UNIVERSIDAD TECNICA FEDERICO SANTA MARIA

EXUMBRA IN SOLEM

DEPARTAMENTO DE OBRAS CIVILES

LA FALLA "MARGA - MARGA" VIÑA DEL MAR - CHILE

ROBERT M. THORSON, Ph.D.

1999

UNIVERSIDAD TECNICA FEDERICO SANTA MARIA
VALPARAISO - CHILE

LA FALLA GEOLOGICA
MARGA - MARGA
VIÑA DEL MAR - CHILE

Robert M. Thorson, Ph.D.

Valparaíso

UTFSM. DEPARTAMENTO DE OBRAS CIVILES
Agosto de 1999

Robert M. Thorson (Ph.D.) es profesor del Departamento de Geología y Geofísica de la Universidad de Connecticut (USA). En reconocimiento a sus méritos académicos y profesionales le fue otorgada de parte de la Fundación Fulbright, la beca de pasantía en Chile «Fulbright Research-Lecturing Award» para el año 1999.

El profesor Thorson ha mantenido contacto con la Universidad Técnica Federico Santa María desde el mes de agosto de 1997, el cual se ha materializado con la incorporación durante el primer semestre de 1999 al Departamento de Obras Civiles como profesor e investigador visitante.

Robert Thorson de 47 años de edad se radicó con su señora e hijos en la ciudad de Viña del Mar y durante su estadía en la zona su esposa Kristine, también profesora universitaria, se relacionó con la Universidad Santa María dictando algunas clases de inglés en el Departamento de Estudios Humanísticos. El Dr. Thorson es un muy fructífero y particular profesional preocupado específicamente de asuntos o problemas geológicos aplicados a ingeniería civil. Durante su estadía en la zona el profesor Thorson se documentó en forma minuciosa respecto la historia geológica, la historia geotécnica y geosísmica de la región y recorrió extensa y detalladamente valles, quebradas y cerros observando con especial atención detalles y/o señales histórico-geológicas que explicaran racionalmente la formación de las ciudades y también comportamientos peligrosos de algunas zonas específicas durante terremotos. A modo de anécdota se puede contar que el Dr. Thorson caminó repetidas veces a pié por la vía del ferrocarril desde El Salto hasta Quilpué, prestando especial atención a la geomorfología tectónica y al mecanismo funcional de la falla del «Marga-Marga», la cual pudo haber sido una de las causas principales de amplificación local que se produjo en el terremoto del 03 de marzo del año 1985 y que dañó severamente a algunos edificios de cuatro pisos en la población Canal Beagle, población ubicada en la ladera de un cerro inmediatamente vecino a la traza de la falla geológica.

El profesor Thorson produjo numerosos informes relacionados con problemas geológicos y sísmicos locales, como lo es la falla geológica del «Marga-Marga», la macro-estratigrafía del plan de la ciudad de Viña del Mar, la génesis, la historia y la evolución de las dunas de Reñaca y las inundaciones producidas por el Río Aconcagua. El profesor Thorson además de su trabajo zonal, conferencias periódicas y colaboración con profesores y memoristas de la Universidad Santa María, mantuvo permanente contacto con el Servicio Nacional de Geología y Minería y con el Departamento de Geología y Geofísica de la Universidad de Chile.

SUMMARY

La ciudad de Viña del Mar está expuesta a severos movimientos sísmicos. Solo a modo de ejemplo tres grandes y bien documentados terremotos sacudieron la ciudad en los años 1822, 1906 y 1985, siendo los dos primeros particularmente fuertes en la Población Vergara, donde inclusive casas de madera de la época sufrieron fuertes daños. Es conocido que la concentración de daño sísmico en el plan de la ciudad de Viña del Mar se debe a la existencia de un relleno sedimentario sobre la roca basal del valle. Sorprendentemente y salvo el trabajo del profesor de la UTFSM Sr. Carlos Aguirre (1986) se ha prestado poca atención a diferenciar este relleno sedimentario en microzonas, diferenciación la cual puede contribuir valiosamente para planificación urbana.

El presente documento recomienda efectuar microzonificación del plan de Viña del Mar desde el punto de vista geológico; resultados preliminares indican patrones sistemáticos del relleno sedimentario a tres distintas profundidades típicas: La textura y propiedades geotécnicas de los estratos de suelo cercanos a la superficie del terreno dependen de su ubicación o sector del plan de Viña, en general se trata de grandes y masivos depósitos u horizontes de arena de origen marino al borde Nor-Oeste del valle, con estratos intercalados de arenas también sedimentarias pero de origen fluvial en el borde Sur y arenas finas con arenas limosas en el borde Nor-Este. A mayor profundidad y exceptuando la «barra» o sector cercano al mar, se encuentra enterrada una antigua laguna. Los depósitos de «laguna» se encuentran a partir de diez (10) metros de profundidad y consisten en estratos alternados de arcilla plástica y fangos orgánicos, suelos sedimentarios blandos que usualmente producen gran amplificación sísmica. A profundidad variable y mayor a treinta (30) metros bajo el nivel del mar se encuentra el lecho rocoso del valle, lecho cuya forma, orientación y profundidad también tiene una gran influencia en la amplificación de la onda sísmica.

Una importante falla geológica («Marga-Marga») documentada primeramente por Grimme y Alvarez (1964) bisecta el plan de Viña entre El Salto y el Muelle Vergara. Esta investigación confirma la existencia de esta falla geológica y su actividad causante de daños sísmicos típicos. Daños severos en edificios altos durante el terremoto de 1985 atribuidos a la ubicación de estructuras sobre un antiguo brazo del Estero de Viña del Mar, pueden realmente haber sido causados por haber sido construidas sobre la falla geológica del Marga-Marga. El patrón de comportamiento lineal de daños registrados durante el terremoto histórico del año 1906 indica que la falla geológica puede haber causado una gran amplificación sísmica en sus vecindades aún sin estar activa (lo que es usual en fallas) y/o que inclusive podría haberse activado.

Una planificación a largo plazo en Viña del Mar debiera tomar en cuenta la presencia de esta falla geológica y la variación de la estratigrafía de los depósitos sedimentarios del valle o plan de la ciudad. Por ejemplo la destrucción de la ciudad de Kobe en Japón durante el terremoto de 1995 se debió a amplificación dinámica de sedimentos blandos situados sobre una falla geológica superficial del tipo «strike-slip», y la destrucción localizada durante los terremotos de Loma Prieta (California, USA, 1989) y de la ciudad de México (1985) también se debió a amplificación dinámica del sismo causada por estratos o depósitos de arcillas, lodos y fangos sedimentarios estuariales y lacustres.

INTRODUCTION

The central sector of «Plan de Viña,» historically known as Poblacion Vergara, was completely destroyed during the 1906 earthquake, and was heavily damaged during the 1985 earthquake (Figures 1 and 2). In contrast the adjacent uplands, which are underlain by granitic and metamorphic rocks, were relatively undamaged. As early as 1915, Ballore (p. 16) recognized that the poor soil performance of Plan de Viña, which included partial liquefaction, was due to the amplification of seismic waves by subsurface soils. «Los effectos producidos en el terremoto fuemos solo la consequencia de la propagación del moviminento sismico en suelos aluviones sueltos e incoherentes, ya sea que se trate de greitas, de derrumbes a de craterlets con eyecciónes de agua, barro y arena.» More recently, Saragoni et al (1986) Celebi (1986), and Aguirre et al. (1896) have analyzed the strong ground motion associated with the 1985 earthquake and its aftershock sequence. They demonstrate that, in addition to material amplification in the soils, the sedimentary basin itself alters the incoming seismic signal by amplifying ground accelerations, by extending the duration of shaking, and by adding a long-period harmonic.

There is, however, a third problem associated with the earthquake hazard of Plan de Viña, one first recognized by Grimme and Alvarez in 1964. They mapped an active Quaternary fault in the lower canyon of the Estero Marga-Marga, called the «Falla Marga-Marga»one whose surface trace bisects Plan de Viña between El Salto and the Muelle Vergara. This study corroborates the existence of this recent fault, demonstrates that damage is consistently concentrated above its trace, and explores the physical mechanisms - wave guide, rupture, sediment thickness, etc. — responsible for localizing the damage.

This study was part of a broader investigation funded by the Bilateral Fulbright Comission between the Republic of Chile and the United States of America that was designed to explore how geology can contribute to engineering practice and to regional-municipal planning. The project was hosted by the Servicio Nacional de Geologia y Mineria in Santiago, but was physically located in, and financially supported by, the Department of Civil Engineering at the Universidad Tecnica Federico Santa Maria in Valparaíso. This report concerns itself only with the engineering geology of «Plan de Viña» the flat estuarine plain on which much of the population of the city lives and works. A bibliography and illustrations are grouped at the back of the report. Additional information related to the broader investigation is contained in a file held in the library at the Universidad Tecnica Federico Santa Maria.

Geology in Chile has traditionally been associated with the mining industry. In the academic sector, it has concentrated on fundamental tectonic processes associated with the Andean continental margin. The geology of unconsolidated materials has generally focussed on problems involving slope stability and groundwater resources. And, of course, geological research in Chile has been overwhelmingly concentrated in Santiago where the faculty, government positions, laboratory facilities, and reference materials are located. It is hoped that this report will illustrate the value of surficial geology in applied earthquake studies, and will enhance the visibility of geology in the coastal zone of central Chile.I am grateful for the support of the faculty and professional staff of the Universidad Tecnica Federico Santa Maria, especially to Prof. Migel Petersen, who arranged my appointment, provided access to unpublished materials, and helped focus my efforts where they would be most useful. Importantly, Miguel withheld hisown conclusions about the soilsbelow Plan de Viña

and the Marga-Marga fault until this project was completed, allowing us to reach the same conclusions independently. Other faculty at UTFSM, especially Carlos Aguirre, Patricio Bonelli, Raul Galindo, Gilberto Leiva, Ludwig Stowas, and René Tobar also contributed their support and their ideas.

Faculty and professional staff from other Chilean universities also shared their facilities and ideas, especially at the University of Chile (Francisco Munizaga, Francisco Hervé, Edgar Kausel, Emilio Lorca, and Rudolfo Saragoni), University Pontifica Catolica de Santiago (Eduardo Palma), University Catolica de Valparaíso (Luis Alvarez, Manuel Cerda, Maria E.Portal M.), University of Valparaíso (Adrian Palacios), and University Austral de Chile (Pedro Contreras). I am also grateful to the Servicio Nacional de Geologia y Mineria, especially to Constantino Mpodozis, who supported my Fulbright application, to Arturo Hauser, my principal contact and advisor, and to Estanislaus Godoy, Mariela Ferrada C., and Lucia Cuitina who were especially helpful. Support from the Instituto Hidrafico de la Armada de Chile is gratefully acknowledged; Lt. Commander Nunez, Juan Fiero, and Rienaldo Adulante helped provide access to tidal data and to the Molo de Abrigo. Patrick Caldwell from the University of Hawaii helped with its analysis. Jorge Jimenez and Fanor Larrain, from the Fulbright Commission, provided indispensible logistical and educational support. I am grateful to the people of Chile, «da gente» for assisting me in my field research, most of which was carried out using public transportation, and on private property. Luis Chirino helped me as a friend during my stay.

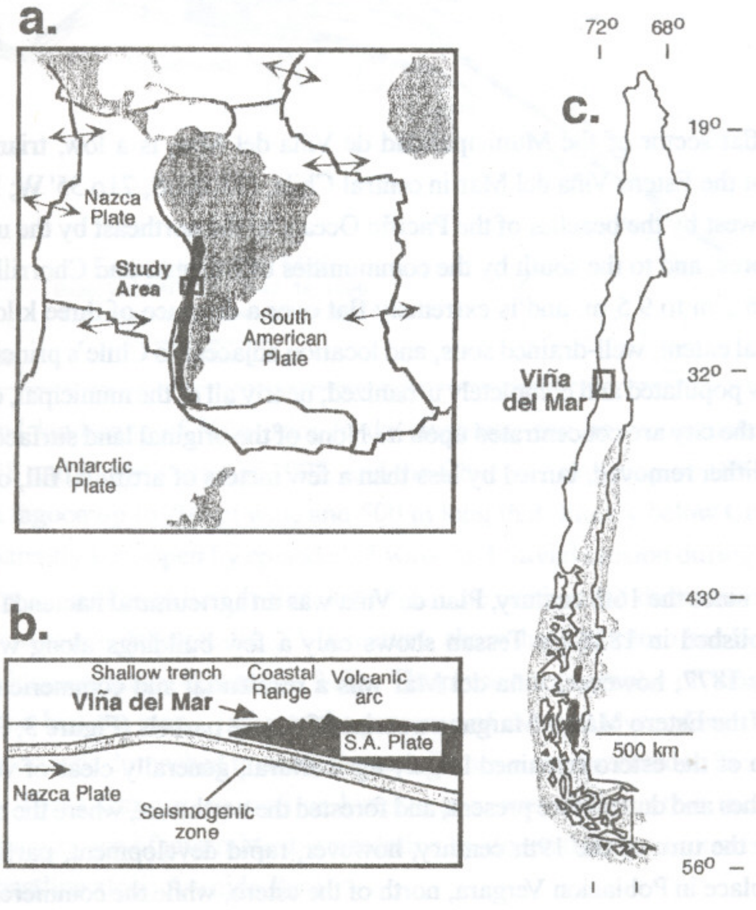


Figura 1

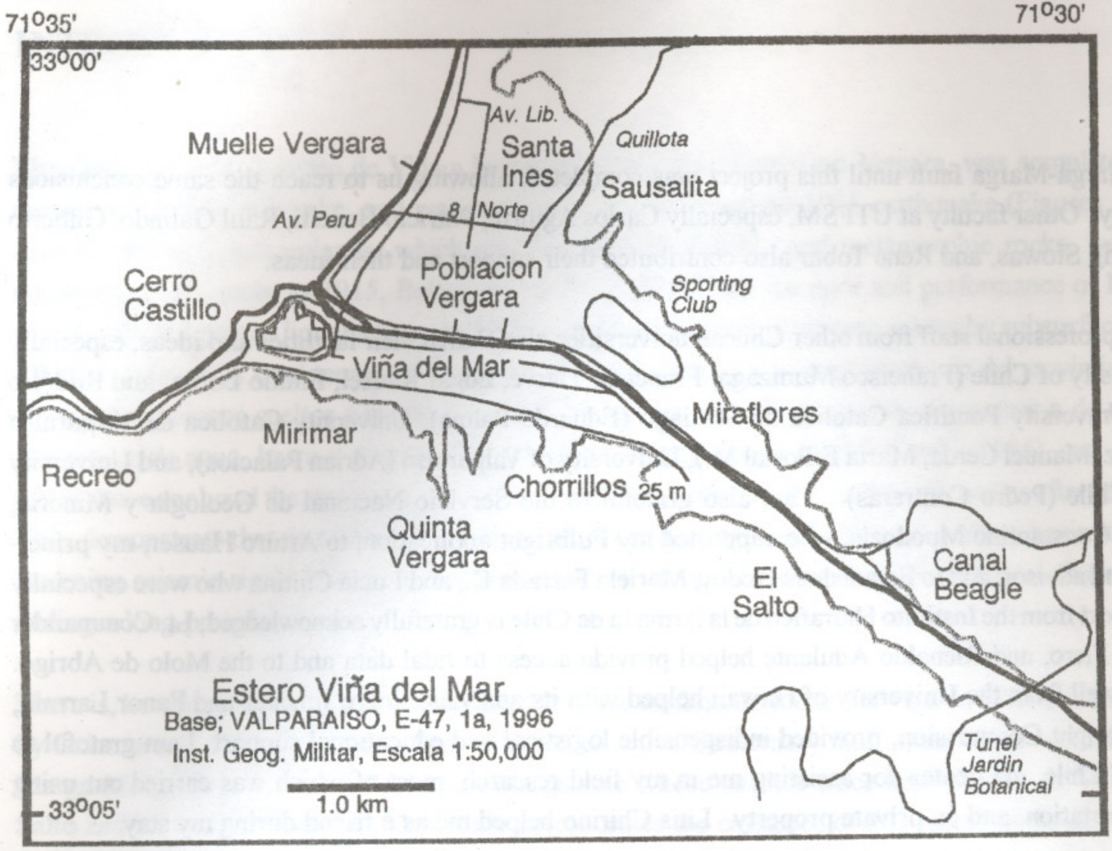


Figura 2

SETTING

«Plan de Viña,» the flat sector of the Municipalidad de Viña del Mar, is a low, triangular-shaped alluvial terrace at the mouth of the Estero Viña del Mar in central Chile, (33.00oS, 71o 35' W; Figures 1 and 2). It is bordered on the northwest by the beaches of the Pacific Ocean, to the northeast by the upland communities of Sausalita and Miraflores, and to the south by the communities of Mirimar and Chorrillos. This plain ranges in elevation between 6.5 m to 9.5 m, and is extremely flat over a distance of three kilometers. Owing to its attractive setting, aerial extent, well-drained soils, and location adjacent to Chile's principal port (Valparaíso), Plan de Viña is densely populated and completely urbanized; nearly all of the municipal, commercial, financial, and service sectors of the city are concentrated upon it. None of the original land surface remains; everywhere the original soils are either removed, buried by less than a few meters of artificial fill, or covered by concrete and buildings.

For most of its history since the 16th century, Plan de Viña was an agricultural hacienda. The earliest detailed government map, published in 1838 by Tessan shows only a few buildings along what is now known as Avenida Quillota. By 1877, however, Viña del Mar was a residential and commerical community laid out along the south side of the Estero Marga Marga in a series of square parcels (Figure 3; Pomar, 1877). At that time, land to the north of the estero remained largely agricultural, generally clear of vegetation towards the northwest, where beaches and dunes were present, and forested the northwest, where the drainage was inhibited by loamy soils. Near the turn of the 19th century, however, rapid development, particularly for houses or «chalets» was taking place in Poblacion Vergara, north of the estero, while the commercial sector south of the estero intensified. By 1910, the estero had been artificially confined to its present course, and urban development proceeded rapidly to the present. What is presently called the Estero Viña del Mar (Inst. Geog. Militar, 1996) has traditionally been called the Estero Marga-Marga. Both names are used in this report. Additionally, the Inst. Geog. Militar uses the spelling «Margamarga.» This reports follows the traditional, rather than the new spelling convention.

