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Paleomagnetic Quantification of Neogene Block Rotations within an Active Transtensional Plate Boundary, Baja California Sur, Mexico

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Glossary

Abbreviations

3V-Az .... Tres Virgenes accommodation zone
AA-Az .... Valle Agua Amarga accommodation zone
AF .... Alternating field
AMS .... Anisotropy of magnetic susceptibility
AV-Az .... Agua Verde accommodation zone
C-Az .... Bahia Concepción accommodation zone
ChRM .... Characteristic remanent magnetization
C-S .... Cabo rift segment
D, Dec .... Declination
DC .... Direction correction
DRM .... Detrital remanent magnetization
GEP .... Gulf Extensional Province
GP .... Guadalupe Plate
GPS .... Global Positioning System
I, Inc .... Inclination
IGRF .... International Geomagnetic Reference Field Model
IRM .... Isothermal remanent magnetization
L-S .... Loreto rift segment
LP-S .... La Paz rift segment
MD .... Multi-domain
MP .... Magdalena Plate
NRM .... Natural remanent magnetization
P-Az .... Puertecitos accommodation zone
PCA .... Principal component analysis
PE-Az .... Puerto Escondido accommodation zone
Pfz .... Pescadero fracture zone
PSD .... Pseudo-single-domain
RP .... Rivera Plate
RTJ .... Rivera triple junction

SB-TAfz ...... San Benito-Tosco-Abreojos fault zone
SC-Az ...... Bahia San Carlos accommodation zone
SD ...... Single domain
SDL...... Sierra de la Laguna
SFI ...... San Francisco Island
SJCb...... San José del Cabo Basin
SJCf ...... San José del Cabo fault
SJI ...... San José Island
SJI-Az ...... San José Island accommodation zone
SLT ...... Sierra La Trinidad
SR-Az ...... Bahia San Rafael accommodation zone
Tfz...... Tamayo fracture zone
TRM ...... Thermoremanent magnetization
T-S ...... Timbabichi rift segment
VFTB ...... Variable field translation balance
VGP ...... Virtual geomagnetic pole

Symbols and constants

α_{95}/A_{95} [°] ...... Radius of the 95% confidence circle of a paleomagnetic direction/pole
λ [°]...... Latitude
Φ [°] ...... Longitude
H_c [mT] ...... Coercive force
H_{cr} [mT] ...... Coercivity of remanence
k ...... Precision parameter for the dispersion of paleomagnetic directions
M_{rs} [Am^2/kg]...... Saturation remanence
M_s [Am^2/kg]...... Saturation magnetization
N ...... Number of specimens
S_{300}...... Bloemendal parameter
T_C [°C] ...... Curie temperature

Abstract

Compared to oceanic plate boundaries which are generally narrow zones of deformation, continental plate boundaries appear as widespread areas in which fault bounded rigid blocks accommodating deformation by vertical-axis rotations are common. Whereas motion of crustal blocks within these plate boundaries causes rather small-scale lithospheric deformation along the boundary zone, the main plates behave more rigidly. Complex deformation patterns of interacting blocks separated by a variety of active faults are the consequence. In order to study the dynamic implications of deformation along an oblique-divergent plate boundary, the Baja California peninsula, Mexico, has been chosen as subject of a detailed paleomagnetic study. Despite its location in a major active transtensional zone, the paleomagnetic work in this area directed towards vertical axis rotations has been little so far. In the course of addressing this problem, classical paleomagnetic methods were applied to analyze over 500 cores taken from Neogene volcanic and sedimentary rocks focussing on three study areas encompassing basin structures – located along the eastern coast of Baja California Sur, a region defined as the Baja California Peninsula Borderland.

In the San José del Cabo Basin – situated at the south-eastern tip of Baja California Sur – paleomagnetic data were gathered from sedimentary rocks located in the western and central part of the basin and used to calculate a mean direction; the result not being statistically different from the North American reference direction implies that these parts of the basin have not been affected by significant vertical-axis rotations. In contrast, the comparison of directions derived from the Middle to Late Miocene La Calera Formation situated in the eastern part of the San José del Cabo Basin and directions calculated from data of Early to Middle Miocene volcanic rocks and dykes located in the adjacent Sierra La Trinidad (to the east) to the related reference direction indicates well-defined clockwise rotations.

The analysis of data derived from the second study area – the Bay of La Paz region dominated by Oligocene to Miocene Comondú Group rocks – reveals a similar pattern of rotations. The declinations of sites sampled in the eastern part of the La Paz Basin suggest only small to insignificant rotations; the same is applicable to sites located south of San Juan de la Costa (to the west of the La Paz Basin) with a mean declination being consistent with the North American reference direction. Whereas the latter result provides evidence that the region west of the La Paz Basin is part of the stable Baja California microplate,

calculated directions of additional sites located to the east of the basin indicate large clockwise rotations.

Data gathered from the third focus area – including sites located on San José and San Francisco Island separated from mainland Baja by the San José Channel – also indicate clockwise rotations along the eastern part of the Baja California Peninsula Borderland. Paleomagnetic declinations derived from the Late Oligocene Salto Formation located at the south-eastern tip of San José Island and from rhyolitic tuffs of the Oligocene to Miocene Comondú Group on San Francisco Island suggest clockwise rotations in the order of 40 to 50°. In contrast, preliminary paleomagnetic analysis carried out on the adjacent mainland suggests only small to insignificant vertical-axis rotations.

Additional results elucidating the overall tectonic history of Baja California are provided by the mean inclinations calculated for the San José del Cabo Basin sediments and sites south of San Juan de la Costa which display a difference of 4° compared to the North American reference direction, a value equivalent to about 450 km of northward translation. This finding is consistent with the assumption that – since 12.3 Ma – approximately 460 km of oblique-divergent plate motion in the Gulf Extensional Province has been accommodated by a single phase of transtensional shearing. Further support for this hypothesis is provided by the comparison of present rotational rates calculated from geodetic data to vertical-axis rotations derived from paleomagnetic data of the present study suggesting an onset of the rotations in the Sierra La Trinidad about 12.5 Ma ago.

On the basis of the results obtained in the course of the present study it is suggested that right-lateral motion along the main plate boundary in the Gulf of California and along some active faults located in the Baja California Peninsula Borderland led to the pattern of clockwise rotations documented east of La Paz as well as in the San José del Cabo Basin/Sierra La Trinidad area, thus resulting in the opening of adjacent triangular shaped basins accommodating northeast-southwest- to east-west-directed extension. This assumption is consistent with findings of several studies involving the tectonic history of Baja California Sur as well as a GPS interseismic velocity field calculated for the area, indicating extension between a stable Baja California microplate and an area including parts of the eastern coast and the islands – equivalent to the Baja California Peninsula Borderland. Taking into account that in the course of the present paleomagnetic study clockwise rotations of San José and San Francisco Island were successfully documented as well, it is assumed that parts of eastern Baja California Sur are being sheared off the stable

microplate through a single phase of transtensional shearing accommodating oblique-divergent motion in the Gulf Extensional Province.

1. Introduction

The Gulf of California represents one of the best examples of an oblique divergent continental rift with the direction of extension being oblique to the rift trend. Whereas the faulting pattern of plate boundaries with orthogonal extension is reasonably well understood, research on both continental and oceanic environments with oblique divergent setting like the Gulf of Aden (Withjack and Jamison, 1986; Dauteuil et al., 2001; Fournier et al., 2004), the Main Ethiopian and Malawi Rifts in East Africa (Acocella and Korme, 2002; Chorowicz and Sorlien, 1992), the Mohns Ridge in the Norvegian Sea (Dauteuil and Brun, 1996), the Reykjanes Ridge (Murton and Parson, 1993; Applegate and Shor, 1994; Clifton and Schlische, 2003) or finally the Gulf of California (Withjack and Jamison, 1986; Umhoefer and Stone, 1996) indicates more complex structural patterns which still remain obscure in several respects. These relevant field studies suggest – with the aid of experimental, analytical and numerical models (e.g., Withjack and Jamison, 1986; Tron and Brun, 1991; Tikoff and Fossen, 1993; Fossen and Tikoff, 1998; Tuckwell et al., 1998; Clifton et al., 2000) – that deformation resulting from oblique rifting is accommodated by normal as well as strike-slip faulting (Fournier et al., 2004; Fournier and Petit, 2007). The amount and orientation of deformation is in this context dependent on the angle between the direction of displacement and the trend of the rift (Withjack and Jamison, 1986; Fournier et al., 2004; Fournier and Petit, 2007). Compared to oceanic plate boundaries which are generally narrow zones of deformation, continental plate boundaries appear as widespread areas where rigid blocks are common (Acton et al., 1991). Motion of crustal blocks within these “diffuse plate boundaries” causes rather small-scale lithospheric deformation along the boundary zone while the main plates behave more rigidly. Complex deformation patterns of interacting blocks separated by a variety of active faults are the consequence. Due to the fact that the margins of these blocks are less pronounced, the identification of boundaries proves to be more difficult than in oceanic environments (Acton et al., 1991).

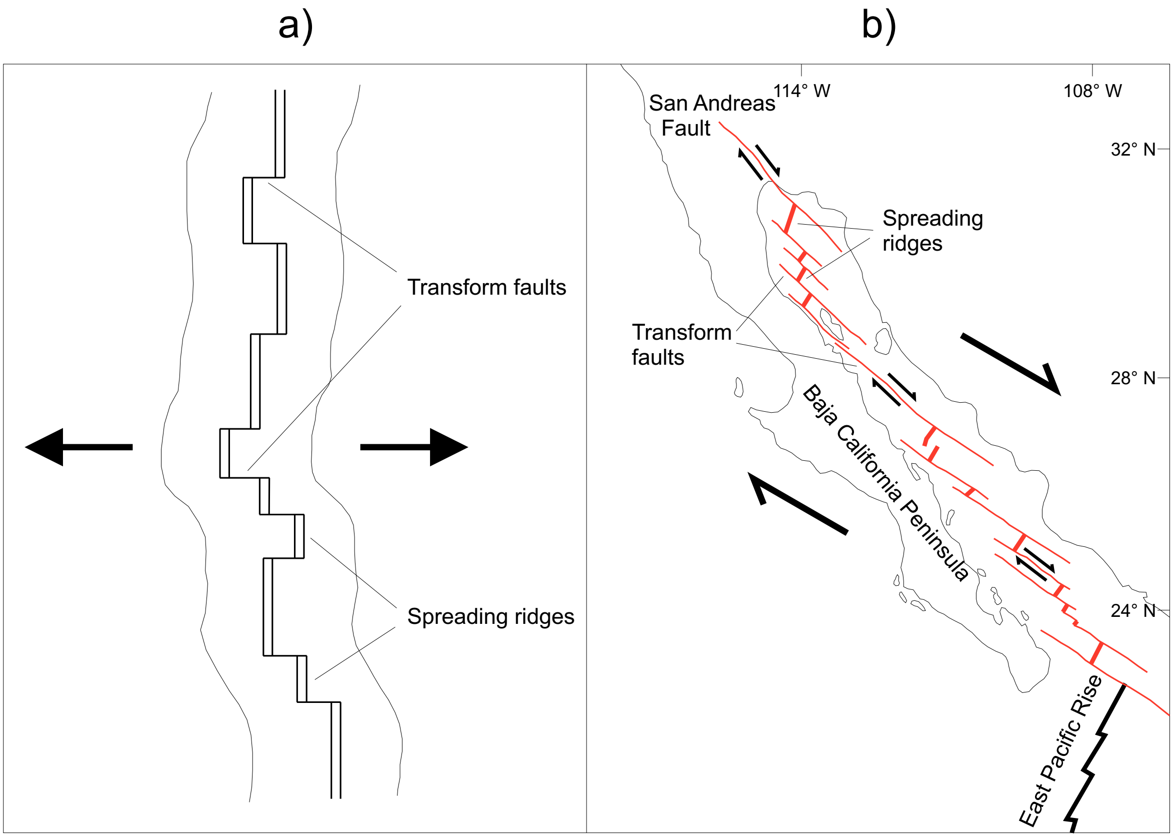

Figure 1.1: (a) Sketch of a typical orthogonal rift with extension (arrows) being perpendicular to the rift trend. (b) Overview of the oblique-divergent plate boundary located in the Gulf of California with extension being oblique to the rift trend (modified from Drake, 2005).

Nevertheless, paleomagnetism has been proven to be a very powerful tool in deciphering the sense and amount of vertical axis block rotations as well as the translation of interacting blocks in complex tectonic settings. The identification of vertical axis rotations – by comparing the expected and the observed paleomagnetic declinations – are considered to be of growing importance for the better understanding of continental deformation, especially in regions affected by a component of strike-slip displacement (Sonder et al., 1994). Such rotations have been detected at many continental plate boundaries including the Himalayan collision zone (Opdyke et al., 1982; Klootwijk et al., 1986; Huang et al., 1992), the Anatolian Trough/Aegean Sea region (Kissel et al., 1989) or northern Israel (Ron et al., 1984; Nur et al., 1989). Discordant paleomagnetic declinations were also identified in regions along the Pacific/North American Plate boundary suggesting the occurrence of significant Neogene rotations (e.g., Kamerling and Luyendyk, 1979, 1985; Luyendyk et al., 1985; Hornafius et al., 1986; Carter et al., 1987; Luyendyk, 1989; Lewis and Stock, 1998). Considering this, a variety of rotating blocks should also be present along the oblique divergent plate boundary in the Gulf of California.

1.1 State of the art

As far as Baja California is concerned, Neogene block rotations have only been fully documented in the northern part (Lewis and Stock, 1998). Paleomagnetic data from Sierra San Fermin in the Gulf of California Extensional Province indicate that localized clockwise rotations of structural blocks about vertical axes – caused by Pliocene to recent extension and dextral shear – occurred in north-eastern Baja California. Observed declinations in upper Miocene and Pliocene ash flow tuffs indicate a net clockwise rotation of 30° ± 16° with respect to localities on the North American craton (Lewis and Stock, 1998). In contrast, paleomagnetic coverage of southern Baja concerning vertical axis rotations is rather thin, except for a study by Schaaf et al. (2000) which suggests a clockwise rotation of 36 to 45° for the Los Cabos Block. Samples for this research, however, were taken from intrusives of Cretaceous age – a fact which complicates a correlation of those rotations to Neogene deformation related to the opening of the Gulf of California. Other paleomagnetic studies in Baja California either addressed paleointensities (Morales et al., 2003; Goguitchaichvili et al., 2003) or focussed on the controversial paleogeographic reconstruction of the Baja California peninsula since late Mesozoic time (Butler et al., 1991 and references therein) and on ways of explaining the discordant paleomagnetic inclinations by inclination shallowing in sediments (e.g., Smith and Busby, 1993; Li et al., 2004; Vaughn et al., 2005) or by regional tilting of plutonic rocks (Butler et al., 1991; Dickinson and Butler, 1998, Boehnel et al., 2002).

Tectonic studies in Baja California Sur were for the greater part related to processes connected to the opening of the Gulf of California by active transtensional rifting leading to the formation of dextral strike-slip faults separated by short spreading ridges along the central part of the Gulf (e.g., Gastil et al., 1981; Lonsdale, 1989; DeMets, 1995; Umhoefer et al., 2002). In addition there are studies focussing on the peninsular margin of the Gulf which are indicative for recent tectonic activity (Staines-Urias and Ledesma-Vazquez, 1996; Munguía et al., 1997; Fletcher and Munguía, 2000). Nava-Sánchez et al. (2001) propose to define the peninsular margin of the Gulf of California as the “Baja California Peninsula Borderland”, a new tectonic element of the Gulf Extensional Province. Their argumentation is based on the analysis of bathymetric, structural and sedimentological data as well as the pertinent observation of the similarity to the morphology of the California Continental Borderland (e.g., Shepard and Emery, 1941; Gorsline and Emery, 1959;

Gorsline and Teng, 1989). The main characteristics of a continental borderland – an irregular morphology including a series of islands separated by basins and troughs with varying depths – which are present in the Baja California region have formed as a result of the opening of the Gulf and are more distinct along the southern half of the Baja peninsula. However, due to an irregular peninsular margin and the onshore location of some meanwhile filled basins, like the Loreto or the San Jose del Cabo basin, limits of the Baja California Peninsula Borderland are not well defined. Seismic and bathymetric data indicate normal faults with a component of lateral strike slip which are still active and related to the north-westward translation of Baja California (Nava-Sánchez et al., 2001). Active faulting in the La Paz Bay area (Fletcher and Munguía, 2000) and microseismicity on Espiritu Santo Island (Munguía et al., 1997) provide further evidence of tectonic activity (Nava-Sánchez et al., 2001).

Miocene extension within the California Continental Borderland – caused by relative movement of the Pacific and the North American Plates – led to clockwise block rotations and the formation of isolated basins which are triangular in shape (Luyendyk et al., 1980; Nicholson et al., 1994). Present extension along the oblique Pacific/North American plate boundary is accommodated by spreading centers in the Gulf of California (Legg, 1991; Atwater, 1998) suggesting the occurrence of similar tectonic processes in this region. Indications for the existence of triangular shaped basins are actually present in the Baja California Peninsula Borderland because most basins in this region are oval or elongated, tend approximately north-south and broaden and deepen northward (Nava-Sánchez et al., 2001). The La Paz Basin, for example, is triangular in shape narrowing toward the south (Cruz-Falcón et al., 2010); the Lobos basin widens to the north – a fact which is assumed to be related to strike-slip faulting along the Espiritu Santo Fault causing a scissor-like opening of the basin (Nava-Sánchez et al., 2001). Taking into account that in the California Continental Borderland formation of triangular basins concurrently occurred with block rotations, vertical axis rotations in the Baja California Borderland should be common as well.

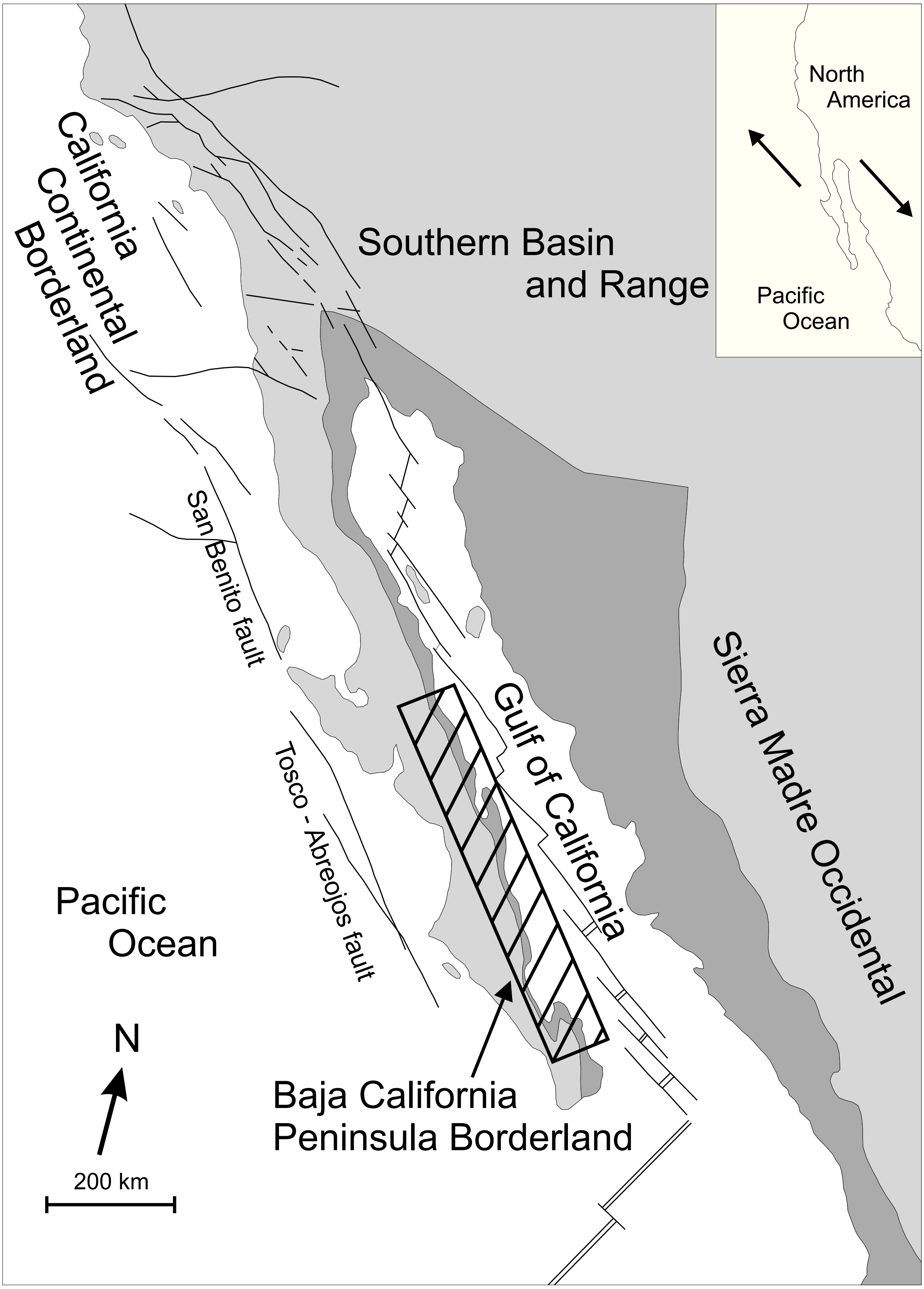

Figure 1.2: Map showing the most prominent tectonic elements in the Gulf of California region including the Gulf Extensional Province (in dark grey) and the Baja California Peninsula Borderland introduced by Nava-Sánchez et al. (2001). The inset in the upper right corner illustrates the relative motion of the Pacific and North American Plates. (Figure modified from Nava-Sánchez et al. (2001) after Stock and Hodges (1989)).

1.2 Scientific aims and study areas

As already described above, paleomagnetic studies were successful in identifying vertical-axis rotations in the northern part of Baja California, whereas studies regarding block rotations occurring in the southern half of the peninsula are sparse. However, microseismicity on Espiritu Santo Island (Munguía et al., 1997) and present faulting in the La Paz Bay area (Fletcher and Munguía, 2000) suggest active tectonics in southern Baja related to the opening of the Gulf of California; bathymetric and seismological research provides indications of a tectonic setting similar to the Miocene setting in the California Continental Borderland where block rotations were common. Therefore, the major aim of the present study is to provide high quality paleomagnetic data in order to prove the existence of rotations in Baja California Sur, to define kinematically distinguishable blocks and to quantify the amounts of vertical-axis rotations with respect to the stable North American Plate. In order to address these issues, three study areas (a, b, c) were selected in the Baja California Peninsula Borderland – as introduced by Nava-Sánchez et al. (2001) – focussing on Neogene rocks within and around basin structures.

(a) The San José del Cabo Basin (Fig. 1.3) situated at the southern tip of the Baja California peninsula is thought to be a half-graben basin which formed in association with the opening of the Gulf of California. It is composed of middle Miocene to Pleistocene sediments accumulated in continental and marine environments. The hanging wall of the basin – located in the east – is composed of Cretaceous granites and local Miocene volcanic rocks. Because of its wedge-like shape widening to the north John Fletcher suggested on the basis of unpublished apatite fission track data that the hanging wall block has rotated clockwise and tilted to the south (Umhoefer, personal communication, 2005). Locally exposed redbeds of middle to upper Miocene age along the eastern side of the basin together with coeval volcanic rocks were the main targets for this study.

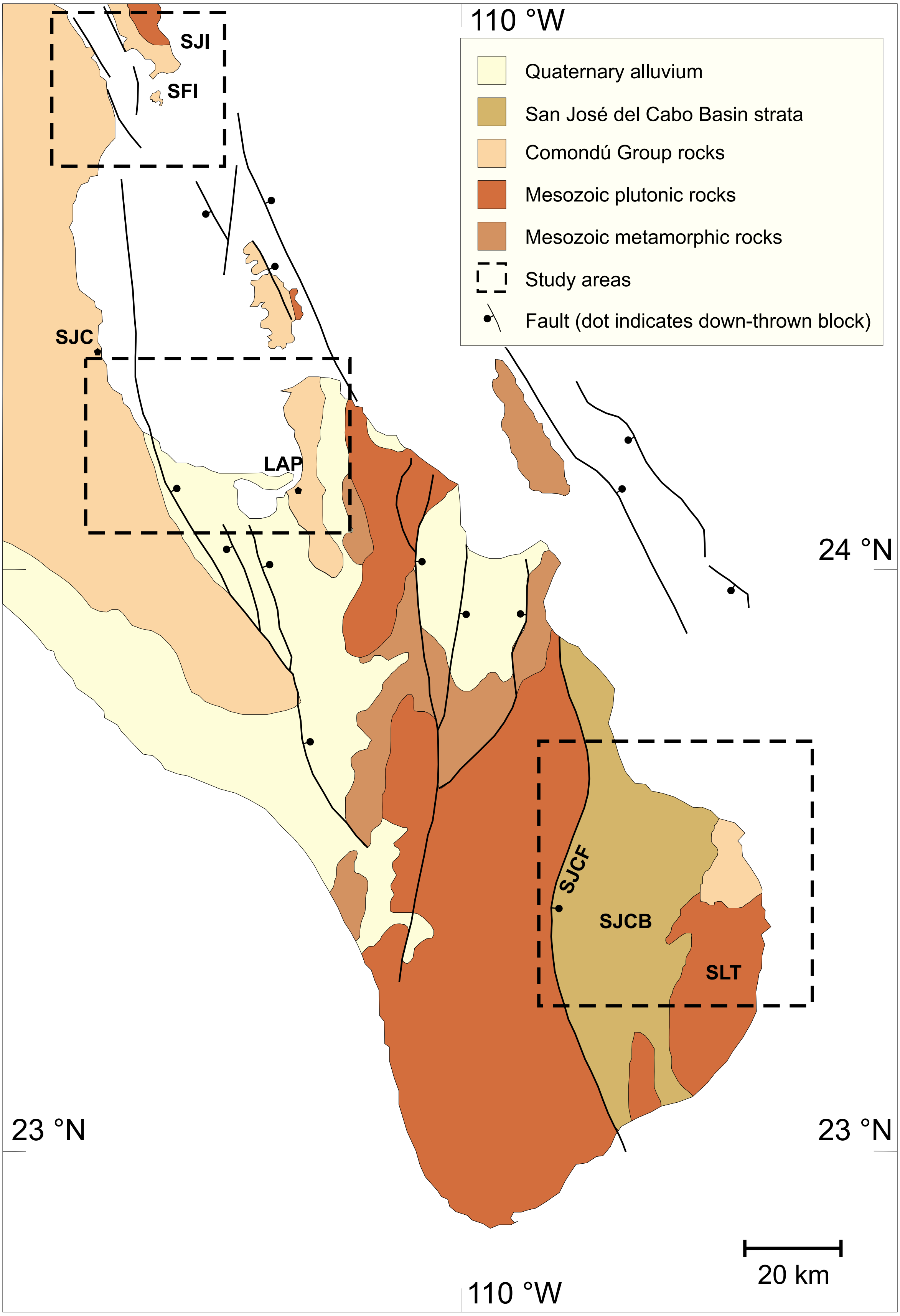

Figure 1.3: Geological and tectonic overview of the southern part of Baja California Sur showing the study areas. (SJI: San José Island; SFI: San Francisco Island; SJC: San Juan de la Costa; LAP: La Paz; SJCB: San José del Cabo Basin; SLT: Sierra La Trinidad; figure modified from McTeague (2006) after Fletcher and Munguía (2000)).

(b) The La Paz Bay area (Fig. 1.3) is characterized by the triangular shaped La Paz Basin as suggested by Cruz-Falcón et al. (2010) because of its narrowing toward the south. To the east as well as to the west the basin is bordered by Comondú Group rocks of Early Miocene age; therefore this setting provides an opportunity for studying rocks of approximately the same age on both sides of the basin. As already mentioned above studies by Munguía et al. (1997) and Fletcher and Munguía (2000) indicate that tectonic processes related to the opening of the Gulf of California are still active which also might be true for vertical-axis block rotations.

(c) The San José and San Francisco Islands (Fig. 1.3) are located about 80 kilometers north of La Paz and separated from mainland Baja by the San José Channel. The smaller San Francisco Island displays anomalously striking bedding which suggests clockwise rotations. This assumption has been confirmed by Drake (2005) who was able to demonstrate that the faults on the island are directed more to the east compared to those on mainland Baja at the same latitude which trend consistently north-east. Based on the results of kinematic analysis and the prevalent orientation of the faults, a clockwise rotation of up to 25° is within the bounds of possibility (Drake, 2005).

A further aim of the present study was the comparison of present day kinematics and large-scale deformation patterns of Baja California Sur - revealed by Global Positioning System (GPS) data (Plattner et al., 2007) - to past vertical-axis rotations reconstructed by paleomagnetic data. In this context the question whether long-term motion deduced from paleomagnetic studies is coherent with the extrapolation of current motions measured by GPS is tried to be answered. Additionally, rock magnetic measurements were carried out routinely in order to identify the carriers of the remanent magnetization.

2. Tectonic evolution of the Gulf of California

During the past couple of years the tectonic evolution of the Gulf of California has become a subject of increasing interest as it was chosen to be a focus site in the MARGINS Program funded by the National Science Foundation (NSF) (http://www.nsf-margins.org/; 28.09.2010). This program is promoting interdisciplinary continental margin research in order to gain a better understanding of the different processes occurring in the corresponding regions. A part of this program - the Rupturing Continental Lithosphere (RCL) initiative - which was founded to provide new insights regarding the kinematics of continental lithosphere deformation, especially strain partitioning and characteristics of rift-related magmas, focuses on the Gulf of California/Salton Trough area (http://www.nsf-margins.org/RCL/RCL.html; 28.09.2010). The main reason for choosing the Gulf of California region as part of this program was its location in a major active transtensional zone providing the opportunity to study an active oblique-divergent plate boundary. Even though the geological and tectonic history of the Gulf of California is reasonably well understood, there are still questions regarding the evolution of the modern Gulf and adjacent regions as well as the present tectonic processes. Various studies were carried out to contribute to the understanding of how this continental plate margin has evolved; the different approaches are summarized in the following paragraphs.

2.1 Subduction of the Farallon Plate and arc-related volcanism (30 – 12 Ma)

Since Middle Paleogene the Pacific Plate has moved in a north-westward direction relative to the North American Plate (Fig. 2.1; Lonsdale, 1991; Bohannon and Parsons, 1995). Contemporaneously, the Farallon Plate – linked to the Pacific Plate by the East Pacific Rise – was subducted eastward beneath the North American Plate; therefore, the present western margin of the Baja California peninsula was located at a convergent plate boundary (Fig. 2.1; Atwater, 1970; Mammerickx and Klitgord, 1982; Stock and Hodges, 1989).

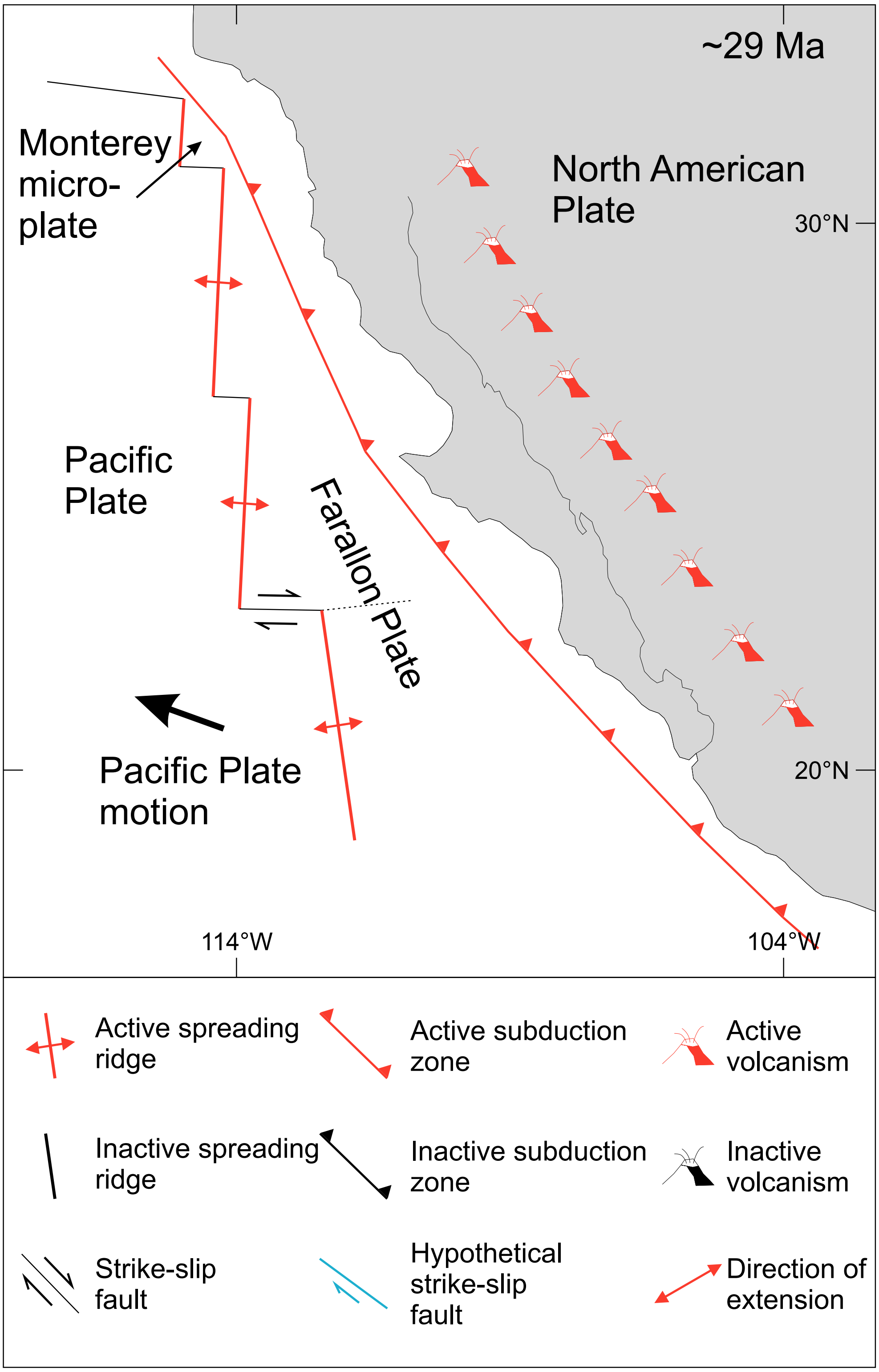

Figure 2.1: Tectonic setting in the present Baja California region about 29 Ma ago. (Figure modified from Drake (2005) and Maloney (2009)).

A stable marine continental shelf which is now the Baja California peninsula was bordered in the east by a subduction-related calc-alkaline volcanic arc – the Sierra Madre Occidental (Hausback, 1984) mainly composed of rhyolite ash-flow tuffs which have been erupted between about 36 and 27 Ma (Fig. 2.1; McDowell and Keizer, 1977; McDowell and Clabaugh, 1979, Wark et al., 1990; Ferrari et al., 1999). Volcanic detritus produced by these eruptions was deposited on the offshore marine shelf (Hausback, 1984). Arc-volcanism migrated to the west and reached the present eastern Baja California peninsula at about 24 Ma (Fig. 2.2; Hausback, 1984; Sawlan and Smith, 1984) and was active until approximately 16 Ma and 11 Ma in northern and southern Baja California, respectively.

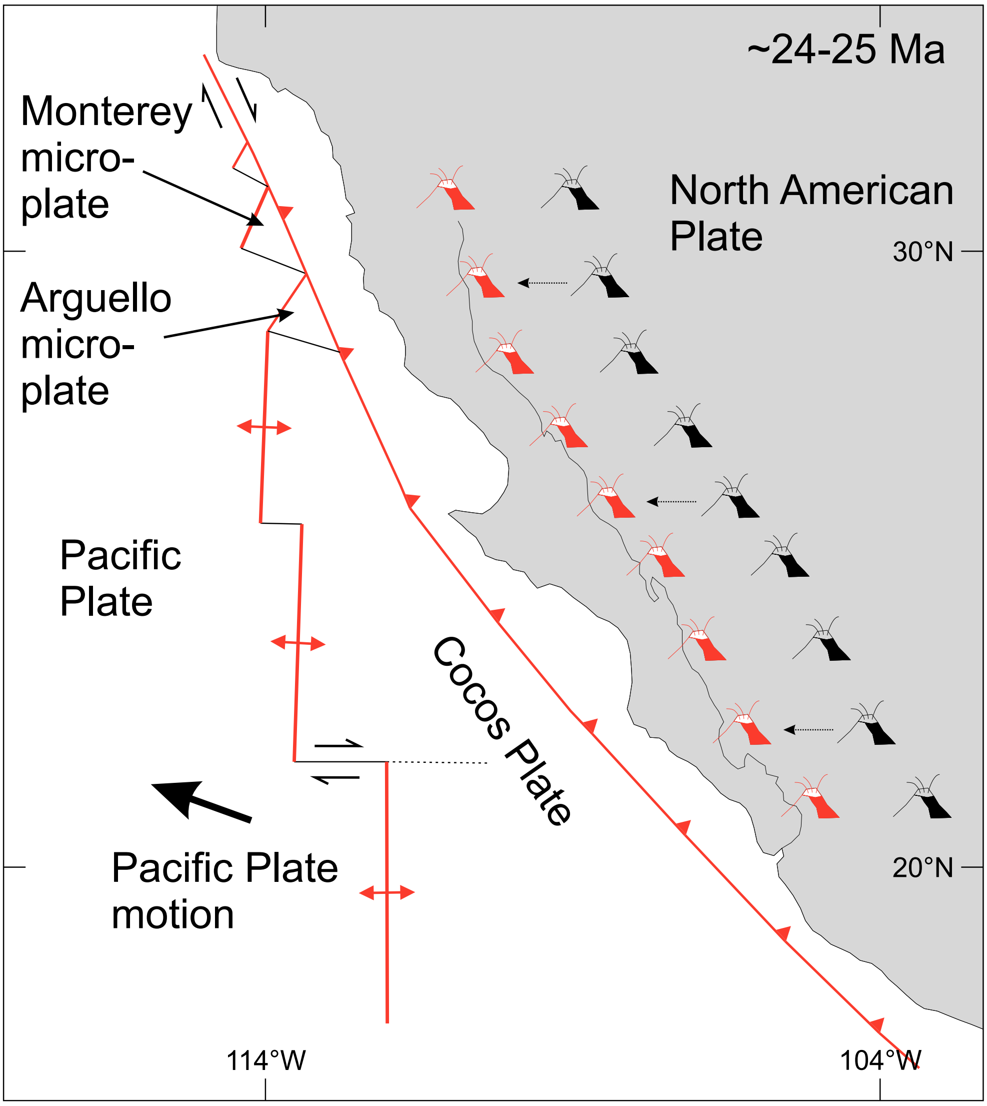

Figure 2.2: Tectonic setting in the present Baja California region between about 24 and 25 Ma. Modified from Nicholson et al. (1994).

