Uplift and subduction erosion in southwestern Mexico since the Oligocene: pluton geobarometry constraints

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Abstract

Details of the late Oligocene to Middle Miocene uplift and tectonic erosion episodes of the southwestern continental margin of Mexico can be inferred using Al2O3 geobarometry of igneous hornblends, geochronology, and field relations. On the basis of such analyses carried out between Acapulco and Huatulco we find the following: (1) Calc-alkaline batholiths exposed along the coast from Acapulco to Huatulco, mostly in the 35–25 Ma age range, were emplaced at depths between 13 and 20 km. (2) The contact relationships between these plutons and their host rocks, and the exposure of volcanic counterparts, 70 km from the coastline, indicate a landward decrease in the amount of uplift. (3) A comparison of the time differences between intrusion and cooling ages of batholiths along the coast suggest that cooling rates were, in general, higher between Acapulco and Huatulco than those along the margin between Puerto Vallarta and Manzanillo, 700 km northwest of Acapulco. (4) The uplift of this coastal belt occurred during the late stages of magmatism and after its cessation, triggering intensive subaerial erosion of supracrustal rocks and the exposure of midcrustal rocks such as granitic batholiths and amphibolite facies metamorphic assemblages of the Xolapa Complex.

These findings, in conjunction with the geometry of the present continental margin, as well as the offshore tectonic and stratigraphic features, support previous interpretations of very active late Oligocene to Middle Miocene subduction erosion after the onset of strike-slip tectonics related to the detachment and subsequent eastward displacement of the Chortis block. Subduction erosion involved both trench sediments and crystalline (continental framework) rocks. Different rates of continental framework erosion are assessed on the basis of the bathymetric fluctuations of the upper slope trench sediments and the age of the accretionary prism. Subsidence of the offshore continental basement suggests intense episodes of basal erosion of lower continental crust, whereas the construction of the present day accretionary prism and the uplift of the upper slope indicate a decline in the frontal and basal erosion of the continental framework. Comparing the calculated depths of pluton crystallization with the present depth of the continental crust subducted slab boundary, interpreted using previously published seismic refraction and gravity models, we conclude that onshore basal erosion played a subordinate role during Miocene episodes of subduction erosion. Major removal of lower crustal sections was probably restricted to offshore regions.

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Plate reconstructions of the Cocos plate and its predecessors with respect to North America indicate that the uplift and probably the offshore subduction erosion in this region coincided with the initial stages of the subhorizontal trajectory of the Guadalupe plate beneath southwestern Mexico.

Keywords: Mexico; Xolapa Complex; Oligocene; erosion; tectonics; geologic barometry

1. Introduction

Tertiary tectonic evolution of southwestern Mexico was characterized by very active tectonic reshaping of the Pacific continental margin. The present proximity of the Tertiary plutonic belt to the trench (Fig. 1) and the lack of mature forearc assemblages are the main indications of tectonic erosion episodes along this margin. Based on the apparent intersection of the regional structural trends of the Xolapa Complex and the continental border, De Cserna [1] first recognized the truncated character of the southwestern continental margin of Mexico. Karg et al. [2] gathered several lines of evidence supporting the interpretation of tectonic erosion along this margin and favored right-lateral faulting as the main cause for the detachment and removal of forearc slices.

However, in most paleogeographic reconstructions of Mexico and the Caribbean region the northern part of Middle America is placed adjacent to the southwestern continental margin of North America [3–6]. This widely accepted interpretation has been derived from the backward paleogeographic implications of the present left-lateral displacement along the Motagua–Polochic Fault System. However, paleogeographic connections between the Mesozoic sequences of southern Mexico and the correlative sequences in the Chortis block have yet to be firmly established.

The along-coast, southeastward decreasing ages of the extinction of calc-alkaline magmatism on the southwestern Pacific margin of Mexico have been largely attributed to the gradual SE displacement of the Chortis block during the formation of the Caribbean Plate [7–10]. However, taking into account the petrological affinities between Chortis and southern Mexico, as well as the maximum displacement estimated in the Cayman Trough [11], intrusion age variations can be attributed to the displacement of Chortis only in the segment between Zihuatanejo to Huatulco [10].

