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Structural and seismographic characteristics of a sector of the Magdalena Shelf, western margin of Baja California, Mexico, from 2D seismic reflection profiles

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Abstract

The Magdalena Shelf, located on the Pacific margin of Baja California, Mexico, is crosscut by the Tosco-Abreojos transform fault system, while the Santa Margarita and San Lazaro faults are sub-parallel and located east of the shear zone that cuts the continental slope longitudinally. Processing and interpretation 2D multichannel marine reflection seismic data show evidence for the structural deformation and seismostratigraphic characteristics of a sector of the shelf. This study allowed mapping unknown faults, of which the two main ones are named Iray and Magdalena Faults. San Lazaro fault has a strike of N 15° W and length of 70 km, with an apparent dip of ~ 42° to the NE. The San Lazaro fault controls the western flank of the basin of the same name forming a semi-graben of 20 km wide and its sedimentary fill of ~ 4.5 km in thickness. The Iray-Magdalena basin has a depth of ~ 4.0 km. We identified six seismic stratigraphic sequences, and two main discordances, which are considered to be regional discordances. One of which is the Cretaceous-Paleogene discordance, and the other corresponds to the Miocene discordance, which has been considered an important geological marker of the tectonic evolution of region. Acoustic basement defines a structural high parallel to the continental slope and aligned with outcrops of the ophiolite complex. The zone of active deformation of the Tosco-Abreojos fault system is between 15 and 18 km wide. This region may contain previously unknown structures and can represent a geological/seismic risk, which can have not only scientific implications, but also social impact in the communities of the region.

Introduction

The shear between the Pacific and North American plates affected the Baja California region in the Middle to Late Miocene, when seafloor spreading of the ridge and subduction of the Farallon plate stopped ~ 12 Ma (Lonsdale 1991). During 20–16 Ma, the oceanic Farallon plate was fragmented into the Guadalupe and Magdalena oceanic microplates when the Pacific-Farallon ridge approached the trench along the western margin of the Baja California peninsula (Atwater and Stock 1998; Lonsdale 1991).

Changes in subduction dynamics, surface deformation, volcanism, and generalized tectonic reorganization have been attributed to the Farallon plate (Dickinson and Snyder 1979; Liu and Stegman 2012). Magnetic anomalies along the Magdalena ridge suggest that seafloor spreading ceased at 12 Ma (Lonsdale 1991). Subsequently, the Guadalupe and Magdalena microplates were accreted onto the Pacific plate (Mammerickx and Klitgord 1982), although segments of the Pacific-Magdalena ridge were abandoned at 8 Ma (Michaud et al. 2005; Fletcher et al. 2007; Tian et al. 2011).

Two kinematic shear phases have been recognized at the edges of the Baja California microplate. During the first phase (12.3–6 Ma), the Gulf of California region underwent orthogonal extension, and dextral shear occurred along faults west of Baja California, thus forming the San Benito-Tosco-Abreojos fault system. This first phase is known as the Proto-Gulf phase (Stock and Hodges 1989). The second phase of transtensional shear occurred during 6–0 Ma, where the majority of the plate movement took place in the Gulf of California, causing the first generalized marine

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incursion, with decreasing activity on faults located west of Baja California (Fletcher et al. 2007).

The fault system along the Pacific margin west of Baja California includes the Tosco-Abreojos dextral shear fault zone along the continental margin and slope (Spencer and Normark 1979; Normark et al. 1987) and the Santa Margarita-San Lazaro fault zone. This major structure has a normal component, reaching a length of approximately 400 km (Brothers et al. 2012). These two fault zones were active during the Neogene and the Quaternary. The Santa Margarita-San Lazaro fault zone is located east of the Tosco-Abreojos fault zone on the Magdalena shelf (Spencer and Normark 1979; Normark et al. 1987). In their study, Brothers et al. (2012) presented a seismic reflection profile through the southern segment of the Santa Margarita fault south of the shelf (Fig. 1), in which the northeast block contains a semi-graben with a sequence of Late Neogene strata and an approximate thickness of 3000 m near the fault.

Some researchers have made valuable contributions to the knowledge of the tectonic evolution of the region located to the west of the Magdalena Shelf. However, there is a clear need to understand the structural framework of this region with greater certainty due to the possibility there may already be existence of tectonically active faults/structures that are hitherto unknown (García-Dominguez 1976; Fletcher et al. 2007; Brothers et al. 2012; González-Escobar et al. 2016; among others). This contribution not only has scientific implications, but it also has a potential social impact in terms of seismic risk, since several population

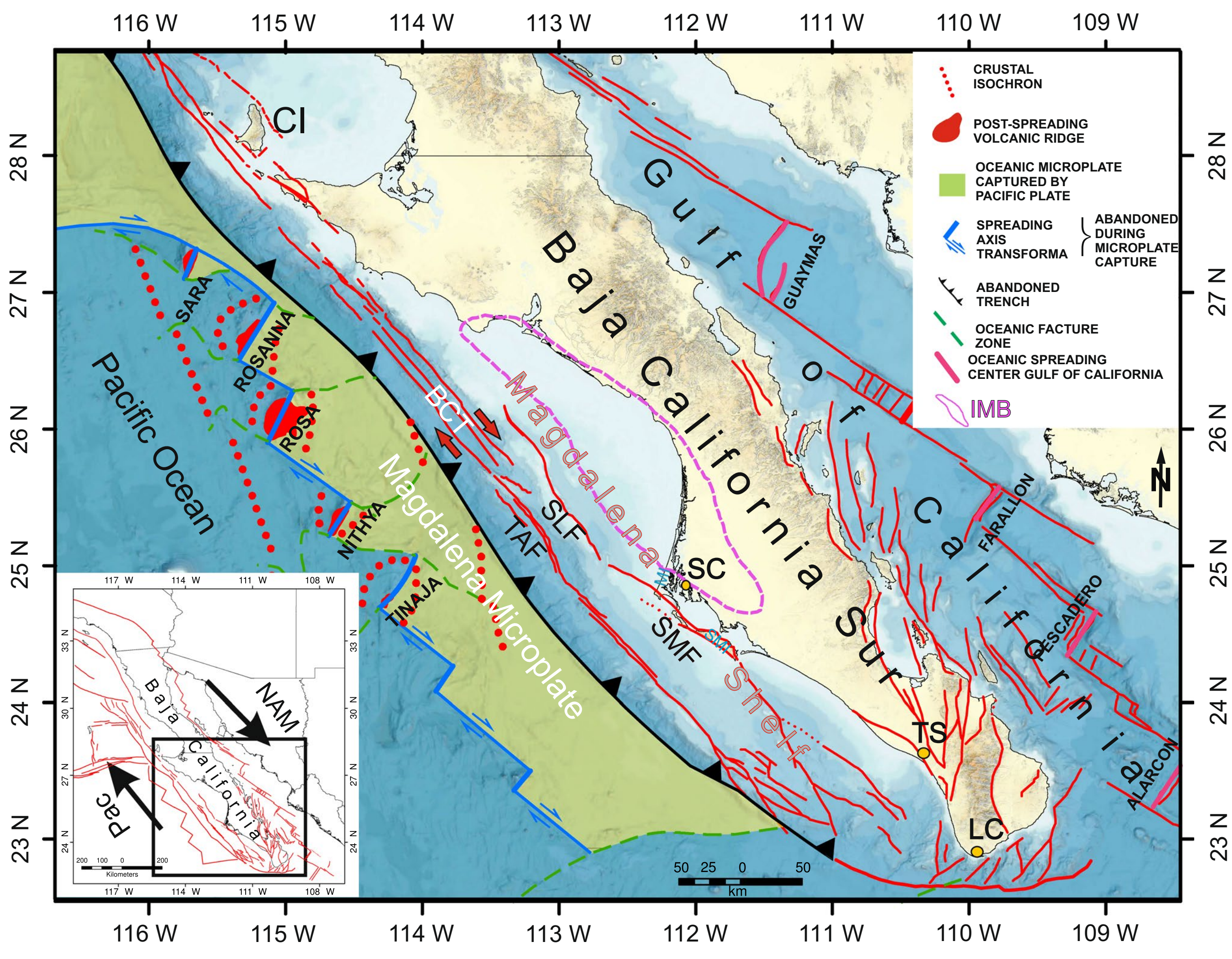


Fig. 1 Seismotectonic map of the Magdalena Shelf and the southern Gulf of California. The inset map shows the major tectonic features of northwestern Mexico and the location of the study area (i.e., Magdalena shelf). Plates: North American, NAM; Pacific, Pac. Patterns of abandoned plate boundaries, fracture zones, and the extent of post-spreading axial ridges (Tian et al., 2011) are also shown. Iray-Magdalena Basin, *IMB* (dashed magenta line, from García-Domínguez (1976)). San Lazaro Fault, *SLF*; Santa Margarita Fault, *SMF*; Tosco-Abreojos Fault, *TAF*; Baja California Trench, *BCT*; Cedros Island, *CI*; San Carlos, *SC*; Todos Santos, *TS*; Los Cabos, *LC*. Modified from Fletcher et al. (2007), Brothers et al. (2012), and Tian et al. (2011)

centers and thermoelectric plants are located near the study area. Here, the objetives are as follows: (1) Do the known faults continue to the north, and if so, in what way do they connect and interact to transfer movement toward structures located further to the north? (2) Are there other faults buried under the sediments of the basin or sub-basins? (3) Does a fault(s) buried under the sediments also cut the basement? (4) How much does the geometry of the sedimentary bodies in the basin(s) affect the shape of the basin(s) and to what degree does the geometry define the basin(s)? (6) Which of these faults cut the seafloor? (7) Is it possible to identify a system of structures that represent a greater seismic risk for the population living in this region? (8) What is the width of the zone of deformation in these latitudes? Answering these questions is especially challenging because all of the main structures are located in a marine region, among other reasons.

