Geofísica Internacional
ISSN: 0016-7169
silvia@geofisica.unam.mx
Universidad Nacional Autónoma de México
México

Garduño-Monroy, Victor Hugo; Soria-Caballero, Diana Cinthia; Israde-Alcántara, Isabel; Hernández Madrigal, Víctor Manuel; Rodríguez-Ramírez, Alejandro; Ostroumov, Mikhail; Rodríguez-Pascua, Miguel Ángel; Chacon-Torres, Arturo; Mora-Chaparro, Juan Carlos
Evidence of tsunami events in the Paleolimnological record of Lake Pátzcuaro, Michoacán, Mexico
Geofísica Internacional, vol. 50, núm. 2, junio, 2011, pp. 147-161
Universidad Nacional Autónoma de México
Distrito Federal, México

Geofísica Internacional (2011) 50-2: 147-161

Original paper

Evidence of tsunami events in the Paleolimnological record of Lake Pátzcuaro, Michoacán, Mexico

Victor Hugo Garduño-Monroy, Diana Cinthia Soria-Caballero, Isabel Israde-Alcántara, Víctor Manuel Hernández Madrigal, Alejandro Rodríguez-Ramírez, Mikhail Ostroumov, Miguel Ángel Rodríguez-Pascua, Arturo Chacon-Torres and Juan Carlos Mora-Chaparro

Received: February 10, 2009; accepted: January 26, 2010; published on line: March 29, 2011

Resumen

El actual lago de Pátzcuaro tiene una elevación de 2035 m sobre el nivel del mar. Históricamente, ha alcanzado una elevación de 2041 m, lo cual aislaba una porción de la isla cerca de la población de Jarácuaro en la parte sureste del lago. Dos trincheras realizadas en la antigua isla revelan secuencias estratigráficas tripartitas similares. En una trinchera de 3.1 m de profundidad, la secuencia de la base a la cima está formada por la *Unidad A* que comprende arcillas y limos ricos en diatomeas plegados y fallados con capas de arena volcánica. Estos depósitos están fechados entre 24 y 10 mil años BP. *Unidad B que comprende* una mezcla caótica de arenas volcánicas y lapilli, con abundantes restos de peces, bivalvos, gasterópodos y ostrácodos, de 10 cm de espesor con un contacto erosivo sobre la *Unidad A*. Los ostrácodos incluyen valvas articuladas con una mezcla de especies pelágicas de agua profunda y especies litorales. Los fragmentos de artefactos cerámicos pertenecientes al Período Post-Clásico (900 a 1520 AD) son abundantes. La *Unidad C* comprende una unidad de 20 cm de espesor de limo arcilloso rico en materia orgánica con restos de gasterópodos, semillas, líticos angulares y fragmentos de piezas cerámicas del Post-Clásico.

La Unidad B sugiere una resedimentación catastrófica de los depósitos del piso del lago atribuidos a un tsunami. La Unidad C es consistente con condiciones sublacustres que están históricamente documentadas de 1858 a 1947. Un tsunami en el Lago de Pátzcuaro en 1858 ha sido registrado históricamente. El tsunami pudo haber sido creado por movimientos de falla o colapso del flanco suroeste de la isla de Janitzio. La ola del tsunami pudo haber contribuido al rápido aumento del lago de Pátzcuaro después del evento sísmico de 1858.

Palabras clave: Tsunamis en lagos, sismicidad histórica, ostrácodos, lago de Pátzcuaro.

Abstract

Modern Lake Pátzcuaro has a surface elevation of 2035 m a.s.l. Historically, it reached an elevation of 2041 m a.s.l., which isolated a portion of the island near the town of Jarácuaro in the southeastern part of the lake. Two trenches in the former island reveal similar tripartite stratigraphic sequences. In a 3.1 m deep trench, the sequence from bottom to top comprises *Unit A* constituted by folded and faulted diatom-rich clay and silt with beds of volcanic sand. These deposits are dated between 24 and 10 ky BP; *Unit B* constituted by a 10 of cm chaotic mixture of volcanic sand and lapilli with abundant remains of fish, bivalves, gastropods and ostracodes that is rests on above an erosional unconformity. The ostracodes include articulated valves with a mixture of deep-water pelagic species and attached littoral species. Highly fractured diatom shows a mixture of planktonic and benthic habitats. Fragments of ceramic artifacts dated to the Post-Classic Period (900 to 1520 AD) are abundant; *Unit C* constituted by a 20 cm thick unit of organic-rich argillaceous silt with remains of gastropods, seeds, angular lithoclasts and fragments of Post-Classic ceramic artifacts.

Unit B suggests a catastrophic resedimentation of lake floor deposits attributed to a tsunami. Unit C is consistent with sublacustrine conditions that are historically documented from 1858 to 1947. A tsunami in Lake Pátzcuaro in 1858 has been historically recorded. The tsunami was created either by fault movement or collapse of the SW flank of the island of Janitzio. The tsunami wave may have contributed to the rapid rise of Lake Pátzcuaro following the 1858 seismic event.

Key words: Tsunamis lakes, historical seismicity, ostracodes, lake Pátzcuaro.

V.H. Garduño-Monroy, D.C. Soria-Caballero, I. Israde-Alcántara, V.M. Hernández Madrigal and M. Ostroumov
UMSNH-IIM, Departamento de Geología y Mineralogía
Edif. U C.U.
Morelia, Mich., México
Corresponding author: vgmonroy@umich.mx

A. Rodríguez-Ramírez, J.C. Mora-Chaparro
Instituto de Geofísica
Universidad Nacional Autónoma de México
Ciudad Universitaria,
Del. Coyoacán 04510

M. A. Rodríguez-Pascua
Investigador Titular de OPI
Área de Investigación en Peligrosidad
y Riesgos Geológicos
Depto. de Investigación y Prospectiva Geocientífica
Instituto Geológico y Minero de España

A. Chacon-Torres
UMSNH - INIRENA

Introduction

Public interest in tsunamis has increased in the wake of the 2004 Sumatra and 2011 Japon events. Although most tsunamis reported in the literature are in marine settings, there have been lacustrine tsunamis associated with earthquakes in Mexico including historical events in Cuyutlan in 1923, and in Zihuatanejo, both in Guerrero state, in 1925; more recently, in Lazaro Cárdenas, Michoacán in 1985, in 1995 in La Manzanilla, Colima, and a 2007 event during which the village of San Juan Grijalva (Chiapas) was destroyed. In this paper, we present evidence of a recent tsunami in Lake Pátzcuaro, Michoacán. We constrain the age of this event using anthropogenic artifacts similarly to Smoot *et al*. (2000) in Owens Lake, California USA.