The tectonic framework of the Acapulco Trench inner slope (Figs. 2 and 3) as well as the stratigraphy along this portion of the trench indicate that sediment subduction and subduction erosion were particularly active processes until the Middle Miocene. Accretionary prism sediments are progressively younger toward the trench, which supports the interpretation of continuous accretion processes from Middle Miocene to the present [12]. Paleobathymetry, inferred from foraminifera content in sediments of Leg 66 DSDP boreholes, indicates a gradual subsidence of the upper slope after intense episodes of uplift and unroofing of batholiths. Borehole 487, located only 50 km from the Acapulco Trench, reached a continental basement, represented by 32 Ma calc-alkaline diorites [13]. Northeastward dipping reflectors under the middle and lower inner slope suggest uplift related to post-Late Miocene sediment accretion.

Subduction erosion has been invoked as one of the processes to account for lost continental crust along ocean margins [14–18]. About 19,000 km of present-day convergent margins display evidence of active sediment subduction without accretionary prisms or with the development of small prisms [18]. There are several lines of evidence indicating that subduction erosion of the continental framework rocks is a relatively common process at destructive margins. This process can be related to frontal or basal erosion [17,18]. Subsidence of the off-shore continental crust, as well as the seaward-tilting unconformity between marine sediments and continental basement, have been related to subcrustal removal of the upper plate at a convergent margin [19,17,18]. Von Huene and Lallemand [17] pointed out a series of seismically modeled features indicating basal erosion effects at the Japanese and Peruvian active margins. In Peru, seaward-dipping Eocene shallow-water beds cover rocks seismically modeled as crystalline basement. At the lower boundary of the accretionary prism, represented by a landward-dipping
décollement, these beds appear to be truncated, suggesting the removal of underlying crystalline basement.

There are many indications that the removal of continental margin segments can also be caused by regional strike-slip faulting associated with oblique convergence and their effects have been recognized in different parts of the circum-Pacific region [20–22].

Tertiary tectonic truncation episodes at the southwestern continental margin of Mexico seem to have occurred in a complex scenario characterized by both lateral displacement and subduction erosion processes. Both processes left recognizable features in the stratigraphy and regional tectonic structure of this region.

The tectonic history of the southwest Mexican continental margin during the Tertiary is characterized by a maximum rate of convergence between the Farallon and North America plates of about 170 mm/yr at about 45 Ma [10]. This is followed by a fragmentation of the Farallon Plate and a gradual decline, punctuated by minor peaks, to the present rate of convergence of 60 mm/yr between the Cocos and North America plates. Periods of fast rates of convergence are likely to coincide with accelerated rates of subduction erosion.

One of the most characteristic tectonic features of southwest Mexico is the exposure of middle crustal Tertiary rocks along the continental margin (Figs. 1 and 2). The most conspicuous indication of the Neogene differential uplift with respect to inland regions are the broad exposures of Oligocene batholiths along the coast and the landward increasing abundance of volcanic counterparts to the north (Fig. 2). Previous episodes of margin uplift are indicated by pre-batholithic mylonitic zones with oblique-normal fault kinematic components separating Cretaceous–Paleogene amphibolite-facies metamorphic rocks from coeval rocks representing higher crustal levels to the north [23,24] (Figs. 1 and 2). These tectonic features have been interpreted in terms of a trans-tensional tectonic regime associated with the early stages of left-lateral displacement affecting this region [23,24]. Robinson et al. [25] suggested that the overall Paleogene evolution of the Xolapa terrane corresponds to a large scale metamorphic core complex.

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![Regional geological map of the Xolapa terrane showing the location of the plutons sampled and the location of sections shown in Fig. 2. Inset shows the plate tectonic setting and the location of the study area. Abbreviations: AC = Acapulco pluton; SM = San Marcos pluton; PV = Puente de Vagas pluton; CG = Cruz Grande pluton; RV = Río Verde pluton; SD = Santo Domingo pluton; HU = Huatulco pluton; MPFZ = Motagua–Polochic Fault Zone; CT = Cayman Trough.](image-url)
Seismic refraction profiling, carried out in the states of Oaxaca and Guerrero, indicates that the depth of the continental crust-subducted slab inter-

face ranges from about 15 to 25 km along the coast [26–28] (Fig. 4). According to the seismic refraction profiling carried out by Nava et al. [27], the minimum depth of about 15 km beneath the coastline corresponds to the Rio Verde region and the maximum estimated depth is about 25 km beneath Punta Maldonado. Based on seismic profiling carried out along the coast, Núñez Cornu (pers. commun.) interpreted a depth of 22 km for the continental crust-subducted slab boundary between Acapulco and Punta Maldonado. Landward, typical crustal thicknesses in southern Mexico range from 40 to 45 km [29].

