Petrofacies and Provenance of the Puente Formation (Middle to Upper Miocene), Los Angeles Basin, Southern California: Implications for Rapid Uplift and Accumulation Rates

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PETROFACIES AND PROVENANCE OF THE PUENTE FORMATION (MIDDLE TO UPPER MIOCENE), LOS ANGELES BASIN, SOUTHERN CALIFORNIA: IMPLICATIONS FOR RAPID UPLIFT AND ACCUMULATION RATES

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Abstract: The Puente Formation is a Middle–Upper Miocene clastic unit lying unconformably on the Lower–Middle Miocene El Modeno Volcanics and Topanga Group, in the Los Angeles basin. The Puente Formation, about 3900 m thick, is composed of conglomerate, sandstone, and mudrock deposited as a submarine fan at bathyal depths. Several intrabasinal discordances suggest tectonic activity during deposition. The succession consists of two main upward-thickening and -coarsening megacycles, reflecting submarine-fan progradation. The Puente Formation is characterized up-section by: (1) thin-bedded sandstone and shale (*La Vida Member*) grading to thick-bedded sandstone and conglomerate (*Soquel Member*); (2) thin-bedded mudrock and sandstone (*Yorba Member*) grading to thick- to very thick-bedded sandstone and conglomerate (*Sycamore Canyon Member*).

Sandstones of the Puente Formation are quartzofeldspathic ($Qm_{35}F_{54}Lt_{11}$); their compositions suggest local provenance from the plutonic, volcanic, and metamorphic rocks of the San Gabriel Mountains and surrounding areas. Petrologic parameters, however, suggest variable contribution of these source rocks through time. Four petrofacies, with distinctive parameters, coincide with the lithostratigraphic subdivisions. Coarse-grained plutonic rock fragments are abundant throughout the succession and consist of plagioclase-rich plutonic rocks, probably sourced, in part, from the Lowe Granodiorite. Lathwork, microlitic to felsitic volcanic lithic grains are also present in the lower and middle part. In the La Vida petrofacies, there is also an intrabasinal contribution (intraclasts and bioclasts) from shelfal areas. In the Yorba petrofacies there is a local increase of volcanic detritus ($Lv/L = 0.81$), represented by coarser volcanic lithics and abundant volcaniclastic matrix. Metamorphic detritus is not very abundant. The Sycamore Canyon petrofacies is dominantly plutoniclastic ($Rg/R = 0.90$; hornblende-bearing plutonic rock fragments), including very abundant hornblende grains. The plutonic detritus is dominantly plagioclase-orthoclase-biotite-bearing in the lower part, and hornblende-bearing in the upper part, suggesting unroofing of the Lowe Granodiorite Complex as a key element of uplift of the San Gabriel Mountains.

Other Neogene sandstones deposited in the Los Angeles Basin also consist dominantly of plutoniclastic detritus related to the unroofing of arc-related plutonic rocks (dissected magmatic arc). For example, the up-section increase in plutonic detritus is consistent with the composition of the Upper Miocene–Lower Pliocene Capistrano Formation ($Qm_{50}F_{47}Lt_3$), which has a composition identical to the Sycamore Canyon petrofacies. There is consistent provenance signal in spite of complex transrotational tectonics, responsible for opening of the Los Angeles Basin, and later transpressional processes, which are still active. Detailed provenance study of the Puente Formation and related units provides important constraints on paleogeographic and paleotectonic reconstructions of southern California basins and uplifts.

INTRODUCTION

The Los Angeles Basin is one of many Neogene basins along the western margin of California (e.g., Crowell 1974, 1987; Blake et al. 1978; Dickinson et al. 1987; Luyendyk and Hornafius 1987; Mayer 1987; Yeats 1987; Biddle 1991; Wright 1991). It is located at the northern end of the Peninsular Ranges, and is bounded on the north by the Transverse Ranges and west by the continental borderland (Fig. 1). The Los Angeles Basin is a small polyhistory basin (e.g., Kingston et al. 1983) that developed within the rapidly evolving San Andreas transform zone, which forms the present boundary between the Pacific and North American plates. The basin began subsiding around 18 Ma and continued until around 3 Ma, when north-south shortening in the area resulted in regional uplift (e.g., Mayer 1991).

Pre–Los Angeles Basin rocks consist mostly of metasedimentary, sedimentary, and plutonic rocks emplaced during the Late Triassic to Early Miocene convergent-margin regime (e.g., Dickinson et al. 1979, 1987; Blake 1991). They include (Fig. 2): (1) Jurassic to Lower Cretaceous metasedimentary rocks (e.g., Santa Monica Slate, Catalina Schist, and Pelona Schist), as well as plutonic rocks (e.g., diorite, tonalite, syenite, granite, and granodiorite) associated with the Mesozoic magmatic arc (Yerkes et al. 1965). Locally, Precambrian metamorphic rocks (gneissic rocks of the San Gabriel Mountains) are part of the basement (Ehlig 1981). (2) Volcanic and sedimentary rocks, which were deposited within the forearc (e.g., Dickinson et al. 1987) during the Late Cretaceous to Early Miocene (e.g., Santiago Peak volcanics, Tuna Canyon, Coal Canyon, Trabuco, Ladd, Williams, Silverado, Santiago, Sespe and Vaqueros Formations).

The general stratigraphy of the Los Angeles Basin (Fig. 2) includes:

(1) The Lower to Middle Miocene Topanga Group, consisting of conglomerate, sandstone, and mudstone, which were deposited at middle-bathyal to nonmarine depths (Yerkes et al. 1965; Yerkes and Campbell 1979; Blake 1991). Interbedded with the Topanga Group are several volcanic units (e.g., Conejo and El Modeno; Shelton 1955; Yerkes and Campbell 1979; Williams 1983).

(2) The Middle Miocene San Onofre Breccia (Vedder and Howell 1976; Stewart 1979) consists of conglomerate and sandstone deposited at bathyal depth and very shallow water, and interfingers and lies unconformably on the Topanga Group. The San Onofre Breccia contains clasts from the Catalina Schist (Stewart 1979), which were derived from the west, indicating that the metamorphic basement was exposed and shed sediment into the Los Angeles Basin by the early Middle Miocene.

(3) the Monterey Formation, resting on Catalina Schist, San Onofre Breccia, and Topanga Group, was deposited during the Middle to Late Miocene in the central part of the basin. It consists of siliceous hemipelagic shale deposited at bathyal depths. Coeval with Monterey deposition, the Modelo and Puente Formations were deposited as turbidites on submarine fans at bathyal depths (e.g., Durham and Yerkes 1964; Yerkes et al. 1965; Yerkes 1972).

(4) The Upper Miocene to Lower Pliocene Capistrano Formation crops out in the southern part of the basin. It rests unconformably on the Monterey Formation and includes a sand-rich turbidite system (e.g., Walker 1975).

(5) The final filling of the Los Angeles Basin is represented by the Pliocene to Holocene Repetto, Fernando, Pico, and La Habra Formations (Yerkes et al. 1965; Yerkes 1972), ranging from bathyal turbidite deposition to inner-neritic and nonmarine deposition.

During the Middle to Late Miocene, subsidence in the Los Angeles Basin

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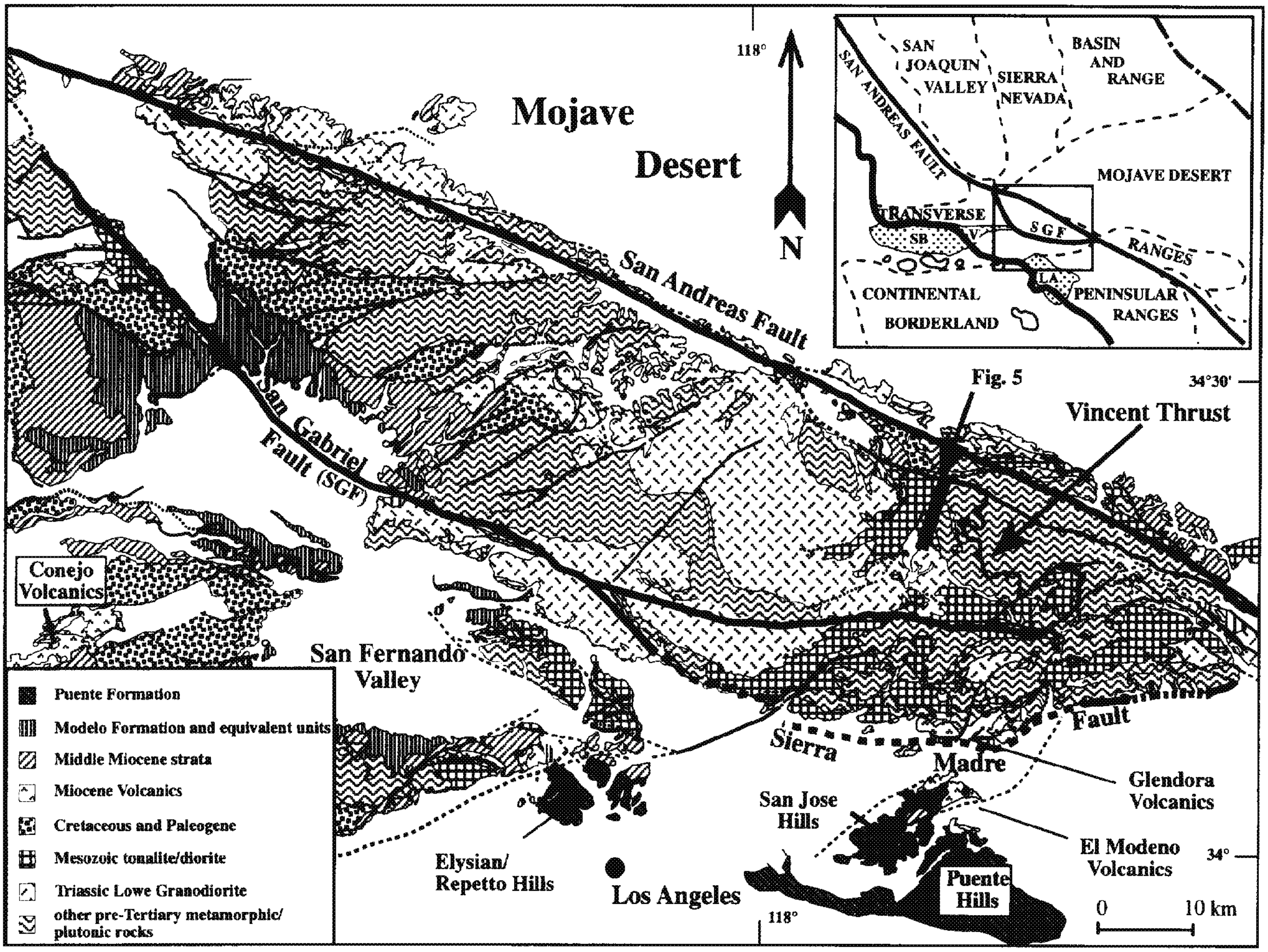