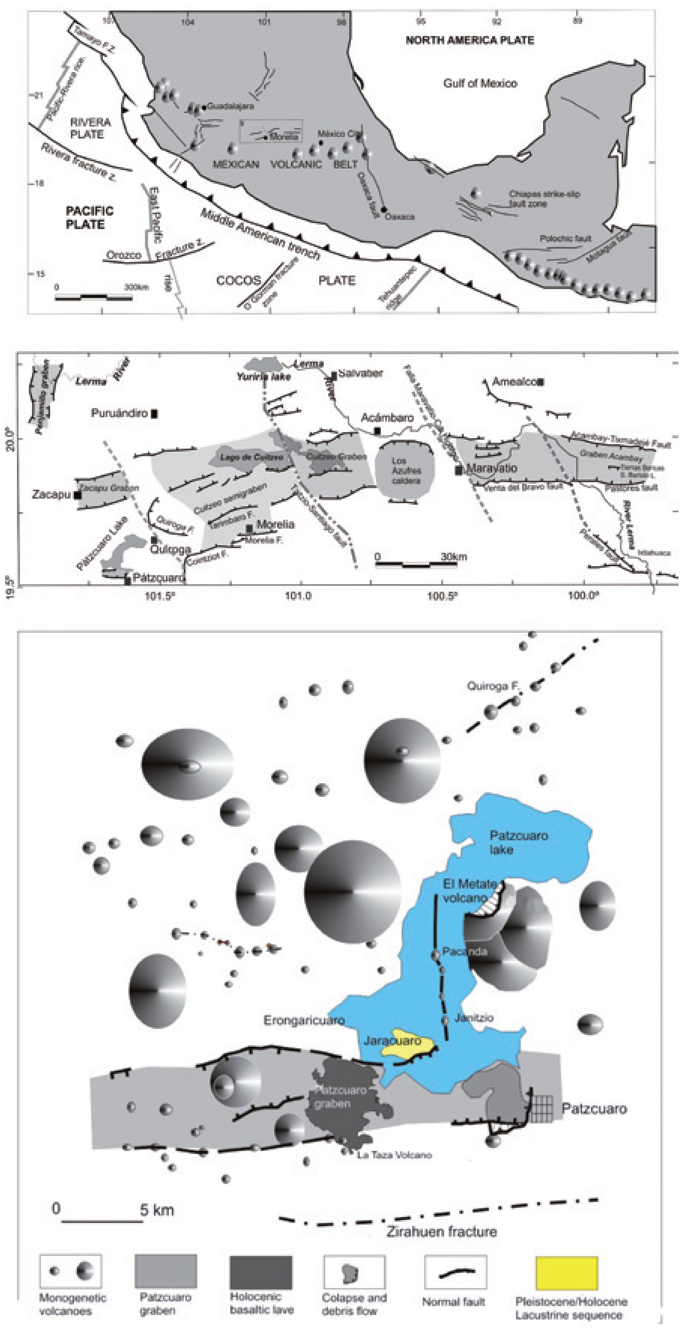


Figure 1. A. Regional tectonic setting. B. Principal faulting in the central part of the MVB., E. Structural map from Pátzcuaro lake.

Lake Pátzcuaro is located in the Michoacán-Guanajuato (Hasenaka, 1994) or Tarasco Corridor (Garduño-Monroy, 1999) monogenetic volcanic field (Figure 1). The lake has a crescentic shape whose southern and northern boundaries are controlled by east-west striking faults (Figure 1b). The basement of Lake Pátzcuaro is formed by Miocene andesites derived from semi-shield volcanoes, ashes, gravel, and breccia dated to 700 ky (Israde-Alcántara *et al*., 2005) derived from the El Metate volcano and associated with fracture systems. Pleistocene – Holocene lacustrine deposits crop out on Jarácuaro which were divided into three units by Israde-Alcántara *et al*. (2005). These folded and faulted deposits were intruded by magma of the La Taza volcano dated at 8430 ± 330 C^{14} yr BP. Luhr and Simkin (1993).

Lake Pátzcuaro basin as asurface of 929 km^2 with a surface elevation ranging from 2027 m asl to 3420 m snl (Amador-García, 2000). The surface of the water body is 126 km^2 (Chacón-Torres and Múzquiz-Iribe, 1997) with 2035 m asl surface elevation. According to the bathymetric map of Chacón (1993), the lake depths vary from a maximum of 1 m in its southern part to a maximum of over 12 m in its northern part. Water enters the lake from rainfall, springs located along the southern margin and inside the lake, and through infiltration from the surrounding landscape (Arias, 1998; Garduño-Monroy *et al*., 2002; Bischoff *et al*., 2004).

The water surface level of Lake Pátzcuaro has experienced numerous fluctuations (O'Hara, 1993; Garduño-Monroy *et al*., 2007; Chacón-Torres, 2009 personal communication) (Figure 2). A maximum lake surface elevation of 2045-2050 m asl was observed by the Spaniards in 1521 and was reported again in 1858 (O´Hara, 1993). A minimum lake surface elevation at 2027 m asl between 350-600 AD is sumarised by Fisher and Pollard (2009, pers. comm.) based on a microtopographic survey on the island of Jarácuaro. The current lake elevation of 2035 m asl was also recorded in 1850 and 1955. According to the bathymetric study by Escalante *et al*. (2003), the surface level reached 2039 m asl in January, 1977, and fell to 2036.5 m asl by 2003. The surface area for the modern lake, at 2035 m asl, is shown in Figure 2 and compared to the maximum lake level of 2045 m asl in Figure 3.

In this paper we present evidence of the effects of a tsunami that was generated during the earthquake of 1858 and greatly affects the south of Lake Pátzcuaro.

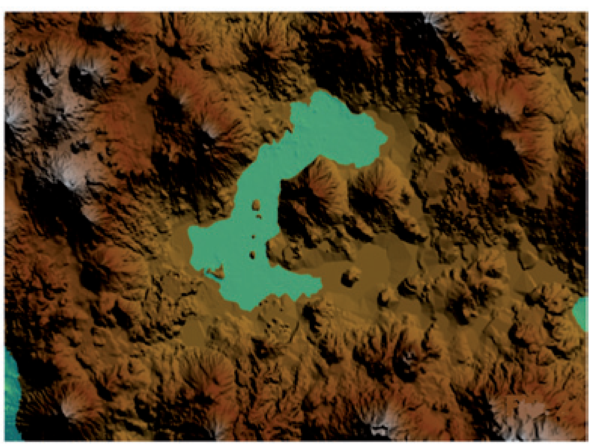


Figure 2. Reconstruction of Lake Pátzcuaro at 2035 m asl in 1850.

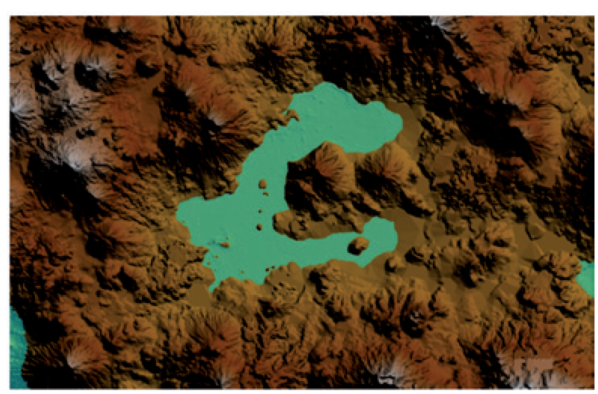


Figure 3. Reconstruction of Lake Pátzcuaro at 2042 m asl in 1521.

The bathymetry of lake of Pátzcuaro

The bathymetric survey presented in this study was used for model generation. Figure 4, shows the bathymetry made by Chacón-Torres (2009, unpublished), in which five considerations are clearly appreciated (Figure 4):

1. The lake is deepest (> 10 m) in its northern sector (between San Jeronimo and Quiroga).

2. The shallower zone (1-3 m) is in the southern part of the lake, between Los Urandenes and Erongaricuaro.

3. Both lake bottom morphologies are divided by two possible E-W normal faults observed at the islands of Janitzio and Tecuana in Figure 4, both generating down faulting towards the north, i.e., the deeper zone.

4. The island of Jarácuaro is observed to be formed by lacustrine sediments that were uplifted over 40 m.

5. The volcanoes El Metate and island of Janitzio display two structures of ancient landslides, whose of which the collapsed materials fell inside the ancient lake.

An analysis of the geometry of the lake bottom and the available data above this high lake level, enable on to observe the following geometry. In the Figure 4b are represented the two levels of

