	P/F	7	0.50	0.05	..	32	0.61	0.08
	V/L	7	0.70	0.10	..	12	0.65	0.11
Cortina ("Lo L")	Q	3	36	1.3	2.25-2.5	26	33	4.2
	F	3	31	0.8	2.25-2.5	26	35	4.8
	L	3	33	2.1	~2.25	26	32	4.2
	M	3	5.7	1.3	0.75-1.25	20	5.0	2.0
	P/F	3	0.71	0.06	..	16	0.72	0.06
	V/L	3	0.71	0.09	..	16	0.77	0.08
Cortina ("Hi L")	Q	4	22	1.9	~2.0	21	22	4.5
	F	4	29	2.7	~2.25	21	29	4.3
	L	4	49	1.6	~2.5	21	49	3.8
	M	4	3.1	1.2	0.5 -1.0	15	2.1	0.9
	P/F	4	0.79	0.04	..	15	0.61	0.14
	V/L	4	0.73	0.08	..	15	0.79	0.08
Boxer ("Hi L")	Q	5	22	5.3	~2.0	6	20	6.2
	F	5	26	1.2	~2.25	6	27	2.3
	L	5	52	5.3	~2.5	6	53	4.6
	M	5	1.3	0.7	~0.5	6	1.1	0.8
	P/F	5	0.76	0.05	..	6	0.72	0.10
	V/L	5	0.86	0.08	..	6	0.85	0.08
Boxer ("Lo L")*	Q	3	53	2.9	~2.5	16	45	8.6
	F	3	22	2.6	2.0 -2.25	16	30	7.1
	L	3	25	1.3	2.0 -2.25	16	25	5.5
	M	3	4.2	1.2	0.5 -1.0	16	3.1	1.7
	P/F	3	0.73	0.03	..	14	0.70	0.07
	V/L	3	0.72	0.08	..	10	0.78	0.08
Lodoga†	Q	8	46	8.2	~2.5	32	48	12
	F	8	20	3.3	2.0 -2.25	32	23	5.7
	L	8	34	8.5	2.0 -2.5	32	29	14
	M	8	2.6	1.2	0.5 -1.0	32	3.0	1.5
	P/F	8	0.88	0.04	..	22	0.81	0.08
	V/L	8	0.72	0.09	..	22	0.67	0.12
Stony Creek§	Q	8	19	5.3	1.75-2.25	33	21	8.4
	F	8	24	3.9	1.75-2.25	33	24	8.8
	L	8	57	7.3	~2.5	33	55	15
	M	8	1.0	0.6	~0.5	30	1.5	1.4
	P/F	8	0.96	0.03	..	28	0.91	0.07
	V/L	8	0.91	0.03	..	25	0.88	0.05

In all cases, points were spaced at distances greater than the diameter of the largest grain counted. Values for Q, F, and L are volumetric percentages of the Q-F-L population. Values for M (mica) are volumetric percentages of the total sand framework. Values for P/F and V/L are decimal fractions. The following statistical measures are given as a guide to the comparative significance of the figures cited (see also Table 2):

(a) N is the number of thin sections (within each grouping) for which values of a given parameter are available.

(b) Mn is the mean value for N sections (see Figs. 3, 4, and 5 for medians and ranges).

(c) SD is the standard deviation (square root of variance) of the mean with respect to the variance for counts of N sections.

(d) CE is the approximate standard deviation of the counting error for a given parameter in a given thin section; as estimated from the graph of Van der Plas and Tobi (1965, Fig. 1); approximate figure given because probable error varies as the percentage of a given constituent varies, even where the number of points counted in each thin section is held constant (CE = $\sqrt{p(100-p)/n}$ where p is the content of a grain type in percent and n is the total number of points in the population counted).

** Small control group probably not fully representative of petrofacies.*

† Two interbedded lithic sandstones similar to Stony Creek petrofacies omitted from statistical summary.

§ Two basaltic sandstones that interfinger with ophiolitic pillow lavas at base of Great Valley Sequence omitted from statistical summary.

TABLE 2. CHART SHOWING SPECIFIC DETRITAL GRAIN PARAMETERS USEFUL FOR DISTINGUISHING BETWEEN VARIOUS PAIRS OF PETROFACIES IN PETROLOGIC INTERVALS OF THE GREAT VALLEY SEQUENCE

	Stony Creek	Lodoga	Boxer ("Lo L")	Boxer ("Hi L")	Cortina ("Hi L")	Cortina ("Lo L")	Rumsey
Rumsey	Q,L,M P/F,V/L	F,M P/F	M	Q,L,M V/L	Q,L,M	Q,L	
Cortina ("Lo L")	L,M P/F,V/L	Q,F	Q	Q,F,L M	Q,L,M		M P/F
Cortina ("Hi L")	P/F,V/L	Q,L P/F	Q,L				P/F
Boxer ("Hi L")	P/F	Q,L	Q,L		M	V/L	F P/F
Boxer ("Lo L")	Q,L P/F,V/L			M V/L		L	Q/F P/F
Lodoga	Q,L V/L		M P/F	F P/F,V/L	F	M P/F	
Stony Creek		M P/F	M		M	Q,F	F