FIG. 1.—Generalized geologic map of Los Angeles Basin and San Gabriel Mountains and locations of Puente Formation outcrops. On inset, LA = Los Angeles Basin; SB = Santa Barbara Basin.

increased drastically, the paleotopography of the basin changed, and two main depocenters received distinct turbidite strata, the Modelo and Puente successions in the western and eastern parts of the basin, respectively. During Puente deposition, major changes in the geometry of the basin, global eustatic sea-level changes, and tectonism occurred; detailed compositional study of this formation is useful for late Cenozoic paleogeographic and paleotectonic reconstruction of southern California. This paper documents the sandstone composition and provenance of the Puente Formation, which constrains source lithology during final development of the Los Angeles Basin.

STRATIGRAPHY AND SEDIMENTOLOGY OF THE PUENTE FORMATION

The Puente Formation is a Middle–Upper Miocene sedimentary succession exposed around the northeastern and eastern margins of the Los Angeles Basin (Fig. 1). It is about 3900 m thick in the Puente Hills, and is composed of sandstone, conglomerate, and mudrock deposited on a submarine fan at bathyal depths (Durham and Yerkes 1964; Yerkes et al. 1965; Yerkes 1972; Blake 1991). It is considerably thinner to the north in the San Jose Hills (Fig. 1) and to the south (Yerkes et al. 1965). Several intrabasinal discordances suggest active tectonics during deposition (Yerkes et al. 1965; Yerkes and Campbell 1979). The Puente Formation is characterized up-section by four stratigraphic members (Fig. 2; Durham and Yerkes 1964): (1) thin-bedded sandstone and shale (1000 m thick, *La Vida Member*) grading to (2) thick-bedded coarse sandstone and conglomerate (900 m thick, *Soquel Member*); (3) thin-bedded mudrock and sandstone (900 m thick, *Yorba Member*) grading to (4) thick- to very thick-bedded coarse-grained sandstone and conglomerate (1100 m thick, *Sycamore Canyon Member*). The succession consists of two main upward-thickening and -coarsening megasequences (e.g., Ricci Lucchi 1975), reflecting submarine-fan progradation.

The La Vida Member rests on the Topanga Group and El Modeno volcanics. This latter unit is dated at 13.7 ± 1.6 Ma using the K/Ar method (Turner 1970). Conformably overlying the La Vida Member is the Soquel Member; a bentonite bed interbedded with the sandstone has an age of 9 Ma (Turner 1970). There is a gradational contact between the Soquel Member and the overlying Yorba Member; conformably overlying the Yorba is the Sycamore Canyon Member, whose youngest beds may be Lower Pliocene (Durham and Yerkes 1964).

Blake (1991) reviewed the biostratigraphy of Neogene deposits of the Los Angeles Basin and assigned a Middle to Late Miocene age to the Puente Formation. The basal unconformity between the Topanga Group and the Puente Formation is dated as 14 Ma and corresponds with possible eustatic sea-level fall (e.g., Haq et al. 1987). Sedimentation in the Los

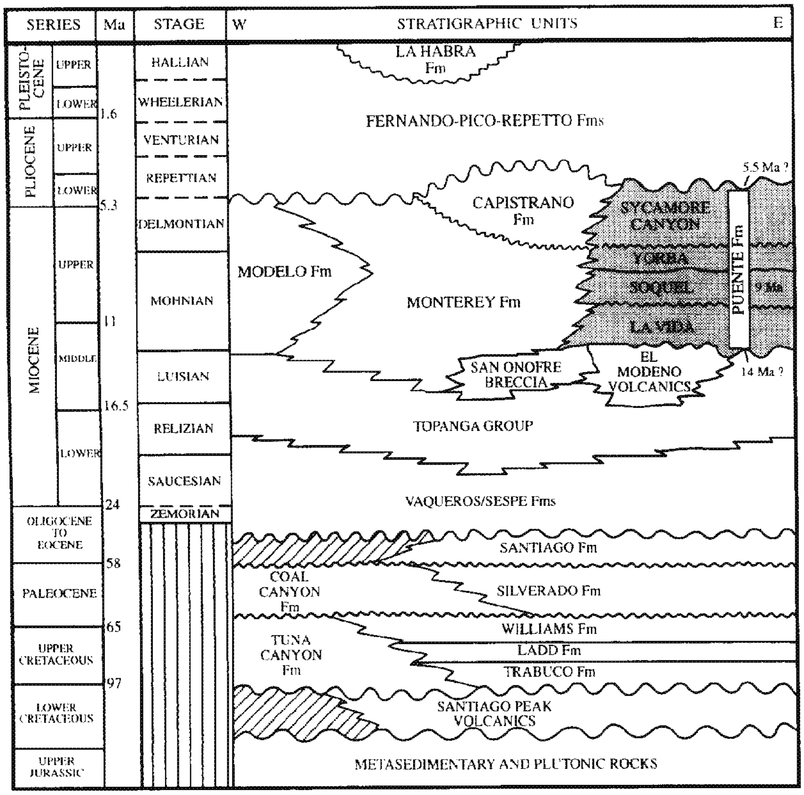

FIG. 2.—Generalized stratigraphic chart for Los Angeles Basin (modified from Blake 1991). Note nonlinear vertical scale.

Angeles Basin from 14 to 5.5 Ma included hemipelagic deposition of the Monterey Formation, and turbiditic deposition on the northern and eastern margins, the Modelo and Puente Formations, respectively, which were probably separated by an intrabasinal bathymetric ridge. The upper unconformity between the Puente Formation and the overlying Repetto and Fernando Formations is dated at 5.5 Ma (Miocene–Pliocene boundary). This latter unconformity may be related to fault movements along the margin of the basin (e.g., Whittier Fault movement dated at about 6.6 Ma; Schwartz and Colburn 1987). However, an eustatic sea-level fall may have also occurred at 5.5 Ma (Haq et al. 1987). The Puente Formation is unconformably overlain by the Pliocene–Pleistocene lower to middle bathyal deposits of the Fernando Formation.

SANDSTONE PETROLOGY

To obtain a representative suite of samples from the Puente Formation, sandstones were collected in two study areas (Puente Hills and Elysian/Repetto Hills; Fig. 1). Sixty-nine samples of unaltered medium to coarse sandstone were selected for thin-section analysis, covering the entire sedimentary succession. Five hundred points were counted by one of us (SC) for each thin section (etched and stained for plagioclase and potassium feldspar) according to the "Gazzi-Dickinson method" (Ingersoll et al. 1984; Zuffa 1985, 1987). Point-count results are recalculated in Tables 1 and 2. For 15 samples, the dense minerals were also analyzed.