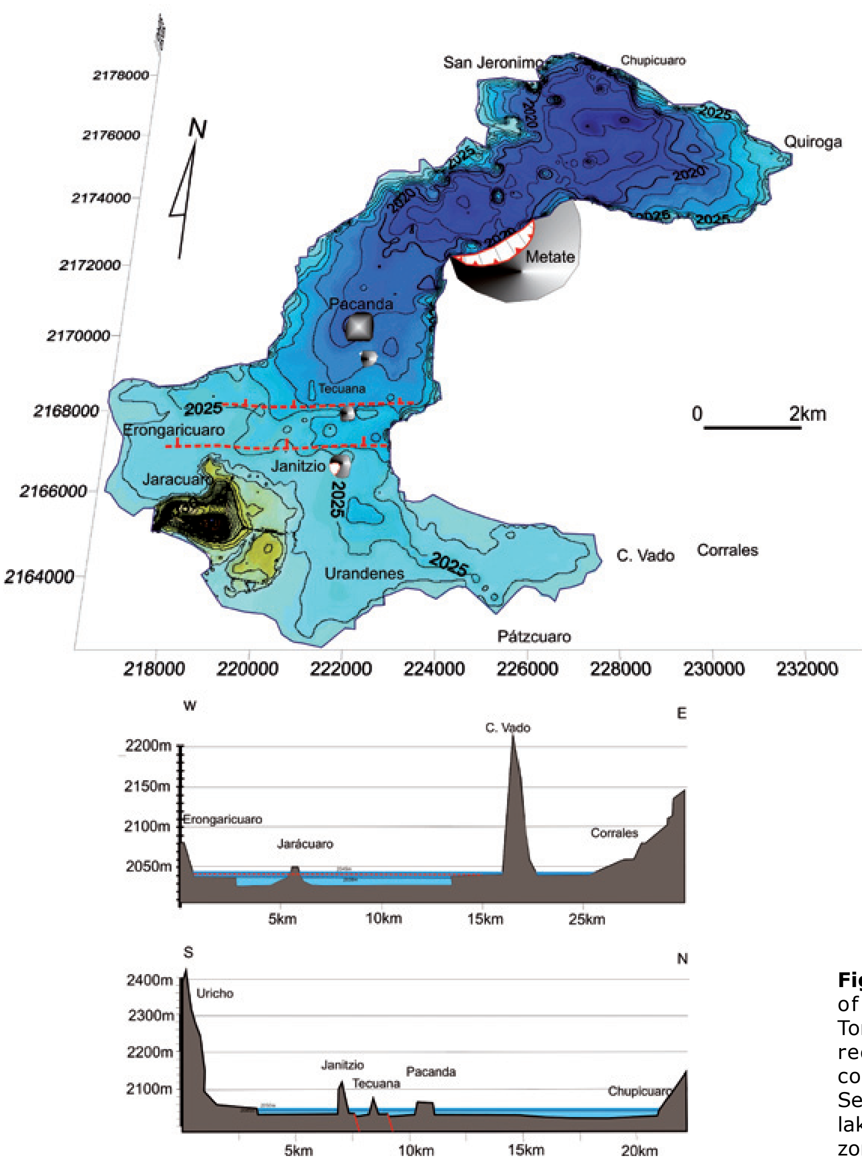


Figure 4. A. Bathymetric map of Lake Pátzcuaro (Chacón-Torres 2009, unpublished). The red dotted lines are possible coseismic ruptures. B and C. Sections showing the depth of the lake and the southern potential zone to be affected by a tsunami.

the lake. One corresponds to a height of 2050 m asl, which could correspond to the scene found by the Spanish in 1521 (Fig. 3). The second is that before 1858 after O'Hara (1993) and of Garduño *et al*. (1997), who reported a rise to 2038 m asl, considering a wave height generated by the 1858 earthquake of more than two meters, note that the potential areas to be affected would only be the southern Lake (Jarácuaro, c. Vado) where the lake could reach a height of 2040 m. Towards the northern part of the geometry of the bottom of the lake does not allow the formation of a wave, because there it is not smooth.

Climate change and human activity

Watts and Bradbury (1982) examined the climatic change in Lake Pátzcuaro using pollen from a long core. They established changes dating from 44 ky to present. They suggested that modern agricultural activity was reflected in the core by increasing marshy environments and the organic sediments content of lake sediment. Street-Perrott *et al*. (1989) noted that the Pátzcuaro basin underwent two episodes of erosion: during the Preclassic period with the introduction of maize cultivation (ca. 3500 C^{14} yr) and during the Late Classic-Colonial periods (900 to 1650 AD) produced by the expansion of agriculture, grazing and wood extraction, after the Spanish conquest. O´Hara (1993) suggested that although climate change had some control on lake levels, that also tectonic and human activities exerted controls. O'Hara and Metcalfe (1995) and Newton *et al*. (2007), however, argued that all of the lake level changes were coincident with climatic changes throughout Mexico. Fisher *et al*. (2003) believed that terrace cultivation in the Pátzcuaro basin led to rapid erosion during periods of population collapse between 120-775 AD and 1520-1960 AD. In contrast, the landscape was stable during the population growth from 776-1520 AD. Metcalfe *et al*. (2007) reported results from two cores from the lake that supported the importance of human impact since Pre-Hispanic times. Garduño-Monroy *et al*. (2002, 2004) and Israde-Alcántara *et al*. (2005) emphasized geologic factors that influenced the lake deposition, particularly the existence of active faults in the zone of Jarácuaro.

Lake Pátzcuaro seismic activity

In 1858 ocurred is a major seismic event in the state of Michoacán. Figueroa considers two islands in the calculation of isoseismal lines; they were Araro and Pátzcuaro, where there churchs collapsed. Singh *et al*. (1996) believe that the 1858 earthquake was an deep subduction intraplate earthquake. Israde-Alcántara *et al*. (2005) and Garduño-Monroy *et al*. (2009) do not preclude the possibility that this event is the product of an E-W fault segment in the south of Pátzcuaro. These authors also consider that the seismic event generated a tsunami in the southern portion of Lake Pátzcuaro and major damage in Jarácuaro, where the church show evidence of rebuilding after 1823 (Figure 5).

In the bathymetric map, there are two linear features interpreted as normal faults that separate a northern deepwater basin from a southern shallow-water basin (Figure 4). The faults were observed on the volcanic islands of Janitzio and Tecuana with blocks falling northward into the deeper basin. Garduño-Monroy *et al*. (1998) argued that lake sediments on Jarácuaro were uplifted over 40 m during the volcanic activity of the La Taza volcano. They also noted that there are landslide slope on the volcanoes El Metate and Isla de Janitzio. These observations indicate that seismic activity has been important in the recent lake history (Figure 1c).

O'Hara (1993) and Garduño-Monroy *et al*. (1997) noted an abrupt rise of lake level in 1858. The comparison of the lake level changes to climate by O'Hara and Metcalfe (1995), however, suggest that dry conditions of that time should have resulted in a falling lake. The lake level rise is coincident with a seismic event during which 120 adobe houses were destroyed (O'Hara, 1993, and Garduño *et al*. 1997). We believe that the reported lake level of 2045 m asl was overestimated due to a large wave formed during the seismic event. We believe that the actual lake level was closer to 2035 m asl.

Methodology

Field work

The area of study is located in the former island of Jarácuaro at southern of Lake Pátzcuaro (Figure 6). Two trenches were excavated and described: one identified as Trench 6 (UTM NAD27 coordinates, 218136 m E, 2165475 m N; elevation, 2037 m asl), 3.1 m depth and located in the vicinity of the access road to Jarácuaro; the second one designated as Trench 7 (UTM NAD27 coordinates, 218436 m E, 2165715 m N; elevation, 2037 m asl), 2 m depth and located at 100 m of the former dock in Jarácuaro. The columns were sampled every 10 cm, or at relevant features. Sampled sediments were placed in plastic bags and labeled. Samples were taken from the western and southern walls of Trench 6 and in the eastern and western walls of Trench 7. A photographic record and sketches (contacts, characteristics of the sediments, organic contents, ceramic) were made in the field using a reference scale.

Figura 5. A. Isosistes of 1858 earthquake, B. Nativity Chappell in Jarácuaro, Michoacán.