Symbols as in Figures 3 to 5.
This material extracted from data in Table 1.
Upper left of diagram includes parameters permitting clear distinctions.
Lower right of diagram includes other distinctive parameters that display some ambiguity for any of several reasons.

the compositions of sandstones from different petrologic intervals observed locally. Similar rocks were avoided where possible in selecting the control group of representative samples. In a sequence so thick and lithologically varied in detail, the concept of petrologic intervals can be applied effectively only if attention is concentrated on the dominant type of sandstone, or petrofacies, represented in each outcrop or packet of beds. Judgment of this kind involves some undeniable subjectivity.

CHARACTERISTICS OF PETROFACIES

The Stony Creek petrofacies (Fig. 6A) includes as much as 5.5 km of Tithonian (Upper Jurassic) and Neocomian (Lower Cretaceous) strata, largely lutites. All but the upper 1 km or less of the section is Valanginian (lower

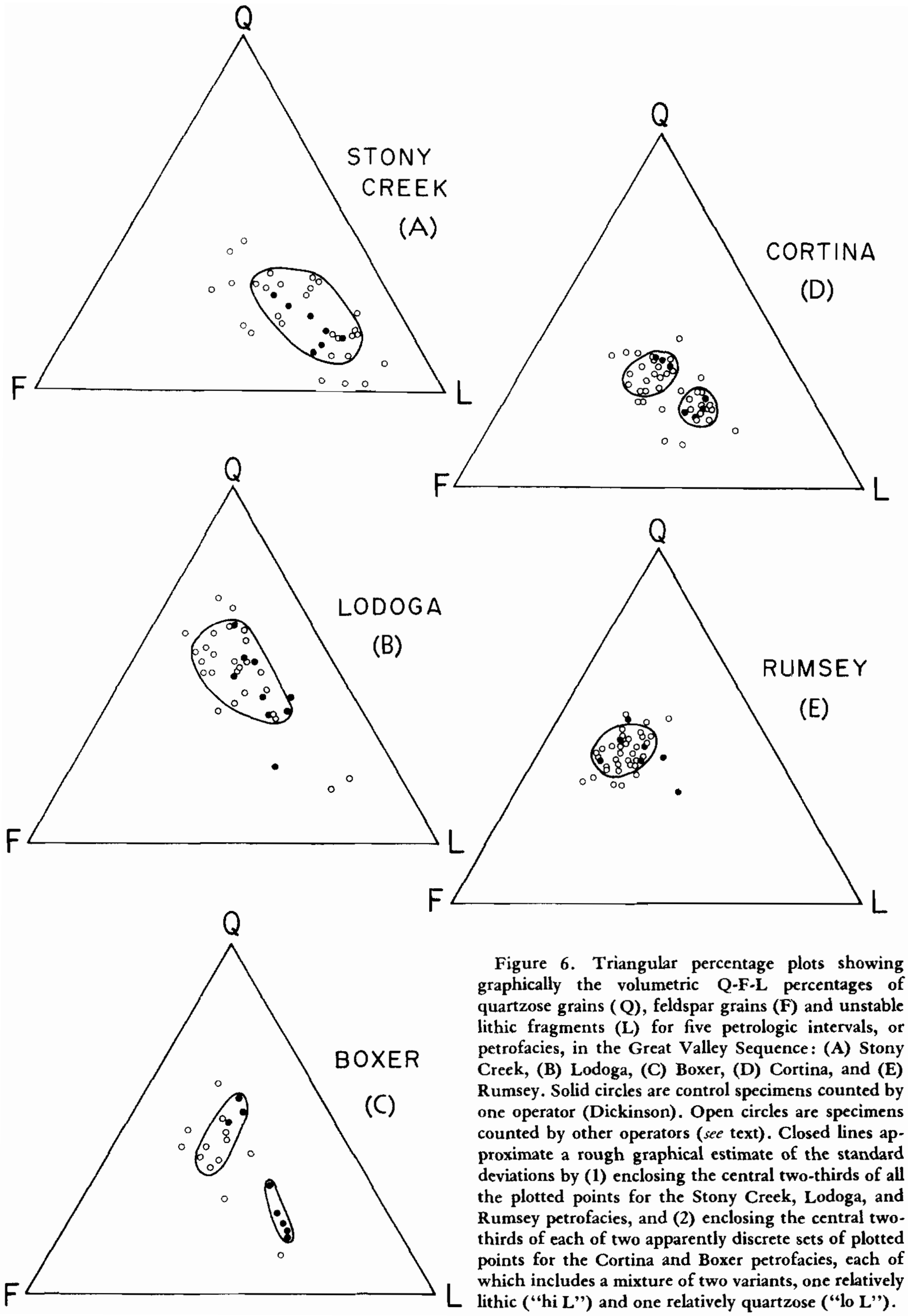

Figure 6. Triangular percentage plots showing graphically the volumetric Q-F-L percentages of quartzose grains (Q), feldspar grains (F) and unstable lithic fragments (L) for five petrologic intervals, or petrofacies, in the Great Valley Sequence: (A) Stony Creek, (B) Lodoga, (C) Boxer, (D) Cortina, and (E) Rumsey. Solid circles are control specimens counted by one operator (Dickinson). Open circles are specimens counted by other operators (*see* text). Closed lines approximate a rough graphical estimate of the standard deviations by (1) enclosing the central two-thirds of all the plotted points for the Stony Creek, Lodoga, and Rumsey petrofacies, and (2) enclosing the central two-thirds of each of two apparently discrete sets of plotted points for the Cortina and Boxer petrofacies, each of which includes a mixture of two variants, one relatively lithic ("hi L") and one relatively quartzose ("lo L").

Neocomian) or older, and contains *Buchia*, but the youngest horizons have yielded Hauterivian (upper Neocomian) and Aptian fossils locally (Rich, in press). At several localities, lutites in the basal part of the section intertongue with pillow lavas, pillow breccias, aquagene tuffs, and locally derived sandstones of basaltic composition which may represent the upper levels of the ophiolitic slab of oceanic crust upon which the Great Valley Sequence was deposited. Sandstones higher in the Stony Creek are dark greenish gray, quartz-poor feldspatholithic rocks ranging from $\sim Q_{12.5}F_{17.5}L_{70}$ to $\sim Q_{30}F_{27.5}L_{42.5}$. In some areas, there is clearly an upward trend from