Comunicaciones Nº 40 (1989): 57 - 68

FALLAMIENTO NORMAL RECIENTE EN LA LAGUNA DE SAN RAFAEL, PROVINCIA DE AYSEN, CHILE AUSTRAL

RECENT NORMAL FAULTING AT THE LAGUNA DE SAN RAFAEL, AISEN PROVINCE, SOUTHERN CHILE

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RESUMEN

El margen occidental de los Andes Australes en los 46°40' latitud Sur está definido por una falla normal activa de rumbo NNE-SSW. Su movimiento más reciente parece haber ocurrido entre 1900–1930 AD, asociado a un sismo de magnitud aproximado, 6,8 que provocó un descenso de 3 m al bloque oeste a lo largo de 25 km. Se le sugiere un intervalo de recurrencia cercano a los 7.000 años durante el Cuaternario.

ABSTRACT

The western margin of the Southern Andes at 46°40'S is defined by an active NNE-SSW normal fault. The most recent movement on this fault involved a 3 m, down to the west displacement, along a 25 km fault segment, and appears to have occureed as recently as 1900 - 1930 AD., in association with an estimated M6.8 earthquake. A recurrence interval of around 7.000 years is suggested for this fault through the Quaternary.

INTRODUCTION

At the southern end of the N-S, coast parallel, Golfo Elefantes fjord (Aisen Province, southern Chile) there is a marked topographic asymmetry. The region to the west comprises low and rounded hills while to the east there is a steep mountain scarp rising to 900m in a horizontal distance of 1.5km. Beyond this first mountain wall there is a region of considerable