Regarding the statements in the previous paragraph, the purpose of this work was to perform a structural and seismic interpretation of the Magdalena Shelf region using PEMEX 2D multichannel seismic profiles. This part of the article includes seismic profiles that cross the shelf with northeast-southwest and northwest-southeast orientations and the configuration of the acoustic basement structure.

Geological setting

The continental platform, or the Magdalena Shelf (Fig. 1), contains a forearc basin that resulted from flexure and subduction of the Farallon plate below the North American plate (Mammerickx and Klitgord 1982). The western end of the Magdalena shelf is composed of ophiolitic rocks having an affinity to an island-arc environment (Rangin and Carrillo 1978; Sedlock 1993) associated with the Mesozoic and Cenozoic subduction (until the Eocene). On the western edge of the Baja California peninsula, the Magdalena Shelf extends eastward to the Sierra La Giganta and seaward to the west, extending ~ 100 km to 200 m below sea level, at the top of the continental slope (Normark et al. 1987). To the northwest, it extends to Isla de Cedros, and it is bounded to the southeast by a submarine basin off Todos Santos (Fig. 1).

Two Neogene fault systems dominate the western margin of Baja California in its south sector: the most studied is the Tosco-Abreojos fault system, which controls the main geomorphological and structural features along the continental margin (Spencer and Normark 1979; Michaud et al. 2005). The Tosco-Abreojos fault zone is a rectilinear zone with a length of 500 km stretching along the western margin of Baja California to the south. It is still considered active; however, the largest displacement occurred during the period 12–5.5 Ma (Spencer and Normark 1979). It is thought that the Tosco-Abreojos fault system acted as a transform fault with right-lateral displacement at the end of the Late Miocene and during the Pliocene and ended with the opening of the Gulf of California (Michaud et al. 2005). Bathymetric data between 27° N and 24.5° N (coordinates of the Tosco-Abreojos fault system) show three elongated basins on the continental slope bounded on its western flank by escarpments that strike N35° W (Spencer and Normark 1979). The sedimentary fill of the depression associated with this basin is affected by flower structures characterized by the coexistence of normal and inverse faults, which produce a synclinal structure (Michaud et al. 2005).

The Santa Margarita-San Lazaro fault zone reaches ~ 400 km in length and is located 40 km to the east of the Tosco-Abreojos fault zone, with a sub-parallel orientation (Fig. 1). Fletcher et al. (2007) report that these fault systems accommodate dextral transtension. The Santa Margarita fault (SMF) segment controls an asymmetric basin of the same name, in which a study by González-Escobar et al. (2016) identified three important reflectors and an angular unconformity that possibly covers the entire Magdalena Shelf, as well as a diffuse reflector related to the ophiolitic complex that emerges in the form of islands on the map (Santa Margarita and Magdalena Islands). This region experiences active seismicity, as reported by Munguía et al. (2015a, b).

Study area

The processed and interpreted seismic profiles lie northwest of Puerto San Carlos, Baja California, covering a linear distance of ~ 400 km (Fig. 2) on the north-central part of the shelf. These profiles allow us to study the structure and seismostratigraphy of the zone, mainly the San Lazaro basin, to estimate the magnitude of the extension associated with this fault zone that accommodates part of the deformation between the Pacific plate and the microplate of Baja California.

Material and methods

Marine seismic reflection data were acquired by PEMEX during the period 1978–1980, in water depths of 60 to ~ 500 m. Seven air guns configured into arrays were towed 2680 m, with a 50-m distance between stations and 25 m between shooting points, with a sampling interval of 4 ms. The seismic data were processed using ProMax® software following a conventional processing sequence (Yilmaz 2001) that included the following: (a) pre-stacking: trace

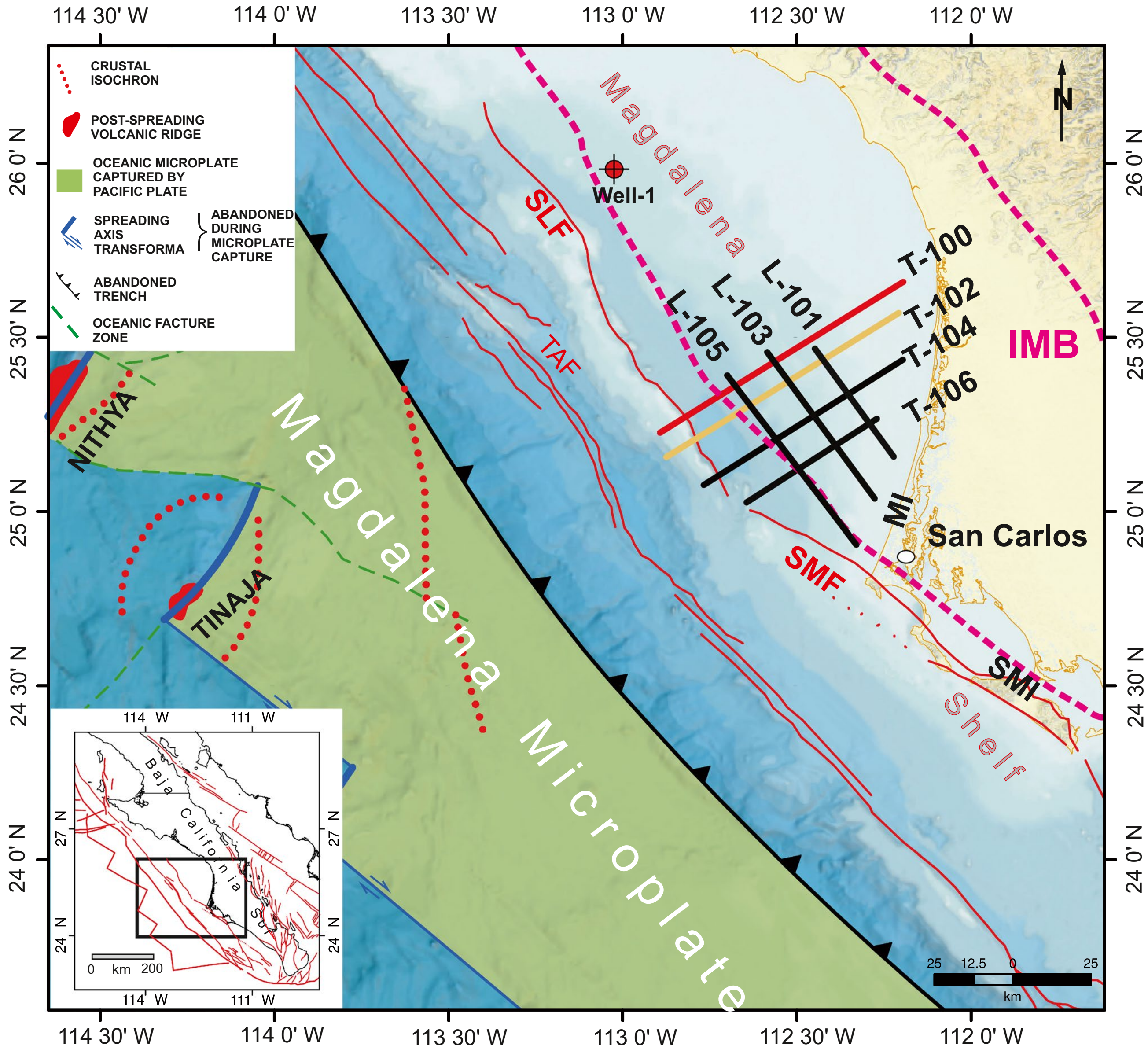


Fig. 2 Seismic reflection profiles used in this study (L- and T-lines). The inset map shows the major tectonic features of northwestern Mexico and the study area location (i.e., Magdalena Shelf). The profiles used in this study are shown along with patterns of extinct plate boundaries, fracture zones, and the extent of postspreading axial ridges (Tian et al., 2011). San Lazaro Fault, *SLF*; Santa Margarita Fault, *SMF*; Tosco-Abreojos Fault, *TAF*; Magdalena, and Santa Margarita Island, *MI and SMI*; Iray-Magdalena Basin, *IMB* (dashed magenta line, from García-Domínguez (1976)). The transverse profiles have an azimuth of 55°, while the profiles longitudinal to the coastline have an azimuth of 145°. Details of the red and brown profiles are shown in Figs. 3 and 4. Well-1 from Lozano-Romen (1976) intersects green schist (ophiolitic complex) at a depth of 1047 m

editing, bandpass filter, geometry, spherical divergence, and deconvolution; (b) stacking: grouping by common depth point (CDP), speed analysis, and correction by normal moveout (NMO); (c) post-stacking: top-mute, automatic gain control (AGC), and migration. The geological interpretation included a study of the main seismostratigraphic and structural characteristics of the seismic sequences.