the most lithic rocks low in the section to the least lithic rocks high in the section (Fig. 8), but no discontinuities occur in the gradual change. The Stony Creek petrofacies is distinctive for the combination of low Q and high L (Fig. 3), high P/F and high V/L (Fig. 4), and low M (Fig. 5). The Q-F-L field (Fig. 7) is partly indistinguishable from those for the lithic ("hi L") variants of the Boxer and Cortina petrofacies, but the latter can be distinguished on the outcrop by their association with intercalated sandstones of the quartzose ("lo L") variants. The lithic ("hi L") variants of the Boxer and Cortina petrofacies can also be distinguished from Stony Creek rocks, with a hand lens in favorable instances, by the presence of pink potash feldspar grains and a higher mica content. The distinction can be confirmed readily if sawed slabs are stained for potash feldspar. Conglomerates in the Stony Creek petrofacies are commonly rich ($\sim$75 percent) in flinty clasts of chert and argillite in various shades of gray.

The Lodoga petrofacies (Fig. 6B) includes about 4 km of Lower Cretaceous (Aptian and Albian) strata, mainly siltstone and mudstone, but contains thick lenticular packets of sandstone at various horizons locally. Sandstones in the Lodoga petrofacies are mainly pale greenish-gray, relatively quartz-rich rocks ranging from $\sim Q_{40}F_{22.5}L_{37.5}$ to $\sim Q_{55}F_{25}L_{20}$. Rare anomalous beds resemble rocks of the underlying Stony Creek petrofacies. There is a tendency for packets of sandstones high in the section to be more quartzose and less lithic than those low in the section, but the change is not regular or systematic. The Lodoga petrofacies is distinctive for the combination of high Q and low L (Fig. 3), coupled with high P/F (Fig. 4), and a high ratio of Q to F (Fig. 3). The Q-F-L field (Fig. 7) is partly indistinguishable from those for the quartzose ("lo L") variant of the Boxer petrofacies and for the Rumsey petrofacies. Both the Boxer and Rumsey, however, contain distinctly more potash feldspar (Fig. 4), which can be seen as pink grains on the outcrop and confirmed by staining slabs. In addition, the quartzose ("lo L") variants of the Boxer petrofacies are intercalated locally with the distinctly different rocks of the lithic ("hi L") variant, and the rocks of the Rumsey petrofacies contain distinctly more mica (M) than the Lodoga rocks (Fig. 5). Conglomerates are rare in the Lodoga petrofacies, and those present contain mainly intraformational clasts.

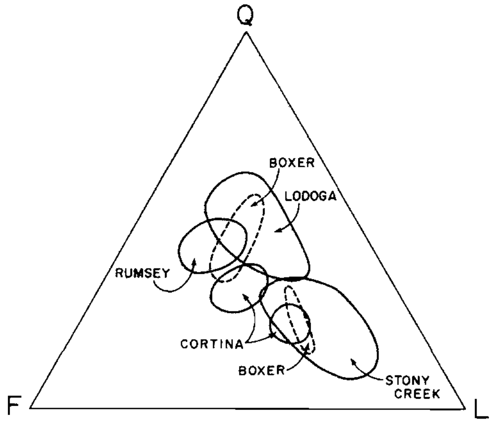

Figure 7. Triangular Q-F-L plot showing all the circled fields of Figure 6 together for comparison.