Grain parameters (Table 1) and the recalculated parameters (Table 2) are those of Dickinson (1985) and Ingersoll and Suczek (1979) for the QmFLt, QtFL, QmKP, QpLvmLsm, and LmLvLs diagrams, and from Critelli and Le Pera (1994) for the RgRvRm diagram (Fig. 3). The RgRvRm diagram is used for both phaneritic rock fragments and aphanitic lithic fragments. Table 1 shows the recalculated parameters Rg, Rv, and Rm; this diagram is especially useful for analysis of mid-crustal provenance. According to the Gazzi-Dickinson method, sand-size quartz, K-feldspar, plagioclase, micas, and dense minerals contained in coarse phaneritic rock fragments are considered as a part of the monocrystalline framework in order to reduce the dependence of modal composition on the grain size of sandstone (Gazzi 1966; Dickinson 1970; Ingersoll et al. 1984; Zuffa 1985, 1987). The detailed modal point-count petrographic classes (Table 1) allow us to recalculate the phaneritic fragments contained in a sandstone. To reduce the dependence of their occurrence on grain size and on the energy of turbidity currents and hydraulic segregation, we collected samples ranging from medium to coarse in grain size and only from Tb intervals of the Bouma sequence (e.g., Critelli and Le Pera 1994).

All of the sandstones of the Puente Formation are quartzofeldspathic ($Qm_{35}F_{54}Lt_{11}$) (Fig. 3). They have not been intensely altered diagenetically and have undergone low to moderate compaction. Poikilotopic calcite (0–12%), and patchy and pore-filling calcite cement (0–6.8%) are the main interstitial authigenic components. There are rare clay-coated grains (0–3.6 %) and authigenic quartz and albite (0–4.2 %). Authigenic calcite preferentially replaces feldspar grains; when the replacement of feldspar is recognized in thin section, the feldspars are included in the recalculated parameters (Table 1). Matrix is moderately abundant (0–15.2%), in the form of protomatrix, epimatrix, and orthomatrix (e.g., Dickinson 1970); the Yorba Member sandstone also includes volcanogenic matrix (fine ash), where authigenic quartz has been recrystallized from fine ash. Rare carbonate matrix in the form of micrite and microspar is present where sandstone has coeval intrabasinal carbonate grains.

Dense-mineral assemblages were recognized during modal analysis, ranging from 0 to 9.8% of whole rock. In addition, a separate qualitative analysis was carried out on a fraction having density greater than 2.967 g/cm^3 (tetrabromoethane) and a size range of 0.0625–0.25 mm. Dense minerals consist of garnet, tourmaline, zircon, cordierite, hornblende, epidote, apatite, sphene, rutile, sillimanite, kyanite, hypersthene, augite, and opaques. Of special note, in the upper part of the Puente Formation (Syc-

TABLE 1.—*Categories used for sandstone point-counts of framework grains and assigned grains in recalculated plots**

Petrographic Classes	Qm F Lt	Qt F L	QmPK	QpLvm-Lsm	LmLv-Ls	RgRv-RmRs
NCE						
Quartz (single crystals)	Qm	Qt	Qm			
Polycrystalline quartz	Lt	Qt		Qp		
Chert	Lt	Qt		Qp		
Quartz in volcanic r.f.	Qm	Qt	Qm			Rv
Quartz in metamorphic r.f.	Qm	Qt	Qm			Rm
Quartz in plutonic r.f.	Qm	Qt	Qm			Rg
Quartz in plutonic or gneissic r.f.	Qm	Qt	Qm			Rg
Calcite replacement on quartz	Qm	Qt	Qm			
K-feldspar (single crystals)	F	F	K			
K-feldspar in volcanic r.f.	F	F	K			Rv
K-feldspar in metamorphic r.f.	F	F	K			Rm
K-feldspar in plutonic r.f.	F	F	K			Rg
K-feldspar in plutonic or gneissic r.f.	F	F	K			Rg
Calcite replacement on k-feldspar	F	F	K			
Plagioclase (single crystals)	F	F	P			
Plagioclase in volcanic r.f.	F	F	P			Rv
Plagioclase in metamorphic r.f.	F	F	P			Rm
Plagioclase in plutonic r.f.	F	F	P			Rg
Plagioclase in plutonic or gneissic r.f.	F	F	P			Rg
Calcite replacement on Plagioclase	F	F	P			
Micas (single crystals)						
Micas in plutonic or gneissic r.f.						Rg
Micas in metamorphic r.f.						Rm
Volcanic lithic with microlitic texture	Lt	L		Lvm	Lv	Rv
Volcanic lithic with lathwork texture	Lt	L		Lvm	Lv	Rv
Volcanic lithic with vitric texture	Lt	L		Lvm	Lv	Rv
Volcanic lithic with felsitic granular texture	Lt	L		Lvm	Lv	Rv
Volcanic lithic with felsitic seriate texture	Lt	L		Lvm	Lv	Rv
Metavolcanic lithic	Lt	L		Lvm	Lm	Rm
Phyllite	Lt	L		Lsm	Lm	Rm
Fine-grained Schist	Lt	L		Lsm	Lm	Rm
Siltstone	Lt	L		Lsm	Ls	Rs
Shale	Lt	L		Lsm	Ls	Rs
Dense minerals (single crystals)						
Dense minerals in plutonic r.f.						Rg
Dense minerals in metamorphic r.f.						Rm
Opaque minerals						
CI						
Bioclast						
Intraclast						
Undetermined grains						

* NCE (noncarbonate extrabasinal grains) and CI (carbonate intrabasinal grains) are those of Zuffa (1985, 1987), while criteria for textural subdivision of volcanic grains are those of Dickinson (1970) and Ingersoll (1983). r.f. = rock fragment.

amore Canyon Member), hornblende grains are more abundant, constituting up to 10% of the sandstone framework.

PETROFACIES CHARACTERISTICS

The sandstones of the Puente Formation are subdivided into four distinctive petrofacies based on visual inspection of the data. These petrostratigraphic units (in the more restricted sense expressed by Mansfield 1971 and Ingersoll 1983) coincide with lithostratigraphic subdivisions; therefore, the same names are used for both types of units.

La Vida Petrofacies.—The quartzofeldspathic sandstone ($Qm_{33}F_{55}Lt_{12}$) of this petrofacies contains abundant plagioclase grains ($Qm_{37}K_{18}P_{45}$) compared to quartz and K-feldspar (P/F = 0.71). Aphanitic lithics (Fig. 3) include abundant volcanics and minor metasedimentary (phyllite and fine-grained schist) and sedimentary (shale and chert) lithics ($Lm_{21}Lv_{78}Ls_{1}$). Volcanic lithics (Fig. 4A) are represented by felsitic, microlitic, and lathwork grains derived from rhyolitic to andesitic and basaltic rocks.

Phaneritic rock fragments (apportioned in Qm, P, K, micas, and dense minerals; see Table 1 for explanation) include plutonic (granodiorite, tonalite, and minor granite fragments; Rg/R = 0.54 ± 0.21) and minor metamorphic (Rm/R = 0.10 ± 0.08) rocks. Plutonic rock fragments include orthoclase-biotite-oligoclase-garnet and orthoclase-oligoclase-biotite-quartz composite grains.

Dense minerals comprise garnet, zircon, sphene, cordierite, sillimanite, tourmaline, hornblende, other undetermined amphiboles, rare hypersthene and augite, and opaques. Coeval intrabasinal grains (bioclasts, intraclasts, and argillaceous rip-up clasts) are also present. Interstitial and secondary components include epimatrix, protomatrix, poikilotopic calcite, authigenic quartz, and albite.

Soquel Petrofacies.—Quartzofeldspathic sandstone of the Soquel Member ($Qm_{42}F_{50}Lt_{8}$) has less volcanic detritus and higher proportions of metamorphic grains and polycrystalline quartz ($Qp_{17}Lvm_{22}Lsm_{61}$; $Lm_{69}Lv_{27}Ls_{4}$) than the La Vida Member. Monocrystalline quartz is also higher, whereas K-feldspar is lower. Phaneritic rock fragments include plutonic (Rg/R = 0.72 ± 0.13) and metamorphic (Rm/R = 0.21 ± 0.09) types. Phaneritic plutonic fragments comprise quartz-feldspar-biotite, quartz-feldspar-garnet-biotite grains, oversized K-feldspar grains, and single garnet crystals. Interstitial and secondary components include orthomatrix, protomatrix, epimatrix, authigenic carbonate, and clay-coated grains.

Yorba Petrofacies.—Quartzofeldspathic sandstone ($Qm_{32}F_{52}Lt_{16}$) of the Yorba Member contains abundant plagioclase and quartz, and minor K-feldspar. Plagioclase grains are twinned, and range in composition from An_{10} to An_{60}, by optical determination. Volcanic lithics are abundant ($Lm_{19}Lv_{81}Ls_{0}$), whereas metasedimentary lithics are subordinate. Volcanic lithic grains (Fig. 4B) include microlitic, lathwork, vitric, and felsitic types ranging from andesite-basalt to dacite-rhyolite compositions. Minor porphyrites and subvolcanic grains, single euhedral zoned plagioclase (An_{40-60}) and mafic minerals, and abundant volcanogenic matrix (fine ash) are present. These volcanic grains are mostly coarser than the nonvolcanic detritus. Coeval intrabasinal carbonate grains (bioclasts and intraclasts) are also present (Fig. 4C). Sphene, zircon, apatite, garnet, epidote, magnetite, hypersthene, augite, and, in the upper part of the Yorba Member, hornblende minerals are present (Fig. 4D).