Results

The interpretation of the seismic profiles is shown in Figs. 3 and 4, which made it possible to identify eight seismic reflectors and the seafloor in the San Lazaro and Iray-Magdalena basins. Likewise, synthetic and antithetic faults were identified, as well as the San Lazaro fault (SLF), which is the main structure in the study area, and which controlled the Neogene evolution of the San Lazaro basin (Fletcher et al. 2007; Brothers et al. 2012). The reflector that defines the boundary between the sedimentary sequence and the acoustic basement was related to a structural high attributed to the ophiolite complex (García-Domínguez 1976).

The seismic profiles show two distinct structural domains. The eastern domain is represented by a forearc basin or the Iray-Magdalena basin, which developed east of the structural high that corresponds to the ophiolitic acoustic basement. This feature also appears in the Santa Margarita and Magdalena Islands (Fig. 2). The western domain is represented by deformation structures of the San Lazaro-Santa Margarita fault system. The seismic profiles are described below, based on their structural characteristics and the main seismic stratigraphic features within these two structural domains.

To the northeast, we observed the eastern domain corresponding to the Iray-Magdalena forearc basin (IMB) (García-Domínguez 1976), where two normal-type faults are present, with an eastward dip that influences the subsidence and the greater thickness of the sedimentary sequence (Figs. 3 and 4). The Iray fault (IF) and the Magdalena fault (MGF) control the change in dip of the horizon that defines the acoustic basement in this sector. These faults are located at a minimum depth of 0.7 km and a maximum depth of 2.5 km. The area to the SW in profiles of the region contains a greater number of normal faults that bound a semi-graben, defined by a change in dip of the fault planes, which mainly fall to the west while a few others fall toward the east. The faults here have shallower depths (0.5–1.5 km) and exhibit small displacements, which was observed through the lack of large fault jumps in the seismic horizons.

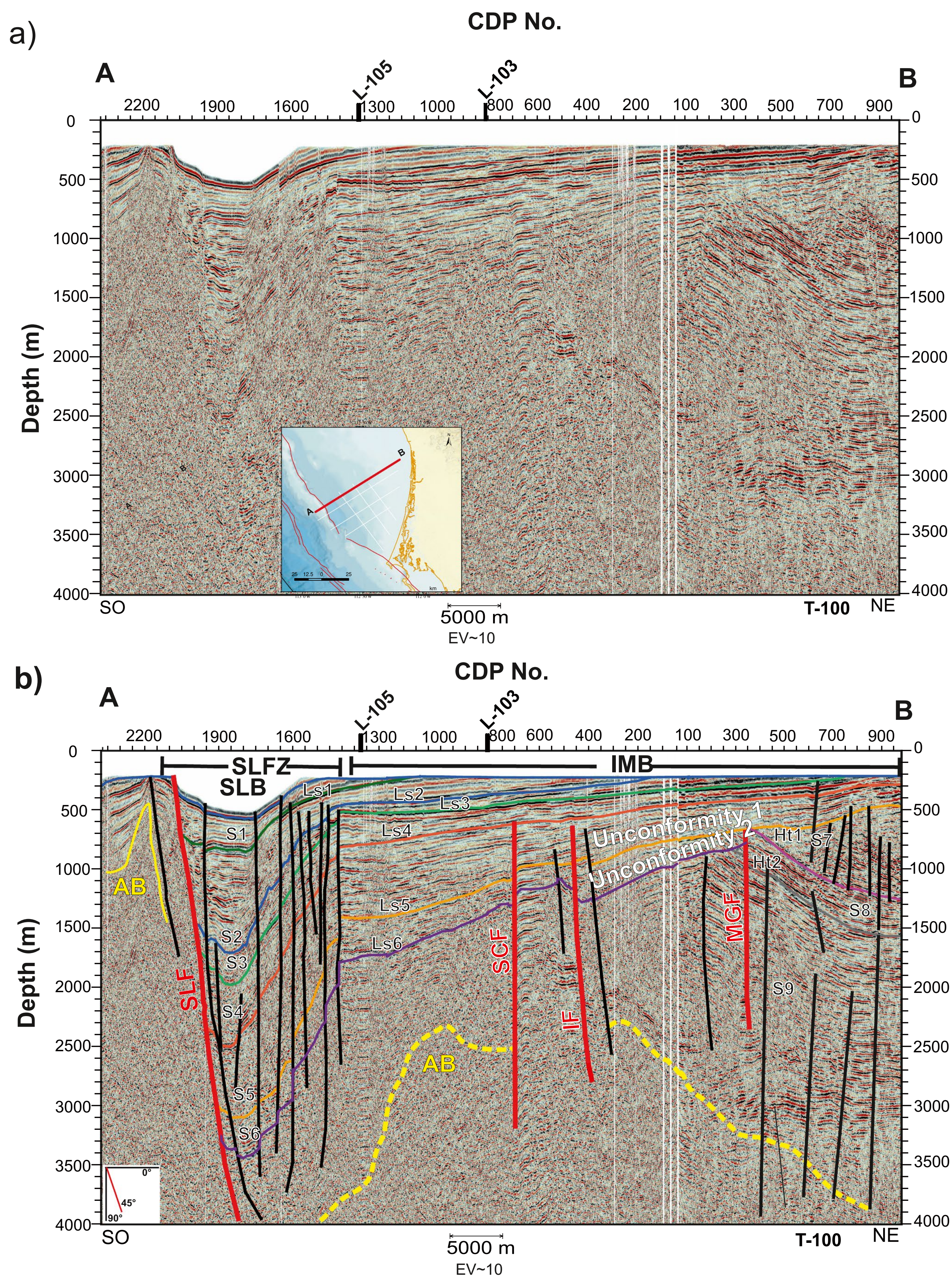
Toward the southwest part of the profile, several normal faults define the depocenter of the San Lazaro basin (SLB) and, therefore, the dip of the sedimentary sequences. In this zone of recent deformation, the SLF is considered to be the main structure, which is normal in character; this fault plane has an apparent dip of 60° NE and a depth range from 0.25 to 4 km that controls the bathymetric escarpment (Figs. 3 and 4). This fault brings two types of lithologies into contact, characterized by two different seismic facies: one of which corresponds to the acoustic basement, and the other corresponds to possible sedimentary rocks. The San Lazaro basin (SLB) is approximately 20 km wide at a depth of 1.0 km. In this basin, it was possible to identify six laterally discontinuous and high-amplitude seismic horizons, with the Ls1–Ls6 limiting sedimentary sequences denoted as S1, S2, S3, S4, S5, and S6. These have greater thicknesses toward the SW and they decrease and merge toward the NE of the seismic profiles. The boundary between the acoustic basement and possible sedimentary rocks defines a structural high, which is visible due to the change in dip of the seismic reflectors; these dive toward the SW and the NE.

Nine sedimentary sequences were identified based on contrasts in acoustic impedance and according to the first- and second-order sequence boundaries identified in this profile. The sedimentary sequences S3, S4, S5, and S6 are continuous and are defined by high-amplitude seismic reflectors. They exhibit a pattern of parallel reflectors whose thickness becomes greater toward the SW, and that merge toward the NE. The seismic reflector Ls5 (brown line) represents a first-order angular unconformity and is identified in this work as unconformity 1. This greater discordance marks a change in the geometry of the strata, below which the sedimentary sequence Ht1 (pink line) is observed between a minimum depth of 0.6 km and a maximum depth of 1.25 km. The sequence Ht1 is inclined toward the NE and ends abruptly at the sequence boundary corresponding to unconformity 1. Influencing this angular unconformity is seismic reflector Ls6 (purple line), which corresponds to the sequence limit and constitutes unconformity 2. Ls6 is truncated toward the NE by a fault with a normal component defined as the MGF. This fault produces a drop in the sedimentary sequence dipping toward the east (Ht2 sequence in gray), which starts at a minimum depth of 0.95 km and extends up to 1.5 km. We consider this fault to be of great importance within the tectonic evolution of the basin since it brings into contact two different deposition patterns: one characterized by continuous, parallel, and high-amplitude seismic reflectors that thin toward the east, and the other that is characterized by continuous, high-impedance, and inclined seismic reflectors, which dip to the NE.