The Boxer petrofacies (Fig. 6C) includes about 1.5 km of entirely(?) Cenomanian (Upper Cretaceous) strata that are mainly mudstone and siltstone, but prominent conglomerate and sandstone packets occur in the lower part of the section. Sandstones in the Boxer petrofacies include two contrasting types that fall into discrete fields on the Q-F-L plot (Fig. 6C), but are apparently intercalated and intertongued in the field. The dominant variant ("lo L") is relatively quartzose ($\sim Q_{45}F_{30}L_{25}$) and the subordinate variant ("hi L") is relatively lithic ($\sim Q_{22.5}F_{27.5}L_{50}$). The two have essentially reciprocal proportions of quartzose grains and unstable lithic fragments (Fig. 3), and also differ in mica content (Fig. 5). The quartzose ("lo L") variant is distinctive in the combination of high Q and low L, coupled with moderate P/F (Fig. 4) and a high ratio of Q to F (Fig. 3). The lithic ("hi L") variant is distinctive in the combination of low Q and high L, coupled with a moderate P/F ratio

(Fig. 4). Possible confusions of each variant with other petrofacies are discussed elsewhere in this section. Conglomerates in the Boxer petrofacies are rich in volcanic, hypabyssal, and plutonic clasts, in roughly that order. In the Great Valley Sequence, they are the lowest conglomerates that contain prominent clasts of rhyolitic welded tuffs and other igneous rocks in which potash feldspar is common as phenocrysts or granular crystals visible with a hand lens. In many of the Boxer sandstones, most notably in those of the quartzose ("lo L") variant but also in those of the lithic ("hi L") variant, gaudy pink potash feldspar sand grains are especially prominent with a hand lens. In younger petrofacies that are also rich in potash feldspar, many of the grains are white or pale pink, and nearly indistinguishable from plagioclase with a hand lens.

The Cortina petrofacies (Fig. 6D) includes 3 to 4 km of mainly Turonian (Upper Cretaceous) strata, but may include Cenomanian strata near the base and probably includes Coniacian strata near the top. Sandstones are dominant in most sections, and include two slightly different types that fall into semi-discrete fields on the Q-F-L plot (Fig. 6D). The two types occur together in roughly equivalent proportions on the outcrop. One variant ("lo L") is relative quartzo-feldspathic ($\sim Q_{32.5}F_{35}L_{32.5}$) with roughly equal Q-F-L proportions, and the other ("hi L") is relatively lithic ($\sim Q_{22.5}F_{27.5}L_{50}$). The two also tend to differ in mica content (Fig. 5). The data suggest that the quartzo-feldspathic ("lo L") variant may be more abundant to the north, and the lithic ("hi L") variant more abundant to the south. Possible confusions of each variant with other petrofacies are discussed elsewhere in this section. Conglomerates in the Cortina petrofacies are rich in intermediate to silicic igneous clasts of volcanic, hypabyssal, and plutonic types, and contain subordinate amounts of metamorphic and argillitic types.

The lithic ("hi L") variants of the Boxer and Cortina petrofacies plot within essentially the same Q-F-L field (Fig. 7), and are essentially indistinguishable on the basis of any petrographic characteristics considered (Figs. 3, 4), though the Cortina rocks of this type tend to contain more mica (Fig. 5). We conclude that the lithic ("hi L") variants in both petrofacies were derived from the same source terrane, and that the two petrofacies can only be distinguished with confidence on the basis of the associated quartzose ("lo L") variants present in each case. Even this distinction is difficult, for the differences between the two are slight, with Q somewhat higher and L somewhat lower in the Boxer petrofacies than in the Cortina (Figs. 3, 7). Commonly, the decidedly rosier tint of the pink potash feldspar in the Boxer petrofacies as compared to the largely white or flesh potash feldspar in the Cortina is a valuable key on the outcrop, and may even serve locally to distinguish between the otherwise identical lithic ("hi L") variants as well as between the quartzose ("lo L") variants. In general, field distinctions that are unsupported by any laboratory work must be regarded as only tentative for the Boxer and Cortina petrofacies.