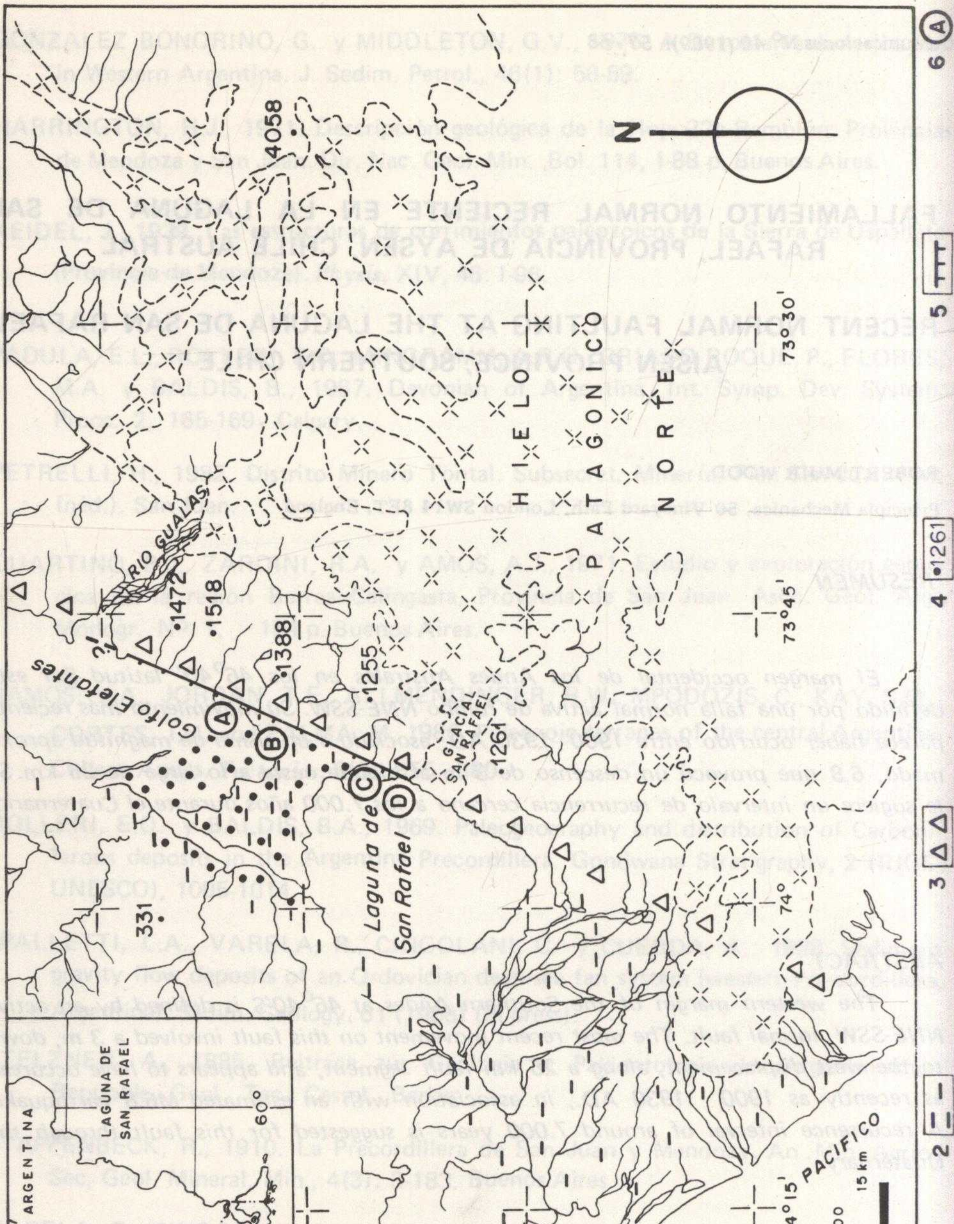

Fig. 1. Mapa de la región aledaña a la falla de San Rafael, Aisen, Chile. 1. Sedimentos lacustres y fluviales del Holoceno medio; 2. Area cercana al nivel del mar; 3. Fuente montañosa andina; 4. Cota; 5. Falla San Rafael; 6. Localidades investigadas.

Fig.1. Map of the region around the San Rafael Fault, Aisen Province, Southern Chile. 1. Region underlain by mid-Holocene lacustrine and fluvial sediments; 2. Land close to sea-level ; 3. Andean mountain front; 4. Spot elevation; 5. San Rafael Fault; 6. Investigation localities.

elevation, including, within 5km, summits between 1200 and 1600m. A few kilometres further inland lies the most northerly South American icecap (the Hielo Patagónico Norte) and the highest mountain in the southern Andes, Cerro St Valentin, 4058m (Fig. 1). The explanation for the contrast in the topography on either side of the fjord cannot be found from the bedrock geology which comprises rocks of the late Mesozoic Patagonian batholith, and metamorphics of both Mesozoic and Palaeozoic ages (Servicio Nacional de Geología y Minería, 1982).

HOLOCENE GEOLOGY

At the southern end of the Golfo Elefantes the fjord has become blocked with glacial debris brought down by various feeder glaciers from the North Patagonian Ice-cap. This region of marshy lowlands surrounds the deep-water 12km by 8km Laguna de San Rafael, formed in the mid-Holocene advance of the San Rafael piedmont glacier. To the north of the lagoon, beyond the fringing walls of moraine that rise to 40m, the land slopes to the north at a gradient of about 1:1000, falling from 6m elevation at the outer edge of the moraine until it passes in salt marshes beneath the waters of the Golfo Elefantes. Over all the land between the lowest and highest extreme tides there are stumps and standing poles of trees, part of an extensive area of forest drowned as a result of subsidence.

The superficial sediments of this low-lying area, exposed in the walls of the tidewater channel (the Río Témpanos) connecting the Laguna San Rafael to the Golfo Elefantes, comprise fluvio-glacial sands and gravels and marine and lacustrine(?) silts. At the southern end of the channel the sediments coarsen and interdigitate with the outer moraine ring around the Laguna San Rafael. The field relations of these sediments are relatively complex. In some sections fluvial sediments underlie moraine. However the gently dipping surface evidently formed from fluvial, and lacustrine deposition in a section of the fjord dammed to the south by the San Rafael piedmont glacier and to the north by the Gualas piedmont glacier, whose outer ring of moraines today form a series of low hills and islands opposite the outlet of the Gualas valley. The peats which developed above the gravels on the outer edge of the San Rafael moraine, were radiocarbon dated as 3,500 $\pm$ 140 years (Heusser, 1960).

THE SAN RAFAEL FAULT

At the foot of the mountains to the east of these lowlands there is a narrow trough, between 5 and 20m in width, and up to 1m deep, marking a line of ponds and bogs. On the eastern side of this trough there is a steep scarp which then passes into the general 30" mountain-side. From both Landsat images and aerial photographs the base of the mountain front defined by this trough is seen to be a very straight linear cutting streams, valleys and almost all the landslide deposits from off the steep mountain side (Fig. 2). In the field there is little exposure along this linear feature

Fig. 2. Foto aérea de la falla San Rafael. Ventisquero San Rafael en el borde inferior derecho.
Fig. 2. Aerial photographs of the San Rafael Fault, San Rafael Glacier and bottom right.

