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Paleoseismic features as indicators of earthquake hazards in North Coastal, San Diego County, California, USA

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Abstract

New road cut and mass-grading excavations in the north coastal area of San Diego County, California expose heretofore generally unrecognized, probable late Holocene tsunami deposits and paleoseismically deformed sediments. Remnant tsunami deposits occur up to 100 + m in elevation around the margins of modern coastal lagoons and estuaries and, combined with local mima mounds of possible sand blow origin, provide indirect but compelling evidence for the late Quaternary activity of onshore and offshore faults in the immediate study area. Probable paleoliquefaction features are regionally widespread and range from fissures filled with sediments derived from overlying marine terrace sand and soil, to the more traditional sand-filled injection dikes and sills, lateral spreads, and filled craterlets. The source of most liquefied sediment is underlying Tertiary "bedrock sand" and local, Quaternary marine-terrace deposits. A paleoseismic liquefaction origin rather than soft-sediment loading is deduced for these features based on morphology, internal stratigraphy, field setting, and near proximity to known seismogenic sources.

Some paleoseismic events impacted late Holocene Indian middens and burial sites. The last seismic event probably occurred within the past 1 to 3 ka, and possibly even records the historic earthquakes of either November 22, 1800 or May 27, 1862. The liquefaction features also affect marine terrace sediments tens of meters above modern regional water levels, inferentially "recording" paleoseismic events in this Mediterranean-type climatic region during winter rains when high-level, perched water saturates the several meter thick source sediments.

Based on their regional extent, the paleoseismic features were likely caused by M ~ 7+ tectonic events inferentially generated by the nearby offshore Newport–Inglewood/Rose Canyon fault system, or possibly by smaller, recently exposed, related and localized faults. Accordingly, the seismic hazard of the north coastal area of San Diego County may be substantially higher than previously assumed, and hence of concern owing to the rapid ongoing and projected population increase.

Keywords: Earthquake indicators; Tsunami deposits; Holocene; California; Paleoseismic events

1. Introduction

The population of southern California is now approximately 20 million and increasing. Much

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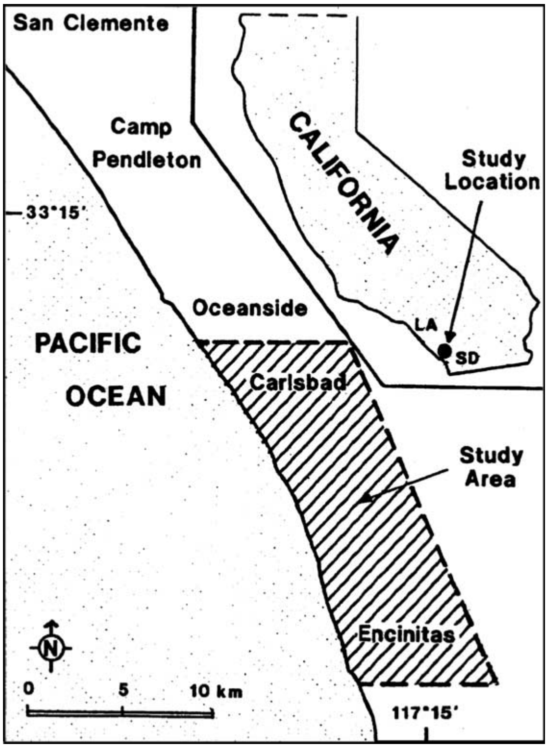

Fig. 1. Map showing location of paleoseismic features along the north San Diego County coast. Los Angeles (LA), San Diego (SD) and the study area (hatchured) are shown for reference.

new growth is taking place along the coastal area of northern San Diego County (Fig. 1). Here, from the shoreline to about 18 km inland, thousands of new houses and commercial centers have been, and are being, constructed. Combined with related road and infrastructure excavation, the new exposures now reveal hundreds of heretofore unrecognized paleotsunami and seismically-induced liquefaction features. Detailed mapping, both in vertical cuts and in continuous, grading-excavations, shows that these features are regionally widespread and recurrent. Accordingly, they provide stratigraphic evidence of late Quaternary, prehistoric earthquakes and possible harbingers of future earthquakes and risk in this part of California. The north coastal area of San Diego County has a typical Mediterranean climate: average annual precipitation is approximately 250 mm; mostly occurring during the winter months of November through March. Much natural vegetation has long been removed, and is now supplanted by exotic introduced species such as eucalyptus, palms, and a host of other decorative plants associated with rapid, post-WW II urban spread.

The presence of people and active faults often form a deadly combination, well demonstrated in California by recent, high-magnitude earthquakes and related damage in the 1971 San Fernando earthquake (Oakshott, 1975), and the 1994 Northridge earthquake (Woods and Seiple, 1995). Neotectonic investigations in California traditionally focus on onshore surface rupture associated with geomorphically well defined fault systems as documented by many workers for the San Andreas and its various splays (Table 1). New investigations now show that many seismic sources are "so-called" blind faults, which can generate high-magnitude earthquakes and yet have only subtle or broadly distributed surface geomorphic expression (Namson and Davis, 1988; Davis et al., 1989; Shaw and Shearer, 2000). Similar blind thrusts and other seismic sources occur immediately offshore the southern California coast as deduced from interpretation of geophysical data (Bohannon and Geist, 1998; Rivero et al., 2000; Figs. 1 and 2; Table 2). Because of their offshore location, the earthquake history of these faults is poorly known; however, it now appears that at least some are recorded by onshore tsunami deposits and related paleoliquefaction features.

Table 1
Local and regional onshore geology

Blake, 1856a,b; Goodyear, 1888; Fairbanks, 1893; Ellis and Lee, 1919; Hertlein and Grant, 1944, 1954; Larson, 1948; Emery, 1950a; Wilson, 1972; Hannan, 1973; Moyle, 1973; Barrows, 1974; Crowell, 1974; Kennedy, 1975; Kennedy et al., 1975; Shepard and Kuhn, 1977; Sieh, 1978; Guptill and Heath, 1981; Emery and Kuhn, 1982; Weber, 1982; Hall, 1984; Kuhn and Shepard, 1984; Eisenberg, 1985; Weldon and Sieh, 1985; Tan, 1986; Harden and Matti, 1989; U.S. Geological Survey [USGS], 1990a; Lajoie et al., 1991; Prentice and Schwartz, 1991; Aydin et al., 1992; Kern and Rockwell, 1992; USGS, 1992, 1998; USGS and Southern California Earthquake Center [SCEC], 1994; Lindvall and Rockwell, 1995; Sims and Garvin, 1995; Tan and Kennedy, 1996; Grant et al., 1999, 2002; Vaughan et al., 1999; Baldwin et al., 2000; Franklin and Kuhn, 2000; Kuhn, 2000; Kuhn et al., 2000, 2004; Lienkaemper, 2001; Grant and Rockwell, 2002; Stone et al., 2002.

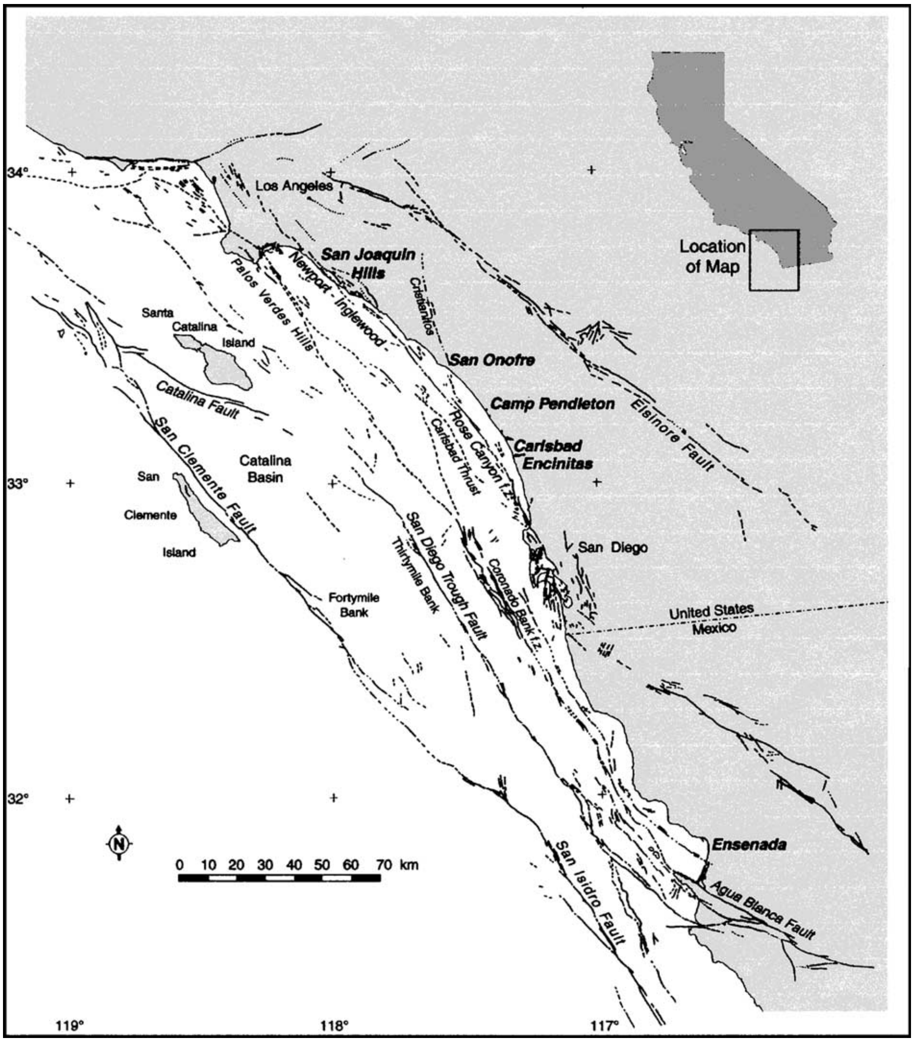

Fig. 2. Major fault zones in the immediate offshore and onshore area of the southern California coast from Los Angeles on the north to near Ensenada in Baja, California on the south. Modified from Legg (1985).

The north coastal paleoliquefaction features are particularly well preserved on flights of marine terraces and within their underlying regressive sands (Figs. 3 and 4). These have been mapped, albeit discontinuously, from approximately San Diego on the south to north of Los Angeles (Fig. 2). Locally, the wave-cut platforms and overlying marine deposits are capped by beach ridges, former dune fields now somewhat lithified. Recent mass-grading (excavations for new houses and commercial development) now exposes hundreds of "anomalous" sedimentary features, which are reasonably judged to be of paleoseismic origin. Accordingly, this paper initially sets forth the geomorphic and neotectonic setting of the study area. This is followed by description of the inferred paleoliquefaction features and the reasons why they are not a result of local loading and soft-sediment deformation. Also discussed is indirect evidence supporting the paleoseismic hypothesis; namely, the inferred seismic origin of local mima mounds, and the character and presence of tsunami deposits. This is followed by interpretation of data concerning paleoseismic recurrence and magni-

Table 2
Offshore geology

Shepard and Emery, 1941; Shepard, 1948; Emery, 1960; Hand and Emery, 1963; Moore, 1969; Moore, 1972; Western Geophysical, 1972; Legg and Kennedy, 1979; 1991; Field and Richmond, 1980; Kennedy et al., 1980a,b, 1985, 1987; Graham and Bachman, 1983; Clarke et al., 1985, 1987, Legg, 1985, 1987, 1991; Darigo and Osborne, 1986; Greene and Kennedy, 1987; Fischer and Mills, 1991, Fischer et al., 1992; Legg et al., 1992, 1994, 2003, 2004; Crouch and Suppe, 1993; Astiz and Shearer, 2000; Rivero et al., 2000; Sliter et al., 2001; Legg and Kamerling, 2003.

tude, seismic source area, and earthquake-hazard impact in this part of California.

This paper also summarizes local technical reports and other papers of limited distribution that initially pointed to and support the paleoseismic hypothesis for the now-documented sand blows, sand dikes, craterlets, sand laccoliths, filled fissures (that is, fissures filled with materials from overlying sediments), and lateral spreads. These reports and other documents bearing upon neotectonics and earthquake hazards in the area are cited in specific categories pertaining to local onshore and offshore geology, liquefaction, paleoseismites, tsunamigenic, and engineering implications (Tables 1–7).