Phanerithic rock fragments include granitoid (Rg/R = 0.48) and minor metamorphic types (Rm/R = 0.12). Plutonic rock fragments are represented by orthoclase-oligoclase-biotite-quartz and orthoclase-hornblende-oligoclase composite grains (Fig. 4E).

The interstitial component includes important volcanogenic matrix (fine ash), which ranges from 3.2 to 15.2% of the whole rock.

Sycamore Canyon Petrofacies.—There is a significant change in sandstone composition at the base of the Sycamore Canyon Member. Sycamore Canyon sandstone is quartzofeldspathic ($Qm_{41}F_{54}Lt_{5}$), including abundant plagioclase (An_{10}–An_{30}) and quartz, and minor K-feldspar. Aphanitic lithics include polycrystalline quartz, volcanic, and metasedimentary grains ($Qp_{34}Lvm_{37}Lsm_{29}$; $Lm_{51}Lv_{49}Ls_{0}$). Abundant phaneritic rock fragments include plutonic rocks (Rg/R = 0.90) (Fig. 4F), represented by quartz-plagioclase, quartz-plagioclase-K-feldspar-hornblende, and quartz-plagioclase-hornblende-epidote composite grains.

The most significant distinguishing characteristic of this petrofacies is the presence of abundant hornblende grains, both as single crystals and crystals in phaneritic plutonic rock fragments, in contrast to biotite-rich plutonic fragments of the other petrofacies.

DISCUSSION OF PETROLOGIC RESULTS

Petrologic characteristics of the sandstone population suggest that the Puente Formation was derived mainly from a crystalline source area (plutonic and subordinate metasedimentary rocks), although an important volcanic contribution is recorded. All samples plot within the continental-block provenance of Dickinson (1985). In spite of the rather homogeneous detrital modes of the formation, some significant petrologic differences allow distinction of four petrofacies, corresponding to lithostratigraphic subdivi-

TABLE 2.—*Recalculated modal point-count data for the Puente Formation*

Sample No.	Qm	F	Lt%	Qt	F	L%	Qm	K	P%	Qp	Lvm	Lsm%	Lm	Lv	Ls%	Rg	Rv	Rm%	P/F	Lv/L
	Qm	F	Lt	Qt	F	L	Qm	K	P	Qp	Lvm	Lsm	Lm	Lv	Ls	Rg	Rg	Rm		
La Vida Member																				
P1	32	62	6	32	62	6	34	22	44	4	58	38	40	60	0	67	17	16	0.66	0.60
P2	38	58	4	39	58	3	39	25	36	19	19	62	77	23	0	72	3	25	0.59	0.23
P3	35	57	8	35	57	8	38	26	36	0	71	29	35	65	0	50	31	19	0.58	0.65
P4	35	63	2	36	63	1	36	22	42	29	29	42	60	40	0	86	3	11	0.65	0.40
P5	36	62	2	36	62	2	36	22	42	0	75	25	25	75	0	91	6	3	0.65	0.75
P6	36	56	8	38	56	6	39	19	42	17	66	17	21	79	0	63	29	8	0.69	0.79
P7	31	64	5	32	64	4	33	24	43	23	63	14	18	82	0	91	7	2	0.64	0.82
P8	37	59	4	37	59	4	38	21	41	0	79	21	21	79	0	76	17	7	0.66	0.79
P9	27	60	13	28	60	12	31	20	49	7	77	16	15	83	2	42	49	9	0.71	0.83
P10	30	52	18	31	52	17	37	17	46	4	66	30	23	69	8	31	50	19	0.73	0.69
P11	32	53	15	32	53	15	38	18	44	3	79	18	18	82	0	45	42	13	0.71	0.82
P12	31	50	19	31	50	19	38	18	44	4	76	20	21	79	0	38	49	13	0.71	0.79
P13	30	57	13	31	57	12	35	18	47	9	71	20	22	78	0	29	55	16	0.72	0.78
P14	32	43	25	33	43	24	43	10	47	6	86	8	9	91	0	15	76	9	0.82	0.91
P15	28	50	22	28	50	22	36	19	45	2	90	8	8	92	0	18	75	7	0.70	0.92
P16	30	45	25	30	45	25	40	16	44	1	93	6	6	94	0	24	71	5	0.73	0.94
P17	32	45	23	33	45	22	42	11	47	6	83	11	11	89	0	32	59	9	0.82	0.89
P18	27	50	23	27	50	23	36	14	50	2	91	7	7	93	0	37	59	4	0.78	0.93
P19	31	49	20	32	49	19	38	20	42	3	88	9	9	91	0	31	62	7	0.68	0.91
P20	28	52	20	29	52	19	35	16	49	4	79	17	18	82	0	22	63	15	0.75	0.82
P21	31	56	13	31	56	13	36	17	47	5	82	13	13	87	0	33	57	10	0.73	0.87
P22	34	57	9	35	57	8	38	17	45	8	77	15	17	83	0	36	50	14	0.73	0.83
P23	34	57	9	34	57	9	37	20	43	5	80	15	16	84	0	51	41	8	0.68	0.84
P24	27	58	15	28	58	14	33	19	48	6	88	6	6	94	0	49	46	5	0.72	0.94
P25	33	56	11	33	56	11	37	22	41	4	85	11	11	89	0	42	52	6	0.65	0.89
P26	28	66	6	29	66	5	31	28	41	12	84	4	4	96	0	84	15	1	0.60	0.96
P27	34	53	13	35	53	12	39	18	43	7	80	13	13	87	0	67	28	5	0.70	0.87
P28	30	61	9	31	61	8	33	12	55	13	76	11	12	88	0	66	30	4	0.81	0.88
P29	35	55	10	37	55	8	39	17	44	17	73	10	11	89	0	62	33	5	0.72	0.89
P30	34	56	10	36	56	8	38	19	43	14	65	21	24	76	0	64	27	9	0.69	0.76
P31	34	57	9	35	57	8	37	20	43	16	63	21	25	75	0	66	23	11	0.69	0.75
P32	31	59	10	33	59	8	35	21	44	20	64	16	20	80	0	66	26	8	0.68	0.80
P33	36	56	8	39	56	5	39	18	43	34	60	6	9	91	0	75	23	2	0.71	0.91
P34	35	53	12	36	53	11	39	17	44	11	78	11	13	87	0	60	35	5	0.72	0.87
P35	33	54	13	35	54	11	38	17	45	19	70	11	13	87	0	62	32	6	0.73	0.87
P40	41	49	10	43	49	8	46	19	35	23	41	36	47	53	0	62	18	20	0.65	0.53
P41	31	54	15	34	54	12	36	15	49	15	11	74	72	13	15	44	8	48	0.77	0.13
P42	46	46	8	49	46	5	50	4	46	24	44	32	26	58	16	55	32	13	0.93	0.58
P43	42	49	9	44	49	7	46	12	42	21	58	21	24	73	3	72	17	11	0.78	0.73
P44	37	49	14	40	49	11	43	17	40	22	67	11	14	86	0	53	37	10	0.70	0.86
P45	47	48	5	47	48	5	50	5	45	0	74	26	26	74	0	85	11	4	0.89	0.74
X	33	55	12	34	55	11	37	18	45	11	70	19	21	78	1	54	36	10	0.71	0.78
SD	±5	±6	±6	±5	±6	±6	±7	±6	±5	±9	±19	±15	±17	±18	±4	±21	±20	±8	±0.07	±0.18
Soquel Member																				
P36	36	54	10	39	54	7	39	15	46	31	33	36	51	49	0	68	14	18	0.75	0.49
P37	40	50	10	43	50	7	45	16	39	32	23	45	67	33	0	52	11	37	0.71	0.33
P38	39	47	14	43	47	10	47	17	36	25	42	33	45	55	0	47	23	30	0.68	0.55
P39	37	57	6	37	57	6	39	19	42	7	72	21	23	77	0	82	12	6	0.69	0.77
P46	43	50	7	44	50	6	46	8	46	4	7	89	84	8	8	74	2	24	0.85	0.08
P61	45	52	3	45	52	3	47	6	47	0	17	83	83	17	0	84	2	14	0.89	0.17
P62	47	49	4	48	49	3	48	6	46	31	13	56	82	18	0	86	1	13	0.89	0.18
P63	40	50	10	41	50	9	44	8	48	10	0	90	83	0	17	73	0	27	0.86	0.00
P64	45	48	7	47	48	5	49	6	45	25	11	64	81	14	5	81	2	17	0.89	0.14
P65	45	47	8	45	47	8	49	5	46	3	0	97	94	0	6	75	0	25	0.90	0.00
X	42	50	8	44	50	6	45	11	44	17	22	61	69	27	4	72	7	21	0.81	0.27
SD	±4	±2	±3	±4	±2	±2	±4	±5	±4	±13	±22	±27	±23	±26	±6	±13	±8	±9	±0.09	±0.26
Yorba Member																				
P47	33	52	15	34	52	14	39	11	50	7	81	12	13	97	0	35	56	9	0.82	0.97
P48	26	58	16	29	58	13	31	17	52	19	67	14	17	83	0	55	34	11	0.75	0.83
P49	39	51	10	41	51	8	44	11	45	20	44	36	44	56	0	46	34	20	0.80	0.56
P50	35	49	16	38	49	13	41	18	41	19	67	14	17	83	0	58	28	14	0.69	0.83
P66	33	47	20	36	47	17	41	14	45	13	70	17	20	80	0	37	48	15	0.77	0.80
P67	35	54	11	36	54	10	40	16	44	7	77	16	17	83	0	64	26	10	0.74	0.83
P68	29	48	23	32	48	20	38	16	46	10	78	12	13	87	0	27	64	9	0.75	0.87
P69	32	52	16	34	52	14	38	14	48	11	77	12	14	86	0	62	28	10	0.78	0.86
P70	29	53	18	31	53	16	35	17	48	12	75	13	15	85	0	44	45	11	0.74	0.85
X	32	52	16	35	52	13	39	15	46	13	71	16	19	81	0	48	40	12	0.76	0.81
SD	±4	±3	±4	±4	±3	±4	±4	±3	±3	±5	±11	±8	±10	±10	±0	±13	±14	±4	±0.04	±0.10
Sycamore Canyon Member																				
P51	44	53	3	45	53	2	45	9	46	20	50	30	40	60	0	92	5	3	0.84	0.60
P52	36	61	3	38	61	1	36	8	56	82	9	9	50	50	0	96	1	3	0.87	0.50
P53	44	51	5	46	51	3	47	12	41	35	30	35	53	47	0	90	4	6	0.77	0.47
P54	49	44	7	51	44	5	53	11	36	19	54	27	67	33	0	83	4	13	0.76	0.33
P56	33	56	11	36	56	8	37	15	48	28	55	17	38	62	0	85	9	6	0.76	0.62