The classic acoustic basement represented as a high-impedance reflector is not observed. On the contrary, in our seismic profiles, the limit between the acoustic basement and possible sedimentary rocks was observed to be diffuse, which corresponds to a structural high that is discernable by the change in dip of the seismic reflectors, in which some sectors dip to the SW and others to the NE. It is found at variable depths of 2.5–3.8 km. The change in basement dip to the east is imposed by what we term the Iray fault (IF), while the San Carlos fault (SCF) controls the drop to the west, resulting in a high basement between these two faults (Figs. 3 and 4).

3D configuration of the main sequence boundaries

Based on acoustic impedance contrasts, reflection patterns, termination of reflectors, and seismic facies, six first-order sequence boundaries (Ls1–Ls6) were identified within the SLB. The seismic reflectors Ls1 to Ls6 are part of the SLB, and they are controlled by the fault of the same name. The


a)
CDP No.
A
B
L-105
L-103
2200
1900
1600
1300
1000
800
600
400
200
100
300
500
700
900
Depth (m)
0
500
1000
1500
2000
2500
3000
3500
4000
SO
NE
T-100
5000 m
EV~10
b)
CDP No.
SLFZ
SLB
IMB
Ls1
Ls2
Ls3
Ls4
Ls5
Ls6
S1
S2
S3
S4
S5
S6
S7
S8
S9
Ht1
Ht2
AB
Unconformity 1
Unconformity 2
SLF
SCF
IF
MGF
0°
45°
90°

◂**Fig. 3** Seismic profile T-100. The NE zone is in the domain of the Iray-Magdalena basin, *IMB*, and the SW side of the profile represents the domain of the San Lazaro fault zone, *SLFZ*. The major sequence boundaries (LS1–LS6) are marked in different colors and correspond to the sedimentary sequences denoted S1–S9. HT1, HT2: truncated horizons 1 and 2. Acoustic basement, *AB*; Magdalena Fault, *MGF*; Iray Fault, *IF*; San Carlos Fault, *SCF*; Magdalena Fault, *MGF*; San Lazaro Fault, *SLF*; Iray-Magdalena Basin, *IMB*; San Lazaro Basin, *SLB*. EV refers to X-axis. The blank sectors within the profile indicate information gaps in the original seismic data

boundaries of sequences Ls5 and Ls6 are considered to be the most important stratigraphically since they represent two regional angular unconformities, which have been designated as unconformity 1 and unconformity 2 (Brothers et al. 2012; García-Domínguez, 1976) (Figs. 3, 4, and 5). SLB is a semi-graben with an average width of ~ 18 km and an estimated depth of 1.0 km, which deepens to the SW. Its depocenter is located at 3.5–4.0 km and its thickness diminishes until it disappears toward the NE. The spatial configuration of the most important sequence boundaries, defined as unconformity 1 and unconformity 2, indicates that they are parallel and that the maximum thickness between the seafloor and unconformity 1 defines the depocenter of the SLB (Figs. 3 and 4). The seismic reflector Ht1 can be seen plunging toward the NE of the cube, indicating that it is part of the old forearc basin whose sedimentary fill forms sedimentary sequence S7, defined by a change in dip of the reflectors toward the east in seismic profiles T-100, T-102, T-104, and T-106. In the Iray-Magdalena basin, two second-order sequence limits (Ht1–Ht2) were identified that define two sedimentary sequences (S7 and S8) that dip to the east (Figs. 3 and 4). Figure 5 shows unconformity 1, which represents sequence limit Ls5 (Figs. 3 and 4), as well as the acoustic basement and the seafloor. In this same sedimentary sequence, CSL corresponds to the sediment thickness between unconformity 1 (Ls5) and the seabed, while sedimentary sequence CIM represents the sedimentary thickness between the basement and unconformity 1 (Ls5). Figure 5 also shows the acoustic basement at its deepest part, overlain by unconformity 1, and finally the seafloor. We note that the acoustic basement displays a significant change in dip, which is caused by the presence of the structural high oriented NW–SE that is observed at minimum average depths of 3.0 km and maximum average depths of 4.5 km.

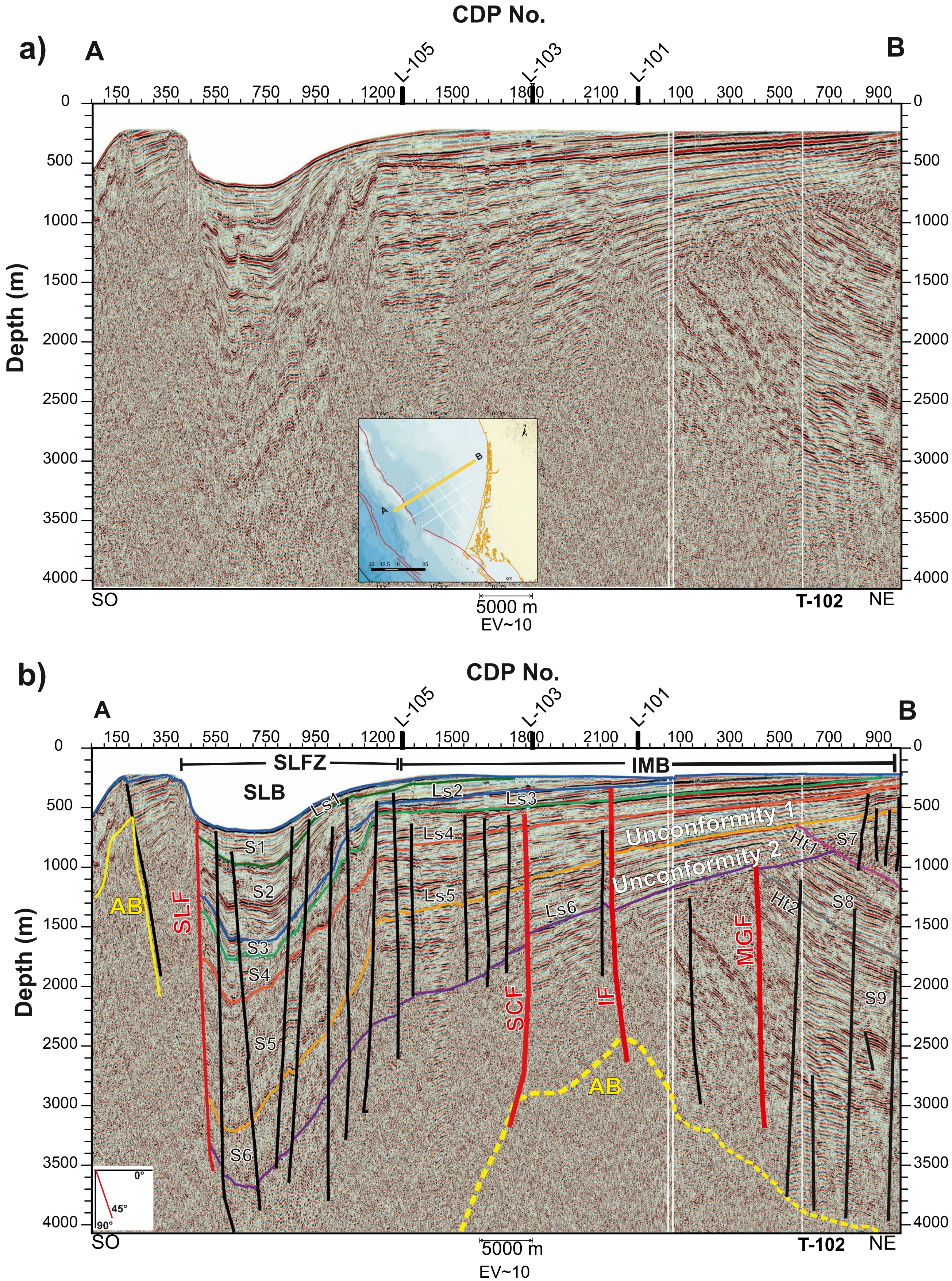
It is evident in the seismic profiles that the boundary between the acoustic basement and the sedimentary sequence is diffuse, as interpreted from the pattern of changes in dip as a function of the structural high. The seismic facies of the structural high is characterized by a chaotic, discontinuous, and low-amplitude internal configuration. This may be related to ophiolitic rocks (Lozano-Romen 1976) that form the nucleus of the structural high, which extends northwards in the Vizcaíno basin and the Lagunitas region (Fig. 8). The high is a transverse block-oriented NW–SE that divides the Vizcaíno and Iray-Magdalena basins. The ophiolitic rocks appear to the south of the study area, on the Santa Margarita and Magdalena Islands (Sedlock 1993).

Fault correlation and historical seismicity

The structural analysis of the profiles is influenced by the correlation between them, resulting in the data shown in Fig. 6, which includes the interpreted seismic profiles reported by González-Escobar et al. (2016). The structural pattern shows a NW–SE azimuthal strike. The most important structures are the San Lazaro Fault (SLF) and the Santa Margarita Fault (SMF), which bound the basins of the same name, while the Iray fault (IF) and the Magdalena fault (MGF) control the change in dip of the horizon that defines the acoustic basement in the sector of the Iray-Magdalena Basin. The SLF can be observed toward the north of the study area to be a normal fault with an average apparent dip of 42° NE. This fault controls the asymmetric semi-graben San Lazaro basin (SLB).

