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Development of a Late Quaternary Marine Terraced Landscape during On-Going Tectonic Contraction, Crescent City Coastal Plain, California

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The Crescent City coastal plain is a low-lying surface of negligible relief that lies on the upper plate of the Cascadia subduction zone in northernmost California. Whereas coastal reaches to the north in southern Oregon and to the south near Cape Mendocino contain flights of deformed marine terraces from which a neotectonic history can be deduced, equivalent terraces on the Crescent City coastal plain are not as pronounced. Reexamination of the coastal plain revealed three late Pleistocene marine terraces, identified on the basis of subtle geomorphic boundaries and further delineated by differentiable degrees of soil development. The youngest marine terrace is preserved in the axial valley of a broad syncline, and the two older marine terraces face each other across the axial region. An active thrust fault, previously recognized offshore, underlies the coastal plain, and folding in the hanging wall of this thrust fault has dictated, through differential uplift, the depositional limits of each successive marine terrace unit. This study demonstrates the importance of local structures in coastal landscape evolution along tectonically active coastlines and exemplifies the utility of soil relative-age determinations to identify actively growing folds in landscapes of low relief.

INTRODUCTION

Marine terraces are a useful datum from which late Quaternary deformation and surface uplift can be inferred (Lajoie, 1986), and marine terraces have been used for these purposes along the Cascadia subduction zone in Oregon and northern California (Merritts and Bull, 1989; Kelsey, 1990; McInelly and Kelsey, 1990; Kelsey *et al.*, 1996). However, the Crescent City coastal plain (Fig. 1), a 6–9-km-wide coastal lowland in northernmost California, has not been an attractive candidate for study of neotectonic deformation because the plain is not terraced with distinct treads separated by risers, as is typical of marine terraces. Despite the lack of well-defined marine terraces, at least part of the coastal plain clearly consists of marine terrace because sea-clif exposures reveal marine sand overlying a shore platform cut in sandstone. Furthermore, a reconnaissance study of soils developed on the coastal plain sand indicated that the coastal plain surface is not all the same age, from which we infer that multiple marine terraces occupy the surface. If true, the coastal plain contains a record of neotectonic deformation heretofore not investigated.

The objective of this paper is to use marine terrace age and distribution to identify the pattern of the late Quaternary deformation in the Crescent City coastal plain area (Polenz, 1997). To accomplish this objective, we determined how many marine terraces make up the Crescent City coastal plain, characterized the soils developed on their surfaces, investigated the cover stratigraphy and the buried bedrock topography underlying the terraces, and estimated terrace ages. Two means are employed to estimate the age of Crescent City marine terraces, amino acid correlation age estimates on fossils and correlation based on soil development of the Crescent City marine terraces to marine terraces 20 km to the north near Brookings, Oregon (Fig. 1) that have assigned ages (Kelsey and Bockheim, 1994).

THE CRESCENT CITY COASTAL PLAIN

On the basis of geomorphology and previous mapping, the coastal plain can be divided into three morphostratigraphic units, Holocene marine and eolian sand near the coast, alluvium deposited by the Smith River, and late Pleistocene marine and eolian sand (Fig. 2) (Maxson, 1933; Back, 1957; California Department of Water Resources, 1987). Despite the low relief, two prominent scarps on the coastal plain serve as a starting point for differentiating the late Pleistocene sediments into possible marine terrace units. An escarpment along the eastern

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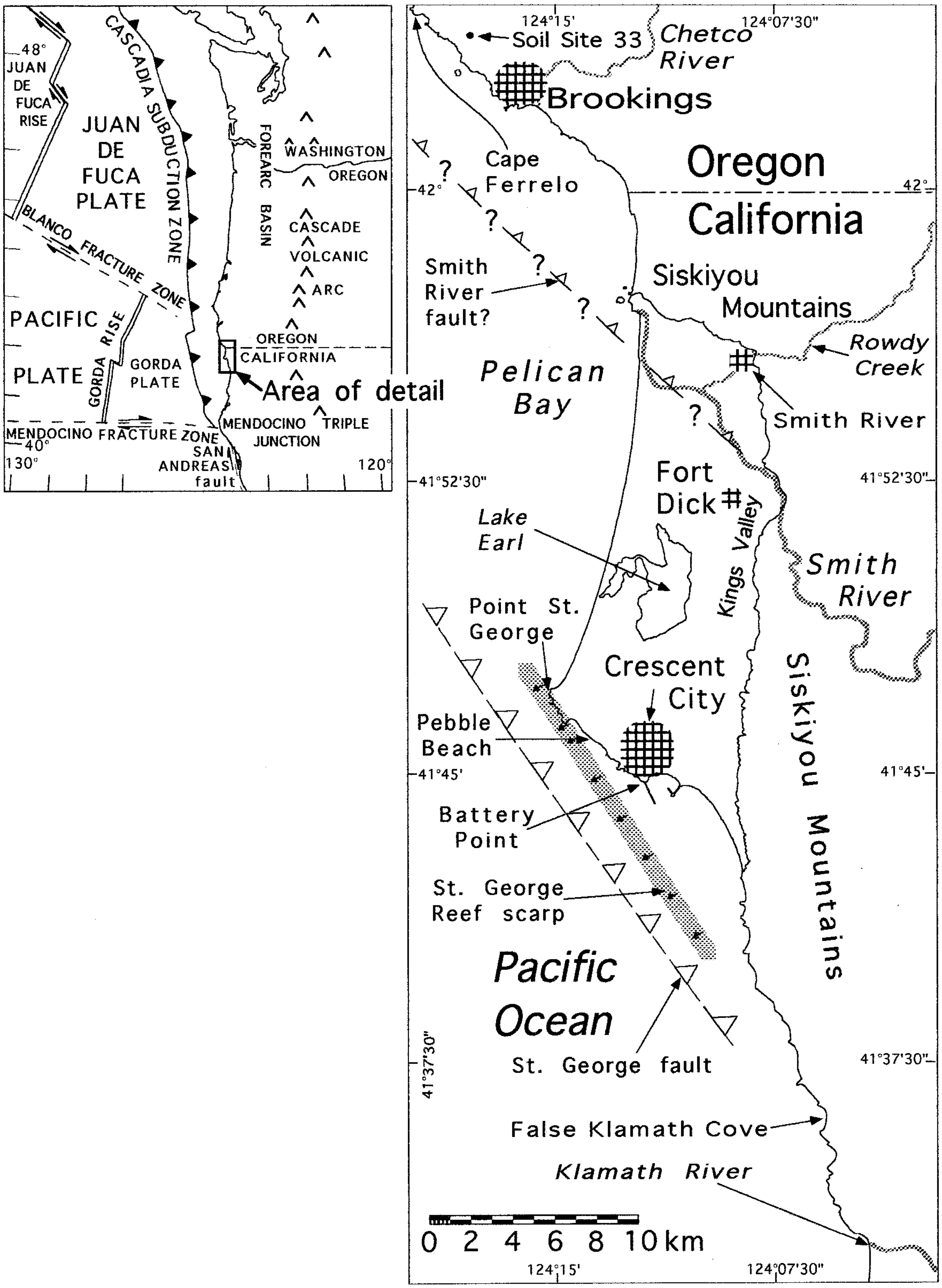

FIG. 1. Regional setting of field area showing Saint George fault and Smith River fault (Clarke, 1992) and Saint George Reef scarp (Roberts and Dolan, 1968).

shore of Lake Earl ("Lake Scarp," Fig. 2) is a candidate paleo-sea cliff, modified by late Holocene lake shore erosion. The scarp is a subtle feature in the south but becomes more prominent (6–12-m-high) northward, before dying out. The Cemetery Scarp (Fig. 2), a 6-m-high scarp that trends northwest across Crescent City, also is a candidate paleo-sea cliff.