In Baja California Sur this volcanism was accompanied by sedimentation of the so-called Comondú Group consisting of minor lava flows, tuff and volcanic breccia, volcaniclastic conglomerate as well as fluvial and eolian sandstone (Fig. 2.3; Hausback, 1984; McFall, 1968; Sawlan, 1991, Umhoefer et al., 2001). After the active Pacific-Farallon spreading ridge (East Pacific Rise) had reached the North American Plate between about 28.5 and 25 Ma in the course of further subduction, the Farallon Plate began to break apart into the Juan de Fuca Plate west of the present United States and the remnant Farallon Plate with the Monterey microplate located in between (Fig. 2.1; Atwater, 1970; Menard, 1978; Atwater, 1989; Lonsdale, 1991; Fernandez and Hey, 1991; McCrory et al., 2009). In the course of continued subduction the Arguello microplate separated from the Farallon Plate which was subsequently fragmented into the Nazca Plate west of South America and the Cocos Plate west of Central and North America about 25 Ma ago (Fig. 2.2; McCrory et al., 2009). In the region of present Baja California the Guadalupe and Magdalena microplates broke off of the northern part of the Cocos Plate at ca. 20 and 14 Ma, respectively, followed by the Rivera microplate at about 12 Ma (Fig. 2.3; Lonsdale, 1991; Atwater, 1989; Atwater and Severinghaus, 1989; Bourgois and Michaud, 1991; Stock and Lee, 1994; Bandy and Hilde, 2000). The assumption that fragmentation of subducting plates is usually accompanied by the formation of triple junctions (Stock and Lee, 1994) turned out to be applicable to the boundary between the Pacific and North American Plates where fragmentation of the Farallon Plate led to the development of the Mendocino and the Rivera triple junctions (Atwater, 1970). Because of the ongoing rupture of the southern Farallon segment into the Guadalupe, Magdalena and Rivera microplates the Rivera triple junction began to migrate southward at 16 Ma until it reached the present mouth of the Gulf of California at 12 Ma (Fig. 2.4; Atwater, 1970).

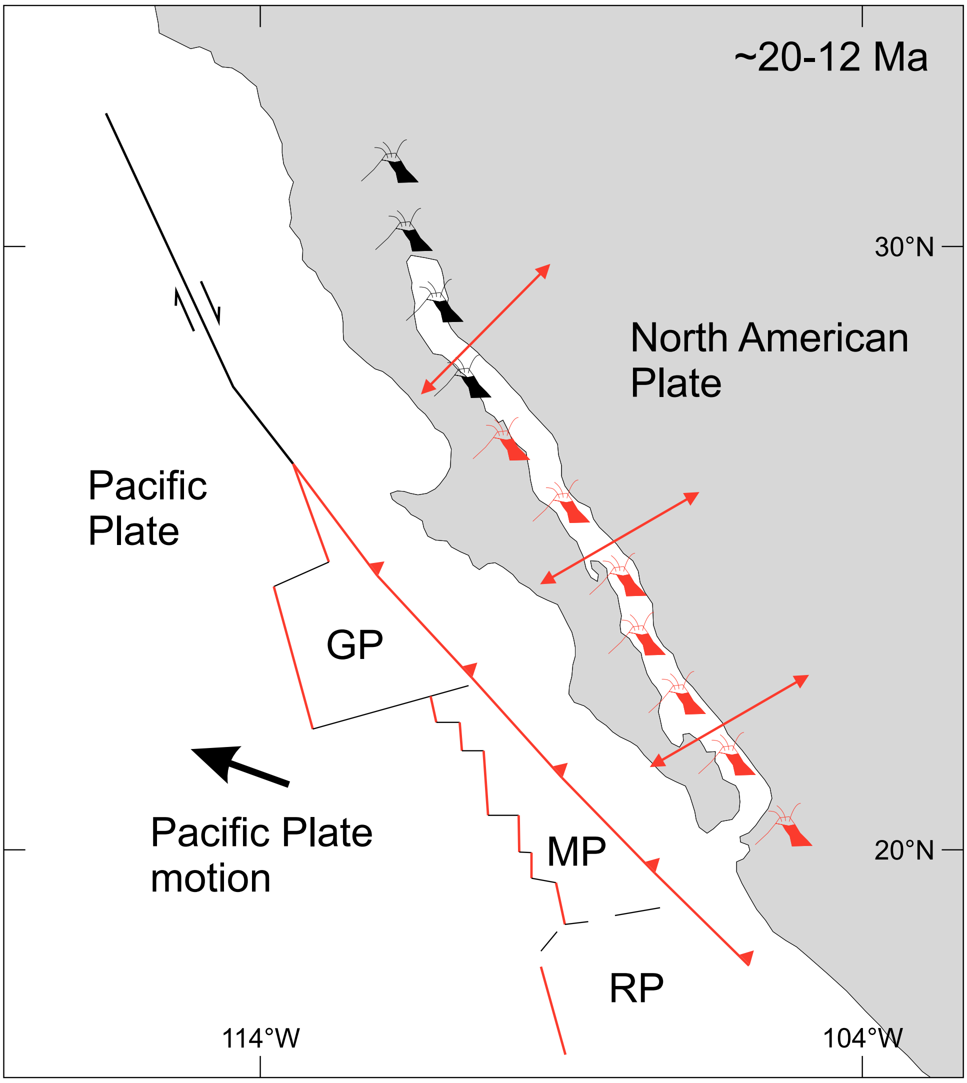

Figure 2.3: Tectonic setting in the present Baja California region between about 20 and 12 Ma. GP: Guadalupe Plate; MP: Magdalena Plate; RP: Rivera Plate. (Figure modified from Drake (2005) and Maloney (2009); for tectonic legend see figure 2.1).

This tectonic process was closely related to the termination of spreading at the ridge boundary between the Pacific Plate and the Farallon microplates and the step-wise southward cessation of subduction. Contemporaneously, microplate capture by the Pacific Plate, progressive development of a right-lateral transform boundary between the Pacific and North American Plates and the end of volcanic arc activity (at ca. 12 Ma) took place (Fig. 2.4; Atwater, 1970; Lonsdale, 1991; Mammerickx and Klitgord, 1982; Stock and Hodges, 1989; Stock and Lee, 1994).

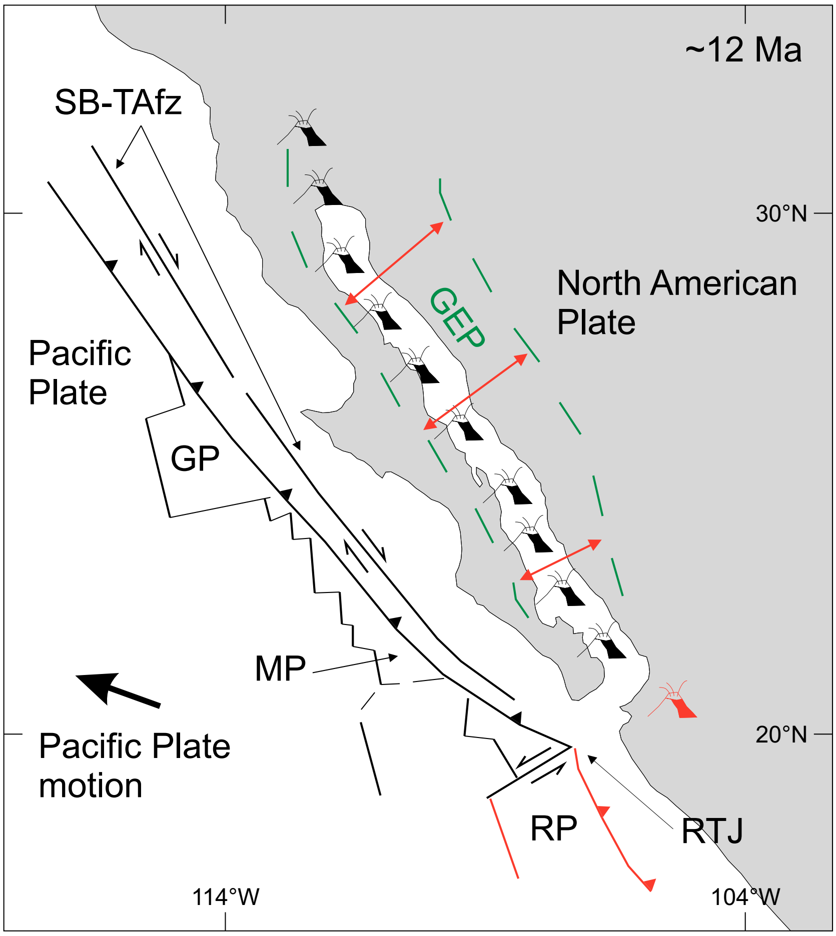

Figure 2.4: Tectonic setting in the present Baja California region at about 12 Ma. SB-TAfz: San Benito-Tosco-Abreojos fault zone; GP: Guadalupe Plate; MP: Magdalena Plate; RP: Rivera Plate; RTJ: Rivera triple junction; GEP: Gulf Extensional Province. (Figure modified from Drake (2005) and Maloney (2009); for tectonic legend see figure 2.1).

For the last years it was widely accepted among the majority of authors that the evolution of the Gulf of California occurred in two distinct stages summarized in the so-called two-phase kinematic model: (1) a so-called proto-Gulf stage of rifting from Middle to Late Miocene characterized by strain partitioning between dextral strike-slip faults west of the Baja California peninsula and ENE-WSW directed extension in the present Gulf of California (Karig and Jensky, 1972; Spencer and Normark, 1979; Hausback, 1984; Stock and Hodges, 1989) and (2) a period of transtensional shearing in the Gulf of California which is still continuing today (e.g., Umhoefer et al., 1994; Oskin et al., 2001). This model has been challenged by an alternative one-phase kinematic model (Gans, 1997; Fletcher et al., 2007; Seiler et al., 2010) in which transtensional shearing in the Gulf of California has already been present since Middle Miocene. The following chapters will present these alternative models and highlight their differences regarding the tectonic evolution.

2.2 Proto-Gulf stage of rifting (12 – 8-6 Ma) – two-phase kinematic model

Due to cessation of subduction and the related tectonic events mentioned above, the long-lived subduction boundary progressively changed from oblique convergence to right-lateral strike slip motion between the Pacific Plate and Baja California resulting in the formation of a transform fault zone east of the former trench – the so-called San Benito-Tosco-Abreojos fault zone (Fig. 2.5; Spencer and Normark, 1979; Hausback, 1984; Stock and Hodges, 1989; McCrory et al., 2009). Whereas it has been commonly accepted that its southern part - the Tosco-Abreojos fault zone located west of the Baja California peninsula – was active from 12.5 Ma to 5-3.6 Ma (Spencer and Normark, 1979, 1989; Lonsdale, 1989; Stock and Hodges, 1989; Stock and Lee, 1994), newer studies indicate current displacement along the fault zone (Dixon et al., 2000; Michaud et al, 2007). After the formation of the Tosco-Abreojos fault zone at about 12 Ma, the relative motion direction between the Pacific and the North American Plates pivoted from about 325° to a more westerly direction and therefore became oblique to the strike-slip fault zone (Hausback, 1984; Stock and Hodges, 1989). This westward drift of the Pacific Plate could have been accommodated either by oblique extension or reorientation of the strike-slip faults to the west of the Baja California peninsula (Hausback, 1984; Stock and Hodges, 1989). However - according to the two-phase kinematic model - extension was initiated to the east of the Baja California peninsula (in the area of the present Gulf of California) during the proto-Gulf phase of rifting from about 12 to 8-6 Ma (Karig and Jensky, 1972). The direction of extension is assumed to have been orthogonal to the former Comondú volcanic arc where crust was generally thermally weakened (Fig. 2.5; Hausback, 1984; Stock and Hodges, 1989) leading to the formation of the Gulf Extensional Province which is comparable to the Southern Basin and Range Province (Gastil et al., 1975; Mayer and Vincent, 1999). Extension was accommodated by normal faults accompanied by graben formation (Hausback, 1984; Oskin et al., 2001) and first marine incursions (Stock and Hodges, 1989; Smith, 1991; McDougall et al., 1999; Oskin et al., 2001; Martín-Barajas et al., 2001; Oskin, 2002; Oskin and Stock, 2003a). The regional strain in the Baja California peninsula area resulting from the relative Pacific-North American motion is therefore thought to have been partitioned between a right-lateral transform component of motion along the Tosco-Abreojos fault zone west of Baja California and a broad east-north-east to west-south-west directed extensional component in the Gulf Extensional Province east of Baja California (Fig. 2.5; Stock and Hodges, 1989; Henry, 1989; Fletcher and Munguía, 2000, Umhoefer et al., 2002).

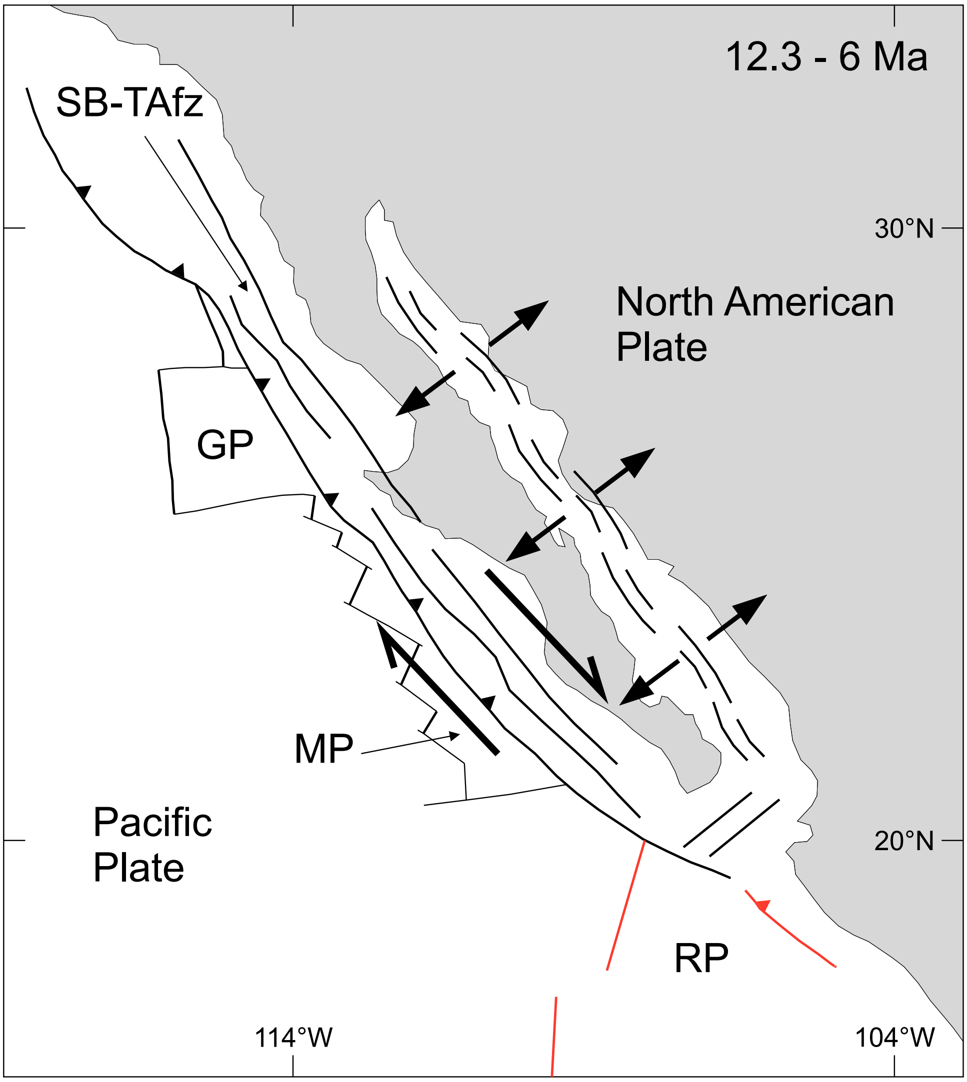

Figure 2.5: Proto-Gulf phase of rifting in the widely accepted model of a two-phase plate tectonic evolution of the Gulf of California and surrounding region from 12.3 to 6 Ma (modified from Fletcher et al., 2007). GP: Guadalupe Plate; MP: Magdalena Plate; RP: Rivera Plate. Divergent arrows perpendicular to the Gulf of California indicate extension; arrows west of Baja California indicate relative motion. For tectonic legend see figure 2.1.

2.3 Alternative model of proto-Gulf development – one-phase kinematic model

As already mentioned above, other studies (e.g. Gans, 1997; Fletcher et al., 2007; Seiler et al., 2010) offer an alternative one-phase kinematic model of the evolution of the Gulf of California which primarily differs from the two-phase kinematic model regarding the first stage of proto-Gulf rifting. Atwater and Stock (1998) calculated the relative Pacific-North American Plate motion since 33 Ma from updated rotations within the Pacific-Antarctica-Africa-North America plate circuit and came to the conclusion that there was no change in motion direction before 8 Ma; only the rate of displacement changed from 33 mm/yr to 52 mm/yr along an azimuth of about 300° at 12 Ma (Atwater and Stock, 1998). Thus, there is no evidence of a pivoting relative motion direction between the Pacific and North American Plates to a more westerly direction shortly after formation of the Tosco-Abreojos fault zone and no stringent necessity for orthogonal extension in the Gulf of California as suggested by earlier studies (e.g. Hausback, 1984; Stock and Hodges, 1989). For this reason newer studies (Gans, 1997; Fletcher et al., 2007) support an alternative model of the proposed proto-Gulf development in which transtensional faulting across the present Gulf of California has already started at about 12 Ma (Fig. 2.6). Gans (1997) analyzed structural and argon-argon data from south-eastern Sonora to gain new insights regarding the tectonic evolution of north-western Mexico; geochronological data of volcanics suggest that nearly the entire extension in Sonora happened between ca. 27 and 12 Ma while subduction was still active. This is supported by other studies focussing on the age of extension (Stewart and Roldan-Quintana, 1994; McDowell et al., 1997) and only small amounts of ENE-WSW extension are thought to have occurred in southern Sonora after about 10 Ma (Gans, 1997) – an assumption which contradicts the orthogonal rifting as suggested by the two-phase kinematic model (Stock and Hodges, 1989) which requires substantial amounts of NE-SW extension in the Gulf Extensional Province during Late Miocene (Gans, 1997). Therefore, Gans (1997) proposed an alternative model in which Baja California started to move with the Pacific Plate shortly after cessation of subduction of the Farallon Plate. According to this model most of the motion between the Pacific and North American Plates occurred along a system of northwest striking, en-echelon strike-slip faults in the present Gulf of California, and therefore it is suggested that the Tosco-Abreojos fault zone only accommodated a small amount of transform motion between the Pacific and North

American Plates (Fig. 2.6; Gans, 1997). Results of a study by Fletcher et al. (2007) are in good agreement with this model. Studies - based on detrital zircon uranium-lead age measurements - regarding the source region of the Magdalena fan indicate that the west-draining portion of the Los Cabos block is the provenance of this fan. Compared to previous studies which suggest that the Magdalena fan's source was situated in the mouth of the Gulf of California (Yeats and Haq, 1981; Ferrari et al., 1999; Marsaglia, 2004) the source region situated further to the north as proposed by Fletcher et al. (2007) implies much smaller amounts of dextral slip along the Tosco-Abreojos fault zone. These results require that most of the motion between the Pacific and North American Plates since about 12 Ma has occurred in the Gulf Extensional Province – a region of weakest lithosphere (Fletcher et al., 2007). Mechanical and thermal crustal weakening along the former volcanic arc probably led to an early initiation of plate margin shearing in this region as proposed by Fletcher et al. (2003a). Another reason for a weakened lithosphere is assumed to be the formation of a deep slab window beneath the proto-Gulf as modelled by Bohannon and Parsons (1995).

An only recently published article by Seiler et al. (2010) provides further support of the one-phase kinematic model established by Gans (1997) and Fletcher et al. (2007). Fault kinematics and paleostress orientations of the Sierra San Felipe fault array (north-eastern Baja California) documented in the course of this study indicate a classification of fault populations into ENE- and SE-directed axes of extension, respectively. Whereas the existence of these two fault populations – which was also verified in other regions of the Gulf Extensional Province – has originally been thought to be indicative of the two different stages encompassed by the two-phase kinematic model, Seiler et al. (2010) are able to demonstrate that the two groups of fault populations are not time-dependent as there is no correlation between the faults of either group and the age of strata cut by them. Furthermore, Seiler et al. (2010) reinterpret paleomagnetic data gathered by Lewis and Stock (1998) regarding vertical-axis rotations in the Sierra San Felipe region. In their study Lewis and Stock (1998) regard the difference (11° ± 17°) between rotations which affected the ~12.6 Ma Tuff of San Felipe (41° ± 9°) and tuffs of ~6 Ma in age (30° ± 15°) as statistically insignificant and propose that all rotations in this region must have happened after the formation of the ~6 Ma tuff units. This assumption is consistent with the two-phase kinematic model in which rotational deformation is thought to have started not before 6 Ma. Seiler et al. (2010), however, regard the paleomagnetic signal of the 12.6 Ma Tuff of San Felipe as being more robust compared to that of the younger tuffs and provide an alternative interpretation for the timing of rotations in the area implying that 25% of the amount of total rotation affected the region before about 6 Ma. Assuming a constant deformation rate since approximately 9-8 Ma (Seiler, 2009) the amount of rotation prior to ~6 Ma is consistent with the extent of deformation which contemporaneously occurred (Seiler et al., 2010). Seiler et al. (2010; page 108) therefore infer that the fault array in the Sierra San Felipe developed "during a single phase of integrated transtensional shearing", a conclusion which can be considered as a strong support of the one-phase kinematic model depicting the evolution of the Gulf of California.

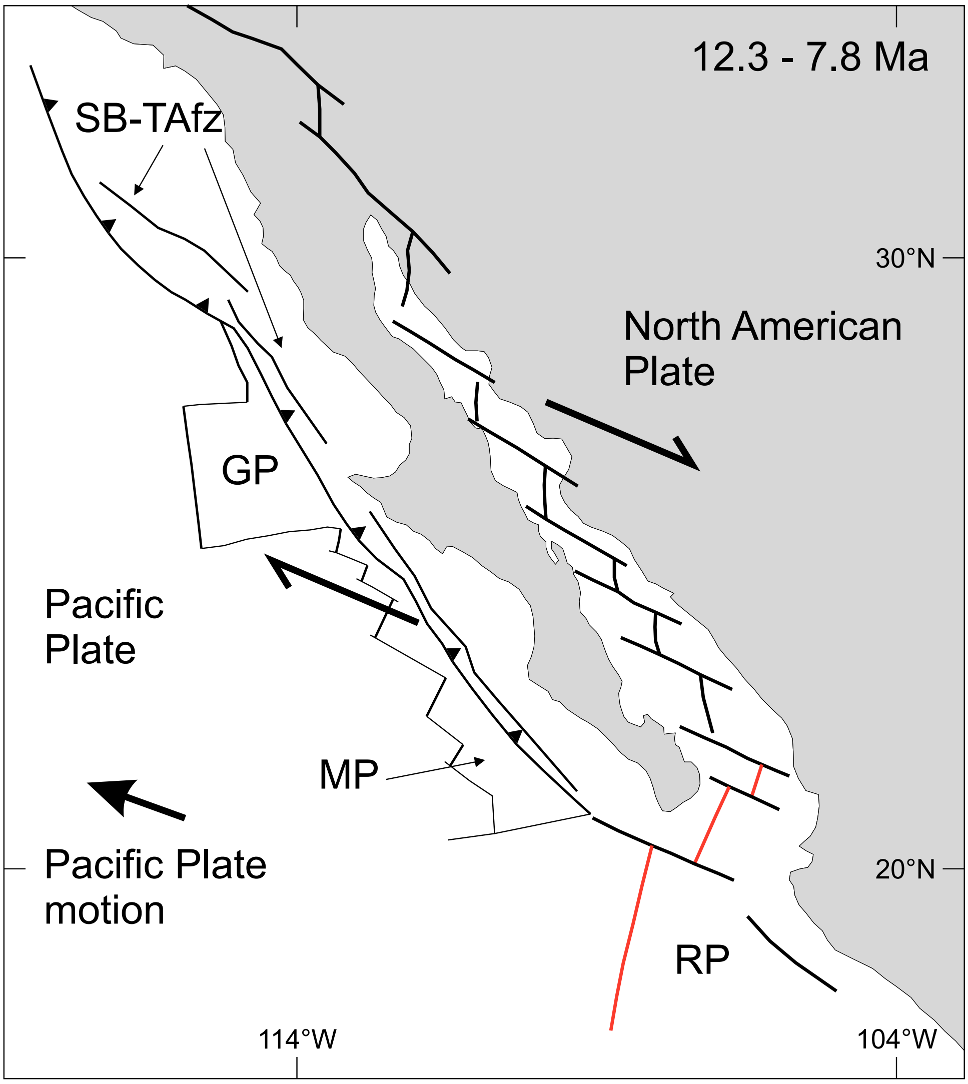

Figure 2.6: Alternative kinematic model of the development of the proto-Gulf adopting the one-phase kinematic model developed by Fletcher et al. (2007). (Modified from Fletcher et al., 2007). SB-TAfz: San Benito-Tosco-Abreojos fault zone; GP: Guadalupe Plate; MP: Magdalena Plate; RP: Rivera Plate. Divergent arrows indicate relative plate motion. For tectonic legend see figure 2.1.

2.4 Oblique-divergent stage (8-6 Ma – present)

Calculations of the relative Pacific-North American Plate motion since 33 Ma based on updated rotation-parameters within the Pacific-Antarctica-Africa-North America plate circuit document that at 8 Ma there was a change of the displacement azimuth from 300° to 323° with a constant rate of about 52 mm/yr (Fig. 2.7; Atwater and Stock, 1998). Since between 8 and 6 Ma the Gulf of California has been characterized by the modern regime of oblique rifting leading to the formation of transform faults separated by pull-apart basins (Fig. 2.8; Lonsdale, 1989; Axen et al., 2000).

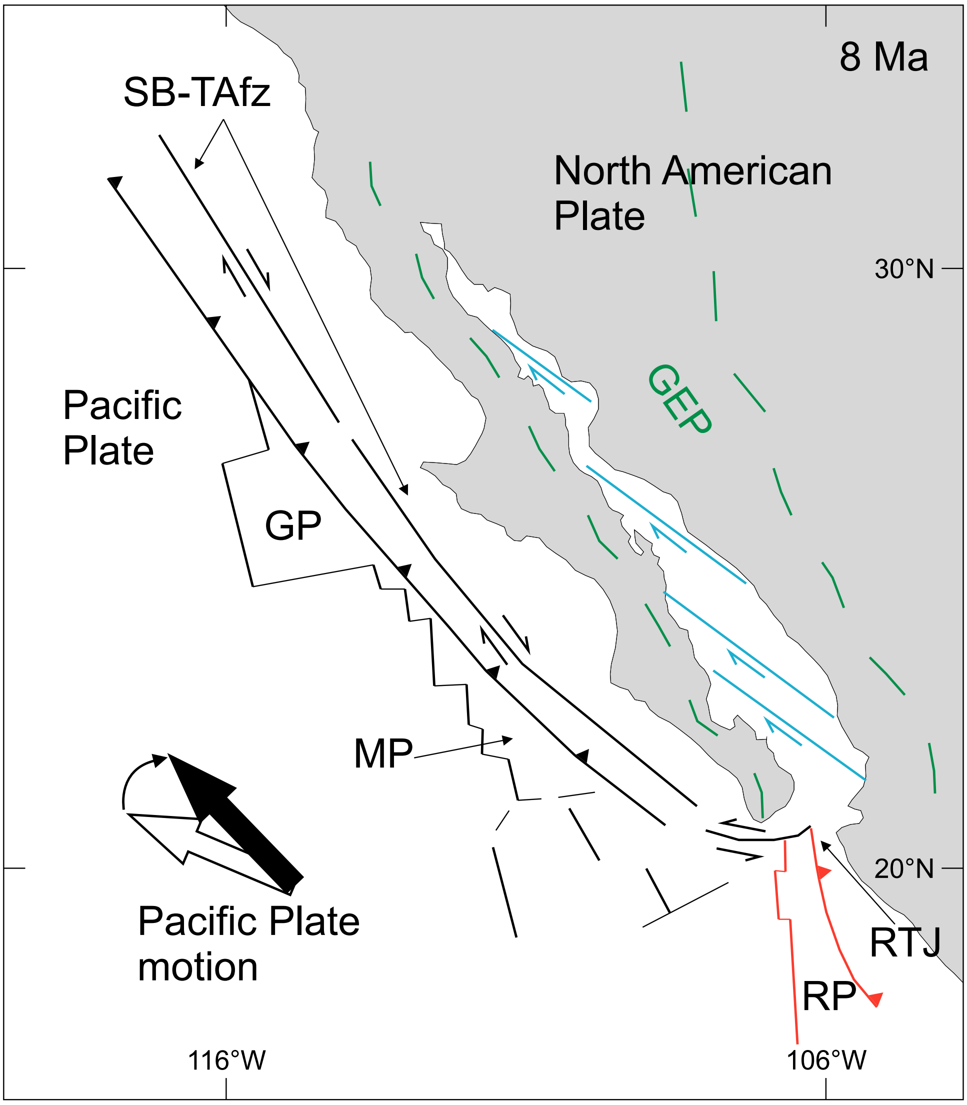

Figure 2.7: Tectonic setting about 8 Ma ago. Notice the change of relative Pacific-North American Plate motion indicated by the arrows. SB-TAfz: San Benito-Tosco-Abreojos fault zone; GP: Guadalupe Plate; MP: Magdalena Plate; RP: Rivera Plate; RTJ: Rivera triple junction; GEP: Gulf Extensional Province. (Figure modified from Drake (2005) and Maloney (2009); for tectonic legend see figure 2.1).

Evidence of early marine incursion between 8.2 and 7.5 Ma - probably caused by intense continental extension - can be found in the southern Gulf of California (Oskin and Stock, 2003a). Oskin et al. (2001) suggest that at about 6 Ma the Pacific-North American Plate boundary migrated eastward and became mostly located within the Gulf of California and connected to the San Andreas fault system in Southern California (Umhoefer et al., 2002); in this context marine environment developed in the northern Gulf between 6.5 and 6.3 Ma (Oskin et al., 2001; Oskin and Stock, 2003a; Aragón-Arreola and Martín-Barajas, 2007). Considering that the oldest magnetically lineated oceanic crust was formed by seafloor spreading across the Alarcon Rise in the southern Gulf of California it is generally assumed that full continental separation between the Baja California microplate and the North American Plate had been completed by 3.6 Ma (Fig. 2.8; DeMets et al., 1987; DeMets, 1995).

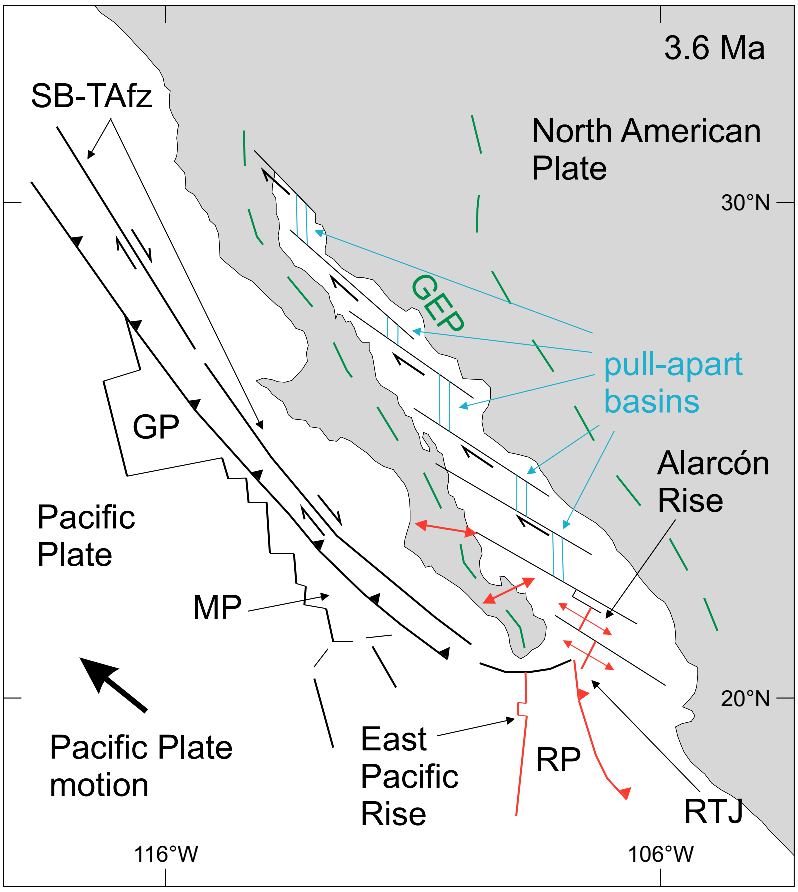

Figure 2.8: Tectonic setting about 3.6 Ma ago. SB-TAfz: San Benito-Tosco-Abreojos fault zone; GP: Guadalupe Plate; MP: Magdalena Plate; RP: Rivera Plate; RTJ: Rivera triple junction; GEP: Gulf Extensional Province. (Figure modified from Drake (2005) and Maloney (2009); for tectonic legend see figure 2.1).

However, there is evidence that this separation did not lead to a full transfer of the Baja California peninsula to the Pacific Plate. If there was rigid coupling between the Pacific Plate and Baja California since 3.6 Ma, all Pacific-North American relative motion would have had to be accommodated within the Gulf of California (DeMets, 1995). Based on the analysis of magnetic anomaly data, however, DeMets (1995) proposes that spreading rates between Baja California and the North American Plate prior to 0.78 Ma were significantly slower in comparison to the Pacific-North American Plate motion. In addition DeMets and Dixon (1999) have determined the rate of relative Pacific-North American Plate motion with the aid of a GPS (Global Positioning System)-derived model and come to the conclusion that this motion has been steady since 3.16 Ma – with a rate of ~52 ± 2 mm/a, thus being faster than predicted by the global NUVEL-1A (DeMets et al., 1990) model. In contrast, seafloor spreading rates in the Gulf of California have increased by 10-15% since 3.58 Ma (DeMets, 1995). This discrepancy leads to the assumption that motion between the Pacific and North American Plates has been partitioned between accelerating seafloor spreading in the Gulf of California and decelerating slip along faults west of the Baja California peninsula, implying a movement of Baja relative to the Pacific Plate (DeMets and Dixon, 1999). This is supported by Michaud et al. (2004) who suggest that the Tosco-Abreojos fault system west of Baja California is still active and accommodates right-lateral slip motion between Baja and the Pacific Plate. This is in good agreement with a study by Dixon et al. (2000) which applies new models of present-day Pacific-North American Plate motion to an investigation of tectonic processes west of Alta and Baja California. GPS experiments and offshore seismicity suggest that sites near the “big bend” in the San Andreas Fault move with the Pacific Plate, whereas coastal sites on the Baja California peninsula south of the Agua Blanca fault move slower than the Pacific Plate (Dixon et al., 2000) implying an incomplete transfer of Baja to the Pacific Plate, indicating microplate behavior. Dixon et al. (2000) also consider the Tosco-Abreojos fault zone a possible tectonic structure accommodating offshore slip motion west of Baja California. The discrepancy of Baja California–Pacific Plate relative motion in combination with offshore seismicity and offset on known faults along the south-western coast of Baja California provide evidence of continued offshore slip along a possible Baja California shear zone west of Baja (Dixon et al., 2000).