The Rumsey petrofacies (Fig. 6E) includes 2 to 4 km of mainly Campanian (Upper Cretaceous) strata, but probably includes Santonian strata near the base and locally includes Maestrichtian strata near the top. Both sandstones and mudstones are abundant. The upper limit of the petrofacies is not well established, and many lower Tertiary sandstones in California have similar compositions (for example, Fig. 8). Sandstones in the Rumsey petrofacies are micaceous, lithofeldspathic rocks with a composition near $Q_{37.5-47.5}F_{30-42.5}L_{15-25}$. Some sandstones not well studied in the upper part of the section may be somewhat more quartz rich, judging from published data on materials from the subsurface (Thomson, 1962). The Rumsey petrofacies is distinctive for the combination of high Q and low L (Fig. 3), locally high F (Fig. 3), low P/F (Fig. 4), and high M (Fig. 5). The Q-F-L field (Fig. 7) is partly indistinguishable from those for the quartzose ("lo L") variant of the Boxer petrofacies, and for the Lodoga petrofacies. The field is also essentially gradational to that of the quartzo-feldspathic ("lo L") variant of the Cortina petrofacies. The high content of both potash feldspar and mica in the Rumsey petrofacies make confusion with the Lodoga petrofacies unlikely, particularly if sawed slabs are stained to display the potash feldspar. The mica is prominent with a hand lens. Confusion with either Boxer or Cortina petrofacies is unlikely because of the much higher content of dark lithic fragments in the lithic ("hi L") variants intercalated with the quartzose ("lo L") variants of those two petrofacies. Confusion with rocks of either the

Lodoga or Boxer petrofacies is also unlikely because of the generally higher ratio of Q to F in those two petrofacies. The latter criterion emphasizes the fact that most geologists would regard the sandstones of the Rumsey as arkoses on the outcrop. Rare conglomerates in the Rumsey petrofacies are rich in granitic clasts.

SOURCE TERRANES

We accept the interpretation that the Sierra Nevada batholith and related plutons represent the roots of a magmatic arc that was active during the Mesozoic (Hamilton, 1969). During its activity, the arc stood as a volcano-plutonic orogen undergoing erosion on the edge of the continent, and fed detritus into the Great Valley trough to the west (Dickinson, 1970b). Ojakangas (1968) argued that petrologic variations in the Great Valley Sequence could be related to periods of known intrusive activity and inferred volcanic activity in the arc. We here evaluate this concept in terms of the 5 petrofacies we have described.

Using the arc analogy, we assume that intrusive episodes represented by granitic plutons in the source region were roughly coeval with volcanic episodes whose products have been stripped away by erosion. The detritus in the Great Valley Sequence was presumably derived in part from eroded volcanic rocks that once covered the source region, but are no longer present there. Variations in the content of unstable lithic fragments, especially volcanic rock fragments, are interpreted as a gross index to the areal extent of surficial rocks, especially volcanic rocks, exposed in the source region at different times. During times when erosion cut deep into the arc source, either because of intermittent uplifts or because of reduced levels of igneous activity, increased amounts of quartzo-feldspathic debris were delivered to the Great Valley trough from plutonic rocks and deep-seated metamorphic rocks. Application of this conceptual model appears to explain the salient petrologic variations that make the five petrofacies distinctive. Figure 9 shows our best estimates of the correlations between petrofacies in the trough and intrusive (-extrusive?) episodes in the source region.

Events prior to deposition of the Great Valley Sequence are not discussed here. The fact that the more westerly exposures of the sequence appear to rest on oceanic crust suggests that the tectonic elements of the arc-

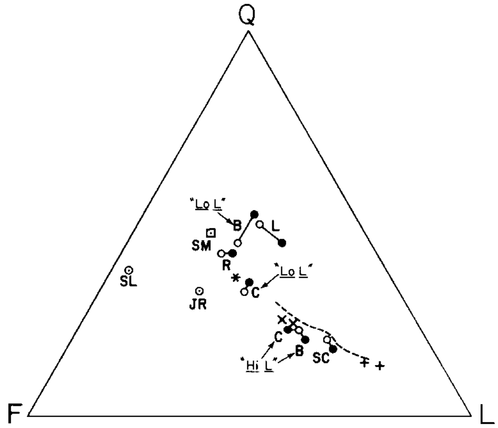

Figure 8. Triangular Q-F-L plot showing approximate median compositions for each petrologic interval, or petrofacies, from points plotted on Figure 6, together with certain other data for comparison. Solid circles are medians for control specimens counted by one operator (Dickinson) and open circles are medians for all specimens counted by all operators (*see* text). Letters beside bars connecting solid and open circles denote petrofacies as follows: SC, Stony Creek; L, Lodoga; B, Boxer (both "hi L" and "lo L" variants shown); C, Cortina (both "hi L" and "lo L" variants shown); and R, Rumsey. Dotted circles show approximate median compositions of other, more feldspathic Upper Cretaceous sandstones in California: JR, Upper Cretaceous sandstones on Joaquin Ridge flanking the southern Great Valley near Coalinga (*after* Mansfield, 1971b), and SL, Upper Cretaceous sandstones on the coastal ridge of the Santa Lucia Range in the Salinian block (*after* W. G. Gilbert, 1971). Dashed line indicates approximate trend of variation among control specimens from the Stony Creek petrologic interval; median compositions of extremely lithic rocks (+'s) low in that interval and of less lithic rocks (X's) high in that interval are also shown for two separate areas studied (Swe, 1968; Rich, 1968). The median composition of lower Tertiary sandstones (*see* text) from the Sierra Madre and adjoining ranges is also indicated by point "SM" *after* Chipping (1970).

trench system had stepped oceanward during the Late Jurassic. Middle Jurassic and older plutons in the Sierran-Klamath region were probably related to a subduction zone extending along the foothills of the Sierra Nevada and through the western Klamath Mountains. This older, pre-Franciscan subduction zone may have been choked by stuffings of arc segments and other bulky crustal increments swept against the pre-existing continental margin from the ocean to the west (for example, Hamilton, 1969).