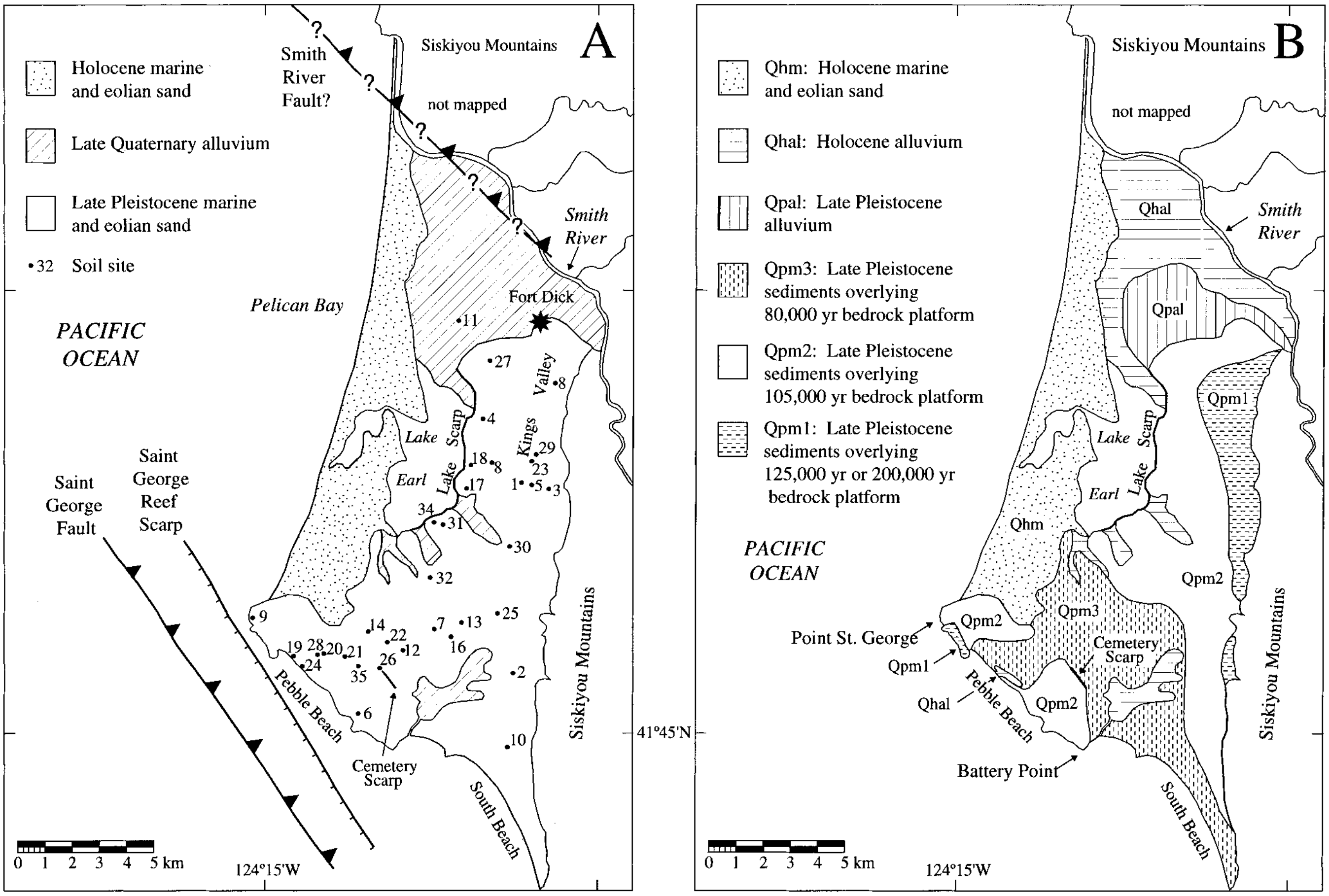

FIG. 2. (A) Crescent City coastal plain showing geologic provinces and soil sample sites. (B) Quaternary geologic map of the Crescent City coastal plain, showing distribution of three late Pleistocene terrace deposits (Qpm3, Qpm2, and Qpm1). Holocene marine and dune sand (Qhm), and alluvium of the Smith River (Qpal and Qhal). The youngest late Pleistocene terrace deposit, Qpm3, extends to the north on the east (oceanward) side of Lake Scarp, where it is covered by Holocene sand or Holocene alluvium of the Smith River. The terrace underlain by late Pleistocene alluvium (Qpal) is higher than the active floodplain of the Smith River (Qhal).

The pre-late Pleistocene units that underlie the coastal plain constitute the planated platform on which late Pleistocene sand is deposited (Fig. 2). These pre-late Pleistocene units include Mesozoic sandstone and volcanic rocks of the Franciscan Formation and the overlying Pliocene–Pleistocene fossiliferous marine sandy mudstone and sandstone of the Saint George Formation (Diller, 1902; Maxson, 1933; Back, 1957; Stone, 1993; Aalto *et al.*, 1995).

The sandy marine terrace cover sediments capping both the Saint George and the Franciscan Formation were defined as the Battery Formation by Maxson (1931). At the type section, the Battery Formation is a 3–5-m-thick section of unconsolidated to consolidated marine sand. In many parts of the coastal plain, the marine sediment is capped by eolian sand; in these areas the thickness of cover sediments locally exceeds 20 m. The age of the Battery Formation is interpreted to be late Pleistocene on the basis of fossils (Addicott, 1963) and an amino acid racemization correlation age estimate of a clam, *Saxidomus giganteus* (Deshayes) (Wehmiller *et al.,* 1977; Kennedy *et al.,* 1982). Alluvial deposits of the Smith River, distinguished by rounded pebble and cobble clasts, blanket the northern part of the coastal plain (Fig. 2).

Faults in the vicinity of the coastal plain include the Saint George fault and the Smith River fault (Fig. 2). These faults have been recognized on offshore seismic lines (Field *et al.,* 1980; Clarke, 1992; S. H. Clarke, personal communication, 1996). The northwest-trending, northeast-dipping Saint George fault parallels the Saint George Reef scarp, which is an 8–9-m-high bedrock ridge identified in the offshore by Roberts and Dolan (1968) (Fig. 1).