GPS measurements by Plattner et al. (2007) indicate that the Baja California peninsula is moving roughly parallel to the Pacific Plate, however, at a rate being ~10% lower (with respect to the North American Plate) supporting the proposed Baja California shear zone. The collision of the Baja California microplate with the North American Plate in the region along the Transverse Ranges and the “big bend” of the San Andreas fault might be a possible explanation for only partial coupling between the Pacific Plate and the Baja California microplate and the tectonic activity along the Baja California shear zone (Dixon et al., 2000; Plattner et al., 2007). This collision might result in the Baja California microplate being sheared off the Pacific Plate along the former subduction plate boundary with formation of the shear zone from north to south (Plattner et al., 2007). This assumption can provide an explanation of the larger relative motion – with respect to the Pacific Plate – of northern Baja California compared to the southern part (Plattner et al., 2007). On the other hand, the different rates of motion can be caused by internal strain deformation within the Baja California microplate, an alternative approach not conflicting with a possible collision along the northern boundary (Plattner et al., 2007).

2.5 Amount of displacement (one-phase vs. two-phase kinematic model)

According to global plate circuit reconstructions the Pacific Plate has moved 640-720 kilometers north-westward relative to stable North America since 12.3 Ma (Fig. 2.9 A; Atwater and Stock, 1998). In the widely accepted model of proto-Gulf rifting authors (Spencer and Normark, 1979; Oskin and Stock, 2003a) suggest that about 300 to 350 kilometers of dextral displacement had been accommodated along strike-slip faults in the Tosco-Abreojos fault zone and that 90 kilometers of orthogonal rifting had occurred in the Gulf of California until the plate boundary became established in the Gulf of California at about 8-6 Ma initiating the second phase of oblique-divergent rifting (Figure 2.9 B). A study by Oskin and Stock (2003a) indicates that since about 12.5 Ma a total displacement of 296 kilometers has taken place across the northern Gulf of California of which only 20 ± 10 kilometers occurred before 6.3 Ma (Figure 2.9 C).

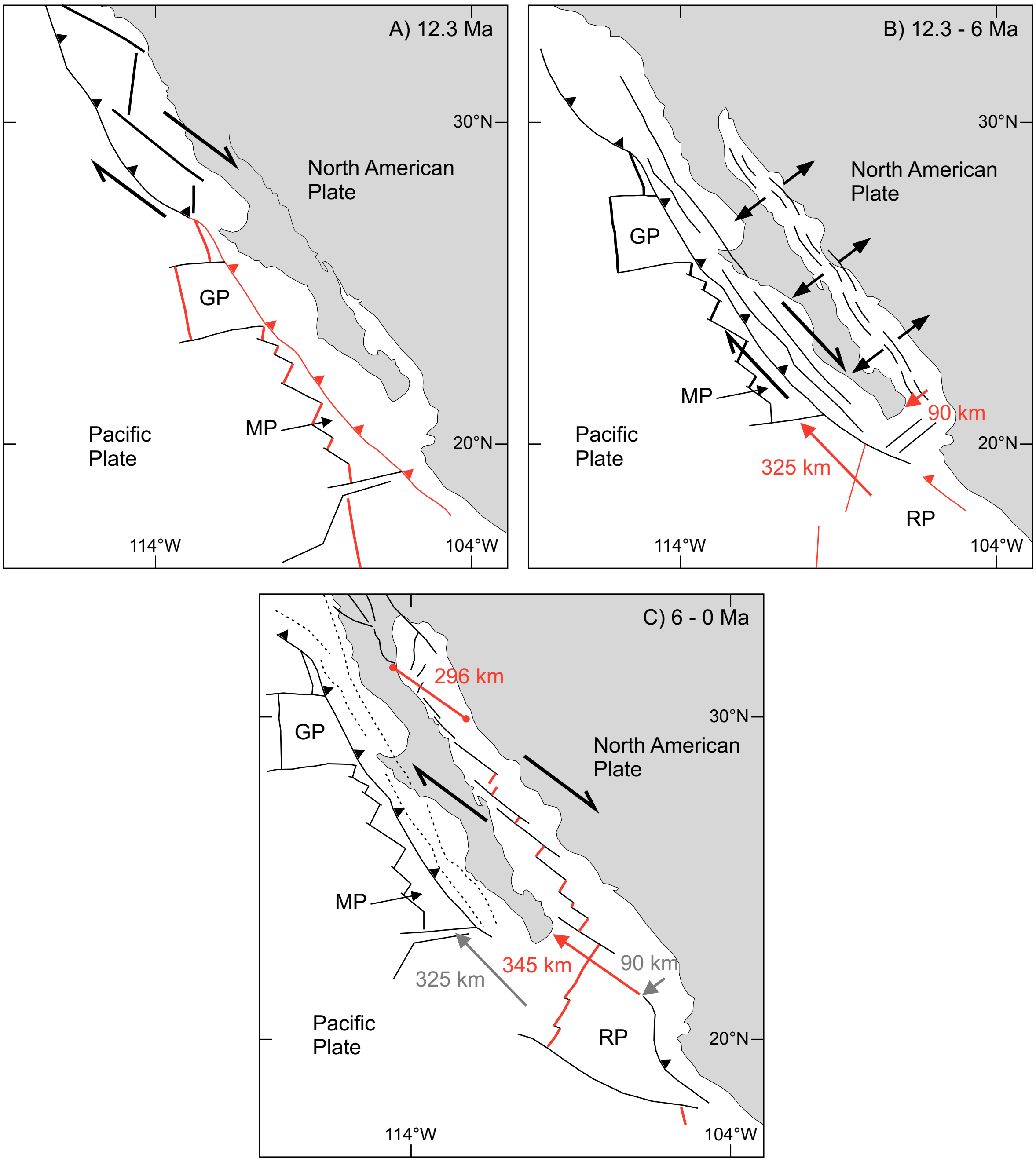

Figure 2.9: Illustration of the widely accepted two-phase kinematic model of the plate tectonic evolution in the Baja California region (modified from Fletcher et al., 2007). A) Pattern of active ridge fragments (red) to the west of the future Baja California peninsula prior to termination of spreading at about 12.3 Ma. B) Proto-Gulf phase of rifting characterized by kinematically partitioned plate motion into 325 kilometers of dextral strike-slip faulting west of Baja California and 90 kilometers of orthogonal rifting in the Gulf of California between 12.3 and 6 Ma. C) It is thought that strike-slip motion on faults west of Baja California diminished starting at about 6 Ma when all plate motion became localized in the present Gulf of California region leading to the accommodation of about 345 kilometers of transtensional deformation. Red line with filled circles (296 kilometers) connects correlated volcanic deposits studied by Oskin and Stock (2003b) (see text for detailed description). GP: Guadalupe Plate, MP: Magdalena Plate, RP: Rivera Plate.

Thus, Oskin and Stock (2003a) have concluded that the difference of about 300-350 kilometers compared to the total relative Pacific-North American Plate motion accumulated outside the northern Gulf of California (Figure 2.9 B). Regarding the time from 6 Ma to present the two-phase kinematic model implies that motion on faults west of Baja California has ceased and that all plate motion has shifted into the present Gulf of California accommodating about 345 kilometers of transtensional strain (Figure 2.9 C) (Fletcher et al., 2007).

The estimated displacement (~700 kilometers) of the southern edge of the Magdalena microplate with respect to the North American Plate after 12.3 Ma – derived from Euler poles calculated by Atwater and Stock (1998) – leads, however, to an unacceptable overlap with the continental margin (Fletcher et al., 2007). For that reason, the one-phase kinematic model (Fletcher et al., 2007) introduces a correction vector with a length of 100 kilometers which delimits the shear accumulated across the Gulf of California and the Magdalena shelf to 610 kilometers (Figure 2.10 A). Fletcher et al. (2007) suggest that motion along faults west of Baja California is limited to 100 ± 50 kilometers since 14.5 Ma (75 kilometers of transtensional shearing before and after 7.8 Ma, respectively; Fig. 2.10 B&C) which represents only one-third of dextral shear compared to the other model. The remaining 460 kilometers of shear must have occurred across the Gulf of California (150 kilometers between 12.3 and 7.8 Ma and 310 kilometers between 7.8 Ma and present; Figure 2.10 B&C). This is consistent with approximately 450-500 kilometers of total displacement across the southern part of the Gulf of California derived of palinspastic reconstructions based on an Airy isostatic model of crustal thickness (Fletcher et al., 2003b; Fletcher et al., 2004). To explain the difference compared to the 296 kilometers of estimated shear in the northern Gulf of California (Oskin and Stock, 2003a), Fletcher et al. (2007) suggest that since 12.3 Ma about 150 kilometers of displacement parallel to relative plate motion are possible, due to Late Neogene deformation along the Sonoran rifted margin (Figure 2.10 C) (e.g., Gans, 1997).

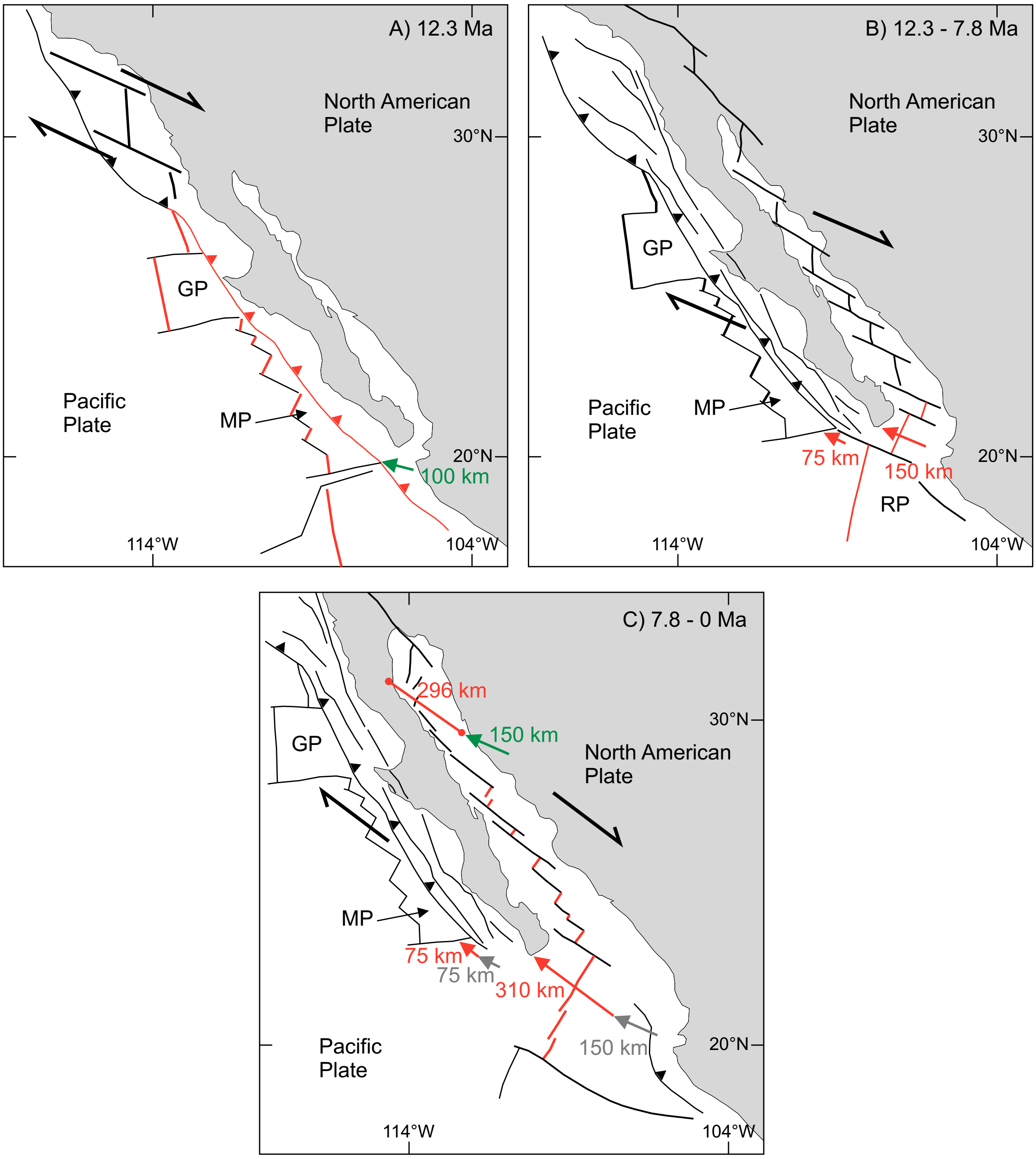

Figure 2.10: Illustration of the improved kinematic model of plate tectonic evolution around the Baja California peninsula (modified from Fletcher et al., 2007). A) Introduction of a correction vector of 100 kilometers due to the restoration of the Magdalena microplate at 12.3 Ma (Fletcher et al., 2007). B) Between 12.3 and 7.8 Ma approximately 75 kilometers and 150 kilometers of offset was produced by transtensional shearing in the continental borderland west of Baja California and the Gulf Extensional Province, respectively. C) From 7.8 Ma to present ongoing transtensional shearing has accumulated additional 75 kilometers and 310 kilometers of displacement in both the continental borderland and the Gulf Extensional Province, respectively. GP: Guadalupe Plate, MP: Magdalena Plate, RP: Rivera Plate.

2.6 Present day setting

One of today's main tectonic structures in Baja California is the Gulf Extensional Province, a region of Miocene to Holocene extension as well as basin and range-type topography surrounding the Gulf of California (Fig. 2.11; Henry, 1989; Stock and Hodges, 1989; Axen, 1995). To the west the Gulf Extensional Province is bordered by the Main Gulf Escarpment, a generally fault-controlled, north-south-striking topographic break separating relatively unfaulted portions of the Peninsular Ranges batholith from a narrow coastal belt and marine shelf characterized by normal faults and isolated basins (Fig. 2.11; Gastil et al., 1975; Umhoefer and Stone, 1996; Fletcher and Munguía, 2000; Umhoefer et al., 2007). On mainland Mexico the Sierra Madre Occidental, a mainly unextended plateau composed of Oligocene to Lower Miocene volcanic rocks, constitutes the eastern boundary of the Gulf Extensional Province (Fig. 2.11; McDowell and Keizer, 1977; Lee et al., 1996; Fletcher and Munguía, 2000).

The modern tectonic regime in southern Baja California is characterized by at least three spatial and distinct systems of faulting (Fletcher and Munguía, 2000). The gulf-axis system in the Gulf of California is dominated by an en echelon series of short oceanic spreading ridges and right-lateral transform faults which are linked to the San Andreas system in the north and accommodate most of the present strike-slip component of transtensional plate motion between the Pacific and North American Plates (Fig. 2.11; Kovach et al., 1962; Hamilton, 1971; Lonsdale, 1989; Fletcher and Munguía, 2000). Faulting, however, is not completely localized within the gulf-axis system as indicated by active deformation resulting in a system of normal faults onshore and offshore along the south-western Gulf of California plate margin implying that the transfer of Baja California to the Pacific Plate is an ongoing process (Fig. 2.11; Dixon et al., 2000; Fletcher and Munguía, 2000; Plattner et al., 2007). In the southern part of Baja California, for example, this active deformation has resulted in at least six earthquakes with a magnitude greater than 5 since 1969 near the city of La Paz (Fletcher and Munguía, 2000; Munguía et al., 2006).

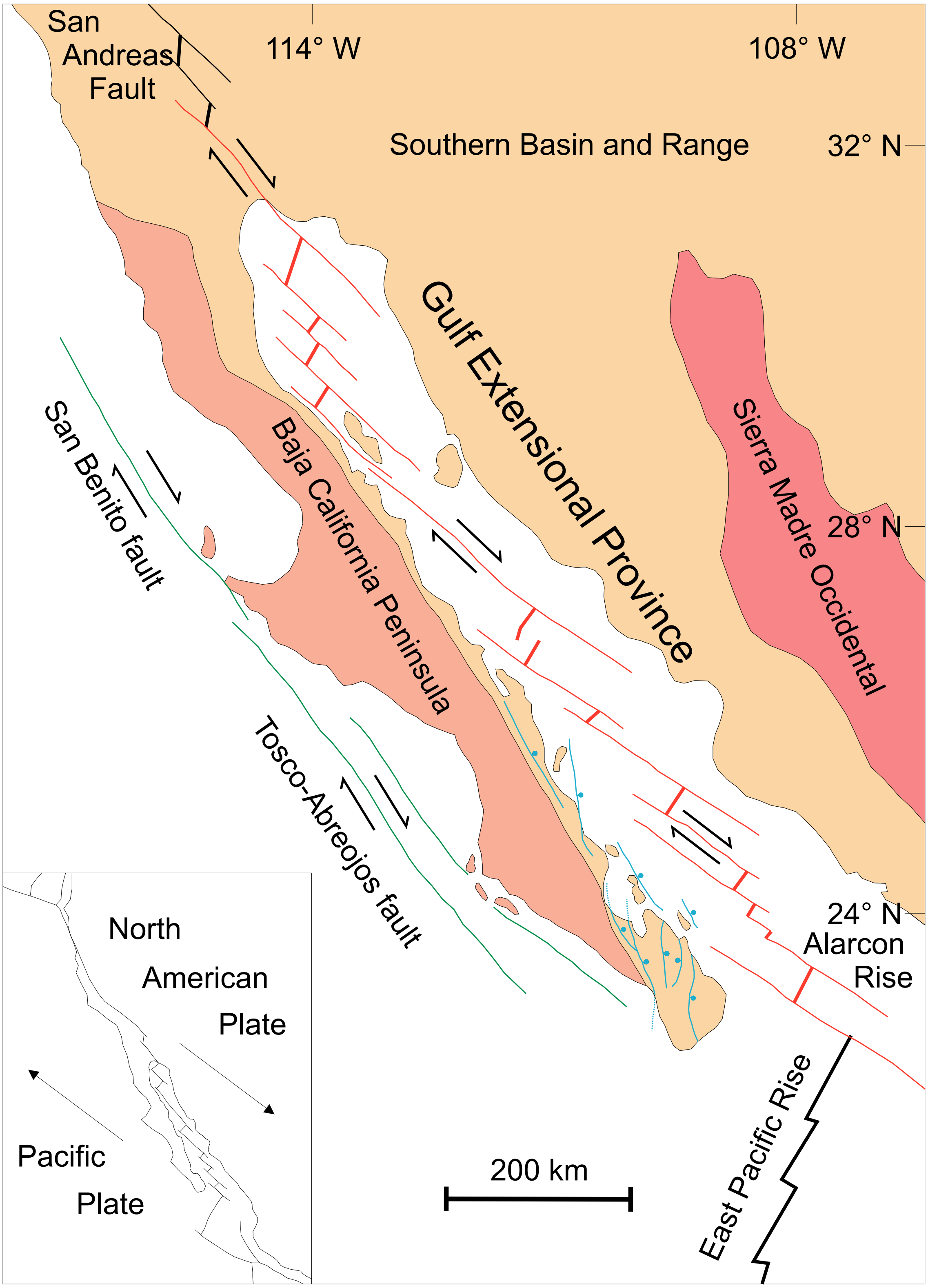

Figure 2.11: Present day tectonic setting in the Gulf Extensional Province and the Southern Basin and Range Province illustrating the main Quaternary fault systems (Gulf-axis system in red, gulf-margin system in blue and borderland system in green). The Gulf Extensional Province is bordered by relatively unfaulted portions of the Baja California peninsula (presented in light red) and the Sierra Madre Occidental (presented in pink). Figure modified from Fletcher and Munguía (2000).

Furthermore, microearthquakes did not occur due to seismic events at the gulf-axis system (Munguía et al., 2006), a fact that confirms the presence of a wide zone of deformation in the gulf-margin system accommodating a part of the relative plate motion between the Pacific and North American Plates – especially the extensional component which is kinematically different from the pull-apart tectonics in the gulf-axis system (Fletcher and Munguía, 2000). The third fault system is situated along the Pacific margin of the Baja California peninsula; this so-called borderland system, including the active right-lateral Tosco-Abreojos and San Benito fault zones, accommodates displacement of the Baja California peninsula relative to the Pacific Plate (Fig. 2.11; Dixon et al., 2000; Fletcher and Munguía, 2000; Michaud et al., 2010).

Along-axis rift segmentation by a series of large normal faults and half-grabens with alternating dip direction and symmetry is common within orthogonal continental rifts and has been observed throughout the world (e.g., Crossley and Crow, 1980; Ebinger et al., 1984; Rosendahl et al., 1986; Morley et al., 1990; Lewis and Baldrige, 1994; Upcott et al., 1996; Umhoefer et al., 2002). Although rifting in the Gulf of California is highly oblique, many features are similar to rifts with orthogonal extension, for example, the splitting into structural segments linked by relatively narrow transfer or broader accommodation zones which allow change of fault style and orientation from one segment to the other (e.g., Ebinger, 1989; Morley et al., 1990; Axen, 1995; Faulds and Varga, 1998; Umhoefer et al., 2002; Sedlock, 2003). In the north-western Gulf Extensional Province Axen (1995) has been successful in identifying three major rift segments with alternating polarity of normal faults and half-grabens separated by accommodation zones (Umhoefer et al., 2002). Axen (1995) furthermore assumed that the western Gulf Extensional Province along the Main Gulf Escarpment might be characterized by segments, ~50 to 150 kilometers in length, separated by accommodation zones (Figure 2.12). Although Axen's (1995) hypothesis was highly speculative, more detailed following up research has been able to confirm rift segmentation along the eastern margin of the Baja California peninsula.

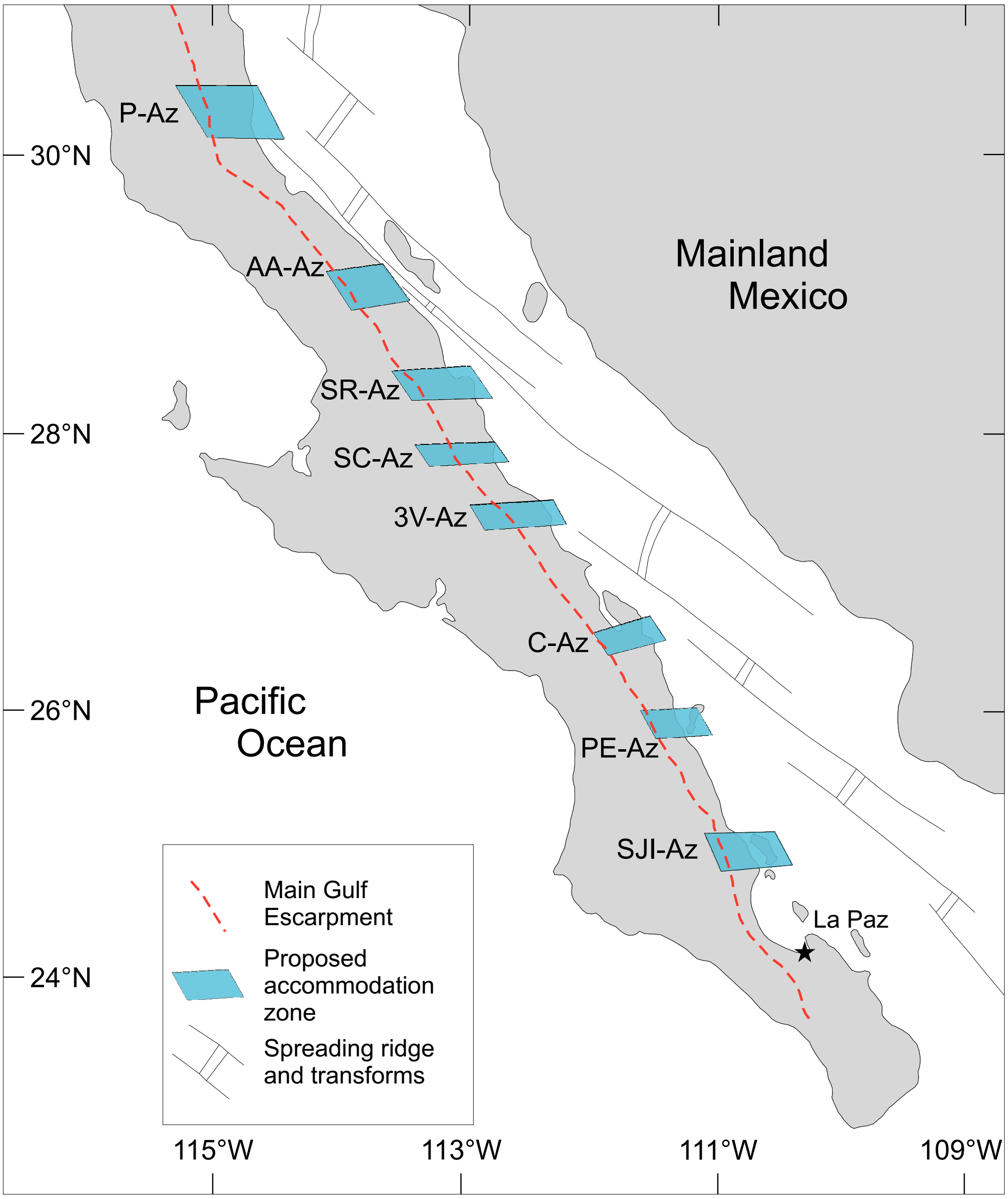

Figure 2.12: Map of accommodation zones in southern Baja California as proposed by Axen (1995). Accommodation zones from north to south: P-Az: Puertecitos, AA-Az: Valle Agua Amarga, SR-Az: Bahia San Rafael, SC-Az: Bahia San Carlos, 3V-Az: Tres Virgenes, C-Az: Bahia Concepción, PE-Az: Puerto Escondido, SJI-Az: San José Island. Map modified from Drake (2005) after Axen (1995).

For example, on the basis of alternating symmetry of major normal faults various studies (Axen, 1995; Fletcher and Munguía, 2000; Umhoefer et al., 2002; Willsey, 2000; Vlad, 2000; Drake, 2005) suggest the existence of four rift segments (Loreto, Timbabichi, La Paz and Cabo segment) in the southernmost part of Baja California (Fig. 2.13; Umhoefer et al., 2007). These segments are commonly linked by accommodation zones (Agua Verde and San José Island accommodation zones) with the exception of the La Paz and Cabo rift segments where a separation by an accommodation zone has not been successfully identified yet (Drake, 2005). Therefore, it is suggested that these two segments constitute a distinct tectonic block which is still dominated by plate motion partitioning as described above (Fletcher and Munguía, 2000; Drake, 2005).

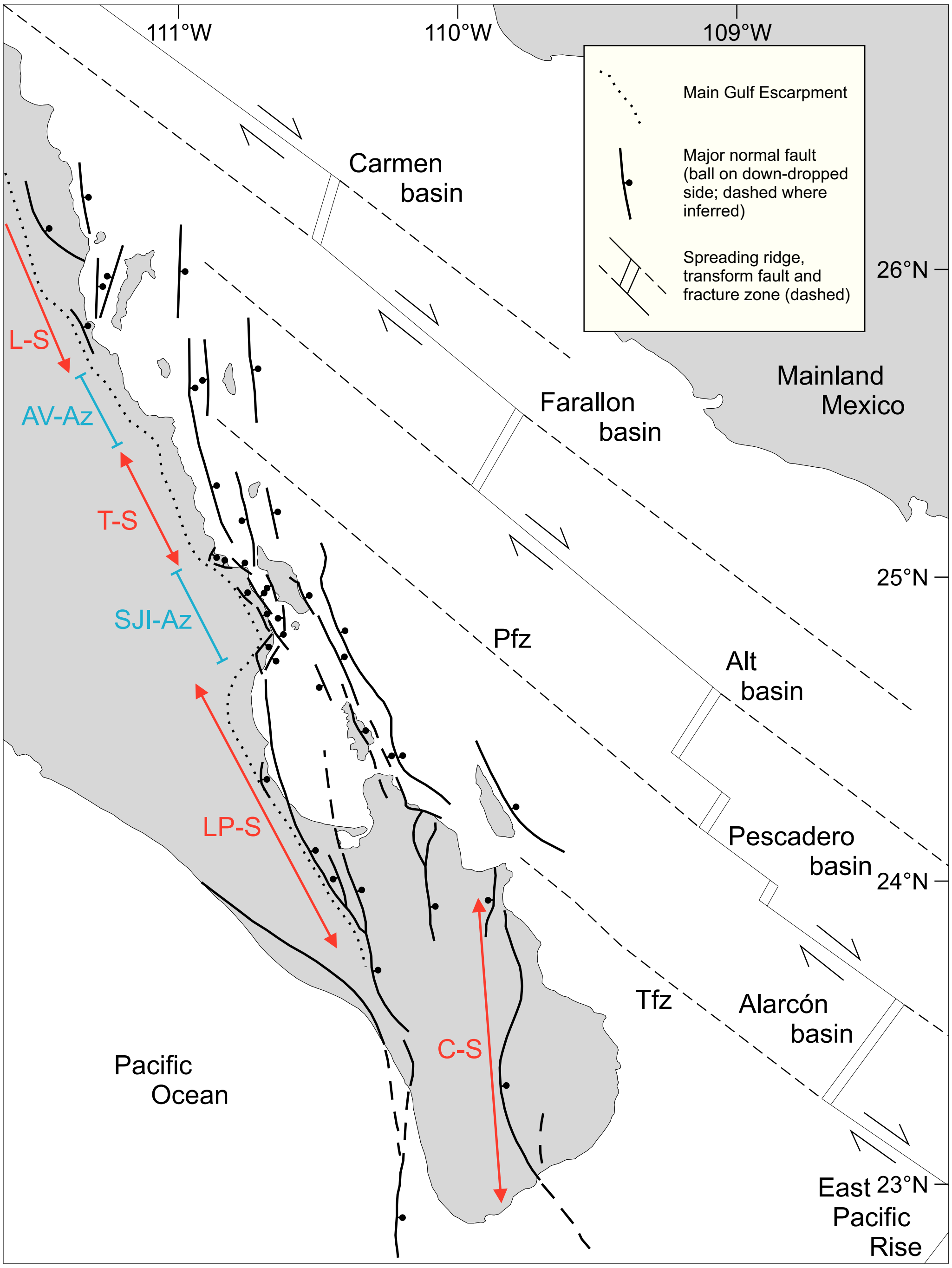

Figure 2.13: Tectonic map of Baja California Sur including the southern part of the Gulf of California. The region east of the Main Gulf Escarpment (dotted line) is characterized by rift segments separated by accommodation zones. (Rift segments: Loreto segment (L-S), Timbabichi segment (T-S), La Paz segment (LP-S), Cabo segment (C-S); Accommodation zones: Agua Verde accommodation zone (AV-Az), San José Island accommodation zone (SJI-Az); Fracture zones: Tamayo (Tfz) and Pescadero (Pfz) fracture zone). Figure modified from Drake, 2005 (compiled after Hausback, 1984; Lonsdale, 1991; Fletcher and Munguía, 2000; Nava-Sánchez et al., 2001; Umhoefer et al., 2002).

3. Geology of the study areas

3.1 San José del Cabo Basin and Sierra La Trinidad

3.1.1 San José del Cabo Basin evolution

The north-south trending San José del Cabo Basin at the south-eastern tip of the Baja California peninsula is part of the Gulf Extensional Province. It is considered to be one of the first half-graben basins which have formed starting in Middle Miocene due to the opening of the Gulf of California (Fig. 3.1; Martínez-Gutiérrez and Sethi, 1997; Oskin and Stock, 2003a; McTeague, 2006). In the east the San José del Cabo Basin is bordered by the Sierra La Trinidad igneous complex ranging in age from Late Cretaceous to Early Tertiary (88.2 – 54.1 Ma) (Gastil et al., 1976) and mainly consisting of granite, granodiorite and rhyolitic lava flows (Fig. 3.1; Martínez-Gutiérrez and Sethi, 1997). Lava flows cropping out in the north-eastern part of the Sierra La Trinidad complex are thought to originate from calc-alkaline volcanism resulting from the subduction of the Guadalupe Plate beneath the North American Plate between about 16 and 13 Ma (Lyle and Ness, 1991). Similarity in petrology between the Sierra La Trinidad complex and the Jalisco block on mainland Mexico (Gastil et al., 1978; Wallace et al., 1992; Ferrari, 1995) and correlation of east tilted blocks located at the southern Sinaloa coast with normal fault traces in the Sierra La Trinidad basement complex indicate that this part of Baja California was adjacent to mainland Mexico until at least Lower Miocene (Stock and Hodges, 1989; Martínez-Gutiérrez and Sethi, 1997).

The San José del Cabo fault and the Late Cretaceous (98.4 to 93.4 Ma) Sierra de la Laguna igneous-metamorphic complex define the western margin of the basin (Fig. 3.1; Gastil et al., 1976; Martínez-Gutiérrez and Sethi, 1997; Fletcher et al., 2000). The crystalline Sierra de la Laguna complex is composed of granite, granodiorite, tonalite, gneiss, schist and mafic dikes (Martínez-Gutiérrez and Sethi, 1997).

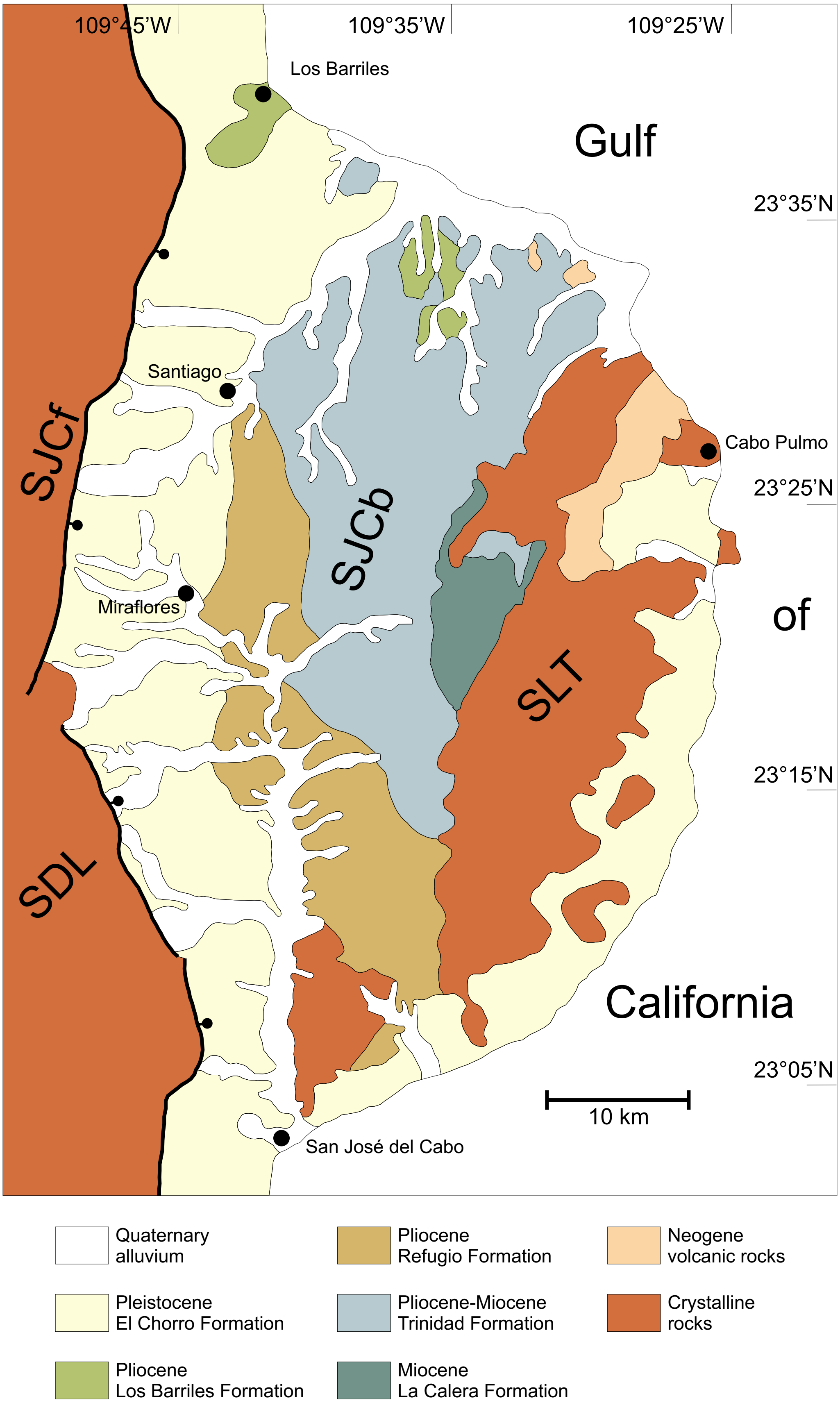

Figure 3.1: Generalized geological map of the San José del Cabo Basin (SJCb) bordered in the west by the Sierra de la Laguna (SDL) and in the east by the Sierra La Trinidad (SLT). (SJCf: San José del Cabo fault; ball on downthrown block). Figure modified from Martínez-Gutiérrez (1994), Martínez-Gutiérrez and Sethi (1997) and McTeague (2006).

The San José del Cabo fault which separates the Sierra de la Laguna from the San José del Cabo Basin extends over a distance of about 80 kilometers and controls abrupt topographic escarpment with more than 1000 meters of relief (Fletcher et al., 2000). Near the surface the fault zone is defined by a high-angle down-to-the-east fault which places Mesozoic crystalline basement against Neogene sediments of the San José del Cabo Basin (McCloy, 1984; Martínez-Gutiérrez, 1994; Fletcher et al., 2000). Based on apatite fission track thermochronology 5.2 to 6.5 kilometers of exhumation has been accommodated by the footwall of the San José del Cabo fault starting in Middle to Late Miocene (Fletcher et al., 2000). The accommodation of uplift occurred with almost no component of strike-slip indicated by fault striae, offset geomorphologic features and earthquake focal mechanisms (Fletcher et al., 2000). Normal faulting along the San José del Cabo fault started nearly contemporaneously with the Rivera triple junction jumping southward about 12 Ma ago. Therefore Fletcher et al. (2000) suggest that far-field stresses and coupling between the Pacific, Farallon and North American Plates dominated crustal extension in the southern Gulf Extensional Province.