In the Stony Creek petrofacies (Fig. 6A), the median content of volcanic rock fragments in the sand framework exceeds 50 percent (Figs. 3, 4). In the lower part of the petrofacies, the content approaches 75 percent, but it declines to 50 percent or less in the upper part (Fig. 8). We interpret this trend as a reflection of the erosion and gradual stripping of volcanic rocks erupted as an accompaniment to the emplacement of plutons at depth during the Yosemite intrusive epoch in the Sierra Nevada (Fig. 9). Volcanic debris related to plutons of generally similar age in the Klamath Mountains and northwestern Nevada (Fig. 9) may well be represented also. As erosion cut gradually into the plutons of the Yosemite and related intrusive episodes, the proportion of volcanic detritus in the Stony Creek petrofacies declined accordingly. It is clear that some of the plutons of these intrusive episodes were fully unroofed and partly eroded during deposition of the Stony Creek petrofacies, for mid-Neocomian strata locally rest unconformably on such batholiths and their metamorphic wall rocks in the Klamath Mountains (Jones and Irwin, 1971).

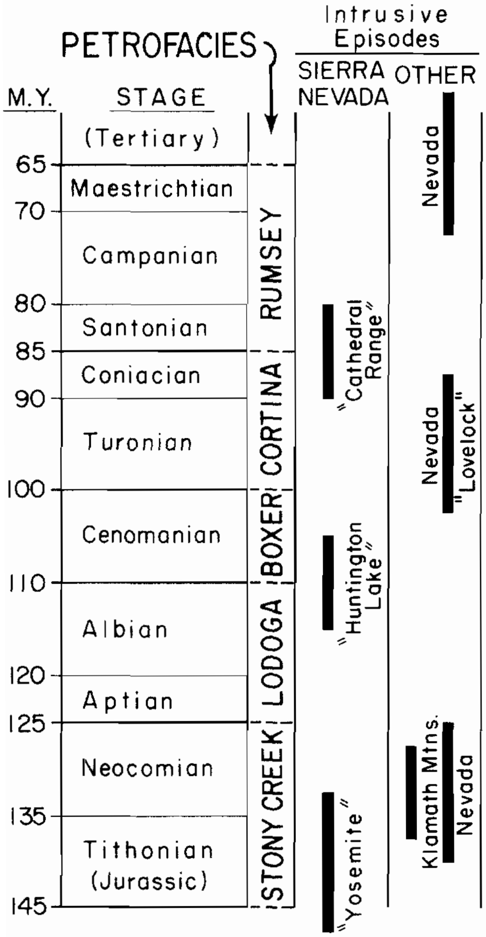

Figure 9. Correlation of petrologic intervals in the Great Valley Sequence, as dated by biostratigraphic stages (*see* Rich, in press), with radiometrically dated intrusive episodes in the Sierra Nevada (Evernden and Kistler, 1970), Klamath Mountains (Lanphere and others, 1968), and northern Nevada (Silberman and McKee, 1971; Smith and others, 1971). Correlation of biostratigraphic stages with radiometric ages is based on a comparative scale adapted mainly from Suppe (1969) and Evernden and Kistler (1970), except that the Geological Society of London scale is used here for the bases of the Maestrichtian and Tithonian; all stage boundaries are adjusted arbitrarily to the nearest 5 m.y., as any implication of greater precision seems unwarranted for our puposes.

In the overlying Lodoga petrofacies (Fig. 6B), the sandstones are more quartzo-feldspathic, and the median content of volcanic rock fragments is only about 30 percent (Figs. 3, 4). The time of deposition coincides with a period of apparent quiescence in the arc magmatism (Fig. 9). We interpret the source terrane for the Lodoga petrofacies as largely the plutons of the Yosemite and related intrusive episodes, together with their wall rocks and local remnants of the eroded surficial cover of volcanics and related sediments. The high quartz content, which is well in excess of 50 percent in some rocks, may indicate, as Ojakangas (1968) noted, that parts of the source region had low relief and underwent deep weathering.

