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DESPLAZAMIENTOS TECTONICOS Y EUSTATICOS DE LA COSTA CENTRAL DE CHILE DURANTE EL NEOGENO

NEOGENE TECTONIC AND EUSTATIC DISPLACEMENTS OF CENTRAL CHILE COASTAL ZONE

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RESUMEN

Se datan numéricamente cuatro discordancias (U1=21.0; U2=13.8; U3=10,5; U4=4.2 Ma), por correlación de los ciclos eustáticos del Neógeno con los eventos transgresivo-regresivos de Navidad, San Antonio y Reñaca. Con esos antecedentes, se infieren los siguientes rangos de desplazamientos tectónicos y de fluctuaciones eustáticas:

Las diferencias de cota para una misma discordancia, en distintas localidades, evidencian desplazamientos de origen tectónico. Considerando a Navidad como un bloque de referencia fijo, el bloque de San Antonio ha subido 12 metros y más al norte, el bloque de Reñaca ha subido 65 metros. Estos desplazamientos, implican la presencia de bloques limitados por fallas de desplazamiento vertical, con rumbo perpendicular u oblicuo a la línea de costa.

El rango de las fluctuaciones eustáticas se infiere de las litofacies y biofacies de las secuencias sedimentarias. La transgresión Burdigaliana implicó un ascenso del nivel del mar de 75 metros. Posteriormente en el Serravaillano, el mar subió 120 metros adicionales, alcanzando una profundidad del orden de los 200 metros. A fines del Serravaillano, el mar desciende 200 metros, retornando a su estado inicial. Durante el Plioceno medio ocurre un ascenso de 10 metros. Finalmente en el Pleistoceno, el nivel del mar desciende 140 metros, hasta alcanzar su posición actual.

ABSTRACT

Four unconformities are dated numerically by correlation of Neogene eustatic cycles and transgressive-regressive events at Navidad, San Antonio and Reñaca (U1=21.0; U2=13.8; U3=10,5 U4=4.2 Ma). On this basis, the following ranges of tectonic displacements and eustatic fluctuations are inferred:

The differences in altitude of one unconformity's surface at different sites, imply vertical displacements of tectonic origin. Taken Navidad as fixed block, the San Antonio block has been uplifted 12 meters and further north the Reñaca block has been uplifted 65 meters. These displacements suggest the existence of blocks limited by vertical faults striking perpendicular or oblique to the coastal zone.

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The ranges of eustatic fluctuations have been inferred from biofacies and lithofacies of depositional sequences. The Burdigalian transgression implied a sea level rise of 75 meters. Later in Serravallian time the sea level raised 120 additional meters reaching about 200 meters in depth. At the end of Serravallian time, the sea level fell 200 meters, recovering the initial stand of sea level. Throughout middle Pliocene, the sea level raised 10 meters. Finally in Pleistocene time the sea level fell 140 meters, reaching the present stand of sea level.

INTRODUCTION

Global sea level has varied about 200 meters during the Cenozoic, in response to global tectonic forces that alter the volume of the ocean basin, and to climatic factors that change the volume of water stored on land as ice (Vail et al. 1977; Haq et al. 1987). Sedimentation, responding to global rising in sea level, has produced depositional sequences, bounded at its top and bottom by unconformable surfaces that are also worldwide synchronous events in geologic time. A depositional sequence is a stratigraphic unit composed of a relatively conformable succession of genetically related strata, bounded at its top and bottom by unconformities or their correlative conformities (Mitchum et al. 1977).

In Central Chile, the emergence of Neogene sequences has produced an outstanding marine terrace, here outlined to discuss the eustatic and tectonic history of the area. The terrace is a subhorizontal surface that, starting at Navidad and up to Reñaca (110 km), narrows in width from 30 to 6 km (Fig. 1). The altitude of this discontinuous flat surface decreases seaward from 140 m above sea level, at the foot the Coastal Cordillera, to an average of 80 m at the coastal cliffs (Alvarez, 1964; Fuenzalida et al., 1965). In this paper, "marine terrace" means the platform like basement that slopes gently seaward, plus the sedimentary sequence (exposed shelf) that decrease landward in thickness. The terrace consists of several Neogene horizontal sequences resting unconformably over a metamorphic and igneous basement of upper Paleozoic to Jurassic ages (Corvalán and Munizaga, 1972; Tavera, 1979; Cecioni, 1980; Hervé et al. 1987). These stratigraphic units crop out along the coastal cliffs and in deep meandering gorges. Vertical faults limiting uplifted, downsunk and tilted blocks of the terrace are also common (Paskoff, 1977).