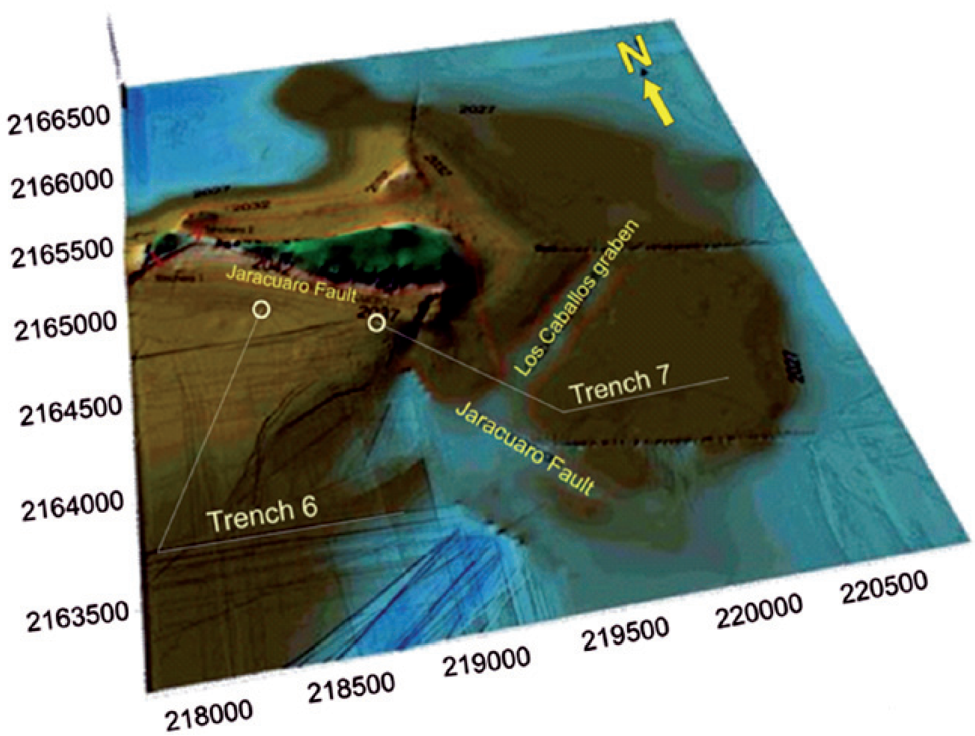


Figure 6. Terrain model based on a detailed topographic of the island of Jarácuaro. With the location of trenches.

Laboratory work

A portion of each sample was subjected to morphometric and morphological analyses in the Geology Laboratory of the Institute of Metallurgic Investigations to determinate form and size of the sediment particles. Samples were dried, homogenized and dry-sieved to separate the sand, silt and clay fractions to obtain the granulometry. Sieves with different mesh openings were used: 0.46 mm and 0.24 mm for sands; 0.122 mm, 0.100 mm, 0.090 mm, 0.073 mm, 0.061 mm and 0.045 mm for silts; and 0.025 mm for clays. Other portions of the samples were subjected to micropalaeontological analyses.

Micropalaeontological analyses

Cleaning and Separation of Ostracodes: 5g of sample were placed in a beaker with 250 ml of distilled water, 0.5 g of sodium bicarbonate and 2.5 ml of concentrated liquid detergent at neutral pH (Extran). Samples were covered and left resting for 7 days. The samples were sieved in with 63, 150 and 250 μm sieves to separate ostracodes valves (juveniles, adults). The residues were dried in ethanol and air-dried at room temperature. The valves were separated with a fine camel hairbrush, identified and counted, and their morphometric data recorded. Ostracodes were mounted with their ventral side up in Plummer micropalaeontological slides with guar gum. Recognition was made based on identification keys of Delorme (1970, 1971), Griffiths *et al*. (1993), Horne *et al*. (2002), Meisch (2000) and Tressler (1959), with emphasis in the shape of the valve, the pattern of muscle scars and the structure of the inner lamella.

Diatom processing. Sediment samples were taken at regular 10 cm intervals. From every sample, 0.5 g was treated with HCl and H_2O_2 to remove carbonate and organic matter respectively. Total abundance determinations were done by counting 500 valves or 100 for diatom poor samples on average in a known volume of sample and are expressed as valves per gram of dry sediment. Only diatoms with an abundance of > 5% are reported.

Analysis of carbon

The contents of carbon in samples was determined by means of a UIC S014 coulometer, either based on the titration of a solution containing the CO_2 produced by the calcination of analyzed materials or on decomposition of carbonates in the sample by acid attack. For Total Carbon analysis, 0.019-0.022 g of dry sediments were weighted, ground and homogenized. Samples were placed on sterilized ceramic trays and processed in an oven.

Estimation of the Percentage of Total Inorganic Carbon (TIC): TIC was assessed by means of a UIC S014 coulometer coupled to a CM 5130 acidification module, consisting of a tube containing KOH and another with $AgNO_3$, an injector of perchloric acid and a tube containing the sample diluted in water, to which acid is added.

Estimation of the Percentage of Organic Carbon (TOC): TOC is estimated by subtracting the TIC from the percentage of total carbon in each sample.

Study area

In the island of Jarácuaro presents outcrops of Upper Pleistocene-Holocene lacustrine sequences that were the product of tectonic events subsequent to the Last Glacial Maximum (22–10 ky). The rising has an E-W direction and the strata presents an inclination towards the SW and W and collapse structures sliding towards the S-SW.

According to Israde-Alcántara *et al*. (2005), a core of the lacustrine sequence shows 3 vertical units:

UNIT 1. OPEN WATER LACUSTRINE DEPOSITS: Conformed by diatomites alternating with clayey and silty strata and some volcanic layers. In the southern portion in the zones of Jarácuaro and Arocutin, the outcrops are dated from 31,810 ± 1610 to 44,100 ± 3000 C^{14}yr BP. Lacustrine sediments in Arocutin were intruded by magma of the La Taza volcano dated at 8430 ± 330 C^{14}yr BP (Luhr and Simkin, 1993). Vertical electric soundings made in Jarácuaro indicate that the volcanic basement is at a depth of 80-100 m. Folding and faulting deforms the lacustrine sequence. The following subunits are recognized in Jarácuaro:

I. A lacustrine sequence presenting intense deformation.

II. A lacustrine sequence in which Upper Pleistocene-Holocene ashes, gravels and diatomites alternate, the sediments being also deformed.

III. Discordances are present in the Holocene lacustrine sequences younger than 3000 years, containing archaeological materials and vertebrate remains, corresponding to sedimentary deposits along normal faults.

UNIT 2. Lacustrine sediments exposed by a recent regression of the lake, including marshes, paleosoils and fluvial deposits of the Upper Holocene. The upper part of that sequence is impacted by human activity (Fisher *et al*., 1999, 2003). In the Los Urandenes region, this sequence is affected by normal faulting.

UNIT 3. Composed of palaeosoils and recent soils over lavas that are classified as Andosols and Luvisols having reddish color and, in some cases, depths of over 2 m.

Results

We describe the lithology and stratigraphy of Jarácuaro emphasizing on the record of the possible tsunami event in the zone.

For more details about the Jarácuaro morphology, we carried out GPS accurate topography with curves up to each meter (Fig. 6). In this detailed topographic map, we can see better the structures of the island, such as major faults E-W (Jarácuaro fault) or NW-SE as in Los Caballos graben. Morphologically E-W faults generate a horst, were a small town is currently located. In this ground model we can see the location of the stratigraphic columns is indicated.

Lithology

The four walls of the trenches display lithological concordance, the same sequence of strata being observed in all of them, the most complete and representative wall is described:

Western Wall, Trench No. 06 / Coordinates: 218136 m E, 2165475 m N, UTM, NAD27. 310 cm depth (Figures 7a and 7b). From the bottom:

Unit A: Laminated layers of clay and silt, light brown to ochre coloration, 290 cm thick, alternating with layers of diatomite and three layers of dark volcanic ash (20, 8 and 5 cm thick), that have high contents of sands and volcanic glass. This unit is faulted and folded and lightly inclinated toward south. Also observed a wedge-shaped cleavage produced by the faulting of silty material, a sand lens, and bioturbation. The sequence is dated to the Upper Pleistocene-Holocene (Israde-Alcántara *et al*., 2005).

Unit B: Grey stratum 10 cm thick, of heterogeneous sands and silts with angular lithoclasts with diameters of 1-5 cm, volcanic glass and fragments of ceramic artifacts dated to the Post Classic period. Its lower contact is an erosional unconformity on Unit A and its upper contact is transitional. It also contains abundant remains of fish bones and scales, bivalves, pulmonated gastropods and ostracodes including articulated, dislocated and mainly fragmented valves, with a mixture of deep-water pelagic species and attached littoral species. The whole unit shows a poorly sorted, chaotic deposit that suggests catastrophic resedimentation of lake floor deposits. We interpreted this deposit as a product of a tsunami wave.