However, given this structural configuration, the SMF is considered to be a relay structure of the SLF, which to our knowledge is reported in this study for the first time. The SMF was identified in the seismic profiles of González-Escobar et al. (2016), who reported an apparent dip of ~ 40° NE, similar to the dip estimated in the SLF in the present study. Both the SLF and the SMF segments accommodate extension and would be part of the system of transtensional structures that affect the Pacific margin and the Magdalena Shelf. There are several synthetic and antithetic normal faults associated with the Santa Margarita-San Lazaro fault system, which controls the sedimentary sequences within the San Lazaro basin. Most of these faults cut the entire sequence and accommodate the vertical displacement and subsidence of the basin. Hence, they are considered to be active since they control the bathymetric scarp observed in the seismic profiles (Figs. 3 and 4). If we consider the Santa Margarita fault to be a San Lazaro Relay fault and the San Lazaro Basin to be sheltered by the San Lazaro fault, the basin reported by Gonzalez-Escobar et al. (2016) in the San Carlos region and that reported by Brothers et al. (2012), controlled by the Santa Margarita fault, are the same basin. This will be demonstrated later in gravimetry and magnetic anomaly maps. Therefore, we consider this basin to be the San Lazaro Sur Basin.

Historical seismicity data show that the Tosco-Abreojos and San Lazaro-Santa Margarita fault system are active, having experienced earthquakes between 1960 and 2016 (Munguía et al. 2015a, b; NEIC 2016). The magnitudes vary in the range of 3.5–5.7 (Fig. 6) with approximate depths in the range of 5 to 15 km. The focal mechanisms reported by Munguía et al. (2015a, b) confirm that there is a regime of



a)
b)
CDP No.
A
B
L-105
L-103
L-101
Depth (m)
SO
NE
T-102
5000 m
EV~10
SLFZ
IMB
SLB
AB
SLF
SCF
IF
MGF
Unconformity 1
Unconformity 2
Ht1
Ht2
S1
S2
S3
S4
S5
S6
S7
S8
S9
Ls1
Ls2
Ls3
Ls4
Ls5
Ls6

◀**Fig. 4** Interpreted seismic profile T-102. The NE zone is in the domain of the Iray-Magdalena basin, *IMB*, and the SW side of the profile represents the domain of the San Lazaro fault zone, *SLFZ*. The major sequence boundaries (LS1–LS6) are marked in different colors and correspond to the sedimentary sequences denoted S1–S9. HT1, HT2: truncated horizons 1 and 2. Acoustic basement, *AB*; Iray-Magdalena basin, *IMB;* San Lazaro Basin, *SLB*; Magdalena Fault, *MGF*; Iray Fault, *IF*; San Carlos Fault, *SCF*; Magdalena Fault, *MGF*; San Lazaro Fault, *SLF*. EV refers to X-axis. The blank sectors within the profile indicate information gaps in the original seismic data

transtensional stress in the Pacific margin west of Baja California. Likewise, the seismic data analyzed by these authors confirm the existence of active faults east of the Tosco-Abreojos fault system, which have the potential to generate earthquakes of low to intermediate magnitudes. This indicates a seismic risk for the population centers within the region, including Puerto San Carlos, where a thermoelectric plant is located.

The current study recognizes the Iray and Magdalena faults for the first time, which are located toward the east of the study area and contained within the Iray-Magdalena basin. They exhibit a strike of N15° W, and apparent dips of 80° NE, and are 34 km in length as measured in the plane of the IF and 23 km in the MGF segment. These faults control the thickness of some sedimentary sequences to the east and also control the change in dip of the horizon that defines the acoustic basement, while the San Carlos fault controls the thickness to the west (Figs. 3 and 4). Although the Iray-Magdalena basin was considered to be inactive (García-Domínguez 1976; Lozano-Romen 1976), in this study we find evidence in the seismic profiles that the Iray and Magdalena faults are active and cut through the most recent sedimentary sequences (Ls2–Ls4) (Figs. 3 and 4). Additionally, a recent seismicity has been reported toward the southeast of the study area (Munguía et al. 2015a, b).

Discussion

Structural characteristics of the San Lazaro-Santa Margarita fault system

The Magdalena Shelf is cut by two major fault systems: (1) the Tosco-Abreojos fault system to the west and (2) the San Lazaro-Santa Margarita fault system to the east. Both systems belong to the Tosco-Abreojos deformation zone of Neogene age (Spencer and Normark 1979; Normark et al. 1987). This zone of deformation extends from the fossil trench at the foot of the continental slope to the Santa Margarita fault that borders the eastern side of the island of the same name. This strip has an average width of ~ 75 km and controls the main geomorphological features and structural factors along the continental margin (Spencer and Normark 1979, 1987). The San Lazaro-Santa Margarita fault system is located 40 km east of the Tosco-Abreojos fault (Fig. 6), which suggests that deformation is partitioned within that strip.

Previous studies have mapped the SMF and SLF as a continuous fault of 400 km in length (Spencer and Normark 1979; Normark et al. 1987). Subsequently, Fletcher et al. (2007) divided it into two sectors: the SMF located to the south and the SLF located north of the Magdalena and Santa Margarita Islands. The SMF likely ends north of the island of the same name since the PEMEX seismic profiles do not show its projection in that direction, nor do they show the bathymetric and structural features observed to the south of the islands (González-Escobar et al. 2016). In the present study, we observe that the relay ramp of the SLF toward the north accommodates the extensional deformation and forms the San Lazaro basin. The passage to the left of the Santa Margarita-San Lazaro fault system is 10 km wide to the west of the SMF projection. It is noteworthy that the SMF has a length of ~ 100 km in the area covered by the seismic profiles (González-Escobar et al. 2016). However, the continental shelf south of the Santa Margarita Island presents bathymetric features which indicate that the SMF changes its orientation toward the southeast, as reported by Brothers et al. (2012), 20 km south of the island. The bathymetric feature is more than 100 km long and may contain other segments connected by relay areas with steps to the right (Fig. 6).

The segment of the SLF is located ~ 10 km northwest of the SMF, with a strike of N15° W, a dip of 42° NE, and a length of ~ 70 km, as mapped within the seismic profiles that were processed in the present study. Furthermore, the bathymetric escarpment of the San Lazaro fault may continue 35 km to the north of our study area, indicating that its total length could be more than 100 km (Fig. 6). The SLF produces a bathymetric depression 15–18 km wide, but the greatest subsidence occurs at a width of 10 km. It is controlled by an assemblage of faults that are synthetic to the SLF in the west margin and antithetic faults in the eastern side of the basin (Fig. 7d). It is possible that the SLF has a deep listric geometry (> 3.5 km). Dip angle measurements vary between the seismic profiles; for example, profile T-100 (Fig. 3) has a 33° dip to the NE, while profile T-102 (Fig. 4) at the SLF has a 60° dip to the NE. Although the fault plane has an average dip of 42°NE, the geometry of the deposits does not show the rollover normally associated with faults having listric geometry, and it is possible that the synthetic faults accommodate a significant part of the subsidence and converge at depth with the SLF.

The orientation and direction of displacement of the SLF and the SMF are similar and are part of a relief structure separated by the structural high of the outcrop subduction