(obscured by the dense vegetation that flourishes in the rainfall of 4,000 mm/yr) although there are a series of waterfalls on cross-cutting streams.

The existence of this narrow trough, its linearity and continuity as seen from aerial photographs (and Landsat images) over 25km, its presence at the base of a steep mountain-scarp, allied with the remarkable topographic asymmetry of the Golfo Elefantes, all strongly suggest that this is an active fault with significant vertical displacement.

Field Investigations

To confirm the outcrop of this fault and to attempt to date the last episode of movement along it, field investigations were undertaken at three localities, identified in fig 1.

Locality A, at the eastern shore of the Rada San Rafael, southern end of the Golfo Elefante.

The fault runs very close to the present-day eastern shoreline of the Golfo Elefantes, passing offshore to the north. About 1500m north of the edge of the salt marshes at the southern fringe of the bay, the mid-Holocene fluvial and lacustrine sediments are exposed as low cliffs, about 3-4m high, in the eroded footwall to the east of the fault (Fig. 3). Exactly the same (silts overlying sands and gravels), near-horizontally dipping, sediments outcrop along sections of the beach to the west of the fault-trace, 3m lower than in the cliff. Although the main fault itself is obscured by thick vegetation, two or three easterly dipping antithetic faults are seen in wave-cut beach sections, trending N 30"E, with offsets of around 50 cm.

Locality C. Río Saltón.

The Rio Salton plunges over a series of waterfalls out onto the flat-lying area of fluvio-glacial sediments at the north-east edge of the Laguna San Rafael. However as the river is choked with boulders there is no exposure of any fault-scarp. To the south of the river, augur samples were taken from the bogs and ponds that have formed in the trough at the base of the mountain-slope. Despite the frequent landslides from this mountain-side (some of which are only a few years old) and the dense forest vegetation, the trough contained only 100-200mm of humus, beneath which lay fluvial sands and gravels identical to the material found at the surface to the east, 0.5 to 1m above the level of the base of the trough. This trough appears therefore to have been downfaulted, as some kind of graben, bounded to the west by antithetic fault(s), as observed outcropping on the beach at locality A. While no clear fault exposures were found at locality C (chiefly because the surface sediments comprise loose gravels), the graben is bounded to the east by a steep, approximately 3m high, scarp at the base of the mountain slope, taken to be the outcrop of the main fault.

Fig.3. Sedimentos lacustres y aluviales del Holoceno medio en el escape de falla erosionado de la falla San Rafael. Orilla oriental del Golfo Elefante (localidad A).

Fig. 3. Mid-Holocene lacustrine and fluvial sediments in the eroded fault scarpe of the San Rafael Fault, exposed on the eastern shore of the southern Golfo Elefante (locality A).

Shallow, narrow, asymmetric grabens, adjacent to the main-fault scarp, have been observed in the aftermath of a number of well-studied 20th Century normal fault earthquakes, as for example in the Borah Peak, Idaho earthquake of 1983 (Crone et al., 1987). The formation of a superficial antithetic fault, reflects a steepening in dip of the main fault as it approaches the surface.

The fresh morphology of the graben all along its length and the absence of significant infill, suggests that the movement was relatively recent. Cores were taken with an incremental borer from six trees straddling the edge of the graben, relative to a control of the thickest (and hence oldest) trees located within 50m to the west. Two trees on the edge of the graben had 54 growth rings, while in the other four the core had narrowly missed the centre of the tree and could only be dated as > 40 years (in two cases) >50 and > 52 years. The two larger trees located away from the graben were 64 years and > 70 years.

Locality D.

Close to the San Rafael glacier the lowland comprises coarse gravels deposited by streams passing from the margin of the ice-sheet at the time of its last advance, that culminated in 1882 (Heusser, 1960). (At its 19th Century maximum the piedmont glacier extended 8km into the lagoon, by 1905 it had retreated to 5km and today passes less than 0.5km into the deep water at the eastern edge of the lagoon). On approaching the glacier the graben becomes less distinct but a series of troughs and hollows can be found at the base of the mountain slope, in sediments deposited during or subsequent to the 19 th Century glacial advance.