The Del Norte fault was proposed by Maxson (1933) to account for the abrupt, north–south trending eastern boundary of the coastal plain with the Siskiyou mountains (Fig. 2). Subsequent workers either have adopted Maxson's (1933) proposed fault (Back, 1957; Roberts and Dolan, 1968; Stone, 1993) or have questioned the fault's existence (California

Department of Water Resources, 1987; España Geotechnical Consulting, 1993). The putative Del Norte fault is omitted from Figure 2 because it is not exposed and evidence for it is equivocal.

DIFFERENTIATION OF MARINE TERRACES USING SOIL DEVELOPMENT

Late Pleistocene marine terrace sediments, which consist mostly of marine and eolian sand but also include silty sand, clay lenses, and gravel, underlie the southern and southeastern half of the coastal plain (Fig. 2A). The eolian sand that partially covers the marine sand does not appear to be significantly younger because no soil development is apparent at the eolian sand/marine sand contact.

We tentatively divided the area underlain by the late Pleistocene marine terrace sediment into three marine terraces (Fig. 2B). Criteria for the mapping of the terraces included reconnaissance soil investigation, subtle (<2 m) topographic changes, and the position of the Lake Scarp and the Cemetery Scarp. For mapping purposes we assumed the Lake Scarp and the Cemetery Scarp were degraded paleo-sea cliffs separating marine terraces of different ages. In the case of the Lake Scarp, the sea cliff face has been freshened by erosion on the east shore of Lake Earl.

In order to test the above-postulated boundaries of the marine terraces, we undertook a more detailed soil investigation, using soil descriptions from the sampling locations of Figure 2A. The test consisted of assessing whether mapped boundaries of the terraces separate marine terrace soils of different relative ages. The use of soil development to identify boundaries between different aged marine terraces is based on the assumption that on flat marine terraced surfaces with identical physiographic setting and parent material, the most important soil-forming factor accounting for a variable degree of soil development, as measured by a soil development index, is time (e.g., Bockheim *et al.*, 1992).

Soil profiles (Table 2) were described using the notation of the Soil Survey Staff (1975) with the modifications of Birkeland (1984). Soil pits were hand dug to the Cox horizon where possible; for a few pits, descriptions were extended downward using a bucket auger (Table 2).

We employed a soil development index (Table 1) developed by Kelsey and Bockheim (1994) for a soil chronosequence on marine terraces at Brookings, Oregon (Fig. 1). This development stage index assumes unconsolidated sandy quartzose parent material. Criteria for the soil development index include depth to the Cox horizon (m), B horizon hue, Bt horizon thickness (cm), maximum B horizon texture development, estimated clay content (%), and maximum clay film development. However, for the Crescent City coastal plain, the B horizon hues did not appear to vary systematically with overall profile development (Table 2), and B horizon hues were omitted from computations of profile development stage. We calibrated the stage development estimates from our soil descriptions to those of Kelsey and Bockheim (1994) by redescribing four of their soil sampling sites in the Crescent City coastal plain (sites 1, 2, 4, 5, Figs. 2A and 3) and one of their sampling sites in Brookings (site 33, Figs. 2A and 3).

When soil descriptions are grouped according to the proposed marine terrace units, the average development index is higher for each older terrace (Fig. 3, Table 2). Because of natural variability in rates of soil development on a single terrace, there is overlap of soil development indices between groups (Fig. 3). Marine terrace boundaries must be consistent not only with the soil development indices but also with the geomorphology of the coastal plain, wherein soil sites of similar relative age can be geographically grouped. Alternative groupings are possible based on the variability in soil development; however, the grouping of soil sites depicted on the map in Figure 2B and delineated graphically in Figure 3 is both consistent with soil relative ages and geographically feasible given the distribution of soil sites on the coastal plain.

The inference that Cemetery Scarp and Lake Scarp are paleo-sea cliffs between marine terraces is compatible with the soil relative ages. In the case of Cemetery Scarp, soil sites on the high side of the scarp (for example, sites 6 and 35, Fig. 2A) have better developed soil than sites to the northeast on the low side of the scarp (for example, sites 12, 14, and 22, Fig. 2A) (Fig. 3). In the case of Lake Scarp, soil sites on the high side of the scarp (for example, sites 17, 18, 31, Fig. 2A) are of intermediate relative age. We infer that the low (western) side of Lake Scarp is underlain by marine sand of the youngest relative age, but we cannot test this because the low side is covered by Lake Earl and Holocene sand dunes. In summary, postulated boundaries of the marine terraces are not inconsistent with terrace relative-ages derived from soil development.

BEDROCK TOPOGRAPHY BENEATH THE COASTAL PLAIN

We used bedrock elevation data to determine whether there is buried bedrock topography that would be consistent with proposed boundaries of the three marine terraces, and to establish shore platform elevations in order to calculate uplift rates. Well records and bedrock outcrops were utilized to reconstruct bedrock topography underlying the coastal plain. From a pool of several thousand well logs, and a geodolite survey of platform elevations in cliff exposures from Battery Point to Point Saint George, 319 data points were extracted to determine bedrock elevation (Fig. 4A). We interpreted some anomalously high bedrock elevations to be possible buried sea stacks, and these elevations were not used in platform reconstructions.

The buried topography is consistent with the inferred distribution of marine terrace units shown in Figure 2A. The relatively youngest late Pleistocene marine terrace covers a northwest-trending trough in the coastal plain where bedrock

TABLE 1
Development Stages of Soils on Elevated Marine Terraces along the Central and Southern Oregon Coast[a]

Development stage	Depth to Cox (m)	B horizon hue	Bt thickness (cm)	Maximum B horizon texture[b] (% clay)[c]	Maximum clay films[d]
1	0.8–1.4	7.5–10YR	0	sil, 1, sl (<30)	1–3npfpo
2	1.0–1.4	7.5YR	<50	sicl, cl, scl (30–40)	2–3n-mkpfpo
3	1.0–1.7	7.5YR	<50	sicl, cl, scl (30–40)	2–3mkpfpo
4	1.4–1.8	5–7.5YR	50–100	sicl, sic, cl, c (35–42)	3–4mkpfpo
5	1.9–2.8	5–7.5YR	100–200	sic, c (40–58)	3–4mk-kpfpo
6	2.6–4.5	5YR	>200	sic, c (40–65)	3–4mk-kpfpo
7	3.2–>4.5	2.5YR	>200	sic, c (45–65)	3–4mk-kpfpo

[a] Table is reproduced from Kelsey and Bockheim (1994).

[b] Abbreviations: l, loam; sl, sandy loam; sil, silt loam; sicl, silty clay loam; sic, silty clay; cl, clay loam; scl, sandy clay loam; c, clay. Abbreviations follow Soil Survey Staff (1975).

[c] Percentage of clay estimated in field for each horizon.