2. Geomorphic and tectonic setting

The geomorphic and tectonic setting of the north coastal, San Diego County area has been described

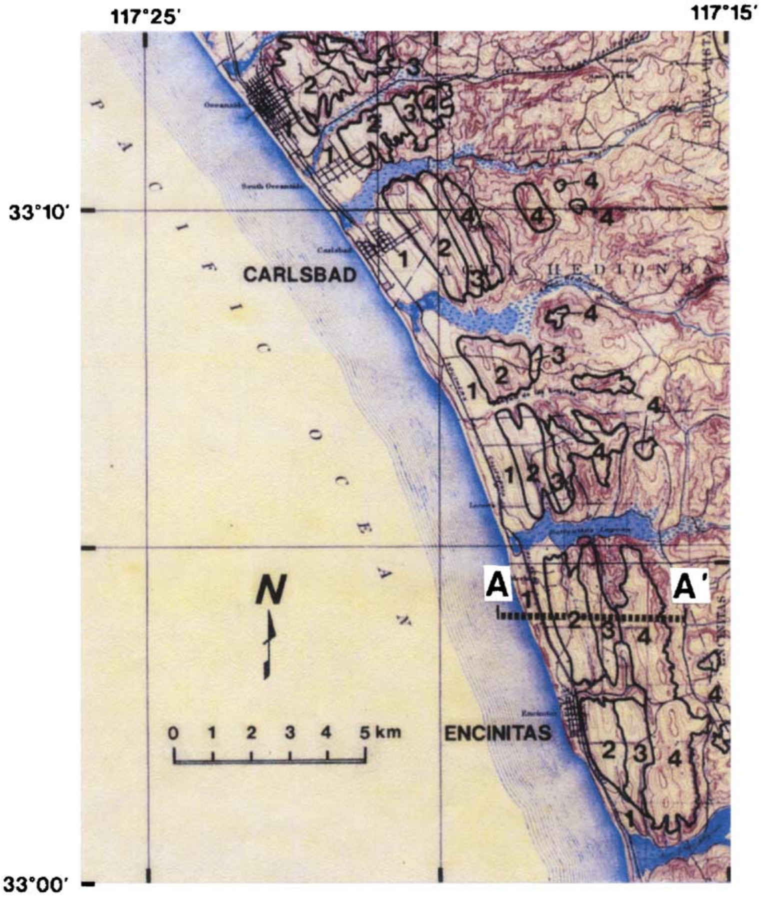

Fig. 3. Marine terraces in the study area. Terrace 1 is topographically lowest and youngest; terrace 4 is highest and oldest. Cross-section A-A’ shown on Fig. 4 (after Tan and Kennedy, 1996; topographic base map from U. S. Geological Survey, 1901).

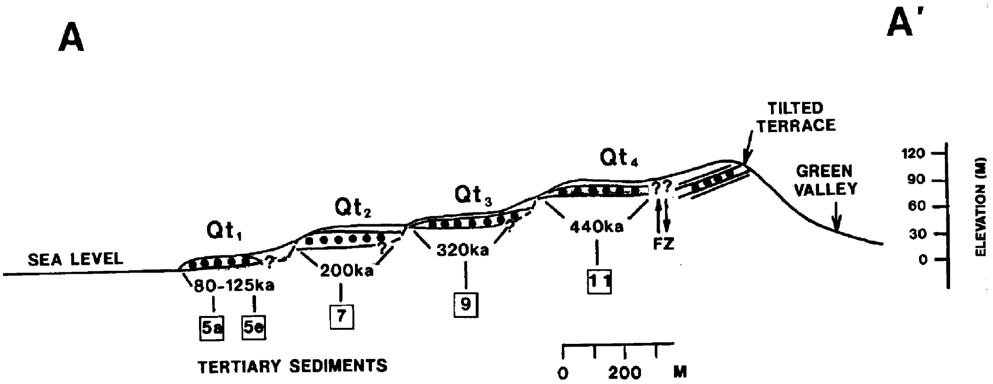

Fig. 4. Schematic cross-section near Encinitas, California (Fig. 3) showing major marine terraces and wave-cut platforms (Qt$_1$ through Qt$_4$). Approximate age of terrace sediments deduced from association with the marine-isotope stage chronology (Shackleton and Opdike, 1976), substage 5a through stage 11. Basal regressive marine sand and cobbles deposited denoted by "dots"; fault zone (FZ); terrace thickness exaggerated.

and refined over the past 100 years (Table 1). In addition to published papers and informal guidebook articles, there is a plethora of pertinent unpublished reports and data compilations, many pertaining to neotectonism and earthquake hazards in the area (Table 6). Some data were originally proprietary, obtained for the mid-1970s geologic investigations at and near the San Onofre Nuclear Generating Station in the northwest corner of the Camp Pendleton Marine Corps Base (Fig. 1). Many associated reports dealt with the origin, relative age and deformation history of coastal marine terraces (Table 6), the same as those in the San Diego County north-coastal area that harbor the postulated paleoseismic features described herein (Table 1).

In 1991, LaJoie et al. summarized marine terrace evolution for this part of California, and dated several erosion platforms using amino-acid and uranium-series techniques. Tan and Kennedy (1996) compiled prior geological mapping for the study area and applied local names for the lower four marine terraces that range in elevation from about 3 to 130 m. Based on association with the marine, oxygen-isotope stage chronology, on local radiocarbon and uranium-series dating, and on relative soil (pedogenic) profile development, the terraces are designated and inferentially dated as: Qt$_1$ (lowest), ~80–125 ka (marine, oxygen-isotope substages 5a through 5e, respectively); Qt$_2$, ~200 ka (stage 7); Qt$_3$, ~320 ka (stage 9), and Qt$_4$, ~440 ka (stage 11; Figs. 3 and 4).

Table 3
Liquefaction issues

Atwater et al., 2001; Obermeier and Dickenson, 2000. *[Regarding U. S. Northwest Cascadian Earthquake of 1700 A.D.]*
Fuller, 1912; Morse, 1941; Saucier, 1987; 1991a,b; Obermeier, 1987, 1989, 1996a,b; USGS, 1990b; Obermeier et al., 1991, 1993, 2004; Marple and Schweig, 1992; Su and Follmer, 1992; Munson et al., 1995; Li et al., 1996; Tuttle et al., 1996; Obermeier and Pond, 1999; Cox et al., 2001; Hough, 2001. *[Regarding Midwestern U. S. Earthquakes.]*
Dutton, 1889; Obermeier et al., 1985, 1990, 2002; Talwani and Cox, 1985; Peters and Hermann, 1986; Amick and Gelinas, 1991; Marple and Talwani, 2000. *[Regarding Charleston, South Carolina Earthquakes.]*
Lawson, 1908; Holzer et al., 1989; 2004; Holzer and Clark, 1993; Meisling, 1979; Jachens et al., 2002; Michael et al., 2002; Rymer et al., 2002a,b; Sylvester et al., 2002. *[Regarding California Earthquakes.]*
Harp et al., 2003. *[Regarding Denali, Alaska Earthquake of 2002.]*
Rajendran and Rajendran, 2003. *[Regarding Kachchh Region, India Earthquakes.]*

Table 4
Paleoseismites

Lamont, 1936; Galli and Ferreli, 1995; Landuzzi et al., 1995; Lucci, 1995; Michetti et al., 1995; Reiter, 1995; Bartholomew et al., 2002; Ettensohn et al., 2002; Greb and Dever, 2002; Mariotti et al., 2002; Merriam and Forster, 2002; Moretti et al., 2002; Obermeier et al., 2002; Stewart et al., 2002; Wheeler, 2002.

Table 5
Tsunamis

Emery, 1950b; Shepard et al., 1950; Natland and Kuenen, 1951; Reimnitz and Marshall, 1965; Coleman, 1968; Eiby, 1982; Foster et al., 1991; Shi et al., 1993; Daag et al., 1995; Dawson, 1994, 1995, 1999; Minoura et al., 1994; Bondevik et al., 1995; Bourgeois, 1995; Carver and Gilpin, 1995; Kelsey et al., 1995; Moore and Lewis, 1995; Nishimura and Miyaji, 1995; Peterson and Priest, 1995; Tuttle et al., 1995; Dawson et al., 1996; Morner, 1996; Borrero et al., 1997; Imamura et al., 1997; Synolakis et al., 1997; Ortiz et al., 1998; Clague et al., 1999; Hindson and Andrade, 1999; Kawata et al., 1999; Takashimizu and Masuda, 2000; Atwater et al., 2001; Carey et al., 2001; Zitellini et al., 2001; Okal et al., 2002a,b; Pratt, 2002; Legg et al., 2003, 2004; Scheffers and Kelletat, 2003; Brookfield, 2004; Costa, 2004.

The marine abrasion platforms are typically sequentially overlain by ~1-m-thick veneer of cobbles (former beach gravel), several meters of regressive marine sand, and locally by prograding continental deposits. Locally, the terrace surfaces are covered by “beach ridges,” former coastal dunes now topographically rounded and often relatively lithified. These beach ridge dune sands and the underlying marine sands are prone to seismically-induced liquefaction when saturated, this typically occurring during winter rains when local perched water levels are common (Kuhn et al., 2000, 2004).

From a tectonic standpoint, several prominent aerial-photographic lineaments trend across the study area (Kuhn et al., 2004). These lineaments form a general rhombohedral pattern, with prominent axes oriented northwest and northeast, respectively (Fig. 5). Some lineaments coincide with NW-trending valleys that define the back edge of the terraces; these are now demonstrably fault related as exposed in road and grading cuts and locally in the sea cliffs (Seitz, 1983; Shepard and Kuhn, 1977; Kuhn and Shepard, 1984). The lineaments and related fault patterns are now identified as possible major ancient tectonic shear zones (Slosson et al., 2000), that are probably re-activated. Additionally, new offshore, seismic reflection profiles document the nearby presence and transtensional and transpressional character of the Newport–Inglewood/Rose Canyon fault (NIRC), a major component of the San Andreas fault system (Fig. 2). The new urban exposures also show that many onshore lineaments are aligned with concentrations of sand dikes and boils, filled fissures and lateral spreads, features herein interpreted to be of paleoliquefaction origin.

Table 6
Unpublished reports

Euge et al., 1972; Western Geophysical, 1972; Fugro, 1975a,b, 1977a,b; Anderson et al., 1977; Ehlig, 1977; Shlemon, 1977, 1978a,b, 1979a,b,c,d.

Table 7
Engineering-geology publications

Housner, 1958; Seed and Lee, 1966; Lee and Seed, 1967; Seed, 1968; Scott and Zuckerman, 1973; Youd, 1973, 1984, 1985; Lowe, 1975, 1976; Youd et al., 1978; Seed and Idress, 1983; National Research Council, 1985; Owen, 1987; Holzer et al., 1989; Meier, 1993; Nichols, 1995.

3. Description of interpreted paleoliquefaction features

In this section, North San Diego County’s liquefaction-induced features are discussed according to their morphology and genesis. The most widespread and common are dikes, sills, and laccoliths. These intrusions occur on marine terraces Qt_1 through Qt_4. Craterlets are common, but principally occur only on two terraces. Likewise abundant are lateral spreads and filled fissures. One terrace has a very irregular and undulating surface topography caused by liquefaction at depth (Fig. 5).

3.1. Sand dikes, sills, and laccoliths

3.1.1. Field observations

Railroad and urban-excavation cuts now expose many dikes filled with fine sand that pierce terrace sediments (Figs. 6 and 7), and such terrace sediments range in age from 100 to over 300 ka. The dikes vary from about a few mm to ~10-cm wide, and often taper upward and locally form cross-cutting patterns (Fig. 8). A trench across prominent aerial lineaments on the lowest coastal terrace (Fig. 5) exposed unmatched soil and stratigraphic units, suggesting that this particular lineament is fault controlled (Franklin and Kuhn, 2000; Fig. 9). The trench also exposed paleoliquefaction features such

Fig. 5. 1953 vertical aerial view of the coastal lagoons and terraces at Carlsbad, California. The circular features located in the center of the photograph are “mima mounds;” many are now confirmed to be “sand blow” deposits. Thus several lineaments include lateral spread surfaces or fissure fills (photograph from U.S. Department of Agriculture Photograph #AXN-8M-100, taken on 11 April, 1953).

as sand dikes, lateral spreads, and a sand laccolith. Locally, the source sands, as exposed in the trench, are traced to the underlying Tertiary marine sand (Fig. 10).