According to Martínez-Gutiérrez and Sethi (1997) first block faulting in the Sierra La Trinidad occurred during Middle Miocene and continued during Late Miocene when Baja California was still part of mainland Mexico, probably related to the initiation of Neogene rifting in the Gulf of California. Deposition of the oldest terrestrial sedimentary unit in the San José del Cabo Basin - the La Calera Formation - started as a consequence of this faulting. During Late Miocene time the San José del Cabo Basin was affected by initial subsidence and relative sea-level rise resulting in a marine transgression associated with the deposition of the lower member of the Trinidad Formation (Martínez-Gutiérrez and Sethi, 1997). During Upper Miocene to Lower Pliocene subsidence of the San José del Cabo Basin and transgression went on (Martínez-Gutiérrez and Sethi, 1997). This is supported by a pre-8.2 Ma subsidence at Isla María Madre as suggested by McCloy (1987) and might be related to the initiation of the development of the Tosco-Abreojos fault about 12 Ma ago (Spencer and Normark, 1979).

Epoch			Stratigraphic units
Cenozoic	Pleistocene		El Chorro Formation
Cenozoic	Pliocene	Late	Los Barriles Formation
Cenozoic	Pliocene	Early	Refugio Formation
Cenozoic	Miocene	Late	Trinidad Formation
Cenozoic	Miocene	Late	La Calera Formation
Cenozoic	Miocene	Middle	Volcanic Rocks
Cenozoic	Miocene	Early	Volcanic Rocks
Cenozoic	Oligocene		
Cenozoic	Eocene		
Cenozoic	Paleocene		
Mesozoic	Cretaceous	Late	Granite / Granodiorite
Mesozoic	Cretaceous	Early	Granite / Granodiorite
Mesozoic	Jurassic		Granite / Granodiorite

Figure 3.2: Table of stratigraphic units located in the San José del Cabo Basin. Dash-dotted line marks unconformities; grey box indicates the absence of deposition. (Figure modified from Martínez-Gutiérrez and Sethi, 1997).

Starting in Lower Pliocene regression initiated in the San José del Cabo Basin leading to the deposition of the upper Trinidad and lower Refugio Formation. Geological record of the coarsening-upward Trinidad Formation suggests uplift within the basin resulting in the initiation of emergence of the Sierra de la Laguna complex. In the northern part of the San José del Cabo Basin this uplift is documented in the Refugio Formation which was also deposited in a coarsening-upward manner (Martínez-Gutiérrez and Sethi, 1997). The shallow marine sandy facies of the Refugio Formation documents continued shoaling of the basin at the end of Late Pliocene suggesting the occurrence of relative sea-level fall or tectonic uplift (Martínez-Gutiérrez and Sethi, 1997). As transgression or regression in the San José del Cabo Basin does not correlate with the global sea-level curve (Haq et al., 1988) Martínez-Gutiérrez and Sethi (1997) suppose that tectonic events – probably extension within the Gulf of California during Miocene to Quaternary – controlled deposition within the basin. It is assumed that in Late Pliocene the depositional environment changed from the marine Refugio Formation to the terrestrial Los Barriles

Formation representing continued regression in the basin and uplift of the Sierra de la Laguna and Sierra La Trinidad complexes which are source regions for sediments deposited in the Los Barriles Formation. These events mark the end of marine and the initiation of terrestrial deposition in the San José del Cabo Basin (Martínez-Gutiérrez and Sethi, 1997). Extension in the Gulf of California caused by seafloor spreading initiated along the East Pacific Rise during latest Pliocene through Pleistocene coincides with continued movement along the San José del Cabo fault (Lyle and Ness, 1991; Martínez-Gutiérrez and Sethi, 1997). During Pleistocene the El Chorro Formation - composed of sediments derived from both the Sierra de la Laguna and the Sierra La Trinidad - was deposited unconformably over older tilted formations and crystalline basement alongside both margins of the San José del Cabo Basin (Martínez-Gutiérrez and Sethi, 1997).

In summary sedimentological features and tectonic structures which are exposed in the San José del Cabo Basin are typical for rift basins and provide evidence of Neogene plate tectonics in the mouth of the Gulf of California since about 12 Ma. Therefore, Martínez-Gutiérrez and Sethi (1997) suggest that the evolution of the San José del Cabo Basin is related to extensional processes leading to the opening of the Gulf of California. Compared to other rift basins in the Gulf of California like the Loreto or Santa Rosalia basins there is no evidence of deposition of volcanoclastic sediments in the San José del Cabo Basin (Umhoefer et al., 1994; Dorsey et al., 1995; Martínez-Gutiérrez and Sethi, 1997).

3.1.2 Geological units in the San José del Cabo Basin and Sierra La Trinidad

3.1.2.1 La Calera Formation

The red-colored La Calera Formation of probably Middle to Late Miocene age is the oldest sedimentary unit in the San José del Cabo Basin. It is composed of conglomerates (mainly at the base of the formation) and sandstone beds which unconformably overlie the La Trinidad basement complex and reaches a thickness of about 300 meters (Martínez-Gutiérrez and Sethi, 1997). Paleotransport indicators like channels, cross-bedding and imbrication show a west-northwest trend of flow patterns of these deposits. Therefore, it is assumed that most of the La Calera sediments originate from the Sierra La Trinidad complex. It is thought that during an initial depositional stage of basin formation the La

Calera clasts were transported to their final position in an alluvial fan environment (Martínez-Gutiérrez and Sethi, 1997). Due to the lack of fossils the La Calera formation has not been dated yet. However, its stratigraphic position between the Sierra La Trinidad basement complex at the bottom and the Trinidad Formation at the top provides an estimated age of Middle to Late Miocene (Martínez-Gutiérrez and Sethi, 1997).

3.1.2.2 Trinidad Formation

The Trinidad Formation conformably overlies the La Calera Formation. Marine fossils being present in the sediment can be seen as evidence of marine deposition and were used for dating, but with varying results (Martínez-Gutiérrez and Sethi, 1997). Whereas McCloy (1984) proposed a Middle Miocene to Upper Pliocene age based on the analysis of mega- and micro-fossils, Martínez-Gutiérrez and Sethi (1997) suggested that deposition occurred between Late Miocene and Early Pliocene. Other studies indicate that sedimentation took place during Lower Pliocene (Pantoja-Alor and Carrillo-Bravo, 1966) or Upper Miocene (Smith, 1991). McTeague (2006) identified the presence of coccolith D. berggrenii in the lower part of the Trinidad Formation suggesting a deposition between 8.6 to 7.4 Ma, i.e. during Late Miocene. Martínez-Gutiérrez and Sethi (1997) propose to divide the formation (with an estimated total thickness of 400 meters) into three facies regarding their deposition in three probably different environments as indicated by a combination of lithology and fossil assemblages. The lower facies is thought to have been deposited under nearshore-lagoonal conditions, whereas the middle facies seems to have accumulated in shelf depths fairly greater than the level of normal wave base. In contrast Fierstine et al. (2001) propose that the middle facies was deposited in water depths of about 100 meters in an offshore environment. Their conclusion is based on the nature of the sediments and the preferred habitat of Makaira nigricans Lacépède (Fossil Blue Marlin), the fossil remains of which can be found in the Trinidad Formation. Finally, the upper facies is characterized by medium- to fine-grained sandstone with cross-bedding and shell fragments indicating a deposition in high-energy, shallow marine waters (Martínez-Gutiérrez and Sethi, 1997).

3.1.2.3 Refugio Formation

The Refugio Formation is the youngest marine deposition which crops out throughout the San José del Cabo Basin and unconformably overlies the Sierra La Trinidad complex in the southern part of the basin but usually grades conformably into the underlying Trinidad Formation, for instance in the center of the basin (Martínez-Gutiérrez and Sethi, 1997). According to Martínez-Gutiérrez and Sethi (1997) the Refugio Formation has a maximum thickness of about 380 meters although no locality exhibits a complete stratigraphic section. The Refugio Formation is generally composed of coarse- to medium-grained beds of gray-white sandstone which is locally interbedded with shale and limestone and characterized by brackish marine fossils. Due to the coarsening-upward and decreasing presence of marine fossils toward its top, the Refugio Formation is thought to represent a regressive sequence of basin filling under shallow marine depositional conditions (Martínez-Gutiérrez and Sethi, 1997). According to McCloy (1984) the Refugio Formation is of Late Pliocene to Pleistocene age whereas Smith (1991) as well as Martínez-Gutiérrez and Sethi (1997) assign an Early Pliocene age based on fossil assemblage and the conformable contact with the Trinidad Formation.

3.1.2.4 Los Barriles Formation

The Los Barriles Formation which can only be found in the northern part of the San José del Cabo Basin is a conglomerate dominated deposit with a thickness of up to about 1650 meters. Martínez-Gutiérrez and Sethi (1997) assume that the Los Barriles Formation was deposited in an alluvial fan environment under semiarid conditions. Due to the fact that no fossils were found within the formation (besides reworked shell fragments) the age can only be assumed by stratigraphy, ranging from Upper Pliocene to Lower Pleistocene (Martínez-Gutiérrez and Sethi, 1997).

3.1.2.5 El Chorro Formation

The El Chorro Formation which is the youngest terrestrial deposit within the San José del Cabo Basin unconformably overlies older sedimentary formations and Mesozoic rocks of the Sierra La Laguna complex. Non-marine, coarse-grained sandstone and conglomerate are the main components of this formation which is thought to represent an alluvial fan deposition of probably Upper Pleistocene to Lower Holocene age with a maximum thickness of about 150 meters. Observed fan morphology and limited indicators of transport direction suggest a predominantly eastward transport direction (Martínez-Gutiérrez and Sethi, 1997).

3.1.2.6 Igneous rocks

Probably Late to Middle Miocene acid volcanic and volcaniclastic rocks which are common in most of Baja California Sur can be found only at the north-eastern boundary of the San José del Cabo Basin north of the Sierra La Trinidad (Martínez-Gutiérrez and Sethi, 1997; Fletcher et al., 2007). Outcrops are localized near Cabo Pulmo and La Ribera. These rocks have not been radiometrically dated yet, but according to Sawlan (1991) they might be correlated with the 25-17.6 Ma ignimbrites of the region surrounding La Paz or those situated in the Sierra Madre Occidental (Carreno and Smith, 2007).

3.2 Bay of La Paz area

3.2.1 Tectonics

The Bay of La Paz area is characterized by several distinct structural features. To the west and northwest the landscape is dominated by the Sierra de la Giganta – the southernmost extent of the Main Gulf Escarpment – with altitudes up to 1500 meters but a considerably declining elevation toward the latitude of La Paz. In the east and southeast the Sierra de la Giganta is flanked by the El Carrizal fault which is considered to be the westernmost fault of the gulf-margin system of southern Baja California Sur (Maloney, 2009). The east-dipping, north-northwest trending El Carrizal normal fault can be traced onshore from Todos Santos, located at the Pacific coast, to the Bay of La Paz and is thought to continue offshore for about 50 kilometers along the coastline toward Punta Coyote (Fig. 3.3; Drake, 2005; Cruz-Falcón et al., 2010); furthermore it defines the western limit of the La Paz Basin.

According to a gravity survey by Busch et al. (2011) the La Paz Basin is relatively shallow (maximum depth to bedrock: 200-500 meters) compared to other basins like the San Juan de los Planes (~1000 - 1500 meters) or the San José del Cabo (1600 - 2700 meters) basins and is thought to be a half-graben encompassing two smaller basins divided by a bedrock high which coincides with a north-south trending lineament. This lineament can also be identified in gravity and magnetic contour maps presented in a study by Cruz-Falcón et al. (2010) and is proposed to be the expression of an east-dipping normal fault called El Centenario. This fault - together with the El Carrizal and Bonfil faults - forms the larger El Carrizal fault system (Fig. 3.3; Drake, 2005). Cruz-Falcón et al. (2010) assume that the La Paz Basin is delimited in the east by the inferred La Paz fault (e.g., Normark and Curray, 1968; Hamilton, 1971; Hausback, 1984), although little is known about it, and its role as a major fault remains controversial (e.g., Fletcher and Munguía, 2000; Fletcher et al., 2000).

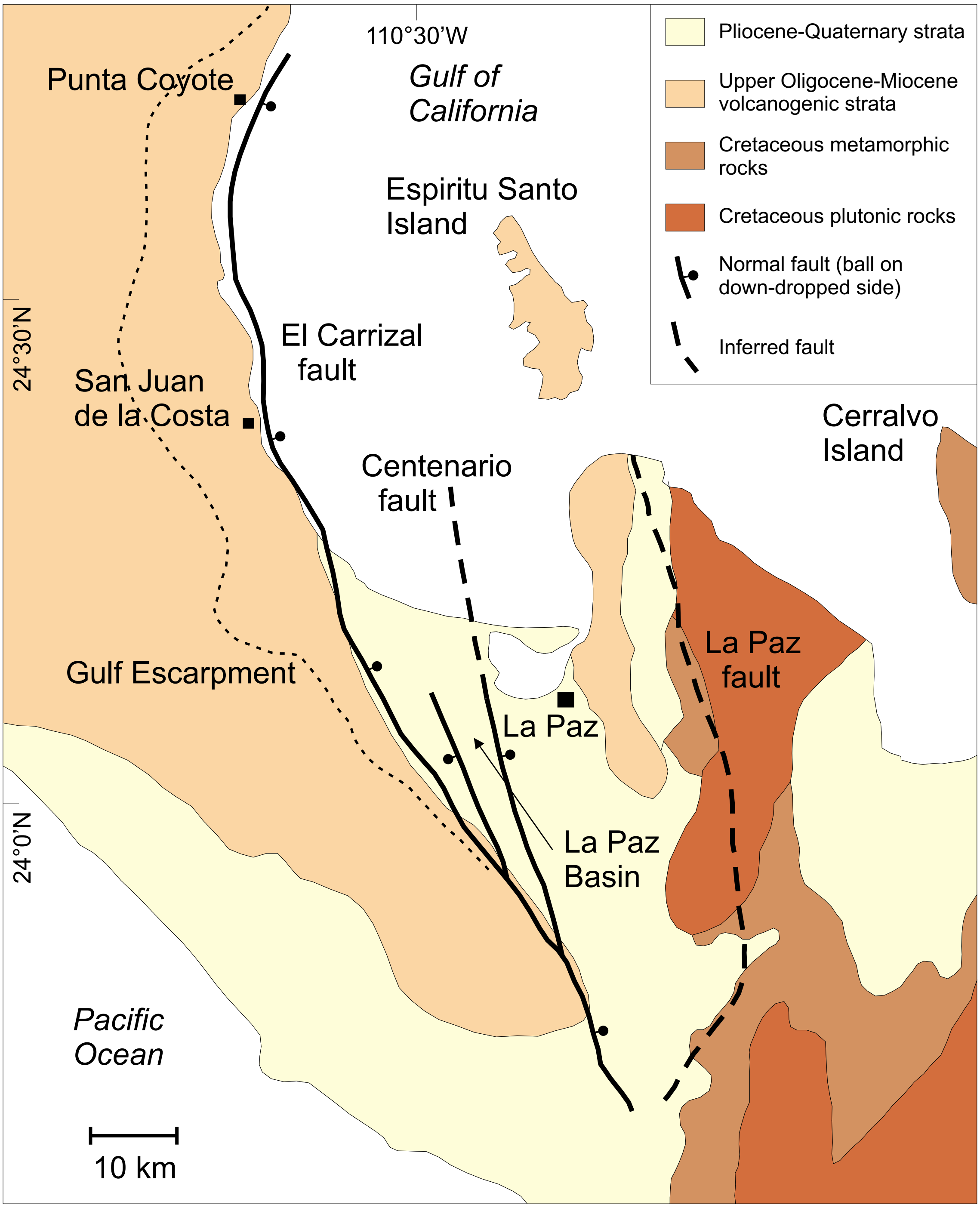

Figure 3.3: Geological map of the Bay of La Paz region in Baja California Sur showing the most important faults referred to in the text. Figure modified from Drake (2005; compiled after Hausback, 1984; Lonsdale, 1989; Fletcher and Munguía, 2000; Nava-Sánchez et al., 2001; Umhoefer et al., 2002), Maloney (2009) and Cruz-Falcón et al. (2010).

3.2.2 Geology

As already mentioned above, the geological evolution of the present Gulf of California region was dominated by calc-alkaline arc and forearc volcanism between 30-25 and 12 Ma (McFall, 1968; Gastil et al., 1979; Sawlan and Smith, 1984; Hausback, 1984, 1987; McLean, 1988; Sawlan, 1991; Umhoefer et al., 2001, 2002) leading to the deposition of volcanic and volcaniclastic rocks along eastern Baja California Sur. The nomenclature of these rocks remained confusing in the past (Heim, 1922; Beal, 1948; McFall, 1968; Demant, 1975; Gastil et al., 1979; Hausback, 1984; Sawlan and Smith, 1984; McLean, 1988; Bigioggero et al., 1996; Dorsey and Burns, 1994; for detailed nomenclature history see Umhoefer et al., 2001) until Umhoefer et al. (1994, 2001) proposed a consistent way to name these rocks following the definition of Heim's (1922), Demant's (1975) and Hausback's (1984) Comondú Formation. With reference to modern stratigraphic definitions (International Stratigraphic Code; Salvador, 1994) Umhoefer et al. (2001) suggest to change the rank of the Comondú Formation to Comondú Group. Furthermore, based on their results for the Loreto area, they divide the Comondú Group into the following three informal units according to the different phases of westward migration of the volcanic arc. The lower clastic unit with an age of about 30 to 19 Ma is thought to have been deposited in a forearc basin setting, whereas the middle breccia and lava flow unit (~19 – 15 Ma) formed from debris flows. The youngest unit of the Comondú Group – the so-called upper lava flow and breccia unit – with an age between about 15 and 12 Ma is thought to have been built up by thick debris flows near volcanic centres (Umhoefer et al., 2001).

Another approach to characterize rocks of the Comondú Group was presented by Hausback (1984) in a volcanic facies model based on work by Vessel and Davies (1981). The Comondú Group rocks were distinguished depending on lateral differences in grain size and lithology caused by their position relative to the volcanic source areas (Fig.3.4). The core facies - composed of lava flows, massive breccia, ashfall and colluvial deposits - dominates the coastal strip of eastern Baja California Sur including the islands in the Gulf of California (Fig. 3.4; Hausback, 1984; Umhoefer et al., 2001).

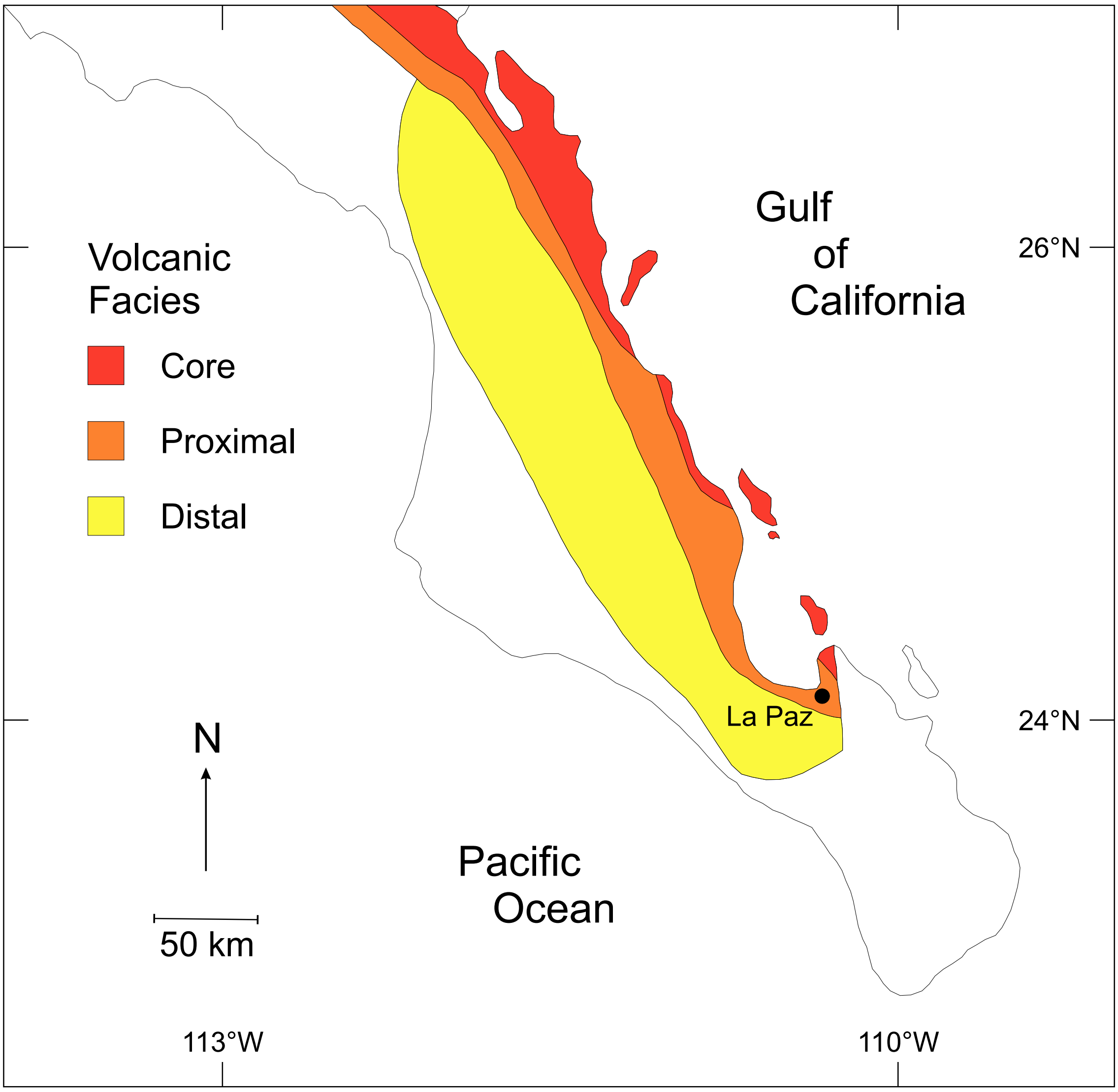

Figure 3.4: Map of the volcanic facies model of Comondú Group rocks in Baja California Sur presented by Hausback (1984) (modified from Hausback (1984) and Umhoefer et al. (2001)).

Exposures of the proximal facies like volcanic breccias, conglomerates, lava flows and sandstones can be found in a band along the eastern side of the Main Gulf Escarpment (Fig. 3.4; Hausback, 1984; Umhoefer et al., 2002). The Main Gulf Escarpment also defines the eastern limit of the distal facies composed mainly of sandstones and conglomerates which become thinner toward the west and finally disappear beneath alluvial deposits (Fig. 3.4; Hausback, 1984). In the region surrounding the city of La Paz the Comondú Group is composed of andesitic lahars, volcanic sandstones and breccia, conglomerates, ash-flow tuffs, lava flows and silicic ignimbrites (Hausback, 1984).

3.3 San José and San Francisco Island

The San José and San Francisco Islands are situated about 85 kilometers north-northwest of La Paz and are separated from mainland Baja by the San José Channel which is suggested to be bordered by a set of right-stepping, east-dipping normal faults in the west and left-stepping, west-dipping normal faults in the east (Fig. 3.5; Drake, 2005). Another east-dipping offshore fault is inferred to be located along the eastern side of San José Island (Umhoefer et al., 2007). Based on the recognition of uplifted marine terraces, linear coastlines and steep cliffs which characterize large parts of San José Island's shoreline it is suggested that these offshore faults are active (Drake, 2005; Umhoefer et al., 2007). The northern and north-eastern parts of San José Island are characterized by two Pliocene sub-basins which are thought to belong to a larger, partly offshore basin (Del Margo, 2002; Umhoefer et al., 2007). The most dominant rock-type exposed on San José Island is Cretaceous granite overlain by Comondú Group rocks at the southern end of the island (Hausback, 1984; Puy-Alquiza, 1992; Umhoefer et al., 2001; Umhoefer et al., 2007). In the south-eastern part of San José Island outcrops of the Salto Formation with a total thickness of 120 meters are exposed (Drake, 2005). This formation pre-dates Comondú Group rocks (age: ~28 Ma; Hausback, 1984) and can be divided into a lower conglomerate and upper cross-bedded sandstone section deposited under fluvial fan conditions and in an eolian and fluvial environment, respectively (Plata-Hernández, 2002; Drake, 2005).

San Francisco Island, situated just 4 kilometers south of San José Island, is dominated by volcanic and volcaniclastic rocks of the Comondú Group (Drake, 2005). The most prominent among these rocks is the San Juan Tuff which is composed of two units of rhyolitic ash-flow tuff with an age of 19.37 ± 0.06 Ma determined for the lower flow unit (Drake, 2005). Outcrops of the Sierra Tarabilles Formation – stratigraphically lying below the San Juan Tuff – comprising rhyolitic ash-flow tuff, fluvial sandstone and conglomerate can be found in the northern third, along the eastern coast and at the south-easternmost part of San Francisco Island. In addition andesitic volcanic breccia, sandstones and conglomerates are exposed (Drake, 2005).

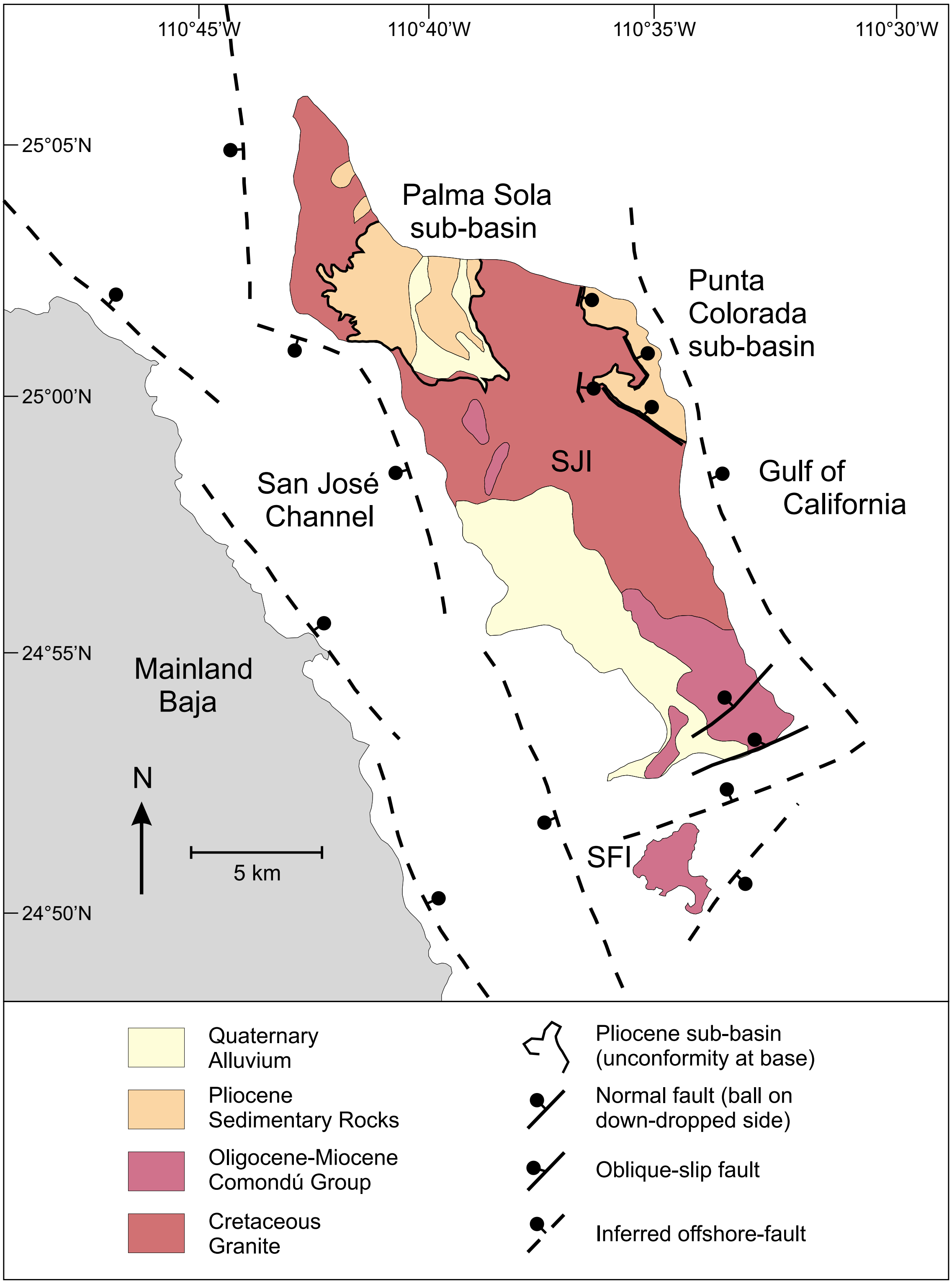

Figure 3.5: Simplified geological map of San José (SJI) and San Francisco Island (SFI) showing the primary onshore and offshore faults in the area (modified from Puy-Alquiza (1992), Del Margo (2002), Drake (2005) and Umhoefer et al. (2007)).

4. Vertical-axis block rotation and previous studies

The identification of crustal block rotations about vertical axes becomes increasingly important when describing continental deformation, especially in regions where shear is distributed in transpressional or transtensional environments or in diffuse plate boundaries (Nelson and Jones, 1987; Sonder et al., 1994; Lewis and Stock, 1998). Compared to oceanic plate boundaries where deformation is typically limited to narrow regions, deformation in areas of continental extension or shortening occurs in much broader zones where rigid blocks are common (McKenzie and Jackson, 1986; Acton et al., 1991). In Greece, for example, active normal faulting and extension can be found over a range of 600 kilometers (McKenzie, 1978), and in Iran active thrusting and shortening occurs over a width of 200-300 kilometers (Jackson and McKenzie, 1984). The most prominent examples of Neogene strike-slip plate boundaries with vertical-axis rotations of up to 90° in several millions of years can be found in northern Israel (Ron et al., 1984; Nur et al., 1989), Southern Asia (Le Dain et al., 1984), the Aegean region (Duermeijer et al., 1999; 2000; van Hinsbergen et al., 2005) and the Alpine fault zone in New Zealand (Walcott, 1984; 1989) and are a common feature of continental deformation (McKenzie, 1990; Lewis and Stock, 1998). A similar setting can be found at the western coast of North America along the boundary between the Pacific and North American Plates where tectonostratigraphic terranes which have undergone significant translation and rotation in Neogene time can be identified (Luyendyk et al., 1980; Johnson et al., 1983; Kamerling and Luyendyk, 1985; Luyendyk et al., 1985; Weldon, 1986; Burbank and Whistler, 1987; Ross et al., 1989; MacFadden et al., 1990; Luyendyk, 1991).

Viscous models of lithospheric deformation are consistent with the observed pattern of block rotations in some of the areas mentioned, leading to the assumption that large-scale shear in underlying deforming lithospheric material may evoke the rotation of small crustal blocks (cp. Sonder and England, 1986; England and Wells, 1991). These plate margins are characterized by considerable non-rigid deformation; additional crustal shortening or extension (rifting) in such regions results in a combination of strike-slip and dip-slip faults instead of simple shear. Analogue modelling of oblique rifting has shown that the acute angle between rift trend and displacement direction defines the relative amounts of extension and shear (Withjack and Jamison, 1986; Tron and Brun, 1991).

For a better understanding of the kinematics of these processes, two-dimensional block models of distributed deformation have been used to elucidate how strike-slip and dip-slip deformation and paleomagnetically identified rotations can be kinematically linked. Furthermore, these models provide the opportunity to study how fault kinematics and block rotations within a zone of distributed shear are related to the relative motion of the rigid tectonic plates on each side (McKenzie and Jackson, 1983; 1986). They predict that in an obliquely divergent setting extension perpendicular to the boundaries of the deforming zone will occur, combined with strike-slip on faults conjugate to the shear direction. This prediction holds true for many areas of Southern California where rotating blocks are bounded by sinistral or obliquely sinistral slip faults which are conjugate to the principal dextral faults of the plate boundary (Bogen and Seeber, 1986; Luyendyk et al., 1985). Along a transtensional plate boundary, as existing in the Gulf of California, a variety of rotating blocks should be present. So far, however, these blocks have only been fully documented in the northern part of Baja California (Lewis and Stock, 1998). Paleomagnetic data from Sierra San Fermin in the Gulf of California Extensional Province indicate that localized clockwise rotations of structural blocks about vertical axes occurred in north-eastern Baja California, in combination with Pliocene to recent extension and dextral shear. Observed declinations in the ~12.5 Ma San Felipe tuff indicate a net clockwise rotation of 41° ± 9° whereas ash flow tuffs with an age of ~6 Ma have recorded 30° ± 16° of clockwise rotation with respect to localities on the North American craton (Lewis and Stock, 1998). Lewis and Stock (1998) proposed that the difference in the amount of rotation (11° ± 17°) between 12.5 and 6 Ma is statistically insignificant and that rotations did not occur until about 6 Ma. These clockwise rotations together with a combination of normal and strike-slip faulting are thought to have accommodated extension at the plate boundary. Furthermore, Lewis and Stock (1998) suggest that shear has possibly been transferred onto faults corresponding to the San Andreas Fault, accounting for clockwise rotation of the Western Transverse Ranges during Late Miocene to recent times. This interpretation is consistent with the classic two-phase kinematic model of rifting in which a phase of extension in the proto-Gulf was followed by the initiation of transtensional shearing at about 6 Ma. In the light of the alternative one-phase kinematic model (Fletcher et al., 2007) Seiler et al. (2010) have reinterpreted the data gathered by Lewis and Stock (1998). They argue that the magnetic signal derived from samples of the San Felipe tuff is more robust compared to the younger tuffs and that the Sierra San Felipe was affected by clockwise block rotations already prior to ~6 Ma.

Furthermore, it is proposed that about 25% of the total rotation in the Sierra San Felipe took place before 6 Ma, a fact which is consistent with the one-phase kinematic model of rifting in the Gulf Extensional Province.

Another study dealing with vertical axis rotations was carried out on Carmen Island east of Loreto in the course of a master thesis (Macy, 2005). Whereas most of the islands in the Gulf of California trend more or less parallel to the Gulf in a northwest-southeast to north-south direction, Carmen Island trends north-northeast-south-southwest and, furthermore, the strike of Comondú Group rocks on the island differs approximately 35°-40° clockwise compared to the same type of rocks on adjacent mainland Baja California. Therefore, it is assumed that Carmen Island was affected by vertical-axis rotations during Miocene to Pliocene time (Umhoefer et al., 2002). To test this hypothesis paleomagnetic rock samples were taken on Carmen Island and compared to samples with a similar age taken on mainland Baja California west of Loreto. Macy (2005) summarized the results of this research in different scenarios favoring the one which suggests the northern two-thirds of Carmen Island having rotated clockwise about 40 to 50° between 12 and 3 Ma and about 10 to 20° since 3 Ma. The southern third, separated from the northern part by the Arroyo Blanco fault, is thought to have rotated clockwise 5 to 7° between 12 and 3 Ma and 3 to 5° from 3 Ma to present (Macy, 2005).

A study carried out by Schaaf et al. (2000) focussed on the pre-Miocene paleogeography of the southern part of Baja California between La Paz and Cabo San Lucas, combining geochronological and paleomagnetic data. Intrusive rocks of the so-called Los Cabos Block show a thermomagnetic remanence probably acquired at the end of the Cretaceous Normal Superchron (cp. Cande and Kent, 1992) between about 80 and 90 Ma. Mixed polarities are assumed to indicate a primary magnetization not affected by recent magnetic overprints. According to Schaaf et al. (2000) the comparison of a paleopole calculated from the paleomagnetic results of the Los Cabos Block with the 100 Ma pole of Globerman and Irving (1988) and the 67-97 Ma pole of Gordon and Van der Voo (1995) for stable North America indicates significant clockwise rotations of 36° ± 11° and 45° ± 9°, respectively. After excluding other tectonic movements the authors suggest that the large clockwise rotation of the Los Cabos Block might be related to the opening of the Gulf of California. Based on geochemical and isotopic data in combination with paleomagnetic results Schaaf et al. (2000) propose a possibly independent paleogeographical evolution of the Los Cabos Block from the northern portion of the Baja California peninsula.