[d] Notations for clay films, number denotes extent of ped faces covered by film: v1, <5%; 1, 5–25%; 2, 25–50%; 3, 50–90%; 4, >90%; n, thin; mk, moderately thick; k, thick; pf, film on ped face; po, film lines the pores. Abbreviations follow Soil Survey Staff (1975).

drops below sea level and reaches a low of about −16 m. The intermediate-age terrace west of Cemetery Scarp has a platform elevation 4–20 m higher than the bedrock trough, and we interpret this higher platform to have been a paleo-island at the time of paleo-sea cliff erosion of Cemetery Scarp. The relatively oldest marine terrace is underlain by a zone of elevated bedrock in the central portion of the easternmost coastal plain. A narrow coastal segment on the west near Point Saint George is also part of this oldest marine terrace, based on a platform elevation 10–20 m higher than the platform for the intermediate age terrace in the adjacent sea cliff. Hence, the relatively oldest marine terrace covers much of the eastern coastal plain and also occurs in a narrow strip on the western fringe of the coastal plain. The fact that the older platforms are generally the higher in elevation reflects ongoing coastal uplift, typical of fold and thrust belts along active tectonic margins (e.g., McInelly and Kelsey, 1990; Berryman, 1993).

AGES OF THE CRESCENT CITY MARINE TERRACES

Aminostratigraphy and soil development are used to correlate the Crescent City marine terraces with numerically dated terraces elsewhere. Marine sand at the Pebble Beach cliff exposures, part of the soil group of intermediate relative age, contains the clam *Saxidomus giganteus* (Deshayes), which gave an amino acid enantiomeric ratio (D/L) of 0.35 (Wehmiller *et al.,* 1977; Kennedy *et al.,* 1982). For the latitude of ca. 42° north, this ratio is indicative of an oxygen isotope stage 5 age (80,000–125,000 yr) (Kennedy *et al.*, 1982). Because the sand at Pebble Beach hosts a cool-water fauna, a stage 5e age (125,000 yr) is unlikely (Kennedy *et al.*, 1982). Therefore, marine sand of the intermediate-age marine terrace was probably deposited during either the 80,000 or the 105,000 yr sea-level high stands. An age estimate of ~80,000 yr for Pebble Beach is supported by new, unpublished amino acid ratios (D. R. Muhs, personal communication, 1996) that are similar to those in this species from Bandon, Oregon, where there is a 83,000 ± 5,000 yr U-series age on coral (Muhs *et al.*, 1990).

The other means of estimating marine terrace ages at Crescent City is through interpretation of soil development. The average soil-development stage estimates for the Crescent City coastal plain are 2.1, 2.8, and 4.1 for the youngest, intermediate, and oldest marine terraces, respectively (Table 2). In the Brookings, Oregon, area, soil-development stage estimates for seven marine terraces are (youngest to oldest) 1.4, 2.4, 3.1, 5.1, 4.0, 4.3, and 6.0 (Kelsey and Bockheim, 1994). The lowest four Brookings terraces were assigned ages of 80,000 (oxygen isotope stage 5a), 105,000 (stage 5c), 125,000 (stage 5e), and ≥200,000 yr (≥stage 7) (Kelsey and Bockheim, 1994). A comparison of the soil development stage estimates from the three marine terraces at Crescent City (2.1, 2.8, 4.1) with the seven marine terraces at Brookings (1.4, 2.4, 3.1, 5.5, 4.0, 4.3, 6.0) suggests that the youngest and intermediate-age Crescent City marine terraces are stage 5. The intermediate-age Crescent City terrace cannot be stage 5e because marine fauna then would be of warm water affinity and the marine fossil fauna of the intermediate-age terrace at Pebble Beach are of cold water affinity (Kennedy *et al.*, 1982). A 125,000 yr (stage 5e) age also is the least likely stage 5 age because the amino acid ratio at the Pebble Beach site is lower than would be expected for a 125,000-yr-old deposit (Kennedy *et al.*, 1982). Therefore, we assign the youngest and intermediate Crescent City marine terraces (Qpm3 and Qpm2) ages of 80,000 yr (stage 5a) and 105,000 yr (stage 5c). The oldest Crescent City terrace (Qpm1) could be 125,00 yr (stage 5e) or 200,000 yr (stage 7), and it is unlikely to be older than stage 7. Marine terraces that are older than stage 7 are infrequently preserved in coastal settings of

TABLE 2
Summary of Soil Properties Used as Relative Age Indicators

Soil site[a]	Depth to Cox (cm)	B horizon hue	Bt horizon thickness (cm)	Maximum B texture[b]	Maximum estimated (% clay)[b]	Maximum clay skins[b]	Development stage[c]
Group 1 (80,000 yr)							
16	95	2.5Y/7.5YR	33	scl	25	3npfpo	1.3
19	94	7.5–10YR	10	sl	10–15	2nbrpo	1.7
24	91	10YR	10	sl	15	N.D.	1.8
20	104	7.5–10YR	16	sl	15–16	1nbr	1.9
28	115	7.5–10YR	79	cl	31	1n-mkpfpo	1.9
14	129	5–10YR	77	cl	32	3nbrpo, 1npf	2.0
13	143	8.75–10YR	92	cl	28	2npfpo	2.1
21	105	5–7.5YR	36	sl	17–18	1npo	2.1
12	123	7.5–10YR/2.5Y	95	cl	30	2mkbrpo	2.1
22	114	7.5YR	51	sl	14	2nbrpo	2.5
7	160	7.5–10YR	93	scl	20	4mkpo	2.9
Mean/mode[d]	128	7.5–10YR	78	sl	28	2nbrpo	2.1
Group 2 (105,000 yr)							
26	>74	10YR	≥74	scl	30	1n	1.7
32	100	7.5–10YR	60	sc	38	1npf	1.8
2	179	7.5–10YR	91	sil	20	2npfpo	2.3
9	122	5–10YR	81	cl	36	2mkpo	2.3
5b	132	7.5YR	63	sicl	33	2npfpo	2.4
5	122	5–10YR	99	cl	28	3mkpf	2.5
17	219	7.5–10YR	179	sicl	30	3npfpo	2.7
30	175	7.5–10YR/2.5Y	150	sicl	30	2mkpf	2.7
18[e]	229	7.5–10YR	196	sicl	30	2–3npf	2.8
15	150	7.5–10YR	141	cl	28	3mkpfpo	2.8
6	142	7.5–10YR/2.5–5Y	117	cl/sicl	28	3mkpfpobr	2.9
35	≥195	2.5Y–7.5YR	≥113	cl	36	2mkpfpo	2.9
10	136	7.5–10YR	92	c	45	2mkpfpo	2.9
31[c]	245	10YR/2.5Y	163	cl	31	2mkpfpo, 1kpf	2.9
4	205	7.5–10YR(/2.5Y)	109	scl	22	3mkpfpo	3.0
4b[e]	180	N.D.	83	scl	N.D.	2–3npo	3.1
25	189	5–7.5YR	57	sicl	33	4npfpo	3.1
27	185	5–10YR/2.5Y	148	cl	39	2mkpfpo	3.1
2b[e]	152	N.D.	65	scl	N.D.	N.D.	3.2
34	274	7.5–10YR/2.5Y	167	cl	31	3n-mkpf	3.4
1	190	5–10YR	136	sic	47	4mk-kpfpo	4.2
1b	172	7.5–10YR	109	sic	48	4mk-kpfpo	5.1
Mean/mode[d]	180	7.5–10YR	123	cl	32	2mkpfpo	2.8
Group 3 (125,000–200,000 yr)							
8	136	3.75–5Y/7.5(–10)YR	117	sic	50	2mkpfpo	3.1
29	249	5Y(/10YR)	198	c	56	2mkpfpo	3.9
23	≥182	N.D.§§	129	c	40–65	3kpfpo	5.3
3	≥400	2.5–5Y/7.5–10YR	≥381	c	70	2–3n-kpfpobr	5.3
Mean/mode[d]	189	5Y/7.5–5–10YR	148	c	53	2–3mk-kpfpo	4.1
Fluvial parent material							
11	171	7.5–10YR	125	sic	45	3mkpfpo	3.8
Brookings[f]							
33b	156	7.5YR	65	sicl	32	3mkpf	3.5
33	228	2.5Y/10YR(/2.5YR)	137	sicl	40	3mk-kpfpo	3.8