Previous investigations of the geology of the sedimentary fill of Viña del Mar are limited. Ballore (1915) described the alluvial soils of Viña in general terms, contrasting them with the collivial (maicillo) soils around the edge of the basin (colluvium), and the fundamental rocks of the upland. The definitive source of information is a report by Grimme and Alvarez (1964), which correctly described Plan de Viña as a sediment-filled

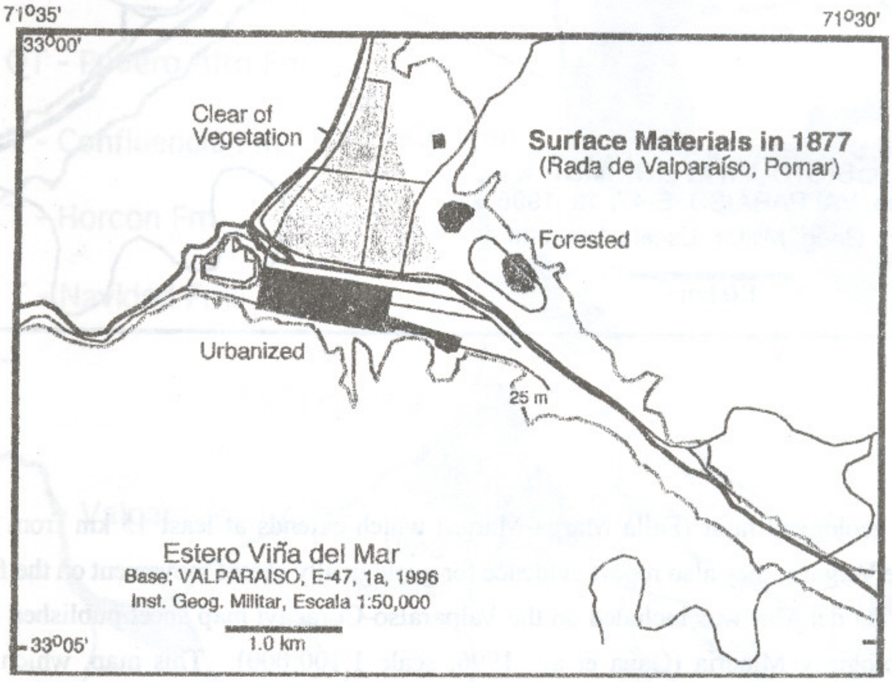


Figura 3

The original soils and landscape of Viña prior to development, can be reconstucted using historic maps. Tessan's map of 1838 and Kraus's map of 1903, and the Chilean Army map of 1891, clearly show that the estero emptied into a lagoon up to 200 m wide and 500 m long that directly below Cerro Castillo (Figure 4). This lagoon was apparently kept open by episodes of wave and fluvial erosion during severe storms, but was intermittently filled by spits of sand that drifted down from the north in the direction of prevailing long-shore drift. The most ancient maps, dating to the XVII century, show that the estero has been locked in its present position since Spanish colonization (Larrain, 1947). The present topography of Viña, as well as the pattern of vegetation shown on historic maps, indicate the presence of a broad levee along the northern bank of the estero, one whose importance diminshed towards the sea. Dunes were restricted to the northwest, immediately behind the beaches. These features, as well as historic accounts, indicate that the very recent geological history of Plan de Viña was one of intermittent innundation by floods during temporals, and by fluctuations in the position of the coastline along Avenida Peru.

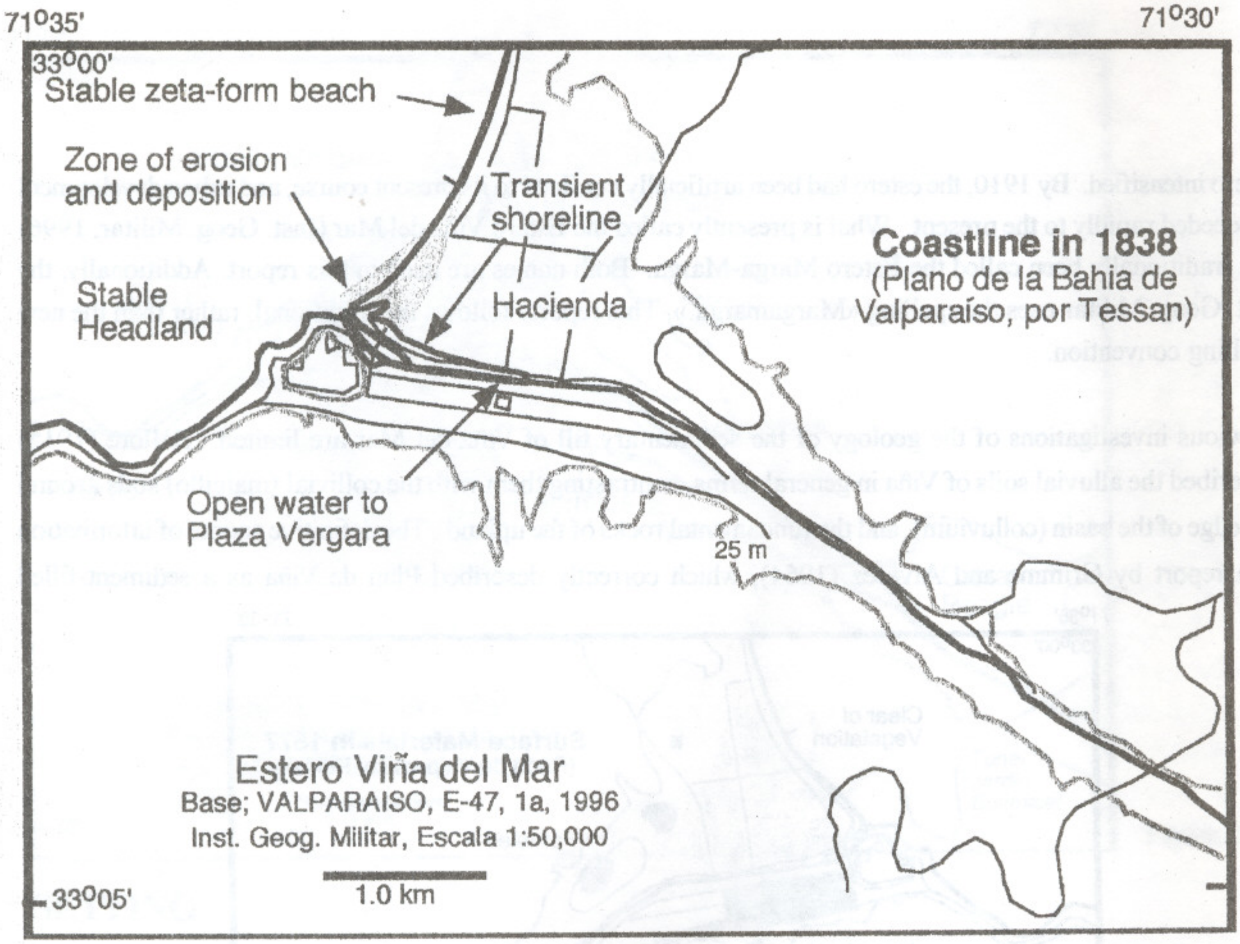


Figura 4

estuary above a geological fault (Falla Marga-Marga) which extends at least 15 km from the Estero Las Palmas to Muelle Vergara; they also report evidence for geologically recent movement on the fault (Figure 5). More recently, Viña del Mar was included on the Valparaíso-Curacavi map sheet published by the Servicio Nacional de Geologia y Mineria (Gana et al., 1996, scale 1:100,000). This map, which was primarily concerned with bedrock units, shows the trace of the Marga-Marga fault as lying just south of the estero, and did not extrapolate its trace beneath Plan de Viña. Both of these government maps portray the surface of Plan de Viña as a single, equivalent geological unit, Qm, the «sedimentos marinos» of Gana et al. (1996) and Qp, the arena y grava de playa» of Grimme and Alvarez (1964). This report differentiates this estuarine unit near the surface into three subunits. More importantly, it subdivides the estuarine fill into three different levels, each with its own material properties.

Ballore (1915), Barrientos (1991), and Compte et al., (1986) have reviewed the historical seismicity in the coastal zone near Valparaiso/Viña del Mar (Figure 6). Locally intense earthquakes responsible for minor damage occur approximately once every decade, with the 1997, 1981, 1971, and 1965 earthquakes being especially relevant in this report. The complete sequence of regionally damaging earthquakes (1575, 1647,

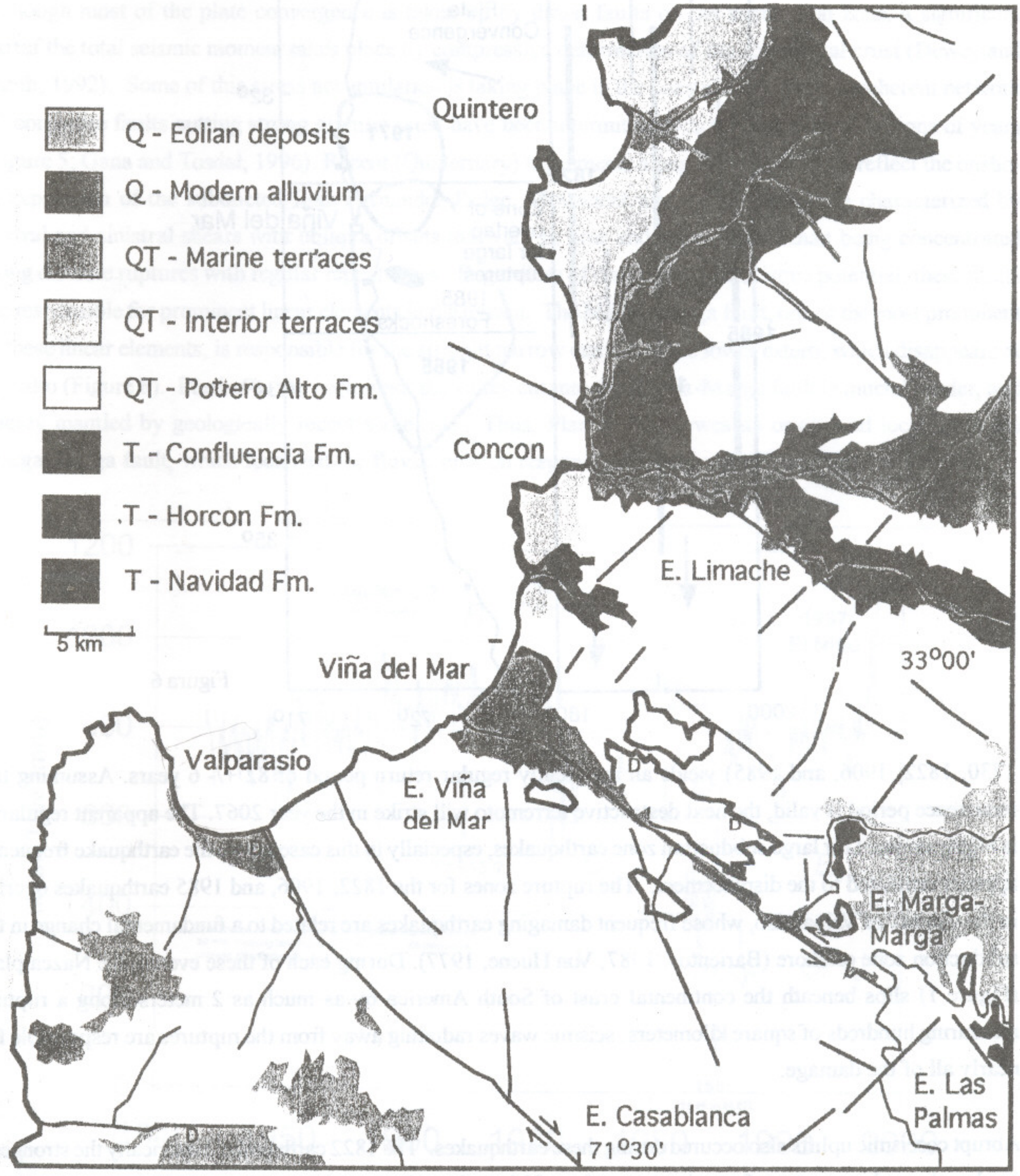

Q - Eolian deposits
Q - Modern alluvium
QT - Marine terraces
QT - Interior terraces
QT - Potrero Alto Fm.
T - Confluencia Fm.
T - Horcon Fm.
T - Navidad Fm.
5 km
Quintero
Concon
E. Limache
Viña del Mar
33°00'
Valparasío
E. Viña del Mar
D
D
D
D
E. Marga-Marga
E. Las Palmas
E. Casablanca
71°30'

Figura 5

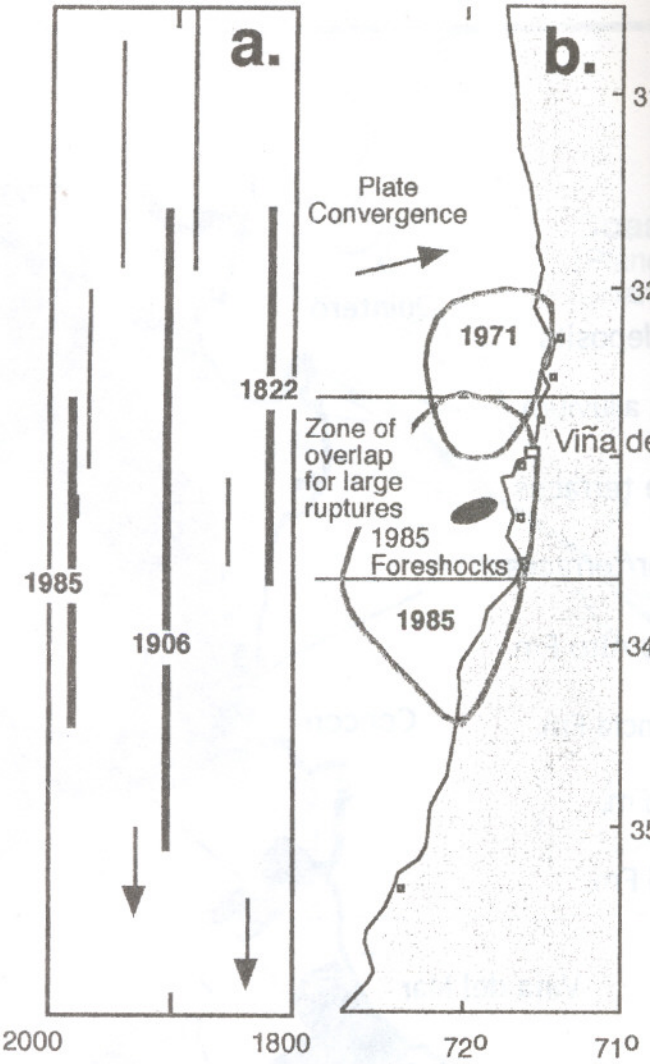
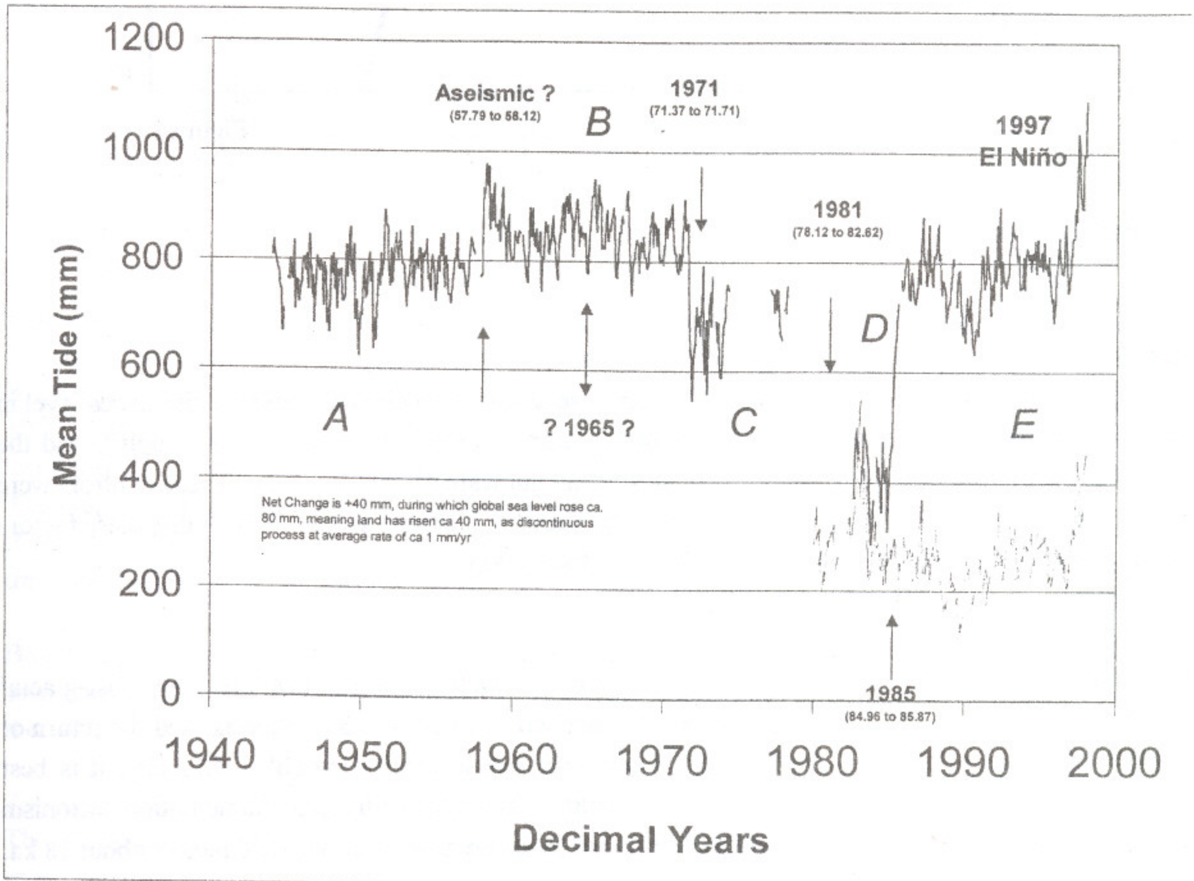


Figura 6

1730, 1822, 1906, and 1985) yields an apparently regular return period of 82 +/- 6 years. Assuming this recurrence period is valid, the next destructive terremoto will strike in the year 2067. The apparent regularity is highly unusual for large subduction zone earthquakes, especially in this case where the earthquake frequency appears unrelated to the displacement. The rupture zones for the 1822, 1906, and 1985 earthquakes overlap in the vicinity of Valparaíso, whose frequent damaging earthquakes are related to a fundamental change in the subduction zone offshore (Barientos, 1987, Von Huene, 1977). During each of these events, the Nazca plate (Figure 1) slips beneath the continental crust of South America by as much as 2 meters along a rupture measuring hundreds of square kilometers; seismic waves radiating away from the ruptures are responsible for nearly all of the damage.

Abrupt coseismic uplifts also occured during these earthquakes. The 1822 earthquake, historically the strongest, produced nearly a meter of coseismic uplift at Valparaíso (Carlos Marquardt, personal communication, referencing Lavenu et al., in press). Ballore (1915) who examined the shoreline and interviewed residents shortly after the 1906 earthquake, reported a regional uplift reaching a maximum of approximately 60 cm between Concon and Valparaíso. During the 1985 earthquake, in contrast, there was not net vertical change of the outer coast (Compte et al., 1986). Instead, the local tidal station on the Molo de Abrigo in Valparaíso subsided by nearly 35 cm (Figure 7).

Although most of the plate convergence is taken up by thrust faults on the subduction zone, a significant partof the total seismic moment takes place by compressive deformation of the continental crust (Dewey and Lamb, 1992). Some of this stress accumulation is taking place in the coastal zone where a coherent network of conjugate faults cutting strong granitic crust have been intermittently active for tens of millions of years (Figure 5; Gana and Tosdal, 1996). Recent (Quaternary) movements along these faults may reflect the onshore expression of the subducted Juan Fernandez Ridge. Movement along these faults are characterized by dextral and sinistral shears with oblique offsets that vary in time and space, rather than being concentrated along discrete ruptures with regular repeat times. Regardless of their cause and seismic potential, these faults are responsible for prominent linear elements in the terrain. The Marga-Marga fault, one of the most prominent of these linear elements, is responsible for the straight narrow canyon of the lower estero, which disappears at El Salto (Figure 8). Further to the northwest, the valley cut into the Marga-Marga fault is much broader, and thickly mantled by geologically recent sediments. Thus, Plan de Viña owes its origin and location to the Marga-Marga fault, which localized the fluvial erosion responsible for the valley.