Beside this more regional research there is an ongoing debate regarding the paleogeographic reconstruction of the Baja California peninsula since Cretaceous time (Butler et al., 1991). Based on unexpectedly shallow inclinations in Cretaceous to Early Paleogene sedimentary as well as plutonic rocks, several paleomagnetic studies (e.g. Teissere and Beck, 1973; Patterson, 1984; Fry et al., 1985; Hagstrum et al., 1985; Beck, 1991) propose a Cretaceous paleolatitude 10 to 15° south of the peninsula's present position and a subsequent northward tectonic transport of up to 2000 kilometers relative to stable North America between Late Cretaceous and Earliest Eocene time (Butler et al., 1991; Gastil, 1991; Lund and Bottjer, 1991; Dickinson and Butler, 1998). In contrast, geological observations provide evidence that such a huge amount of northward translation is not required and that the present Baja California peninsula was adjacent to north-western Mexico in Cretaceous time. This assumption is based on positive correlation of Paleozoic rocks exposed on the Baja California peninsula as well as on mainland Mexico (Gastil, 1991) and is supported by plate-circuit and palinspastic reconstructions (Atwater and Stock, 1998; Fletcher et al., 2003) as well as similar detrital zircon ages of Paleozoic rocks in north-eastern Baja California and the Cordilleran margin (Gehrels et al., 2002; Li et al., 2004). The conflicting interpretations of paleomagnetic and geological data led to the development of possible explanations for the presence of shallow inclinations. According to several authors (e.g. Butler et al., 1991; Dickinson and Butler, 1998; Butler et al., 2001; Kodama and Ward, 2001) postdepositional compaction can explain inclination flattening in sedimentary rocks. On the other hand the shallow inclinations found in paleomagnetic data gathered from plutonic rocks might be explained by large-scale westward regional tilting (Butler et al., 1991; Dickinson and Butler, 1998). Furthermore, some of the anomalously low inclinations are assumed to result from later remagnetization of sedimentary rocks possibly caused by hydrothermal fluids (Smith and Busby, 1993; Hagstrum et al., 1985; Hagstrum and Sedlock, 1998; Symons et al., 2003).

The coincidence that the effects of postdepositional compaction of sediments and the westward tilting of plutonic rocks lead to a similar amount of inclination shallowing has already been described by Butler et al. (1991). For some authors (e.g. Sedlock, 2003) this high level of coincidence seems to be too unlikely to occur throughout all of Baja California, and therefore it is suggested that a possible northward translation should not be completely excluded from further discussion about the paleogeographic history of Baja California.

5. Field and laboratory methods

Samples for paleomagnetic analysis were collected using a portable fuel-powered drill with diamond bits. At least five cores with a diameter of 25 mm were drilled from each site and individually oriented using a clinometer and a magnetic compass. Some orientations were additionally checked with a solar compass. Sedimentary rocks had to be drilled with an electric-powered drill, as fuel-driven drills were too powerful resulting in disintegrated drill cores. In the laboratory up to six 22 mm long cylindrical specimens were cut from the core samples for further analysis. Prior to demagnetization the anisotropy of magnetic susceptibility (AMS) of most of the specimens was measured routinely.

The majority of specimens was subjected to progressive thermal demagnetization (performed with Schonstedt and ASC furnaces) in 24 heating steps at most with peak temperatures of 700°C. Where thermal demagnetization proved to be ineffective in isolating the characteristic remanent magnetization (ChRM), stepwise alternating field (AF) demagnetization was applied in up to 18 steps in maximum fields of 100 mT (in exceptional cases 200 mT) using a 2G AF system. Measurements of the remanent magnetization were carried out using a 2G cryogenic magnetometer housed in a magnetically shielded room in the paleomagnetic laboratory of the Department of Earth and Environmental Sciences (Ludwig-Maximilians-Universität München, Geophysics section). Magnetometer operating, data acquisition and visualization of measurement progress were performed by using the software Cryomag (Wack, 2010). To detect possible heat-induced changes in the magnetic mineralogy of thermally demagnetized specimens, low-field magnetic susceptibility was monitored throughout the whole demagnetization process.

After correcting all compass readings for the magnetic declination – which was between about 9° 5'E and 9° 35'E in the study areas for 2008 (according to the International Geomagnetic Reference Field Model (IGRF), version 11; www.ngdc.noa.gov/ geomagmodels/Declination.jsp; 07.01.2012) – magnetization directions were structurally corrected by rotating the measured bedding plane into the horizontal plane about the strike axis. Measured directional data has been corrected into stratigraphic coordinates and plotted as stereographic projections and orthogonal Zijderveld-plots (Zijderveld, 1967). The characteristic remanent magnetization directions have been obtained by applying principle component analysis (PCA; Kirschvink, 1980) on linear demagnetization trajectories. Mean directions of different sites/groups of sites have been calculated following the method of Fisher (1953).

6. Paleomagnetic results

In order to gather information on possible vertical-axis rotations the calculated mean declination of each site/group of sites was compared to a reference direction derived from the pole position of North America. Age-dependent directions were calculated using Besse and Courtillot's (2002) paleopoles for the North American craton (cp. Table 1). As the difference of calculated declinations varies only by 0.1° between the southern- and the northernmost site, it was decided to use the longitude and latitude of a site near La Paz (centrally situated; latitude: 24.1°N, longitude: 249.7°E) for calculating the reference directions.

Table 1: Reference directions for Baja California derived from the North American pole position for different ages (Besse and Courtillot, 2002).

Window [Ma]	Age [Ma]	Dec [°]	Inc [°]	α_{95} [°]	λ(°N)	Φ(°E)	A_{95} [°]
0	2.1	356.4	43.4	3.1	86.5	180.7	3.0
5	3.1	355.8	43.1	2.7	86.1	174.8	2.6
10	11.9	354.1	42.3	3.2	84.6	164.4	3.1
15	14.8	353.0	42.1	3.3	83.6	163.0	3.2
20	19.6	350.2	40.7	4.8	81.0	156.2	4.5
25	26.0	352.1	42.5	5.5	82.8	165.7	5.3

Window: age of the center of the window; Age: mean age computed from the data; Dec/Inc: Declination and Inclination of the calculated reference direction; α_{95}: radius of 95% confidence about mean direction; λ(°N) and Φ(°E): latitude and longitude of mean virtual geomagnetic pole (VGP); A_{95}: uncertainty at the 95% confidence level; a site-latitude of 24.1°N and a site-longitude of 249.7°E has been used for calculating reference direction.

Results obtained from the comparison of declinations with calculated reference directions are not appreciably biased by major plate tectonic movements (Lewis and Stock, 1998). Significant Neogene rotation of the Baja California peninsula is ruled out by geological constraint as well as by paleomagnetic studies (Hagstrum et al., 1987; Hausback, 1988). Spreading in the Gulf of California is responsible only for less than 3° of clockwise rotation of the entire peninsula (Stock and Hodges, 1989) which is not resolvable within the error limits of paleomagnetic data (Lewis and Stock, 1998). For the analysis of vertical axis rotation and related errors the approaches of Beck (1980) and Demarest (1983) have been used.

6.1 San José del Cabo Basin and Sierra La Trinidad

In order to gain information on the timing of possible vertical-axis rotations it was tried to cover all geological formations mentioned in chapter three. Because of the basin structure and erosional processes it was difficult to find proper outcrops for drilling samples. Due to its conglomeratic nature the Los Barriles Formation was not sampled at all.

6.1.1 La Calera Formation

The La Calera Formation was sampled about 18 kilometers west of Cabo Pulmo. In an area of about one square-kilometer a total of 91 cores from eleven different beds was taken focussing on the fine-grained layers of the sandstone sequence. The samples yield natural remanent magnetization (NRM) intensities ranging from 0.18 mA/m to 5.7 mA/m with an average of 2.2 mA/m. Although alternating field demagnetization was successful in isolating the characteristic remanent magnetization, most of the specimens were subjected to thermal demagnetization. Temperatures of about 200 °C were sufficient to remove a minor secondary overprint of probably viscous origin. The remanence which is thought to be a detrital remanent magnetization (DRM) was lost at temperatures of up to 680 °C indicating the presence of magnetic minerals with high curie temperatures like hematite (Fig. 6.1).

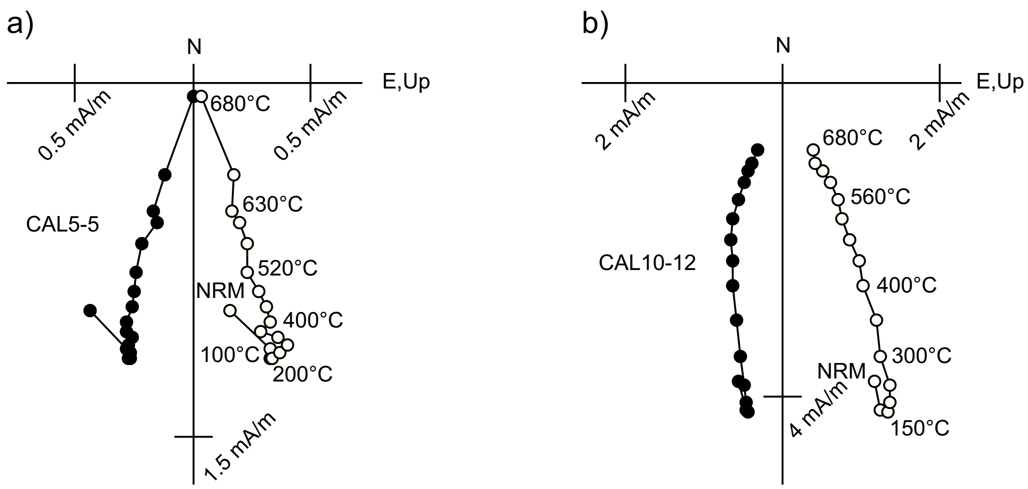

Figure 6.1: Orthogonal vector projections in stratigraphic coordinates of representative specimens of the La Calera Formation. Filled (open) symbols indicate projections onto the horizontal (vertical) plane.

Whereas the main part of the sampled beds shows reversed polarities, normal polarities can be found as well. Because of the presence of these reversals a possible remagnetization of the Calera Formation is very unlikely. Only the oldest of the sampled beds (CAL11) differs from the other sites regarding the ChRM direction (no rotation) and the rockmagnetic parameters (see chapter 7 for more details). In addition it shows a tendency to more greenish shades whereas the younger beds are characterized by a reddish color typical for this formation. This difference might stem from chemical alteration caused by fluids passing through the rock; the magnetization therefore is not assumed to be primary. Due to the reversed polarity of this site a present day field overprint can be excluded. Nevertheless, site CAL11 was excluded from further analysis. This is also true for data of sites CAL4 and CAL9 which show transitional behavior and site CAL2 which is characterized by very low inclination values. The calculation of the mean direction for the remaining seven sites (including six reversed and one normal polarity, fig. 6.2) results in a declination of 207.9° and an inclination of -19.7° with k = 77.2 and α_{95} = 6.9° in geographic coordinates. The Fisherian distribution gets enhanced after structural correction leading to a declination of 200.5° and an inclination of -19.6° with k = 353.1 and α_{95} = 3.2° in stratigraphic coordinates (Figure 6.3).

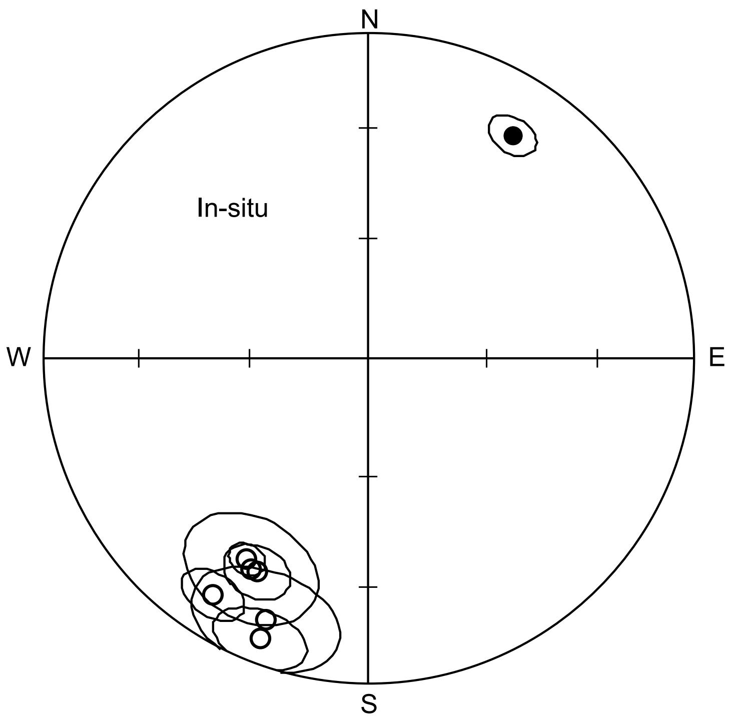

Figure 6.2: Stereographic projection of mean site directions from seven different beds of the La Calera Formation in geographic coordinates. Filled (open) symbols indicate projection of lower (upper) hemisphere.

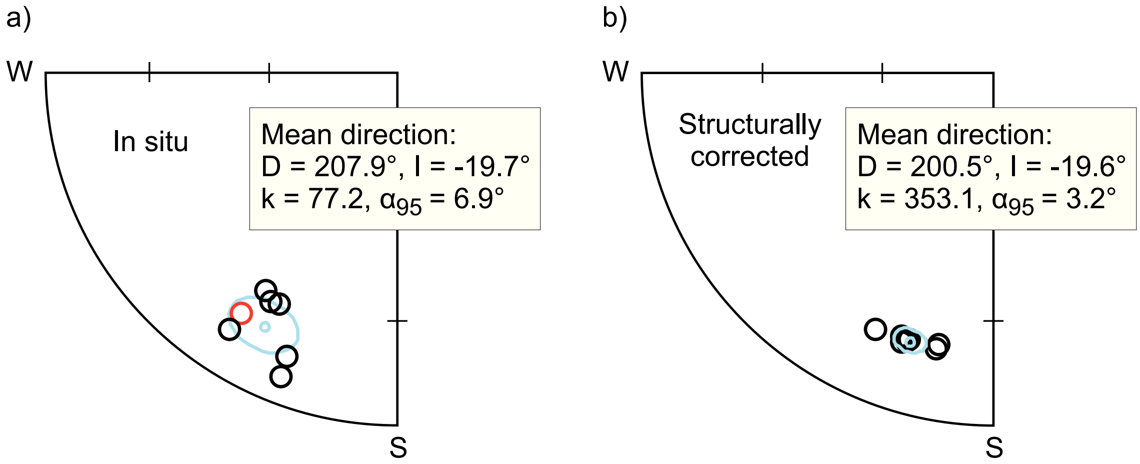

Figure 6.3: a) Same figure as 6.2 but site with normal magnetization has been transferred to reversed polarity (red circle). Mean direction in geographic coordinates is indicated by small blue circle with error ellipse. b) Calculation of mean direction in stratigraphic coordinates. Note the smaller error ellipse compared to a).

In order to determine the relative timing of magnetic remanence and tectonic deformation (Watson and Enkin, 1993) several relevant tests were developed. The so-called fold test introduced by Graham (1949) is able to distinguish between pre- and post-tilting remanence: if the magnetization of rocks occurs before/after tectonic deformation, the restoration to original bedding will cause movement of magnetization directions toward/away from parallelism, respectively. The first attempt to formulate a statistical test on the basis of Graham's (1949) theory was made by McElhinny (1964). He suggested to estimate the Fisher (1953) concentration parameter on the basis of mean paleomagnetic directions before and after bedding correction by submitting the ratio of the k-values to a significance test by Watson (1956). But as pointed out by McFadden and Jones (1981), the k-values of the mean direction before and after tectonic correction are not statistically independent, but linked through the known bedding direction, superseding the application of Watson's significance test (Watson and Enkin, 1993). Therefore, Watson and Enkin (1993) argue that significance tests are not suitable for the analysis of remanence directions before and after bedding correction, and that this problem should be formulated in terms of parameter estimation. The optimum concentration of remanence directions is given by estimating the degree of untilting, and as Watson and Enkin (1993) point out, confidence limits can be given by using parametric resampling techniques. Assuming that the highest concentration of remanence directions coincides with the timing of remanence acquisition, magnetization can be regarded as pre-tilting if the best concentration does not significantly differ from full tectonic correction (100% untilting). If, on the other hand, the in situ stage (0% untilting) is part of the confidence interval, the age of magnetization can be considered post-tilting. Results lying in between point to a more complicated magnetization acquisition like, for example, a syn-folding remanence (Watson and Enkin, 1993).

Applying the method of Watson and Enkin (1993) to the mean directions of sites of the La Calera formation leads to a best estimate of the degree of unfolding of about 95% at the time of magnetization (Fig. 6.4). This value is not significantly different from that of full tectonic correction (100% unfolding) indicating that the age of the remanence can be considered pre-tilting.

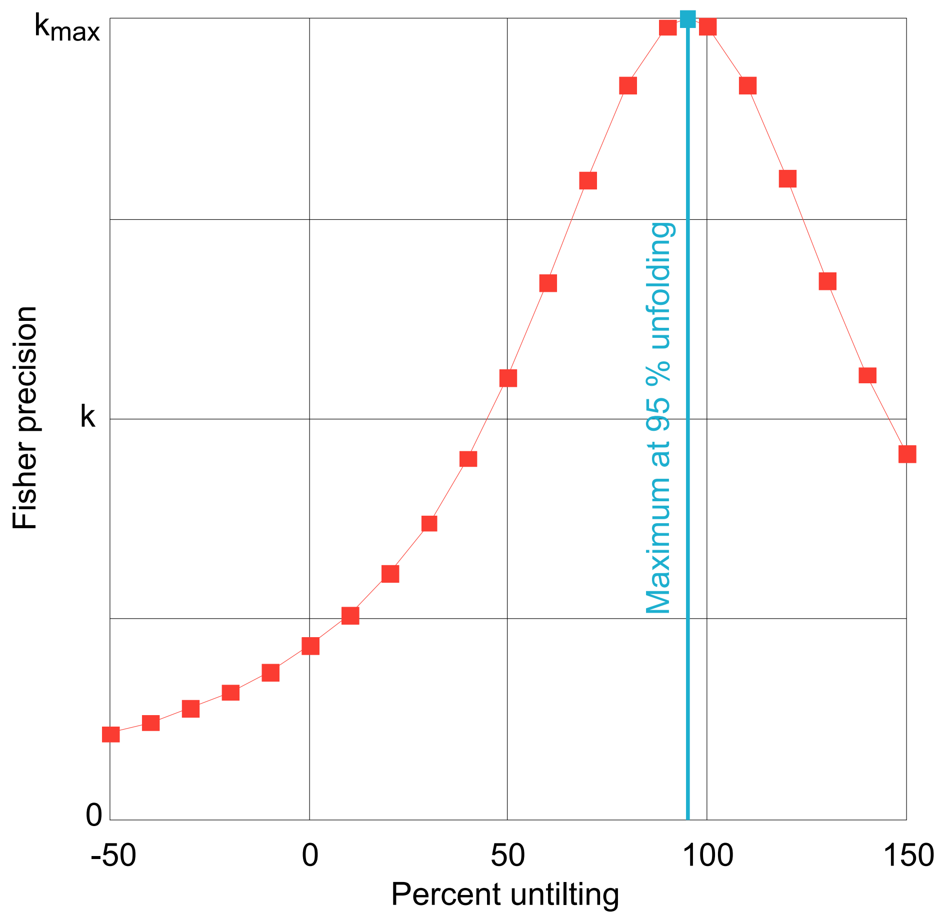

Figure 6.4: Application of fold-test on site mean directions of the La Calera formation following the method of Watson & Enkin (1993). Plot calculated using the program PMGSC (developed by R. Enkin and colleagues) shows Fisher's precision parameter k as a function of the degree of untilting. Note that the maximum value of k is reached at 95% unfolding indicating a positive fold-test.

Another approach regarding the timing of remanence acquisition in relation to tectonic tilting has been made by Enkin (2003). The so-called direction-correction (DC) tilt test resembles a combination of Watson and Enkin's optimal concentration test (Watson and Enkin, 1993; described above) - determining the degree of untilting - and McFadden's azimuth correlation test (McFadden, 1990) which verifies if the site mean directions are linked to their corresponding bedding corrections.

Applying Enkin's (2003) DC tilt test to the same data set mentioned above provides a DC slope of 91.11 ± 10.38% (cp. red line in fig. 6.5) almost reaching the optimal degree of untilting, with a value of 100% (black line in fig. 6.5). Hence, the DC test is positive indicating that the remanence of the La Calera Formation was acquired pre-folding.

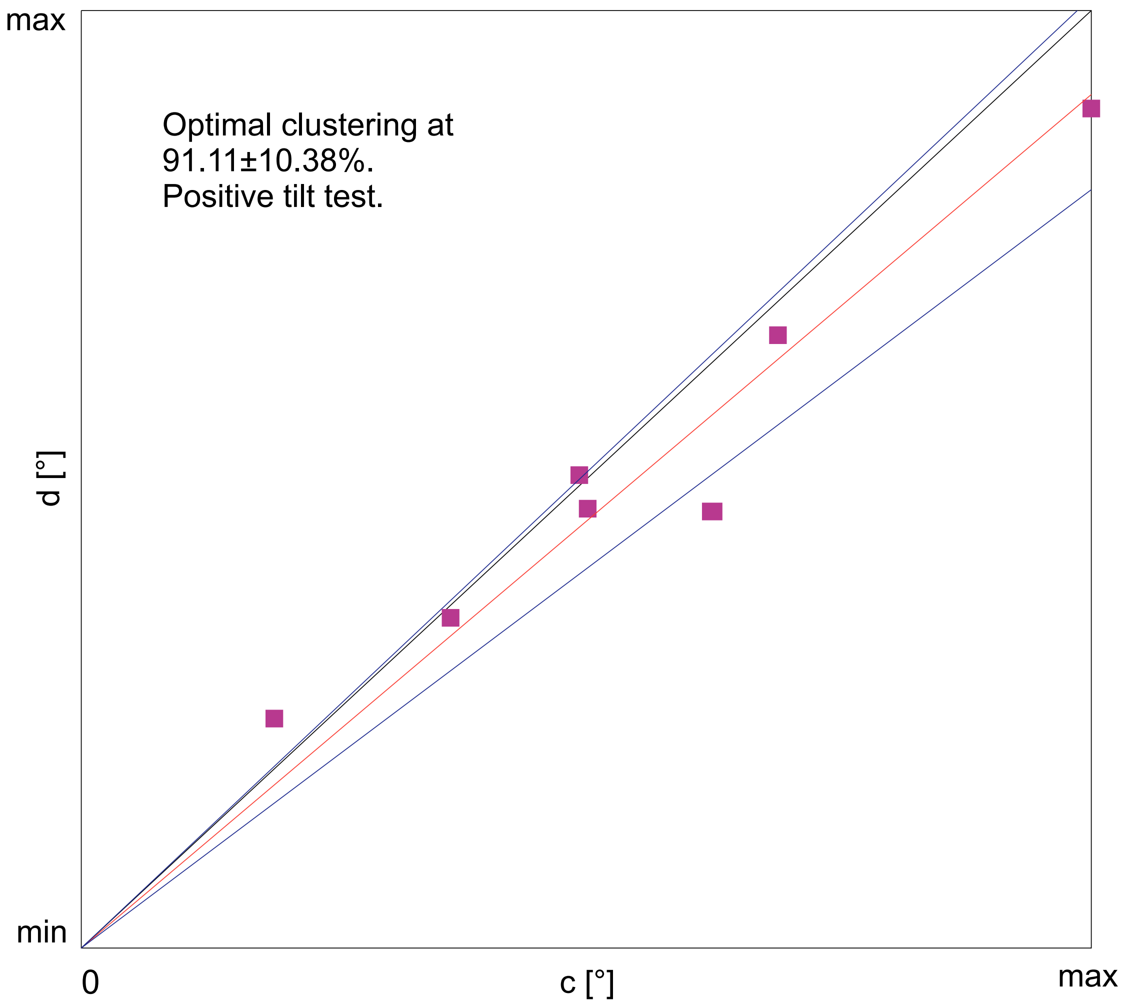

Figure 6.5: Plot of the direction-correction tilt test (Enkin, 2003) with an optimal clustering at 91.11±10.38% (red line) which is not significantly different from the optimal degree of untilting (100%; black line) and therefore indicative for a pre-tilting remanence. The direction-correction plot was created using the program PMGSC developed by R. Enkin and colleagues.

Both the fold test (Watson and Enkin, 1993) and the DC tilt test (Enkin, 2003) indicate a pre-folding remanence age of the La Calera Formation sediments strongly supporting the primary character of magnetization. As already mentioned above, the calculated mean direction shows a declination of 200.5° and an inclination of -19.6°; a k-value of 353.1 and an α_{95} of 3.2° are indicative for high quality paleomagnetic data. The formation is assumed to be of Middle to Late Miocene age; hence, the 10 Ma window has been used for calculation of the reference direction (Dec = 354.1°, Inc = 42.3°, resp. Dec = 174.1°, Inc = -42.3° for reversed polarity; table 1). Comparing this direction with the La Calera Formation's mean direction implies a net clockwise rotation of 26.4° ± 3.5°. The observed inclination value of -19.6° is relatively low compared to the expected value of -42.3° and might stem, at least in part, from inclination shallowing. Differences of 10° are not uncommon, and even a flattening of up to 17° has been observed (for example in paleomagnetic data gathered from the Point Loma Formation in Southern California; Tan and Kodama, 1998).

6.1.2 Trinidad Formation

The Trinidad Formation was sampled at three sites – two located about 12 kilometers south and one about 6 kilometers southeast of Los Barriles. The NRM of these samples lies between 0.056 and 1.39 mA/m with an average value of 0.237 mA/m - being one order of magnitude lower than that of the La Calera Formation samples. Alternating field demagnetization was the preferred choice for specimens of two sites (BUV3 and BUV5), whereas thermal demagnetization turned out to be more efficient regarding specimens of site BUV2 (Fig. 6.6).

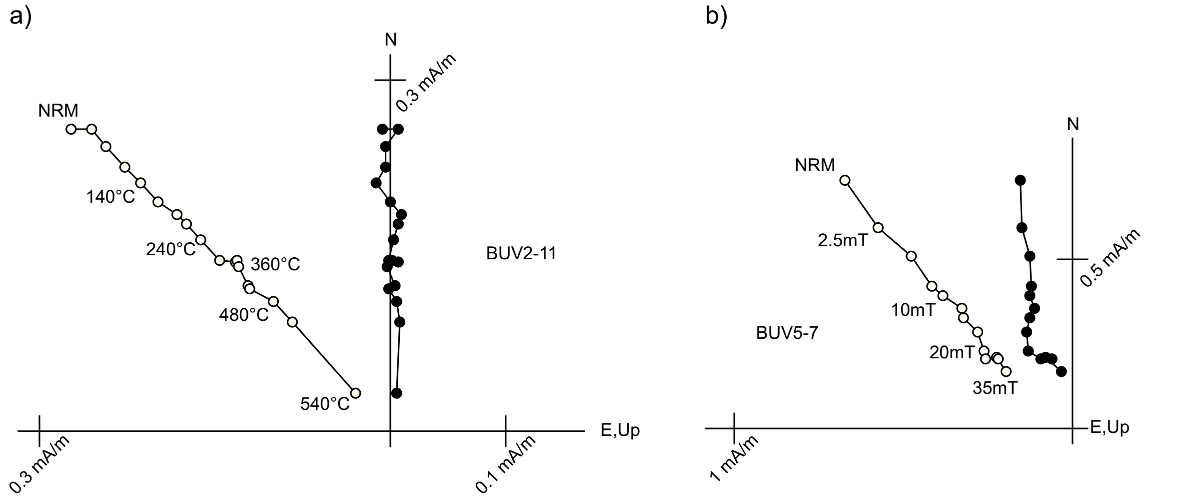

Figure 6.6: Orthogonal vector projections of representative specimens sampled from the Trinidad Formation showing a) thermal and b) alternating field demagnetization. Filled (open) symbols indicate projections onto the horizontal (vertical) plane.

The calculation of mean directions yields comparable but not identical directional data. The mean directions of two sites in immediate vicinity (BUV3 and BUV5) show similar declinations and inclinations which are unfortunately characterized by relatively large error values (BUV3: Dec = 344.2°, Inc = 50.3°, k = 21.4, α_{95} = 20.3°, N = 4; BUV5: Dec = 350.0°, Inc = 60.8°, k = 23.6, α_{95} = 19.3°, N = 4). Paleomagnetic data of the third site (BUV2) result in an observed characteristic remanent magnetization direction with a declination of 2.0° and an inclination of 39.3°, being more reliable regarding the statistical parameters (k = 98.8, α_{95} = 7.7°, N = 5). Assuming a Late Miocene to Early Pliocene age the reference direction for the Trinidad Formation was calculated on the basis of the 5 Ma window (Dec = 355.8°, Inc = 43.1°; cp. table 1). Depending on the site examined the comparison between the reference and the site mean direction implies a clockwise rotation of 6.2° ± 9.5° for site BUV2 and counter-clockwise rotations of 11.6° ± 29.7° and 5.8° ± 36.6° for sites BUV3 and BUV5, respectively. Due to the large errors, the calculated amounts of rotation for sites of the Trinidad Formation are not well defined.

6.1.3 Refugio Formation

Samples of the Refugio Formation were taken at two sites - one situated directly at highway MEX1 about three kilometers southeast of the village Santiago, the other located six kilometers southeast of Miraflores. The NRM of the Refugio Formation samples lies between 0.911 and 94.5 mA/m. Alternating field as well as thermal demagnetization leads to good results, with a minor overprint of probably viscous origin being removed at about 240°C or 10 mT, respectively (Fig. 6.7).

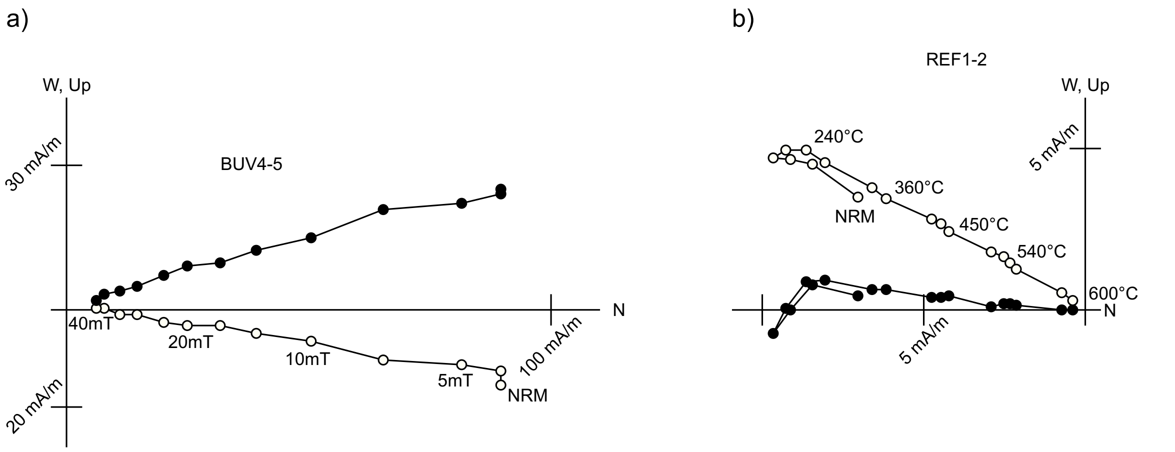

Figure 6.7: Demagnetization plots in stratigraphic coordinates of representative specimens from the Refugio Formation. Filled (open) symbols indicate projections onto the horizontal (vertical) plane.

The mean direction calculated for site BUV4 is characterized by normal polarity with a declination of 345.1° and an inclination of 22.6° (k = 28.1, α_{95} = 17.6°, N = 4), whereas the reversed magnetized site REF1 shows a declination of 185.2° and an inclination of -34.0° (k = 135.9, α_{95} = 6.6°, N = 5). The Refugio Formation is assumed to be deposited in Early Pliocene; for that reason the 5 Ma window was chosen for calculating the reference direction (Dec = 355.8°, Inc = 43.1° or Dec = 175.8°, Inc = -43.1° for reversed polarity, respectively; cp. table 1). The difference in declination – between observed and expected direction – suggests a counter-clockwise rotation of 10.7° ± 19.4° for site BUV4 and a clockwise rotation of 9.4° ± 7.8° for site REF1.

6.1.4 El Chorro Formation

The youngest continental deposit, the El Chorro Formation, was sampled at one site (BUV1) south of the village of Los Barriles. The samples yield NRM values ranging from 0.074 to 0.35 mA/m. As alternating field demagnetization did not lead to satisfying results, the specimens were subjected to thermal demagnetization; about 120°C were sufficient to remove a minor secondary overprint (Fig. 6.8). All samples exclusively showed normal polarity.

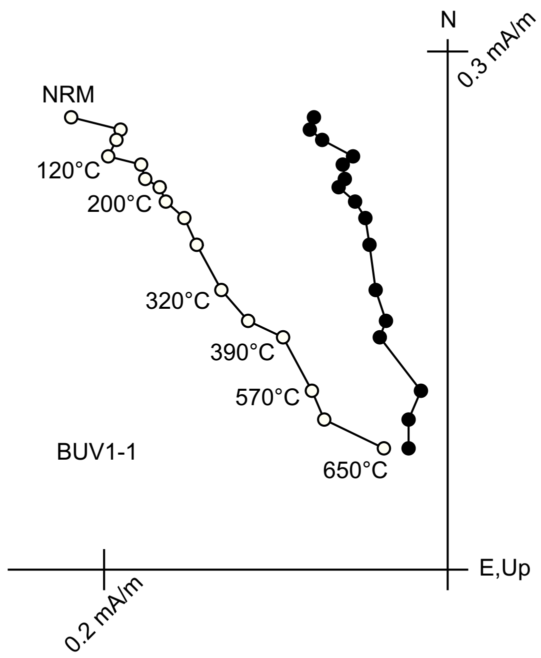

Figure 6.8: Demagnetization plot in stratigraphic coordinates of a representative specimen of the El Chorro Formation. Filled (open) symbols indicate projections onto the horizontal (vertical) plane.

Calculation of the site mean direction yields a declination of 346.1° and an inclination of 25.8° (with k = 57.8 and α_{95} = 16.4°, N = 4). A comparison of this direction to the Pleistocene reference direction (Dec = 356.4°, Inc = 43.4°; 0 Ma window, cp. table 1) implies a clockwise rotation of 10.3° ± 18.5°.

6.1.5 Igneous rocks

In the Sierra La Trinidad - about seven kilometers southwest of Cabo Pulmo - samples of a sequence of four volcanic flows (PUL4) with an average thickness of one meter were drilled. The natural remanent magnetization of the specimens from the different volcanic flows ranges from 4.04 to 10.6 mA/m. Thermal demagnetization led to good results showing exclusively reversed paleomagnetic directions (see example in fig. 6.9); probably preserved as a thermoremanent magnetization (TRM).

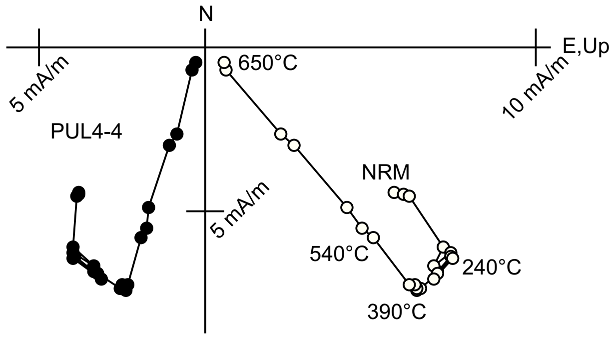

Figure 6.9: Demagnetization plot in stratigraphic coordinates of representative specimen from volcanic flows showing reversed polarity. Filled (open) symbols indicate projections onto the horizontal (vertical) plane.

The calculation of the mean direction based on the combined data of the different flows reduces the effects of paleosecular variation. The direction exhibits a declination of 195.2° and an inclination of -42.9°; a Fisher (1953) precision parameter of k = 417.3 and an α_{95} of 6.0° are indicative for high quality paleomagnetic data. Volcanics in the region of the San José del Cabo Basin and the Sierra La Trinidad were formed in Early to Middle Miocene. Therefore, the 20 Ma window was chosen for calculating the reference direction leading to a declination of 350.2° and an inclination of 40.7° (Dec = 170.2°, Inc = -40.7° for reversed polarity, cp. table 1). The comparison of the calculated mean direction of the volcanic flows (Dec = 195.2°, Inc = -42.9°) to the expected direction implies a clockwise rotation of 25.0° ± 7.6°.

Three different dacitic dykes (PUL5, 6, 7), oriented near-vertically with an roughly east-west directed contact to the surrounding rock, were sampled about 11 kilometers south-southwest of Cabo Pulmo. These dykes, sampled within a distance of a few hundred meters, are thought to represent remains of the same event of intrusion. All specimens were subjected to thermal demagnetization and showed exclusively normal polarities with a natural remanent magnetization ranging between 18.1 and 383.0 mA/m (Fig. 6.10).