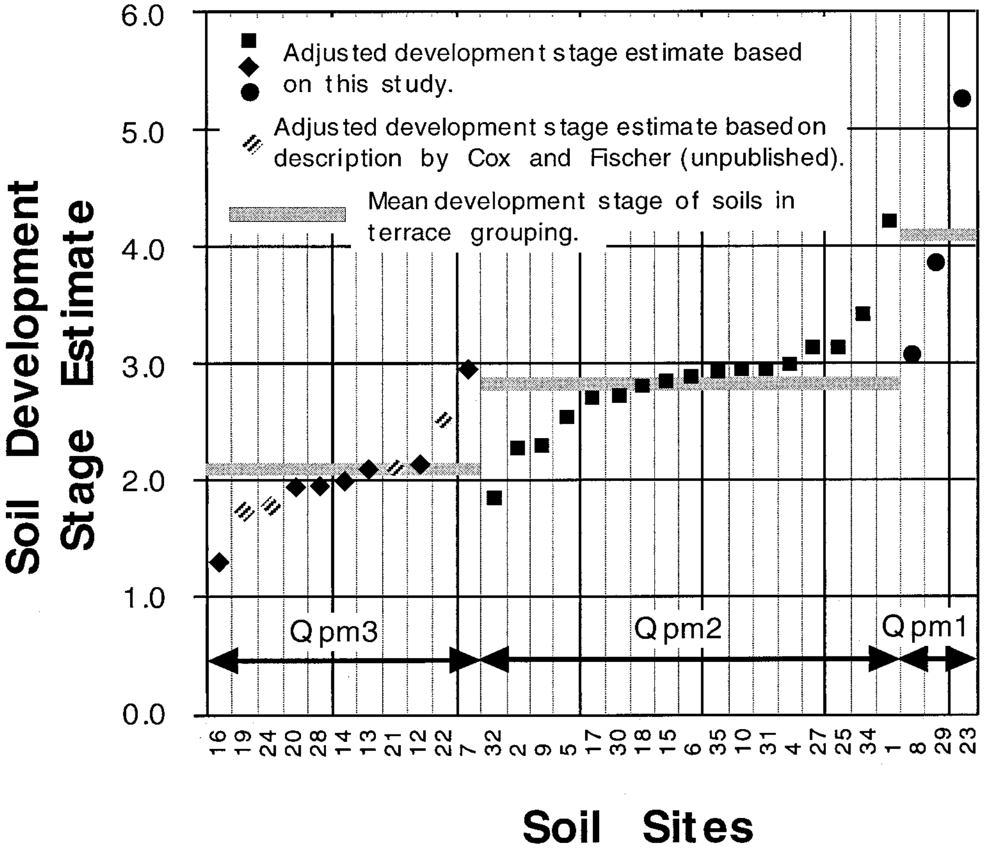

FIG. 3. Soil development stage estimates for Crescent City coastal plain soil descriptions. Sampling sites (horizontal axis) are located in Fig. 2A. Stage estimates (vertical axis) use the development index of Kelsey and Bockheim (1994).

northern California and Oregon, and they are only preserved along coastal reaches where uplift rates are >0.5 mm/yr (Kelsey and Bockheim, 1994; Kelsey *et al.*, 1996). Therefore, we assign the oldest marine terrace on the Crescent City coastal plain to be either stage 5e or stage 7, and the marine terraces at the Crescent City coastal plain tentatively are assigned age estimates of 80,000 yr (Qpm3), 105,000 yr (Qpm2), and 125,000 or 200,000 yr (Qpm1).

Note. All sites are sand parent material, unless noted otherwise. N.D. indicates no data.

[a] The 40 soil sites include sites described by three different groups of investigators: five sites (sites 19, 20, 21, 22, 24) described by K. Cox and F. Fisher (unpublished data, 1988), five sites (1b, 2b, 4b, 5b, 33b) described by Kelsey and Bockheim (unpublished data and 1994), and the remaining 30 sites described by Polenz and Kelsey (this paper). In order that the calculated soil development stages for these three soil groups can be directly compared, the development stages determined from the Cox and Fisher soil data (unpublished data, 1988) and the development stages determined from the Polenz and Kelsey soil data (this paper) were adjusted such that they could be directly compared with soil development stages determined by Kelsey and Bockheim (1994). Adjustment factors were computed from a comparison of development stage determinations of identical soil sites by different groups of investigators (sites used for this purpose were 1, 2, 4, 5, 20, 28, and 33). The development stage (far right column) thus incorporates an adjustment factor of 0.8 for converting Polenz and Kelsey development stage data to data comparable to Kelsey and Bockheim (1994) and a factor of 1.4 for converting Cox and Fisher development stage data to data comparable to Kelsey and Bockheim (1994).

[b] See Table 1 for explanations.

[c] Development stage is the arithmetic mean of the estimated development stages of Bt horizon thickness, depth to Cox, maximum estimated percentage of clay, and maximum clay skins.

[d] Mean or mode: For B horizon hues, maximum B textures, and maximum clay skins, the mode is reported. For depth to Cox and maximum percentage of clay, the mean is reported. The data of Cox and Fischer (sites 19–22, 24) and sites 1b, 2b, 4b, 5b, 33b of Kelsey and Bockheim are excluded from these calculations. Soil sites 3 (alluvial fan parent material) and 26 (soil is truncated at top) are also excluded.

[e] Soil descriptions 18, 31, 2b, and 4b are based on a hand auger instead of a pit.

[f] Brookings (Oregon) soil sites: 33b is site RR3 of Kelsey and Bockheim (1994), located on the 125,000-yr terrace. Site RR3 had a development stage of 3.0; it is here reported as 3.5 because color development was disregarded in computing the stage index. Site 33 is the same soil site but described by Polenz and Kelsey.