Although emergence (or submergence) of marine features may result from tectonic or eustatic changes, the occurrence of Miocene eustatic cycles along the Pacific coast of South America seems to be evident from the present distribution of fossiliferous localities (Martínez, 1990). Because of this, the Miocene sequences are here considered as the starting point for the analysis of the displacements of the coastal zone. The minimum data required to discuss this topic are the present altitude of the unconformities and their numerical ages. The available topographic charts issued by the Instituto Geográfico Militar (1968) give the altitude of the features but the known biostratigraphic ages of the sequences, not been numerical, preclude obtaining meaningful data on the vertical displacement rates. Because of this, the presently known chronology of fluctuating sea levels (Haq et al. 1987), is used to imply numerical ages for the sequence boundaries.

The mentioned approach requires the use of paleontologic, sedimentologic and tectonic pieces of evidence, related to well known stratigraphic cross sections in areas

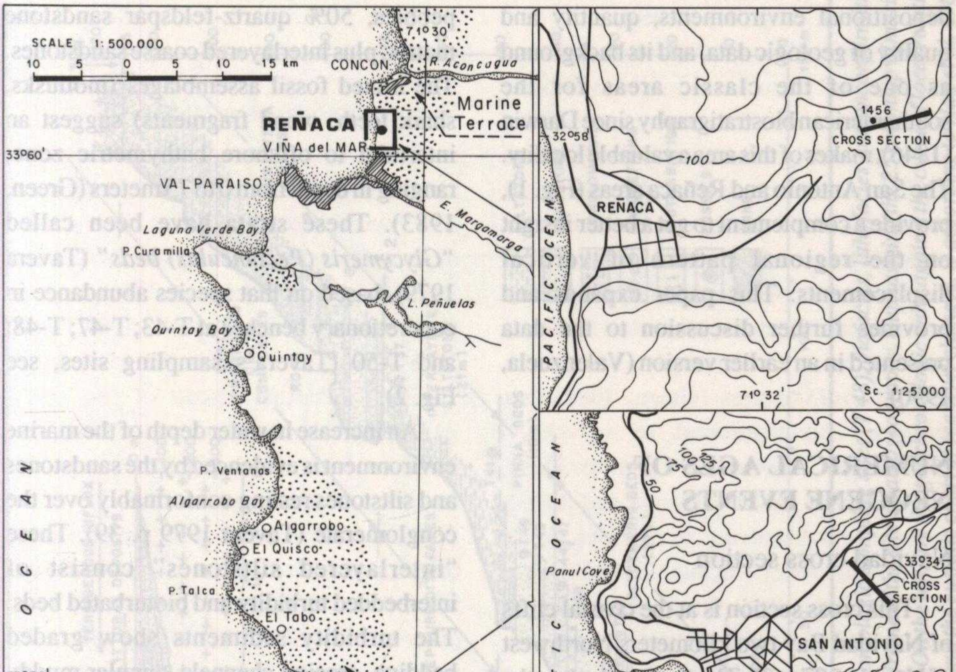

Figure 1. Location map of the Central Chile coastal zone. It shows the marine terrace and studied areas (rectangles). The maps on the right show the site of the cross sections at Navidad (lower), San Antonio (middle) and Reñaca (upper).

where structural deformation is not too intense. In this sense, the Navidad area is the ideal place to integrate the sedimentary record and the eustatic chart of sea level cycles. Its sedimentary thickness, variety of depositional environments, quantity and quality of geologic data, and its background as one of the classic areas for the southamerican biostratigraphy since Darwin (1846), makes of this area a valuable locality. The San Antonio and Reñaca areas (Fig. 1), provide a complement to get a better insight on the regional pattern of vertical displacements. This paper expands and provides further discussion to the data presented in an earlier version (Valenzuela, 1990).