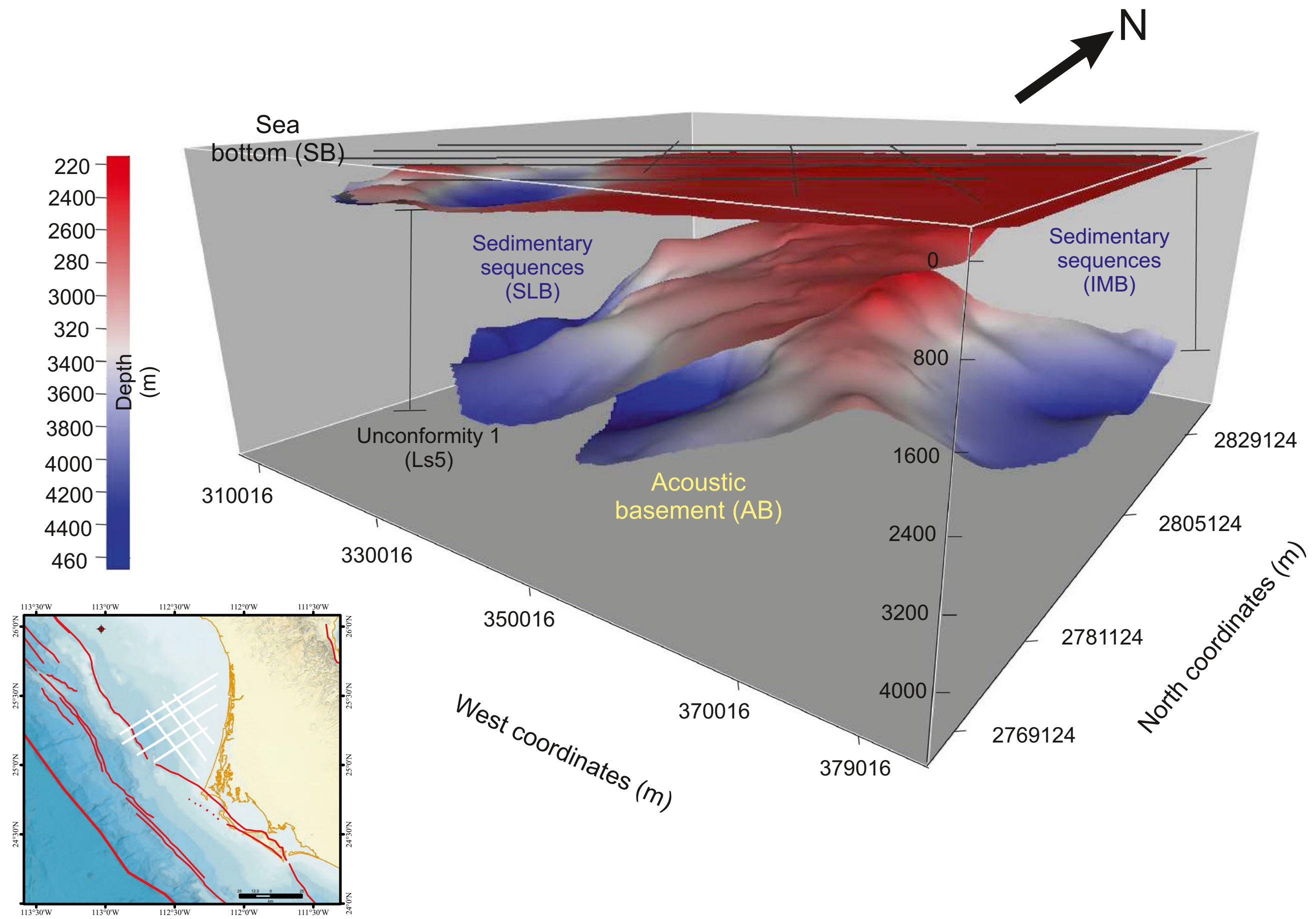


Fig. 5 Three-dimensional view representing the character of the seismic reflectors within the San Lazaro Basin, *SLB*, viewing the depocenter of the SLB; the features visualized in this view from base to top include mismatch 2, the seismic reflector corresponding to truncated Horizon 1 (Ht1), sedimentary sequence 7 (S7), unconformity 1, and the seafloor. San Lazaro Basin, *SLB*; Iray-Magdalena Basin, *IMB*. The color bar indicates the greatest depths in blue and shallower depths in red. The coordinates are represented in UTM zone 12

complex in the Margarita and Magdalena Islands. We conclude that these faults accommodate the extensional component of the Tosco-Abreojos fault system that accounts for a small part of the relative displacement between the Pacific and North American plates.

Sequence boundaries in the San Lazaro basin

Eight seismic reflectors were identified in the San Lazaro basin, that we interpreted as sequence boundaries (Ls1–Ls6, Ht1–Ht2) based on acoustic impedance contrasts and seismic facies (Figs. 3, 4, and 5). Reflectors Ls1–Ls6 delimit sedimentary sequences S1–S6, which are syntectonic and associated with the SLF. The age of the SLB sedimentary fill is unknown, but Brothers et al. (2012) (Fig. 7b) correlated the Tosco-Abreojos basin with the development of the mid-Miocene-age Magdalena fan (Yeats and Haq 1981). We speculate that major eustatic changes during the Neogene may have been responsible for these sequences. The sea level change curve of Haq et al. (1987) indicates important variations during the Late Miocene and Pliocene–Quaternary, with at least seven maxima in this period and with amplitudes greater than 100 m. The Magdalena shelf has a shallow bathymetry, and such changes in sea level should have influenced the lithology and geometry of the basin fill. Sequence boundaries Ls1–Ls6 are mainly high-amplitude reflectors that cross the whole basin and thin toward the east. It is possible that these continuous horizons represent maximum flooding surfaces during periods of high sea level (high stand), similar to the current level. The centennial records of the last five millennia indicate suboxic conditions and a considerable contribution of biogenic sediments associated with high productivity in the current upwelling region of California. In conditions of low sea level, a portion of the terrigenous sediments of the shelf were transported toward the basin and produced thicker sequences within the San Lazaro and Santa Margarita basins.

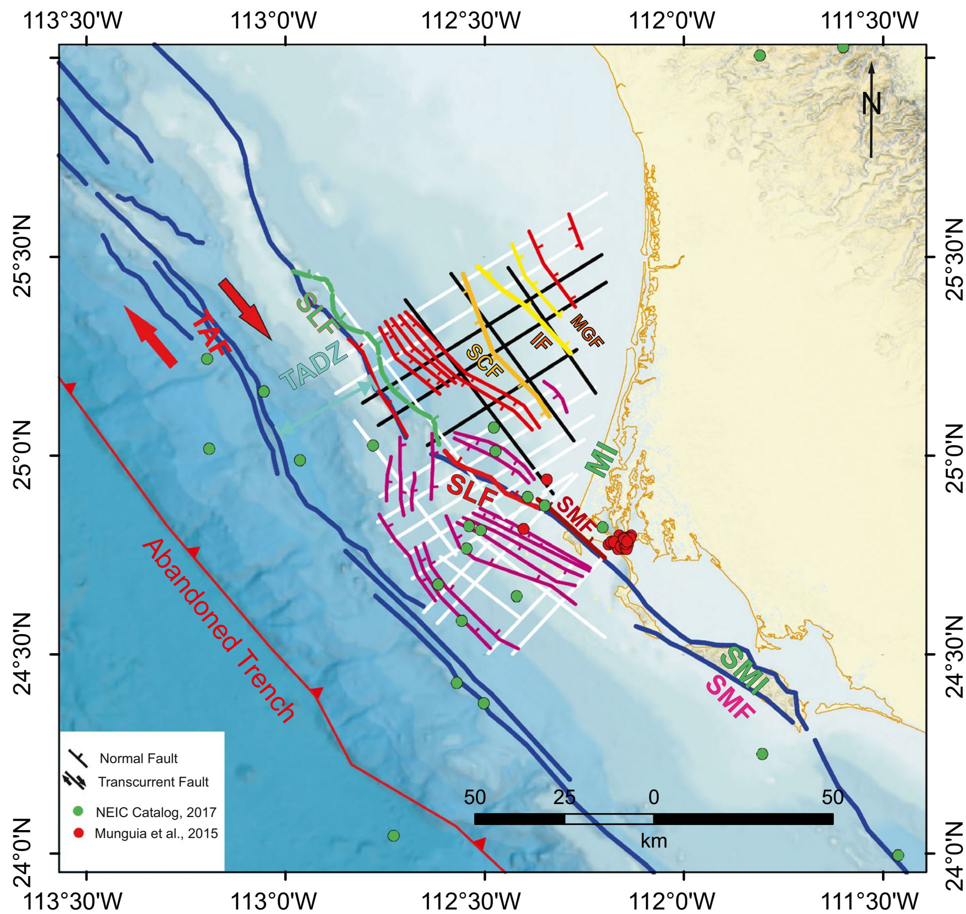


Fig. 6 Structural map and seismic activity in the study area. The profiles marked in black and the faults in red and orange are those that have been interpreted in the current study. Profiles in white and faults in purple were reported by González-Escobar et al. (2016). Faults marked in blue were reported elsewhere in the literature (e.g., Fletcher et al. 2007; Brothers et al. 2012). Green circles correspond to earthquakes taken from the USGS database (http://earthquake.usgs.gov/) for the period 1960–2016. The circles in purple correspond to earthquakes reported by Munguía et al. (2015a, b). Tosco-Abreojos Deformation Zone, *TADZ*; Tosco-Abreojos Fault, *TAF*; San Lazaro Fault, *SLF*; Santa Margarita Fault, *SMF*; Iray Fault, *IF*; Magdalena Fault, *MGF*; Magdalena and Santa Margarita Islands, *MI* and *SMI*

Seismostratigraphic characteristics (sequences and sequence boundaries in the Iray-Magdalena basin)

Sequences S7 and S8 represent the upper part of the sedimentary fill of the Iray-Magdalena basin and may be of Paleogene age (García-Domínguez 1976) (Fig. 7b). Below the Ht2 horizon is a strong concordant sedimentary sequence that reaches 2.0 km in thickness and overlies acoustic basement. The seismic profiles do not have sufficient resolution and do not allow for a more detailed analysis of the relief; however, we propose that this corresponds to subduction complex rocks, which include green schists, metamorphosed oceanic sediments, and blueschist-facies rocks (Sedlock 1993).