Net Change is +40 mm, during which global sea level rose ca. 80 mm, meaning land has risen ca 40 mm, as discontinuous process at average rate of ca 1 mm/yr

Figura 7

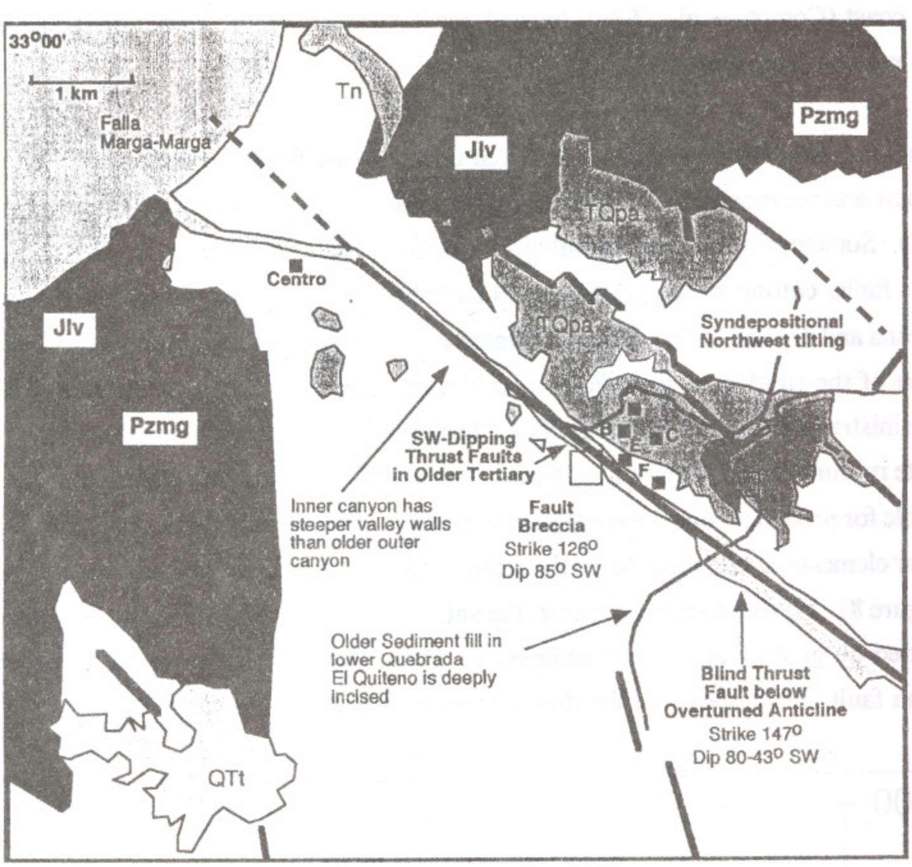


Figura 8

STRATIGRAPHY

Fundamental Controls

The sediment fill beneath Plan de Viña developed in reponse to three principal factors: the rise in sea level in response to global deglacation during the last 18,000 years; the relatively steady tectonic uplift, and the supply of sediments to the estuary from the coast and the inland watershed (Figure 9). These controls were not unique to Viña del Mar or to the central chilean coast, but were global in scope. Essentially, these factors constrained how the sedimentary fill in Plan de Viña had to develop.

Global Sea level

Global sea level has risen approximately 120 meters since 18,000 years ago (18 ka). This post-glacial transgression was caused by the melting of northern hemisphere, mmid-latitude ice sheets, and the return of the meltwater to the global ocean. The history of sea level rise is locally variable. Globally, it is best constrained in Barbados, an area relatively free of complexities associated with rapid sedimentation, tectonism and age-dating (Fairbanks, 1989). Sea level reached its minimum elvation of about -120 meters about 18 ka. After an interval of slow transgression, sea level rose rapidly from about -100 to -15 meters between about 13 ka and 8 ka, as the bulk of the ice sheets melted. Global sea level has risen only slowly since that time, except for a recent accleration associated with the present global warming.

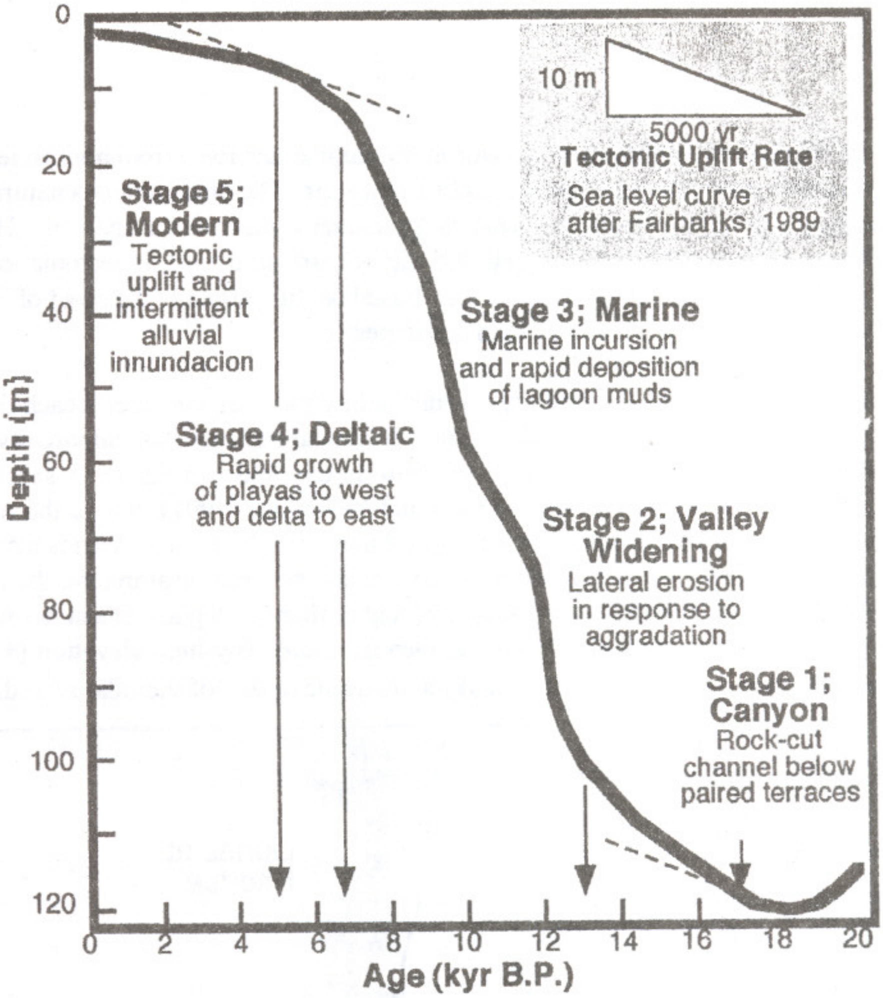


Figura 9

Bathymetric features on the continental shelf just north of Viña del Mar indicate that this reconstruction applies to the central Chilean coast (Figure 10). In front of the Aconcagua River, the -100 meter contour line is straightened and locally eroded in a manner consistent with beach erosion at that depth (Armada de Chile, 1965). The -50 meter contour line clearly shows the presence of an enormous alluvial fan that was submerged too rapidly to be significantly eroded (this was the time of maximum rise of sea level about 10,000 yr BP). The presence of a straight ragged coastline at the -20 m contour, a canyon below Concon near that elevation (Caviedes, 1972), and the dunes of Ritoque all indicate that the postglacial transgression had slowed by the time sea level had reached this elevation.

Based on these relationships, Plan de Viña at 18 ka would have been the site of a deep valley cut into an older sedimentary fill above the Marga-Marga fault. The site would have been submerged as sea level rose rapidly, then filled with sediment as the rate of sea level rise decellerated.

Tectonic Uplift

The Chilean coast has experienced uplift throughout its recent geological history. The rate of uplift variesin space and time, and is only poorly dated. The most direct, but short-term constraint on the average uplift rate is from the tidal record on the Molo de Abrigo in Valparaíso (Figure 7). During the interval spanned by the tidal record (1943-1998) global sea level has risen approximately 80 millimeters at a variable rate averaging about 2 mm/yr. Over the same interval, however, the tide at Valparaíso has risen from a mean level of about 800 mm, a rise of approximately 40 mm, or approximately 1 mm/year. The discontinuous nature of the tidal record, one segmented by frequent co-seismic movements, precludes a more exact analysis. However, the apparent 40 mm difference between the global signal and the Valparaíso record, is tectonic in origin, and reflects the integrated history of specific co-seismic events. Based on this estimate, the coast of Valparaíso is presently rising relative to the sea by at a rate less than 1 mm per year.

A comparable tectonic uplift rate (0.3 to 0.5 mm/yr) is indicated by radiocarbon-dated beach deposits near Coquimbo (Isla, 1989; Ota and Paskoff, 1993). There, the postglacial transgression apparently culminated about 6 ka; since that time, beaches have prograded seaward as the land has risen. A similar rate was obtained at Caleta Michilla in northern Chile by Leonard and Wehmiller (1991), where the transgression peaked at about 6.2 ka, leaving behind a coastal terrace about 2 meters high. Plan de Viña is also an uplifted marine terrace; away from the estero, where the surface is only thinly covered by alluvium, the its surface is generally 8.5 to 9.5 m above sea level datum, several meters higher than the highest storm berm. If Plan de Viña also emerged from the sea beginning about 6-7 ka, then its anamously high elevation (+2-3 m) also would yield a short-term tectonic uplift rate of <1 mm/yr, comparable to that of the tidal record.

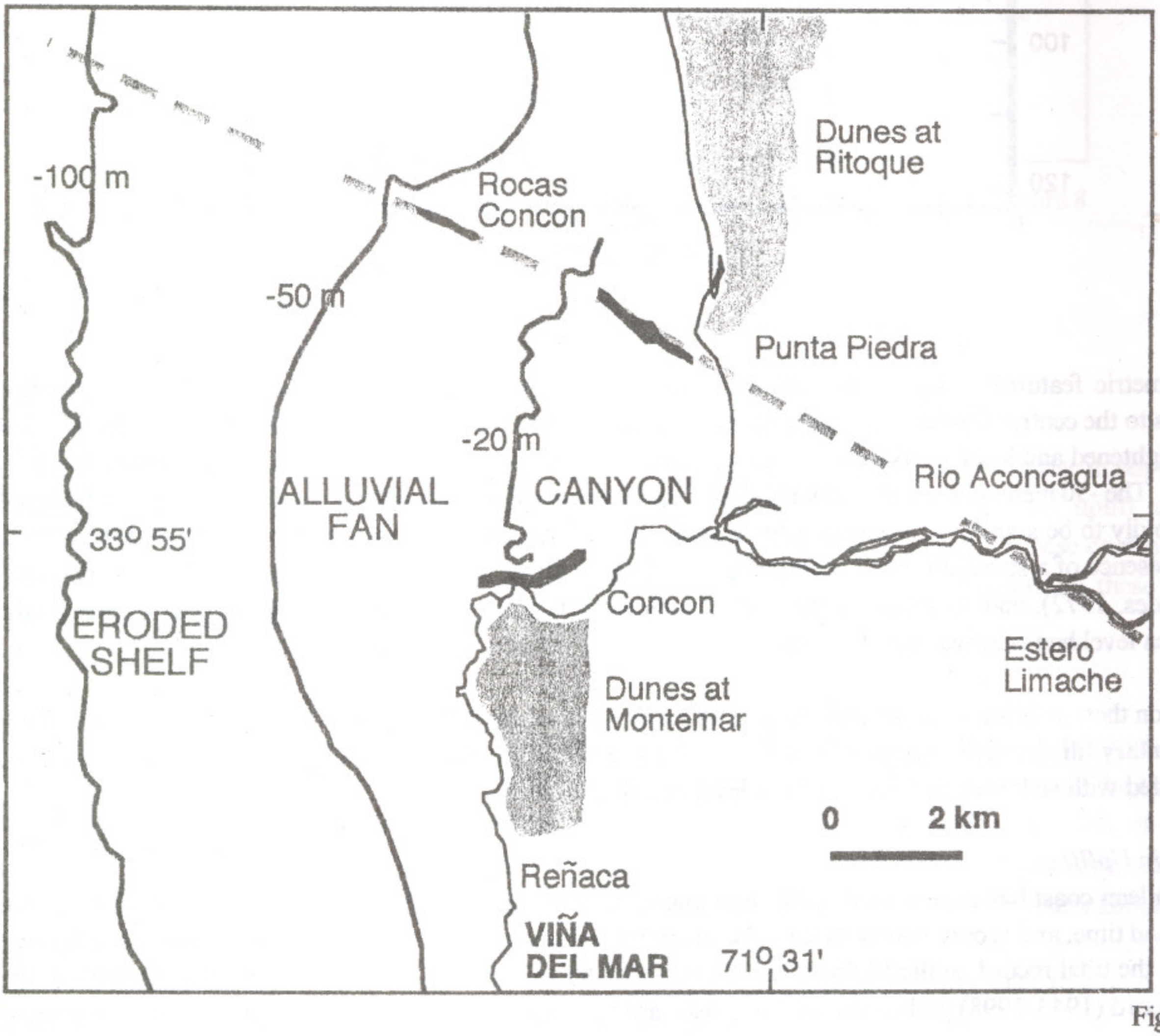


Figura 10

A longer-term constraint on the rate of uplift can be achieved by assuming that the prominent low terrace in the Viña-Valparaíso area (Figure 11; Playa Ancha, U. Santa Maria, Recreo, Cerro Castillo, Sausalito, etc) correlates to the prominent low terrace found to the north, where it is dated by amino acid techniques (Leonard and Wehmiller, 1991) and by correlation (Isla, 1989) to about 125 ka. This surface, which averages about 40-60 m above sea level near Viña, if of equivalent age, would yield an uplift rate of 0.4 to 0.5 mm/yr. This correlation and uplift rate are supported by even longer-term (millions of years) studies of uplifted marine terraces (Paskoff, 1970; Grimme and Alvarez, 1964), sediment balance (Kiefer et al., 1997), and rock exhumation (Kurtz et al., 1997).

Sediment Flux

The Mediterranean climate of central Chile is governed principally by the annual variation in insolation characteristic of mid latitudes, and by its geographic location relative to two largely stationary currents, one in the ocean called the Humboldt Current, which brings cold, subantarctic waters to mid latitude, and one in the atmosphere, called the Southwestern Pacific Anticyclone, which brings air northward for most of the year. The persistent pattern of winds from the southwest ensures a prolonged dry summer and wave climate dominated by a persistent littoral climate with of waves directed towards the north-northeast.

Early in the postglacial transgression, the shoreline lay significantly west of Viña del Mar. When the sea penetrated far enough inland, however, the once-continuous beach was broken up into a series of «pocket» beaches in which the sand was trapped between bordering headlands. Each headland created a zone of flow separation in its northeastern quadrant and intensified wave refraction. Both effects are responsible for creating a southward drift of sand north of bedrock headlands. Historically, this countercurrent was responsible for building sand spits across the estuary from the north, and is also responsible for maintaining the present bar at the mouth of the estero.

In the upland watershed of the Estero Marga-Marga there is enough annual moisture to thoroughly wet the surface soils, leaching the granitic bedrock, and producing a thick mantle of maicillo. Period drought conditions, however, ensure a sparse vegetation cover. Between major storms, sand liberated by weathering collects in stream beds through the processes of dry ravel, small debris flows, and small alluvial fans from quebradas and gullies, in a process very similar to those operating in California USA (Muhs et al., 1987). During severe storms, however, it is flushed toward the coast by traction in the stream bed. The Estero Marga Marga, which flows all year between great extremes in flow, is particularly volatile owing to its relatively large size, steep slopes, and short concentration time.

Wetter conditions during the peak of the last glacial maximum (16-24 ka; Portal, 1993; Veit, 1996) would have been associated with both increased weathering as well as increased sediment retention by vegetation. Thus, the postglacial transition was likely a time of increased sediment flux into the Estero Viña del Mar, as its upland watershed experienced gradual dessication. The details of climate change and their influence on the sediment flux are largely unknown.

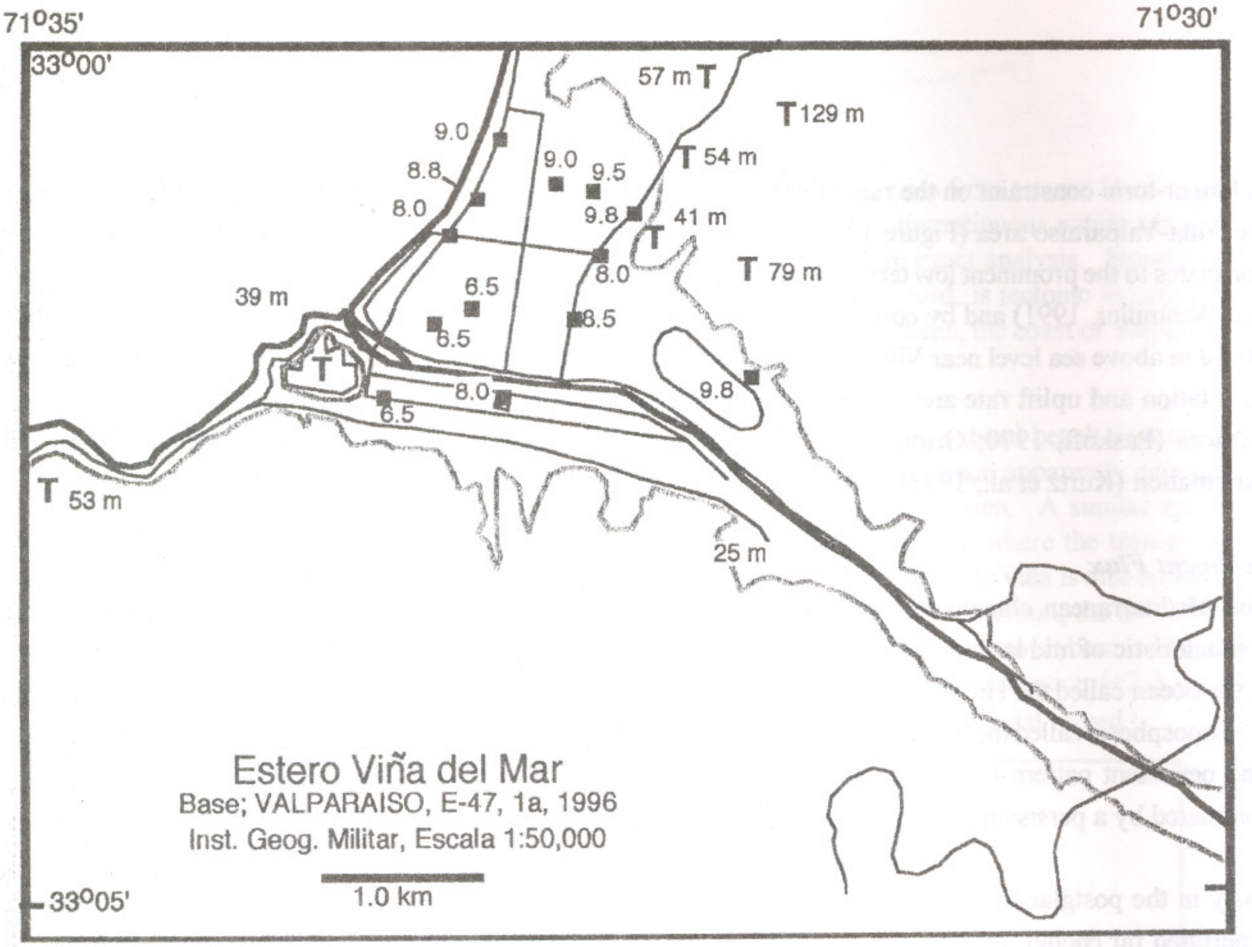


Figura 11

Observed Stratigraphy

The stratigraphy of Plan de Viña is based on four separate sources of information (Figure 12). Most important is a series of eight borehole up to 38 m deep contined in Appendix 1 of Grimme and Alvarez (1964). Two deep borehole logs were provided by Miguel Petersen, one of which (MS-4) is the only core inland of the estuary. A variety of borehole logs, most of which were shallower than 8 meters, were reported by Luengo (1986); they help constrain the stratigraphy near the surface (Figure 13). Finally, a deep excavation centered at 14 Norte and 1 Oriente provided an opportunity to examine the sediments directly, although only at a distance. These data are summarize in Figure 14, which contains a schematic section of the borehole logs drawn parallel to the estero. Depths below the surface reported in the borehole logs were converted to the altitude above and below mean sea levels using data from the GIS system.