NUMERICAL AGES OF NEOGENE EVENTS

Navidad cross section

This cross section is at the coastal cliffs of Navidad Bay two kilometers Northwest of Navidad (Fig. 2). The section depicts the stratigraphic synthesis of early/middle Miocene horizontal units, spreading over 2.000 sq. km (Cecioni, 1978; Osorio, 1978; Tavera, 1979; Frassinetti and Covacevich, 1981-1982; Martínez, 1990). The upper sketch, is the conceptual frame of the site's paleogeography, emphasizing the 18 km onlap of marine deposits and the sea level rise in the range of 200 meters. On the left, the geochronologic units are plotted against the curve of local relative changes of sea level (RCSL). The known chronologies of these fluctuating sea levels (Haq et al. 1987), match the sequence boundaries.

The section consists of two transgressive units separated by a regressive erosion event located at the top of the "interlayered siltstones". The basal unit rests unconformably over 10 meters of barren sandstones veneering the tonalitic basament. The marine basal layer is a 27 meter thick concretionary and fossiliferous conglomerate. It consists of 30% angular metamorphic fragments, 20% andesitic pebbles, 50% quartz-feldspar sandstone matrix, plus interlayered coarse sandstones. The mixed fossil assemblages (mollusks, shark teeth, wood fragments) suggest an intertidal to offshore bathymetric zone, ranging in depth from 0 to 75 meters (Green, 1983). These strata have been called "*Glycymeris (Pectunculus) beds*" (Tavera 1979), based on that species abundance in concretionary benches at T-43; T-47; T-48; and T-50 (Tavera's sampling sites, see Fig. 2).

An increase in water depth of the marine environment is evidenced by the sandstones and siltstones resting conformably over the conglomerate (Tavera 1979 p. 39). These "interlayered siltstones" consist of interbedded turbidity and bioturbated beds. The turbidity sediments show graded bedding, erosion channels, angular muddy fragments, and flattened mud balls. According to Osorio (1978), the ostracode species included in these layers "are restricted to a depth beyond 200 meters but some occasional shallow species indicate redeposition in a deeper media". These data suggest an open sea environment and water depths in the range of several hundred meters. On the basis of these facts, the botton and top surfaces of this 58 m unit are respectively correlated in figure 2, to the lower and higher stands of the Burdigalian-Serravallian eustatic supercycle (Haq et al. 1987).

The top of the "interlayered siltstones" is another unconformity surface showing flute solemarks (striking 75º East), of 4 cm in amplitude and 10 to 15 cm in wave length. The basal layer above this erosion surface is a coarse sandy turbidity showing armored