The low content of potash feldspar in both the Stony Creek and Lodoga petrofacies is in general harmony with the petrology of the inferred sources. Plutonic rocks of latest Jurassic and earliest Cretaceous age in the Sierra Nevada and Klamath Mountains are largely plagioclase-rich varieties (Lanphere and others, 1968; Bateman and Dodge, 1970), and their eruptive equivalents were andesitic to dacitic in composition. The slight decrease in P/F ratio (Fig. 4) and the increase in M (Fig. 5) from the Stony Creek to the Lodoga petrofacies may reflect the fact that coarsely crystalline potash feldspar and mica would occur in greater abundance in a dominantly plutonic source than in a dominantly volcanic source having the same chemical composition.

The Boxer petrofacies (Fig. 6C) differs from the Lodoga petrofacies in two significant respects. Sandstones containing 50 percent of volcanic rock fragments appear in the section once again, though in subordinate amounts, and the median content of potash feldspar is about double previous levels in the more quartzofeldspathic rocks (Figs. 3, 4). The potash feldspar occurs both as separate crystals and as phenocrysts in volcanic rock fragments. We interpret these changes in the detritus to indicate that detrital contributions from volcanic and plutonic rocks related to the Huntington Lake intrusive epoch were reaching the trough during deposition of the Boxer petrofacies. The presumed peak of the Huntington Lake intrusive epoch coincides roughly with the onset of Boxer deposition (Fig. 9). Mid-Cretaceous granitic rocks in the Sierra Nevada are characteristically granodiorite plus calcic quartz monzonite (Bateman and Dodge, 1970), and their eruptive equivalents were probably dacitic to rhyodacitic.

The differences between the Boxer and Cortina petrofacies (Fig. 6D) are slight (Figs. 2, 3, 4), as discussed above. Similar sandstones containing about 50 percent of volcanic rock fragments in the framework were supplied in variable amounts to the trough throughout Boxer and Cortina deposition. These are the more lithic or "hi L" variants (Figs. 2, 4, 7, 8) that are intercalated with the more quartzose or "lo L" variants. Their presence suggests that semi-continuous magmatic activity occurred in the arc during both Boxer and Cortina deposition, as is suggested also by the plutonic activity in Nevada during the Lovelock intrusive epoch, which apparently bridged the time gap between the Huntington Lake and Cathedral Range intrusive epochs in the Sierra Nevada (Fig. 9; *see also* Smith and others, 1971). An appeal could be made instead to the shunting of sediment dispersal paths back and forth to tap alternately plutonic and volcanic terranes. We prefer the hypothesis of intermittent volcanic activity in the source region to account for the irregular intercalation of "hi L" variants from local and temporary volcanic piles with "lo L" variants derived from areas where the volcanic cover was locally or temporarily breached.

The slight but distinctive differences between the compositions of the more quartzofeldspathic ("lo L") variants of the Boxer and Cortina petrofacies are difficult to interpret. As the Boxer rocks of this type share a high quartz content with the Lodoga petrofacies, it may be that they were derived in part from the same latest Jurassic and earliest Cretaceous plutonic rocks. They must have received contributions as well from mid-Cretaceous plutonic rocks to account for certain differences between Boxer and Lodoga rocks noted above. Perhaps by Cortina deposition the mid-Cretaceous plutonic rocks bulked large enough to dominate the plutonic contributions, and this circumstance could be reflected by the slight differences between the quartzo-feldspathic ("lo L") variants of the Boxer and Cortina petrofacies. Alternatively, Boxer and Cortina deposition may have tapped provenances in different parts of the arc characterized by slightly different petrology, just as the locus of magmatic activity apparently shifted with time (Fig. 9). The resolution of the available petrographic data is inadequate to decide such questions.

Sandstones in the Rumsey petrofacies (Fig. 6E) approach a classic arkosic composition, and about half the feldspar is potash feldspar. The onset of Rumsey deposition coincides roughly with the presumed peak of the Cathedral Range intrusive epoch (Fig. 9), when most of the vast quartz monzonite plutons of the Sierran crest were emplaced (Bateman and Dodge, 1970). We infer that the principal sources for the detritus in the Rumsey petrofacies were igneous rocks related to this magmatic activity. The eruptive equivalents were probably rhyodacitic to rhyolitic, and the volcanic rock fragments in the Rumsey rocks are more commonly silicic felsites than those in any of the older petrofacies. Much greater volumes of quartzofeldspathic sand from plutonic rocks are present in the Rumsey. Toward the end of Rumsey deposition, the Sierran block must have become nearly the eroded stump it was during the somewhat later deposition of gold-bearing Tertiary gravels in lowlands flanking rolling plateaus. We find no detrital record in the Great Valley sequence of the "Laramide" or early Tertiary magmatism in the Great Basin, and conclude that igneous debris from that terrane was probably not carried in quantity across the site of the present Sierran block to the coastal region.