Of particular relevance to origin is the relationship of the sand laccolith and the overlying topography (Fig. 11). Here the sand laccolith is demonstrably fed by several sand dikes, which in turn had locally pierced and or otherwise given rise to an irregular, micro-topography. The overlying surface bears a soil likely no more than about 2 to 3 ka old profile and perhaps much younger (Shlemon, 1999, pers. com.) based on the relative degree of development. The liquefied sediments exposed in this trench vary in age from late Holocene to probably late Pleistocene, and demonstrate that two and perhaps several seismic events occurred in this area. The Tertiary source sands here are still relatively cemented and therefore prone to liquefy under seismic loading (Fig. 10). Terrace sediments containing the dikes vary widely in origin, ranging from Pleistocene (?) regressive marine and clay-rich marsh and lagoon deposits to prograding continental and eolian deposits.

Other trenches on the same marine terrace exposed more sand sills, dikes, laccoliths, and warped argillic soil horizons (Fig. 12), as well as highly contorted lateral spreads that flowed over deformed, tilted sandflat and marsh sediments (Fig. 13). Also observed were liquefied and offset channel-lag deposits in

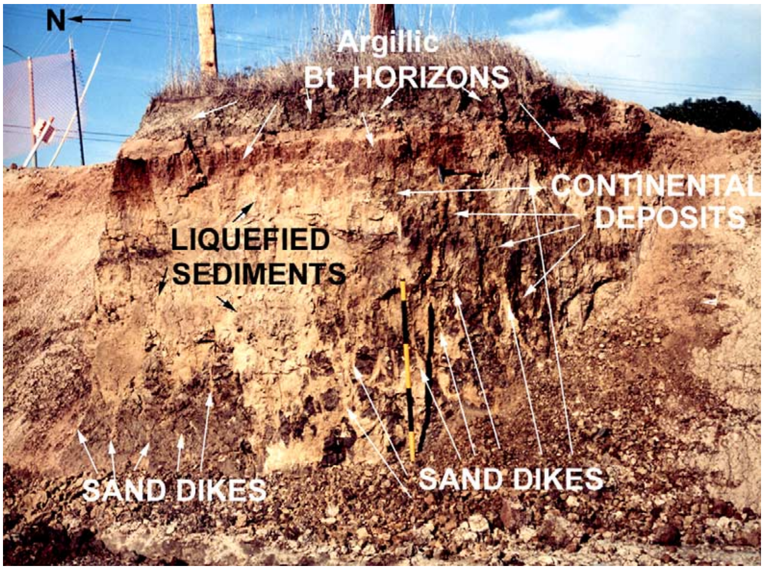

Fig. 6. View (1994) of a railroad cut exposure showing fine grain, tan and white sand dikes cutting into and through continental deposits and into an overlying Bt argillic soil horizon at Carlsbad, California (15.24 m el. MSL).

which the adjacent horizontal bedding had been uplifted and eroded (Fig. 14).

Likewise evident are irregularly shaped clay beds with entrained sand, showing that the sand had moved laterally and upward. Implicitly the contorted clay and sand probably moved plastically to nearby swales, ultimately giving rise to the undulating, modern ground topography.

On adjacent terraces, urban grading cuts exposed polygonal, reticulated, and sand-filled features (Fig.

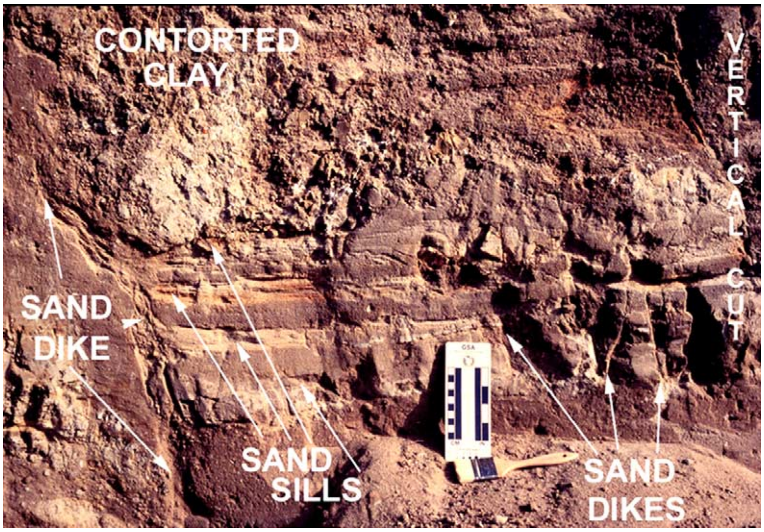

Fig. 7. View (1994) of sand dikes cutting vertically through clay-rich estuarine deposits at Carlsbad, California (13.41 m el. MSL). Note: Numerous multi-colored “source sand sills” are confined by clay layers, forming sand dikes that fine upward.

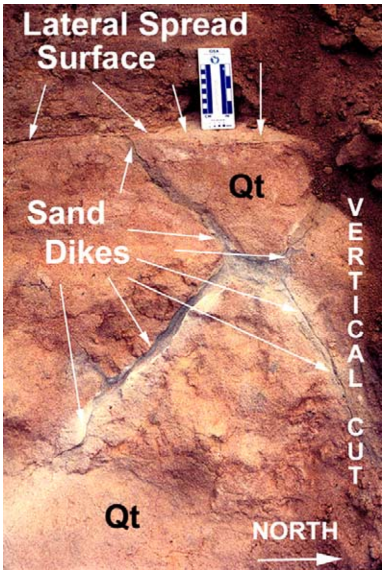

Fig. 8. A vertical cut exposing sand-dikes cutting coastal terrace sands at Carlsbad, California (46.63 m el. MSL). Note: The scale is resting on a lateral spread surface which has cutoff the underlying sand dikes, which are injected from below.

15). Where exposed vertically the sand fillings proved to be tabular dikes, which often trended along pre-existing tectonically-related stress fractures. The dikes are filled with upward-fining, loosely-packed, clean and cohesionless sands. And here, too, some sands are traced to their source in their underlying Tertiary marine beds. Also, as exposed in the various cuts, the dikes are horizontally sheared by lateral spreads (Fig. 8); and where coalescing, the sand dikes are injected into overlying coastal terrace sediments and often form sand laccoliths (Fig. 12).

Terrace Qt_2 exposures show the local presence of gravel-bearing sands at, and near, the tops of vents (Fig. 16). These gravels are similarly traceable into the underlying source sediments, where they have been dragged upward and truncated by lateral spreads. The gravel at the top of the dike may well stem from gravel entrainment during eruption of the liquefied sediment, a phenomenon resulting from strong seismic shaking (Prentice et al., 1992; Meier, 1993; Yegian et al., 1994).

3.1.2. Source mechanism

The geometry and character of the sand-filled dikes observed in the study area is very similar to those reported to have originated as a result of seismic liquefaction as documented by Obermeier (1996b) Also, north San Diego County dikes are associated with sand-filled laccoliths, similar to the seismic-induced features of Obermeier (1996a). Accordingly, the sand dikes, sills, and laccoliths are most likely, heretofore, unrecognized paleoseismic features.

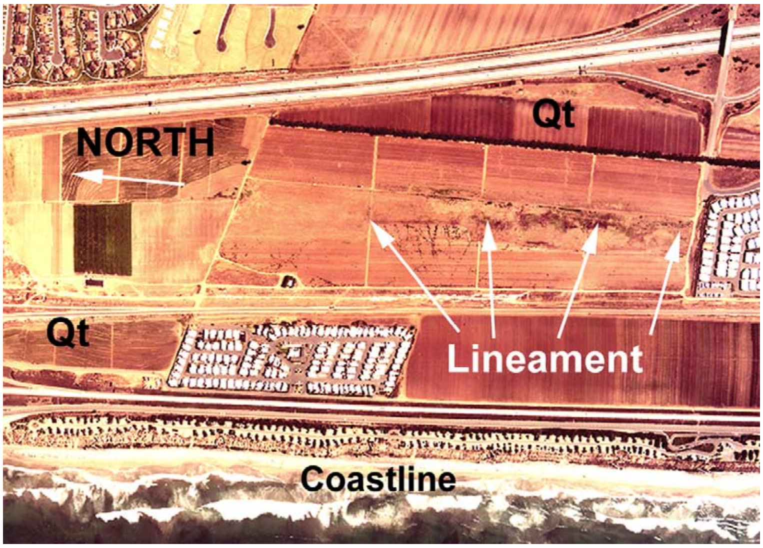

Fig. 9. 1994 color aerial photograph taken along the lowest coastal terrace at Carlsbad, California. Note: The strong, dark lineament coincides with depressions.

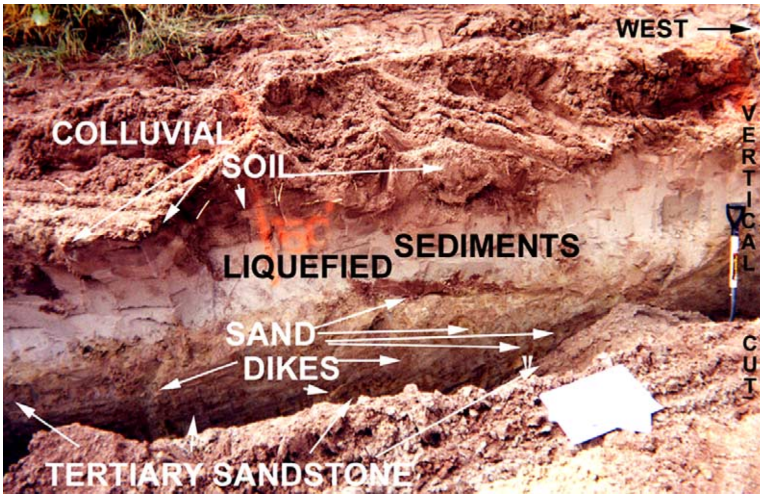

Fig. 10. Trench cut into a coastal terrace at Carlsbad, California exposing liquefied sediments (light layer) overlying the Eocene-age Santiago Formation (B member) with numerous sand dikes emanating from below.

3.2. Craterlets

Obermeier (1996a) pointed out that liquefaction-induced craterlets were extensively produced during the 1886 Charleston, South Carolina earthquake. Similar swarms of craterlets occur in the study area, particularly in terrace Qt_4 (Figs. 3 and 17) likewise supporting a probable seismic origin.

In plan view, the filled craterlets are nearly circular throughout their height and vary in diameter from about 0.3 to 2.0 m (Fig. 18). Their heights vary from about 2 to 10 m. At depth, their internal stratigraphy is characterized by vertical zones of upward-fining, clean, fine- to medium-grained sands, locally varying in color and texture (Fig. 19). These sands, as recorded during field observations, are injected through each other and locally into and through a central core. The upper part of most craterlets appears to be a collapse feature, creating depressions 0.5 to 1.3 m deep (Fig. 20). These craterlets are confined to an

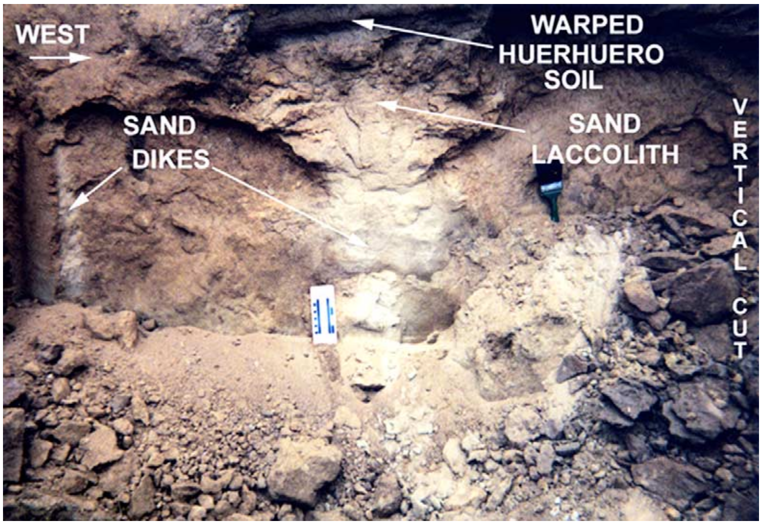

Fig. 11. Closeup view of warped Holocene colluvial sediments and sand dikes exposed in a trench cut into a coastal terrace at Carlsbad, California. Note: Location is the same as Fig. 9.