Landslide Scars

All along the mountain slope above the outcrop of the San Rafael Fault, there are numerous landslide scars (Fig. 4 taken at locality B). For many of these scars the regeneration of the forest with young Nothofagus trees has reached a similar stage strongly suggesting that they were contemporaneous, although two separate stages of regeneration, and hence ages of landslides can be discerned. The dating of succession ecologies around Laguna San Rafael was achieved by (Heusser, 1960), from work undertaken on the colonization of moraines. Full regeneration was found to take around 100 years. The degree of regeneration of the more recent landslide scars along the mountain-side suggests that many of them formed at a period about 25 years ago, probably as a result of the great 1960 earthquake Plafker and Savage, 1970; Veblen and Ashton, 1978). The older generation of landslide scars could reflect strong ground shaking associated with the fault movement that formed the graben. Prior to 1960 the previous great subduction zone earthquake known to have accurred in this region was in 1837.

Fig.4. Regeneración parcial de cicatrices de derrumbes y árboles anegados en buen estado de conservación. Borde SE de Rada San Rafael (localidad B).

Fig.4. Partial generation of landslide scars and well preserved "drowned" tress adjacent to the San Rafael Fault, at the south-eastern edge of the Rada the San Rafael, (locality B).

Drowned Forest

The large region of drowned forest found throughout the lowlands of this region is chiefly attributable to the coseismic subsidence associated with large subduction zone earthquakes. Nineteenth Century explorers who described the drowned forests around the Laguna San Rafael were told by local fishermen that this was the result of the great 1837 earthquake, and there is supporting evidence from tree - rings to corroborate this date (Muir Wood, 1978). However trees killed in 1837 are relatively poorly preserved, comprising either single rotted trunks or stumps. Yet towards the eastern margin of the lowlands a number of the dead trees preserve some of their upper branches (Fig. 4 at locality B). From observations on the preservation of trees in the Chonos islands to the north, sunk in the 1960 earthquake, relative to those sunk in 1837, the degree of preservation of trees at locality B suggests they died closer to 30 than 150 years earlier.

CONCLUSIONS

The observations detailed above are all consistent with a late Holocene displacement episode for the San Rafael Fault. The 3m of observed displacement of sediments formed at around 3,500 years bp. places an upper age constraint on this fault movement, while a number of other lines of evidence suggest that the displacement is very recent. These include: a) the graben associated with the fault passes through sediments deposited in the late 19th Century; b) trees growing across the graben bounding fault had a maximum proven age of 54 years; c) the graben had little infilling debris, and d) 'drowned' trees adjacent to the fault (and potentially related landslide scars) are less than 100 years old. These observations are most compatible with a fault displacement event before 1930, and probably after 1910.

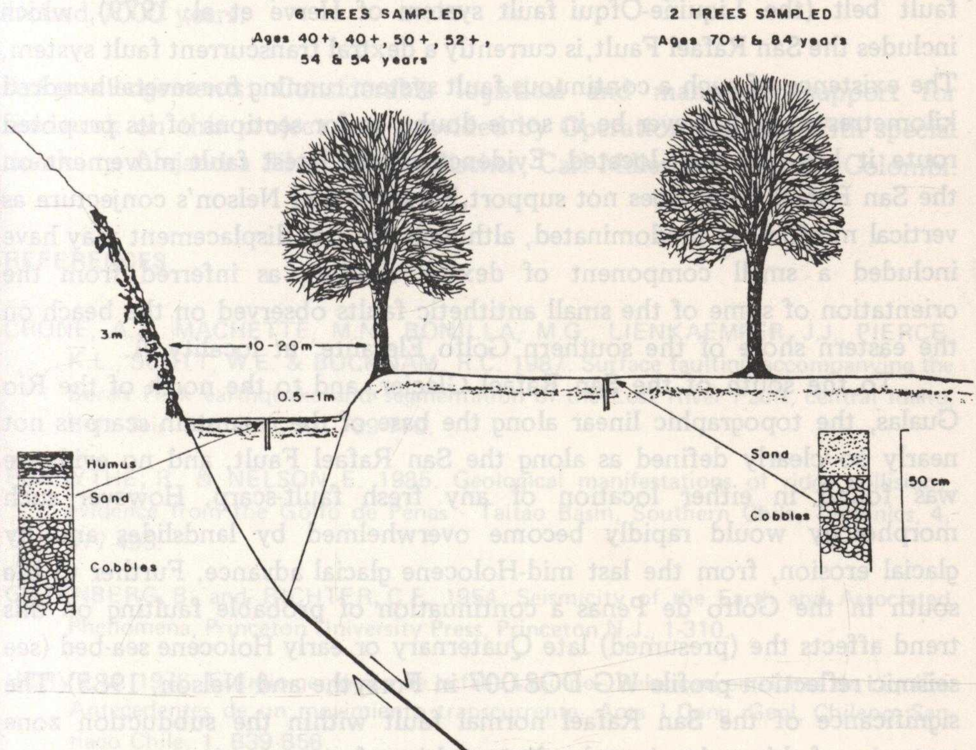

Fig. 5. Perfil esquemático: a través de la falla San Rafael.
Fig. 5. Cross-Section through San Rafael fault.