PETROFACIES BOUNDARIES

We have discussed the relation between the petrologic intervals and magmatic events in the source region as if the petrofacies are truly time-stratigraphic units. This cannot be true in detail, even if the significant magmatic episodes were synchronous along the whole length and span of the arc. In the plate tectonic model for arc-trench systems, rough synchroneity of tectonic and magmatic events throughout an arc is conceivable, for the underlying control is the relative motion of vast, intact plates of lithosphere. However, the sedimentary expression of the events in nearby depositional basins probably could not be perfect in timing. Local vagaries in the rate of dissection and complex routes of sediment dispersal are likely to affect the positions of petrofacies boundaries in derivative sedimentary successions. Our data indicate that the time-stratigraphic variation in petrofacies boundaries is generally too slight to detect in an over-all regional survey.

In one instance, we apparently have detected the locally time-transgressive nature of a petrofacies boundary. In the Budden Canyon traverse (Fig. 2) at the northern end of the region considered, Neocomian rocks are assigned to the Lodoga petrofacies, whereas apparently correlative strata farther south belong to the Stony Creek petrofacies. The Budden Canyon area (Fig. 1) is the only one of our traverses that lies north of the Paskenta–Elder Creek–Cold Fork system of transverse faults (Jones and others, 1969). This system was active during the Cretaceous as a complex left-lateral strike-slip fault zone along which the Klamath Mountains segment of the Mesozoic arc was stepped westward 100 km or more with respect to the Sierra Nevada segment (Jones and Irwin, 1971). The system can be viewed either as a tear fault in the overriding plate of the arc-trench system or as a transform between two uncoupled arc segments. In either case, our data suggest that the erosional history of the arc segments north and south of the transverse fault zone was different. We have interpreted the transition from the Stony Creek to the Lodoga petrofacies as an indication that the volcanic cover associated with the Yosemite intrusive epoch and its correlatives had been stripped away to expose the plutons themselves. We conclude, therefore, that this degree of dissection was achieved north of the transverse break in the gross structural trend of the arc source earlier than to the south. The inference is in harmony with the fact that Neocomian rocks rest unconformably on granitic source rocks north of the transverse fault belt, but are nowhere exposed now in that position farther south. We note that the petrofacies boundary between the Stony Creek and Lodoga petrofacies is the one most likely to be significantly time-transgressive. It apparently involves only the erosional dissection of a pre-existing volcano-plutonic orogen, and not the onset of additional magmatic activity in the arc source.

The other petrofacies boundaries apparently reflect in some measure the onset of fresh magmatic episodes in the arc source. In each case, the basal strata of our upper three petrofacies include prominent coarse-grained sandstone units in many areas (Fig. 2). Beneath several of these units, there is local evidence for slight structural discordance in the form of apparently disharmonic wrinkles or plunging folds in the regional homocline along the western flank of the Great Valley (Rich, in press). We doubt that unconformities in the sense of subaerial erosion surfaces are present anywhere along the homoclinal outcrops in the region considered, although correlative unconformities may well be present closer to the arc source in the subsurface beneath the Great Valley to the east. On the outcrop, the disharmonic structures probably reflect submarine deformation contemporaneous with sedimentation. In any case, the occurrence of structural discontinuities near petrofacies boundaries, coupled with the floods of coarse detritus that appear to initiate each new petrofacies, are features of importance. They suggest a fundamental linkage between magmatic, tectonic, erosional, and depositional events close enough to explain the regional synchroneity of petrofacies along the full length of the arc trend considered in this paper.

We note that Peterson (1965, 1967a, 1967b) correctly called attention to the regional significance of stratigraphic discontinuities at the horizons we here recognize as petrofacies boundaries. Although previously we and others have discounted his conclusions on this point, we now find ourselves in agreement with his statement: "These stratigraphic patterns indicate a succession of transgressive-regressive cyclic episodes probably directly related to diastrophism in the Nevadan belt" (Peterson, 1965). To this we would add that the diastrophic episodes were probably directly related to prominent magmatic episodes in the arc.

CONCLUSIONS

The definition of petrofacies based on certain key proportions of detrital grains in sandstones of the Great Valley Sequence has led us to the recognition of petrologic intervals that are nearly synchronous throughout a large region in northern California. The petrofacies are much more persistent laterally than are lithofacies based on the traditional criteria of grain size and bedding style. The mapping of petrologic intervals based on petrofacies offers a fresh means to establish gross stratigraphic relations in areas of complex structure. We hope that the petrologic intervals within the Great Valley Sequence may have analogues that will be useful for mapping within the coeval Franciscan Assemblage, where structural analysis of any kind presents a severe challenge.

The nature of each petrofacies can be explained by reference to known magmatic and inferred tectonic episodes in the source region, which was a late Mesozoic arc along the Sierran-Klamath belt. We suspect that similar close tectonic linkage between source region and depositional basin is characteristic for all sedimentation directly related to arc-trench systems, where uplift of sources and subsidence of basins spring from the same causes.

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