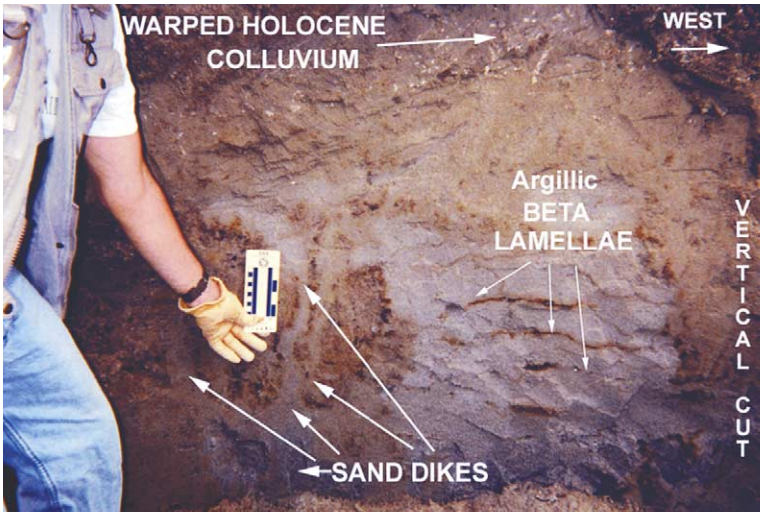

Fig. 12. Exposure of a storm-drain cut into the lowest coastal terrace (15.54 m el. MSL) at Carlsbad, California. Note: Multi-colored sand dikes are traceable from marsh source sands (located at base of brush), are upward-fining, and cut through, offset, and warped "beta" (argillic) lamellae.

ancient beach ridge, where the dike sand demonstrably originated as fluidized sediment transported upward from underlying Tertiary marine sands. Locally, the internal stratigraphy of the craterlets shows that they were likely produced during two or more discrete episodes (Fig. 18).

The craterlets also occur in sediments filling linear swales along the back edge of terrace escarpments and local beach ridges (Figs. 3, 4, and 17). Here the craterlets are filled by fluidized sediment, which later was replaced almost entirely by silica. These features occur near the base of the wave-cut platform and grade into a strongly cemented, 1- to 2-m-thick silcrete duripan. Based on local geomorphic and stratigraphic relations, it is deduced that the craterlets similarly formed by seismic liquefaction,

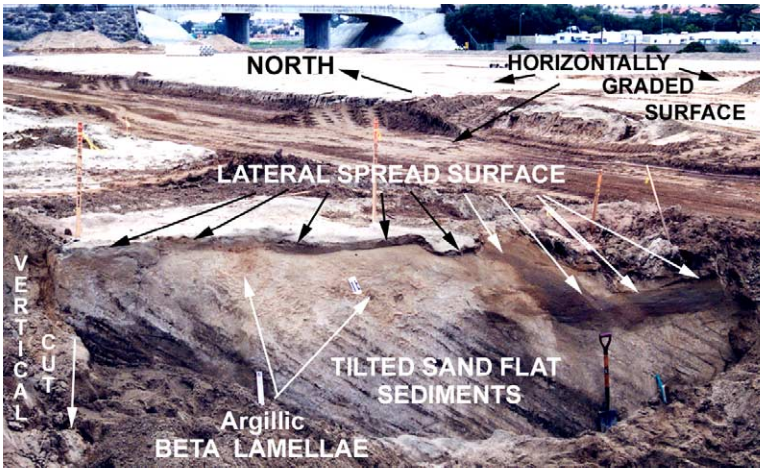

Fig. 13. A construction trench in the lowest coastal terrace (15.84 m el. MSL) at Carlsbad, California exposing tilted paleosand flat sands and marsh sediments, overlain by remnant v-shaped wedges of "beta" (argillic) lamellae, and capped by a clay-rich lateral spread, which flowed easterly, forming a depression. Note: These same sediments, as exposed in sea bluff exposures located 100 m to the west, dip to the west or are near-horizontal.

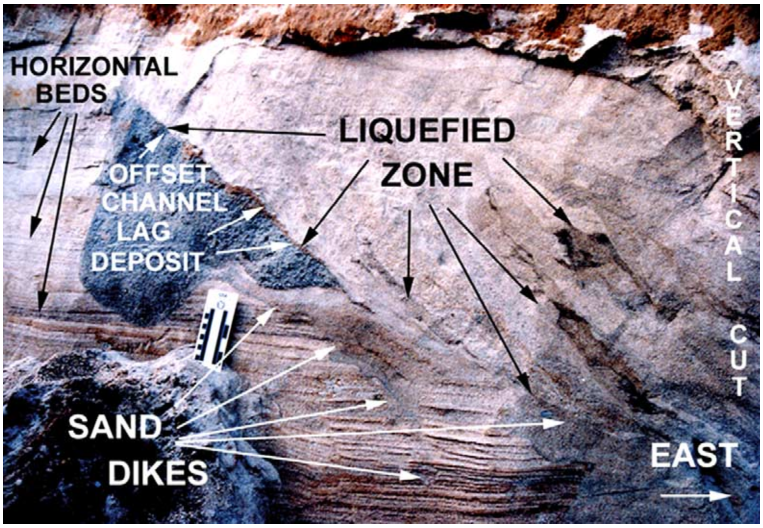

Fig. 14. A construction trench exposing marsh and sand flat sediments vertically cut by sand dikes at Carlsbad, California (19.50 m el. MSL). The liquefied, dragged, and offset channel-lag deposit and that the adjacent bedding has been eroded.

comparable to that reported by Twidale (1976), in Australia.

Elsewhere many craterlets in late Quaternary sediments are characterized by N30W to N70W filled fissures. These craterlets were later offset by the filled fissure deposits which, themselves, trend from N–S to approximately E–W. These particular craterlets vary in diameter from about 1.2 to 1.5 m, have a central

Fig. 15. A horizontally-graded terrace surface at Carlsbad, California (46.32 m el. MSL) exposing polygonal-shaped, “reticulated” multi-colored sand-filled features. Note: Vertical cuts of these same polygonal features expose numerous, adjacent, coalescing, upward-fining sand dikes demonstrably injected from below and not the result of surface infill.

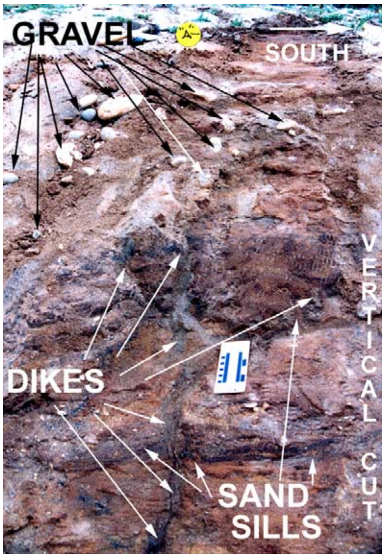

Fig. 16. Near-vertical exposure in a coastal terrace made for a major highway cut at Carlsbad, California (33.52–35.05 m el. MSL). Note: The gravel to boulder-bearing sands, deposited in a very fine, well-sorted dark mineral-rich matrix, are observed at the top of vents, and traceable to sand sills and dikes emanating from underlying marine source sands.

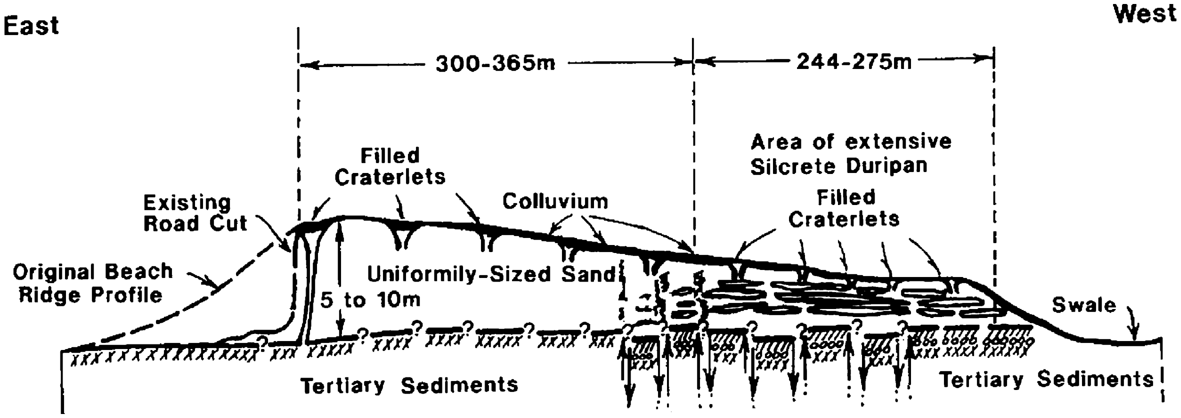

Fig. 17. Schematic vertical section of ancient barrier bar (beach ridge) showing sediment types, filled craterlets, and approximate abrasion platform contacts (former shorelines) at Encinitas, California (see Figs. 3 and 4). Adapted from Obermeier (1996b), his Fig. 13, p. 20.

core, and are formed during at least two intrusive episodes (Fig. 18).

3.2.1. Source mechanism

The craterlets in the study area are likewise interpreted as of paleoseismic liquefaction in origin, based mainly on the similarity of their internal stratigraphy, their morphology, and their occurrence in tectonic regimes where such craterlets have been previously described. For example, Dutton (1889), noted swarms of similar appearing craterlets, and deduced them to be liquefaction features associated with the 1886 Charleston, South Carolina earthquake of M∼7.2. More recently, similar liquefaction-induced craterlets were regenerated in the Kachchh Region of India following the M∼7.7 earthquake in 2001 (Rajendran and Rajendran, 2003). A likely earthquake origin for the study area craterlets is also indicated by the sand-filled tabular fissures whose overall dimensions and shapes suggest that they are “incipient craterlets” (features described by Obermeier, 1996b).

Although yet uncertain, the source of the strong seismic shaking may well be “hidden” or “blind” faults directly beneath the site, locally enhanced by topo-

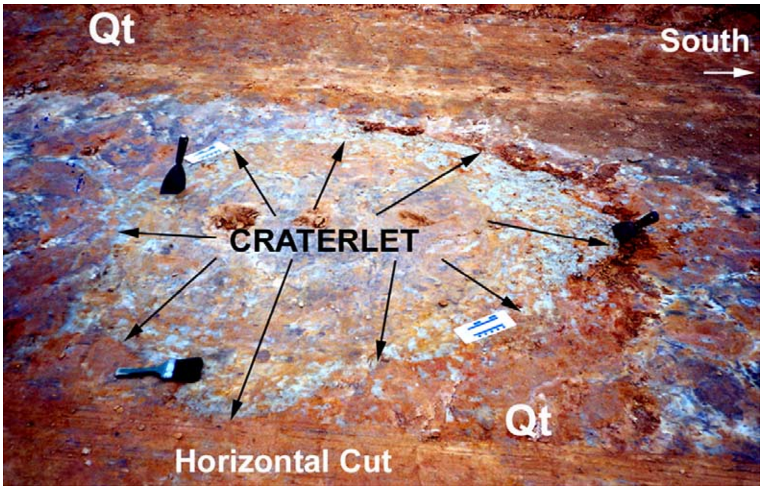

Fig. 18. Near-circular paleoliquefaction features (craterlets) exposed on the surface during construction grading on a coastal terrace at Encinitas, California (110.94 m el. MSL). Note: The boundary is outlined by scraping tools and scales.

graphic amplification, a phenomenon observed during the 1971 M~6.6 San Fernando, California earthquake (Saul, 1975, p. 68–69), and during the 1886 M~7.2 earthquake at Charleston, South Carolina (Obermeier, 1996a, p. 345).

Also suggestive of local faulting is the apparent displacement of terrace Qt_4 (Fig. 17), which, to the east, dramatically increases in dip (Fig. 4). Exposures here show that Qt_4 is apparently offset by a fault zone 3–4 m wide. Local faulting and regional tilting in this area has been postulated by others, although few urban and related grading cut exposures were then available (Wilson, 1972; Hannan, 1973; Eisenberg, 1985; Lajoie et al., 1991; Tan and Kennedy, 1996).