Unit C: A 20 cm thick dark brown unit of organic-rich argillaceous silt with minimal sand content, and lightly disturbed by recent soils. Contains abundant organic matter, roots, seeds, remains of pulmonated gastropods, some dislocated valves of ostracodes, angular lithoclasts and some fragments of Post-Classic ceramic artifacts. This unit is consistent with sublacustrine conditions (Fig. 8).

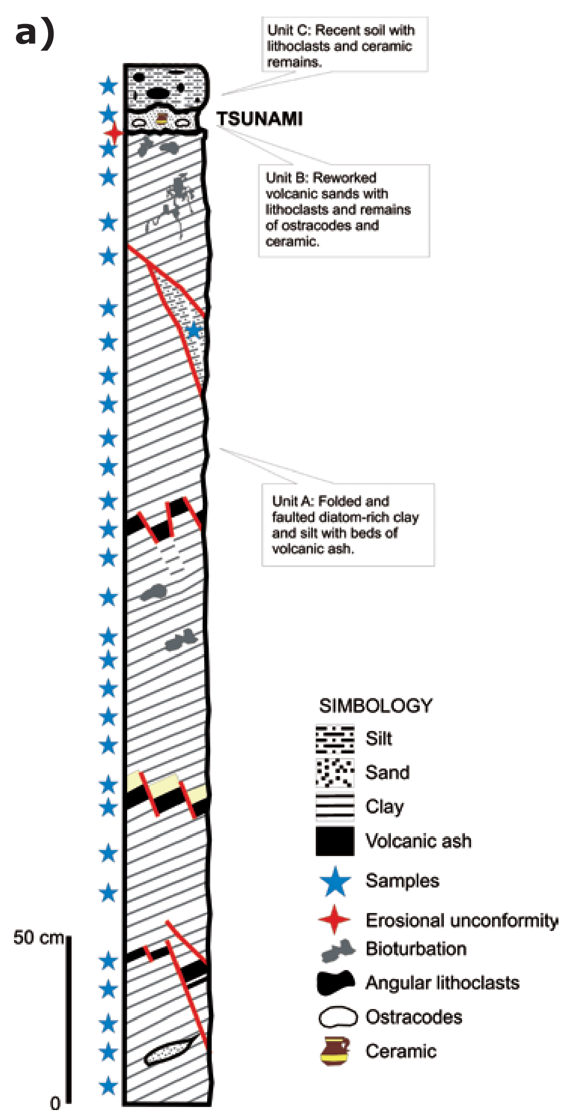


Figure 7a. Lithological column of western wall, trench 6 and photograph of wall.

b)

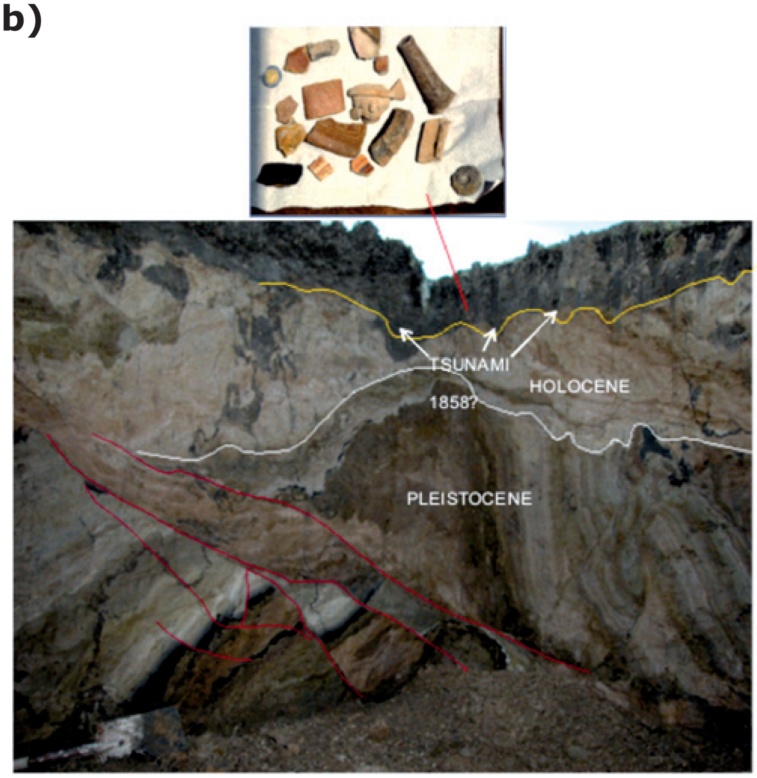


Figure 7b.

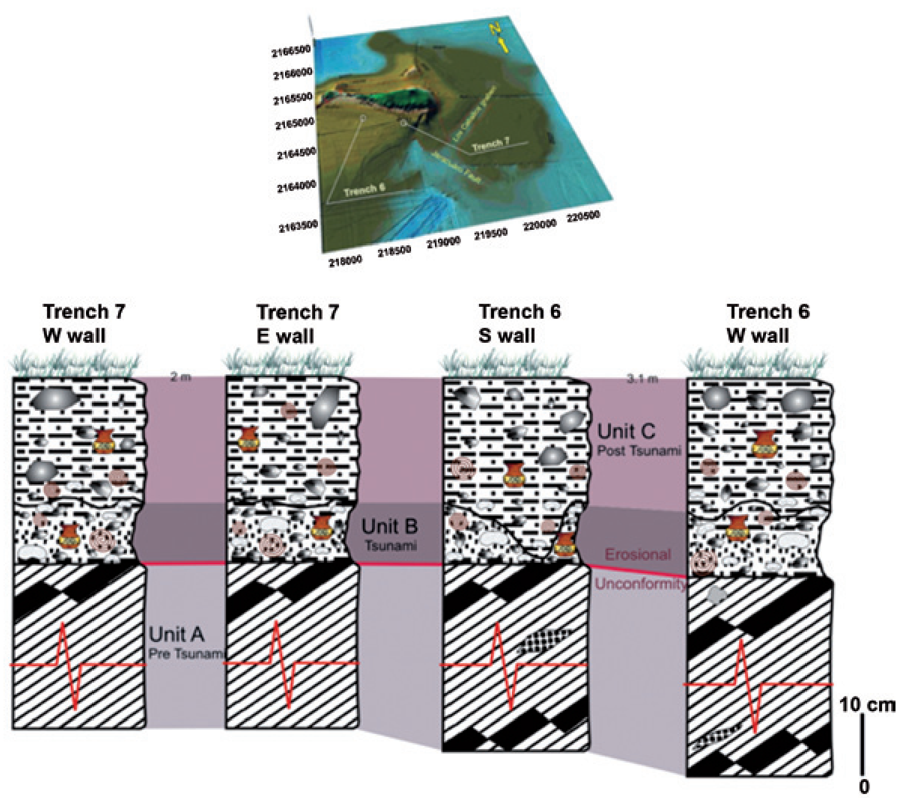


Figure 8. Stratigraphic correlation of the valley of Jarácuaro.

Granulometry analysis

The sediment of Unit A has a high content of clays and silts, and avoid of sands and larger lithoclasts. This fine granulometry is consistent with a low energy environment (Fig. 9). Sands of homogeneus size and composition dominate in the beds of volcanic ash. The sediments of units B and C had coarser granulometry, dominated by silts and a wide range of size sands and by andesitic and basaltic angular lithoclasts with variable diameter. This change in the granulometry suggests an abrupt change in the energy of the lacustrine environment, presumably due to high-energy waves caused by the tsunami.

Micropalaeontological analyses

Because the thickness of unit B is < 10 cm, a single sample embraced the whole layer, and two samples embraced the totality of unit C, but only the lower one contains ostracodes. Ostracodes were absent from all samples of unit A, but were abundant in the sample from unit B and in one of the samples from unit C. In unit B, the dominant species are the deep-water pelagic species *Candona Pátzcuaro* (Figure 10a) and *Limnocythere itasca* (Figure 10f), *Heterocypris* cf. *punctata* (sublittoral, Figure 10b) and the attached littoral species *Physocypria globula* (Figure 10g), *Potamocypris smaragdina* (Figure 10e), *Potamocypris unicaudata* (Figure 10d) and *Potamocypris variegata* (Figure 10c). We observed a high ratio of juveniles to adults (8:1), suggesting these were in situ communities, even though the majority of shells are fragmented. In unit C, the dominant species are *Potamocypris smaragdina*, *Limnocythere itasca,* and several scattered valves of *Candona Pátzcuaro* and *Heterocypris* cf. *punctata*; the shells were less fragmented and less abundant than in unit B.