Present crustal thicknesses along the coast imply a loss of significant masses of continental lithosphere. Possible mechanisms for such removal of material
2. Tectonic framework

The conspicuous belt of Upper Cretaceous–Paleogene batholiths occupying the southwestern continental margin of Mexico intrude two distinct terranes characterized by different stratigraphic and petrologic assemblages. From Puerto Vallarta to Tecpan the host rocks are mainly unmetamorphosed Jurassic to Early Cretaceous volcano-sedimentary sequences of the Guerrero terrane [30–33]. In the western portion of the Guerrero terrane these sequences unconformably cover older, poorly known, assemblages of oceanic affinity [34,35]. The Lower Cretaceous volcano-sedimentary sequences are the most characteristic feature of the Guerrero terrane [36] and their origin has been interpreted in terms of a volcanic island arc accreted in the Late Cretaceous to the western margin of continental Mexico [37–39]. From Tecpan to east of Huatulco, undeformed Tertiary plutons intrude a relatively narrow belt of amphibolite-facies rocks, including paragneiss, orthogneiss, amphibolite, mica-schists and marble, forming a plutonic metamorphic tectonostratigraphy defined as the Xolapa terrane by Campa and Coney [36] (Fig. 1) and later renamed the Chatino terrane by Sedlock et al. [40]. The metamorphic assemblages of the Xolapa terrane show the effects of different degrees of anatexis and are locally overprinted by mylonitic zones located mainly at its northwestern boundary [8,23,25]. Recent Rb–Sr and U–Pb age determinations of the metamorphic rocks forming the Xolapa Complex document metamorphic events which occurred between the Lower Cretaceous and early Tertiary. Nd model ages [8] and U–Pb zircon
inherited ages ranging from 1 to 1.5 Ga [9,25] suggest a tectonic evolution linked to the pre-existing continental margin, represented by the Acatlan and Oaxaca Complexes of early Paleozoic and Late Proterozoic age, respectively.

The left-lateral and oblique-normal kinematics of the mylonite zones affecting the Xolapa terrane rocks are consistent with interpretations which place the detachment of the Chortis block from a position offshore of the Xolapa terrane. Along-coast magmatism migration rates estimated by Herrmann et al. [9] and by Schaaf et al. [10] are higher than those calculated by Rosencrantz and Selater [11], who based their calculations on the study of the magnetic anomalies and the bathymetry of the Cayman Trough. This indicates that final arc magmatism along the southwestern continental margin of Mexico occurred northwest and southeast of the southeastward migrating trench–trench–transform triple junction before its rapid extinction [10].

After the gradual cessation of the calc-alkaline magmatism along the continental margin of Oaxaca and Guerrero, from the Oligocene to Early Miocene, the locus of arc magmatism migrated landward, reaching, during the Pliocene, the latitude of the Trans-Mexican Volcanic Belt (TMVB) [9]. The present day arc–trench gap in southern Mexico and the oblique position of the TMVB with respect to the Middle America Trench has been attributed to lateral variations in the geometry of the subducted slab once they are decoupled from the overriding plate [41–43]. These lateral variations have been attributed by Pardo [43] to the combined effect of along-trench changes in age of the subducted plate, convergence rate and absolute motion of the upper plate toward the trench. Beneath the Guerrero and Oaxaca regions the subducted slab is subhorizontal at distances from the trench between 110 and 275 km and at depths of about 50 km. The 100 km depth contour of the subducted slab interpreted by Pardo [43] fits approximately the southern front of the Plio–Quaternary volcanism of the TMVB.