The northwestern and southeastern ends of the depositional basin are illustrated by Cores A-13, and MV-4, respectively. Core A-13, located beneath Avenida San Martin at the northwestern end of the sedimentary basin, is dominated by cleanly-washed sand (most of which is well sorted or poorly graded). This core is similar to MS-19, which contains a better description, and is also consistent with the stratigraphy at locality TH-1, in which accretionary strata of beach sand outcrop above unweathered, wave-eroded bedrock. Lluengo (1986) also interprets these sediments as beach sands, which extend to a depth to at least -22 m.

Beyond the southeastern limit of the sedimentary basin is Core MV-4, which is located in the Canyon of the Marga-Marga. It shows three major units. At the top is about seven meters of maicillo-derived, micaceous, sandy alluvium deposited by the Estero, which contains minor amounts of silt and fine sand. This modern fluvial unit overlies a prominent interbedded sequence nearly 25 meters thick dominated by sand and finegravel, and in which silty woody horizons occur repeatedly at a spacing between 0.5 and 2.0 m. The origin of the woody horizons is not clear from the descriptions, but the regularity of the sequence suggests that they represent punctuated changes on the surface of an aggrading delta. Since the postglacial transgression was not punctuated by abrupt steps, the abrupt reversals from woody to non-woody horizons likely represent discrete co-seismic events. This is weak, but direct, evidence that regular earthquakes and coseismic uplifts of today are part of a long-term pattern. At the base of the core is maicillo, which extends to an elevation of about 21 m below sea level. Because this core was taken directly in the center of the valley, the maicillo probably represents the depth to which the valley was cut during full-glacial time.

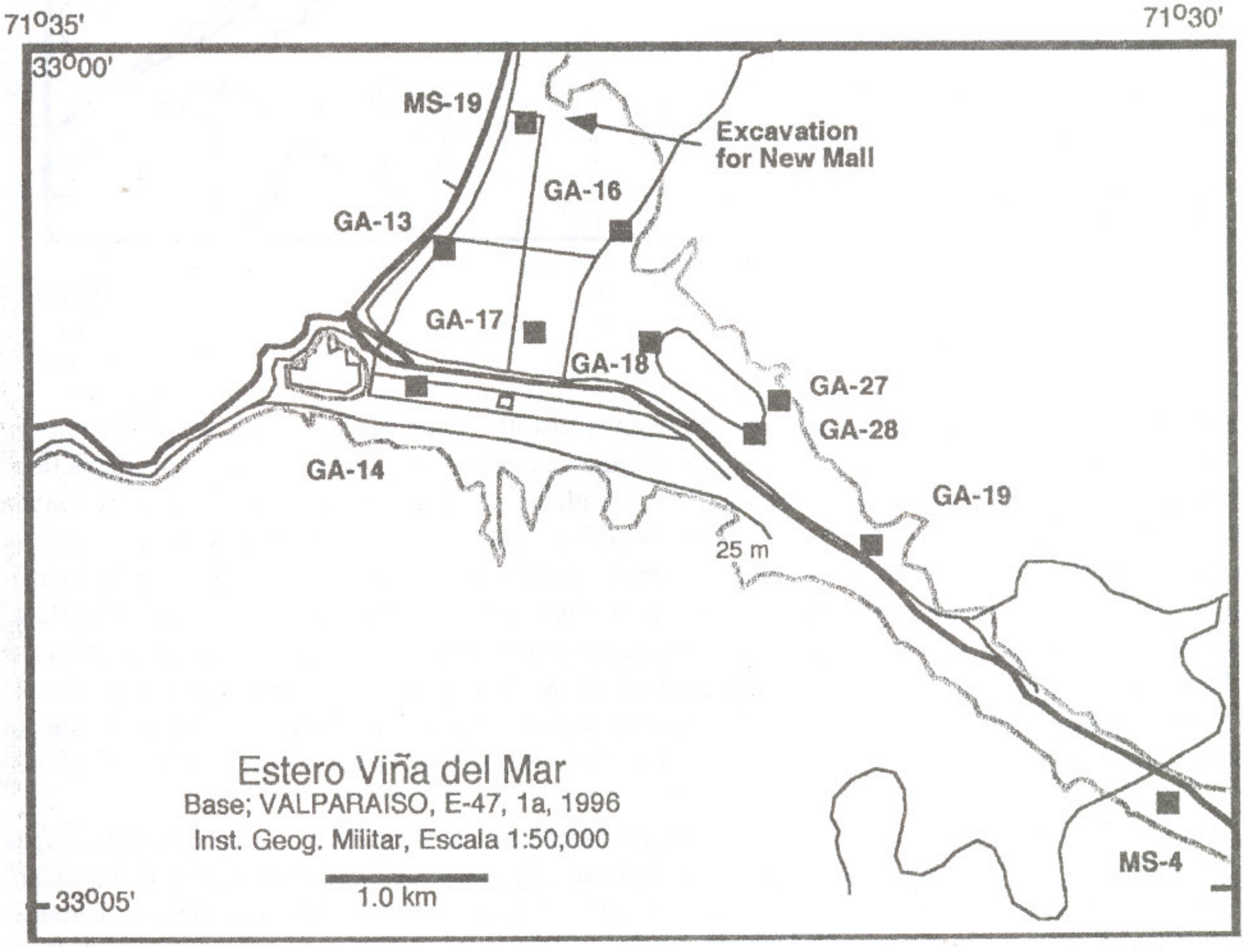


Figura 12

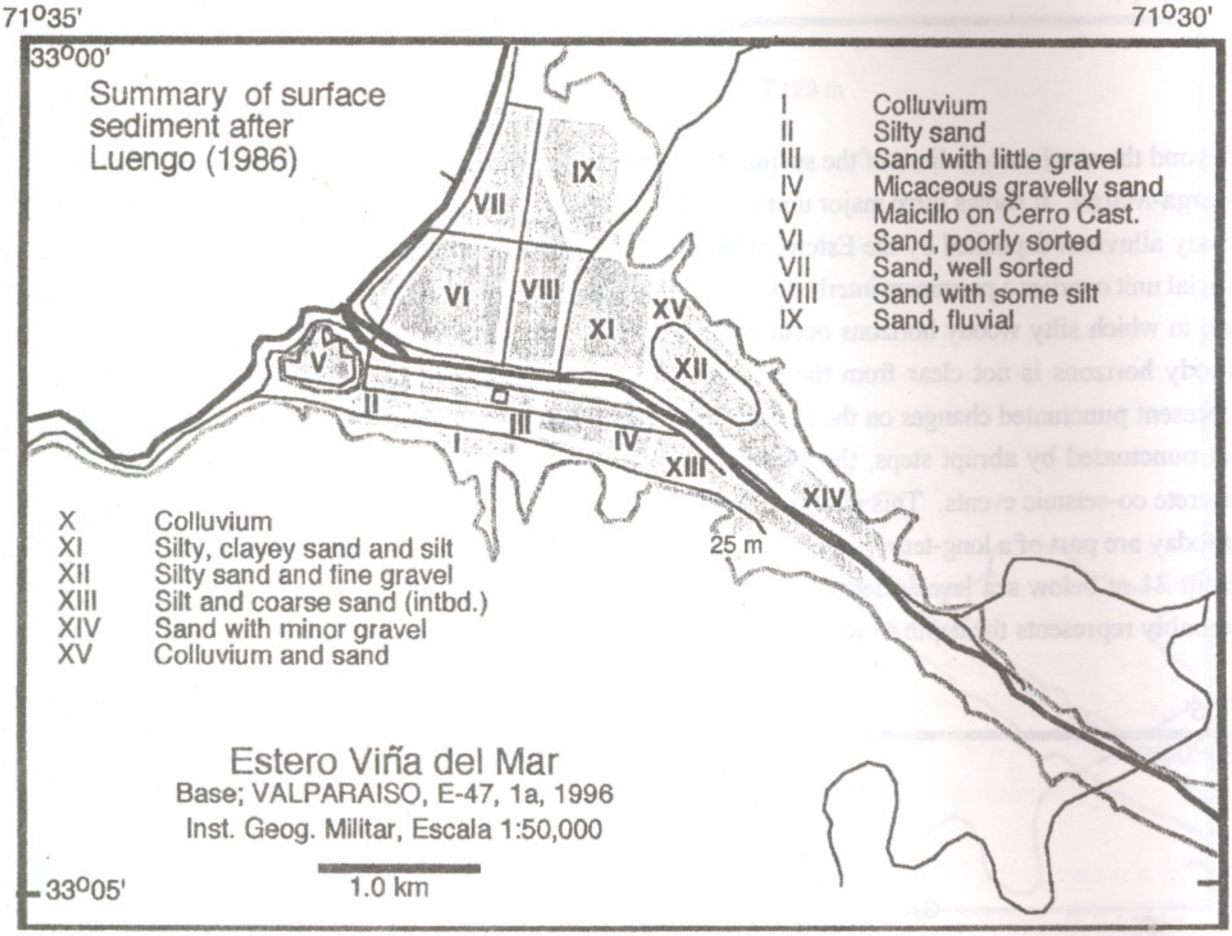


Figura 13

The stratigraphy in the center of the sedimentary basin is best illustrated by Core A-28, which shows three major units. At the top is nearly 5 m of silt, clayey silt, and fine sand in beds laid down during overbank flood events of the estero. These strata are clearly associated with the modern alluvial surface because the contain historic artifacts, and lie immediately below the artificial fill. This floodplain sediment overlie 12 meters of coarser, sandy fluvial deposits free of organic material whose lithology indicates derivation from the Marga-Marga. At greater depth, the coarse alluvial deposits overlie a minimum of 16 meters of dark gray to black, sandy muds containing lenses and beds of clay, silt, fango, vegetation fragments, and the remains of marine mollusks. These features indicate deposition in a quiet-water, generally anoxic, marine embayment characterized by high biological productivity and into which sediments accumulated rapidly. Fango is now accumuating in closed depressions in the Mar de Chile in front of Viña del Mar (Kraus, 1903), but only at a depth below 30 m.

This lagoon deposit, defined by the presence of marine shells and dark, sulfurous smell («putrefacto») is present in every core between GA-13 and MS-4, which mark the marine and terrestrial limits of the lagoon, respectively. Decomposition of the organic remains in still underway, as indicated by the pervasive «marshy» smell released during excavations. Importantly, the top of the unit containing fango or concha shells is consistently between -9 and -12 m below sea level, which is now approximately 16 m to 20 m below the ground surface. Based on global sea curves, this depth corresponds approximately to a time of about 6-8 ka, a time when the transgression began its abrupt decelleration.

At this depth, the estuarine muds are bracketed between beach sediments to the northwest and delta alluvium to the southeast. These bracketing depositional environment, the properties of the sediment (fango, clay, marine fossils) and the age, clearly indicate deposition in a lagoon between a sand bar (spit) to the northwest and a freshwater-delta to the east. Eventually, the lagoon sediments were buried by marine sands from the west and alluvium from the southeast. This contact is highest in the middle of the basin (A-28) an observation consistent with a lagoon filling from both ends simultaneously as the rise in sea level slowed down.

The maximum depth of the lagoon sediments is poorly constrained. To the east, core VM-4 terminated in maicillo at a depth of about -22 m. This likely marks the bottom of the bedrock valley at this site, approximately10 km inland from the coast. At cores GA-18 and GA-14, the marine muds overlie a hard, dark, partly cemented later interpreted by Grimme and Alvarez as a possible paleosol. The conformity in elevation of these two deposits supports this interpretation that a former valley fill was downcut during the last glaciation. In the center of the valley, the lagoon sediments may exceed 30-40 m in thickness.

Stratigraphic Model

The stratigraphy observed in Plan de Viña is consistent with the external constraints involving global sea level, tectonic uplift, and sedimentation rate. Five stages, can be recognized, and their ages correlated with reference to sea level history (Figures 15 and 9). Stage boundaries represent thresholds during which the direction and/or rate of relative sea level changed dramatically.

Stage 1 - Canyon : There is no bathymetric evidence for a deep submarine canyon or a broad alluvial fan on the continental shelf fronting Viña, which would have been about 11 km wide. Additionally, this interval was likely a time of increased sediment retention in the upper watershed. During the fall of sea level at least 100 m, the Estero Viña del Mar would have entrenched its channel well below the -22 m indicated by the base of the deepest core. The modern gradient of the Estero Marga-Marga is relatively uniform at about 0.0026 (2.6 m/km), and is governed by the slope required to transport its sandy bedload. Assuming the same gradient across the continental shelf, approximately 30 m of gradient would have been required simply to transport similar maicillo-derived sand to the edge of the paleo-shelf. Using this constraint, and assuming a tectonic uplift of 10 meters since this interval, the Estero Marga-Marga probably cut its bed no deeper than about 80 meters at the western edge of Plan de Viña. A minimum depth for incision can be obtained using the same gradient, but projecting it downstream from the maicillo encountered at a depth of -21 m at MS-19. Using this technique, the bed of the Estero probably lies at a depth greater than -37 meters, about ten meters below the lowest core (A-13). These estimates are poorly constrained. If downcutting took place in the bedrock along the Marga-Marga fault, it is likely that the topography below a depth of about 50 meters would be a narrow notch, rather than a broad valley, one perhaps not unlike that of the present estero east of El Salto. Such a valley would be particularly well developed at the western edge of Plan de Viña where the fault crosses Avenida San Martin.

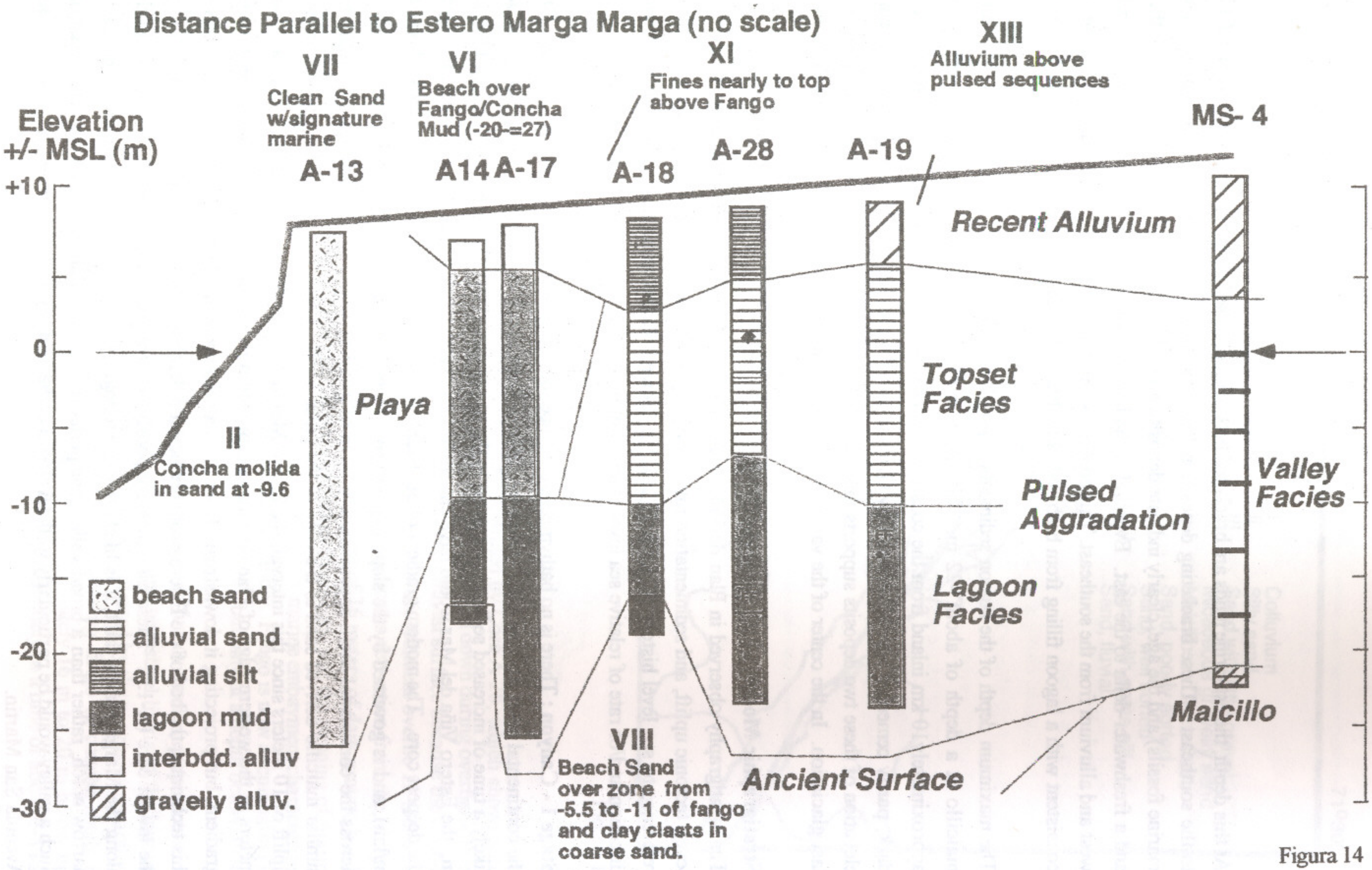

Distance Parallel to Estero Marga Marga (no scale)
Elevation +/- MSL (m)
+10
0
-10
-20
-30
VII
Clean Sand w/signature marine
VI
Beach over Fango/Concha Mud (-20-=27)
XI
Fines nearly to top above Fango
XIII
Alluvium above pulsed sequences
A-13
A14
A-17
A-18
A-28
A-19
MS- 4
Recent Alluvium
Playa
Topset Facies
Valley Facies
Pulsed Aggradation
Lagoon Facies
Maicillo
Ancient Surface
II
Concha molida in sand at -9.6
VIII
Beach Sand over zone from -5.5 to -11 of fango and clay clasts in coarse sand.
beach sand
alluvial sand
alluvial silt
lagoon mud
interbdd. alluv
gravelly alluv.