The absence of ostracodes in unit A may reflect an unfavorable depositional environment or lack of preservation in older deposits. The mixture of deep-water pelagic and littoral attached species of ostracodes, from circumneutral to alkaline conditions, as well as the abundance of fragmented valves, in unit B suggests that they have been redeposited from their original environment. The presence of closed carapaces is interpreted by De Deckker (2002) as evidence of rapid burial. Boomer *et al*. (2003), indicate that an assemblage of shells with a high ratio of juveniles to adults with mostly disarticulated valves and a few closed caparaces, indicates a high-energy thanatocenosis with some post-mortem alteration due to currents, waves or biological activity. These observations indicate that unit B was deposited rapidly by currents that reworked a number of lake-bottom and littoral environments. The assemblage in unit C was interpreted as low-energy remants of the event that deposited Unit B, allowing the deposition of not fragmented shells.

Diatom analysis. The results of diatoms analyses show a dominance of *Aulacoseira ambigua var. robusta*, followed by *Aulacoseira ambigua, Aulacoseira islandica, Aulacoseira granulata, Gomphonema spp.* and *Stephanodiscus niagarae* in unit A with excellent in situ preservation. In unit B, were found highly fragmented valves of mixed habitats like planktonic species *Aulacoseira ambigua*, *Aulacoseira distans, Anomoeoneis sphaeropora, Stephanodiscus niagarae, Stephanodiscus asteroides,* and the littoral-attached species *Epithemia adnata*

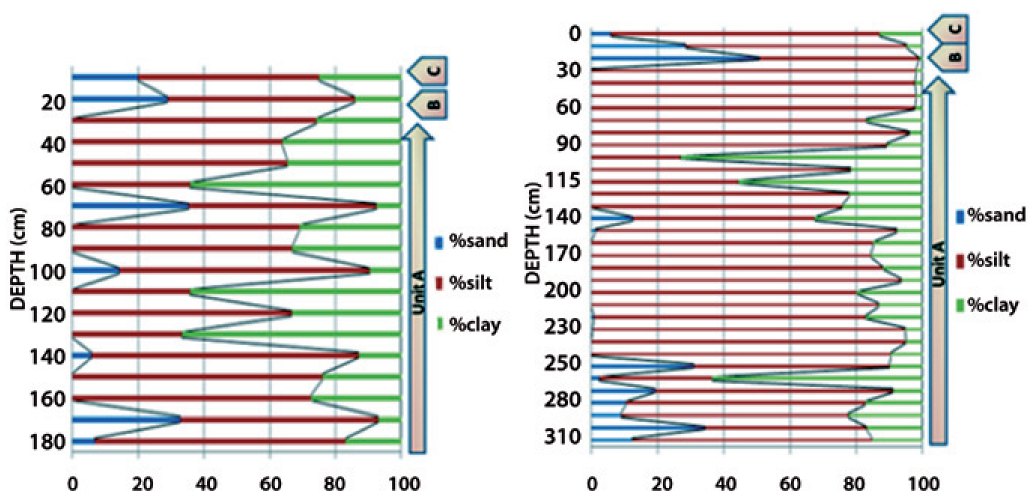
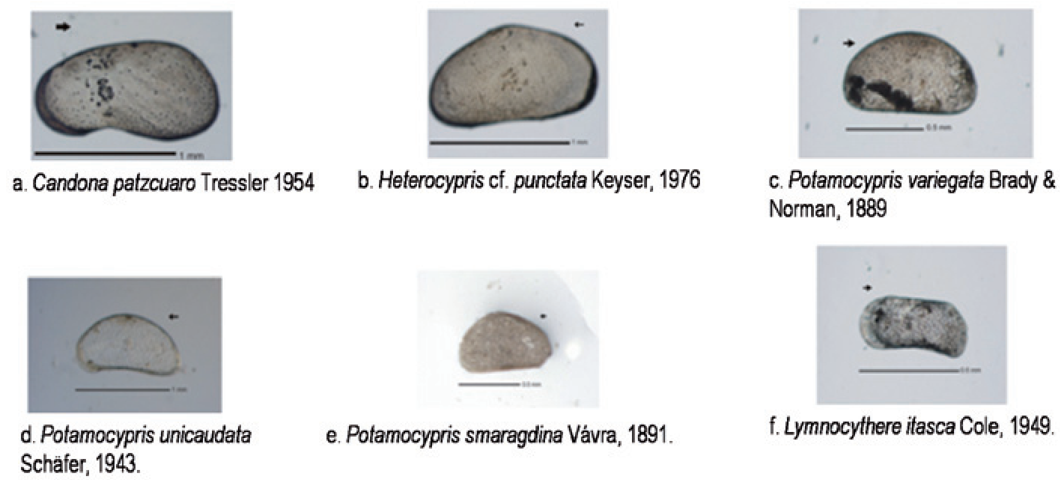


Figure 9. Variation along the column of particle size. Deeper sediments are mostly silty, some samples shifting to clayey or to coarse silts and sands.



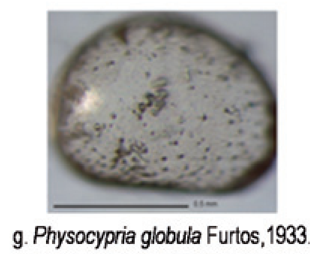


Figure 10. a) *Candona patzcuaro*, adult male; b) *Heterocypris* cf. *punctata*, adult; c) *Potamocypris variegata*, A-1; d) *Potamocypris unicaudata*, A-1; e) *Potamocypris smaragdina*, A-1; f) *Lymnocythere itasca*, adult male; g) *Physocypria globula*, A-1.

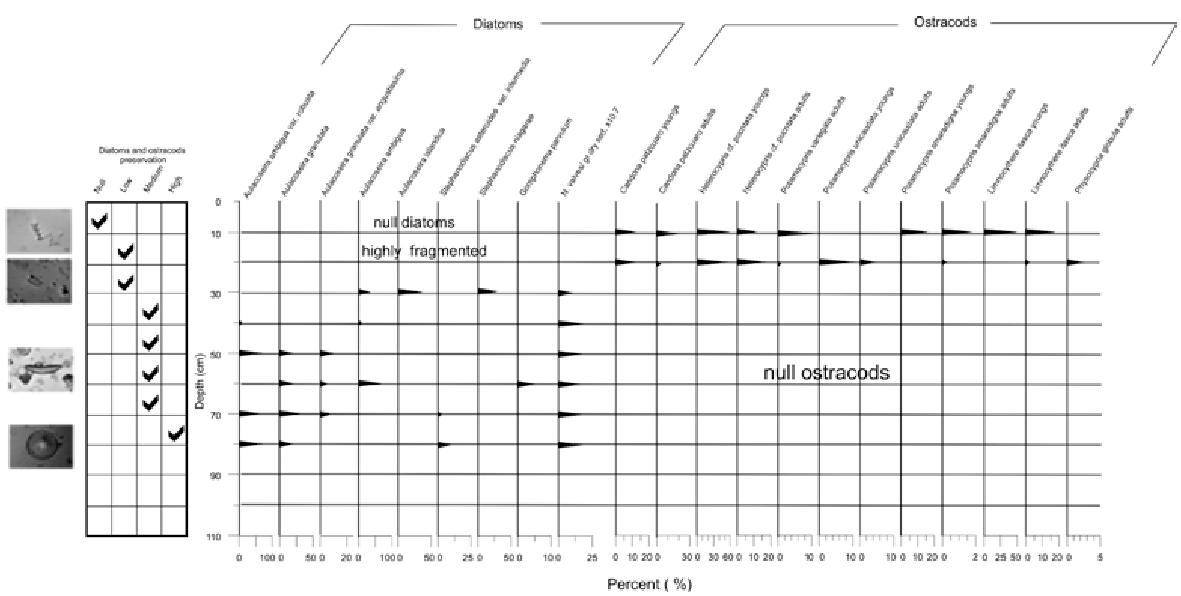


Figure 11. Analyses of populations of diatoms and ostracodes.

and *Pinnularia spp.*, with several heterogeneous lithoclasts. In unit C are only found smaller lithoclasts of reworked volcanic glass and very scattered and fragmented diatom remains from planktonic species and fitolites that represents grass from littoral zone. The highly fragmented diatom valves found in the recird suggest redeposition of the sediments. The detailed ostracods and diatoms record is summarized in Figure 11.