Conceivably, although unlikely, the craterlets may owe their origin to some unique, local artesian condition. This postulate, however, is rejected as a source mechanism because the study area craterlets are regionally extensive, and it occurs up-slope from dune field swales where local perched water would most likely occur. Additionally, the craterlets lack a regional hydrogeologic recharge/source area to supply the necessary head for their sole occurrence.

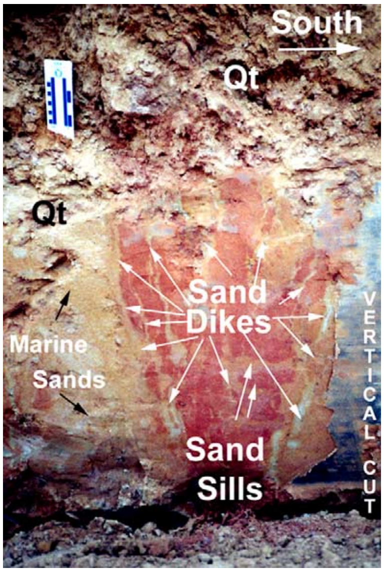

Fig. 19. Paleoliquefaction feature exposed in a vertical cut during construction grading on a coastal terrace at Encinitas, California (102.41 m el. MSL). Note: The multi-colored "flowering upward" feature, cuts through marine terrace sands and underlies the "craterlet" seen in Fig. 18. The blue hue on the right was made by the scraper blade on the terrace wall.

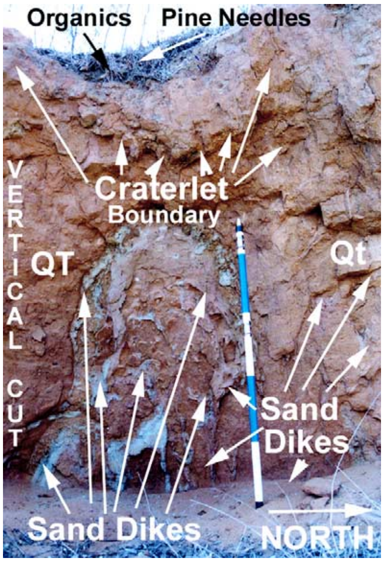

Fig. 20. Paleoliquefaction features exposed in a vertical escarpment along a coastal terrace at Encinitas, California (118.87 m el. MSL). Several episodes of upward-fining, multi-colored, tonal and textured sands are postulated to have been injected through each other, into and through a central core, and exhibit a "collapsed" infilled cone at the top.

3.3. Lateral spreads

3.3.1. Field observations

The myriad of new road cuts and grading pads on terraces Qt_1 through Qt_4 expose many dikes and other ground failure features typically associated with seismically-induced lateral spreads, features well described by Seed (1968) and Youd (1984), and depicted graphically by Obermeier (1996a, Fig. 7, part 3).

The new cuts now provide cross-section plan views, thereby permitting above-average field documentation of lateral spread extent and morphology.

The lateral spreads are exemplified by large blocks that are bordered by dikes, which are nearly linear in plan view. The dike sidewalls and widths range from about ~5 to about 45 cm; many have a left or right-step, en-echelon plan-view pattern. In vertical cuts, horizontal ground shifting is apparent by the truncation and general displacement of sand dikes and filled fissures (Fig. 15).

The lateral spreads occur on 1°–8° slopes, although locally slopes may exceed 10° forming minor "landslide" topography (Fig. 13).

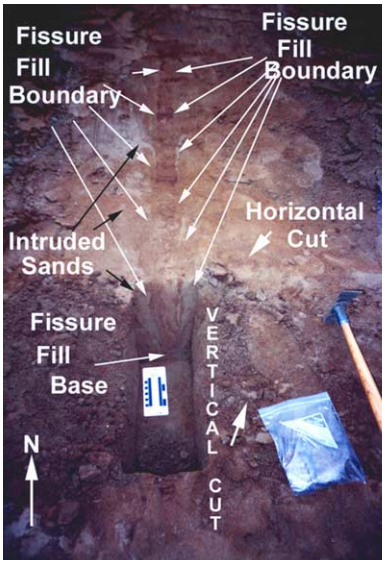

Fig. 21. Paleoliquefaction features (fissure fill and intruded sands) exposed by construction grading on coastal terrace at Carlsbad, California (16.45 m el. MSL). Note: The fissure fill, measuring 3.81–5.08 cm wide, consists of down-dropped colluvium in terrace sands, is near-vertical to vertical below the surface, and becomes wedge-shaped with depth.

3.3.2. Source mechanism

According to Youd (1984), lateral spreads can take place on slopes as low as 0.1° in the form of laterally moving landslides of non-liquefied sediments moving atop a liquefied layer. Such lateral spreads may also form grabens at their headwall and thrusting shear zones at the toe (Seed, 1968; Obermeier, 1987). The study area features are morphologically similar to those described by Seed, Youd, and Obermeier and, because they are in direct association with tabular sand dikes, sand laccoliths, and filled fissures, they are therefore interpreted as similarly being of seismic liquefaction origin (Fig. 13).

3.4. Filled fissures

3.4.1. Field observations

Hundreds of filled fissures are exposed in new excavations on marine terraces. These fissures are vertical to near-vertical fractures that widen near the ground surface. Most pinch out at depth. They range in height and width from about 5 to 35 cm and from 4 to 8 cm, respectively. Sediments filling the fissures have two sources; some demonstrably emanated from the ground surface and apparently moved downward through gravitational flow (Fig. 21); but other fissures are clearly filled with sand emplaced by fluidization of underlying Tertiary sediments. In sectional view many fissures are tabular and have laminations that parallel fissure walls. Also, many filled fissures cross-cut one another and thus may be highly contorted (Fig. 22).

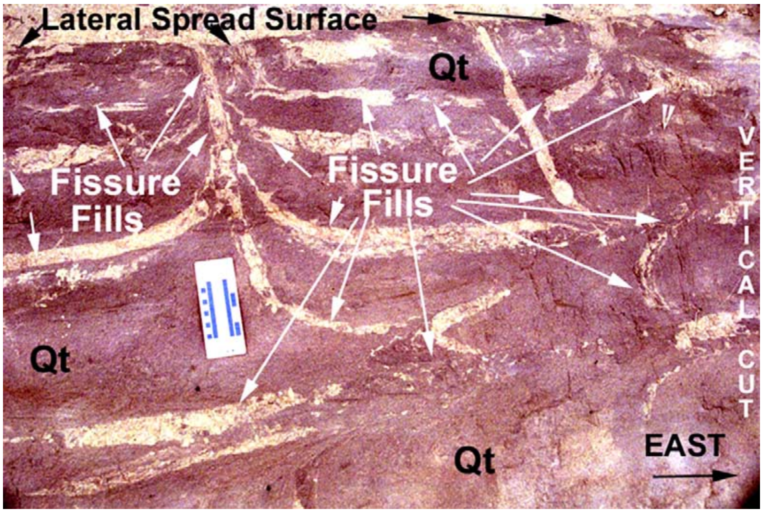

Fig. 22. Paleoliquefied features (fissure fills and lateral spreads exposed on a steeply dipping cut slope on a coastal terrace at Encinitas, California (71.32 m el. MSL). Note: Northwest, northeast, and east–west fissure fill sediments offset, drag, and even reverse themselves in a strike-slip mode. Also note that a laterally-spread liquefied layer at the top has cut off fissure fills.

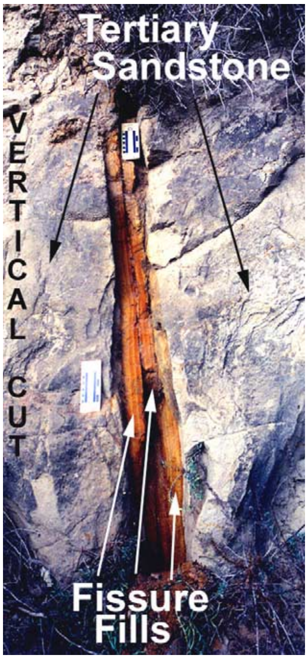

Fig. 23. Exposure displaying 3 epochs of Quaternary terrace fissure fills (from 3.81 to 5.08 cm wide), down-dropped into the underlying "parent" Tertiary sandstone at Carlsbad, California (6.09–7.62 m el. MSL).

The filled fissures occur on a wide age range of sediments; and locally some appear to penetrate into the underlying Tertiary parent sandstone (Fig. 23), and even form wedge-shaped down-dropped blocks (Fig. 24).

3.4.2. Source mechanism

Based on their widespread occurrence, on the multiple sources of fill, and on their association with lateral spreads, the study-area, filled fissures probably formed recurrently.

Locally some fissures may be associated with landslides, themselves possibly induced by seismic events. Indeed, it is also plausible that some filled fissures reflect faulting at depth, for the surface fissure pattern mimics bedrock fractures. Regional faulting is largely strike-slip (Sylvester, 1988; Weldon et al., 1996), and this style of deformation typically gives rise to reversal of throw, transtensional and transpressional fractures and thus to widespread complex ground fissuring (Obermeier et al., 2004).

4. Basis for a liquefaction origin

A proposed seismic liquefaction origin for the filled fissures is similarly based on comparing the morphology of these features with those described elsewhere that are associated with documented seismicity (Tables 1–3). Specifically, the filled fissures in the study area are very similar to those described by Sims and Garvin (1995) who analyzed and described liquefaction features associated with the M ~ 7.1, 1989 Loma Prieta, California earthquake.

Alternative mechanisms for origin of the filled fissures range from local artesian flow to wave-cutting along paleo-shorelines. But these hypotheses are untenable in the study area for artesian flow is not, and has not occurred given the local geomorphic, hydrogeologic, and stratigraphic setting, and wave-cutting is similarly ruled out owing to relative "recency" of liquefaction in marine terrace sediments now tens of meters above present sea level. Of particular interest, however, is the nearby presence of the active Newport–Inglewood/Rose Canyon fault zone, and a related blind thrust immediately offshore (Fig. 2). According to Rivero et al. (2000) and Legg (personal communication, 2004) the blind thrust extends directly under the study area, and may be capable of generating seismic events of M ~ 7.0 or greater (Kuhn et al., 2000, 2004).

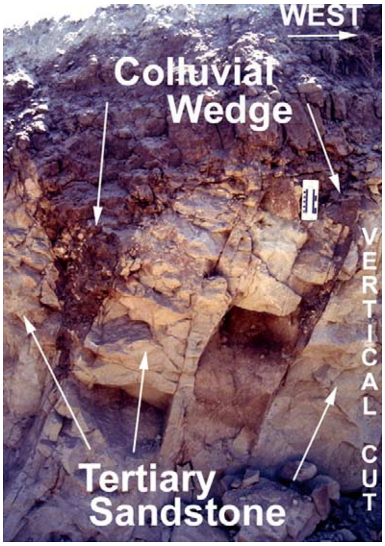

Fig. 24. Colluvial wedges; inferred to be large fissure fills exposed in Tertiary sandstone (fractured grey-white unit) at Carlsbad, California (6.09–7.62 m el. MSL).

5. Indirect paleoseismic evidence

Mima mound topography also characterizes much of the North San Diego County study area. Although these features alone do not provide incontrovertible evidence for local-area paleoseismicity, their presence compliments and otherwise supports major seismic events in the late Quaternary. Extensive mound fields were once in evidence (Orcutt, 1887) and visible on aerial photography taken along the North San Diego County coastal surfaces, prior to urbanization (USGS, 1947; USDA, 1953). Scattered mounds still occur in Carlsbad and Encinitas and on the Camp Pendleton Marine Base. As shown on aerial photographs and originally noted in soil surveys (USDA, 1918, 1973), continental and estuarine deposits located on coastal terraces Qt_1 at Carlsbad are mantled by a local microrelief or hummocky landscape of "mima mounds," each of which is usually less than ~1 m high and 2 to 3 m in diameter (Fig. 5).