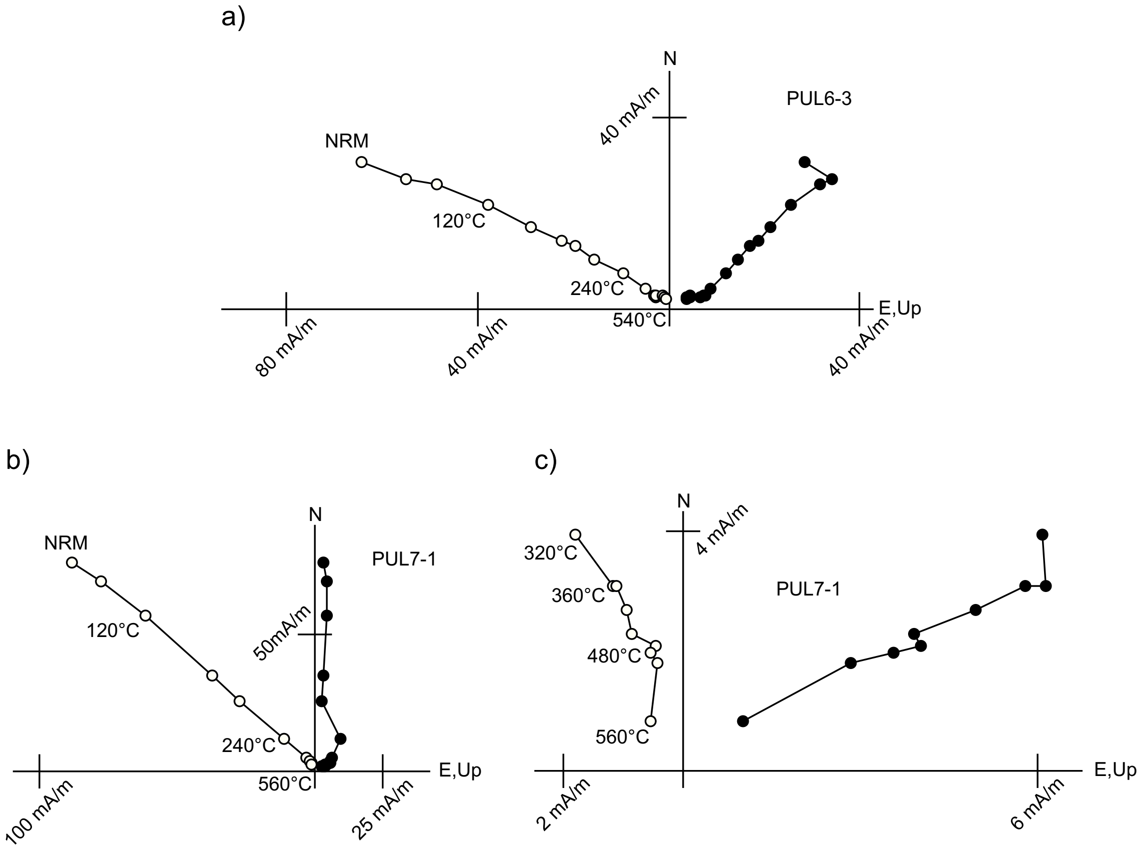

Figure 6.10: Demagnetization plots in stratigraphic coordinates of representative specimens from dykes located in the Sierra La Trinidad. a) After removal of small overprint at low temperatures in specimen PUL6-3 demagnetization vector heads directly toward the origin. b) Complete demagnetization path for specimen PUL7-1 and c) zoom into the last demagnetization steps. Filled (open) symbols indicate projections onto the horizontal (vertical) plane.

Similar paleomagnetic directions support the assumption that the formation of the different dykes took place in a narrow time interval. Therefore, paleomagnetic data of all dykes were averaged to obtain a single mean direction (Dec = 66.9°, Inc = 6.8°, k = 38.2, α_{95} = 6.5°, N = 14; fig. 6.11). This approach also yields the advantage of minimizing the effects of paleosecular variation. As these dykes have not been dated yet, it is assumed that they are of at least the same age as the volcanic rocks in the Sierra La Trinidad which are thought to be formed in Early to Middle Miocene. Hence, the corresponding reference direction was used (Dec = 350.2°; Inc = 40.7°; cp. Table 1) suggesting a clockwise rotation of 76.7° ± 6.7°.

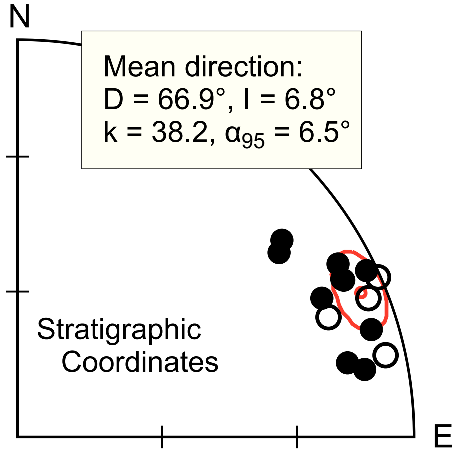

Figure 6.11: Stereographic projection in stratigraphic coordinates showing the magnetization direction of each specimen from three different dykes and the calculated mean direction with error ellipse (in red). Filled (open) symbols indicate projection onto the lower (upper) hemisphere.

6.1.6 Summary

As already mentioned above, paleomagnetic data of most of the San José del Cabo Basin sediments are characterized by large error values (cp. error ellipses in figure 6.12) with error cones enclosing the reference direction (Fig. 6.13). The mean direction of all sampled formations (except the La Calera Formation) was calculated revealing a declination of 352.2° and an inclination of 39.1° (k = 24.8; α_{95} = 13.7°; cp. fig. 6.12). This result is consistent with the expected directions calculated for the 10 Ma (Dec = 354.1°, Inc = 42.3°) and the 5 Ma (Dec = 355.8°, Inc = 43.1°) window, respectively, and might be an indication that the investigated formations did not experience any kind of vertical-axis rotation. This assumption, however, does not seem to be valid for the La Calera Formation and the adjacent Sierra La Trinidad. Samples of volcanic flows (PUL4) located in the latter, for instance, show well defined paleomagnetic directions implying a clockwise rotation of 25.0° ± 7.6°. Additionally, the analysis of three dykes (PUL5, 6, 7) sampled farther to the east led to reliable paleomagnetic data suggesting a clockwise rotation of 76.7° ± 6.7°. The La Calera Formation situated in the eastern part of the San José del Cabo Basin provided high quality paleomagnetic data as well, documented by a k-value of 353.1 and an α_{95} of 3.2°. A positive fold test (Watson and Enkin, 1993) and a positive DC tilt test (Enkin, 2003) suggest that the magnetization of the La Calera Formation sediments has been acquired prior to any kind of folding, supporting the primary character of the remanent magnetization. The analysis regarding vertical-axis rotations implicates a net clockwise rotation of 26.4° ± 3.5°.

In summary, the paleomagnetic study in this area shows that the Sierra La Trinidad and the eastern part of the San José del Cabo Basin experienced significant clockwise rotations of different degree, whereas the rest of the San José del Cabo Basin was affected by only insignificant rotation or no rotation at all (Fig. 6.12 & 6.13).

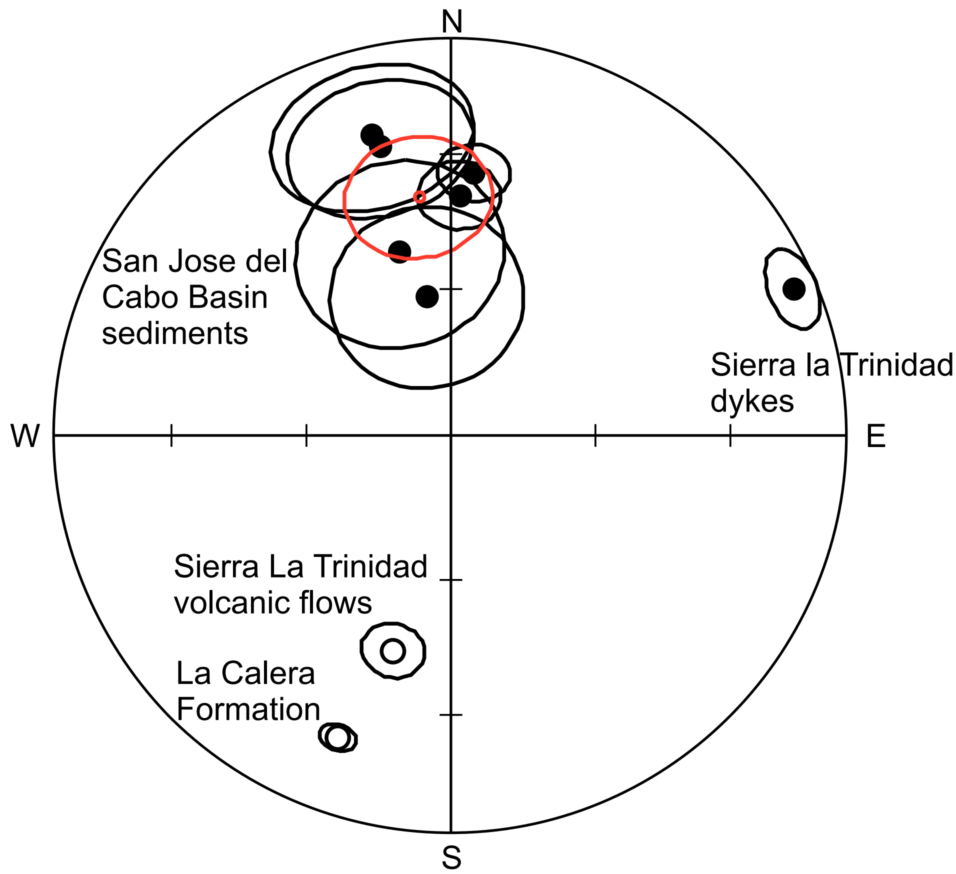

Figure 6.12: Stereographic projection summarizing all mean directions calculated for sites in the San José del Cabo Basin and the Sierra La Trinidad. Small circle and error ellipse in red indicate mean direction of the San José del Cabo Basin sediments (Dec: 352.2°; Inc: 39.1°, k: 24.8, α_{95}: 13.7°). Filled (open) symbols indicate projection onto the lower (upper) hemisphere.

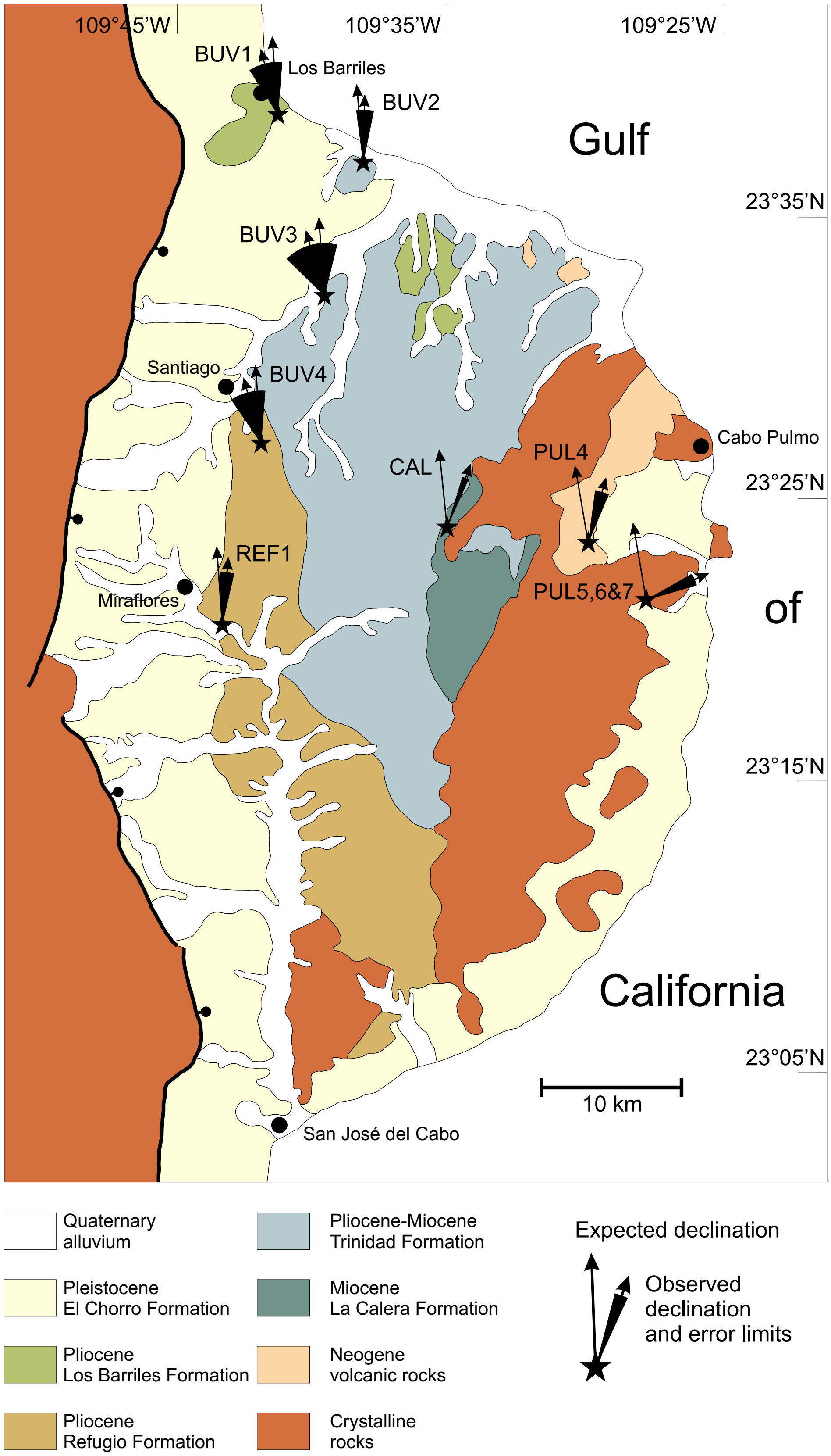

Figure 6.13: Summary of vertical-axis rotations in the San José del Cabo Basin and the Sierra La Trinidad showing the calculated amounts of rotation with error limits for each site. The western part of the study area is characterized by small amounts of rotations with partially large errors limits whereas the eastern part includes sites with large and well-defined rotations. Figure after Martínez-Gutiérrez and Sethi (1997) adopted from Martínez-Gutiérrez (1994) and modified after McTeague (2006).

6.2 Bay of La Paz area

6.2.1 La Paz area

In the direct vicinity of the city of La Paz samples of three sites were collected being part of the lower Comondú Group. Two of these sites are located at the eastern city limit and composed of rhyolitic ash-flow tuffs (LAP1, LAP 3). These tuffs were dated by Hausback (1984, page 229; samples number 45 and 238 with ages of 20.0 ± 0.4 Ma and 23.2 ± 1.6 Ma, respectively). The third site (LAP2) situated at the southern periphery of La Paz consists of rhyodacite lava flows and can also be correlated with a dated sample of Hausback (1984, page 229; sample number 3 with an age of 19.1 ± 1.2 Ma). Furthermore, about 8 kilometers northeast of La Paz samples of a tuffaceous sandstone were taken at a roadside outcrop (LAP4), and two dykes within a distance of 200 meters were sampled 15 kilometers north of La Paz (LAP6, LAP7). As the specimens responded very well to thermal demagnetization, this technique was used without exception. The natural remanent magnetization intensities of the rhyolitic ash-flow tuffs (LAP1, LAP3) range from 104 to 512 mA/m; specimens of the rhyodacite lava flows (LAP2) show similar intensities ranging from 162 to 302 mA/m. Demagnetization diagrams of specimens from these sites are characterized by very stable demagnetization paths decaying linearly toward the origin and reveal only a single component of magnetization leading to well defined characteristic remanent directions (Fig. 6.14). The calculated mean directions for sites LAP1 and LAP3 are of reversed polarity with a declination of 176.3° and an inclination of -24.4° ($k = 304.3$, $\alpha_{95} = 3.5°$, $N = 7$) and a declination of 167.7° and an inclination of -28.8° ($k = 282.6°$, $\alpha_{95} = 3.3°$, $N = 8$), respectively. Specimens of site LAP2 are characterized by normal polarity with a mean declination of 347.6° and a mean inclination of 16.0° ($k = 216.1$, $\alpha_{95} = 4.6°$, $N = 6$). The statistical parameters k and α_{95} show that the calculated mean directions are well defined and very reliable.

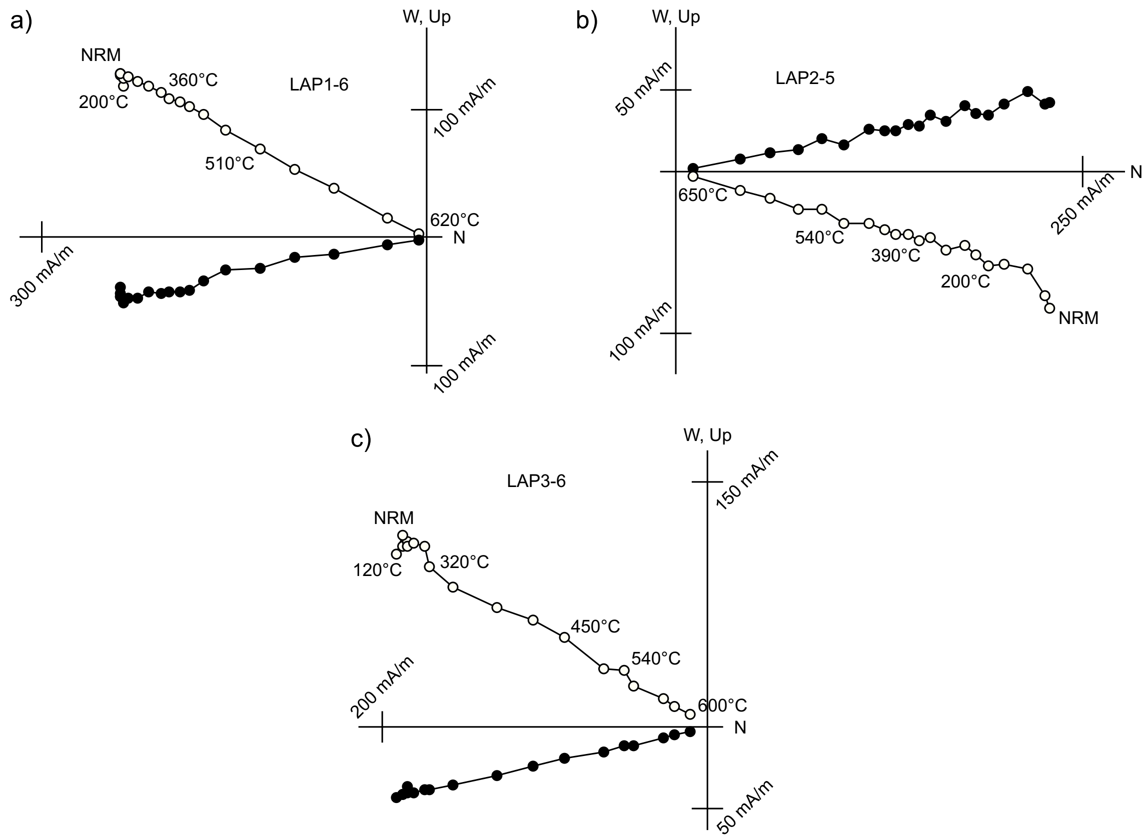

Figure 6.14: Demagnetization plots in stratigraphic coordinates of representative specimens from sites in the direct vicinity of the city of La Paz. Filled (open) symbols indicate projections onto the horizontal (vertical) plane.

Tuffaceous sandstone specimens of site LAP4 reveal NRMs between 178 and 417 mA/m. Demagnetization plots (Fig. 6.15) are not as stable as those of sites LAP1 to LAP3 but, nevertheless, it was possible to interpret the results yielding an acceptable mean direction (Dec = 46.9°, Inc = 17.4°, k = 67.7, α_{95} = 15.1°, N = 4). Two dykes (LAP6 and LAP7) sampled north of La Paz display NRM values between 75 and 1888 mA/m. After the removal of an overprint at temperatures below approximately 360°C, the decay of magnetization follows a linear trend toward the origin (Fig. 6.16). The direction of this overprint is similar to the direction of the present-day field as indicated by data of site LAP6 (Fig. 6.16a) - in contrast to data of site LAP7 which, however, show similar demagnetization curves (Fig. 6.16b). The mean direction calculated for the specimens of the dykes significantly differs from those of other sites near La Paz. With a declination of 291.1° (Inc = -61.3°, k = 113.0, α_{95} = 5.2°, N = 8; Figure 6.17) the dykes seem to be rotated clockwise to a great extent.

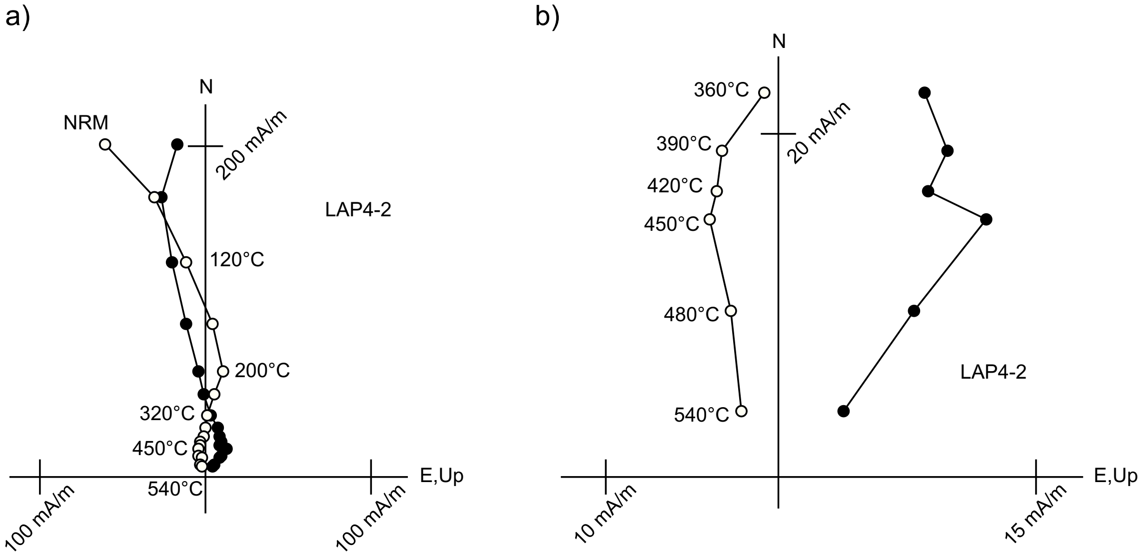

Figure 6.15: Representative example of thermal demagnetization plot in stratigraphic coordinates showing a) complete demagnetization procedure and b) zoom into last demagnetization steps of a tuffaceous sandstone specimen from site LAP4. Filled (open) symbols indicate projections onto the horizontal (vertical) plane.

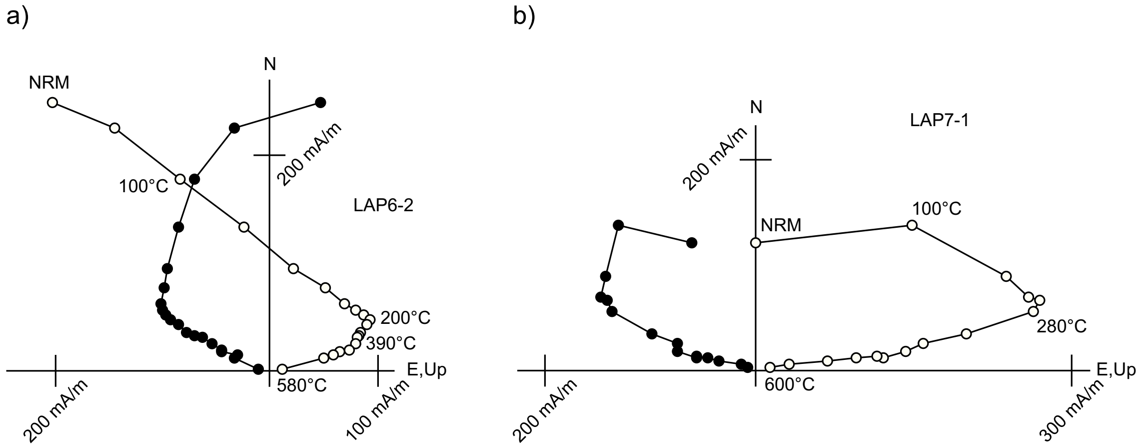

Figure 6.16: Demagnetization plots in stratigraphic coordinates of representative specimens from two dykes situated northeast of the city of La Paz. Note the present day field overprint in a). Filled (open) symbols indicate projections onto the horizontal (vertical) plane.

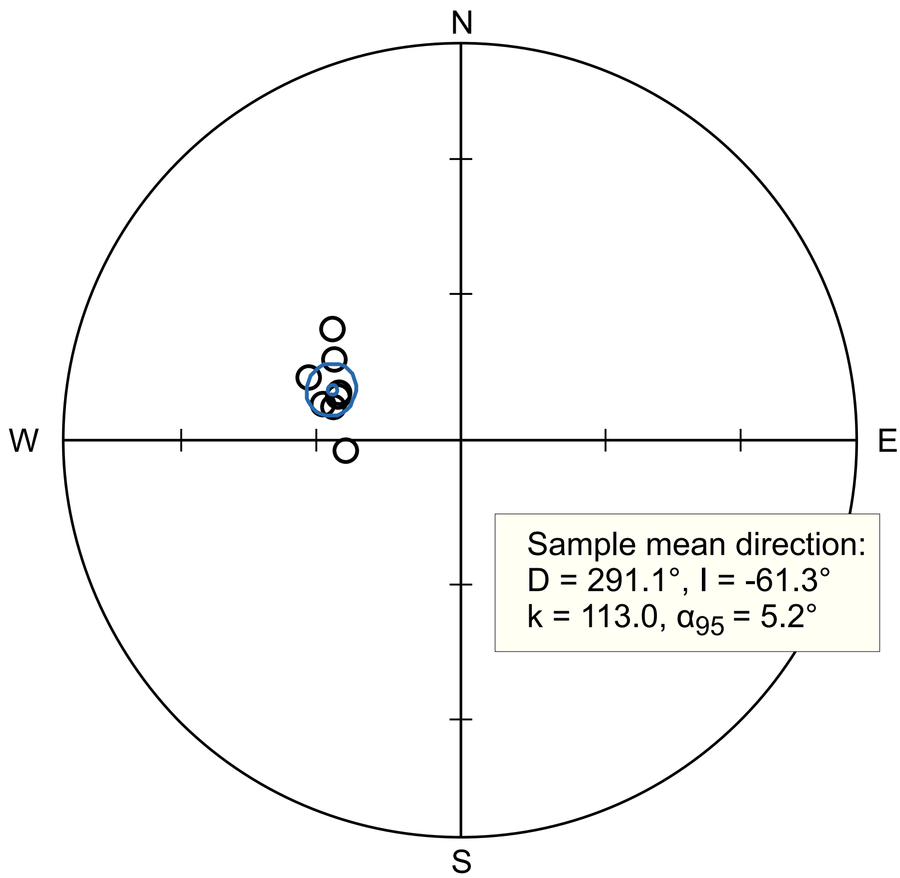

Figure 6.17: Stereographic projection of specimen magnetization directions in stratigraphic coordinates gathered from dykes situated northeast of La Paz (calculated mean direction with error ellipse in blue). Open symbols indicate projection onto the upper hemisphere.

6.2.2 Summary of La Paz area data

Paleomagnetic results of sites in the direct vicinity of La Paz are summarized in table 2 and figure 6.18. Table 2 also includes ages determined by Hausback (1984) which can be correlated with sites LAP1 to LAP3 of this study.

Table 2: Site mean paleomagnetic directions for sites in the vicinity of La Paz

Site	Dec	Inc	N	k	α_{95}	Age*
LAP1	176.3°	-24.4°	7	304.3	3.5°	20.0
LAP2	347.7°	16.0°	6	216.1	4.6°	19.1
LAP3	167.7°	-28.8°	8	282.6	3.3°	23.2
LAP4	46.9°	17.4°	3	67.7	15.1°	
LAP6&7 (Dykes)	291.1°	-61.3°	8	113.0	5.2°	

Dec, Inc: site mean declination and inclination; N: number of specimens; k: precision parameter (Fisher, 1953); α_{95}: 95% cone of confidence; *Age: K-Ar age (in Ma) from sampled unit (Hausback, 1984).

The resulting mean directions of sites LAP1, LAP2 and LAP3 are consistent with paleomagnetic data of Hagstrum et al. (1987) obtained from sites nearby. As the sampled rock formations can be correlated with a K-Ar radiometrically determined age between about 19 and 23 Ma (Hausback, 1984; table 2), the 20 Ma window was used for calculating the reference direction (Dec = 350.2°; Inc = 40.7°; respectively Dec = 170.2°; Inc = -40.7° for reversed polarity; cp. table 1). The comparison of the expected and observed declinations (cp. table 2) indicates a clockwise rotation of 6.1° ± 3.8° for site LAP1 and counter-clockwise rotations of 2.5° ± 4.8° and 2.5° ± 3.7° for sites LAP2 and LAP3, respectively. Site LAP4 – located northeast of La Paz and composed of a tuffaceous sandstone - yields a mean direction with a declination of 46.9°. This implies 56.7° ± 15.9° of clockwise rotation compared to a reference direction calculated for stable North America (20 Ma window; Dec = 350.2°, Inc = 40.7°; cp. table 1). The amount of rotation is significant although the range of error resulting from the more dispersed ChRMs is larger than for other sites in the vicinity of La Paz, yet reliable.

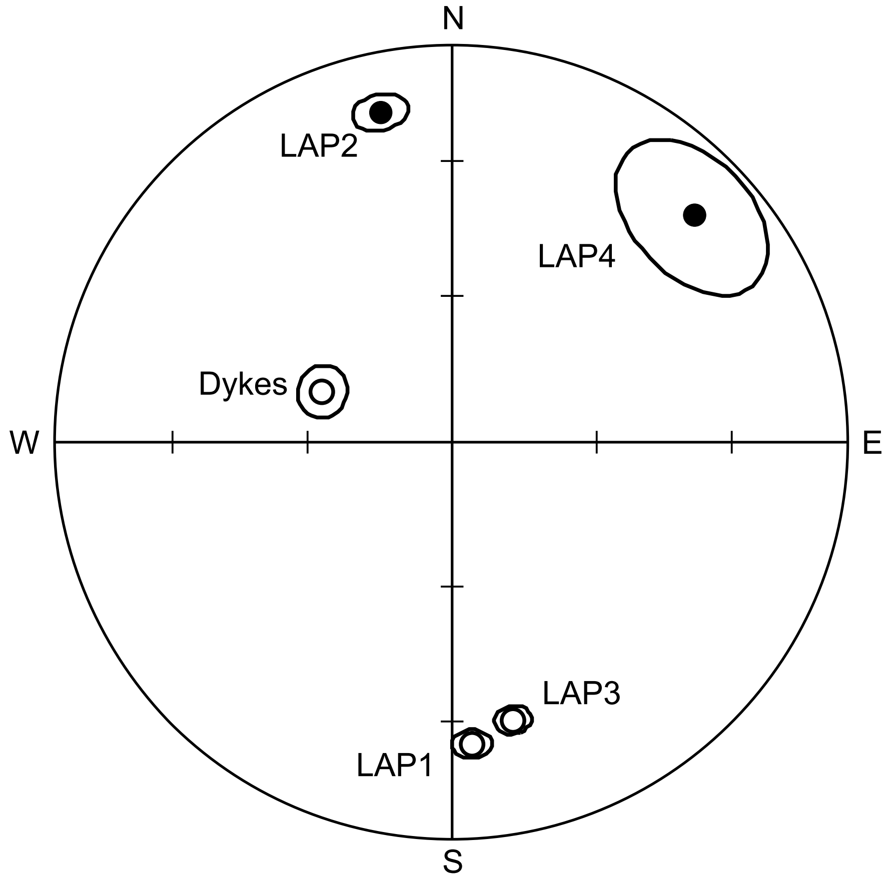

Figure 6.18: Stereographic plot summarizing the mean directions calculated for sites in the region of La Paz. Filled (open) symbols indicate projection onto the lower (upper) hemisphere.

As already mentioned above, the mean direction calculated for the dykes north of La Paz (LAP6 and LAP7) yields a declination (Dec = 291.1°) significantly different from the other sites near La Paz (table 2). With respect to the expected direction (Dec = 350.2°, Inc = 40.7°; Dec = 170.2°, Inc = - 40.7° for reversed polarity, respectively; cp. table 1) the area encompassing the dykes seems to be affected by a relatively large amount of clockwise rotation (120.1° ± 9.3°).

Figure 6.19 summarizes the rotations calculated for the region around La Paz with respect to the sample locations. The south-eastern part of the area drawn in figure 6.19 does not seem to be affected by major vertical-axis rotations. Paleomagnetic data of sites LAP1, LAP2 and LAP3 suggest only insignificant discordances from the expected direction. Farther to the north, however, calculated declinations of sites LAP4 and LAP6&7 indicate large clockwise rotations.

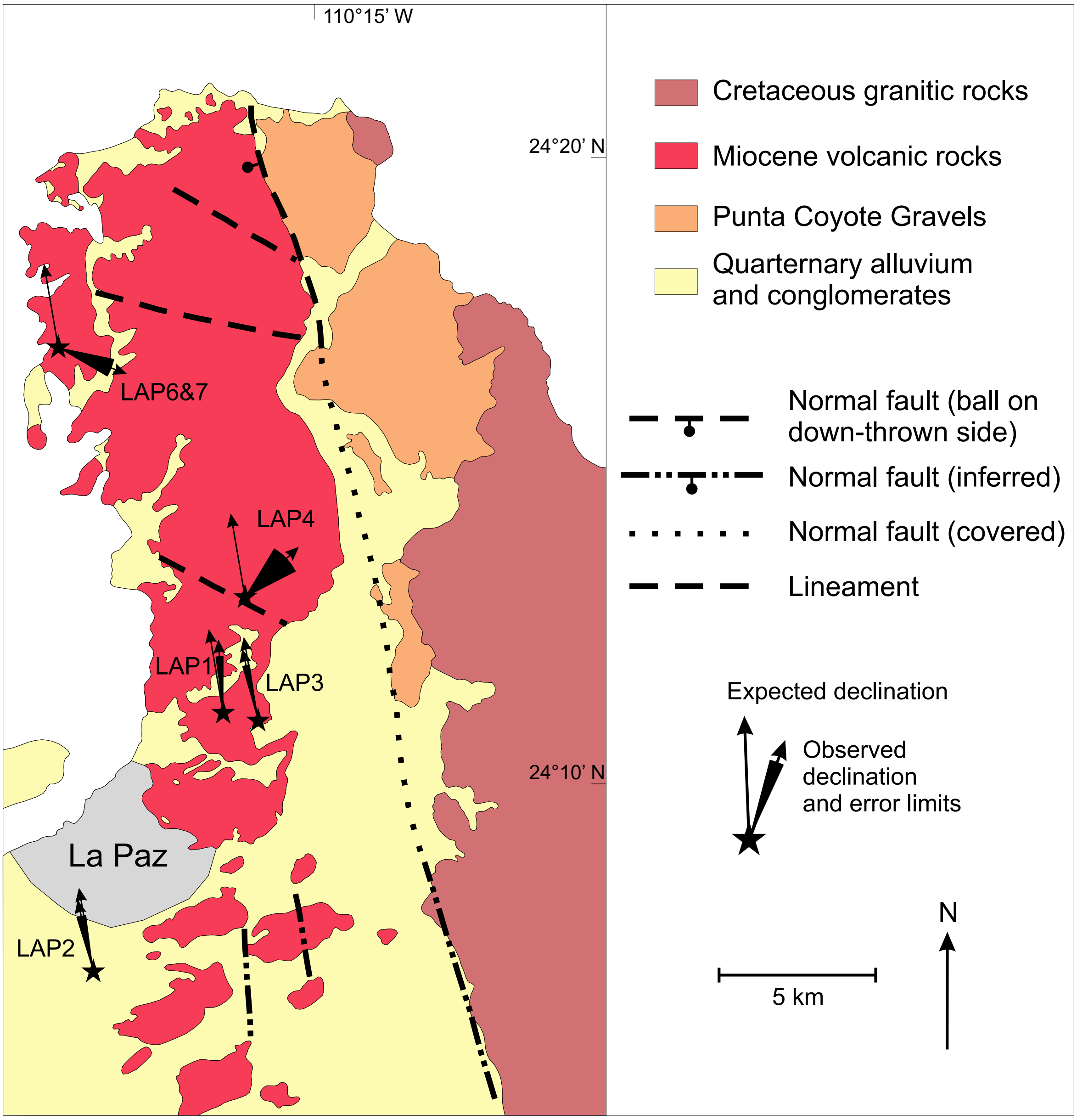

Figure 6.19: Geological and tectonic map of the area near the city of La Paz including observed declinations for paleomagnetic sites with respect to the expected direction. The region in the direct vicinity of La Paz is characterized by only minor to insignificant rotations whereas data of sites farther to the north argue for significant clockwise rotations. Figure modified from Aranda-Gómez and Perez-Venzor (1988).

6.2.3 San Juan de la Costa

Along the coastline south of San Juan de la Costa a total of 11 sites was sampled mainly at roadside outcrops covering a distance of 10 kilometers. Whereas the majority of these sites is composed of rhyolitic ash-flow tuffs (SJC2, SJC4, SJC6 - SJC11) samples of ignimbrites (SJC1, SJC3) and a volcanic lava flow (SJC5) were collected as well. According to Hausback (1984) and Hagstrum et al. (1987) the estimated age of the sampled rocks ranges between approximately 20 and 23 Ma. Specimens of the sites south of San Juan de la Costa responded very well to thermal demagnetization. Therefore, this technique was used exclusively with the exception of a few sister-specimens which were subjected to alternating field demagnetization showing a comparable demagnetization behavior. The NRM of the sampled ignimbrites (SJC1, SJC3) ranges from 113 to 1120 mA/m. Although demagnetization experiments led to reliable results, these sites were excluded from further interpretation. The calculated site mean direction of SJC1 yields a southward-directed declination and a downward-directed inclination (Dec = 193.9°, Inc = 26.1°, k = 69.0, α_{95} = 8.1°, N = 6; Fig. 6.22). The declination of site SJC3 differs significantly from adjacent sites (Dec = 47.7°, Inc = 16.5°, k = 180.2, α_{95} = 3.8°, N = 9; Fig. 6.22). An explanation for the anomalous directions can possibly be provided on the basis of the rapid cooling of ignimbrites after formation. The remanent magnetization preserved in the rocks represents only a "snapshot" of the ancient magnetic field. For that reason variations of the earth's magnetic field like secular variation or excursions are suspected to be responsible for the divergent site mean directions of SJC1 and SJC3. The same is accurate for the sampled volcanic flow (SJC5; NRM: 277 – 3270 mA/m): even though the directions of individual specimens are dispersed they show a pattern which might be interpreted as a result of an excursion or even the reversal of the earth's magnetic field (Fig. 6.20). Consequently this site was excluded from further analysis as well.