Organic and inorganic carbon contentes

Estimations were made of total inorganic carbon and total organic carbon. Only the more complete wall is described.

Trench No. 6, Western Wall

The following values of TOC and TIC in relation with the stratigraphic units were observed (Fig. 12 and Table 1):

Table 1. Carbon content of samples of the upper 80 cm of the western wall of trench 6. (TIC= Total inorganic carbon; TOC = Total organic carbon).

DEPTH (cm)	TIC (%)	TOC (%)
10	0.6245	3.6976
20	0.7965	0.2715
30	0.0363	0.3977
40	0.1849	0.5895
50	0.6199	0.3672
60	0.0149	0.4227
70	0.0975	0.4462
80	0.1457	0.6023

· Throughout Unit A, the value of TOC varied from 0.60 % to 0.36 %, while that of TIC remaining at about 0.1 %, except for an increase at a depth of 50 cm (0.6199%).

· In Unit B TOC decreased to 0.27 % and TIC increased to almost 0.8 %, probably due to its high content of carbonate ostracode valves and gastropods shells.

· In Unit C the value of TOC shows an abrupt increase to 3.69 %, while that of TIC decreases to 0.2 %.

Discussion and conclusions

Units B and C unconformably overlie the older deformed sediments of unit A. All characteristics of unit B, the sharp erosional basal contact, poor sorting including cm-scale lithoclasts and mixture of deep-water and littoral attached populations of highly fragmented ostracods and diatoms, all point to a rapidly deposited flow. The age of this event is constrained by the occurrence of ceramic shards identified from the Classic period (ca. 900 AD) within it. We can rule out unit B as a volcanic deposit from the range of grain types within it, particularly the ostracodes. We argue that it must represent a tsunami deposit that reworked sediment from the lake floor. Unit B shares the characteristics of poor sorting, admixed lithoclasts, and reworked deepwater shells with tsunami deposits described by Minoura *et al*. (1994) in Japan.

The geological studies made in Lake Pátzcuaro have substantially modified the knowledge about its origin: the lake registers numerous past major geological events, such as the avalanche of the El Estribo volcano, the emplacement of the

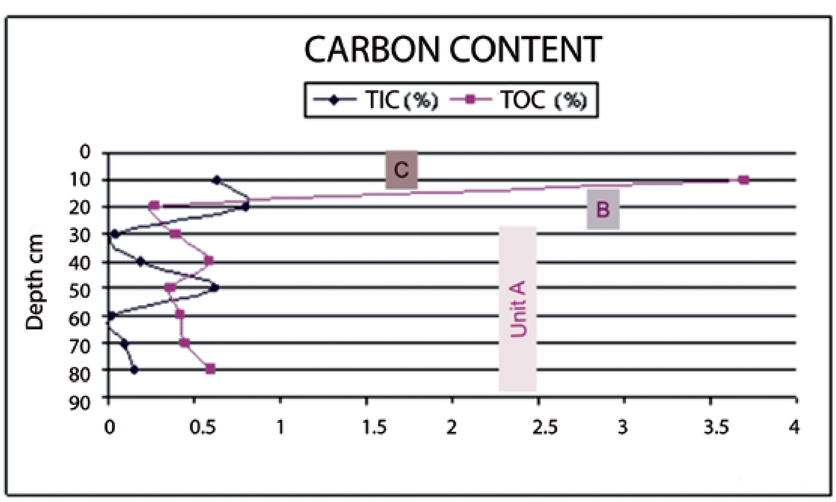


Figure 12. Relation between carbon content and depth (TIC= Total inorganic carbon; TOC = Total organic carbon) in western wall of trench 6.

La Taza volcano and the historical seismicity. The results presented here lead to formulation of two hypotheses regarding arrival of volcanic sand to the southern border of Lake Pátzcuaro:

1. Sands are primary deposits of a historic volcanic eruption from a volcanic edifice close to the lake. This possibility has been discarded based on the characteristics of the deposit, i.e., the sand is reworked, there is presence of ostracodes and diatoms of deep and shallow lacustrine habitats; presence of large, very angular lithoclasts, clays, silts and shards of Tarascan ceramic.

2. The sandy sediments are the product of a high energy wave deposit (tsunami) that caused the mixing of materials from different lacustrine environments, such as littoral and deep-water ostracods and diatoms, whose valves are highly fragmented. Planktonic diatoms dated post 12 ky (Metcalfe *et al.,* 2007) *(Stephanodiscus asteroides var. intermedia)* were observed mixed with modern diatom assemblages *(Aulacoseira granulata).* Another components in the matrix of the sediments included clays, ceramic shards and others. Despite a dating of these sediments is unavailable, ocurrence of ceramic shards and other artifacts places this deposits after the Classic period (ca. 900 AD).

Based on the known historical background, the most important seismic event in Hispanic times was the earthquake that occurred in the year 1858, recorded in the rising by several meters of the water level of the lake.

Taking into consideration the bathymetry, the 1858 water level rise and the characteristics of the deposits, we may conclude that the tsunami could be associated to two possible origins: the cosismic breakage of one of the E-W faults seen in the bathymetry which causes the collapse of the SW flank of the island of Janitzio. The scenario would be of small waves in the deeper sectors of the lake (N and NE) and important waves in the shallower sector that is towards the south where it has been reported that 120 adobe houses were destroyed (Fig. 13).

Acknowledgements

This work was supported by the CONACyT grant 37334-T and by the Coordinación de la Investigación Científica-UMSNH (1.17). Thanks to M.C. Neftalí Razo Pérez for his contribution in the TIC-TOC analyses. Thanks to Sergio Zárate for translating the manuscript.

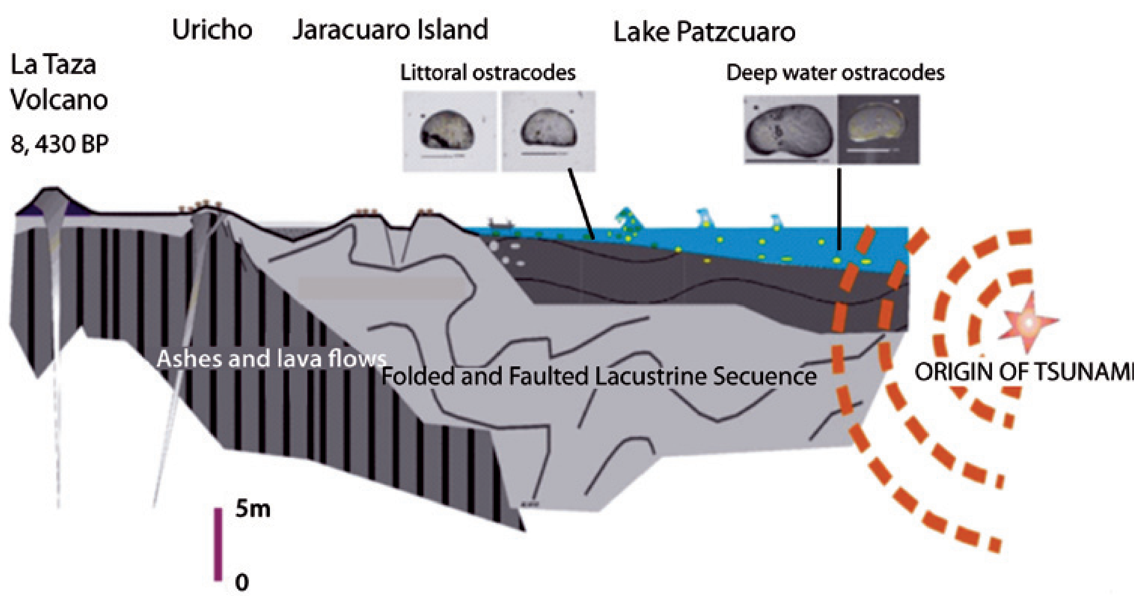


Figure 13. Schematic representation of the development of the tsunami in the southern border of Lake Patzcuaro.