3. Plutons: petrological and geochemical features

Batholiths exposed along the Guerrero and Oaxaca continental margin range in composition from tonalities to alkali feldspar granite (Fig. 5), but most of them fall in the granodiorite and granite fields. Most typical accessories are biotite and hornblende and minor accessories are titanite, magnetite, zircon and apatite. Potassium feldspar crystals generally exhibit patches of perthite and microcline with common myrmekite haloes. Plagioclase compositions are near uniform above An(36) and locally display zoned textures. Positive initial eNd values (0 to +4) and low ⁸⁷Sr/⁸⁶Sr ratios (0.7045–0.7055) indicate mantle-derived magmas with a relatively low degree of crustal contamination [44,45] Solís-Pichardo (pers. commun.).

The Acapulco intrusive displays petrological characteristics and K–Ar and Rb–Sr dates which differ from most of the batholiths in the Xolapa terrane. The eastern portion of the Acapulco intrusive consists of a quartz-syenite that gradually changes toward the west to alkali feldspar granite with rapakivi texture.

Variations in initial Nd and Sr isotopic ratios, as well as distinct K–Ar ages obtained from different petrological fractions, indicate that large batholiths of the Xolapa terrane are the result of coalescent individual plutons rather than large comagmatic intrusives.

Samples selected for Aluminum-in-hornblende analyses were taken from plutons considered to be
post-metamorphic on the basis of structural relationships and available geochronologic data. These plutons account for about 50% of the Xolapa terrane by area and they do not show extensive indication of regional deformation. The Pochutla and Huatulco plutons are locally affected by mylonitic deformation in well bounded shear zones located mainly at the northern boundary of the Xolapa terrane. The other plutons studied do not seem to be involved in mylonitic deformation; north of Acapulco, Tertiary plutons intrude a mylonitic zone with sinistral oblique-normal fault geometry [24]. The post-metamorphic

Table 1
Electron microprobe analytical results of representative hornblendes from the plutons studied

<table>
<thead>
<tr>
<th>Sample</th>
<th>Acapulco</th>
<th>San Marcos</th>
<th>Puente de Vigas</th>
<th>Cruz Grande</th>
<th>Rio Verde</th>
<th>Sto. Domingo</th>
<th>Huatulco</th>
</tr>
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<tbody>
<tr>
<td>SiO₂ (wt. %)</td>
<td>43.80</td>
<td>47.02</td>
<td>44.69</td>
<td>45.94</td>
<td>44.68</td>
<td>46.45</td>
<td>43.79</td>
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<td>TiO₂</td>
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<td>1.35</td>
<td>1.24</td>
<td>1.17</td>
<td>1.16</td>
<td>1.35</td>
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<tr>
<td>Al₂O₃</td>
<td>8.66</td>
<td>7.67</td>
<td>9.13</td>
<td>9.14</td>
<td>9.82</td>
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<td>0.00</td>
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<tr>
<td>Fe₂O₃</td>
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<td>0.00</td>
<td>2.96</td>
<td>1.27</td>
<td>1.89</td>
<td>1.29</td>
<td>5.20</td>
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<td>FeO</td>
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<td>16.86</td>
<td>15.40</td>
<td>17.54</td>
<td>15.08</td>
<td>15.79</td>
<td>15.29</td>
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<tr>
<td>MnO</td>
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<td>0.57</td>
<td>0.41</td>
<td>0.77</td>
<td>0.41</td>
<td>0.48</td>
<td>0.62</td>
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<tr>
<td>MgO</td>
<td>7.50</td>
<td>11.65</td>
<td>11.10</td>
<td>10.38</td>
<td>11.29</td>
<td>11.84</td>
<td>9.19</td>
</tr>
<tr>
<td>CaO</td>
<td>10.66</td>
<td>11.41</td>
<td>11.84</td>
<td>11.50</td>
<td>11.96</td>
<td>12.08</td>
<td>11.93</td>
</tr>
<tr>
<td>Na₂O</td>
<td>1.61</td>
<td>1.15</td>
<td>1.14</td>
<td>1.36</td>
<td>1.19</td>
<td>1.31</td>
<td>1.21</td>
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<tr>
<td>K₂O</td>
<td>0.80</td>
<td>0.76</td>
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<td>1.00</td>
<td>1.15</td>
<td>0.80</td>
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</tr>
<tr>
<td>H₂O</td>
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<td>100.26</td>
<td>101.01</td>
<td>101.18</td>
<td>100.63</td>
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<td>0.00</td>
</tr>
<tr>
<td>Total</td>
<td>100.27</td>
<td>100.26</td>
<td>101.01</td>
<td>101.18</td>
<td>100.63</td>
<td>101.65</td>
<td>101.64</td>
</tr>
</tbody>
</table>