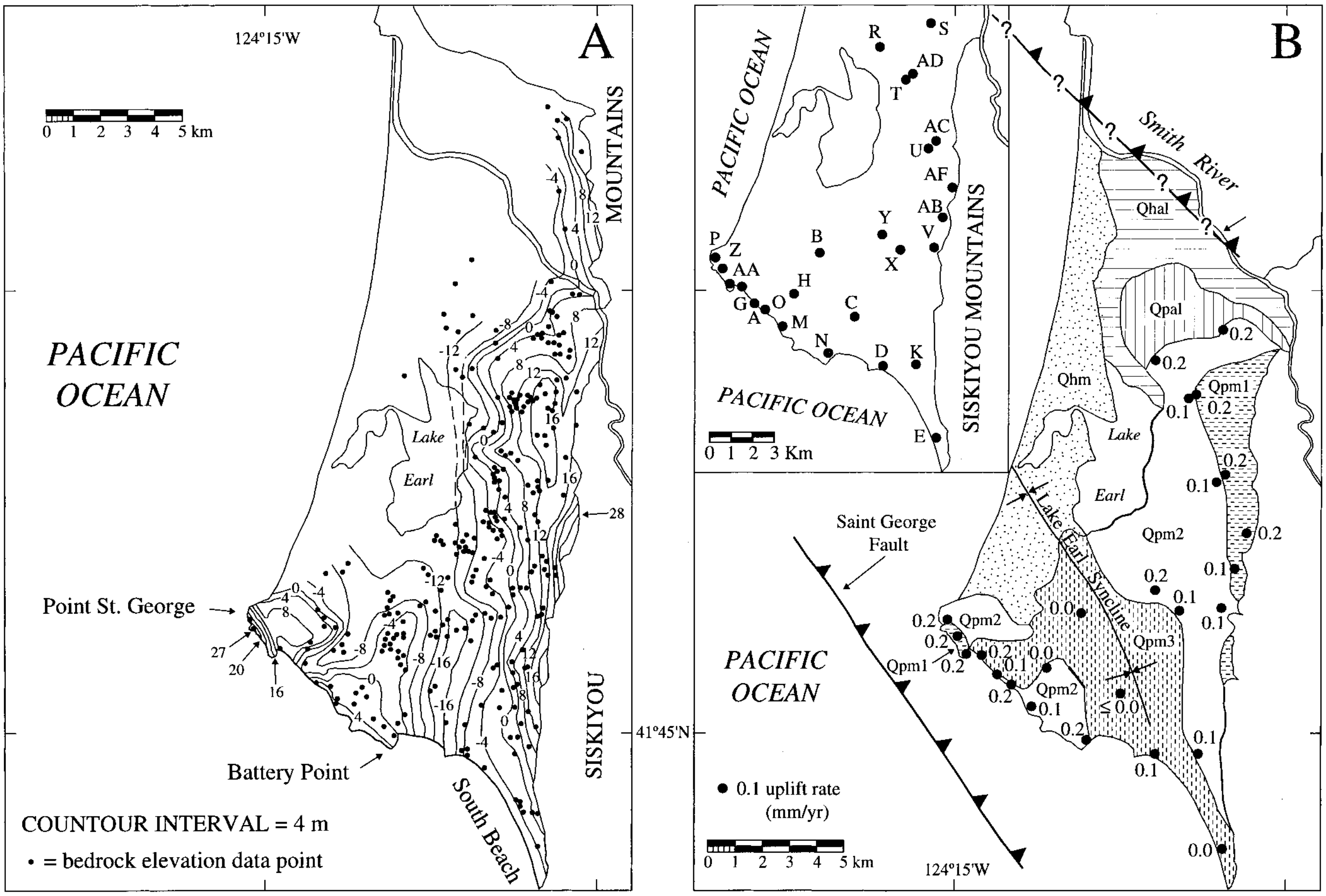

FIG. 4. (A) Contoured elevation map of bedrock surface underlying marine terrace cover sediment. “Bedrock” includes the Jurassic–Cretaceous Franciscan complex sandstone and volcanic rock and the Miocene–Pliocene Saint George Formation mudstone and sandstone. Data points represent records of individual wells or clusters of several wells. A few points represent elevation data obtained from outcrops or excavations. The elevation of the continuously exposed bedrock surface between Point Saint George and Battery Point was determined by level survey. (B) Map depicting estimates of uplift rate (mm/yr) for last ca. 100,000 yr at coastal plain sites. Site designations (inset) correlate to site descriptions in Table 3. Uplift rates are the minimum values (Table 3), and in the case of the Qpm1 platform, uplift rates are calculated assuming the age of the platform is 125,000 yr. Shaded units, see Fig. 2B legend.

UPLIFT RATE ESTIMATES

To calculate an uplift rate, the age of the bedrock platform, the elevation of the paleo-platform at the time of formation, and the present elevation of the platform must be known. Uncertainties in the uplift rate are a consequence of uncertainty in determining the initial and present elevation of the site at which uplift rate is calculated, as described in the footnotes to Table 3. The most significant source of uncertainty is the initial elevation of the bedrock platform at the point of measurement, when that point of measurement is seaward or bayward of the active sea cliff at the time the platform was occupied. Under these circumstances, the paleo-gradient of the bedrock platform must be approximated based on measurements of modern platform gradients (see footnote, Table 3). Finally, in the case of the oldest marine terrace, the underlying platform could be either 125,000 or 200,000 yr in age; therefore, the range in uplift rate for the Qpm1 terrace reflects not only the uncertainty in initial and present elevation of the bedrock platform at a measurement site but also uncertainty in the age of the platform (Table 3).

Uplift rates for the Crescent City coastal plain (Table 3) are 0.0–0.3 mm/yr. The range of uplift rate at a measurement point (the difference between the maximum and the minimum rate) is in most cases 0.1 mm/yr (Table 3). The range of uplift rate for both the Qpm2 (105,000 yr) platform and the Qpm1 (125,000–200,000 yr) platform is on the order of 0.1–0.3 mm/yr. The range of uplift rate for the 80,000-yr platform is lower, between ≤0.0 and 0.2 mm/yr. Although the uplift rates largely overlap between the older two platforms and the younger platform, the uplift rate differences between the youngest platform and the older two platforms (only the youngest platform has uplift rates that are ≤0.0 mm/yr) are apparent not only in modern elevations of platforms of different ages but also in a comparison of the present platform elevation to platform elevation at the time of platform cutting (Table 3).