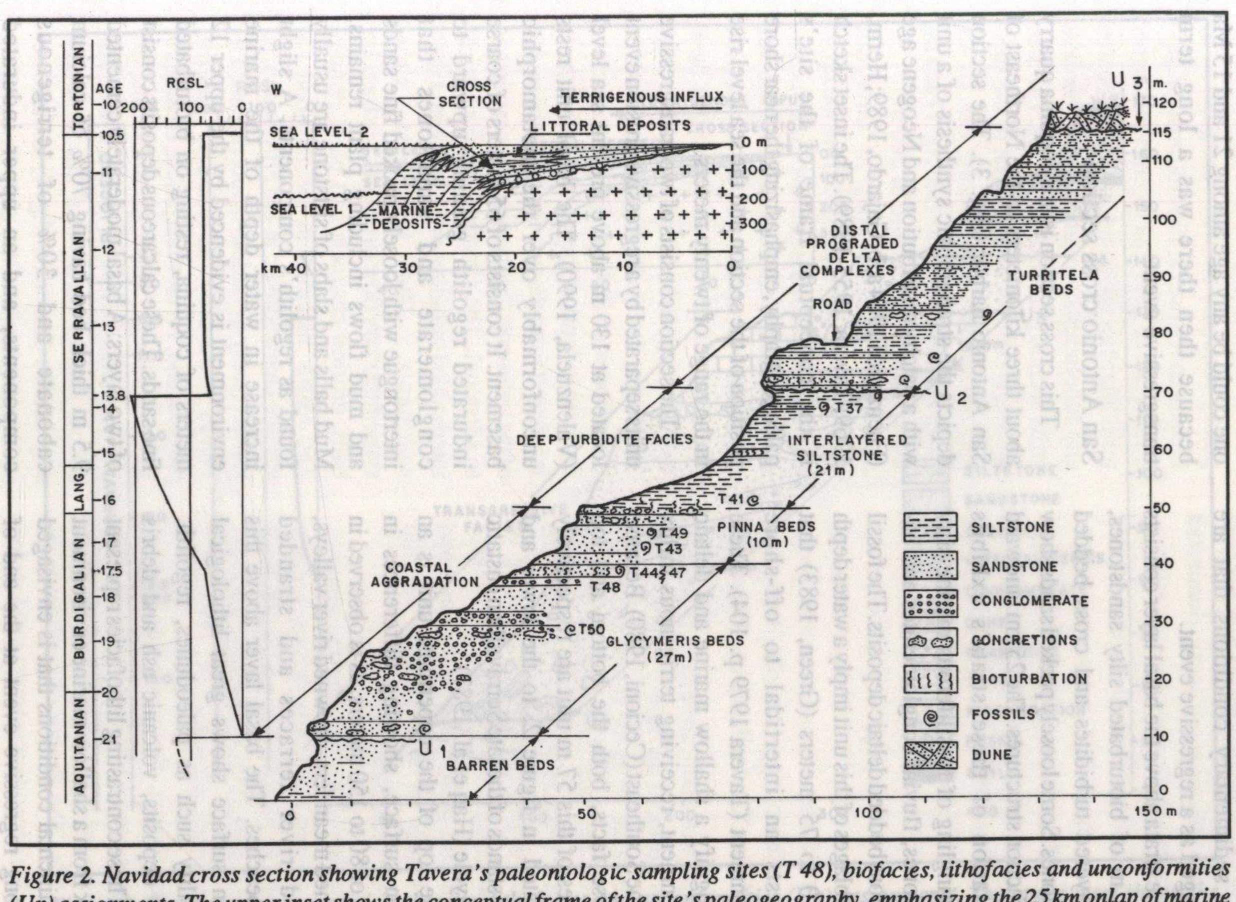

Figure 2. Navidad cross section showing Tavera's paleontologic sampling sites (T 48), biofacies, lithofacies and unconformities (Un) assignments. The upper inset shows the conceptual frame of the site's paleogeography, emphasizing the 25 km onlap of marine deposits and the sea level rise in the range of 200 meters. On the left, are the geochronologic units against the curve of local relative changes of sea level (RCSL). Ages are in million years, and the eustatic chart of sea level changes, is according to Haq et al. 1987.

mud balls, andesitic pebbles and coal fragments, in a fine ashy matrix (Chambers et al. 1985). These contrasting lithofacies represent a break from deep to shallow water sedimentary conditions that are envisaged as a regressive event.

The strata above the basal layer consists of 57 m of bioturbated silty sandstones, interlayered turbidites and cross bedded sandstones. Some loosely packed sands show liquefaction structures. The 25 km landward correlation of these strata's exhibits intermingling of fossiliferous marine silty sandstones, fluvial conglomerates and barren cross bedded deltaic deposits. The fossil assemblages of this unit imply a water depth from 0 to 75 meters (Green, 1983) that suggests an intertidal to off-shore environment (Tavera 1979 p. 104). These data signify a shallow marine and deltaic environment, receiving terrigenous influx from the Southeast (Cecioni, 1980). Because of these facts, both the bottom and top surfaces of this 57 m unit are respectively correlated in figure 2, to the lower and higher stands of the late Serravallian eustatic supercycle (Haq et al. 1987).