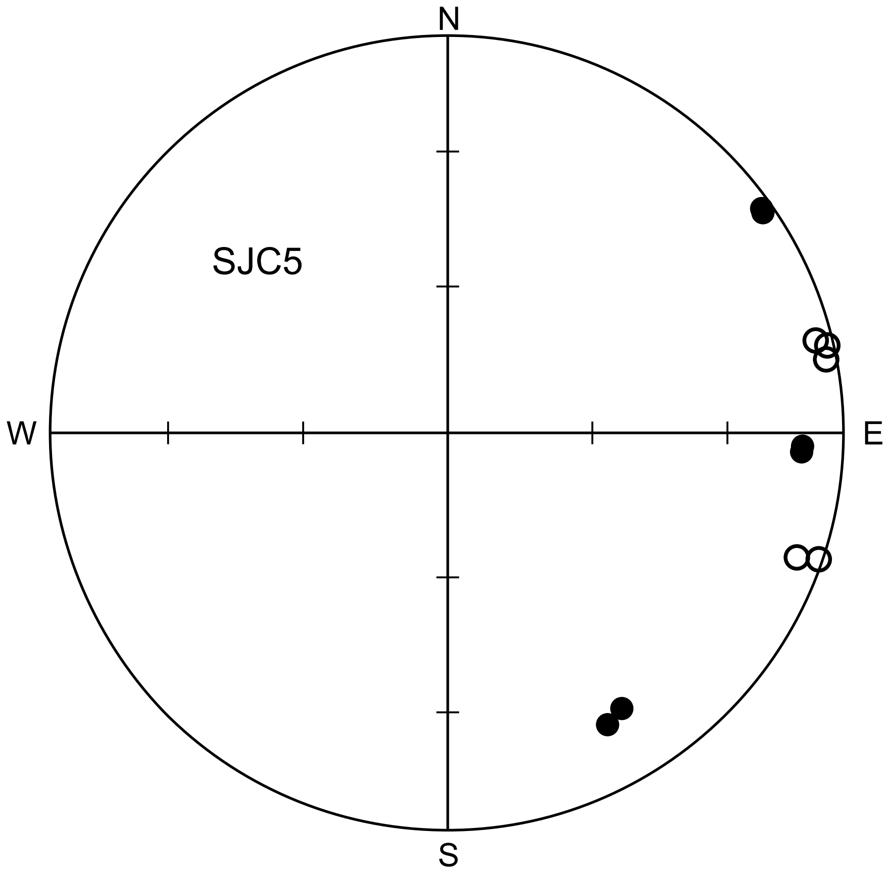

Figure 6.20: Paleomagnetic directions of specimens from a volcanic flow south of San Juan de la Costa. Unstable directions might be due to cooling during a reversal or excursion of the magnetic field. Filled (open) symbols indicate projection onto the lower (upper) hemisphere.

The rhyolitic ash-flow tuffs (SJC2, SJC4, SJC6 to SJC11) exhibit NRM values ranging between 5.54 and 416 mA/m. Two of these sites were also excluded from further interpretation: site SJC2 reveals a mean direction with a southward-directed declination and a downward-directed inclination as SJC1 (Dec = 165.4°, Inc = 10.1°, k = 136.4, α_{95} = 5.2°, N = 7; fig. 6.22), which can in this case be attributed to a possible orientation error. The anomalous direction of site SJC11 (Dec = 282.0°, Inc = 47.5°, k = 63.6, α_{95} = 5.8°, N = 11; fig. 6.22), on the other hand, might express local deformation due to the site's position in the direct vicinity of the El Carrizal fault. The specimens of the remaining sites (SJC4, SJC6 to SJC10) show well defined demagnetization behavior (Fig. 6.21) and mean directions with northward-trending declinations and downward-directed inclinations (cp. table 3 and fig.6.22).

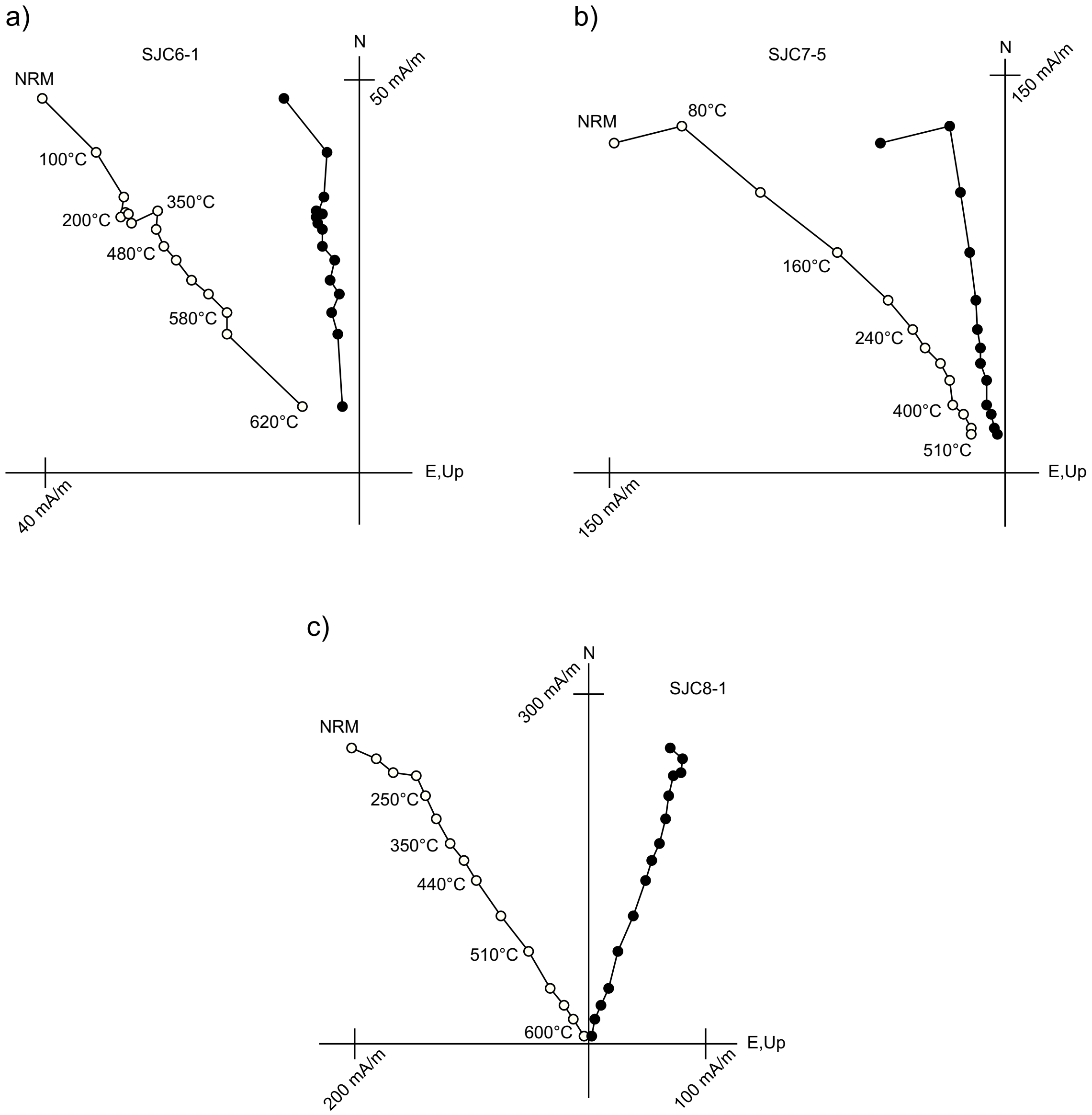

Figure 6.21: Representative thermal demagnetization plots of specimens from sites south of San Juan de la Costa in stratigraphic coordinates. Open (closed) symbols indicate projection onto the vertical (horizontal) plane.

6.2.4 Summary of San Juan de la Costa data

The paleomagnetic results of sites situated south of San Juan de la Costa are summarized in table 3 and figure 6.22. Table 3 also includes age determinations by Hausback (1984) which can be correlated with sites SJC7, SJC8 and SJC10 of this study.

Table 3: Site mean paleomagnetic directions of sites south of San Juan de la Costa

Site	Dec	Inc	N	k	α_{95}	Age*
SJC1	193.9°	26.1°	6	69.0	8.1°	
SJC2	165.4°	10.1°	7	136.4	5.2°	
SJC3	47.7°	16.5°	9	180.2	3.8°	
SJC4	347.1°	50.2°	5	82.0	8.5°	
SJC5	n.a.	n.a.	n.a.	n.a.	n.a.	
SJC6	345.3°	52.0°	8	71.8	6.6°	
SJC7	353.5°	44.9°	11	75.1	5.3°	~22
SJC8	12.8°	25.2°	5	127.4	6.8°	~22
SJC9	334.3°	18.1°	7	258.7	3.8°	
SJC10	358.4°	25.6°	7	65.7	7.5°	~22
SJC11	282.0°	47.5°	11	63.6	5.8°	

Dec, Inc: site mean declination and inclination; N: number of specimens; k: precision parameter (Fisher, 1953); α_{95}: 95% cone of confidence; *Age: estimated by petrologic and geomorphic correlation with dated units or on the basis of dated over- or underlying layers (Hausback, 1984).

As already mentioned, only sites SJC4 and SJC6 to SJC10 provide useful paleomagnetic results for further interpretation. Data of these sites are characterized by northward-directed declinations and downward-directed inclinations (cp. table 3 and fig. 6.22). Therefore, these directions were used to calculate a mean direction for the area south of San Juan de la Costa with a declination of 352.3° and an inclination of 36.7° (k = 19.4, α_{95} = 15.6°). Although the statistical parameters imply larger uncertainties as a consequence of the relatively wide dispersion of site mean directions, the comparison of this study's mean direction with the mean direction calculated by Hausback (1988) for sites in the San Juan de la Costa area shows good consistency. With a declination of 354.2° and an inclination of 35.8° (k = 18, α_{95} = 9.9°) Hausback's (1988) direction is not significantly different. The reference direction calculated for the 20 Ma window (Dec = 350.2°, Inc = 40.7°; cp.

Table 1) is consistent with data of this study as well and implies a clockwise rotation of 2.1° ± 18.6°. The insignificance of this rotation suggests that the coast south of San Juan de la Costa was not affected by rotations at all.

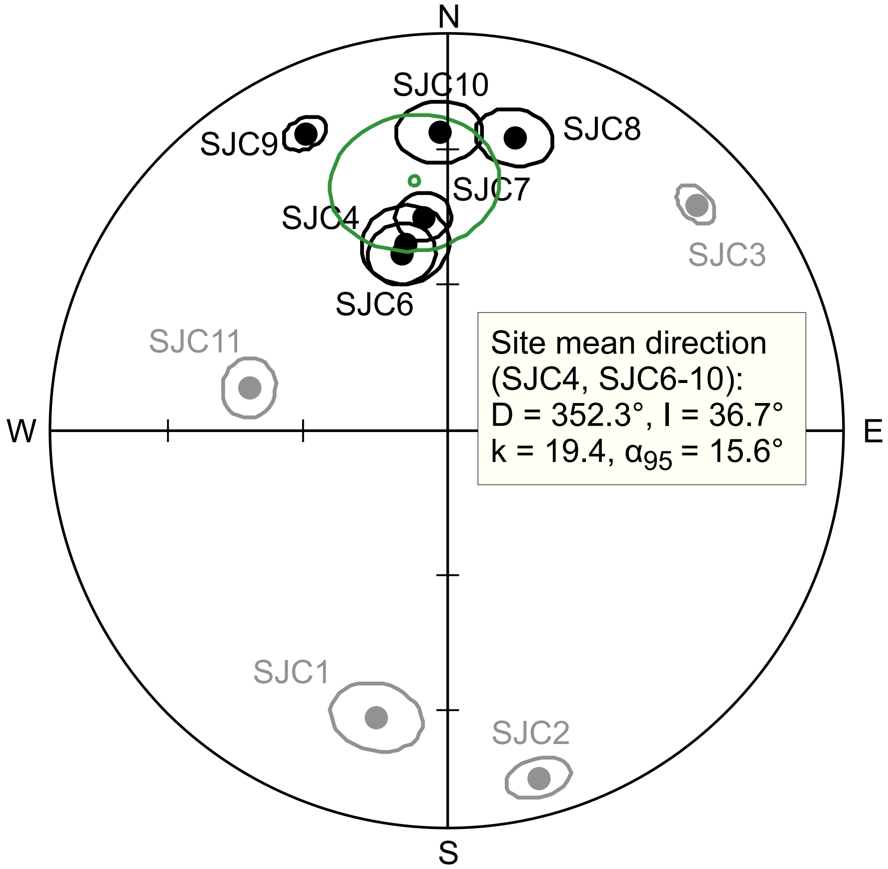

Figure 6.22: Site mean directions with 95% confidence limits for sites south of San Juan de la Costa. Small green circle: mean direction calculated for sites SJC4 and SJC6 to SJC10 with 95% confidence limit (green ellipse). Filled (open) symbols indicate projection onto the lower (upper) hemisphere. Site mean directions in grey shade were excluded from the calculation of the mean direction.

6.3 San José and San Francisco Island

6.3.1 San José Island

At the south-eastern end of San José Island several units of the Upper Oligocene Salto Formation were sampled covering a distance of 400 meters along a coastal cliff. The steeply dipping units mainly include red sandstones (SJI1, SJI4 – SJI7, SJI9), but samples of rhyolitic tuffs (SJI3, SJI8) and of a dyke (SJI2) intruded into the Salto Formation were also collected. As the specimens of the red sandstones (with very low NRM values ranging from 0.3 to 6.7 mA/m) unfortunately showed unstable demagnetization behavior, it was not possible to obtain characteristic remanent magnetization directions – with one exception: demagnetization data of specimens from site SJI5 were suitable for calculating a site mean direction (Dec = 228.5°, Inc = -26.3°, k = 344.3, α_{95} = 13.5°; Fig. 6.23b).

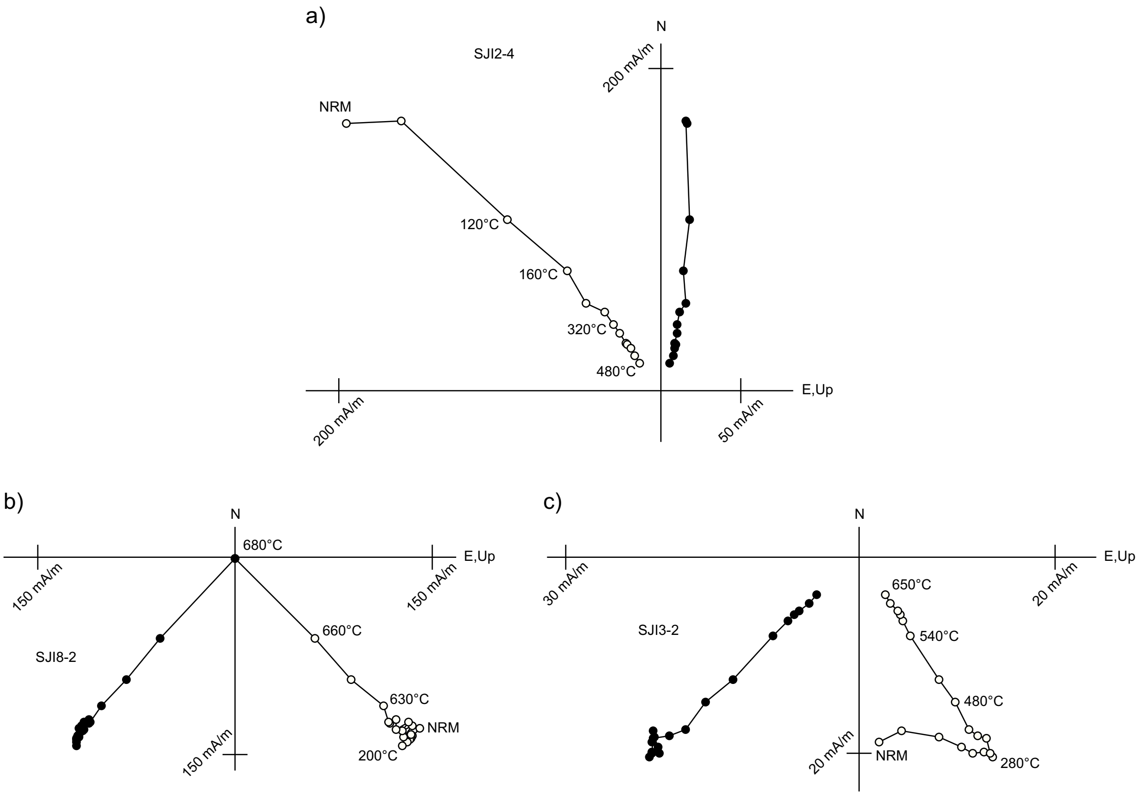

Figure 6.23: Representative thermal demagnetization diagrams of specimens from a) a dyke, b) a red sandstone and c) a rhyolitic tuff sampled at the south-eastern part of San José Island.

Natural remanent magnetization intensities of the rhyolitic tuff specimens - ranging between 27.2 and 242 mA/m - are up to three magnitudes higher than those of the red sandstones. This difference is also expressed in a much more stable demagnetization behavior (Fig. 6.23c) yielding reliable and consistent site mean directions (SJI3: Dec = 224.0°, Inc = -20.9°, k = 290.0, α_{95} = 4.5°, N = 5; SJI8: Dec = 222.8°, Inc = -36.3°, k = 360.7, α_{95} = 6.5°, N = 3). Including the similar direction of site SJI5 a mean direction for the Salto Formation on San José Island was calculated (Dec = 225.2°, Inc = -27.9°, k = 96.7, α_{95} = 12.6°). Assuming a later formation of the dyke (NRM intensity between 168 and 328 mA/m) which intruded into the Salto Formation, its directional analysis is treated separately revealing a site mean direction of normal polarity (Dec = 13.3°, Inc = 34.0°, k = 255.0, α_{95} = 4.8°, N = 5; Fig. 6.23a) differing from the reversed directions of the Salto Formation sites.

6.3.2 San Francisco Island

On San Francisco Island a total of seven sites was sampled from coastal exposures at four different locations including a volcanic lava flow (SFI1) at the southern tip, a second lava flow (SFI3) as well as a rhyolitic tuff (SFI2) at the south-eastern coastline and, finally, two sandstones (SFI4, SFI5) and two additional rhyolitic tuffs (SFI6, SFI7) at the north-eastern and west-central coast of San Francisco Island, respectively. The sandstones sampled on island pose the same problem as already experienced on San José Island. Although they display a stronger natural remanent magnetization (57.1 – 356 mA/m) the demagnetization behavior was unstable preventing the calculation of reliable site mean directions; the same was true for the volcanic lava flows with NRM intensities between 21.0 and 385 mA/m. In contrast, specimens of the rhyolitic tuffs with NRMs ranging from 35.2 to 595 mA/m showed a stable demagnetization behavior. After the removal of minor overprints at temperatures below approximately 300 °C demagnetization curves linearly decay toward the origin displaying a single component of magnetization (Fig. 6.24).

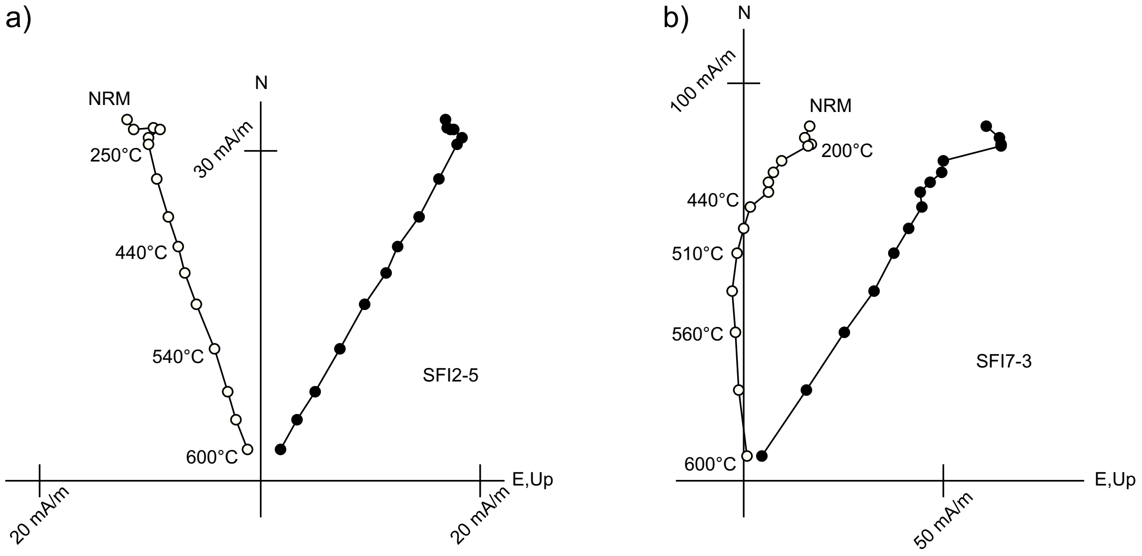

Figure 6.24: Thermal demagnetization plots in stratigraphic coordinates of representative specimens from rhyolitic tuffs on San Francisco Island. Filled (open) symbols indicate projections onto the horizontal (vertical) plane.

The calculation of site mean directions – which are well defined regarding the statistical parameters k and α_{95} - yields northward-directed declinations and downward-directed inclinations (SFI2: Dec = 29.1°, Inc = 15.5°, k = 173.9, α_{95} = 3.3°, N = 12; SFI6: Dec = 30.3°, Inc = 8.3°, k = 367.2, α_{95} = 3.5°, N = 6; SFI7: Dec = 35.2°, Inc = 4.0°, k = 146.7, α_{95} = 5.0°, N = 7).

6.3.3 Summary

Figure 6.25 summarizes the paleomagnetic results of sites sampled on San José and San Francisco Island. As already mentioned, the paleomagnetic directions of three sites on San José Island were used to calculate a mean direction with a declination of 225.2° and an inclination of -27.9° (k = 96.7, α_{95} = 12.6°).

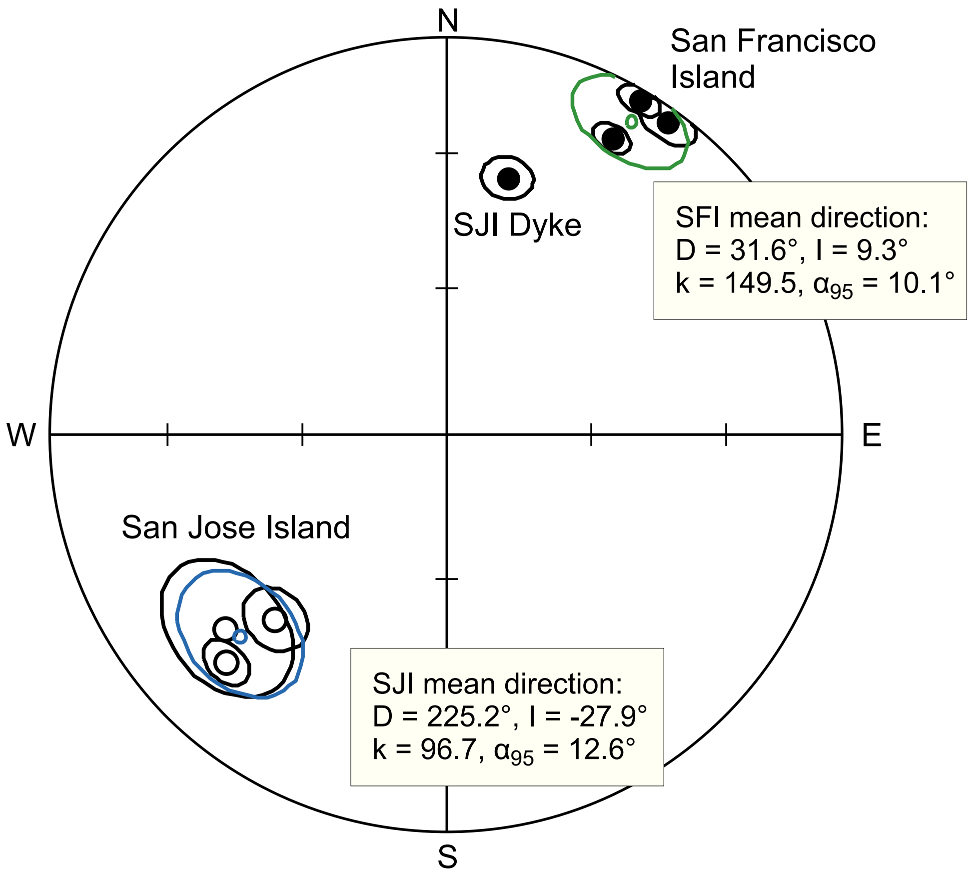

Figure 6.25: Stereographic projection of site mean directions with 95% confidence limits for sites on San José and San Francisco Island. Small green/blue circle: mean direction calculated for sites on San Francisco/San José Island with 95% confidence limit (green/blue ellipse). Note that the site mean direction of a dyke sampled on San José Island is not included in the calculation of the SJI mean direction (see text). Filled (open) symbols indicate projection onto the lower (upper) hemisphere.

The sampled units are associated with the Late Oligocene Salto Formation. Therefore, the 25 Ma window was used to calculate the reference direction (Dec = 352.1°, Inc = 41.8° and Dec = 172.1°, Inc = -41.8° for reversed polarity; cp. table 1). The comparison of the mean direction of San José Island - at least its south-eastern part - and the expected direction indicates a clockwise rotation of 53.1° ± 14.2° (Fig. 6.26).

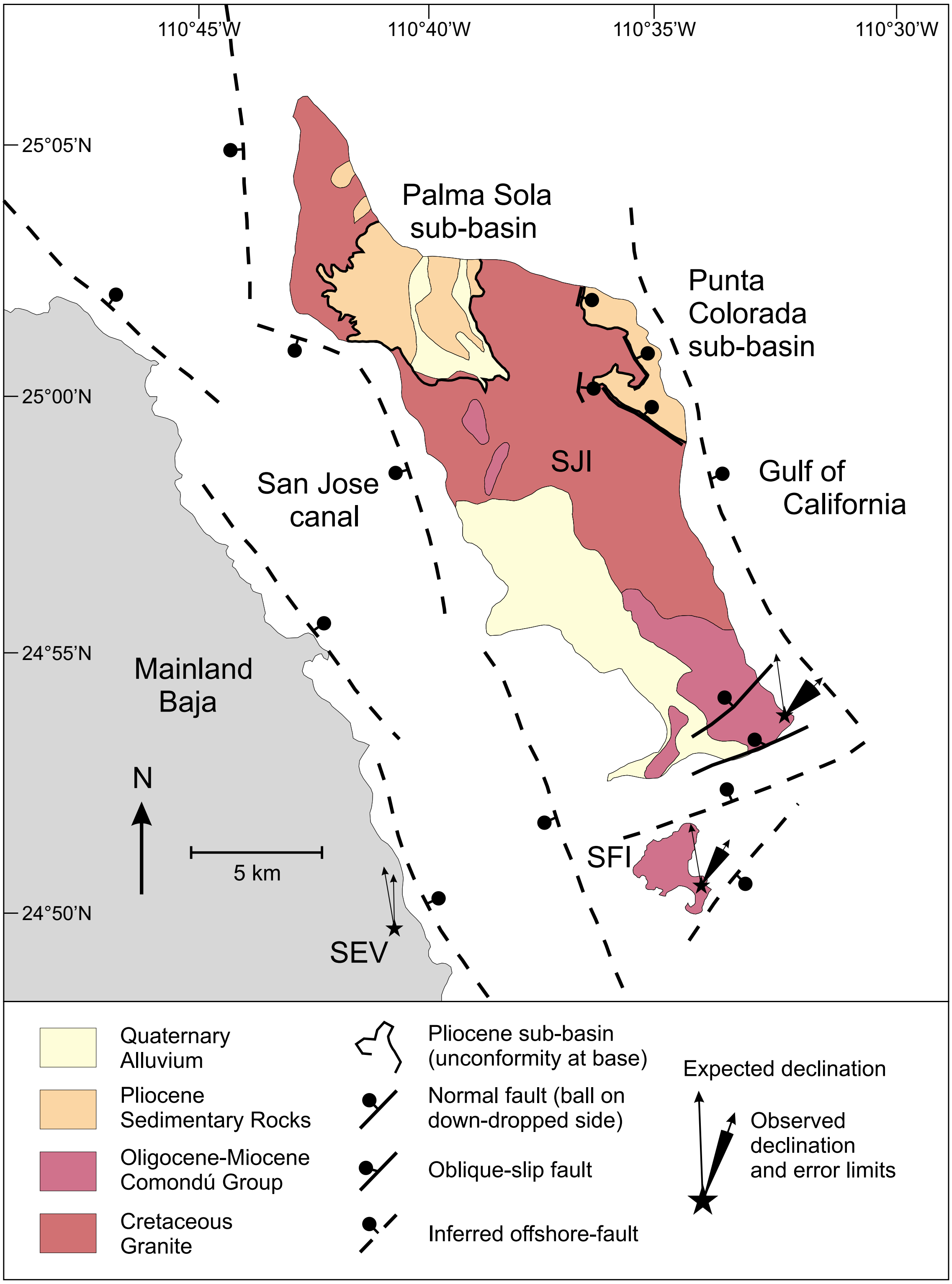

Figure 6.26: Simplified geological map of San José (SJI) and San Francisco Island (SFI) showing the calculated amounts of rotation and error limits with respect to the North American reference direction (modified from Puy-Alquiza (1992), Del Margo (2002), Drake (2005) and Umhoefer et al. (2007)).

When comparing the site mean direction of the dyke on San José Island (which is thought to be younger than the sampled units of the Salto Formation) with a reference direction calculated for the 20 Ma window (Dec = 350.2°, Inc = 40.7°; cp. table 1) a clockwise rotation is observed as well (23.1° ± 5.6°) which shows, however, less than half the amount of rotation calculated for sites of the Salto Formation.

Paleomagnetic results of sites SFI2, SFI6 and SFI7 were used to calculate a mean direction for San Francisco Island as well. A mean declination of 31.6° (Inc = 9.3°, k = 149.5, α_{95} = 10.1°) corresponds to 41.4° ± 10.4° of clockwise rotation (Fig. 6.26) in comparison to a calculated reference direction with a declination of 350.2° (20 Ma window; cp. table 1). In order to gather reference data from mainland Baja, a further site located at the same latitude as the islands and associated with the Comondú Group was sampled (SEV in fig. 6.26). Unfortunately most of the specimens of this site disaggregated during thermal demagnetization; alternating field demagnetization did not lead to satisfying results either. Only one sample remained stable during the complete thermal demagnetization process yielding a declination of 359.0° in stratigraphic coordinates. This value suggests only minor clockwise rotation and leads to the assumption that San José and San Francisco Island experienced a tectonic history different from adjacent mainland Baja. Due to the fact that this assumption is only based on data of a single specimen, it has to be regarded as highly speculative.

7. Rockmagnetic studies

7.1 Methods

In order to gather information on the magnetic mineralogy of the sampled rocks and to identify the magnetic carriers, a series of rockmagnetic measurements was conducted on at least one specimen per site (94 in total). About 300 mg of unweathered sample material were analyzed using a Variable Field Translation Balance (VFTB); the acquisition of isothermal remanent magnetization (IRM), backfield curves and hysteresis loops were measured at room temperature in maximum fields of 900 mT. Curie temperatures (T_C) were estimated on the basis of strong-field thermomagnetic curves measured in temperatures up to 700°C. Hysteresis parameters M_s (saturation magnetization), M_{rs} (saturation remanence) and H_c (coercive force) were determined from hysteresis loops after correction for the paramagnetic contribution. A calculation of H_{cr} (coercivity of remanence) and the S_{300}-parameter (Bloemendal et al., 1992) was conducted by analyzing the backfield curve. Furthermore, the shape of IRM acquisition curves – especially the segment in which saturation is reached – can provide an indication of the content of low- and high-coercive minerals.

7.2 Results

Parameters from hysteresis and backfield measurements were used for an estimation of the magnetic domain state by plotting the ratios H_{cr}/H_c versus M_{rs}/M_s according to Day et al. (1977). Data of all specimens fall in the pseudo-single-domain (PSD) grain-size region typical for magnetite. However, these results have to be treated with caution as a mixture of single-domain (SD), PSD and multi-domain (MD) particles shows PSD-behavior in most cases. Therefore, an interpretation regarding the grain size distribution is not valid for most of the natural rocks (Goguitchaichvili et al., 2001).

7.2.1 San José del Cabo Basin and Sierra La Trinidad

The IRM acquisition curves of specimens from the Refugio (REF, BUV4), Trinidad (BUV2, 3, 5) and El Chorro (BUV1) Formations rise rapidly and reach saturation in fields of about 300 mT indicating the presence of low to medium coercivity minerals like (titano-)magnetite (Fig. 7.1a). This assumption is supported by S_{300}-parameters ranging from 0.85 to 0.94. Analysis of thermomagnetic curves reveals Curie temperatures between 569°C and 581°C typical for magnetite. A few specimens show an additional T_C around 500°C indicating the presence of titanomagnetite (Fig. 7.1b).

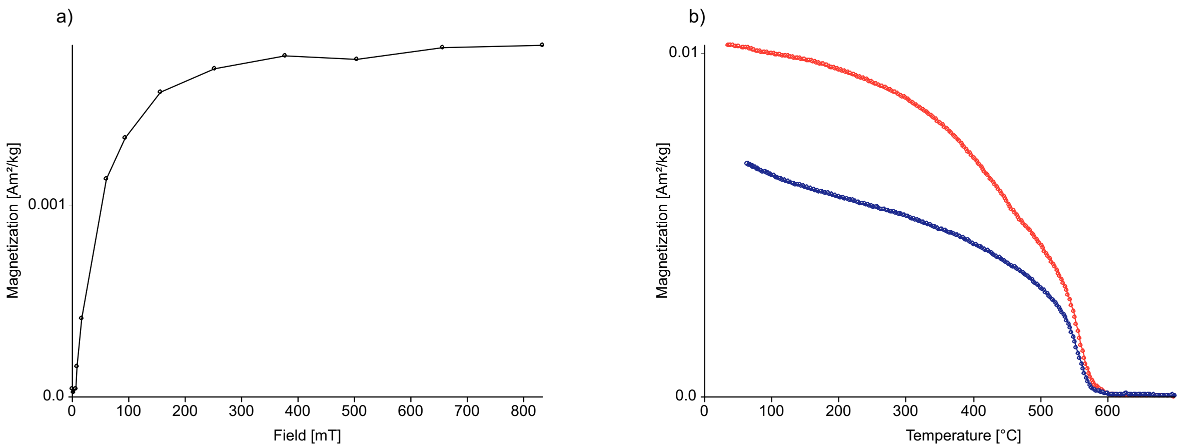

Figure 7.1: (a) Typical IRM acquisition curve obtained from specimens of the Refugio, Trinidad and El Chorro Formations showing saturation at about 300 mT, consistent with remanence carried by low coercivity minerals. (b) Thermomagnetic curve indicating Curie temperatures of about 500°C and 570°C suggesting the presence of titanomagnetite and magnetite, respectively.

As already mentioned in chapter six the oldest bed (CAL11) sampled from the Calera Formation exhibits different rockmagnetic parameters compared to those of the younger beds. IRM acquisition curves, for example, of specimens of site CAL11 increase nearly linearly (Fig. 7.2b), indicating a large content of high coercivity minerals (like hematite), whereas specimens from the other beds show at least a tendency of saturation in fields of about 800 mT (Fig. 7.2a). This fact is also reflected by a relatively low S_{300}-parameter for specimens of the oldest bed (0.46 compared to about 0.76 for younger beds). Two Curie temperatures of 570°C and 639° indicate that magnetite and hematite are the dominant carriers of magnetization in specimens from the younger beds (Fig. 7.2c). CAL11 specimens show a Curie temperature of 640° which is attributed to the presence of hematite as well, but in contrast to the younger beds a second Curie temperature of about 120°C is suggested on the basis of thermomagnetic curves (Fig. 7.2d). This finding might be an indication for the presence of goethite which could also explain the lack of saturation in IRM acquisition curves and support the assumption that chemical alteration caused by oxygen and water affected these rocks.