TABLE 2.—*Continued*

Sample No.	Qm F Lt%			Qt F L%			Qm K P%			Qp Lvm Lsm%			Lm Lv Ls%			Rg Rv Rm%				
	Qm	F	Lt	Qt	F	L	Qm	K	P	Qp	Lvm	Lsm	Lm	Lv	Ls	Rg	Rg	Rm	P/F	Lv/L
P57	36	56	8	38	56	6	39	15	46	24	32	44	65	35	0	83	6	11	0.76	0.35
P58	41	57	2	41	57	2	42	12	46	20	40	40	50	50	0	92	4	4	0.80	0.50
P59	44	50	6	46	50	4	46	13	41	31	27	42	61	39	0	90	3	7	0.76	0.39
P60	41	55	4	43	55	2	43	13	44	47	33	20	38	62	0	96	2	2	0.77	0.62
X	41	54	5	42	54	4	43	12	45	34	37	29	51	49	0	90	4	6	0.79	0.49
SD	±5	±5	±3	±5	±5	±2	±5	±2	±6	±20	±15	±12	±11	±11	±0	±5	±2	±4	±0.04	±0.11

sions. Several petrologic parameters indicate that the Puente sandstones are volcani-plutoniclastic (La Vida and Yorba), plutoni-metamorphiclastic (Soquel), and plutoniclastic (Sycamore Canyon).

The four sandstone petrofacies record abrupt changes of lithic-grain and rock-fragment populations (Fig. 3). The La Vida and Yorba petrofacies have abundant volcanic detritus, in contrast to the Soquel and Sycamore Canyon petrofacies, which have more abundant metasedimentary, and particularly phaneritic plutonic rock fragments. A possible volcanic source area is the Glendora Volcanic Complex (and/or associated volcanic features), including abundant basalt, andesite, dacite, and rhyolite lava and pyroclastic rocks (Shelton 1955) interfingered with middle Miocene marine sediments of the Topanga Group.

The Soquel and Sycamore Canyon petrofacies record abrupt influxes of plutoniclastic detritus. However, type and content of the plutonic detritus changes vertically in the section. The Sycamore Canyon petrofacies (above the stratigraphic horizon dated at approximately 7–5.5 Ma) records a sudden change in the nature and abundance (up to 90%) of the plutonic detritus compared to the other petrofacies. The abundance of coarser hornblende grains, as single grains and within phaneritic fragments, suggests a morphostructural change in the source terranes or progressively deeper erosion of the plutonic complexes.

The crystalline nature of the source areas for all petrofacies has a clear relationship with the metasedimentary and granitoid terranes of the Transverse Ranges. Several petrologic parameters suggest derivation of detritus from nearby San Gabriel Mountains basement. The San Gabriel Mountains include two distinctive terranes separated by a major Paleocene thrust fault (Vincent Thrust): the lower plate consists of Upper Cretaceous metasedimentary rocks (i.e., Pelona Schist), whereas the upper plate consists of Precambrian gneissic and amphibolitic rocks, the Triassic Lowe Granodiorite Complex, and Upper Cretaceous granitic rocks (Fig. 5; Ehlig 1981). The composition of the Lowe Granodiorite Complex varies from hornblende diorite and quartz diorite in the lower part to albite-rich granodiorite and syenite in the upper part. Specifically, the lower part of the plutonic complex includes abundant coarser phenocrysts of hornblende, orthoclase, and oligoclase and minor quartz. The upper part of the plutonic complex includes a garnet-orthoclase zone, a minor hornblende zone, and a biotite-orthoclase zone (Ehlig 1981). The change from dominantly hornblende-bearing to dominantly biotite-bearing rocks is abrupt.

The plutonic rock fragments of Puente sandstone change stratigraphically. The La Vida and Soquel petrofacies include orthoclase-biotite-oligoclase and oligoclase-orthoclase-garnet fragments. Garnet is present, whereas hornblende is minor; orthoclase crystals are generally coarse-grained. The upper Yorba petrofacies and particularly the Sycamore Canyon petrofacies include hornblende-orthoclase, hornblende-orthoclase-oligoclase, and minor quartz fragments; hornblende is very abundant as megacrysts.

The distinctive characteristics of the plutonic detritus in the Puente sandstones suggest an inverted stratigraphic zonation of the Lowe Granodiorite Complex, indicating sequential unroofing of the upper plate of the Vincent thrust and particularly of the Lowe Granodiorite Complex (Fig. 6).

COMPARISON WITH RELATED SANDSTONES

Rapid convergence of the Farallon and Pacific plates with North America during latest Cretaceous and Paleogene (Laramide Orogeny) induced uplift of the roots of the Cretaceous magmatic arc, producing the source terrane for an immense volume of detrital sediment that was deposited in the forearc region (e.g., Snyder et al. 1976; Coney 1978; Dickinson 1981; Nilsen 1987). Active subduction of oceanic lithosphere of the Farallon Plate beneath the North America Plate ended near the Oligocene-Miocene boundary in southern California, as the arc-trench system was converted into a transform margin and a series of strike-slip basins developed along the previous forearc region (e.g., Atwater 1970; Dickinson 1976). Southern California sandstone petrofacies record this change from Late Cretaceous to the present (e.g., van de Kamp et al. 1976; Dickinson et al. 1979, 1987; Girty 1987).

Sandstone assemblages of the Upper Cretaceous to Upper Eocene are prevalently turbidite sandstones having a close relationship with the Great Valley Group, as defined in northern and central California (e.g., Ingersoll 1983). The Upper Cretaceous Tuna Canyon Formation, the Paleocene Coal Canyon Formation, the Eocene Liajas Formation, Matilija Sandstone, and Coldwater Sandstone, and the Oligocene Sespe Formation are the main sandstone units deposited in southern California during the Paleogene; they evolved from turbidite facies to shallow-water facies and finally to Oligocene alluvial strata (e.g., Link 1975; Howell and Link 1979; Yerkes and Campbell 1979; Link and Welton 1982; Dickinson et al. 1987). All of these sandstones are quartzofeldspathic, representing the "ideal arkose" of Dickinson (1985) and testifying to the plutonic nature of their provenance from the root of the Mesozoic magmatic arc (van de Kamp et al. 1976; Helmold 1980; Link and Welton 1982; Helmold and van de Kamp 1984; Dibblee 1989; Lane 1989).

The virtually continuous section in Wheeler Gorge (Transverse Range; Link and Welton 1982; Helmold and van de Kamp 1984) testifies also to a progressive decrease in phaneritic plutonic fragments, from Rg/R 0.88 for Cretaceous turbidites to 0.74 for the Matilija Sandstone to 0.63 for the Sespe Formation, and relative increase of metamorphic detritus (Rm/R), from 0.09 for Cretaceous turbidites to 0.34 for the Sespe Formation (Critelli, unpublished data). The increase of metamorphic detritus from the Cretaceous to the Oligocene suggests progressive exhumation of metasedimentary terrane in the source area, probably related to uplift of the Transverse Ranges during Paleogene time.

Within the Neogene and Quaternary sandstones/sands of the Los Angeles Basin, the Topanga Group consists of quartzofeldspathic plutoniclastic sandstone and interfingered coeval volcanic (i.e., Conejo Volcanics) and volcaniclastic rocks. Significant volcanic contribution is represented within the Topanga sandstones from both arc-related paleovolcanic detritus, and partially intrabasinal Conejo neovolcanic detritus (Critelli and Ingersoll 1995).