The displacement (3m) and fault length (25km as mapped from aerial photographs) with estimated down-dip fault width of 20km and rigidity of 3.7 x 10" dyn cm^{-2}, suggest a Moment of around 5 x 10^{26} dyne cm, for this earthquake, from which a magnitude (Mw) of 6.8 can be calculated (Kanamori, 1977). From comparison with other comparable Chilean events such an earthquake is likely to have had a macroseismic field of radius about 300km. However no macroseismic or instrumental epicentres are known for an event of this size at this period. This is perhaps unsurprising. In 1920 the nearest significant settlements were probably in Chiloe, 400km to the north, or in Argentina 300km to the east. Thresholds for instrumental event location in this region between 1910 and 1930 were probably between M6.5 and M7. A magnitude (Ms) 7.1 earthquake on 1927/11/1 at 44.3° S, 73°W (Gutenberg and Richter, 1954), fits the age estimate, but an association with a tsunami in the outer Aisen Fjord at 45.3°S, demonstrates that this event could not have been mislocated from the San Rafael Fault, 130km to the south. Therefore the date of the San Rafael Fult earthquake, remains unknown.

Forsythe and Nelson (1985) have proposed that a major coast parallel fault belt (the Liquiñe-Ofqui fault system of Hervé et al; 1979), which includes the San Rafael Fault, is currently a dextral transcurrent fault system. The existence of such a continuous fault system running for several hundred kilometres must however be in some doubt, as for sections of its proposed route it has not been located. Evidence of the latest fault movement on the San Rafael Fault does not support, Forsythe and Nelson's conjecture as vertical motion has predominated, although the last displacement may have included a small component of dextral motion, as inferred from the orientation of some of the small antithetic faults observed on the beach on the eastern shore of the southern Golfo Elefante at locality A.

To the south of the San Rafael Glacier, and to the north of the Río Gualas, the topographic linear along the base of the mountain scarp is not nearly so clearly defined as along the San Rafael Fault, and no evidence was found in either location of any fresh fault-scarp. However such morphology would rapidly become overwhelmed by landslides and by glacial erosion, from the last mid-Holocene glacial advance. Further to the south in the Golfo de Penas a continuation of probable faulting on this trend affects the (presumed) late Quaternary or early Holocene sea-bed (see seismic reflection profile WG DO8-007 in Forsythe and Nelson, 1985). The significance of the San Rafael normal fault within the subduction zone tectonics of this region is to be discussed in a future paper.

The bevelled ridges of the western margin of the adjacent Andes rise above the fault scarp at an angle close to 30", from sea-level to 900m. The thickness of sediments beneath the Golfo Elefante has not been explored by reflection or refraction seismology, but to the south of the Isthmus of Ofqui, along a continuation of this mountain front, there is a decrease in the size of the negative Bouguer anomaly in passing towards the east (Forsythe and Nelson, 1985). There is thus no evidence for a deep sedimentary basin along the line of the Golfo Elefante and the low-lying isthmus. Extrapolating the rounded summit topography of the easterly dipping Taitao Península across the Golfo Elefante suggests that around 200 - 300m of Quaternary sediment is located in the hanging wall of the

San Rafael Fault. The total offset from the top of the mountain-scarp to the base of the sediment pile is therefore estimated as 1200m, or ~ 400 fault movements equivalent to the most recent displacement.

The recurrence interval of the San Rafael Fault is known to be longer than 3500 years, but must also be sufficiently frequent to have constructed a steep 900m high mountain wall, in the face of pronounced glacial erosion. The present tectonic configuration of this region is believed to date from 3Ma, when a section of spreading ridge collided with the neighbouring Taitao Península (Forsythe and Nelson, 1985). To have achieved 400 x 3m fault displacements in this period requires an average recurrence interval of around 7000 years.

Acknowledgements: Considerable logistical and manpower support for fieldwork on this project was provided by Operation Raleigh. With special thanks to Alejandra Silva, Nicole Fischer, Carl Miller and Antonio Colombi.

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