Figura 14

Stage 2 - Valley Widening : The period from about 18 ka to about 13 ka would have been a time when sea level rose gradually relative to the land. Under these conditions, sand-dominated alluvial rivers such as the Estero Marga-Marga aggrade their beds, especially if they are laterally confined. Under these circumstances the full-glacial valley, probably cut to bedrock, would have started to fill with sandy-sediment under subaerial conditions. The width of the arroyo cannot be predicted because there are no lateral constraints. The modern estero between El Salto and Tunel Jardin Botanica may be a modern analog.

Stage 3 - Marine: The interval from about 13 ka to about 7 ka coincides with the major climatic, oceanographic, and sea-level changes associated with deglaciation. Throughout the globe, sea level rosenearly 100 m in about 5,000 years, nearly ten times faster than today's rate of 2 mm/yr, flooding coastal estuaries. At the same time, the climate shift from full glacial to interglacial conditions in central Chile would have likely released a great flux of sediment into the Estero Marga Marga. Plan de Viña was completely submerged as the sea transgressed past Sporting Club. Sand from a delta at the head of the estuary and from the coast near Las Salinas, would have poured into the estuary, raising its bottom as sea level rise continued. Strata composed of of plastic clay within the marine sediments suggest that the embayment was deeper than the influence of waves and currents, and may represent brief reductions in the supply of sand.

Stage 4 - Deltaic: The interval from sometime between about 8 ka to 5 ka would have been one of transition. The transgression would have decellerated to approximately that of tectonic uplift, allowing time for longshore drift to create a conspicuous bar along the northwestern side of Plan de Viña, and for alluvial sediment moving down the estero Marga Marga to build a delta, which prograded westward, and which was probably deflected towards the south side of the basin by the bar to the northwest (Figure 16). With sea level no longer rising quickly, sediment from these two sources would have rapidly filled the lagoon as the marine spit and terrestrial delta encroached upon each other, finally coalescing. Deposition within the lagoon ended near its center.

Stage 5 - Modern: Plan de Viña eventually emerged from the sea. As uplift proceeded, the main channel would have become fixed permanently between the head of the basin (near Miriflores), and the base of Cerro Castillo, where it was locked into place by the south-drifting sand. Accretion of beach sand between storms would likely have plugged the mouth of the estero, enhancing the deposition of overbank muds and sands on the surface of the alluvial plain, forming a broad levee on the north side of the estero, and a backswamp between the bar to the northwest and the valley wall to the northeast (Figure 17). A similar senario took place in Renaca when a marine embayment was pinched off by south-drifting sand, forcing the deposition of soft soils below the northern edge of the basin.

The contemporary shoreline at Viña del Mar is also a consequence of tectonic uplift. South of Cerro Castillo and north of Punta Salinas, the coast is punctuated by a ragged fringe of rock extending between 50-100 m offshore from bold headlands. The top of this fringe is quite level, being approximately 1-2 meters above the normal level of waves, and sloping slightly towards the sea. This fringe is a rock-cut platform that has been uplifted tectonically within the last several thousand years. Its width and height are consistent with the combined vertical uplifts of the 1822 and 1906 earthquakes, although earlier events are probably responsible for it as well.

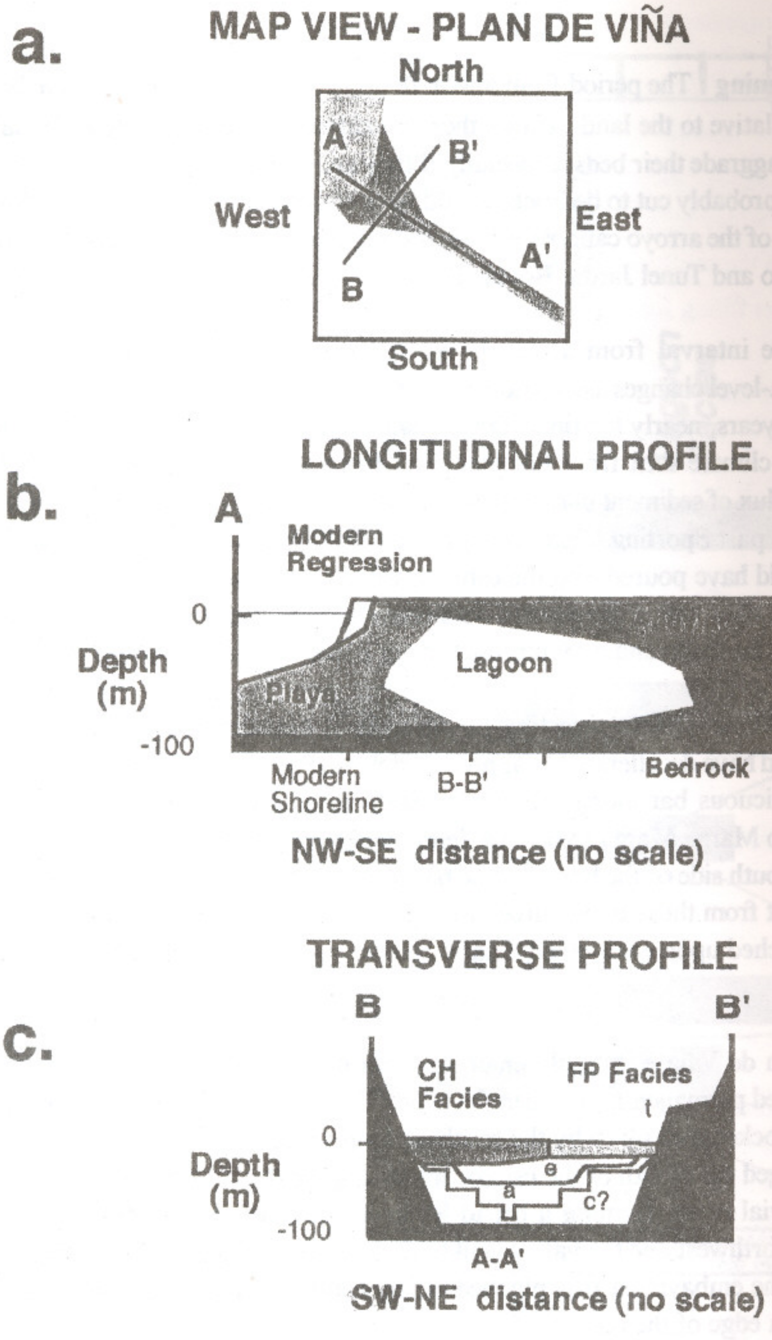

a.
MAP VIEW - PLAN DE VIÑA
North
A
B'
West
East
A'
B
South
b.
LONGITUDINAL PROFILE
A
A'
Modern Regression
0
Depth (m)
Lagoon
Playa
-100
Modern Shoreline
B-B'
Bedrock
NW-SE distance (no scale)
c.
TRANSVERSE PROFILE
B
B'
CH Facies
FP Facies
t
0
Depth (m)
e
a
c?
-100
A-A'
SW-NE distance (no scale)

Figura 15

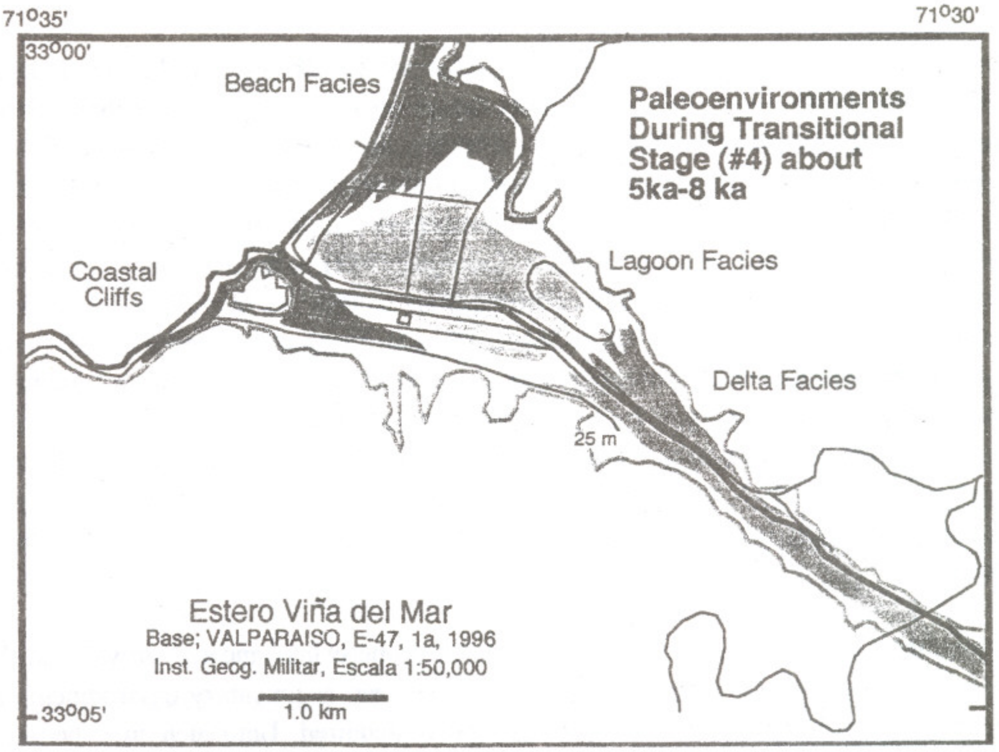


Figura 16

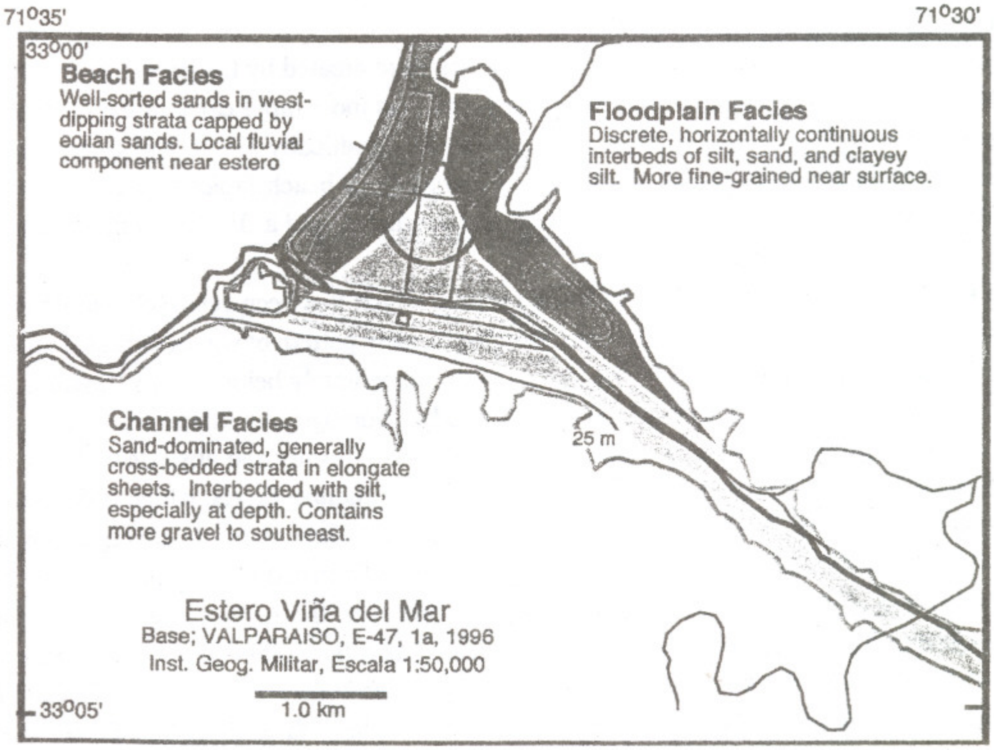


Figura 17

SUBSURFACE MATERIALS

Microzonation studies of Viña del Mar performed after the earthquake of March 3, 1985 clearly acknowledge the fundamental difference in earthquake response between the alluvial soils of the lowland (Plan de Viña) and those of the adjacent uplands. Differentiating soils within the sedimentary basin of Plan de Viña, however, has proven more difficult owing to the broad and erratic pattern of damage to houses and the municipal network (Perez C., 1988), to the relative uniformity of near surface materials (Luengo N., 1986), to the localization of severe damage to tall edificios (Calcagni, 1988), to the difficulty in using geophysical techniques (Verdurgo, 1995), and to the possibile existence of an ancient course in the estero Marga-Marga (Aguirre et al., 1986). For example, Perez (1988, p. 16) reports that damage from the 1985 earthquake, was concentrated «... en los sectores de suelos blandos cercanos al lecho de estero marga-marga y tambien en algunos zonas arenosas de la costa.» The most specific attempt thus far is by Luengo (1986) who subdivided the Plan de Viña into 15 homogenous blocks (Figure 13), each of which was characterized by different surface materials. The zones were arbitrarily bounded by the rectilinear pattern of streets; for example, Avenida Libertad and 8 Norte are particularly important boundaries in this scheme, yet do not coincide with changes in near-surface materials.

A stratigraphic approach to microzonation can, when properly implemented, provides an alternative to existing techniques. However, it requires that linkages between sedimentary environments (called facies) and geotechnical properties be made, and that more data be acquired. Until such time, the engineering performance of soils beneath Plan de Viña can best be approached by considering three vertical zones, each of which is laterally variable.

Surface Geology

Engineering soils in the uppermost 15 (+/-) meters were created by the progressive vertical sedimentation of a relatively stable depositional system. Deposition was most rapid early in the process, when sea level was rising more quickly, and when Plan de Viña was topograhically lower, and thus able to flood more often. There are three principal facies recognized (Figure 17): a beach facies to the north and northwest near the coast, an alluvial channel facies to the south and southeast, and a floodplain facies to the northeast.

The **beach facies** was controlled by the shoreline, which has been relatively stable during the last several thousand years because it is in equilibrium with the incident pattern of waves refracted around Punta Valparaíso, whose action forces the mouth of the Estero to lie immediately below Cerro Castillo. Soils near beach are dominated by subrounded, well-sorted (poorly graded) homogenous sands, whose generally good foundation performance and good drainage result from their bulk uniformity and absence of fine-grained materials. To the east and south the near-surface materials are alluvial channel facies, which is dominated by subhorizontal elongate sheets of traction-deposited sand and fine gravel. These deposits are especially complex north of the estero, where overbank flooding led to the construction of a broad levee in the vicinity of 1 Norte to 3 Norte. In the northeastern part of the sedimentary basin, however, the surface materials are finer grained, and are dominated by silts and fine sands which accumulated as a floodplain facies.Drainage is more poor here than elsewhere in the city because the area lies in a topographic saddle between the colluvium to the north, and the north levee of the Estero Marga Marga to the south. These three dominant facies, are gradational to one another, interfingering at depth, especially at the triple point where all three coincide. Foundation stability is generally good.

During the last several thousand years prior to the historical period, the system seems to have stabilized, and little sediment has accumulated. A slight westward movement of the coastline may have taken place in response to tectonic uplift; a thin mantle of eolian soils and coastal washover deposits developed near the coast, and the surface of the alluvial plan has been intermittently innundated by severe floods. Agricultural and urban activities have since obliterated all of the original surface morphology, and are now the dominant landscape agents.

Plan de Viña is now a terrace (Figure 14), uplifted along with the wave-cut platform bordering it to the north and south. Any additional uplift of the terrace will steepen the gradient of the lower Estero, helping to mitigate the problems of flooding and stagnant circultation by deepening the channel and enhancing sediment transport. Raising of the rock-cut platform fronting Cerro Castillo may lead to a westward progradation of the beach by strengthing the refraction of waves behind it. A negative consequence of uplift is the raising of the salinity-flocculated lagoon muds at depth into the freshwater aquifer, which may reduce their foundation strength.

Buried Lagoon

The deposits below a depth of about 15 meters follow a different pattern, one dominated by rapid deposition of muddy sand in a saline lagoon (Figure 16). At its maximum extent, the lagoon extended over the entire surface of Plan de Viña to El Salto. At its minimum it was a probably a small depression above the geographic center of the lagoon (just north of Core GA-17) which probably lies in the block bounded by Libertad, 6 Norte, Quillota, and 2 Norte. The lagoon is well represented in the subsurface stratigraphy extends parallel to the trend of the valley from the junction of calle Limache and Valparaíso, northwest to approximately 3 Poniente and 7 Norte. It is generally north of the Estero and west of Sporting Club.

The shear strength of this material is highly variable. For example, many of the cone penetration tests extending below about 15 m show a reversal in strength, becoming weaker (<30 blows per foot) at depth. Others, perhaps because they are located on caliche-hardened paleosols, or because they are massive silt, become stronger with depth. A representative example a core penetrating into the lagoon sediments is Core A-55.2 in Luengo (1986), located just north of the junction of 1 Norte and Libertad. At this location, the shear strength rises with depth to about 12 m, but falls dramatically below -14 m depth, declining to the base of the core at 27 m depth. Sample 8, from 16.1-17.25 m depth (SM; silty sand), had a specific weight of onlyh 1.27 T/m3, and with nearly all (81%) of the material finer than 4.75 mm.

Eyewitness accounts of soil behavior during the terremoto of 16 Agusto, 1906, indicate that the soils above the lagoon, which coincides with Poblacion Vergara, performed very poorly. For example, at the eastern end of the lagoon, El Mercurio de Valparaíso coverage reported that «La calle Valparaíso esta' in gran parte tambien destruida...de un extremo a otro, se sufre una impresion de armago desconsuelo, pues, sin duda, en la parte de Viña de mar quemas ha sufrido.» Speaking more generally about the soils to the west, El Mercurio reported «Poblacion Vergara ... es en las mas lamentables condiciones. La poca salidez del suelo en esa parte fue' causa de su destruccion.... Poblacion Vergara esta completamiente destruida ... Necesariamente habra in fluido para esto la clase de terreno, que no ofrecia base solida para edificios de material.» The most striking and unequivocal report of poor soil performance is from Rozas and Cruzat (1906). «Uno de los hechos que llamo' la atencio'n la noche del 16, fue' que en los momentos mismos en que se sucedi'an los temblores ma's fuertes, en la calle de Limache, frente a' la Rfineria de Azu'car, se abrio' una profunda grieta por donde sali'a el auga a' borbotones e' igual cosa sucedio' en varias partes de la poblacion Vergara, donde se formaron verdaderas lagunas, sobre el nivel de las calles...(Rosaz and Cruzart, 1906). Descriptions of dewatering, fissure formation, subsidence, and general loss of strength were restricted to the soils in Poblacion Vergara, generally above the buried lagoon, generally from near the head of the estero, extending westward towards its center.

Poblacion Vergara was also singled out with respect to the intensity of ground shaking, independent of foundation strength. For example, Rozas and Cruzat (1906, p. 248) reported that « Los construiciones de cal y ladrillo derumbia'rose sin excepcion ninguna. Por el contrario, los de madera, aun en la poblacion Vergara, se mantuvieron en pie.» Larrain (1946, p. 273) stated: «Poblacion Vergara, se derrumbaron casi sin excepcio'n.» Ballore (1915, p. 16) was specific in attributing the poor soil performance to material amplification, the «.. propagacion del moviminento sismico en suelos aluviones sueltos e incoherentes...»