The San Onofre Breccia consists of coarse-grained gravity-flow deposits cropping out on the western border of the Los Angeles Basin (Vedder and Howell 1976; Stewart 1979). Sandstones are quartzofeldspathic ($Qm_{49}F_{36}Lt_{15}$), including abundant metavolcanic, metasedimentary, and

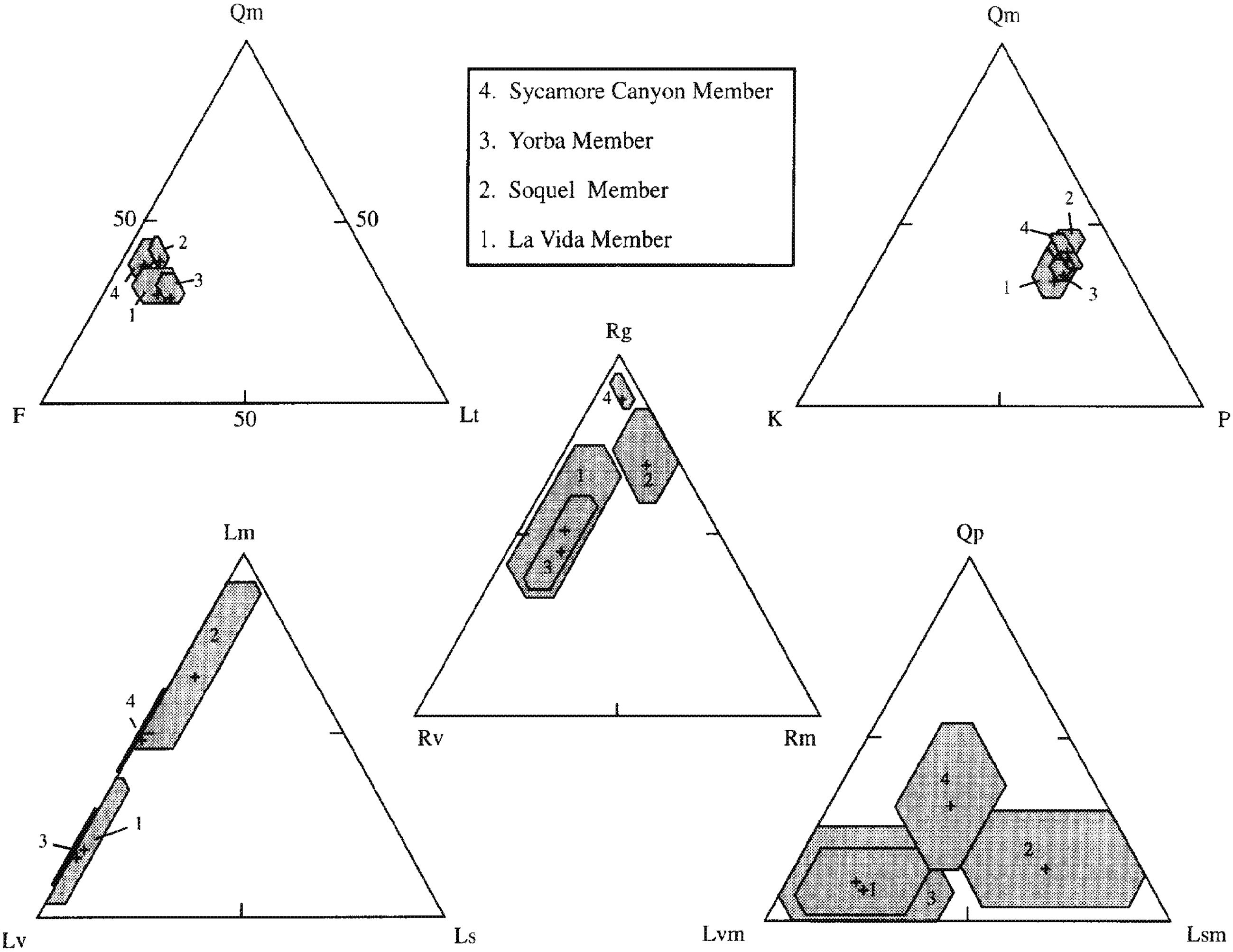

FIG. 3.—QmFLt, QmKP, QpLvmLsm, LmLvLs, and RgRvRm diagrams of the Puente Formation sandstones (see Tables 1 and 2 for explanation of symbols). Numbers are sandstone petrofacies. Polygons are one standard deviation on either side of mean.

volcanic lithics ($Lm_{89}Lv_{11}Ls_0$; $Qp_{12}Lvm_{39}Lsm_{49}$); the presence of glaucophane and glaucophane-schist detritus suggests contribution from high-pressure low-temperature metamorphic assemblages represented by the Mesozoic subduction complex exposed on Santa Catalina Island. Both phaneritic and aphanitic fragments indicate that plutonic detritus is subordinate ($Rg_{21}Rv_6Rm_{73}$; Critelli, unpublished data).

The Modelo Formation in the Santa Monica Mountains is subdivided into three petrofacies, including metamorphi-plutoniclastic, volcani-plutoniclastic, and plutoniclastic sandstones. The lower petrofacies reflects a local provenance from underlying basement. The middle and upper petrofacies reflect provenance from volcanic and plutonic rocks widespread in the San Gabriel Mountains (Rumelhart and Ingersoll 1994).

The Upper Miocene–Lower Pliocene Capistrano Formation ($Qm_{50\pm5}F_{47\pm5}Lt_{3\pm1}$; $Rg_87Rv_1Rm_{12}$) is similar to the Sycamore Canyon petrofacies. The quartzofeldspathic sandstones of the Lower Pliocene to Middle Pleistocene Fernando Formation ($Qm_{34}F_{58}Lt_8$) and the Upper Quaternary sandstone/sand of the La Habra Formation ($Qm_{28}F_{70}Lt_2$) include abundant phaneritic plutonic and metamorphic rock fragments ($Rg_{71}Rv_5Rm_{24}$ for Fernando Formation and $Rg_{82}Rv_1Rm_{17}$ for La Habra Formation; Critelli, unpublished data), reflecting dissection of the Transverse Ranges (i.e., the San Gabriel and/or Santa Ana Mountains). In addition, the presence of siliciclastic sedimentary lithics ($Lm_{59}Lv_{22}Ls_{19}$ for the Fernando Formation and $Lm_{71}Lv_{17}Ls_{12}$ for the La Habra Formation) suggests recycling of detritus from deformed Cretaceous, Paleogene, and Neogene sedimentary units.

CONCLUSIONS AND PALEOTECTONIC IMPLICATIONS

The Puente Formation is composed of two main turbidite megasequences (e.g., Ricci Lucchi 1975): the lower megasequence includes the La Vida and Soquel members, whose ages range from (?)14–12 Ma to about 8 Ma, and the upper includes the Yorba and Sycamore Canyon Members (8 Ma to 5.5 Ma). The Puente Formation is underlain and overlain by unconformities (Durham and Yerkes 1964; Yerkes et al. 1965; Yerkes 1972). In spite of its rather homogeneous composition, several petrologic parameters allow discrimination of four petrofacies, corresponding to the lithostratigraphic subdivisions of the Puente Formation. The petrofacies may be distinguished based on the following characteristics:

(1) Volcanic detritus is abundant in the lower parts of each megacycle (La Vida and Yorba Members);

(2) Volcanic-rich petrofacies (La Vida and Yorba) include lathwork, microlitic, felsitic, and subordinately vitric lithics, including zoned plagioclase ($An_{20\text{-}60}$), biotite, hornblende, hypersthene, and augite, testifying to a provenance from basaltic, andesitic, dacitic, and rhyolitic lava and pyroclastic