The top of the uppermost unit is an erosion surface, showing differences in height of 80 to 150 meters, as is observed in deepened meanders, drowned river valleys, eroded river terraces and stranded paleobeaches. The basal layer above this erosion surface shows great lithological variability such as paleodunes, regolith, fluvial deposits, volcanic ash and debris flow. These contrasting lithofacies represent a break from a shallow marine environment to continental conditions that is envisaged as strong regressive event at the end of middle Miocene.

Because of these facts, the numerical ages assigned to the unconformities are U1=21.0 Ma (early Burdigalian); U2=13.8 Ma (early Serravallian); U3=10.5 Ma (late Serravallian) respectively. The degree of confidence on these figures is high for the second and third assignments but the first one could be any age among 21 and 15 Ma because then there was a long term transgressive event.

San Antonio cross section

This cross section is at a coquina quarry about three kilometers to the Northeast of San Antonio harbor (Fig. 3). The section depicts the stratigraphic synthesis of a unit with a patchy distribution and Neogene age (Fuenzalida 1964 a, b; Gajardo, 1989; Herm, 1969; Tavera, 1955-1989). The inset sketch is the conceptual frame of the site's paleogeography, emphasizing the near shore position of the section and the sea level rise in the range of twenty meters.

The section consists of two transgressive units separated by a regressive erosion event located at 130 m above present sea level (Valenzuela, 1990). The basal unit rests unconformably over the metamorphic basement. It consists of 65 meters of coarse indurated regolith grading upward to conglomerate and sandstones that intertongue with loosely packed fine sands and mud flows including plant remains. Mud balls and slabs of siltstone are usually found as regolith's components. A slight increase in water depth of the marine environment is evidenced by the upper 12 meters of coquina, resting on bioturbated fine sands. These calcareous deposits consist of two layers: A basal moderately cemented 9.5 m thick bed having 70% of calcium cabonate and 30% of terrigenous components, and an upper indurated coquinite with 89% of carbonates.

The top of the coquinite is an unconformity surface showing pot holes (3 to 5 m in deep) filled with sandy con-