TABLE 3
Uplift Rate Estimates

Location (see Fig. 4B)	Platform ages[a] (10^3 yr)	Elevation of platform[b] (m)		Distance to nearest back edge (km)	Paleo-sea level[c] (m)	Initial elevation[d] (m)		Uplift rate[e] (mm/yr)	
		min	max			max	min	min	max
A	80	5	8	0.5	−4	−8	−11	0.2	0.2
B	80	−9	−7	1.5	−4	−15	−24	0.0	0.2
C	80	—[f]	−15	1.1	−4	−12	−18	≤0.0	0.0
D	80	−8	−6	1.2	−4	−12	−20	0.1	0.2
E	80	−4	−2	0.2	−4	−5	−7	0.0	0.1
G	80	6	6	0.1	−4	−5	−5	0.1	0.1
H	80	−10	−5	0.2	−4	−5	−7	0.0	0.0
K	105	−1	1	0.7	−1	−15	−28	0.1	0.3
M	105	3	4	0.5	−1	−11	−21	0.1	0.2
N	105	−1	1	1.2	−1	−17	−29	0.2	0.3
O	105	6	6	0.5	−1	−11	−21	0.2	0.3
P	105	14	17	0.4	−1	−9	−17	0.2	0.3
R	105	5	8	1.5	−1	−19	−31	0.2	0.4
S	105	4	5	0.8	−1	−14	−26	0.2	0.3
T	105	8	10	0.1	−1	−2	−5	0.1	0.1
U	105	10	13	0.2	−1	−5	−9	0.1	0.2
V	105	13	15	0.1	−1	−2	−5	0.1	0.2
X	105	−9	−7	1.7	−1	−21	−33	0.1	0.2
Y	105	−7	−6	2.2	−1	−24	−36	0.2	0.3
Z	125	26	29	0.5	6	−4	−14	0.2	0.3
	200	26	29	0.5	6	−4	−14	0.1	0.2
AA	125	23	26	0.5	6	−4	−14	0.2	0.3
	200	23	26	0.5	6	−4	−14	0.1	0.2
AB	125	20	27	0.2	6	2	−2	0.1	0.2
	200	20	27	0.2	6	2	−2	0.1	0.1
AC	125	15	21	0.7	6	−8	−22	0.2	0.3
	200	15	21	0.7	6	−8	−22	0.1	0.2
AD	125	13	15	1.7	6	−18	−37	0.2	0.4
	200	13	15	1.7	6	−18	−37	0.2	0.3
AF	125	26	29	0.1	6	4	2	0.2	0.2
	200	26	29	0.1	6	4	2	0.1	0.1

[a] See text for discussion of platform age assignments. For the oldest platform, there are two candidate ages.

[b] Estimates of bedrock elevation from well records. Maximum and minimum estimates reflect uncertainty as to location of well and elevation of ground surface at well site location.

[c] Paleo-sea level estimates from Muhs (1992) and Muhs *et al.* (1992).

[d] Initial elevation is a function of paleo-sea level, distance of site from back edge, and the assumed paleo-platform slope. For sites on 125,000–200,000-yr and 105,000-yr platforms (Qpm1 and Qpm2), platform slopes of Bradley and Griggs (1976) for high energy coastlines were used (0.02–0.04 for inner 600 m and 0.007–0.017 for platform >600 m from coast). For sites on 80,000-yr platform (Qpm3), modern gradients (0.005–0.013), approximated from the bedrock platform map (Fig. 4A) were used. These gradients are upper limiting values for the original gradients because any folding of the Qpm3 surface would have steepened the original platform gradients. The paleo-littoral environment at the Crescent City coastal plain was a bay partially sheltered by the Siskiyou Mountains to the east and Point St. George headland and the Saint George reef scarp to the west; therefore, uplift rates shown on Figure 4B assume the minimum platform gradients of Bradley and Griggs (1976) to reflect the relatively low-energy environment within the bay.

[e] Minimum uplift rate estimates were calculated using the minimum difference between modern and initial platform elevation (i.e., incorporated minimum paleo-platform gradient). Maximum uplift rate estimates were calculated using the maximum difference between modern and initial platform elevation (i.e., incorporated maximum paleo-platform gradient).

[f] Only maximum limiting elevation is reported because well did not penetrate into bedrock platform.

DISCUSSION

Folding

The youngest marine terrace occurs within a bedrock trough, has the lowest uplift rate and is flanked by progressively older marine terrace sediments on either side. The two older marine terraces overlie areas of relatively elevated bedrock and have slightly higher uplift rates (Fig. 4). We infer that the bedrock trough and the overlying youngest marine terrace sediment define the axial region of the Lake Earl syncline (Fig. 4B). The syncline axis is flanked by terrace back edges (including Cemetery Scarp) that face each other across the region of lowest bedrock.