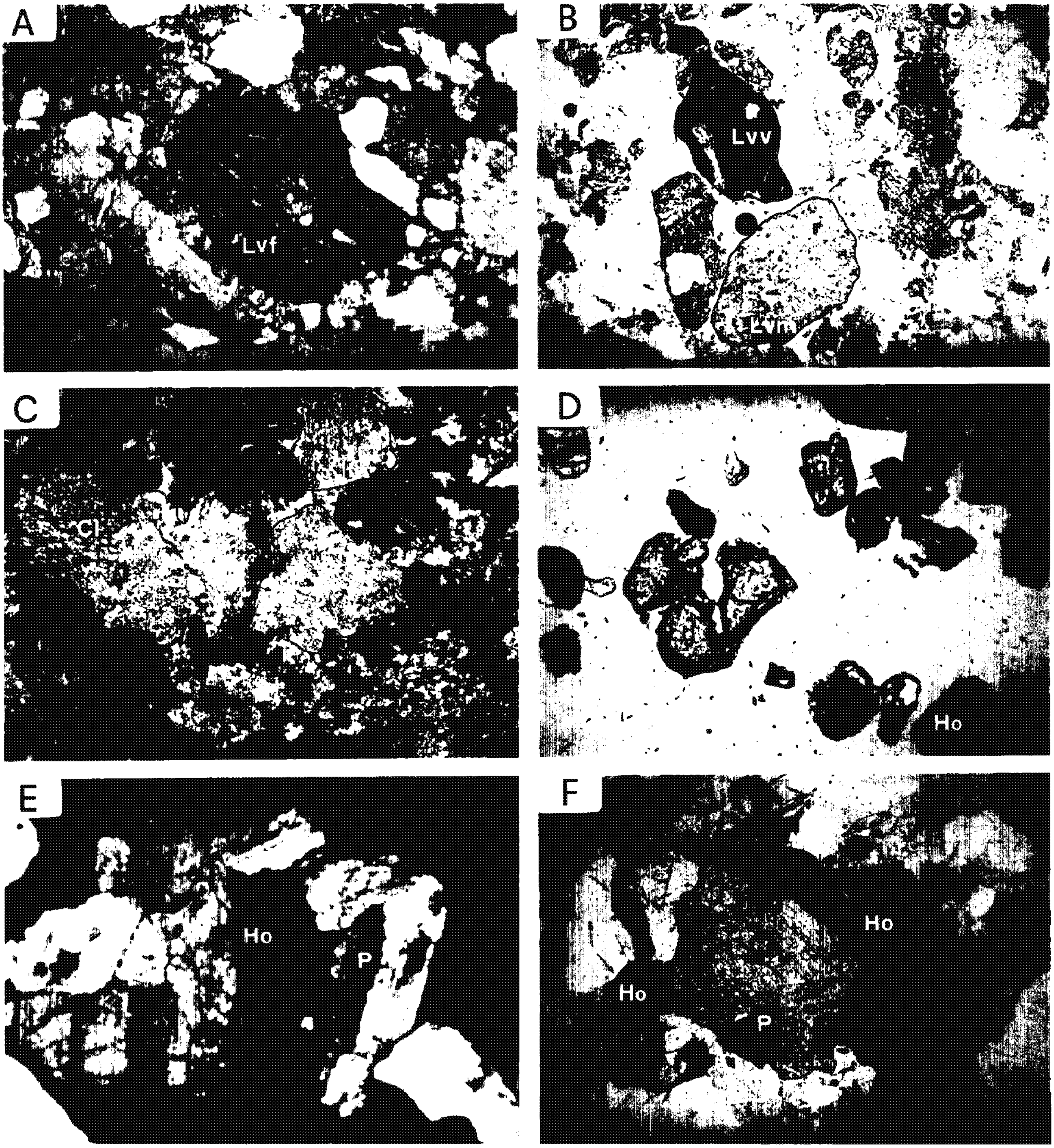

FIG. 4.—Photomicrographs of sand grains from Puente Formation. La Vida petrofacies: **A)** felsitic seriate volcanic lithic grain (Lvf). Yorba petrofacies: **B)** vitric (Lvv) and microlitic (Lvm) volcanic lithic grains; **C)** intrabasinal carbonate grains (Cl); **D)** single grains of garnet (g) and hornblende (Ho); **E)** lowest occurrence of hornblende-bearing plutonic detritus (Ho = hornblende; P = plagioclase) in upper Yorba Member. Sycamore Canyon petrofacies: **F)** plutoniclastic petrofacies containing abundant hornblende(Ho)-plagioclase(P)-bearing plutonic detritus; arrows indicate abundant single crystals of hornblende. Plane-polarized light (**A**, **B**, **C**, **F**) and crossed nicols (**D**, **E**). Horizontal dimension is 2.5 mm in all frames.

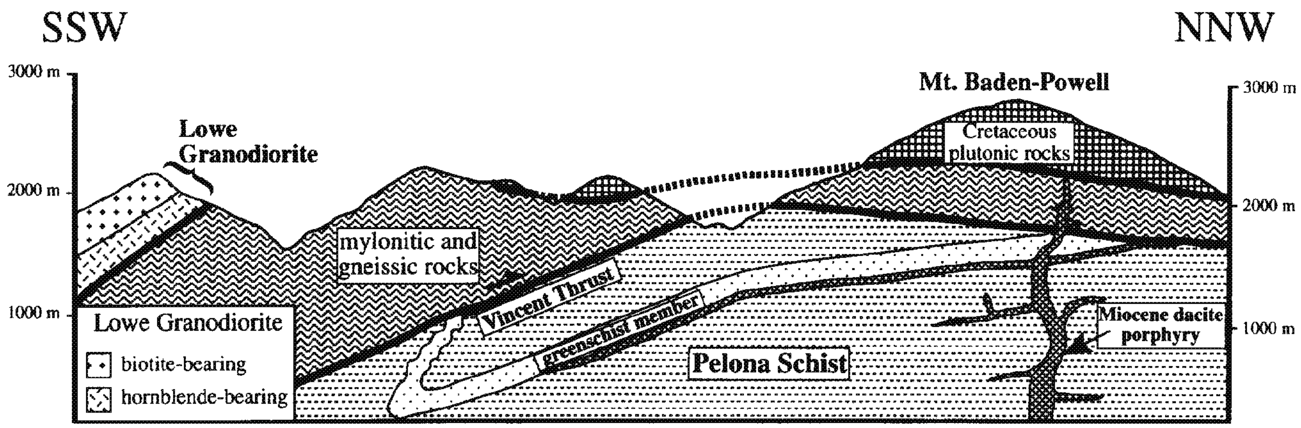

FIG. 5.—Schematic cross section of central San Gabriel Mountains (modified from Ehlig 1981).

rocks of the nearby Glendora Volcanic Complex and related volcanic complexes.

(3) Hornblende content is markedly higher in the upper megasequence (upper part of Yorba Member and Sycamore Member), whereas in the La Vida and Soquel members, less abundant hornblende is mixed with garnet, opaques, zircon, tourmaline, hypersthene, augite, epidote, sphene, and apatite.

(4) Plutonic detritus is more abundant in the upper parts of the two megacycles (Soquel and Sycamore Canyon Members) relative to lesser amounts of metamorphic detritus.

(5) Plutonic detritus is prevalently biotite-bearing in the La Vida and Soquel Members and the lower part of the Yorba Member; it is dominantly hornblende-bearing in the upper part of the Yorba Member and the entire Sycamore Canyon Member (Fig. 6).

(6) Plutonic detritus is particularly abundant in the Sycamore Canyon Member, above the stratigraphic horizon dated at approximately 7–5.5 Ma, where over 90% of the framework is plutonic detritus. The plutonic detritus is mineralogically similar to the Lowe Granodiorite Complex, which forms the frontal terrane of the southern San Gabriel Mountains (i.e., the Vincent Thrust and the Sierra Madre Thrust; Fig. 5).

(7) The Lowe Granodiorite Complex is dominantly hornblende-bearing diorite and syenite in the lower part and biotite-bearing granodiorite and syenite in the upper part. Vertical trends of the plutonic detritus in the Puente Formation mimic trends in the inverted plutonic zones of the Lowe Granodiorite Complex (Fig. 6).

(8) The deep unroofing of the Lowe Granodiorite terrane suggests rapid uplift and related high accumulation rates (Fig. 7), particularly during de-

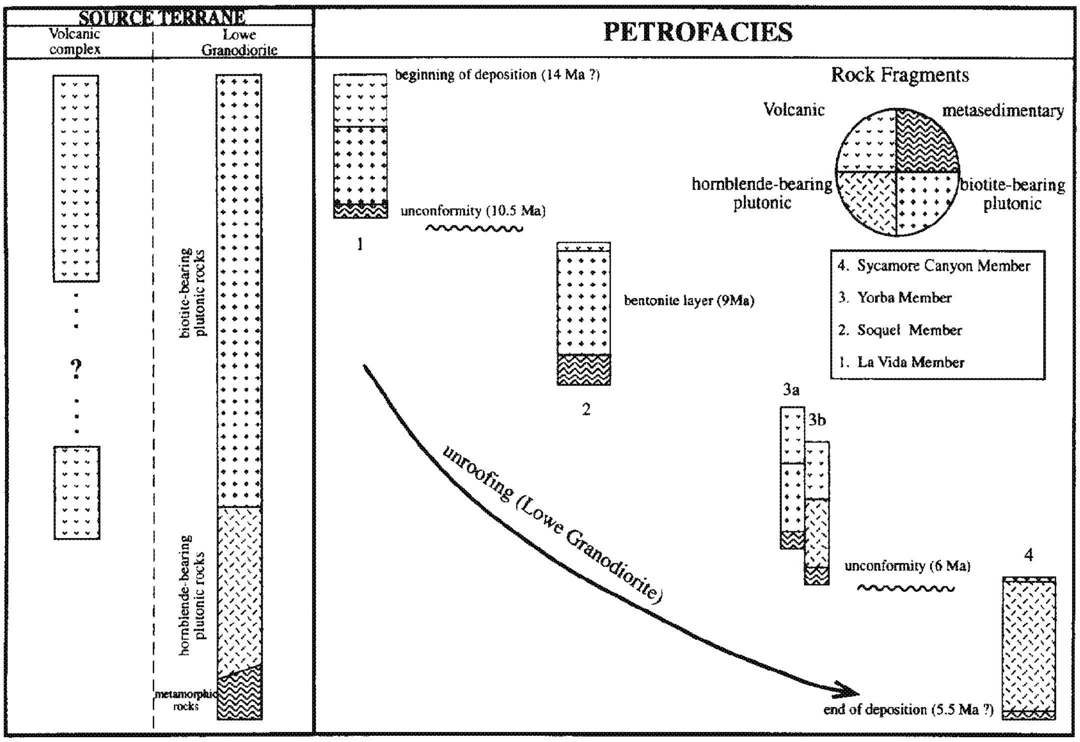

FIG. 6.—Sequential sandstone provenance of Puente Formation, showing relationship between source terrane and petrofacies. See text for discussion.