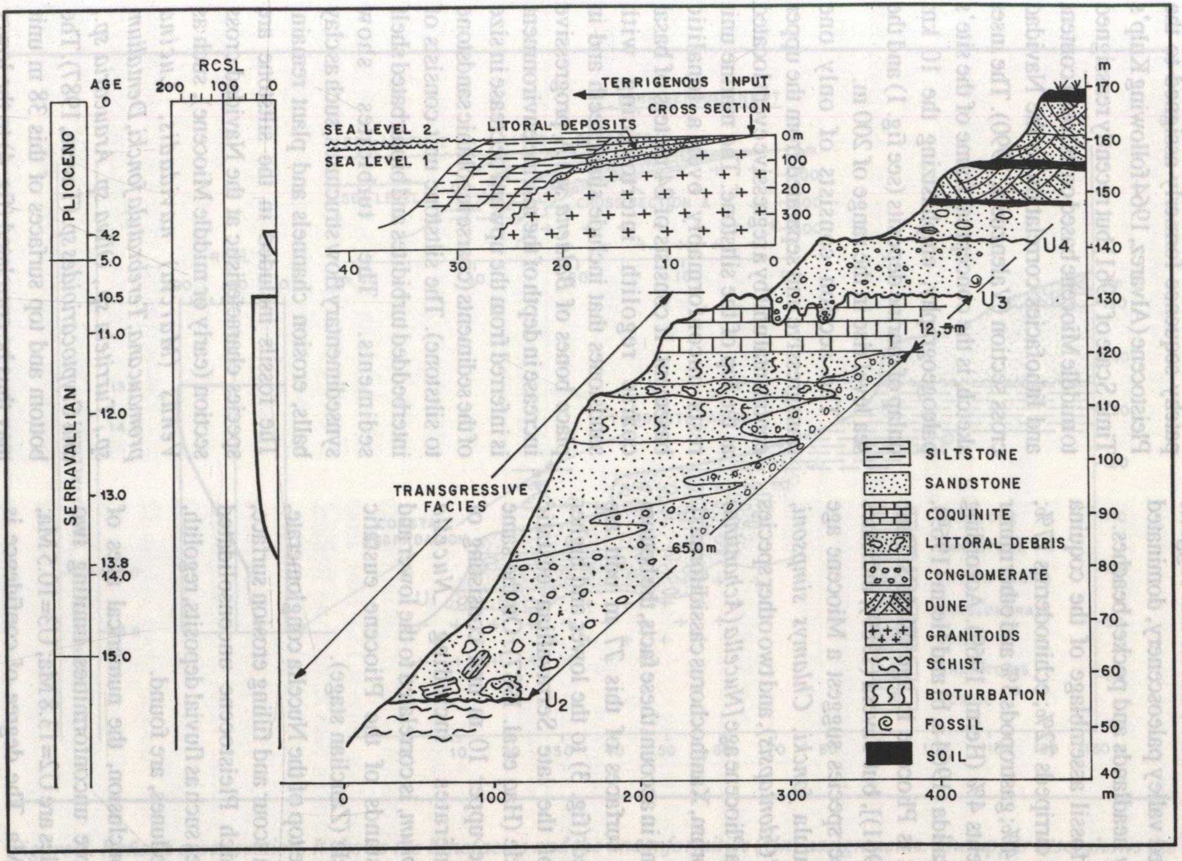

Figure 3. San Antonio cross section showing lithofacies and unconformities (Un) assignments. The upper inset shows the conceptual frame of the site's paleogeography, emphasizing the near shore position of the section and the sea level rise in the range of 20 meters. For the left inset, see figure 2 caption and explanation.

glomerates including cetacean bones and well preserved shells of Nucella crassilabrum. This basal unit grade laterally northwards and southwards to beach gravels and cliff carved rock's debris that suggests a drowned valley paleoscenery, dominated by rocky headlands and pocket beaches.

The fossil assemblage of the coquina includes cirripeds 72%; echinoderms 17%; bivalves 4%; gastropods 3% and other minor components 4% (Herm, 1969). According to Fuenzalida (1964 a, b) and Herm (1969), this unit is Pliocene in age (Kulp's Time Scale, 1961)], but Tavera (1989), indicates that three species suggest a Miocene age [Terebratula *foncki, Chlamys simpsoni, Lamma (Odontapsis)*, and two other species indicate a Pliocene age *[Nucella (Achantina)* crassilabrum, Xanthochorus cassidiformis].

Taking in account these facts, the bottom and top surfaces of this 77 m unit are correlated (fig. 3) to the lower and higher stands of the late Serravallian eustatic supercycle (Haq et al. 1987). On the same basis, the upper 10 m unit consisting of conglomerates including *Nucella crassilabrum,* is correlated to the lower and higher stands of the Pliocene eustatic supercycle (Zanclian stage).

At the top of the Nucella conglomerate, there is a scour and filling erosion surface, over which Pleistocene unconsolidated lithologies such as fluvial deposits, regolith, and paleodunes, are found.

In conclusion, the numerical ages of these three unconformities limiting two supercycles are U2=13.8 Ma; U3=10.5 Ma; U4=4.2 Ma. The degree of confidence is high for the second assignment and low for the first one. The last one might be a million years younger (3.2 Ma), because two Pliocene transgressive events have been recognized worldwide (Haq et al. 1987).

Reñaca cross section

This cross section is at a brick factory (Bulnes Nº 1456), 2 km East of Reñaca (Fig. 4). The section depicts the synthesis of a patchy sequence formerly assigned to the Pleistocene (Alvarez, 1964 following Kulp's Time Scale of 1961) but recently reassigned to middle Miocene based on its fossil content and lithofacies correlation to the Navidad cross section (Valenzuela, 1990). The inset sketch, is the conceptual frame of the site's paleogeography, emphasizing the 10 km onlap of marine deposits (see fig. 1) and the sea level rise in the range of 200 m.