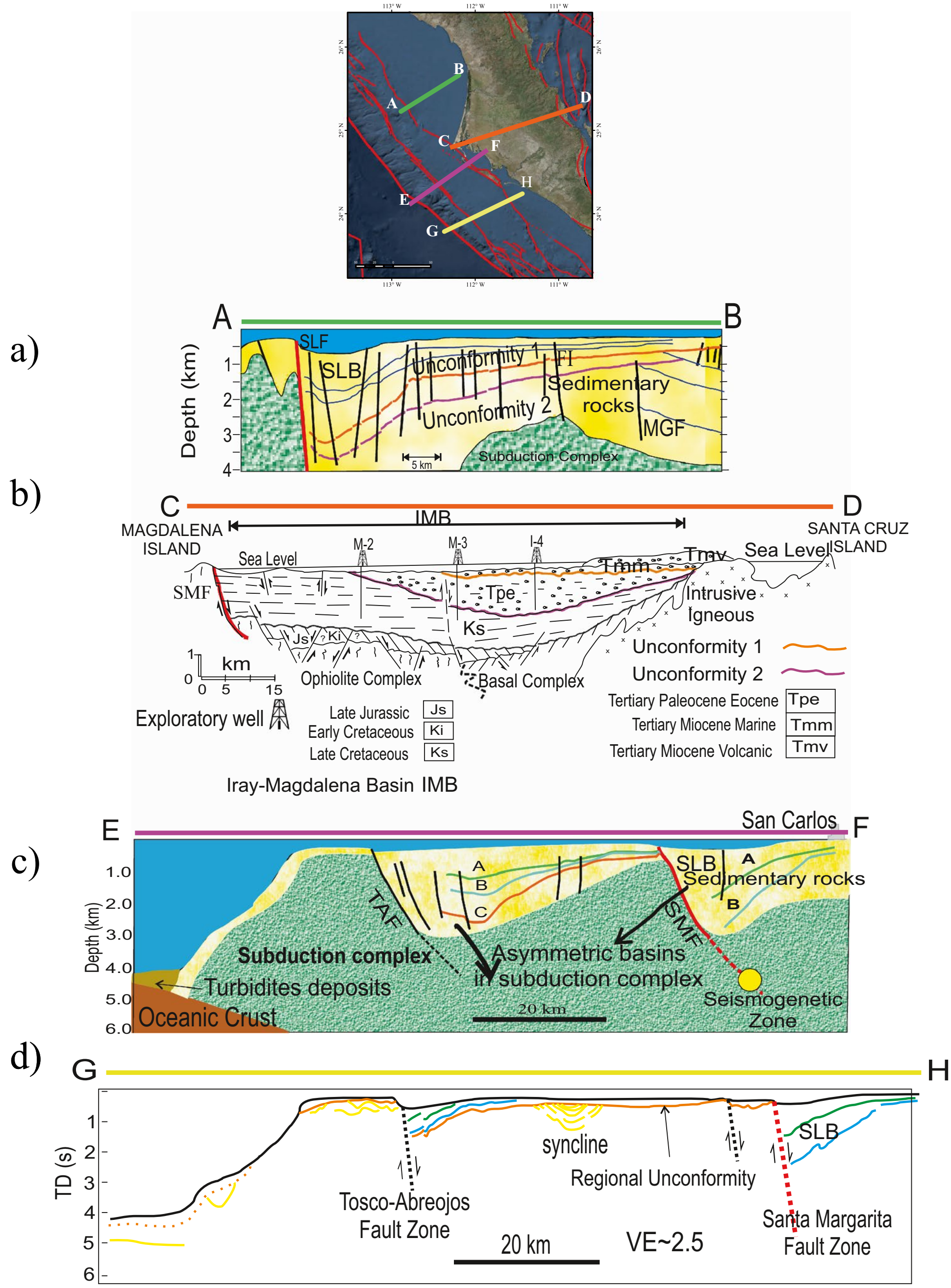
Sequences S7 and S8 dip to the east and are truncated by discordance 2, which is the most prominent on the continental shelf. This unconformity (Fig. 7b) marks the exhumation of the forearc basin, possibly at the end of the Paleogene and in the early Neogene (García-Domínguez 1976). Fletcher et al. (2007) propose that unconformity 1 is a Miocene abrasion surface that was active during the final subduction of the Farallon plate. Unconformity 1 is a continuous horizon over the whole shelf and divides two main sequences that correspond to two major tectonic events, and marks the resumption of sedimentation in the continental shelf.

The beginning of marine sedimentation in the Magdalena shelf may be associated with tilting of the peninsula due to the rift in the Gulf of California. The uplift of the rift flank in the Loreto region has been documented to have occurred during the late Miocene (Mark et al. 2014). This is consistent with the resumption of marine sedimentation during the Late Miocene-Pliocene that is observed in different areas of the continental shelf of Baja California Sur (Brothers et al. 2012; González-Escobar et al. 2016). These authors consider the erosional discordance to mark a change in tectonic regime and reorganization of the plate boundary that affected the Magdalena Shelf in such a way that the compressive regime dominated during the Middle Miocene, followed by a transtrensive tectonic regime during the capture of the Baja California micro-plate by the Pacific plate.

Acoustic basement

The reflector that marks the boundary between the acoustic basement and the sedimentary sequence is diffuse in most of the seismic sections; however, based on the changes

Fig. 7 Location map of the comparative profiles from north to south: **a**, **b**, **c**, and **d**, in the region of the Magdalena shelf. **a** Seismic profile A–B reported in this study, denoted by the green line on the location map. **b** Schematic profile C–D from the study by García-Domínguez (1976), orange line in the location map. **c** Seismic profile E–F of Gonzalez-Escobar et al. (2016) denoted by the purple line on the location map. **d** Seismic profile G–H of Brothers et al. (2012), denoted by the yellow line on the location map



in dip described by the structural high, it was possible to locate its depth in time (Figs. 3 and 4). Additionally, the exploratory WELL-1 intersected green schist, which is interpreted as part of the ophiolitic complex of Cretaceous-Upper Jurassic age (absolute age of 127 ± 10 Ma at a depth of 1047 m (Lozano-Romen 1976)). Although WELL-1 is located 250 km to the north of the study area, it confirms that the structural high is part of the subduction complex. The structural high extends from the Iray-Magdalena basin to the north and continues in the Vizcaino basin and the Alto de Lagunitas region. The last reflector is a basement elevation oriented NW–SE that divides the area into the Vizcaino basin to the north and the Iray-Magdalena basin to the south (Lozano-Romen 1976).

In the Santa Margarita and Magdalena Islands, rocks associated with the ophiolitic complex overlie blue schist (Sedlock 1993). In these islands, the ophiolitic complex includes a melange with blocks of ultramafic rocks, gabbros, diabases, and other mafic volcanic rocks, as well as flint and clastic metasedimentary rocks. This lithological package is deformed and metamorphosed. The age of the protolith, deformation, and metamorphism is unknown, but Baldwin and Harrison (1992) reported amphibole ages in several blocks that represent the age of metamorphism, which ranges from 103 to 94 Ma.

Figure 7 shows a series of schematic profiles over the Magdalena Shelf in the region and vicinity of the study area. The presence of the Santa Margarita fault was reported by Garcia-Domínguez 1976 (Fig. 7b), González-Escobar et al. (2016) (Fig. 7c), and Brothers et al. (2012) (Fig. 7d). Figure 7a shows the main characteristics present in the region from profile T-100. Only the SLF is observed in this profile, but when the absence of the SMF and the observations from the other schematic profiles are taken into account, we conclude that the SLF is a relay structure of the SMF. We can confirm the observations of the abovementioned authors that the discordance has a consistent regional presence and that the faults and stratigraphic sequences exhibit the same behavior throughout the region.

The SLF can be observed in some of the profiles in the present study, including those reported by González-Escobar et al. (2016). In this regard, the study by Munguia et al. (2015a) on the seismic activity and its focal mechanisms is considered by the present authors to indicate that the region is subject to transtensional stress. It can also be seen that the San Margarita Basin (SLB) appears in Figs. 3, 4, and 7a, c, and d, while it is absent to the north (Fig. 7a). Hence, the SLB is bounded to the north where it is replaced by the SMF and the SLF (Fig. 6). This also coincides with a relative low in the gravimetric anomaly map (Fig. 8). Concerning the discordances, unconformity 2 is present in the whole region, while unconformity 1 was observed toward the north by Garcia-Domínguez (1976), within the terrestrial region, and in the present study in the marine region. In a study by Garcia-Domínguez (1976), the Iray-Magdalena basin extends into the terrestrial region, as shown in Fig. 7b, which corresponds to profile T-100 in Fig. 3.