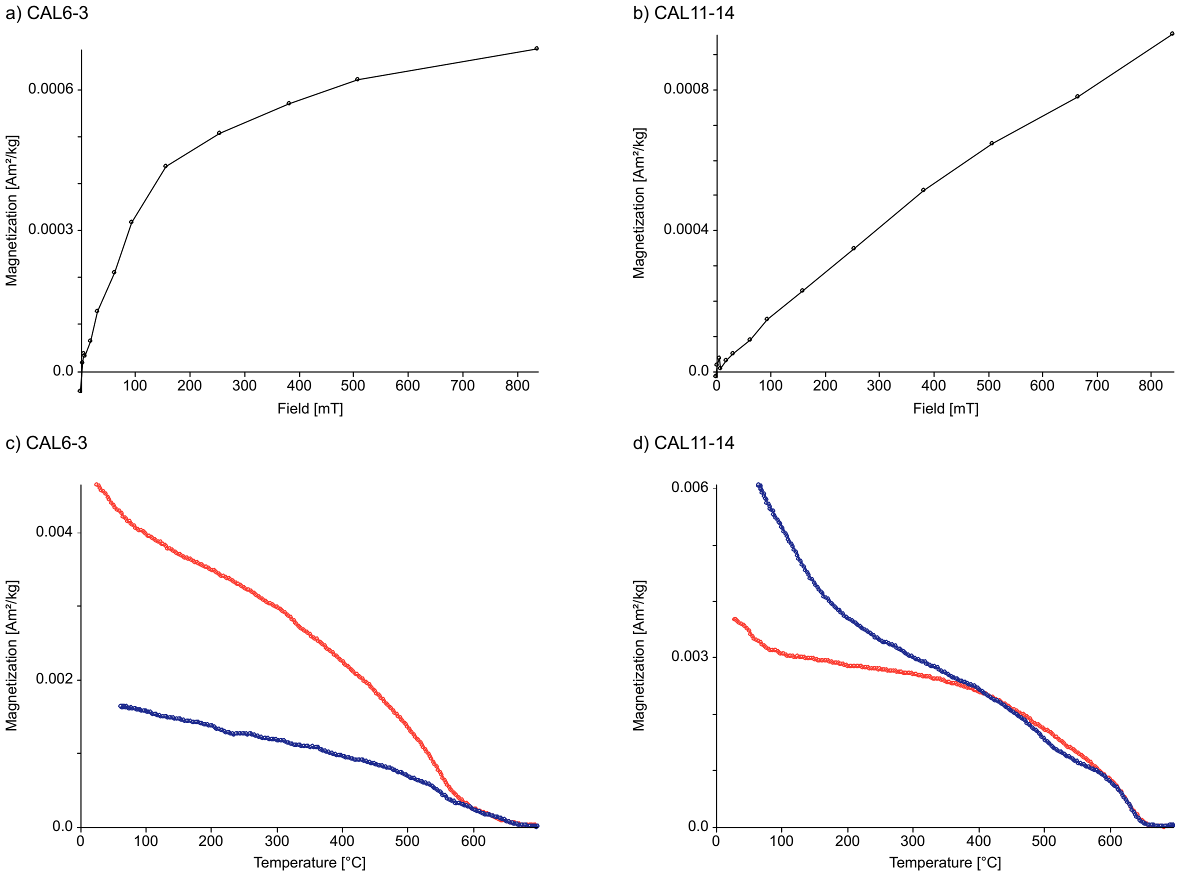

Figure 7.2: (a) and (b) IRM acquisition curves and (c) and (d) thermomagnetic curves obtained from specimens of different sites of the La Calera Formation. See text for details.

Specimens of volcanic flows (PUL4) and dykes (PUL5, 6, 7) sampled in the Sierra La Trinidad acquire a saturation IRM in fields of 400 mT and 250 to 350 mT, respectively, indicating low to medium coercivity minerals as predominant carriers of magnetization. Curie temperatures of 350 to 400°C and around 570°C suggest that titanomagnetite and magnetite are likely to carry the remanence. In some specimens of site PUL4 an additional Curie temperature of about 625°C was identified which can probably be attributed to a small content of hematite.

7.2.2 Bay of La Paz area

IRM acquisition curves of sites LAP1 to LAP4 show saturation in fields between 250 and 300 mT, suggesting a dominance of low coercivity minerals like (titano-)magnetite. This assumption is supported by the analysis of thermomagnetic curves revealing a Curie temperature of approximately 580°C for sites LAP1 to LAP3, which indicates that magnetite is the only magnetic carrier. Specimens of site LAP4 show a slightly lower T_C of 554°C suggesting that low-Ti titanomagnetite carries the remanence. Magnetite is also assumed to be the dominant magnetic phase in specimens from dykes north of La Paz, based on IRM saturation in fields between 200 and 300 mT and Curie temperatures of about 573°C. IRM acquisition curves of most specimens from sites south of San Juan de la Costa (SJC) reach saturation in fields of about 250 mT. Curie temperatures ranging from 491 to 582°C suggest that (titano-)magnetite with varying Ti-content is the main carrier of remanence in these rocks.

7.2.3 San José and San Francisco Island

Specimens of rhyolitic tuffs (SJI3, SJI8) sampled on San José Island did not reach saturation in the available fields of IRM experiments. After rising steeply in fields below 100 mT the slope of IRM acquisition curves flattens and shows a tendency of saturation at 800 mT. Considering the wasp-waisted shape of the hysteresis loops, this behavior is assumed to be due to a mixture of titanomagnetite and hematite present in the specimens (Fig. 7.3a). Curie temperatures of 544°C and 652°C confirm this assumption (Fig. 7.3b). The red sandstones (SJI1, SJI4 – SJI7, SJI9) on San José Island exhibit similar IRM acquisition curves; thermomagnetic curves are characterized by two Curie temperatures as well. However, in this case - besides hematite - pure magnetite is suggested to be the main carrier of magnetization based on Curie temperatures of about 580°C and 655°C. In contrast, specimens of the dyke (SJI2) which intruded into the Salto Formation show only a single Curie temperature of 580°C. This value together with a saturation of the IRM acquisition curve at 100 mT indicates that magnetite is the dominant carrier of remanence.

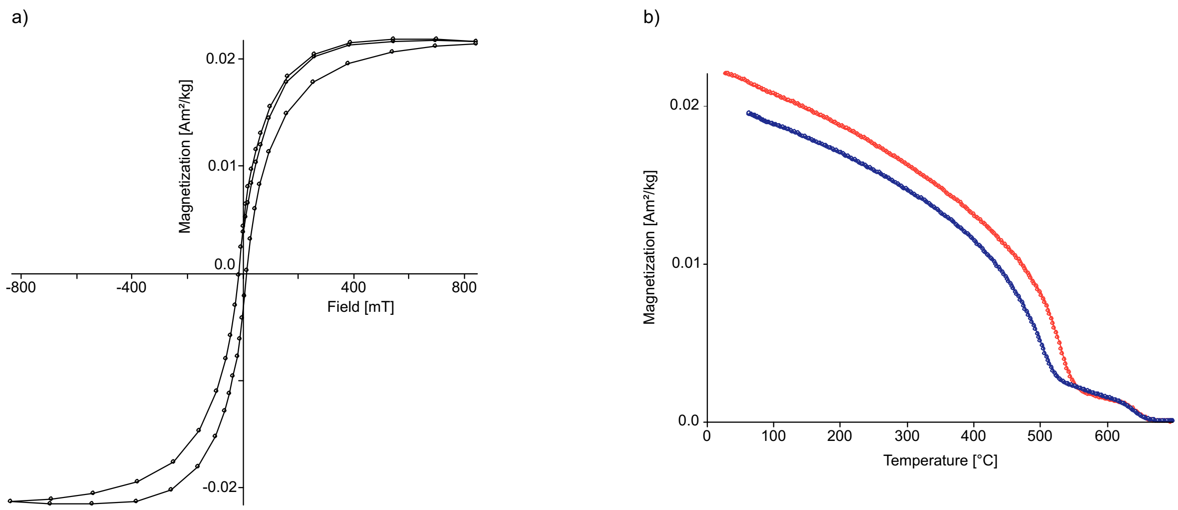

Figure 7.3: Rockmagnetic curves obtained from rhyolitic tuff specimens sampled on San José Island. (a) Wasp-waisted hysteresis loop indicative of magnetic minerals with different coercivity. (b) Thermomagnetic curve revealing Curie temperatures of 544°C and 652°C suggesting titanomagnetite and hematite to be carriers of magnetization.

Rhyolitic tuffs sampled on San Francisco Island (SFI2, 6, 7) show similar rockmagnetic properties to those on San José Island: IRM acquisition curves rise rapidly in fields up to 100 mT but do not reach complete saturation in the available measuring range; hysteresis loops are characterized by a wasp-waisted shape and thermomagnetic curves reveal - in most cases - Curie temperatures of about 539°C and 664°C indicating low-Ti titanomagnetite and hematite being the dominant magnetic minerals. However, some samples exhibit a Curie temperature of 580°C (besides the one attributed to hematite) corresponding to magnetite instead of titanomagnetite. In summary, results of the rockmagnetic experiments confirm that samples used for paleomagnetic analysis carry a stable characteristic remanent magnetization.

8. Discussion and conclusion

In the course of the present work over 500 samples were collected in three study areas (a, b, c) located in the Baja California Peninsula Borderland. Paleomagnetic analysis was successful in identifying vertical-axis rotations which were until now fully documented only for the northern part of Baja California (Lewis and Stock, 1998). Focussing on Neogene rocks within and around basin structures it was possible to define rotating blocks and quantify the amounts of vertical-axis rotations with respect to the North American reference direction.

(a) San José del Cabo Basin

Specimens of Late Miocene to Pleistocene sedimentary rocks collected in the San José del Cabo Basin show small counter-clockwise as well as clockwise rotations characterized by large error limits overlapping the North American reference declination. The calculated mean direction (Dec = 352.2°, Inc = 39.1°) of all related sites is not statistically different from the 10 Ma (Dec = 354.1°, Inc = 42.3°) and the 5 Ma (Dec = 355.8°, Inc = 43.1°) reference directions. On the basis of these results it can be assumed that the central part of the San José del Cabo Basin was not affected by significant block rotations. In contrast, data of Early to Middle Miocene volcanic rocks and dykes situated in the Sierra La Trinidad and Middle to Late Miocene sedimentary rocks located in the eastern part of the San José del Cabo basin indicate large well-defined clockwise rotations of up to 76.7° (with error values below 8°). Positive fold (Watson and Enkin, 1993) and DC tilt tests (Enkin, 2003) carried out for the sedimentary La Calera Formation provide evidence of a primary pre-folding remanent magnetization.

Data gathered in the course of the present study support the suggestion of John Fletcher (personal communication Umhoefer, 2005) that – based on apatite fission track data and the northward widening wedge-like shape of the San José del Cabo Basin – the hanging wall block bordering the eastern part of the basin was affected by clockwise vertical-axis rotation. Further support is provided by AMS-data of sites situated in the north-central part of the basin which indicate E-W directed extension being consistent with the opening of a triangular shaped basin in consequence of clockwise rotation to the east (Fig. 8.1a).

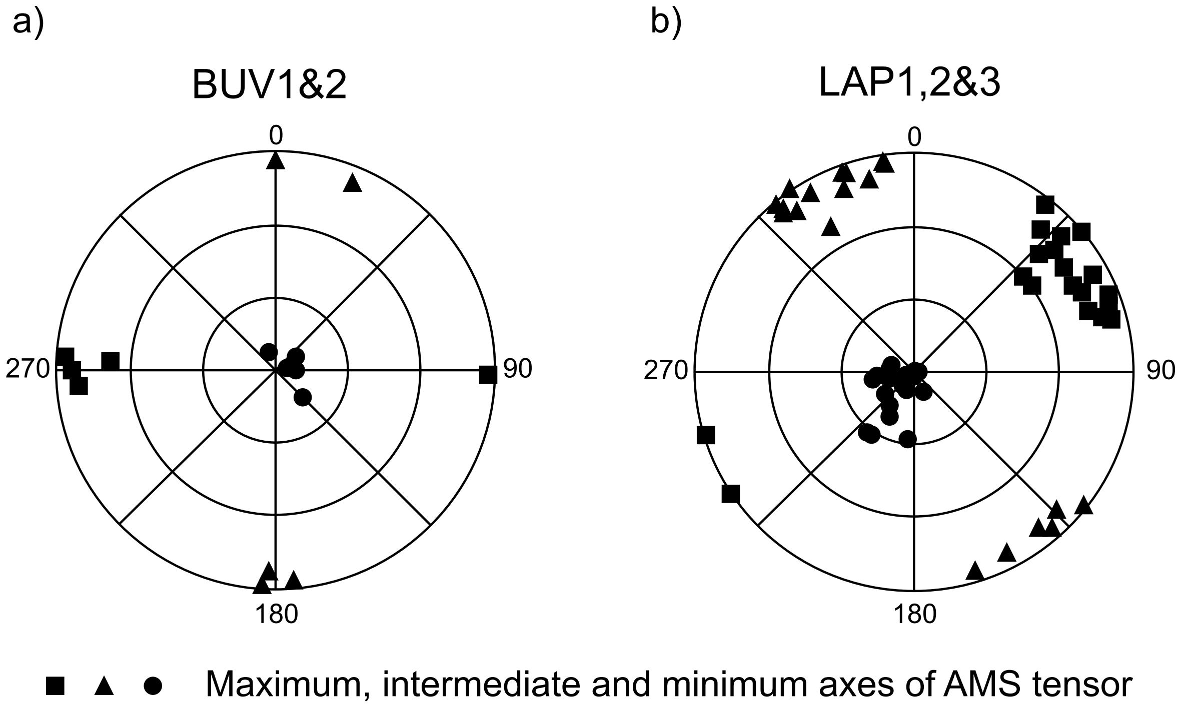

Figure 8.1: AMS-Plots of a) two sites situated in the north-central part of the San José del Cabo Basin and b) three sites located in the direct vicinity of La Paz indicating E-W- and NE-SW-directed extension, respectively.

(b) Bay of La Paz

Early Miocene rhyolitic ash-flow tuffs and rhyodacite lava flows of the Comondú Group were sampled at three sites at the eastern limit of the La Paz Basin. Paleomagnetic data derived from samples of these sites are well-defined but indicate only minor to insignificant rotations (2.5° ± 3.7°; 2.5° ± 4.8° and 6.1° ± 3.8°) when compared to the reference direction. Nevertheless, AMS-data of these sites argue for NE-SW directed extension possibly perpendicular to major faults or alignments (Fig. 8.1). At a greater distance from the basin, however, samples of a tuffaceous sandstone situated north-east of La Paz and of two dykes located north of La Paz yield large discordant declinations compared to the reference direction calculated for stable North America, suggesting clockwise rotations of 56.7° ± 15.9° and 120.1° ± 9.3°, respectively.
To the west of the La Paz Basin – south of San Juan de la Costa - paleomagnetic data of Early Miocene rhyolitic ash-flow tuffs with an estimated age between about 20 and 23 Ma (Hausback, 1984; Hagstrum et al., 1987) argue against the occurrence of vertical-axis rotations. The mean direction calculated from data of six sites (Dec = 352.3°, Inc = 36.7°) is not significantly different from the North American reference direction (Dec = 350.2°,

Inc = 40.7°) suggesting a negligible clockwise rotation of 2.1° ± 18.6°. This fact leads to the assumption that the area to the west of the El Carrizal fault system has not experienced major rotations and therefore most likely is part of the stable Baja California microplate. The La Paz Basin is - as already mentioned in the introduction – triangular in shape as suggested on the basis of its narrowing toward the south (Cruz-Falcón et al., 2010). There are also indications that the La Paz Bay area is still tectonically active due to the opening of the Gulf of California (Munguía et al., 1997; Fletcher and Munguía, 2000). Thus, on the basis of the paleomagnetic data gathered in the course of the present study it is assumed that the La Paz Basin has formed through possibly still ongoing clockwise rotation of the block to the east whereas the area west of the El Carrizal fault is part of the stable Baja California microplate and has not been affected by major rotations. Support for this assumption is provided by AMS-data of sites LAP1, LAP2 and LAP3 indicating a NE-SW-directed extension (Fig. 8.1b).

(c) San José and San Francisco Islands

The mean direction (Dec = 225.2°, Inc = -27.9°) calculated from paleomagnetic data of two rhyolitic tuffs and a red sandstone of the Late Oligocene Salto Formation shows a discordant declination suggesting the occurrence of 53.1° ± 14.2° of clockwise rotation which affected at least the south-eastern tip of San José Island. In addition the site mean direction (Dec = 13.3°, Inc = 34.0°) of an undated dyke which intruded into the sampled units of the Salto Formation – and which therefore has to be less in age – implies a clockwise rotation of about 20°. This, being less than half the amount of rotation as calculated for the Salto Formation, implies that the area already has rotated over 30° before the intrusion of the dyke which therefore might be caused by tectonic processes related to the opening of the Gulf of California.

In the case of San Francisco Island a mean direction was calculated on the basis of paleomagnetic data gathered from three sites composed of Oligocene to Miocene Comondú Group rhyolitic tuffs (Drake, 2005). The mean declination of 31.6° is indicative for a clockwise rotation of 41.4° ± 10.4° in comparison to the corresponding North American reference direction. Specimens from a reference site being part of the Comondú Group on mainland Baja (located at the same latitude as the islands) unfortunately turned out to be unstable during the thermal demagnetization procedure; only one specimen remained intact in the course of the complete demagnetization process. A declination value of 359.0° obtained from this single dataset suggests only minor clockwise rotations in the area. Paleomagnetic data of this study confirms the clockwise rotations predicted by Drake (2005) but exceed his presumed value (25°) by approximately 100%. However, reconstruction on the basis of the amount of calculated clockwise rotations of the roughly northeast-southwest running normal faults - located in the southern part of San José Island and north as well as south of San Francisco Island – would result in NNW striking faults being consistent with fault strikes in other parts of Baja California Sur (cp. fig. 6.26).

Further results regarding the tectonic evolution of the Baja California Peninsula

The mean inclinations calculated for sites south of San Juan de la Costa (Inc = 36.7°) and the San José del Cabo Basin sediments (Inc = 39.1°) - which are not assumed to be affected by vertical-axis rotations – can contribute to the discussion about the significance of the one- and two-phase kinematic models. The comparison to the reference inclinations (Inc = 40.7° for sites south of San Juan de la Costa and Inc = 43.1° for the San José del Cabo Basin sediments) reveals a difference of 4°, corresponding to about 444 kilometers of northward translation. This amount of translation is consistent with the one-phase kinematic model developed by Fletcher et al. (2007; cp. figure 2.10 B&C) which implies that 460 kilometers of shear has occurred across the Gulf of California since 12.3 Ma (in contrast to 345 kilometers of shear which are suggested by the two-phase kinematic model). A similar amount of displacement across the southern part of the Gulf was derived from palinspastic reconstructions (Fletcher et al., 2003b; Fletcher et al., 2004). The one-phase kinematic model also implies that the related northward translation has been continuous since 12.3 Ma (150 kilometers between 12.3 and 7.8 Ma; 310 kilometers between 7.8 and 0 Ma; Fletcher et al., 2007). Geodetic data of the eastern part of the San José del Cabo Basin and the Sierra La Trinidad indicate present rotational rates of about 2°/Ma (Fig. 8.2; Hackl, personal communication, 2012). Extrapolation of this rate into the past – under the assumption that rotations related to the opening of the Gulf of California occurred continuously as well – implies an onset of rotation of the La Calera Formation about 13 Ma ago (clockwise rotation of 26.4° ± 3.5°) and of the volcanic flows in the Sierra La Trinidad about 12.5 Ma ago (clockwise rotation of 25.0° ± 7.6°). These results are in very good agreement with the one-phase kinematic model which proposes that oblique rifting and related shear already started at 12.3 Ma - without a phase of orthogonal rifting as proposed in the two-phase kinematic model. The estimated onset of rotation is also consistent with the beginning of subsidence of the San José del Cabo Basin as documented by the oldest sedimentary deposit – the above mentioned Middle to Late Miocene La Calera Formation (Martínez-Gutiérrez and Sethi, 1997).

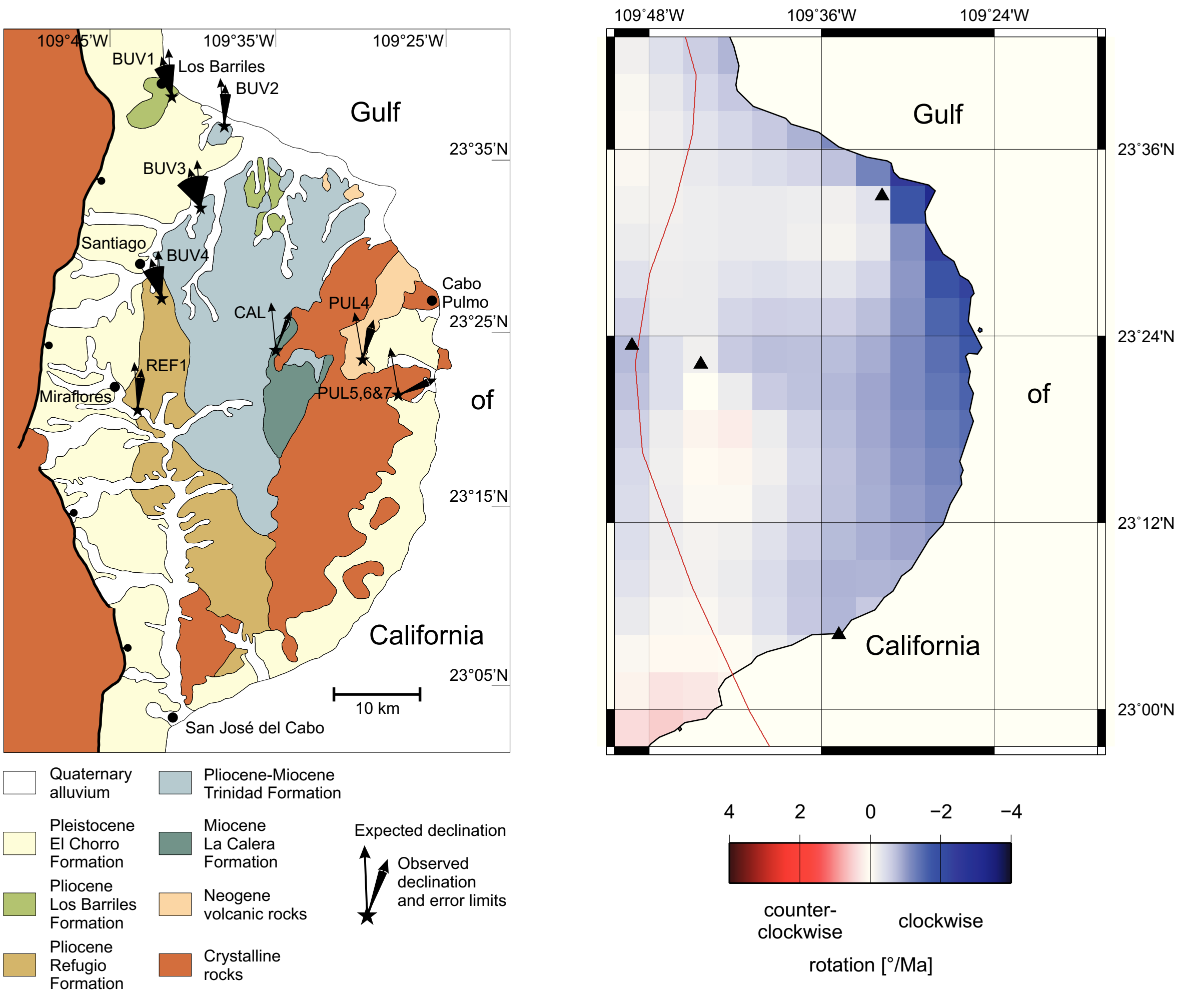

Figure 8.2: Left: Paleomagnetic rotations calculated for sites located in the San José del Cabo Basin and the Sierra La Trinidad. Right: Contour plot of the same area illustrating geodetic rotational rates calculated from GPS velocity data (Hackl, personal communication, 2012). Triangles indicate location of GPS stations.

A possible explanation for the pattern of rotations found in the San José del Cabo Basin/Sierra La Trinidad area might be that vertical-axis rotations occurred only during Middle to Late Miocene as rotations could not be verified in younger rocks. However, on the basis of recent geodetic data (Hackl, personal communication, 2012) indicating active vertical-axis rotations in the eastern part of the San José del Cabo Basin and the Sierra La

Trinidad this assumption has to be discarded. Another approach to an explanation seems feasible after taking a closer look at the area between La Paz and San José del Cabo (Fig. 8.3) which reveals a landscape obviously characterized by a sequence of triangular or wedge-shaped basins - namely the La Paz, San Juan de los Planes and San José del Cabo basins - bordered by structural highs (Sierra Las Cruces, Sierra La Laguna and Sierra La Trinidad); a pattern comparable to a hand with spread fingers (representing the structural highs).

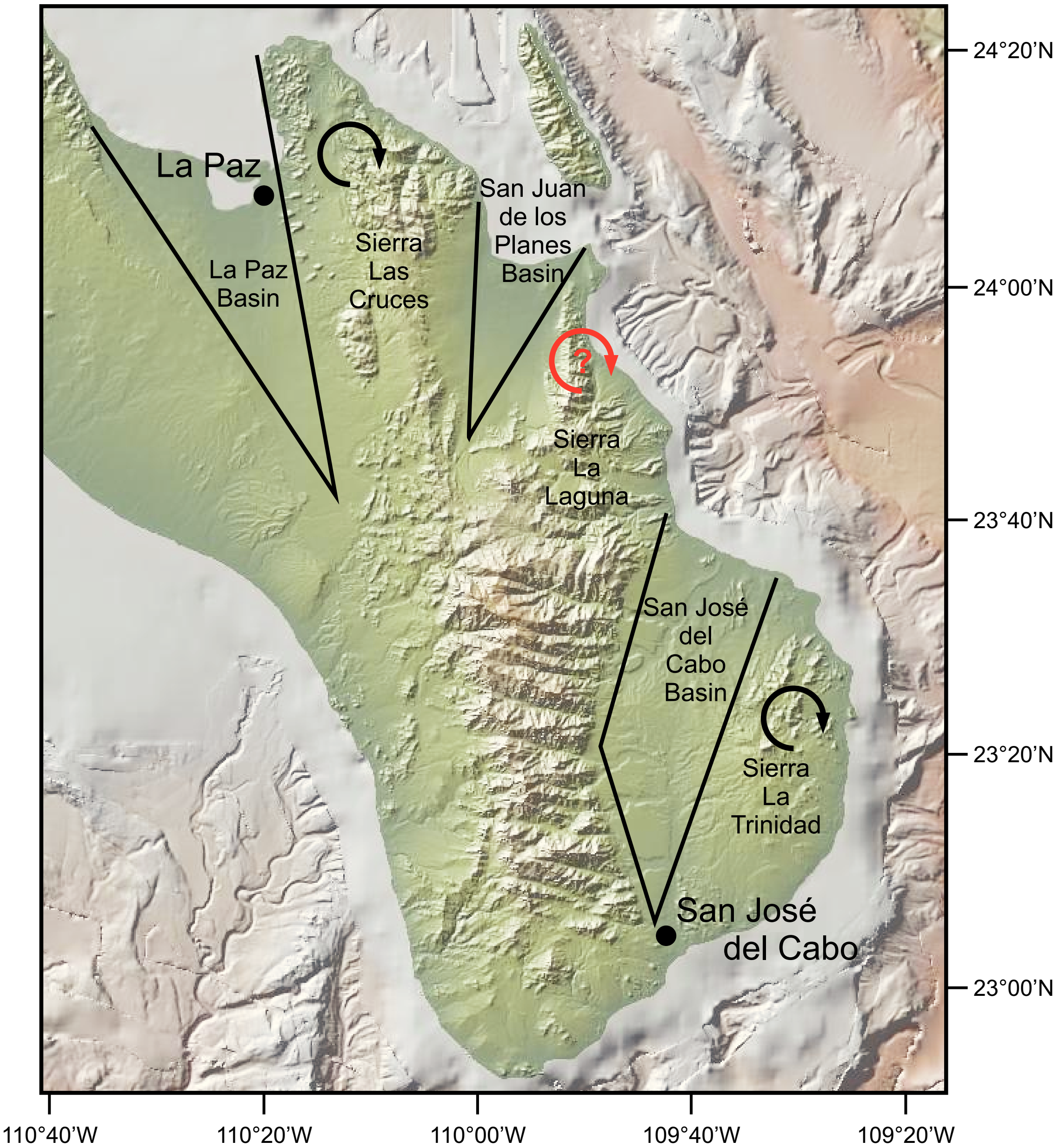

Figure 8.3: Map showing the southern tip of Baja California and illustrating triangular shaped basins (La Paz Basin, San Juan de Los Planes Basin, San José del Cabo Basin) separated by structural highs (Sierra Las Cruces, Sierra La Laguna, Sierra La Trinidad) which are assumed to be rotated clockwise. Basemap from GeoMapApp (www.geomapapp.org).

Considering this feature of the landscape it is assumed that at the southern tip of Baja California parts of eastern Baja California Sur are being sheared off the stable microplate through right-lateral motion along the main plate boundary in the Gulf of California and along some active faults located in the Baja California Peninsula Borderland. A similar scenario has already been inferred regarding the Lobos basin situated offshore north of Espiritu Santo Island which is thought to have opened in a scissor-like fashion (Nava-Sánchez et al., 2001).

On the basis of the results obtained in the present study it is suggested that the tectonic processes mentioned above led to the clockwise rotations documented east of La Paz as well as in the San José del Cabo Basin/Sierra La Trinidad area and resulted in the opening of adjacent triangular shaped basins accommodating northeast-southwest- to east-west-directed extension. A similar extension direction has already been documented in these regions on the basis of Neogene and Quaternary fault analysis by Angelier et al. (1981). Due to the fact that the occurrence of rotations could not have been confirmed inside the studied basins it is suggested that the extension only led to vertical movements of the basin fillings. Taking into account that in the course of the present paleomagnetic study it was possible to document clockwise rotations of San José and San Francisco Island located farther to the north (see above), the assumption that parts of eastern Baja California Sur are being sheared off the stable microplate might be extended to the entire Baja California Peninsula Borderland (Fig. 8.4a).

Confirmation of this hypothesis is provided by several studies and a preliminary GPS interseismic velocity field for Baja California Sur (Malservisi, personal communication, 2011; fig. 8.4b) with respect to a fix southern Baja California (defined as described by Plattner, personal communication, 2007). Late Miocene marine rocks of the Santa Rosalia Basin - situated in the northernmost part of the Baja California Peninsula Borderland – were sampled in the course of a geochronological and a preliminary magnetostratigraphical study by Holt et al. (2000; fig. 8.4a). Paleomagnetic data indicate that no major rotations have affected the sampling area since about 7 Ma (Holt et al., 2000) which therefore possibly is part of stable Baja California. Tortuga Island, however, separated from mainland Baja by the Tortuga Trough might potentially have rotated clockwise. The Bahia Concepción Basin located about 50 kilometers to the south of the Santa Rosalia Basin represents the largest fault-bounded bay at the eastern coast of Baja California and is assumed to have developed by Late Miocene east-west-directed extension (Fig. 8.4a; Ledesma-Vázquez and Johnson, 2005); further support for this is provided by geodetic data suggesting eastward-directed motion (Fig. 8.4b). Although no paleomagnetic data is available for the Concepción Peninsula its detachment from stable Baja in association with clockwise rotation might be imaginable; especially considering the noticeable coastline.

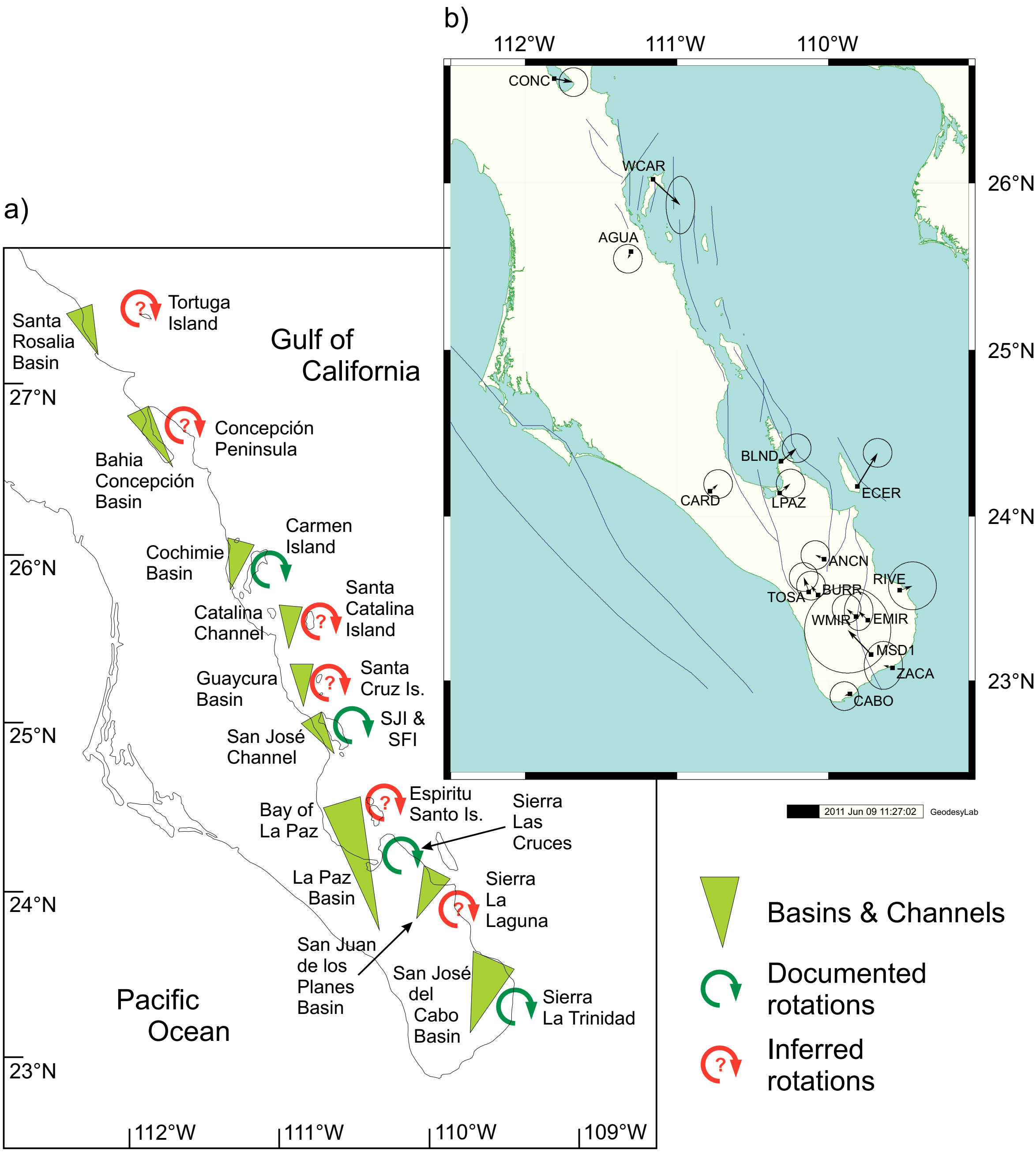

Figure 8.4: a) Map of southern Baja California illustrating the location of basins and channels along the eastern coast. Green and red circular arrows indicate documented and inferred clockwise rotations. b) GPS interseismic velocity field for Baja California Sur (Malservisi, personal communication, 2011).

Carmen Island - situated east of Loreto and separated from mainland Baja by the Cochimie Basin - is characterized by an anomalous NNE trend which, together with the orientation of bedding, suggests that the whole island has rotated clockwise about 35 to 45°. Further support for this assumption is provided by the occurrence of deformation recognized along the northern coast of the island (Umhoefer et al., 2002). A preliminary study by Macy (2005) supplied first paleomagnetic data indicating clockwise rotations in the northern part of Carmen Island of about 40 to 50° between 12 and 3 Ma and approximately 10 to 20° since 3 Ma. In addition a GPS station located at the northern tip of the island provides data suggesting a southeast-directed displacement which is consistent with the assumption that Carmen Island has rotated clockwise. In contrast, paleomagnetic data gathered from sites west of Loreto - which are thought to be part of the stable Baja California microplate - indicate no major rotations since Miocene. Other islands like the Santa Catalina, Santa Cruz and Espiritu Santo Islands which are separated from mainland Baja by the Catalina Channel, the Guaycura Basin and the Bay of La Paz, respectively, were possibly affected by clockwise rotations through right-lateral shear as well.

The paleomagnetic results of the present study already discussed above are also consistent with the velocity field measured at GPS stations located at the southern tip of Baja California Sur (Fig. 8.4b). In the region of La Paz data of two GPS stations (LAPZ, BLND) predict northeast-directed motion which is coherent with the AMS-data of the present study and supports the assumption of clockwise rotations occurring in the area east of La Paz. At the northern end of the Sierra La Trinidad geodetic data of another GPS station (RIVE) suggests roughly east-directed displacement consistent with AMS-data of this study and the assumption that the Sierra La Trinidad region rotated clockwise leading to the opening of the San José del Cabo Basin. In contrast, geodetic data gathered from GPS stations located in the western part of the San José del Cabo Basin (WMIR, EMIR, MSD1, ZACA) and farther to the northwest (ANCN, TOSA, BURR) indicate north-westward translation parallel to the Pacific Plate motion.

In summary, the findings of several studies involving the tectonic history of Baja California Sur as well as the GPS interseismic velocity field discussed above indicate extension between a stable Baja California microplate and an area including parts of the eastern coast and the islands – equivalent to the Baja California Peninsula Borderland. This tectonic scenario is consistent with paleomagnetic data provided by the present study and supports the assumption that parts of eastern Baja California Sur are being sheared off the stable microplate through a single phase of transtensional shearing accommodating oblique-divergent motion in the Gulf Extensional Province. In order to confirm this theory it is necessary to continue geodetic measurements and carry out further paleomagnetic studies along the eastern coast of Baja California Sur, especially in areas where extension has already been documented.

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