The section consists of only one transgressive unit separated from the upper continental unit by a regressive event located at the top of the siltstone. The marine unit rests unconformably over a tonalitic basement. It consists of 24 meters of basal coarse regolith intertonguing with sandstones that include shark teeth and in place bones of *Balaena sp.* A progressive increase in depth of the marine environment is inferred from the upward decrease in size of the sediments (coarse regolithic sandstone to siltstone). The siltstone unit consists of interbedded turbidites and bioturbated shelf sediments. The turbidites show synsedimentary flow structures, such as clay balls, erosion channels and plant remain. The fossils included in the siltstone are species characteristic at the Navidad cross section (early or middle Miocene), such as *Venus (Marcia) navidadis, Lucina promaucana, Terebratula foncki, Dentalium sp., Turritela sp., Oliva sp. Araucaria sp., and Cryptocarioides sp.* (Tavera, 1987). The bottom and top surfaces of this 38 m unit may thus be correlated (fig. 4) to the lower and higher stands of the early Serravallian eustatic supercycle (Haq et al. 1987).

Above the siltstone's unconformity, the sedimentary environment changes from marine to continental conditions. The

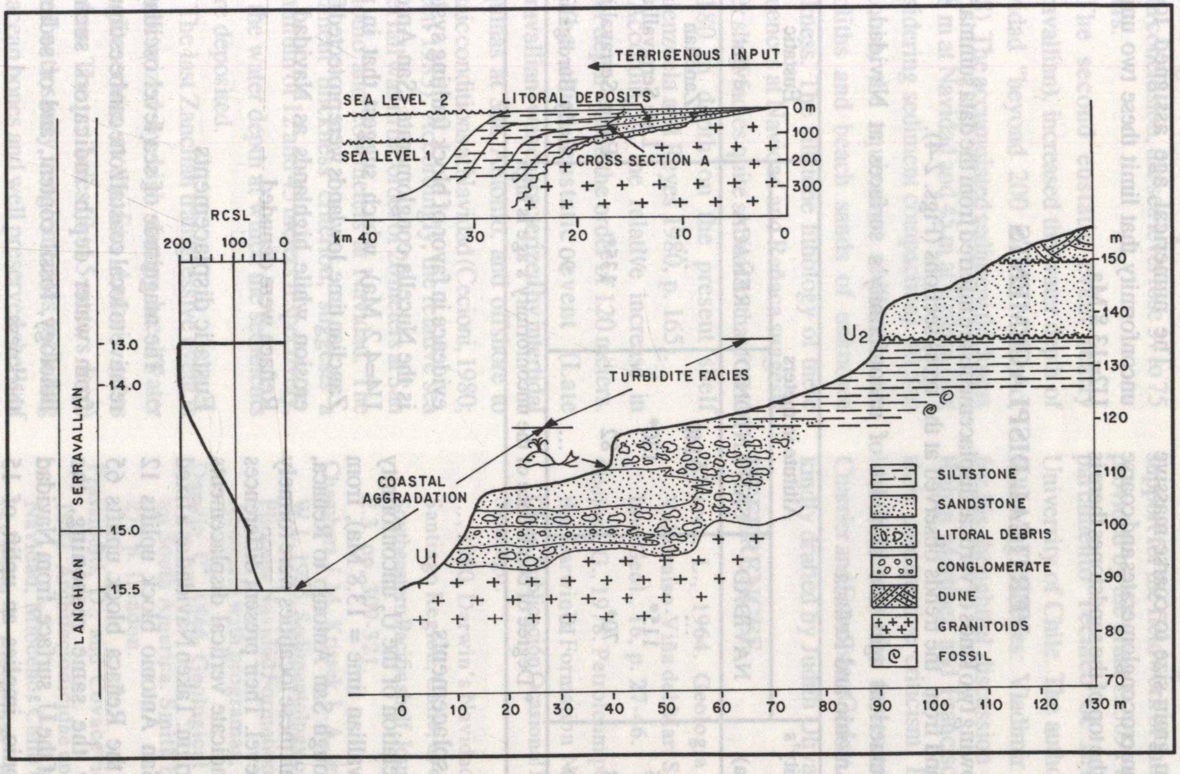

Figure 4. Reñaca cross section. It shows the lithofacies and the unconformities (Un) assignments. The upper inset shows the conceptual frame of the site's paleogeography, emphasizing the 18 km onlap of marine deposits and the sea level rise in the range of 200 meters. For the left inset, see figure 2 caption and explanation.

lithologic break (fossiliferous siltstone below and barren sandstone above), indicates an environment change from marine to continental conditions. The strata of the upper unit are cross bedded fine sandstones upward increasing in grain size to coarse massive sandstones, micro conglomerates and coarse regolith. At the top of the sandstones there is an erosion surface that shows differences in relief of 20 to 150 meters, as observed in four systems of andesitic stranded paleodunes.