The Bouguer and magnetic anomaly map (Fig. 8) contains information from the study by Sandwell et al. (2014). In Fig. 8a, the location of a structural high with values between 80 and − 110 mGal is noted. Also, the alignments of the gravimetry anomalies suggest the continuation of this structural high toward the area northwest of the Magdalena Shelf, reaching the Lagunitas structural high. It is noteworthy that the San Lazaro basin (LSB) has an expression in the gravity anomaly map with values between 10 and − 50 mGal (Fig. 8), denoting a depression similar to the depression observed in the seismic profiles that were processed and interpreted in this work (Figs. 3 and 4). The character of the anomaly continues toward the southeast, where we consider the San Lazaro Basin South (SLBS, Fig. 8) to be located. These results clearly show that the negative magnetic anomaly that corresponds to the offshore islands can be traced NW to the very western end of the profiles discussed here. Another, separate magnetic low intersects the seismic reflection profiles further north. We consider the anomaly to the south to be a single body that, upon reaching the San Lazaro Basin (Fig. 8), becomes divided into two belts of the subduction complex that flank said elongated basin. This effect is observed in both types of anomalies (gravimetry and magnetic). This separation coincides with the acoustic basement high that was observed in the two profiles shown here below the Iray-Purisima Basin (Figs. 3 and 4).

Conclusions

In the western continental margin of Baja California, observations indicate that a change in the direction of the Pacific-North American plate boundary caused the system of transtensive deformation during the Neogene that cuts across the external part of the continental shelf and the break in the slope. In the processed and interpreted seismic profiles, two structural and stratigraphic domains were identified: the eastern domain is characterized by the forearc basin of the Cretaceous-Tertiary (Iray-Magdalena basin), while the western domain is represented by the deformation system associated with the Neogene Tosco-Abreojos fault system, specifically regarding the San Lazaro-Santa Margarita fault system. The San Lazaro and Santa Margarita basins are asymmetric and sub-parallel to the Tosco-Abreojos fault zone. The zone of active deformation between the San Lazaro fault and the Tosco-Abreojos fault is ~ 30 km (Figs. 6 and 7).

The SLF was mapped with a length of 70 km within the studied seismic mesh, but the bathymetric feature to the north indicates that it could reach 100 km in length. It is a normal fault, with a strike of N15° W and an average apparent dip of 42° NE. The deformation zone of the SLF reaches a width of 15 to 18 km and contains several faults that are synthetic and antithetic to the main fault that accommodates subsidence and defines the depocenter of the San Lazaro basin. The average width of the deformation zone is ~ 17 km, and it widens to the north, where the width of the bathymetric depression reaches 20 km in the east–west direction. Toward the south, the basin loses bathymetric expression, but the SMF is located ~ 10 km east of the SLF. The southern end of the SLF and the northern segment of the SMF are interpreted as forming a relay structure that accommodates most of the extensions in the Tosco-Abreojos system.

The Santa Margarita-San Lazaro fault system is considered active because it affects the bathymetric escarpment of the San Lazaro basin (Figs. 3, 4, and 5). This observation is consistent with the historical earthquake registered in local and regional seismic networks, with magnitudes between 3.5 and 5.7, during the period 1960–2016 (Munguía et al. 2015a, b; NEIC 2016).

The Iray-Magdalena basin in the central-eastern part of the Magdalena shelf is considered to be tectonically active due to the fact that the Iray fault (IF) and the Magdalena fault (MGF), as reported for the first time in this work (to

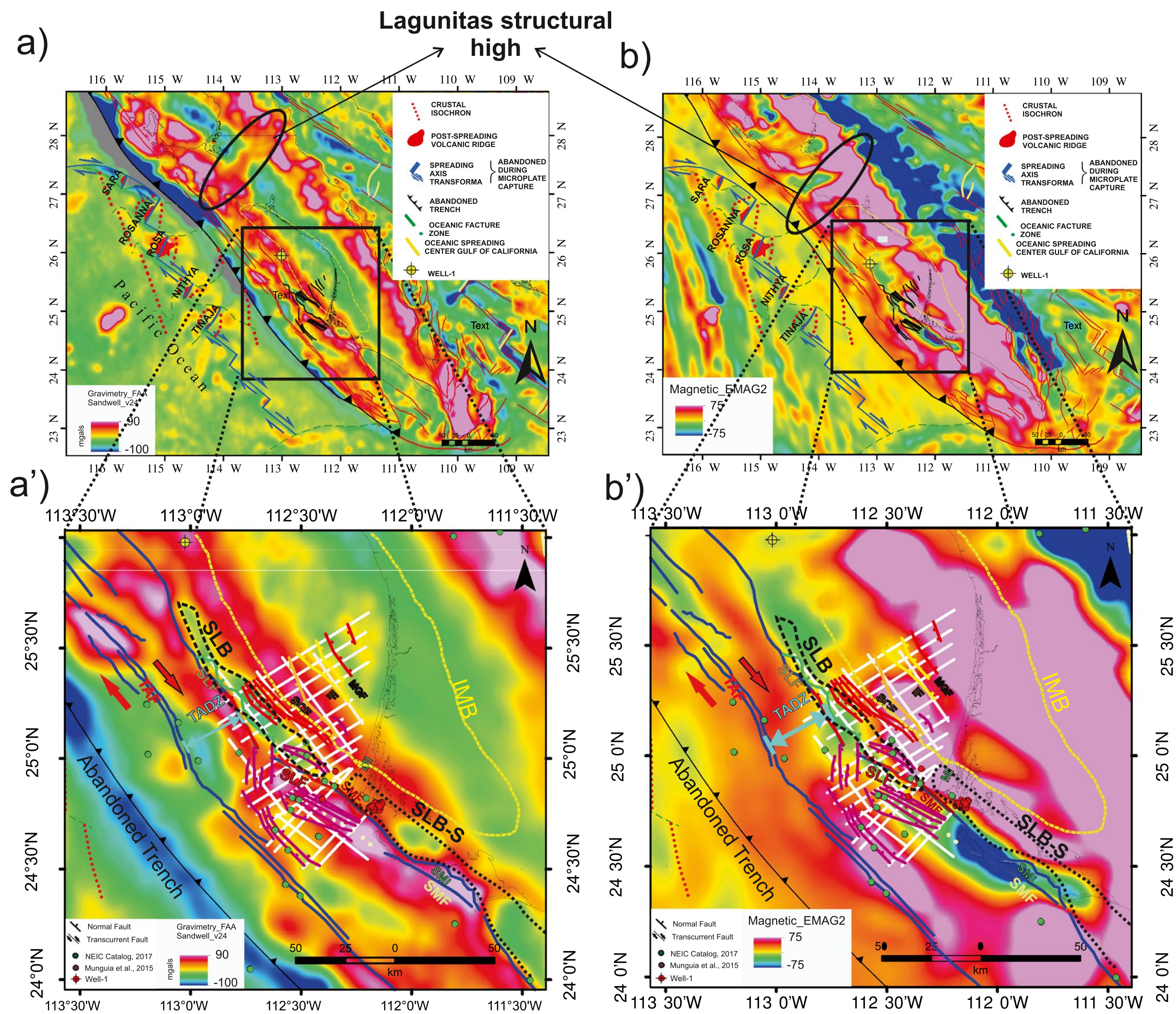


Fig. 8 Map of Bouguer and magnetic anomalies prepared with data from Sandwell et al. (2014), Maus et al. (2009) and the GeoMapApp. a) and a') are the Bouguer anomaly, while b) and b') indicate magnetic anomalies. Structures interpreted in both this work and those reported by González-Escobar et al. (2016) are shown. The San Lazaro Basin (SLB) observed in the analyzed data presented here is shown, together with the San Lázaro Basin South (SLB-S). A good correlation with the anomaly map and the Iray-Magdalen basin is observed. One can also clearly see the Lagunitas structural high. Iray-Magdalena Basin, *IMB*; Tosco-Abreojos Fault, *TAF*; San Lazaro Fault, *SLF*; Santa Margarita Fault, *SMF*; Magdalena Island, *MI*; Santa Margarita Island, *SMI*; Tosco-Abreojos Deformation Zone, *TADZ*. WELL-1 from Lozano-Romen (1976) cut green schist (ophiolitic complex) a 1047 m of depth

the best of our knowledge), intersect the S1 to S6 sedimentary sequences. In addition, recent seismic activity to the west and the northwest of Puerto San Carlos has been reported (Munguía et al. 2015a, b).

For the first time, in this work, we interpret the presence of 6 stratigraphic sequences (S1–S6) and their respective sequence boundaries (Ls1–Ls6), as shown in the processed seismic profiles (Figs. 3 and 4). This seismo-stratigraphic interpretation is a novel contribution from this study.

Two angular unconformities were identified that correspond to the first-order sequence boundaries Ls5 and Ls6 that we term unconformity 1, which may be Miocene in age (c.f. Fletcher et al. 2007; Brothers et al. 2012). Unconformity 2 is of Cretaceous-Paleogene age (García-Domínguez 1976). The seismic reflectors Ls1–Ls4 are interpreted as maximum flooding surfaces due to third-order eustatic changes (Haq et al. 1987) that occurred between Late Miocene and Quaternary time.

The geometry of the acoustic basement is defined by the top of the subduction complex. Based on studies by García-Domínguez (1976) and Sedlock (1993), the subduction complex can be inferred to contain the ophiolitic rocks that outcrop in the Santa Margarita and Magdalena Islands located the south of the study area.

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