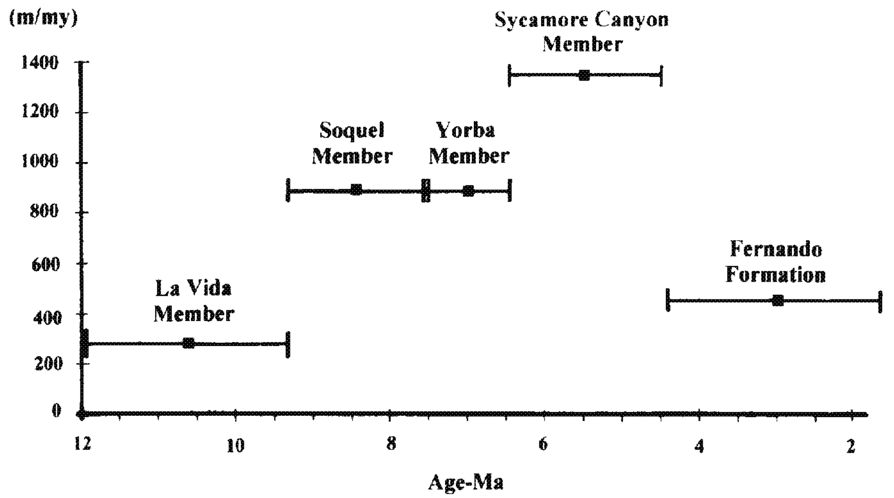

FIG. 7.—Decompacted sediment accumulation rate in m/my (vertical axis), from Blake (1991). Rates for Puente members and Fernando Formation are plotted at approximate midpoints for age ranges on horizontal axis (see Fig. 2).

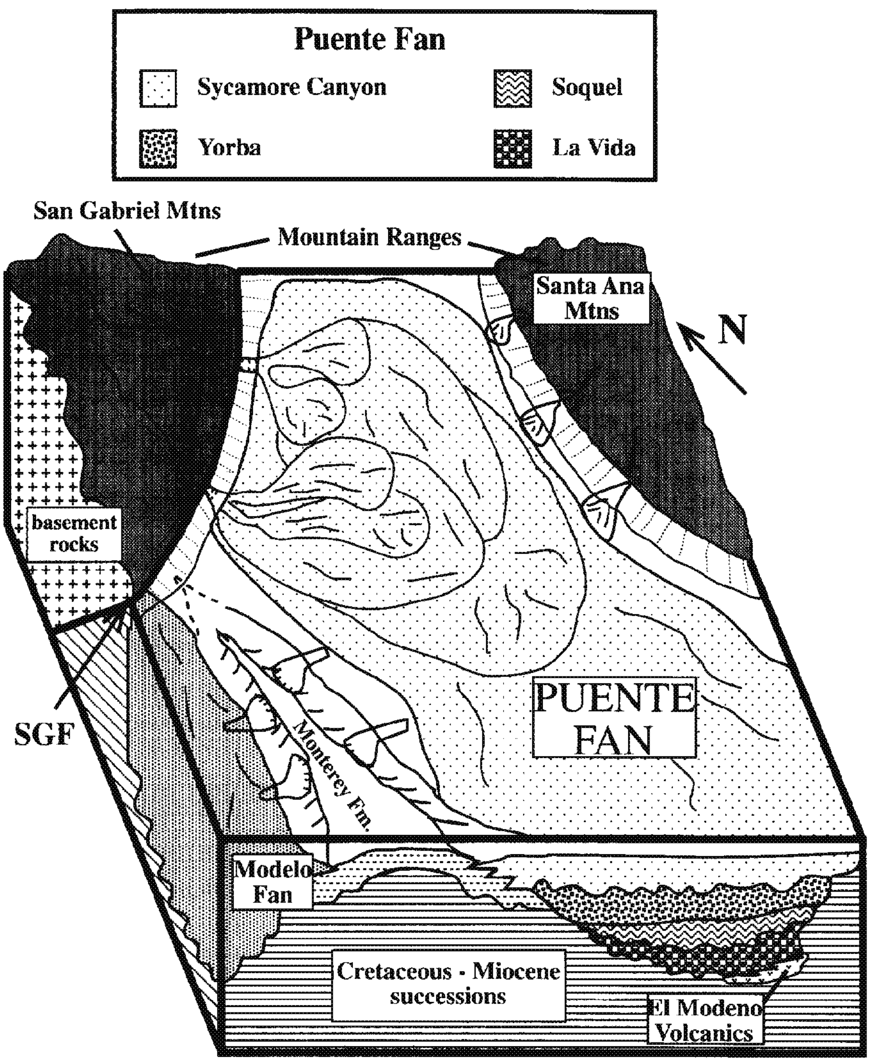

FIG. 8.—Paleogeographic block diagram of Puente subbasin during deposition of Sycamore Canyon Member.

position of the upper parts of the two Puente megasequences (i.e., the Soquel and Sycamore Canyon Members, at about 10–8 Ma and 7–5.5 Ma, respectively). Rapid uplift occurred at about 6 Ma, as suggested by stratigraphic discordance of the Sycamore Canyon Member with the Yorba Member, drastic increase of plutonic detritus (Rg/R is 0.48 in Yorba Member and 0.90 in Sycamore Canyon Member), and high hornblende content (about 10% of the total sandstone framework for the Sycamore Canyon Member). The accumulation rate changed during deposition of the Puente Formation; it was low (less than 200 m/my) during deposition of La Vida Member, increased from 300 m/my to 900 m/my during Soquel and Yorba deposition, then drastically increased to 1400 m/my during Sycamore Canyon deposition, followed by a rapid fall during the Pliocene (Fernando Formation; Fig. 7).

(9) The effects of increased uplift of the San Gabriel Mountains are also evident in the Upper Miocene to Lower Pliocene Capistrano Formation, having compositional characteristics identical to the Sycamore Canyon petrofacies, and the Lower Pliocene to Middle Pleistocene Fernando Formation, having abundant plutonic and metamorphic detritus. The increased metamorphic detritus suggests complete exhumation of the San Gabriel Mountains, where metamorphic terranes are present in the structurally deep parts of the range.

Relationships between sandstone composition and source lithology provide constraints on uplift, denudation rates, and accumulation in a transform setting. Generally, these relationships have been documented in rapidly evolving collisional mountain chains (e.g., Himalayan Chain) and related foreland sediment accumulation (e.g., Burbank and Beck 1991; Harrison et al. 1993). The relationship between rapid unroofing and uplift rates is well documented in terms of composition of clastic strata (e.g., Graham et al. 1986; Jordan et al. 1987; DeCelles 1988; Critelli and Ingersoll 1994; Critelli and Le Pera 1994). The Los Angeles Basin is an excellent example of very rapid denudation in a rapidly uplifted mountain chain (the San Gabriel Mountains) and rapid accumulation in an adjoining subsiding basin. During the last 14 m.y., a sedimentary succession 7000 m thick has accumulated (dominantly in deep water), resulting in a 500 m/my mean accumulation rate. The present height of the San Gabriel Mountains (about 3000 m a.s.l.) and their proximity to the Los Angeles Basin suggest rapid movement of several million tons/yr of sediments through relatively short rivers directly to bathyal depths. The rarity or absence of intrabasinal carbonate grains in the Puente sandstones suggests the absence of a shelfal area and a direct connection between subaerial drainage systems and submarine canyons (Fig. 8; e.g., Ingersoll and Graham 1983).

In conclusion, the Puente Formation represents a confined turbiditic clastic wedge within the rapidly subsiding Los Angeles Basin (Fig. 8). During the middle Miocene, a structural paleo-high within the north-central Los Angeles Basin separated the Modelo and Puente turbidite systems (Fig. 8). Detrital-mode evolution suggests a dominant plutonic provenance from the unroofing of the Lowe Granodiorite complex and related rocks. This terrane was the frontal part of a major thrust fault of the southern edge of the San Gabriel Mountains during right slip along the San Gabriel Fault. Changing plutonic detritus in Puente sandstones from biotite-bearing to hornblende-bearing reflects unroofing of the Lowe Granodiorite, suggesting rapid uplift from about 10 Ma to 5.5 Ma during deposition of the two plutonic-bearing petrofacies (and continuing to the present). This conclusion indicates a close connection among Puente deposition, San Gabriel Mountains uplift, and San Gabriel Fault displacement. Movement along the San Gabriel Fault might have been responsible for rotation of blocks, reactivation of thrust faults, rapid uplift, and high rates of exhumation and denudation of the San Gabriel Mountains. The Puente Formation represents deposition during transpression along the northeastern margin of the Los Angeles Basin, concurrent with more transtensional margins to the south and west.

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