5.1. Field observations

Site-specific excavation of Carlsbad and Encinitas coastal mound sites show that some mound fields are aligned along fissure fills and laterally spread depressions called "vernal pools". The mound topography and adjacent vernal pools are irregular. They appear concentrated along some lineaments, possibly fault or fracture zones, a phenomena reported elsewhere in California (Shlemon et al., 1973). The mounds are typically subrounded, are frequently confined by an expansive clay cap, and are often filled by clean white to tan sand, giving rise to a dramatic contrast in color and grain-size, when compared with the generally dark-colored clayey sediments characteristic of surrounding continental or estuarine deposits. As exposed in grading cuts, some mounds directly coincide with sand dikes and sand laccoliths. These sand dikes, which are tabular and tubular in plan view, are traceable to underlying sand source beds derived from Tertiary bedrock. Most terraces are burrowed, and the sand dikes, sills and source sands are often occupied by ground squirrels and gophers that indicate an ongoing biogenic maintenance by rodents. Similar-appearing mound complexes in the San Clemente area, about 48 km to the north, have been interpreted to be mainly constructional (bioturbation), in origin (Shlemon et al., 1997), however a paleoseismic origin was not precluded.

5.2. Multiple origin of mounds

There are many hypotheses for the origin of mounds: eolian deposits (Barnes, 1879); water-deposited features (Dietz, 1945); water and glacial combined (Newcomb, 1952; Washburn, 1997); physical or chemical segregation (Ritchie, 1952); features created by human agency (Aten, 1981); ants, ground squirrels or pocket gophers (Dahlquist and Scheffer, 1942; Arkley and Brown, 1954; Cox, 1990, 1991); seismogenic (Berg, 1990; Riefner and Pryor, 1996), and "multiple origins" (Krinitzsky, 1949).

5.2.1. Source mechanism

Some of the Carlsbad and Encinitas mounds evidently originated as sand blows, and were then later colonized by fossorial rodents. Also some the mounds apparently formed during genesis of sand laccoliths, which hydraulically deformed the overlying clay expansive cap where fluidized sand could not escape to the ground surface. Many of the associated vernal pools were in part created by lateral spreads which are linear in plan view (Kuhn et al., 2000).

The Carlsbad and Encinitas mima-mound topography, is therefore a probable important indicator of paleoseismicity because morphologically similar features are associated with tabular sand dikes, sand laccoliths, sand blow deposits, lateral spreads, filled fissures and plausible tsunami features (Kuhn et al., 1995a,b,c, 2000, 2004). This is contrary to observations from the extensively studied New Madrid Seismic Zone where seismicity apparently did not produce mima mounds (Saucier, 1991a). It should be noted that from aerial photos, the New Madrid sand blows are similar in form to mounds; however, agricultural leveling for almost 200 years has destroyed much of their relief.

6. Age of liquefaction features

6.1. Evidence for quaternary paleoseismic events

6.1.1. Field observations

Features interpreted to be of seismic liquefaction origin in the Carlsbad to Encinitas area include extensive swarms of craterlets, principally found on the ~440 ka terrace Qt_4 (Fig. 4). Moreover, fissure fills, sand dikes, lateral spreads and mounds occur on all terraces, which vary in age from ~ 80 ka to 440 ka. A "classic" exposure at one location in Carlsbad shows that 11 epochs of paleoliquefied sand dikes, fissure fills, and lateral spreads probably occurred during the past 120 ka (Figs. 25 and 26).

6.2. Evidence for Holocene paleoseismic events

6.2.1. Field observations

The north coastal area of San Diego County contains widespread Paleo-Indian sites, some of which are radiocarbon-dated at more than 8 ka (Breschini et al., 1992). These archaeological sites consist of burials, "kitchen middens," and transitory camps that contain diverse artifacts dated mainly by shells and charcoal (Carter, 1957; Gallegos, 1987, 2002). Several early-to-late Holocene archaeological sites have been affected by paleoseismic features. For example, liquefied sand dikes and sills extend upward, intrude and deform midden deposits located on the Qt_1–Qt_4 terraces in the Carlsbad area (Fig. 3). Further, based on radiocarbon-dating, at least one major event took place about 6 to 8 ka bp (Smith, 1996). Some of these liquefaction-deformed archaeological sites occur on uplifted 60-m high, marine terrace deposits, well above Holocene regional water levels (Shlemon and Kuhn, 1997; Fig. 27). It is thus inferred that liquefaction likely took place during the winter rainy season when the high-level terrace sands contained perched water (Kuhn et al., 2000).

Other archaeological evidence suggests that seismically-induced liquefaction may have taken place as recently as 2 to 3 ka ago (Franklin and Kuhn, 2000). Indeed, an archaeological site at Batiquitos lagoon in Carlsbad (Gallegos and Associates, 1997) exposed an intact prehistoric hearth. One test pit in the center of the site (feature 97-1) exposed artifacts and shells that were apparently offset and locally dragged upward by fissure fill sediments (Fig. 28). The deformed artifact horizons yield radiocarbon dates of 0.9 to 1.3 ka, documenting incontrovertible evidence for paleoseismic liquefaction and ground deformations in late Holocene time (Fig. 29).

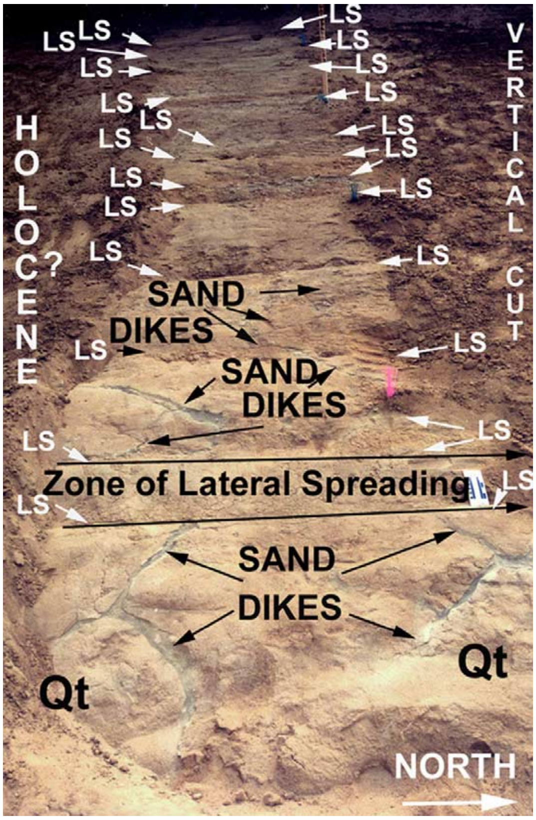

Fig. 25. Photograph of a vertical cut exposing sand dikes cutting coastal terrace sands at Carlsbad, California (47.24–51.81 m el. MSL) Note: The scale is resting on a lateral spread surface that has cut-off the underlying sand dikes, which were injected from below. At least 10 episodes of lateral spreads cut-off sand dikes. Measured sections of multiple lateral spread surfaces in vertical cuts are shown in Fig. 26.

7. Tsunamigenic features

The possible tsunamigenic features identified in this investigation are based on comparison with stratigraphic relations and internal characteristics of tsunami deposits recorded elsewhere (Table 5).

7.1. Field observations

Many abrupt, chaotic, convulsive sedimentary features now exposed in the north coastal area of San Diego County cannot be simply explained by non-seismic soft-sediment deformation, nor by variations

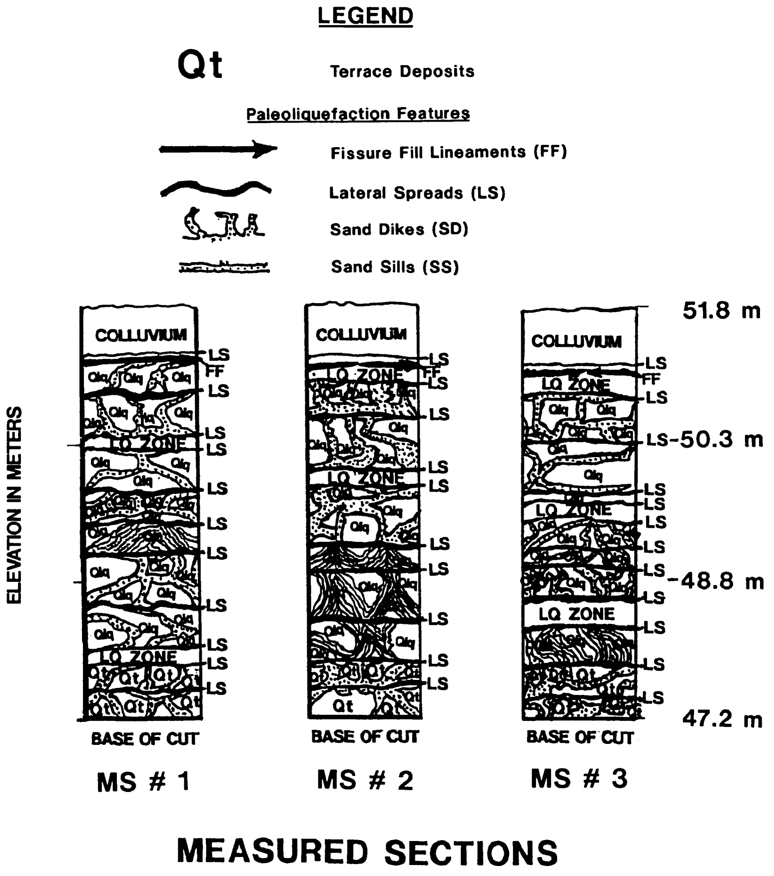

Fig. 26. Measured sections of vertical cuts made 15 m apart showing multiple lateral spread surfaces. Same location as seen in Fig. 25.

and cyclicity of storm deposits ("tempestites," of Aigner, 1985). Rather, the features are similar to those formed by (1) ancient earthquakes ["seismites" (Seilacker, 1969, 1984)]; 2), turbidity current deposits ["turbidites" (SEPM, 1951; Kuenen, 1947, 1957, p. 231)], and; 3) modern tsunami deposits ["tsunamites" (Pratt, 2002)]. Many coastal features also show unusual chaotic variations here likewise inferred to be caused by paleoliquefaction. Typically, a locally generated tsunami deposit can also be deformed by large aftershocks.

The convulsive features in the north coastal Carlsbad–Encinitas region have characteristics that are in common with other tsunamis described elsewhere (Table 5). Specifically:

(1) The presence of chaotic, turbid, sedimentary debris (Fig. 30), commonly mixed with wood fragments, shells, clay balls and pods of sharp, angular pieces of terrace deposits and bedrock, and locally capped by peat (Fig. 31).
(2) The initial event deposits grade from coarse to landward-fining, rather than landward-coarsening, typical of "tempestites" (storm deposits).
(3) The pebbles are imbricated (Fig. 32).
(4) The landward movement of sediment is "lobe form" (Fig. 33), similar to those in the Philippines Islands produced by the 1994 Mindoro earthquake (Daag et al., 1995).
(5) The "v-shaped" chaotic features were inferentially caused by an abrupt "hydraulic jump" when tsunami waves reach a "bedrock high" or very resistant surface feature (Fig. 34), a phenomenon often associated with fluid-like features exposed in the overlying sediments (Morner, 1996; Fig. 35), and;

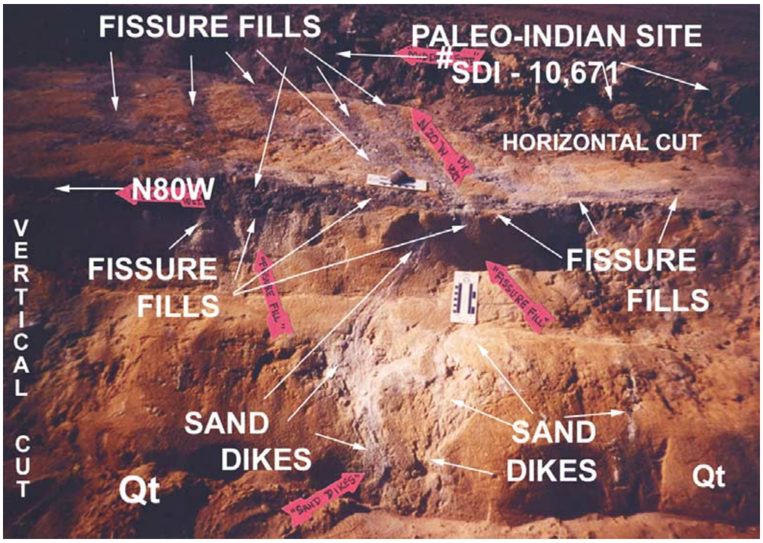

Fig. 27. Paleoliquefaction features exposed by grading deform, cut, and offset a shell (*Argopecton* sp., *Chione* sp.), charcoal, and artifact-rich, Indian midden site located on a 60 m high, now well-drained terrace at Carlsbad, California. Note: Arrows point to sand dikes, fissure fills (trending N20W and N80W), and lateral spreads that crosscut the terrace sands and offset each other.