Bibliography

Amador García A., 2000, Simulación dinámica del impacto ambiental por actividad agrícola en la cuenca de Pátzcuaro, Mich. Tesis de Maestría. Facultad de Biología, UMSNH. 101 pp.

Arias M.J., 1998, Los sedimentos lacustres del margen meridional del lago de Pátzcuaro como indicadores de su ambiente en los últimos miles de años. Biology Faculty, Thesis, UMSNH. México.

Bischoff J.L., Israde I., Garduño V.H., Shanks W.C., 2004, The springs of lake Pátzcuaro: chemistry, salt – balance and implications for the water balance of lake. *App. Geochem.* 19, 1827–1835.

Boomer I., Horne D.J., Slipper I.J., 2003, The use of Ostracods in palaeoenvironmental studies or what can you do with an Ostracod shell? Paleontological Society Papers V.9. From: Bridging the Gap, cap 9, 153–180.

Bridgwater N.D., 1995, Non - marine ostracods as indicators of Holocene environmental change in Central Mexico. PhD Thesis, Kingston University.

Chacón-Torres A., 1993, Pátzcuaro un lago amenazado. UMSNH. Secretary of Cultural and University Extension. México.

Chacón-Torres A., Múzquiz-Iribe E., 1997, Climatic trends, water balance and lake Pátzcuaro, a tropical high altitude lake. *Quat. Int.*, 43-44, 121-131.

De Deckker P., 2002, Ostracod Palaeoecology. In The Ostracoda: Applications in Quaternary Research. *Geophys. Mono.* 131, 121–133. EUA.

Delorme L.D., 1970, Freshwater ostracodes of Canada, part II: Subfamilys Cypridopsinae, Herpetocypridinae and family Cyclocyprididae. Part III: Family Candonidae. Part V: Family Limnocytheridae, Loxoconchidae. Canadian *Journal of Zoology*, 48, 253 – 266; 1099 – 1127. 49, 43–64.

Delorme L.D., 1990, The use of Ostracodes in paleo-environmental reconstruction. Short Course 2: Biological Techniques in Paleoenvironmental Interpretation. First Joint Meeting, Canadian and American Quaternary, 115–136.

Escalante M., González J., Morales R., Salcedo E., Rodríguez C., 2003, Simulación del impacto de diversas acciones de recuperación sobre el lago de Pátzcuaro. Yearbook IMTA. Pp. 32–39.

Fisher C.T., Pollard H.P., Frederick C., 1999, Intensive agriculture and socio – political development in the Lake Pátzcuaro Basin, Michoacán, México. *Antiquity* 73, 642–649.

Fisher C.T., Pollard H.P., Israde I., Garduño V.H., Banerjee S., 2003, A reexamination of human induced environmental change within the Lake Pátzcuaro Basin, Michoacán, Mexico. Proceedings of the National Academy of Sciences. April 15, 2003, 100, 8, 4957-4962.

Garduño-Monroy V.H., Israde I., Francalanci L., Carranza O., Chiesa S., Corona P., Arreygue E., 1997, Sedimentology, volcanism and tectonics of the southern margin of the lacustrine basins of Maravatío and Cuitzeo, Mich., México. International Association of Volcanology and Chemistry of the Earth's Interior (IAVCEI). General Assembly, 1997 19-24, Puerto Vallarta, México, 15 pp.

Garduño-Monroy V.H., Cuevas A., Escamilla R.J., 1998, Descripción histórica de la sismicidad en Colima, Jalisco y Michoacán. UMSNH and University of Colima. México. 172 pp.

Garduño-Monroy V.H., 1999, El vulcanismo del Mioceno – Pliocuaternario de Michoacán. Carta Geológica de Michoacán Escala 1:250 000. IIM. UMSNH. México: 27–44.

Garduño-Monroy V.H., Israde I., Arreygue E., 2002, La inquietante evolución de las cuencas lacustres en zonas volcánicas, ejemplo. La cuenca del lago de Pátzcuaro, Michoacán, México. Aportes al proyecto Pátzcuaro. Estudios, propuestas y avances para la restauración del Lago de Pátzcuaro, 25-68.

Griffiths HI., Rouse A., Evans J,G., 1993, Processing freshwater ostracods from archaeological deposits, with a key to the valves of the major British genera. Circaea, The Journal of the Association for Environmental Archaeology 10, 2, 53–62.

Hasenaka T., 1994, Size, distribution and magma output for shield volcanoes of the Michoacán-Guanajuato volvanic field. Central Mexico. *J. Volc. Geother. Res.*, 63, 13-31.

Horne D.J., Cohen A., Martens K., 2002, Taxonomy, morphology and biology of Quaternary and living Ostracoda. The Ostracoda: Applications in Quaternary Research. *Geophys. Mono.* 131, 5–36.

Israde Alcántara I., Garduño V.H., Fisher C.T., Pollard H.P., Rodríguez M.A., 2005, Lake level change, climate, and the impact of natural events: the role of seismic and volcanic events in the formation of the lake Pátzcuaro Basin, Michoacán, Mexico. Elsevier. *Quat. Int.* 135, 35–46.

Luhr F., Simkin T., 1993, Paricutín, the Volcano born in a Mexican Cornfield, Geoscience Press, Phoenix, Arizona, 424 pp.

Meisch C., 2000, Freshwater Ostracoda of Western and Central Europe. Spektrum Akademischer Verlag GmbH, Heidelberg, Berlin. 522 pp.

Metcalfe S.E., Davies S.J., Braisby J.D., Leng M.J., Newton A.J., Terrett N.L., O'Hara S.L., 2007, Long and short-term change in the Pátzcuaro Basin, central México. Palaeogeography, Palaeoclimatology, Palaeoecology*,* 247, 272-295.

Minoura K., Nakaya S., Uchida M., 1994, Tsunami deposits in a lacustrine secuence of the Sanriku coast, northeast Japan. *Sed. Geol.*, 89, 25–31.

Newton A.J., Terrett N.L., O'Hara S.L., 2007, Long and short-term change in the Pátzcuaro Basin, central Mexico. Palaeogeography, Palaeoclimatology, Palaeoecology, 247, 272–295.

O'Hara S.L., 1993, Historical Evidence of fluctuations in the level of Lake Pátzcuaro, Michoacán, México over the last 600 Years. *Geograph. J.*, 159, 1, pp. 51-62.

O'Hara S.L., Metcalfe S.E., 1995, Reconstructing the climate of Mexico from historical records. *The Holocene* 5, 485–490.

Rodríguez-Pascua M.A., Garduño V.H., Israde I., 2004, Evidencias paleosísmicas en fallas activas y sedimentos deformados del Lago de Pátzcuaro. Jarácuaro, Michoacán, México. Geotermas 6, 3, 151-154.

Singh S.K., Ordaz M., Pérez-Rocha L., 1996, The great Mexican earthquake of 19 june 1858: expected ground motion and damage in Mexico City from a similar future event. *Bull. Seism. Soc. of America*., 86, 6, pp.1655-1666.

Smoot J.P., Litwin R.J., Bischoff J.L., Lund S.J., 2000, "Sedimentary record of the 1872 earthquake and "Tsunami" at Owens Lake, southeast California". *Sed. Geol.*, 135, 241-254.

Street Perrott F.A., Perrott R.A., Harkness D.D., 1989, Anthropogenic soil erosion around lake Pátzcuaro, Michoacán, México, during the Preclassic and Late Postclassic – Hispanic periods. *Am. Antiq.*, 54, 4, 759–765.

Tressler W.L., 1959, Ostracoda. En Fresh – Wather Biology. W.T. Edmondson. Second edition. EUA. 657–701 pp.

Watts A.W., Bradbury J.L., 1982, Paleoecological studies at Lake Pátzcuaro on the West-Central Mexican Plateau and at Chalco in the Basin of Mexico. *Quat. Res.,* 17, 56-70.