The mechanism by which seismic waves were responsible for the upwelling of groundwater during 1906 can be understood with reference to observations made elsewhere shortly after the 1985 earthquake. For example, Avecedo M. and Orozco S. (1986) reviewed ground failures in the ports of San Antonio and Valparaíso after the 1985 earthquake, where seismically induced compaction of artificial fill and late Quaternary sediments caused vertical settlement of large structures; they also pointed out that the amount of setting was related to the local earthquake intensity. Ortigosa de Pablo (1986) also demonstrated that the pattern of subsidence was related to the engineering strength of the artificial fill and natural sediments both north and south of Viña del Mar. Cyclic vibrations, especially when the vertical accelerations are strong, allows sediment grains to move into more stable arrangements under high overburden stress. Such settlement causes flexure and local extension of the overlying materials, which, if rigid, lead to the the development of fissures, through which expelled pore-water can reach the surface.

The historic reports of consolidation, dewatering, and rupture of soils above the buried lagoon are circumstantially supported by the presence of faint lineaments evident on aerial photographs taken prior to the 1985 earthquake (Figure 18). Recognition of such lineaments is subjective, even impressionistic, and is thus difficult to defend scientifically without object-recongition and image-enhancement software. The presence of the linements was, however, weakly confirmed by three individuals in «blind tests;» They were able to identify one or more lineaments without being prompted to their locations. As mapped, the primary set of lineaments generally trend northwest, parallel the estero, although a second set, trending northeast, parallels to the coast.

The origin of the lineaments is not known. They probably represent the alignment of several different kinds of features: perhaps slight changes in surface moisture, topographic relief at depth, construction history. The frequency of the linements, their distribution, and their orientation are consistent with the interpretation that they were created by sediment compaction and flexing above the buried lagoon, perhaps during the 1906 earthquake, when such fissures were reported by eyewitnesses.

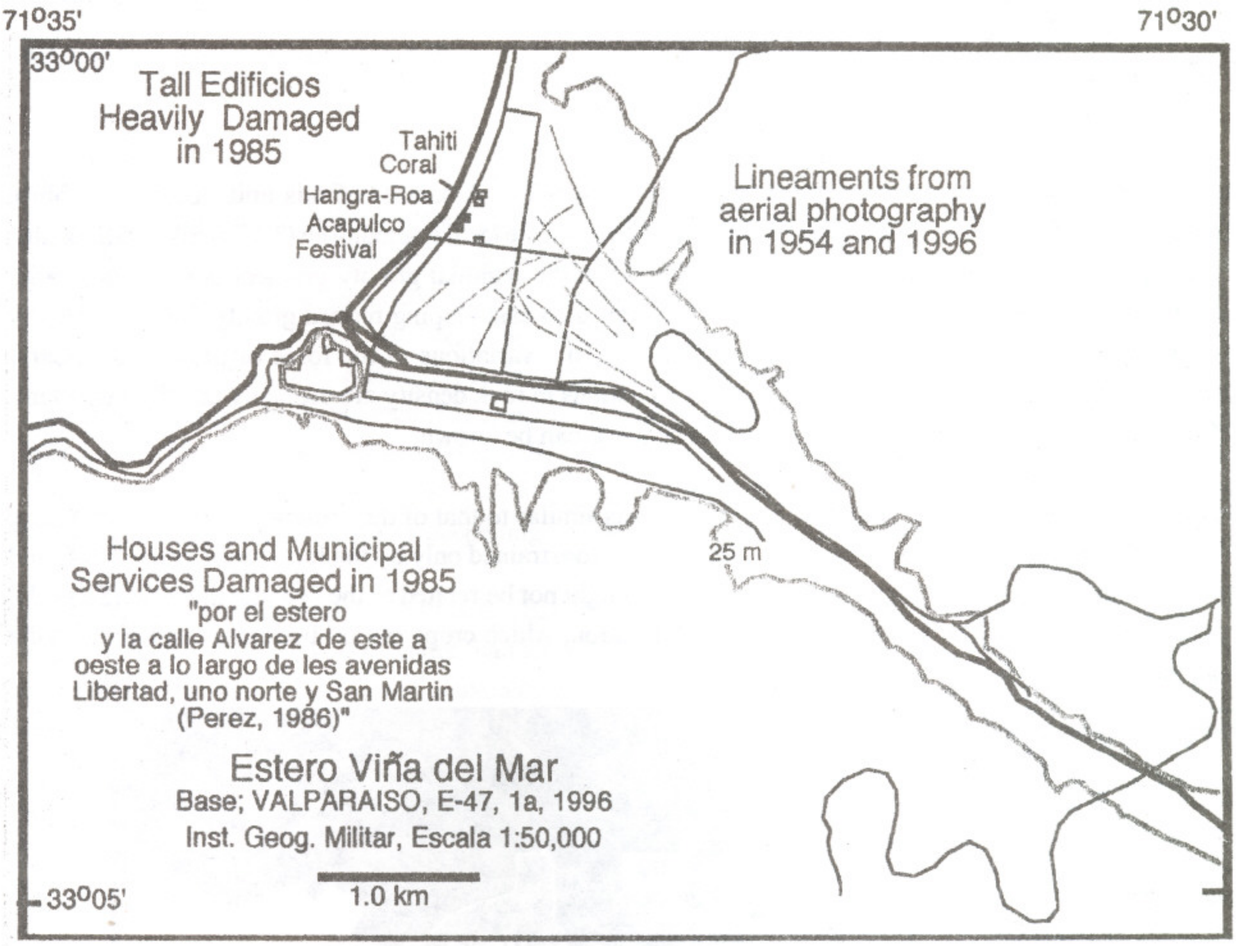


Figura 18

Buried Valley

The estero Marga Marga cut into its bed during the last glaciation, forming a valley now buried by the sediment fill (Figure 15). None of the boreholes penetrate deeply enough to help constrain the shape of the valley. Seismic refraction techniques have been successfully used to used to image sediments offshore from Valparaíso (von Huene et al, 1997), but this technique is poorly suited to Plan de Viña, where the sediments are more coarse grained, and which is completely covered beneath concrete and artificial fill. Other geophysical techniques such as microvibration (Perez, 1988), and ground-penetrating radar are also poorly suited to this heavily urbanized condition.

At the present time, estimates for the depth to bedrock beneath Plan de Viña are based on slight variations in the force of gravity measured at discrete sampling points (Verdugo P., 1995). His study assumed a uniform contrast between sediment density (2.03 g/cc) and rock density (2.67 g/cc), and a regional gravity gradient of 0.75 mgal/km directed N25E. Using these assumptions, he converted the differences in measured gravity into differences in sediment thickness, which he interpreted as being roughly symmetrical around the center of the sedimentary basin, reaching a thickness over 200 m.

Studies by Grimme and Alvarez (1964) and Gana et al. (1996), however, indicate that a variety of different rock units extend below Plan de Viña (Figure 8). Of particular concern is the metavolcanic unit «Jlv» which underlies the southwestern (Cerro Castilla) and northeastern (Sausalito) sectors of the sedimentary basin, and whose closest outcrops are bounded by steep faults (Figure 19). A sample of this unit, locally a gabbro, yielded a density of 2.94 g/cc, substantially higher than one from the local granodiorite (2.67 g/cc). Additionally, the assumption of an northeast-trending linear decrease in the regional gravity gradient is no longer valid. Recent work by Cañuta C., and Ziñiga R. (1998), portrays an east-sloping reginal gravity field, and clearly shows the influence of the heavier rocks beneath the basin. Variations in the force of gravity are clearly influenced by the depth of the sedimentary fill, but variations in rock density are probably equally important. A refined gravity model is needed before depth to bedrock can be known.

Assuming that the longitudinal gradient of the estero was similar to that of the present, the base of the valley lies between a depth of -40 m to -80 meters. Its width is constrained only by the location of cores A-14, and A-18. Sand and gravel, if detected deeper than -80 m, might not be related to the last glacial cycle (Stage 1). It could be gravel from the Tertiary Potrero Alto formation, which crops out on both sides of Plan de Viña within one kilometer of the coast.

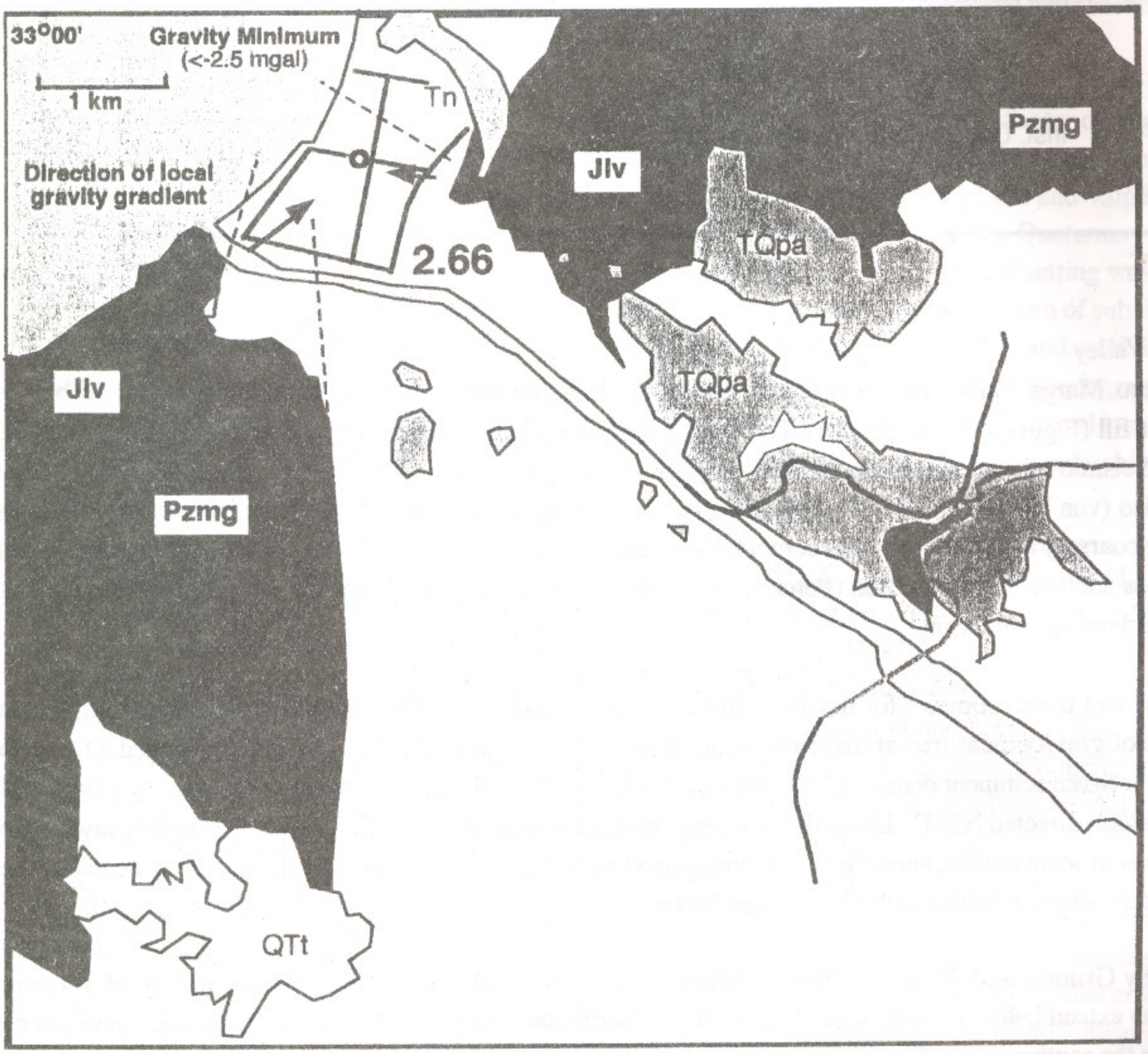


Figura 19

MARGA MARGA FAULT

Fault Trace

Patchy remnants of the Potrero Alto deposits, of Pliocene-Quaternary age, are well preserved at high levels (100-150 m altitude) on both sides of the Estero Marga Marga in Quinta Vergara, Sausalita, and Miriflores Alto (Figure 8). These outcrops demonstrate that the present course of the Marga-Marga is quite ancient, and that it was originally quite broad. Today, however, the Marga-Marga valley, especially between Viña del Mar and Quilpue, is essentially a straight, narrow canyon whose map trace is slightly concave to the northeast. Above an altitude of about 80 meters the canyon is relatively broad and dissected by small quebradas. Below 200 meters, however, the gradient of the valley spurs increase dramatically, forming a straight inner canyon with valley wall slopes averaging about 25 degrees. A straight inner canyon with cascading tributaries is considered diagnostic of a rapidly deepening valley (Keller and Pinter, 1999).

In contrast, the longitudinal gradient of the Estero through its inner canyon is exceptionally low. The first (25 m) contour line crosses the river more than ten kilometers inland from the coast. The community of El Salto, is located at the mouth of the inner canyon about 2 km inland from the coast. The name «El Salto» translates as «the jump» and indicates the historical presence of an abrupt change in gradient now complely obscured. A pronounced lithologic weakness that is straight, weak, and nearly verticall must lie beneath the valley, traits used by Grimme and Alvarez (1964) to identify the Marga Marga fault. The straightness of the fault over a length of ten kilometers indicate that it is (or originally was) one with significant horizontal (strike-slip) displacement.

Field evidence collected during this study confirms the existence of a geologic fault below the Marga Marga. Recent excavations through the maicillo between Chorrillos and El Salto, on the southwestern side of the valley, reveal a brecciated fracture zone in pink granite ranging in thickness from 0.1-1.2 m, striking exactly parallel to the valley, and dippng 85 degrees to the southwest. Within the brecciated zone, individual fragments, as well as the wall rock, are encrusted with a clay-rich, unweathered, greenish-gray fault gouge containing en-echelon steps, but without conspicuous slickenmarks. The gouge had a sheen, indicating allignment of microscopic particles. These features are diagnostic of frictional abrasion and shear in an environment of high ambient lithostratic stress. At the same site, the fault zone extended continuously upward to an elevation of about 60 meters to the contact between unweathered bedrock and the overlying sandy gravel. Where the contact intersected the fault, a lens of gravel thickened abruptly from 1-3 m directly above the fault scarp, indicating that the scarp was present during deposition.

Recent Displacement

Secondary deformation within the older Potrero Alto deposits exposed in the new roadcuts north of the tunnel Jardin Botanical indicate sinistral (left-lateral) strike slip motion on this fault in the recent geological past (Figure 20). Near the middle of the exposed section, the Potreo Alto deposits, which include what are probably Quaternary soils, are cut by a thrust fault outcropping continuously for more than 80 meters, occurring on both sides of the road, and which propogated upward through the sediment pile, terminating just below the surface, which appear to be upwarped. Reconstruction of the fault geometry yields a minimum of about 15 meters displacement, in which shortening took place on a fault striking 30 degrees to the northwest and dipping approximately 40 degrees to the southwest.

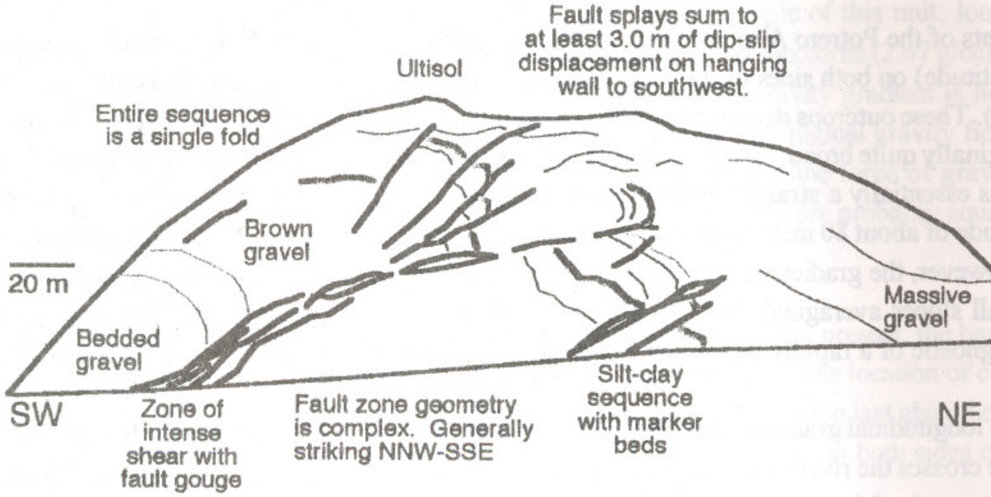


Figura 20

This fault indicates intense local compression, which is most easily explained as a secondary consequence of horizontal (strike-slip) displacement between crustal blocks in the Canal Beagle area. More specifically, localized compression leading to small thrust faults and anticlines often take place in «stepovers» where the displacement along one strand of a strike slip fault is transferred to another. The kinematics of the blind thrust at Canal Beagle require a sinistral (left-lateral) component of motion, which is consistent with the pattern mapped by Gana and others (1996) on the two nearest strike-slip faults.

Local compression associated with a stepover may also be responsible for the unusually deep set of incised meanders near the junction of the Esteros Marga Marga and Las Palmas (Figure 5), which form a conspicuous anomaly in the othersise straight reaches guided by faults. There, both of the esteros are are deeply entrenched below a broad strath terrace. Elsewhere, such incised meanders represent the path of a stream «frozen» into its position by a pulse of rapid uplift (e.g. Merrits and Ellis, 1994). Such a localized uplift may be due to a stepover between fault traces in the Embalse Poza Azul and in the lower canyon of the Estero Marga-Marga.

Equally compelling neotectonic features are present within Casablanca Valley, and the Estero Limache, adjacent valleys to the south and north, repsectively. In Casablanca Valley, laterally offset valleys, sag ponds, recent scarps, and entrenched canyons form a coherent pattern of local displacements along a master fault which parallels the one in the Estero Marga-Marga, and which is mapped as having dextral displacements. The Estero-Limache, also contains clear evidence for fault motion; there, deformation leading to incised menaders is young enough to have also created scarps on the modern floodplain of the lower Estero Limache, and to have influenced sedimentation in the channel of the Aconcagua River along a line that continues to Rocas Concon.

Evidence for geologically recent, but prehistoric, displacement along the Marga-Marga and adjacent faults is thus compelling. The subregional scale of these features, as well as their continuity in time and space, indicate that they are deep-seated within a strong, ancient, granitic crust. In this context, there is no reason why any or all of these features are not capable rupturing during subduction zone events, contributing to the seismic signal. The burden of proof should rest with those who would interpret the faults as incapable of surface rupture, rather than with those who interpret them as active.

Earthquake of March 3, 1985

Tall apartment buildings along Avenida San Martin suffered extensive damage during the 1985 earthquake (Figure 18). Calcagni (1988) carried out a systematic study of damage to 45 buildings between 9 and 23 floors in height. Two sustained very serious damage (level 3; Hanga-Roa and Acapulco), five sustained level 2 damage, and seven were completely undamaged. With one exeption, all of the heavily damaged buildings (Level 2 and 3) were located between 8 Norte and 10 Norte along Avenida San Martin. The most heavily damaged and oldest of these buildings (Acapulco) sustained damage during all three of the recent earthquakes (1965, 1971, and 1985; Monge et al, 1986).