(6) The abrupt landward termination of sand wedges has an angle similar to, but steeper than dunes (Daag et al., 1995; Fig. 36).

Because of their similar internal stratigraphy and occurrence on former abrasion platforms on modern "bedrock highs," the anomalous, chaotic, con-

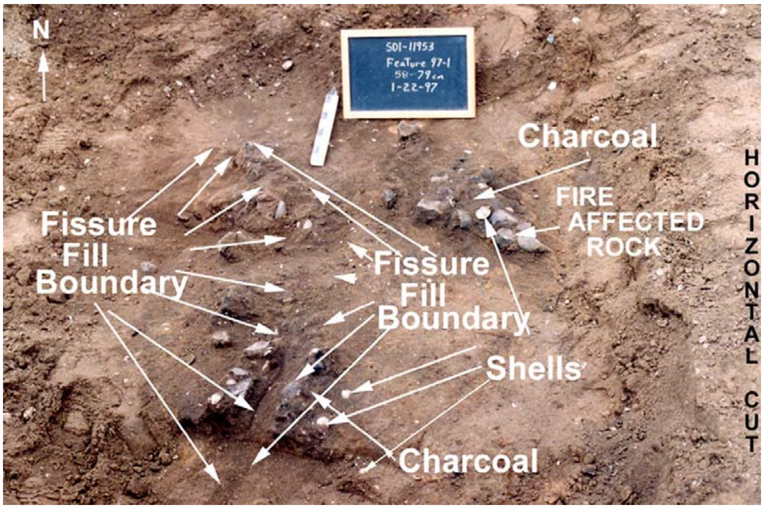

Fig. 28. An archaeological site located along the north side of Batiquitos Lagoon at Carlsbad, California (5.18–5.48 m el. MSL). Note: Paleoliquefaction features (fissure fill and liquefied sediments) appear to offset, dragged, and disrupted fire-affected rocks and 0.9 to 1.3 ka year old, calibrated radiocarbon-dated shells (i.e. *Argopecton* sp., *Chione* sp.) and charcoal (photograph: Courtesy of Dennis Gallegos).

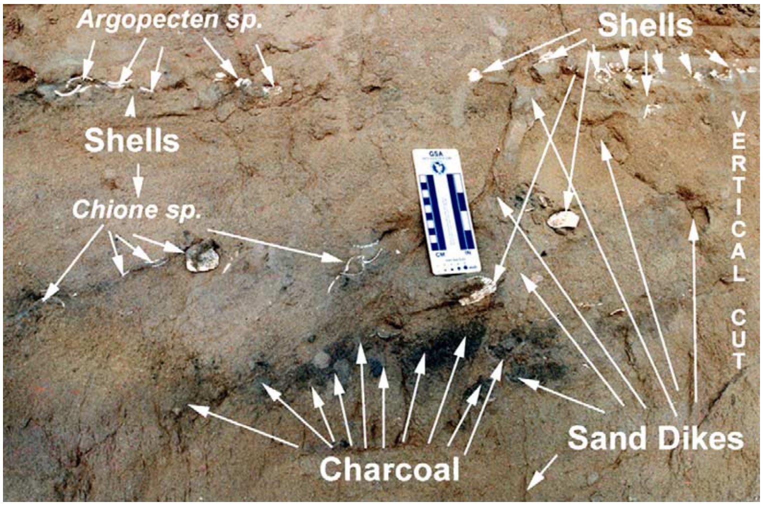

Fig. 29. Paleoliquefaction features exposed in a cut slope on the north side of Batiquitos Lagoon at Carlsbad, California (6.09–7.62 m el. MSL), located near the site seen in Fig. 26. Note: Shell horizons (*Argopecton* sp., *Chione* sp., and *Ostrea lurida*), charcoal, fire-affected rock fragments, and cobbles are offset, dragged, and liquefied upward into pre-existing fractures and into sand dikes.

vulsive, deposits in the Carlsbad to Encinitas area were likely produced by paleoseismic events, and hence are here deduced to be tsunamigenic in origin.

7.2. Local tsunami mechanism

Although Emery (1960, p.124) indicated that southern California was not immune to tsunamis,

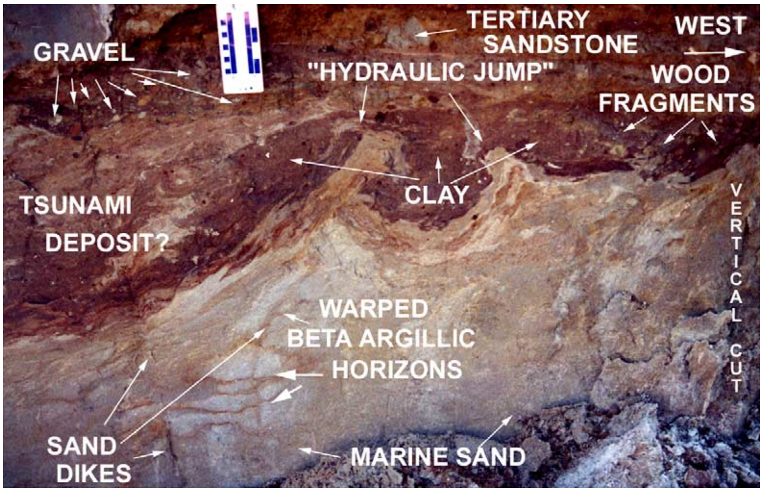

Fig. 30. View looking south of a storm drain trench wall cut into a coastal terrace exposing possible tsunami deposits at Carlsbad, California (15.54 m el. MSL). Note: Exposed are highly disturbed, contorted, chaotic, turbid sediments and debris overlying liquefied and dragged Bt horizons resting on a Tertiary sandstone abrasion platform. The upper half of this exposure interpreted as tsunamigenic in origin, for it also displays a distinct “hydraulic jump”, markedly different from documented paleoliquefaction features documented elsewhere.

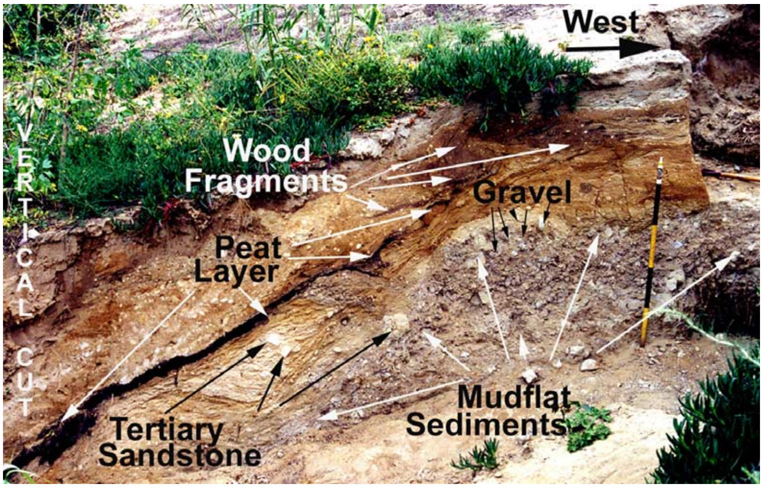

Fig. 31. “Anomalous sediments” inferred to be tsunami deposits exposed in a vertical cut adjacent to a coastal lagoon at Carlsbad, California (6.70–9.14 m el. MSL). Note: The Jacob staff (scaled in 1′ increments), rests in highly disturbed, mudflat sediments containing shells (*Chione* sp.), rock and clay fragments, overlain by chaotic, convulsive, turbid, sedimentary debris, including wood fragments, sharp angular pods of terrace deposits and Tertiary sandstone “bedrock”. These sediments are capped by lagoonal tidal flat organic-rich sands, “peat”, pieces of terrace sands and other chaotic sediments.

many considered that San Diego was relatively safe owing to the bordering, wide continental shelf that inhibits seismically-induced wave attack generated outside the region (Van Dorn, 1965). Recently, however, geophysical research shows that the southern California Continental Borderland is crossed by many active faults with characteristics capable of producing large-scale, coseismic sea floor deformation during submarine earthquakes (Legg, 1991; Legg and Kennedy, 1991; Rivero et al., 2000; Grant and Rockwell, 2002). Additionally, local strong seismicity generated by any potential local earthquake sources,

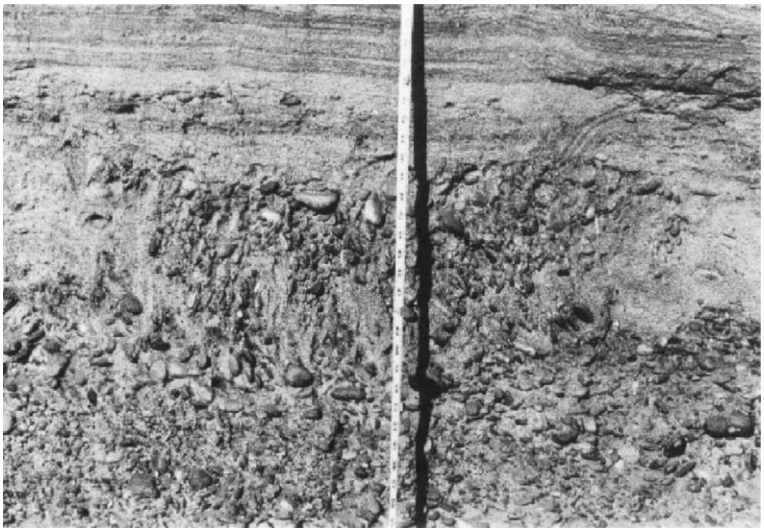

Fig. 32. An abrupt, highly localized, disrupted, “chaotic” imbrication of marine gravels exposed in a vertical excavation in the lowest coastal terrace showing possible tsunamigenic and/or paleoliquefaction features at Carlsbad, California (3.04–3.35 m el. MSL). Note: Tape measure (in in.) for scale (1 in. = 2.54 cm).

Fig. 33. View of landward-fining sand layers forming lobes on on-lapping coastal terrace sands at Carlsbad, California (20.72–21.33 m el. MSL). Note: Putty knife rests against terrace sands for scale; also see irregular sharp contact with white sands at top of photo. These features are morphologically similar to tsunami deposits photographically documented during the 1994 Mindoro event in the Philippine Islands (Daag et al., 1995).

both onshore and offshore, could trigger large-scale slope failures and thereby generate local tsunamis (McCarthy et al., 1993; Borrero et al., 2001; Legg et al., 2003). Additionally, many large slope failures have been mapped in the southern California Continental Borderland (Field and Richmond, 1980; Clarke et al., 1985, 1987; Legg and Kamerling, 2003), even off Carlsbad and Encinitas (Greene and Kennedy, 1987; Clarke et al., 1987; Fig. 37). Paleoseismic investigations also show large coastal earthquakes occurred within the Holocene, and historically at least four measurable local tsunamis impacted the southern California region in 1812, 1862, 1927, and 1930 (McCulloch, 1985; Lander et al., 1993). Accordingly, evidence for paleotsunamis is abundant, and the potential for future impact is high (McCarthy et al., 1993; Legg et al., 2003, 2004).

8. Potential seismic sources

Based on the extent (730 km), character, and distribution of paleoseismic features and the residual evidence afforded by mima-mound topography and tsunamigenic deposits, it seems likely that the causative earthquakes were of at least M ~ 7.0 (Kuhn et al.,

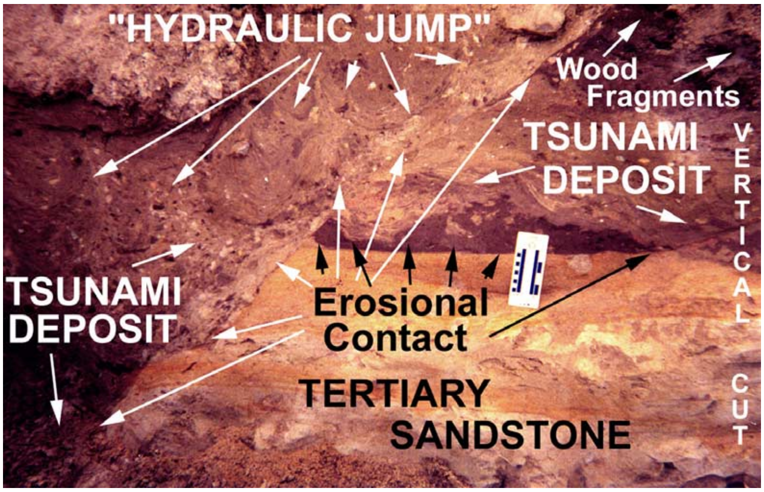

Fig. 34. North wall of a sewer-line trench cut into a terrace and exposing a possible paleotsunami deposit at Encinitas, California (93.26 m el. MSL). Note: The scale is located on a Tertiary-age sandstone abrasion platform, which is unconformably capped by a chaotic, turbid deposit containing small angular pieces of terrace and "parent" Tertiary sandstone and small rocks. Also note the "v-shaped upward climbing" chaotic features interpreted to result from an abrupt "hydraulic jump" created when tsunami waves reached a bedrock high.