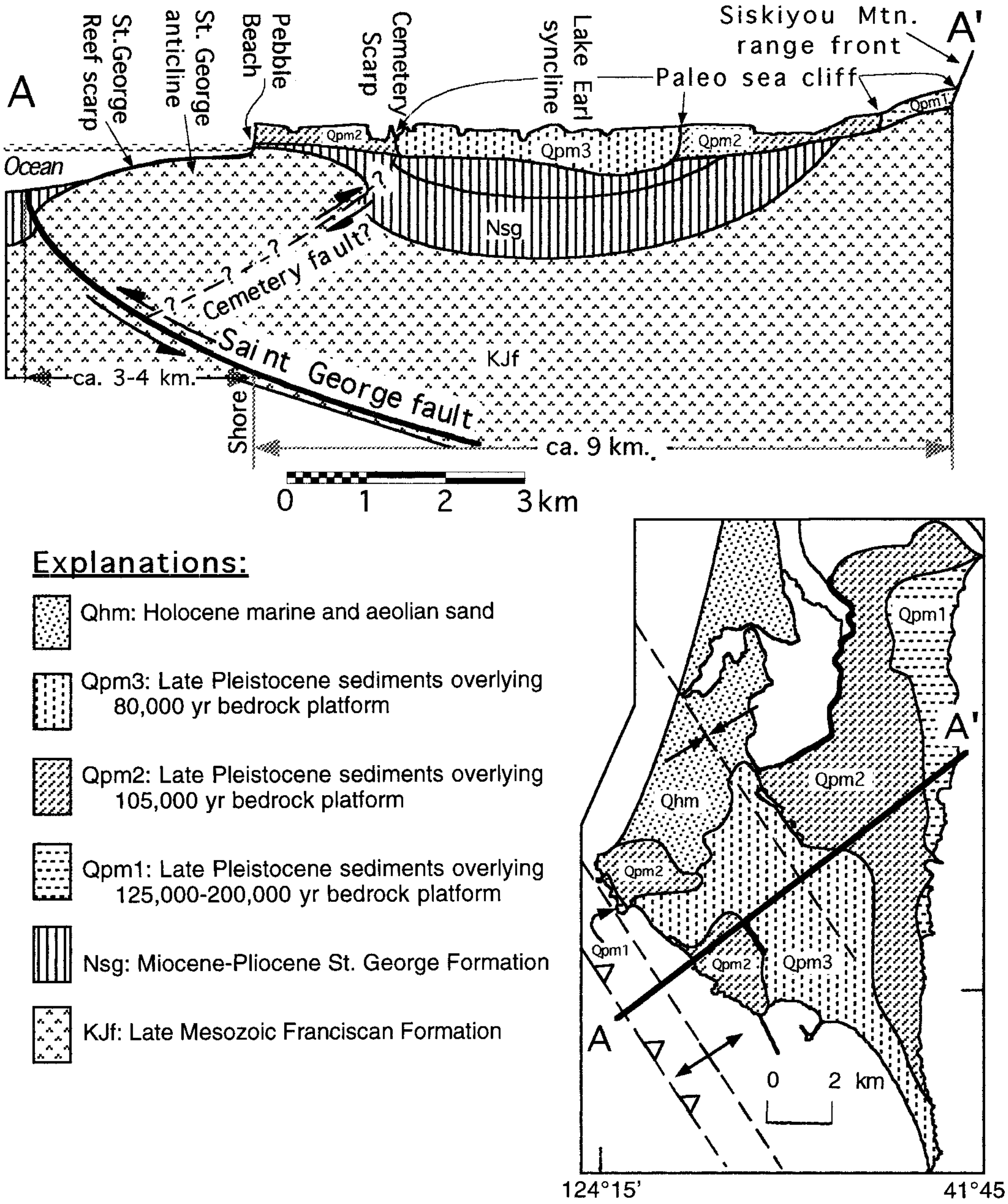

FIG. 5. Northeast-trending geologic cross section across the Crescent City coastal plain, showing Saint George anticline, Lake Earl syncline, and inferred Cemetery fault on the hanging wall of Saint George fault. The topographic relief and thickness of Quaternary sediment (Qhm, Qpm3, Qpm2, Qpm1) are depicted at 20× vertical exaggeration. For pre-Quaternary units (Nsg, KJf), thickness, contact relations, and folds are schematic.

Folding of the Lake Earl syncline is responsible for several geomorphic attributes of the coastal plain. The syncline accounts for the elevated bedrock at Point Saint George; this bedrock promontory is on the uplifted southwest limb of the fold (Fig. 4). The syncline accounts for the gradual southward disappearance of Lake Scarp because the scarp is buried by eolian sand in a zone of zero uplift or subsidence in the center of the Lake Earl syncline (Fig. 4B). The syncline also accounts for the unusual landward-facing aspect of the Cemetery Scarp, because the 80,000-year-old paleo-sea cliff faced landward toward the axial region of the syncline, which was occupied by ocean at that time. Therefore, late Pleistocene growth of the Lake Earl syncline provides a structural context for the distribution of late Pleistocene sediment and bedrock platforms on the Crescent City coastal plain.

Marine Terrace Deformation as a Response to Plate-Margin, Fold-and-Thrust Belt Tectonics

The Lake Earl syncline is a contractional structure within the fold-and-thrust belt of the Cascadia subduction zone. The northwest-trending, northeast-dipping Saint George fault (Field *et al.*, 1980; Clarke, 1992) (Figs. 2 and 5), which has cumulative separation estimated to exceed 1 km (S. H. Clarke, personal communication, 1996), is offshore just to the west of the zone of relatively high uplift rates at Point Saint George. We infer that this zone of high uplift rates defines not only the southwestern flank of the Lake Earl syncline but also the northeastern flank of the Saint George anticline, the anticlinal axis of which is expressed geomorphically on the sea floor by the Saint George reef scarp (Fig. 2A). We interpret the Lake Earl syncline and the Saint George anticline to be products of movement on the Saint George thrust fault, with the syncline being a hanging wall syncline and the anticline being a hanging wall anticline, both in the upper plate of the Saint George thrust fault (Fig. 5). Late Pleistocene growth of the anticline and syncline underscores the influence of local structures on uplift rates of coastal landscapes in the fold-and-thrust belt of active continental margins (Muhs *et al.*, 1990; McInelly and Kelsey, 1990; Berryman, 1993).

Examination of well logs in the Crescent City area leads us to speculate that Cemetery Scarp is a fault scarp in addition to being a contact between two marine terraces. A well 450 m southwest of the scarp penetrates through surface sand and gravel and then through 26 m of bedrock before again penetrating sand and gravel. One interpretation of this stratigraphy is that the well first penetrated the upper plate of a reverse fault and then penetrated gravel and sand again because the stratigraphy was repeated in the footwall of the fault. Additional evidence that the Cemetery Scarp may be a reverse fault scarp is that the scarp is aligned with a prominent linear sand ridge 2.5 km to the northwest. The possibility that Cemetery Scarp may extend northwestward beyond its bound as a marine terrace back edge, combined with the apparent repeat of stratigraphic section in the well, lead us to hypothesize the presence of a northwest-trending, southwest-dipping low-angle reverse fault parallel to the strike of the Saint George fault but antithetical to its dip. If the well penetrates the fault plane and the fault intersects the surface at Cemetery Scarp, then the fault dips about 6° to the southwest and would be a back thrust above the Saint George fault (dashed fault, Fig. 5).

Previous workers (Maxson, 1933; Stone, 1993) inferred that the mountain front at the eastern edge of the Crescent City coastal plain is defined by the Del Norte fault, along which the coastal plain is downthrown relative to the Siskiyou Mountains. The Del Norte fault also was evoked to explain northeast tilting observed in rocks along Pebble Beach (Stone, 1993). However, the northeast dip of strata along Pebble Beach is better explained by growth of the syncline and anticline within the hanging wall of the Saint George thrust fault. The proposed Del Norte fault follows the eastern edge of the older two marine terraces on the Crescent City coastal plain. At least during the late Quaternary, the landscape feature called the Del Norte fault is more likely to have been an eroded paleo-sea cliff last active about 105,000–200,000 yr ago.

CONCLUSION

On the basis of geomorphic, geologic, pedologic, and subsurface data, we infer that three late Pleistocene marine terraces are preserved on the Crescent City coastal plain, a coastal surface of low relief that is located within the fold-and-thrust belt of the Cascadia subduction zone. The two oldest marine terraces face each other across a northwest-trending valley; the valley is underlain by a bedrock trough occupied by the youngest marine terrace. Distribution of the three terraces is a function of late Pleistocene growth of the Lake Earl syncline, with the older terraces preserved on the syncline limbs and the youngest terrace preserved in the axial trough. Although the range of late Pleistocene uplift rate on the coastal plain is only 0.0–0.3 mm/yr, the older terraces on the flanks of the fold nonetheless have slightly higher uplift rates (0.1–0.3 mm/yr) than the axial region of the fold (≤0.0–0.2 mm/yr). These uplift rate differences are apparent through comparison of the present elevation of bedrock platforms to the elevation of these platforms when they were cut.

Active deformation of the Crescent City coastal plain is driving broad folding of the coastal plain, which accounts for marine terrace distribution and topography of underlying marine platforms. Deformation in the hanging wall of the Saint George thrust fault has dominated the evolution of the coastal plain through controlling the uplift history of marine terraces formed during sea-level high stands 80,000–200,000 years ago. A fault within the coastal plain, which would be a back thrust antithetical to the Saint George fault, may surface at the boundary between two marine terraces. This hypothesized fault cuts across the urban center of Crescent City. Our studies add new evidence for the importance of local, active structures on landscape evolution on the Pacific coast of North America.

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