This pattern of localized damage contrasts with the more widely distributed and occasional damage to smaller buildings, 809 of which were examined by Perez (1988). After eliminating other causes of failure, Calcagni concluded that local failure to tall buildings along Avenida San Martin was caused by their «ubicados en los suelos de la antigua desembocadura del Estero Marga-Marga.» He based his interpretation of an ancient river course on a map drawn in 1848 during pre-construction planning for the ferrocarril, which showed a single drainage line bisecting the estero Marga Marga in Poblacion Vergara. Aguirre et al (1986, p. E74) had reached a similar conclusion on different evidence; they related unusual soils in building foundation to an ancient bed or course of the Marga Marga. «En elgunos puntos hasta 300 metros del estero se han encontrado bolsones de limo-arcilloso saturado, altamente organico, y muy plastico, a profundidades entre los 3 a los 6 metros, indicadores del antiguo lecho y/o curso del propio estero marga-marga. Estos bolsones de suelo blando han obligado a mas de una edificacion en altura a ser estructurada con fundacaces sobre pilotes.»

The interpretation of an ancient course of the estero in this vicinity conflicts with the available geological evidence, which indicates that nearly all of the upper 5 m of sediment was deposited as ancient river sediment (channel bars and levee-splay deposits). Without exception, these sediments are composed of cross-bedded sands and sandy silts devoid of plastic clay and organic material. Additionally, these alluvial deposits do not reach the coast near Avenida San Martin, where the sediments are exclusively marine in origin.

Detailed maps of the shoreline published in 1838 and 1871, indicate that the railroad map of 1848 used by Calcagni was overgeneralized. Notably, two of the maps (Tessan, 1838; Kraus, 1903) clearly show the mouth of the estero immediately below Cerro Castilla (then called Pte Callao), as well as the growth of sand bars (spits) propagating into a small lagoon from the north, the same direction from which the a bar is now formed each summer, and in which it sloped prior to urbanization (Pomar 1877). Similar features, notably a single branch of the Estero Marga-Marga in Plan de Viña, are present on all fourteen of the historic maps examined. A single branch (at least under equilibrium conditions) is also required by the Holocene geology and modern wave climate.

The zone of weak soil interpreted as an «ancient course of the Marga Marga» - large fragments of soft, plastic, saturated, organic clays - requires an explanation. This description resembles that of the estuarine muds and fango deposits reported only greater depths by Grimme and Alvarez (1964). Throughout the recent geologic past, the gradient on the Marga Marga has been very low, and its floodplain has been rising, rather than being downcut. Thus, it would have been extremely unlikely that an «ancient course» could have cut to a depth (-15 m) required to entrain the «fango» and move it to within a few meters of the surface. If the near-surface material is indeed derived from depth, then the only plausible mechanism for its upward emplacement would be during the upward flow of water along a coseismic fracture. Such an interpretation, although not proven, is factually consistent with the accounts of fissure formation, the upward flow of water, and transient lagoons (Rozas and Cruzat, 1906). It is quite possible that a weak zone formed coseismically could have been exploited by the Marga-Marga until it was later plugged by south-drifting sand.

The concentration of damage to tall buildings coincides exactly with the projection of the Marga Marga fault beneath Poblacion Vergara; only a 10% extension of the straight fault trace is required. Perez (1988, p. 22) considered the presence of this fault as one of many possible explanations for the localized damage. «Es obviamente... confactores como son el suelo la fundacion, la construcion misma (calidad, tipologia, edad, materiases, etc.), la presence y posible activismo de la falla del estero marga marga, la topografia, la direccion de las ondas seismicas, etc...» He did not, however, explain the mechanisim for this correlation.

Whatever explanation is invoked to explain the damage, it must account for the fact that severe damage during 1985 did not mirror the fault trace, but was instead was concentrated only at the outer coast and near the head of the sedimentary basin. It is possible that the damage was concentrated to the west because the beach sediments were less resistant to shaking. However, this is also the place where the valley of the Marga-Marga must be deepest. The presence of a deep, sediment filled canyon in this vicinity, one parallel to the fault trace, cannot be ruled out.

Earthquake of August 16, 1906

One of the challenges in seismic risk assessment for Plan de Viña is to explain why the damage during the 1985 earthquake was so different from that of the 1906 earthquake. The simplest explanation is that the hypocenter for the 1906 (and 1822) events was closer than for the 1985 event. Four historic sources, however — the first-hand reporting of El Mercurio (1906), systematic descriptions by Rozas and Cruzat (1906), the technical reconnaissance of Ballore (1915), and a review by Larrain (1946) - suggest the possibility that the Marga-Marga fault was directly involved in contributing to the damage.

Four localities in Viña del Mar were severely affected (Figure 21). To the west was (1) Pobulacion Vergara, where shaking was intense enough to destory wooden buildings and to cause subsidence. (2) Near the intersection of Limache and Valparaíso streets, Rozas and Cruzat described a single deep crevasse that opened at the moment of strong shaking, and from which gushed turbulent water. El Mercurio also reported «desconsuelo», in this area, claiming that «... sin duda .. [es] la parte de Viña de mar quemas ha sufrido. El Salto, to the east, was decribed by Rojas and Cruzard (1906) as the locality where terremoto was felt with the greatest intensity; apparently, the onset of shaking was abrupt, with houses «cayer al suelo» at the «primer remeson.» Finally, within a few days after the earthquake, the railroad was functioning from El Baron (Valparaíso) to El Salto, as well as from

Quilpe to the east. But the track between El Salto and Quilpue was a complete ruin (4) It is here that the tracks were described as having a «zig-gag» pattern by Ballore, in which the bolts were snapped and the rails opened up in large gaps. This took place on terrain that was generally flat, suggesting that the ground have have been sheared by horizontal surface rupture.

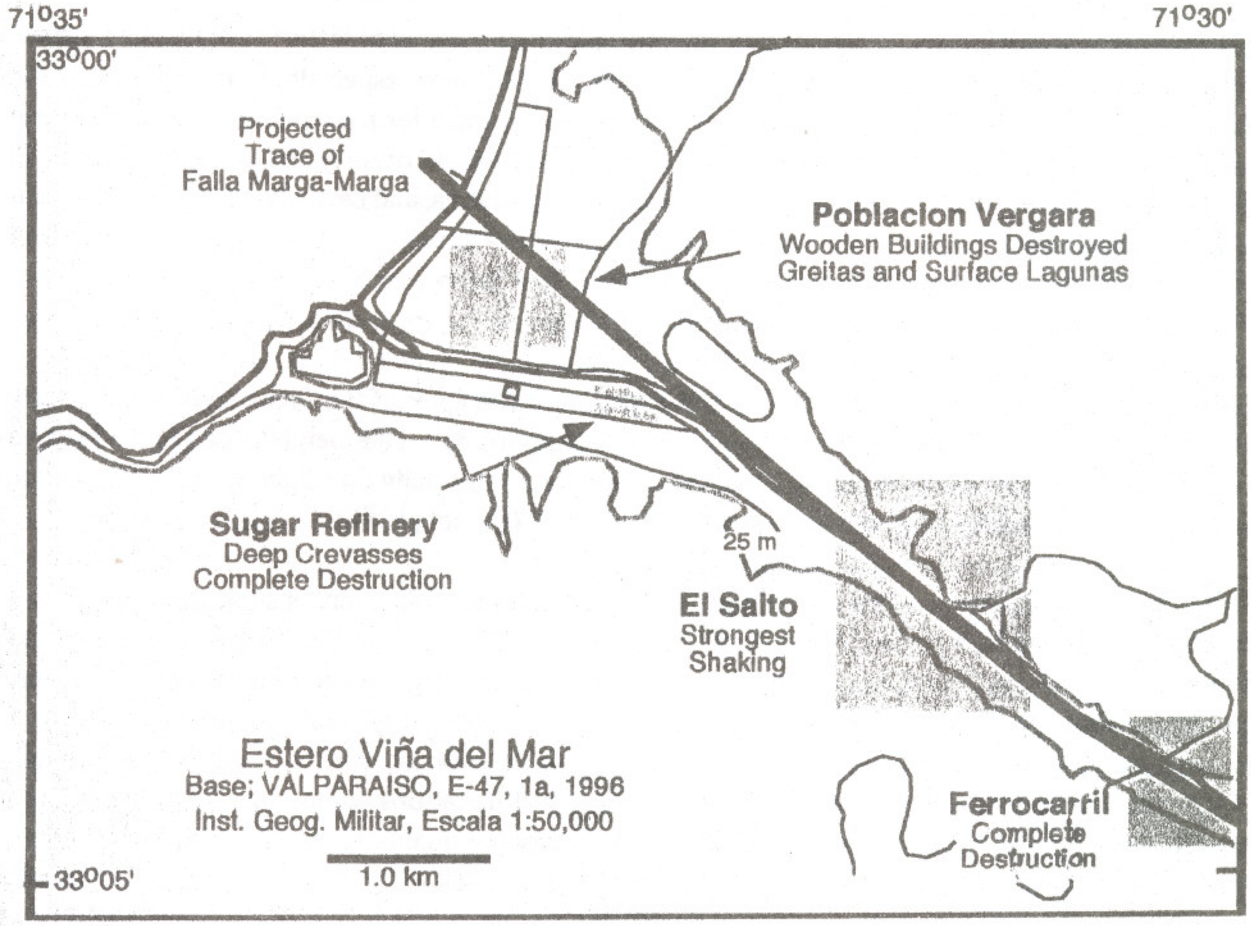


Figura 21

These four sites are crudely aligned from northwest to southeast, directly above the Marga Marga Fault. Other sites within the sedimentary basin, but further from the fault, were not as severely affected. Three mechanisms by which the fault could localize the damage are suggested below. Wave Guide: The fault zone within the rock (being a low-velocity zone) may have captured, refracted and concentrated seismic energy moving outward from the subduction zone earthquake, sending it upward. This may have enhanced shaking locally, leading to the secondary effects associated with the consolidation and dewatering of soils responsible for fissure formation and the «lagunas.» Fault rupture and movement at depth could have contributed to the seismic signal, as well as the surface ruptures in the sedimentary cover; according to this explanation the «lagunas» in Poblacion Vergara could have developed above shear fractures (Reidel Shears) associated with horizontal displacement at depth. A third possibility is that the linear pattern is indirectly related to the fault through the mechanism of sediment thickness. The valley is deepest, and therefore the sediment fill the thickest, along the fault trace; amplification of seismic shaking may have been a function of sediment thickness. A fourth possibility is that one or more pre-historic ruptures of the fault had taken place, and that the sediments associated with the healed ruptures consituted a weak zone reactivated by the 1906 and 1985 events.

Evidence supporting the «wave-guide» hypothesis include the absence of historic accounts of surface rupture, as well as the absence fault scarps elsewhere in the valley, especially in the canyon of the Marga Marga. Evidence supporting the rupture hypothesis includes the opening of a single deep fissure near the Sugar Refinery, exactly above the fault. Description of early and abrupt shaking at El Salto is consistent with both the wave guide and rupture hypotheses, and partially refutes the sediment thickness hypothesis.

Canal Beagle

The sector of Viña del Mar known as Canal Beagle lies at the apex of the Pleistocene sedimentary basin, directly north of the Marga-Marga fault trace (Figure 8). This neighborhood received an unusually high level of damage during the 1985 earthquake, especially on ridges where topographic amplification is thought to have played an important role. (Celebi (1986).

Topographic amplification of the aftershock sequence from the 1985 event is supported by the pair of recordings situated on granite (Unit Jlt of Gana et al., 1996), and Unit PZ granito of Grimme and Alvarez (1964); the station on the steepest part of the ridge had significantly higher amplifications. The ridge effect alone, however, cannot explain why the maximum ground accelerations at Canal Beagle during the aftershock sequence were recorded at station C, which is located on a much broader ridge at comparable altitude. Also, accelerograms for stations within the sedimentary rocks beneath Canal Beagle area (A, B, and C) had a spectral response qualitatively different from those on the granite (F and E); the incoming waves were delayed as much as 1.8 seconds and arrived much more abruptly.

Unusually high peak accelerations at Station C and the differences in spectral behavior (delay, abruptness) are probably due to changes in incoming seismic waves within a relict sedimentary basin first recognized by Grimme and Alvarez (1964; depositos estuarales), remapped by Gana et al (1996; Potrero Alto), and studied more completely during this investigation. The relative importance of the roles of the sedimentary basin, the «ridge-effect» and the proximity to the Marga-Marga fault await further investigation.

DISCUSSION

Rupture of the Marga Marga fault during the 1906 event is an unproven, but likely, hypothesis. Although the crust beneath central Chile appears to be seismically quiet (Riddell and Villablanca, 1986), faults such as the Marga-Marga must be releasing some strain during subduction thrust events, and there is no geophysical reason why such strain release could not take place seismically. The dearth of crustal earthquakes detected in the forearc crust of Chile could be due, in part, to the difficulty in locating earthquake foci, especially shallow ones. It could also be due to the fact that the seismic signal from crustal earthquakes is lost in the «noise» of the larger subduction thrusts which trigger them. Alternatively, the apparent absence of shallow crustal events may be real, but due to the aseismic release of strain in the upper plate (Nelson and Manley, 1992).

Weak, circumstantial evidence suggests that the shallow crust is itself a local source of seismic waves. The most direct evidence is the seismic analysis of the 1939 Chillan earthquake (Campos and Kausel, 1990), which took place within the crust, rather than on the subduction zone. Second is the apparent sequence of events during the 1906 earthquake in Valparaíso (Urrutia de Hazbun, and Lanza Lancano, 1993, p. 159) in which the initial, prolonged episode of cyclic shaking was followed nine minutes later by a much more abrupt, but stronger event. The third line of possible support is the accelerograph data for the earthquake of March 3, 1985 (Saragoni et al., 1986), in which two stations, Llolleo, (0.85 g) and Mephilla (0.59 g), had unusually strong vertical accelerations. Both lie within a fault zone that has been active during late Quaternary time. Bracketing stations to the north (Quintay; 0.13 g and Rapel; 0.11g), had vertical accelerations typical of those of remote sites. The vertical accelerograph for Llolleo is especially anomalous in its polarization, and may be related to the liquefaction in that vicinity (Ortigoso de Pablo, 1986).

Although much smaller than subduction zone earthquakes in terms of moment release, earthquakes within the crust beneath heavily urbanized zones are responsible for most of the damage and loss of life, especially when they are shallow. For example, the 1995 earthquake in Kobe, Japan had a magnitude ML=6.9, significantly smaller than the 1965 and 1971 events near Valparaíso, yet it killed more than 5000 people and caused more than 200 billion dollars worth of damage (Yeats et al., 1996); this event was caused by dextral motion along a small strike slip fault in the upper plate within a subduction margin. The Marga-Marga fault is also a strike slip fault in the upper plate of a subduction zone.

Amplification of seismic waves by the lagoon sediments beneath Plan de Viña poses a less dramatic, but more threatening, earthquake hazard than actual rupture. Material amplification (Newmark and Rosenbluth, 1971) of similar estuarine lagoon sediments was clearly responsible for the selective damage to the San Francisco Bay (USA) area during the 1989 Loma Prieta Earthquake (M 7.1), in which collapse of the Nimitz Expressway was restricted to similar deposits. Material amplification was clearly responsible for the intense shaking of Poblacion Vergara during the 1906 earthquake, which was strong enough to destroy wooden houses. Amplification was apparently also responsible for coseismic settlement of soft soils at depth, which, in turn, caused surface ruptures, fluidization, and loss of foundation strength near the surface. There is no reason why such a response could not occur in the future. Buildings designed to withstand intense shaking, could be damaged by the tilting of discrete blocks between ruptures extending upward from the soft materials at depth, or by the localized loss of support above fluidized fissures.

Proximity to the Marga-Marga fault appears to be important, regardless of what mechanisims are involved. Damage along Avenida San Martin during the 1965, 1971, and 1985 earthquakes took place only above the fault in an area of otherwise homogenous soils and adequate bearing strength. Canal Beagle, also heavily damaged during 1985, lies immediately adjacent to the fault, where its older sediment fill magnified the shaking even more. Especially strong and abrupt shaking at El Salto during the 1906 earthquake, and destruction of the railroad only in the canyon of the Marga-Marga suggests that proximity to the fault mattered then, as well.

Although much larger in scale, the Mexico City earthquake of 1985 provides a reasonable analog for potential damage at Plan de Viña. Both cities are built built on the flat surface of a sedimentary basin containing a thick stratum of fine-grained sediments at depth. In Mexico City, seismic waves, generated by a distant subduction thrust were amplified by the geometry of the depositional basin, with the area of maximum damage being localized directly above a buried stratum of fine-grained sediments. These combined effects also take place in Plan de Viña, where the trace of the Marga-Marga fault adds a third, largely unknown risk. . The destruction of Poblacion Vergara during 1906 could be due to the fortuitously bad combination of all three factors: basin amplification, material amplification, and fault displacement at depth.

CONCLUSIONS

1.- Poblacion Vergara in Viña del Mar, which was almost completely destroyed during the 1906 earthquake, is underlain by muddy Holocene lagoon sediments that amplified, seismic ground shaking, especially during the 1906 earthquake. These lagoon sediments lie just beneath the elevation (- 9 to 11 m) reached by most geotechnical investigations.

2.- Geological faults are common in the coastal zone near Viña del Mar, some of which show compelling evidence for geologically recent displacement. The most topographically prominent of these faults — the Marga-Marga fault — bisects Viña del Mar between El Salto and the Muelle Vergara. Earthquake damage is concentrated above this fault, which may have ruptured historically.

3.- Numerical modeling of the amplication of seismic waves in the alluvial basin of Viña del Mar is limited by the poor constraint on «depth-to-bedrock.» Estimates for the shape of the valley based on geophysical techniques are suspect. An inductive geological approach suggests that the buried valley below Plan de Viña is largely symmetrical, and has a depth of only -40 to -80 meters below sea level.

4.- Vertical co-seismic movements associated with strong historic earthquakes (1822 and 1906) are generally upward, and are not likely to exceed one meter. Such uplifts, especially if large, will be generally favorable to Plan de Viña because they will help stabilize the beach, facilitate surface drainage, reduce the exposure to flooding, and improve water circulation in the estero.

REFERENCES

Historic Maps

1600s Plano dela Hacienda dela Viña dela Mar. In Larrain, 1946, p. 69, labeled «Plano de fines del siglo XVII.

1712 Carte particuverse de la rada de Valparaíso, labeled «Plano de Freiser, 1712,» in Larrain, 1946.

1764 Birt, Jose Antonio, Plano del Puerto y Fortificaciones de Valparaíso. Archivo general de indias. Sevilla. Lam no. 106 en Atlas Cartografico de Reino de Chile Siglos XVII-XIV. Inst. Geog. Militar, Santiago, 1981.