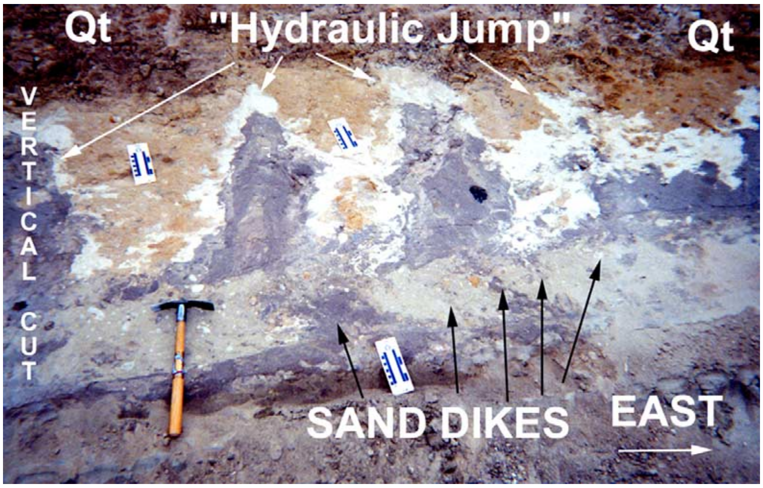

Fig. 35. North wall of a cut slope exposing possible tsunamigenic and/or paleoliquefaction features at Encinitas, California (95.09 m el. MSL). Note: These features are the same as seen in Fig. 34 but are 3 m higher in the section.

2000, 2004). The specific fault(s) that triggered the liquefaction and likely secondary surface faulting is not well constrained. However, the likely seismic sources are the Newport–Inglewood/Rose Canyon Fault Zone (NIRC), ~4–6 km offshore and possibly under the study area (Kuhn et al., 2000, 2004), other Continental Borderland faults (Legg, 1991), and possible site-specific faults (Figs. 1 and 2).

8.1. Newport–Inglewood/Rose Canyon fault zone

The Newport–Inglewood/Rose Canyon fault zone (NIRC) is the longest and most active in the north-coastal San Diego County area (Figs. 2 and 37). It is therefore the most likely seismogenic source for the observed paleoseismic features (Lindvall and Rockwell, 1995; Grant et al., 1999; Rivero et al., 2000;

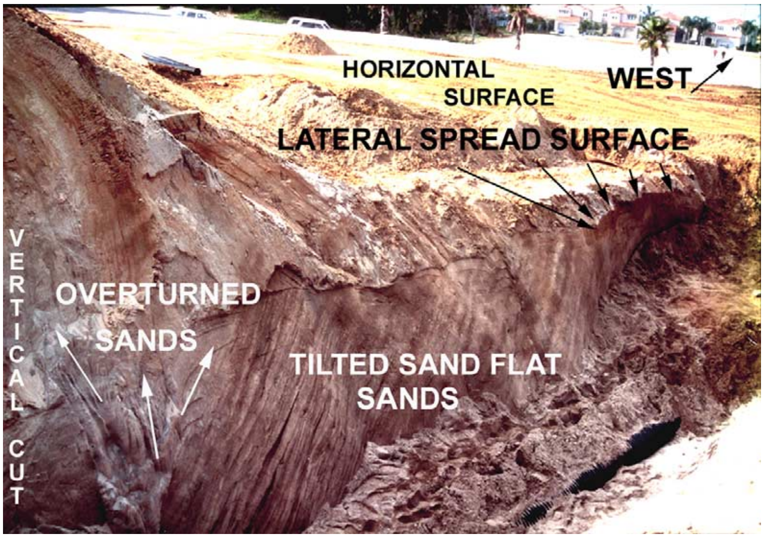

Fig. 36. View looking southwest at abnormally tilted “sand flat” sediments exposed in a storm-drain trench cut into a coastal terrace at Carlsbad, California (28.65–29.26 m el. MSL). Note: The bedding dip varies from near-vertical (left) to 75 to 80 degrees (middle) to 46 degrees (right), to locally completely deformed. This exposure is morphologically a “twin” of deposits photographically documented during the tsunami that followed the 1994 Mindoro earthquake in the Philippine Islands (Daag et al., 1995).

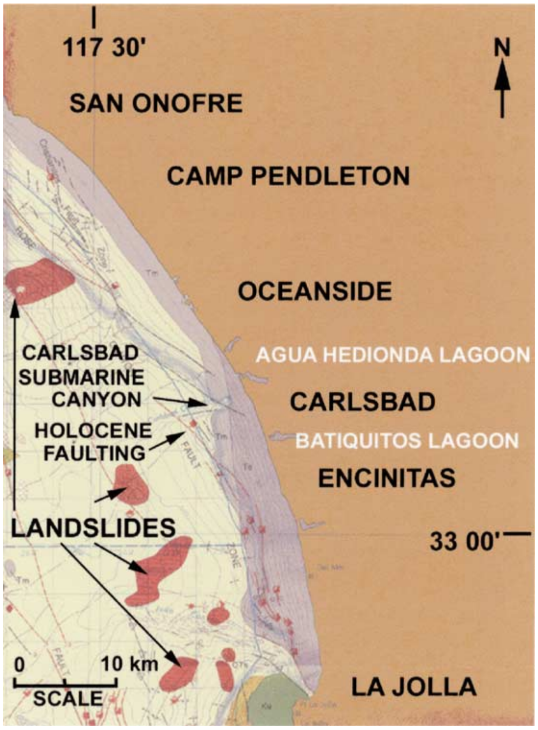

Fig. 37. Portion of a “Geologic map of the inner-southern California Continental Margin”. Note: The red square (located at the Carlsbad Submarine Canyon) indicates sea floor faulting that cut strata of Holocene age. Also note the adjacent large submarine landslide (adapted from: Clarke et al., 1987).

Grant and Rockwell, 2002). It has also been suggested that the NIRC dips eastward beneath the coast (Kuhn et al., 1994), possibly merging with a deep northeast-dipping Neogene detachment fault system (Legg, 1991; Crouch and Suppe, 1993). Though presently somewhat speculative, an east-dipping seismogenic zone under Carlsbad to Encinitas may trap seismic wave energy in the hanging wall (Legg et al., 1994; Kuhn et al., 2000, 2004).

Approximately 1.5 km offshore lies the Carlsbad Submarine Canyon (Shepard and Emery, 1941), characterized by Holocene sea floor offset, and large subsurface landslides (Kennedy et al., 1985, 1987; Fig. 37). Similarly, Fischer et al. (1992) indicated that a coastal “tectonic dam” had beheaded the former drainage in the Carlsbad area. These tectonic features are directly offshore the Holocene liquefaction and tsunamigenic, chaotic features described in this paper (Kuhn et al., 2000).

North to northeast-trending branching and secondary fault zones also extend onshore from the NIRC (Hannan, 1973; Adams and Frost, 1981). These are exemplified by the Cristianitos fault zone near San Onofre (Western Geophysical, 1972; Moyle, 1973), and by an unnamed fault zone about 10 km north of Carlsbad (Euge et al., 1972). The Carlsbad to Encinitas area is located at a major transition in the NIRC, the “Carlsbad–Encinitas Overstep” of Fischer and Mills (1991), where the offshore Rose Canyon fault zone changes from a more northerly, transtensional trend to a more westerly, transpressional trend along the South Coast Offshore Zone (Kuhn et al., 2000). In sum, the NIRC, other nearby offshore faults, plus possible local onshore faults are all capable of generating relatively high-magnitude earthquakes. These collectively can produce the myriad of paleoseismic features now exposed in the north San Diego County area.

8.2. Urbanization-caused increase in the hazards of seismically-induced liquefaction

The population of coastal North San Diego County is expected to triple over the next decade (SANDAG, 1991). Excavations of new residential tracts have provided excellent exposures of the neotectonic features described herein, and likely will continue largely on the marine and non-marine terraces. Terrace sediments are typically fine to medium sands, which are inherently susceptible to liquefaction when saturated. Although permanent ground water levels are presently low along the undeveloped coast, shallow perched water tables occur locally. Also, surface water also recharges perched and regional water levels via pre-existing fractures and sand dikes (Fig. 38). Almost all water for urban landscaping and recreational use is imported, so that soil moisture and infiltration will likely increase from the present 250 mm/year to an anticipated 2000 mm/year in the coming decade (Shlemon and Kuhn, 1997). Groundwater is typically perched within the Quaternary sediments (terrace deposits) on the underlying, relatively impermeable bedrock surface or “hardpan.” These “high-elevation” perched water levels will rise an expected ten-fold owing to urban-water infiltration (Shlemon, 2000). The active NIRC is within 4 to 6 km of the coast, and if an east-dipping fault plane exists at depth, coastal development will lie within the 5-km, near-

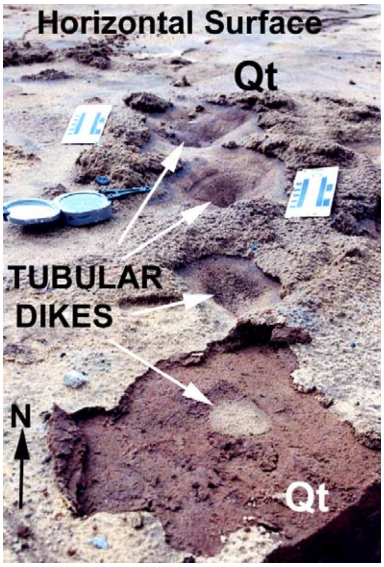

Fig. 38. Horizontal exposure made by grading on a coastal terrace at Carlsbad, California (29.26 m el. MSL). Note: Rainfall-induced surface runoff water flows into the subsurface along pre-existing fractures and sand dikes, thus recharging groundwater levels.

source zone for this active fault. Consequently, enhanced shaking may be expected from moderate to large earthquakes along this portion of the NIRC. Such strong shaking increases potential liquefaction of late Pleistocene sands and in the overlying engineered fills. Accordingly, the potential for coastal area, liquefaction-induced ground failures will likely increase during the coming decades. Structures may then be subject to permanent ground displacements associated with lateral spreading, as well as widespread sand blows and fissuring. Such hazards have heretofore been largely ignored.

9. Conclusions

Recent man-made exposures at Carlsbad and Encinitas reveal late Pleistocene to probable Holocene faults, tsunamigenic deposits, and ground-failure hazards. Features interpreted to be of seismic liquefaction origin are widespread and common in the study area. Paleoliquefaction features include sand-filled dikes and sills, lateral spreads, filled craterlets, fissures fills, and other unconsolidated sand deformations derived from underlying Tertiary and Pleistocene marine and dune sediments. A paleoseismic liquefaction origin, rather than soft-sediment loading is deduced for these features based on internal stratigraphy, morphology, field setting, and proximity to active faults. The paleoliquefied sands are upward-fining, penetrate and locally deform regressive marine and prograding continental deposits and soils that mantle marine-terrace platforms at elevations from about 3 m to 130 m, and such marine-terrace platforms range in age from about 80 ka (lowest) to 400 ka. Some injection dikes and fissure fills are young, for they displace Holocene, Native-American Indian middens, burial grounds, and transitory camps, located on 60-m high terraces, far above modern regional ground levels. The paleoearthquakes were likely at least M ~ 7, and may have occurred during unusually wet times, when perched groundwater saturated underlying sediments. Many paleoseismic events probably originated on the nearby Newport–Inglewood/Rose Canyon fault system. Eastern dipping segments of the NIRC project under the north coast of San Diego County. Accordingly, the seismic hazard of this area may be substantially higher than heretofore assumed.

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