The numerical age assigned to the unconformity that limit these two units is U2=13.8 Ma.

VERTICAL DISPLACEMENTS

The following two kinds of vertical displacements are inferred from the data summarized in Table 1, and from the trends observed at the cross sections (Figs. 2-4).

Table 1. Numerical ages and altitudes of unconformity's surfaces at Navidad, San Antonio and Reñaca.

Unconformity's AGE (Ma)	Altitute in meters			Eustatic event
	NAVIDAD	SAN ANTONIO	REÑACA	
U_4=4.2	…	140	…	Zanclian
U_3=10.5	115*	130*	…	Late Serravallian
U_2=13.8	70*	82	135*	Early Serravallian
U_1=21.0	10	…	90	Early Burdigalian

* Degree of confidence of the unconformity's age is high

Tectonic displacements

The correlation of the U_2 unconformity (early Serravallian time = 13.8 Ma), from Navidad through San Antonio to Reñaca, implies that all these localities were formely at the same level. Their present differences in altitude indicate vertical displacements of tectonic origin. Taken Navidad as a fixed block, the San Antonio block uplifts 12 meters and the Reñaca block uplifts 65 meters. By the same reasoning, the correlation of the U_3 surface, from Navidad to San Antonio, implies an uplift of 15 meters of the San Antonio block. These northward's increasing differences in altitude suggest a vertical block faulting system that is perpendicular or oblique to the coastal zone. Another rather indirect evidence in favor of block faulting systems is the Nucella conglomerate (San Antonio U4=4.2 Ma), which suggest that in post Zanclian time, lowlands were protected from erosion while highlands as Navidad and Reñaca were denuded.

Eustatic displacements

The magnitude of sea level oscillation relative to local coastal zone can be estimated from water depth indicators such as lithology, fossil content, and or sediment thickness.

The early Burdigalian transgression at Navidad implied a progressive change from high energy breakwater conglomerates to low energy offshore sandstones.

The fossil content of these beds suggests a 0-75 m water depth (Green 1983; Tavera 1979 p. 104). The sediment thickness (Glycymeris plus Pinna beds) sets a minimum for the sea level rise of 37 m (not considering sediment compaction).

In conclusion, the sea level rose 37 to 75 meters.

The second eustatic event (early Serravallian), increased the water depth of Navidad "beyond 200 meters" (Osorio, 1978). The accumulated sediment thickness is 58 m at Navidad and 45 m at Reñaca (not considering sediment compaction). At San Antonio, the equivalent sediments are regoliths and beach sands of unknown thickness. The siltstone lithology of these sequences at Navidad and Reñaca suggests outer shelf facies quite similar to that found at 180 m depth on the present shelf (Valenzuela and Reyes 1980, p. 165).

Accordingly, the relative increase in water depth was in the order of 120 meters.

The third eustatic event (Late Serravallian) was characterized by intertidal coquinas at San Antonio, and offshore to deltaic conditions at Navidad (Cecioni, 1980; Green 1983). Accordingly, the relative sea level fall was in the order of 20 meters at San Antonio and 200 meters at Navidad. The sediment thickness criterion, suggests a minimum of 12 and 45 meters respectively, for the water depth at which the sediments were deposited.

The last Zanclian transgressive event is characterized by high energy breakwater conglomerates at the San Antonio cross section. The pot holes (3 to 5 meters deep) filled with sandy conglomerates including cetacean bones and well preserved shells of *Nucella crassilabrum* imply a minumum sea level rise in the range of 10 meters.

After the Pliocene event, evidence of a general Pleistocene regression implies a sea level fall from 115 to 140 meters, as inferred from the present altitude of the unconformity surfaces.

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