1838 Ingeniero Hidrafico de la Marina Francesa, Plano de la Bahia de Valparaíso, (Levantdo por el Señor de Tessan).

1849 Plano Topografico y geologico de la republica de Chile, Pissis, A., Paris, 1:250,000

1877 Rada de Valparaíso, Hidrografia oficial, por Cap. De Frag. Granado Luis Pomar. Escala 1:20,000.

1891 Plano General de los operaciones del Ejército Consitucional. 28 Agusto. 20 m contour.

1903 Planos de Valparaíso por el Reporte Kraus. Folio of maps with text.

1910 Oficina Hidrafica de Chile, Costa de la Chile, Valparaíso. 1:20,000.

1926 Inst. Geog. Militar, Edicion 1926, Hojas XLIII-180 por Concon y Vecinidad.

1951 Inst. Hidrafico de Armada de Chile. Puerto y Bahia de Valparaíso. Escala 1:30,000.

1965 Inst. Hidrafico de Armada de Chile, Bahia Quintero a Bahia Valparaíso. Escala 1:50,000.

1985 Inst. Hidrafico de Armada de Chile, Bahia y Puerto de Valparaíso 1:10.000. Hidrofia en 1985.

1992 Inst. Hidrafico de Armada de Chile. Mar Presencial; formas de relieve submarino. Escala 1:10.000,000.

Articles and Books

Aguilar, R., Antonio, 1994, Infome MS 1949-94, Geotechnical report for borehole at Avenida San Martin

Aguirre, Carlos A., Petersen, Miguel A., and Perez, Luis Eduardo, 1986, Microzonification sismica de la Ciudad de Viña del mar. En 4as, Journadas chilenas de sismologia engenieria antisismica, 1986, Viña del Mar, p. E70-E84.

Andrade, J., Belisario y Castro, A., 1987, Antecedentes sobre la valorization y manejo de costas arenosas en Chile. Rev. Geográfica de Chile Terra Australis, V. 30: 151-157.

Atwater, Brian F., Jime'nez Nu'Nez, He'ctor, and Vita-Finzi, Claudia, 1992, Net late Holocene Emergence despite earthquake-induced submergence, south-central Chile. Quaternary International, v. 15/16, p. 77-85.

Ballore, Montessus de, 1915. Historia Sismica de los Andnes Meridiones al sur del paralelo XVI. Quinta Parte, El terremot del 16 de Agosto de 1906. Santiago, Imprenta lithografia «Barcelona, Santiago-Valparaíso.

Barrientos, Sergio E., 1991, Large events, seismic gaps, and stress difussion in Central Chile. In, Tectonics of the southern Central Andes, K.J Reutter, E. Scheuber, and P.J. Wigger, Eds., 111-117.

Bonelli, Patricio, Tobar, René and Leiva, Gilberto, 1999, Experimental study on failure of reinforced concrete building. ACI Structural Journal, V. 96, p. 3-7.

Castillo, Jorge Eduardo, 1988, Propocion de un espectro de deseño sismico para la zona epicentral del terremota del 3 de marzo de 1985. Memoria para optar al titulo de Ingeniero Civil, Universidad de Chile Facultad de ciencias fisicas y mathematicas, Depto de Ingenieria civil. 284 p.

Cañuta C., Jorge y Zuñiga R., Hector, 1998, Carta Gravimetrica de Chile, No. 1, ISSN 0717-2796, 1:500,000.

Caviedes, Cesar L., 1972, Geomorfolía del Cuaternario del valley del Aconcagua, Chile Central. Cuadernaos geograficos Friburgueses, Numero 11, Freiburg, Alemania.

Celebi, M., A feature of the 3 march 1985 Chile Earthquake; Topographical and geological amplification. In 4as, Journadas Chilenas de Sismologia e Ingenieria Antisismica, UTFSM, p. C1-C19.

Comte, D., Eisenberg, A., Lorca E., Pardo M., Ponce L., Saragoni, R., Singh, S.K., and Sua'rez, G., 1986, the 1985 Central Chile Earthquake: A Repeat of previous Great Earthquakes in the Region? Science, v. 233, p. 449-453.

Dewey, J.F. and Lamb, S.H., 1992, Active Tectonics of the Andes. Tectonophysics, 205: 79-95.

Eisinberg, A., Comte, D., Pardo, M., Ponce, L., Singh, S.K., and Suarez, G., 1986, Sismicidad historica y el terremota del 3 marzo en la zona central de chile. P. A108-a119 en 4as Jornadas chilenas de sismologia engenieria antisismica, Viñal del Mar.

El Mercurio de Valparaíso, 1906, Detailles de la castastrofe, En Ediciones de Domingo 19 a Martes 21 de Agosto de 1906 (Núm. 24,238 a Núm 24,240).

Fairbanks, R., 1989, (No title available): Nature, v. 342, p. 637.

Fresard, M. and G.R. Saragoni, 1986, Analysis de los acelerogramas y de los danos de los sismos de 1981 en la zona central de Chile. In 4as Journadas Chilenas de Sismologia Eingenieria Antisismica, UTFSM., p. F93-F111.

Gana, Paulina, and Tosdal, Richard M., 1996, Geocronologi'a U-Pby K-Ar en intrusivos del Paleozoico y Mesozoico de la Cordillera de la Costa, Región de Valparaíso, Chile, Revista Geologica de Chile v. 23, p. 151-164.

Gana F., Paulina, Wall Z., Renate, y Gutierrez, P., 1996, Mapa geologico del area de Valparaiso-Curacavi, Servicio Nacional de Geologia y Mineria, Mapas geologicos No. 1, Escala: 1:100.000, incluyendo Leyenda Ampliada y Listado de yaciementos.

Grimme, Kurt and Alvarez, Leonardo., 1964, Es Suelo de Fundacio'n de Valparaíso y Viña del Mar. Institute de Investigaciones Geologicas Chile, Boletin No. 16.

Isla, F.I., 1989, Holocene sea level fluctuations in the southern hemisphere. Quaternary Science Reviews, v. 8, p. 359-368.

Keller E., and Pinter, N., 1996, Active Tectonics, Upper Saddle River, NJ, Prentice hall, 338 p.

Kiefer, Ernst, Dorr, Mathias J., and Ibbeken, Hillert, 1997, Gravity-based mass balance of an alluvial fan giant: the Arcas Fan, Pampa del Tamarugla, Northern Chile. Revista Geologia de Chile v. 24, p. 165-185.

Kraus, J., 1903, Projecto de mejoramiento del Purto de Valparaíso. Delft, 1903. 5 volumes.

Kurtz, Andres, C., Kay, Suzanne M., Charrier, Reynaldo, and Farrar, Edward, 1997, Geochronology of Miocene plutons and exhumation history of the El Teniente regioin, Central Chile (34-35oS). Revista Geologica de Chile v. 24, p. 75-90.

Larrain, Carlos J., 1946, Viñal del Mar. Editorial Nascimento, Santiago Chile.

Lavenu, Alain, Marquardt, Carlos, Comte, Diana, Pardo, Mario, Ortlieb, Luc., and Monfret, Tony, in press, Quaternary extensional deformation and recent vertical motion along the Chilean coast (between 23ºS and 47ºS).

Leonard, Erick M., and Wehmiller, John F., 1991, Geochronology of marine terraces at Caleta Michilla, northern Chile; Implications for late Pleistocene and Holocene uplift. Revista Geologica de Chile, v. 18, p. 81-86.

Luengo, N., Roberto P., 1986, Actualization de zonification de suelos en Viña del Mar. Univ. Tecnica Federico Santa Maria. Valparaíso, Facultad de Ingeniería Deptaramento de Obras Civiles,

Marrett, R., and Allmendinger, R.W., 1990, Kinematic analysis of fault-slip data, Journal of Structural Geology, 12, 973-986

Merrits, D., and Ellis, M., 1994, Introduction to special section on tectonics and topography, Journal Geophys. Res., 99, p. 12,135-42.

Monge, Joaquín, Moroni Y., Maria O, Garcia A., Americo, 1986, Edificios de Hormigon Armado, Chapter 6 in Es Sismo del 3 de marzo 1985, Chile: Acero Comercial, SA, Santiago, p. 111-146.

Muhs, D. R., Thorson, R.M., Clague, J.J., Mathews, W.H., McDowell, P.F., and Kelsey, H.M., 1987, Pacific Coast and Mountain System. In Graf, W.L., ed., Geomorphic systems of North America: Boulder, Colorado, Geological Society of America Centennial Special Volume 2, p. 517-581.

Nelson, Alan R., and Manley, William F., 1992, Holocene coseismic and aseismic uplift of Isla Mocha, South-central Chile. Quaternary International, v. 15/16, p. 61-76.

Newmark and Rosenbluth, 1971, Principles of Earthquake Engineering.

Ortlieb, Luc, 1994, Las Mayores precipitaciones historicas en Chile central y la chronología de events ENOS en los siglos XVI-XIX. Revista Chilena de Historia Natural, v. 67: 463-485.

Paskoff, Roland, 1970, Recherches Geomorphologiques dans le Chile Semi-Aride, Bordeaux, Biscay Freres, p. 190-191

Paskoff, Roland, CuitiNo, and Petoit, Robert., 1998, Carácter relicto de la gran duna de Iquique, Región de Tarapaca', Chile. Revista Geologica de Chile, v. 25, p. 255-263.

Perez, C., Luis Eduardo, 1988, Microzonification sismica de la construcciones de la ciudad de Viña del Mar. Memoria en Obras Civiles. U.Tech.Fed. Santa Maria.

Portal M., Maria Eliana, 1993, Vestigios Paleoclimaticos en la Cordillera de la Costa. Interfluvio Petorca-Maipo, Chile Central. Revista Geografica de Valparaíso, NO. 24-25, p. 131-160.

Riddell, Rafael, C., and Villablanca, F., Ricardo, 1986, Reisgo sismico en Chile: p. F130-F151 in 4as, Journadas Chilenas de Sismologia Eingenieria Antisismica, UTFSM.

Rivano, Sergio G., 1996, Geologia de las hojas Quillota y Portilla. Unpublished report in library of Servicio Nacional de Geologia y Mineria.

Rivano G., S., Sepulveda H., P., Boric P., R., Espiñeira T., D., 1993, Mapa Geológico de las Hojas Quillota y Portillo (escala 1:250.000) Servicio Nacional de Geologia y Mineria.

Rivano, Sergio G., 1984, Geologia del meso-cenozooico entre los 31° y 33° Lat. Sur. Seminario Actualization de la geologia de chile, Apuntes. Servicio Nacional de Geologia y Mineria. P. K1-k17.

Rozas, Alfredo Rodríges y Carlos Gajardo Curzat, 1906, La Catástrofe del 16 Agosto de 1906 en La República de Chile, Barcelona. Special Collections in UTFSM Accession #5532.

Sapunar P., Pedro, 1986, Monografia de las obras portuarias de Valparaíso. Revista de Marina 3/86. P. 267-293.

Saragoni, G. Rodolfo, Paulina González, and Yarcelo Fresard, 1986, Analysis de los aclelerogramas del terremota del 3 de marzoo de 1985, en 4as Jornadas chilenas de sismologia e ingenieria antisismica, p. A27-a58., Viña del mar, Chile.

Urrutia de Hazbun, Rosa y Carlos Lanza Lancano, 1993, Catastrofes en Chile, 1541-1992. Editorial La Nori'a Chile. No. 77.373 y 86.18.

Veit, 1996, Southwesterlies during the Holocene deduced from geomorphic and pedologic studies in Norte

Chico: Palaeo No° 123, p. 107-129.

Verdugo P., Alejandro Isaac, 1995, Estudio geofisico de los suelos de fundacion para una zonification sismica de Valparaiso y Viña del mar. Memoria Para Optar al Titulo de Ingeniero Civil, Univ. de Chile, Dept. Ingenieria Civil.,

Von Huene, R., Corvalan, J., E.R. Flueh, K. Hinz, J Korstard, C.R. Ranero, W. Weinrebe, and the CONDOR Scientists, 1997, Tectonic control of the subducting Juan Fernandez Ridge on the Andean margin near Valparaíso, Chile.

Yeats, Robert S., Sieh, Kerry, and Allen, Clarence R., 1997, The Geology of Earthquakes. New York, Oxford Univ. Press, 568 p.

Ya'nez, Gonzalo A., Gana, Paulina, and Fernández, Ricardo, 1998, Origen y significado geológico de la anomalía Melipilla, Chile central. Revista Geológica de Chile, Vol. 25, No. 2, p. 175-198.

FIGURE CAPTIONS

Figure 1. Location of the study area. Map view (a) and cross-section (b) of tectonic setting after Yeats et al., 1997. Viña del Mar lies landward of the accretionary wedge in the forearc above Mesozoic intrusive and metamorphic rocks. Study area is centered near 33°S and 71°W, just north of the area glaciated during late Quaternary time (shaded).

Figure 2. Base map of the Estero Viña del Mar (also called Estero Marga-Marga) showing local place names referred to in the text. Thick gray line, the +25 m contour, outlines the estuarine plain «Plan de Viña» beneath the historic communities of Poblacion Vergara (north of the estero), Viña del Mar (south of estero), and Santa Ines. Selected roads (Avenida Libertad, 8 Norte, Avenida Peru, and Sporting Club) are also shown.

Figure 3. Early government map of Viña del Mar originally drawn at the scale of 1:20,000. This is the only 19th century map showing the urban district and natural vegetation. Much of Plan de Viña was clear of natural vegetation and presumably under cultivation. Patches of forest coincide with floodplain facies, which accumulated in a levee backswamp.

Figure 4. Comparison of shoreline features between the modern base map of Viña del Mar and the most detailed early map (Tessan, 1838). Note single channel of the estero, former sand spits built from the north into a lagoon, and open water to Plaza Vergara, features also shown on other maps descrubed in references (1600's, 1712, 1764, 1849, 1877, 1891, and 1903). Modern shoreline conversions took place prior to 1910.

Figure 5. Geology of the study area after Rivano et al. (1993) and Gana et al. (1996). Potrero Alto deposits in the canyon of the Estero Marga-Marga (unshaded, enclosed by heavy line) and the modern alluvium in Valparaíso lie in Neogene half-grabens. Other unshaded areas are underlain by fundamental rocks. Note pattern of faults with displacements from Gana et al. (1996) and this study. Especially prominent are faults in the Esteros Casablanca, Marga-Marga, and Limache, all of which show late Quaternary displacements.

Figure 6. Seismic setting of the Valparaíso area after Compte et al (1986). Time-distance diagram (a) shows rupture length for three well documented large earthquakes (1822, 1906, 1985). Map of the coastline shows selected seismic features and the location of Viña del Mar within the overlap zone for large earthquakes.

Figure 7. Mean monthly tide at the Molo de Abrigo (Valparasío, top line) and a reference station at Caldera (30°S, lower line), based on data from the Armada de Chile and the University of Hawaii Sea Level Center. Significant earthquakes occured on March 28, 1965, July 8, 1971, October 16, 1981, and March 3, 1985. Record is discontinuous, and broken into segments A-E.

Figure 8. Geologic setting of Viña del Mar (after Gana et al., 1996) showing location of geological features described in the text and location of accelerograph stations reported by Celebi (1986). Outcrop of the Potrero Alto deposits north of the estero (Tqpa) lies within a half-graben dipping northward. Other units include: QTt, marine terraces; Pzmg, basement rocks; Jlv, metavolcanic Jurassic rocks; Tn, marine Navidad formation. Most of the area (white) underlain by Jurassic intrusive rocks.

Figure 9. Sea level curve of Fairbanks (1989) based on U-series dates from Barbados coral. Tectonic uplift rate for Viña del Mar is estimate from several techniques (see text). Thresholds (arrows) indicate fundamental changes in emergence and submergence which controlled the subsurface geology in Viña del Mar.

Figure 10. Bathymetry of the continental shelf after the Armada de Chile (1965) and geologic features described in text (Andrade and Castro, 1987; Caviedes, 1972). Submarine features are consistent with conventional global sea level history (Fairbanks, 1989). Geologic fault in the lower estero Limache extends to Rocas Concon, which are interpreted as pressure ridges along a fault trace.

Figure 11. Measured elevations from the 1999 Geographic Information System data base for the Municipality of Viña del Mar. Symbols «T» show spot elevations for prominent marine terraces. Heavy gray line shows +25 m contour interval.

Figure 12. Borehole records used to reconstruct the stratigraphy below Viña del Mar. Material descriptions for boreholes labeled GA from Grimme and Alvarez (1964). Boreholes MS from Miguel Petersen at UTFSM. Excavation locates a visual sighting.

Figure 13. Zonification of soils beneath Plan de Viña after Luengo (1986). Descriptions indicated by Roman numerals are based on materials in the upper 7-8 m. Note that zone boundaries coincide with street network and make no provision for the Falla Marga-Marga.

Figure 14. Panel diagram of borehole stratigraphy below Plan de Viña drawn parallel to the axis of the estero. Location of cores shown in Figure 12. Descriptions below Roman numerals based on reference cores used by Luengo (1986). Depths below the surface are converted to elevations using modern GIS data base. Solid gray line at top is schematic representation of the topography and bathymetry from modern maps.

Figure 15. Schematic diagrams showing inferred stratigraphy below the level of known borehole records, based on sea-level history and the hydrology of the Estero Viña del Mar. Sketch map (a) shows location of longitudinal profile (b) and transverse (c) profile. In transverse profile, CH (channel) Facies and FP (floodplain) Facies are shown. At depth are estuarine facies (e), alluvial fill (a) and colluvial (c?) materials. Marine interglacial (?) terrace indicated by letter «t.»

Figure 16. Subsurface geologic map of Plan de Viña during Stage 4 (Delta) of the present marine transgression, which took place some time between about 5 ka and 8 ka. The materials shown represent those occurring below -10 m elevation. Boundary of the lagoon (at its largest extent) concides with finer-grained materials at depth, especially near its center. All boundaries are schematic. The Falla Marga-Marga bisects the lagoon parallel to its long axis.

Figure 17. Generalized geologic map of Plan de Viña showing materials above -10 m. All units are interbedded and gradational. The geology at depth (Figure 16) is different from that near the surface. Circle represents zone of maximum complexity, where all three facies interfinger above the center of the ancient lagoon.

Figure 18. Map showing air-photo lineaments of unknown origin from frame 092 of the 1954 CAL.FL aerial survey and from 1996, as discussed in text, and the location of edificios suffering substantial damage during 1985 (Calcagni, 1988). Quote from Perez (1988) summarizes damage to houses in 1985. The lineaments are concentrated above the center of the buried lagoon, and may reflect ground failures.

Figure 19. Geologic map of Viña del Mar (see Figure 8 for unit descriptions) showing projection of fault contacts (dashed lines) and features associated with the gravity model of Verdugo (1995). Note that the location of the gravity minimum does not coincide with the deepest part of the valley, which should occur at the coast. Two uniform gravity gradients (arrows) are oriented directly away from high denisty rocks.

Figure 20. Schematic drawing of strata from the Potrero Alto formation exposed in a roadcut midway between Puente Jardin Bootanical and the summit of Canal Beagle (located on Figure 8). Strata are pervasively deformed by features associated with a blind thrust fault, interpreted to be associated with a stepover between strands of the Marga-Marga Fault.

Figure 21. Locations of four phenomena associated with the earthquake of August 16, 1906 relative to the trace of the Marga-Marga Fault. Sources include reporting by the El Mercurio de Valparaíso (1906), Rozas and Curzat (1906), Ballore (1915) and Larrain (1946).