Cations calculated on the basis of 23 oxygens and 13 cations —(Ca + Na + K)

| Ti            | 0.2547   | 0.1507   | 0.1384         | 0.1310     | 0.1294    | 0.1488       | 0.1286   |
| Al            | 1.5645   | 1.3415   | 1.5969         | 1.6037     | 1.7166    | 1.4202       | 1.7613   |
| Cr            | 0.0000   | 0.0000   | 0.0000         | 0.0000     | 0.0000    | 0.0000       | 0.0000   |
| Fe³⁺          | 0.0000   | 0.0000   | 0.3309         | 0.1417     | 0.2108    | 0.1419       | 0.5822   |
| Fe²⁺          | 2.8791   | 2.0676   | 1.9118         | 2.1839     | 1.8681    | 1.9360       | 1.9313   |
| Mn            | 0.0718   | 0.0716   | 0.0515         | 0.0971     | 0.0515    | 0.0596       | 0.0781   |
| Ni            | 0.0000   | 0.0000   | 0.0000         | 0.0000     | 0.0000    | 0.0000       | 0.0000   |
| Mg            | 1.7135   | 2.5769   | 2.4554         | 2.3032     | 2.4899    | 2.5870       | 2.0369   |
| Ca            | 1.7678   | 1.6142   | 1.8827         | 1.8343     | 1.9006    | 1.8773       | 1.9007   |
| Na            | 0.6339   | 0.3309   | 0.3280         | 0.3926     | 0.3422    | 0.3723       | 0.3499   |
| K             | 0.1571   | 0.1439   | 0.2026         | 0.1899     | 0.2176    | 0.1496       | 0.2257   |
| F             | 0.0000   | 0.0000   | 0.0000         | 0.0000     | 0.0000    | 0.0000       | 0.0000   |
| Cl            | 0.0000   | 0.0000   | 0.0000         | 0.0000     | 0.0000    | 0.0000       | 0.0000   |
| H             | 2.0000   | 2.0000   | 2.0000         | 2.0000     | 2.0000    | 2.0000       | 2.0000   |

Pressure (kbar) | 4.47  | 3.40  | 4.62  | 4.56  | 5.20  | 3.78  | 5.41
Calculated Depth (km) | 16.9  | 12.9  | 17.5  | 17.6  | 19.6  | 14.3  | 20.4
Present crustal thickness (km) | 22.2  | 22.2  | 22.2  | 22.2  | 15.1  | 21.1  | 19.
Fig. 6. Age data for 3 of the plutons studied. All available mineral ages for each of the plutons is shown as well as the calculated cooling rates derived from them. For details regarding the age data see table 1 in [10]. Closure temperatures of 700°C for zircon U-Pb, 520°C for hornblende K- Ar, 320°C for biotite Rb-Sr, and 280°C for biotite K-Ar were used for the cooling rate calculations. Cooling rates were only calculated between ages whose error ranges do not overlap.

Common late-stage magmatic features include swarms of aplitic dikes with no preferred orientation on a regional scale. On the scale of individual plutons, however, they have a generally consistent orientation. North of Acapulco E-W-trending diabase dike swarms indicate a mafic component within the latest episodes of Tertiary plutonism in the region.

Fig. 6 shows age data from previous studies along the continental margin obtained using different methods [9,10,45]. Cooling rates inferred from closure temperatures of different isotopic systems are variable among the coastal plutons and reach values up to 119(+55, -21)°C/Ma. Cooling rates calculated by Schaaf [46] in the Puerto Vallarta batholith, 700 km northwest of Acapulco, are slightly lower (45°C/Ma, no error given) than those of the area studied. Despite the influence that the volume of plutons and the temperature of the host rocks can have upon the calculated cooling rates, we suggest that uplift rates of the continental margin were higher in the area studied than in the Puerto Vallarta region.

4. Hornblende geobarometry

In order to estimate the depth of emplacement of the batholiths along the coast, we applied aluminum-in-hornblende geobarometry to selected samples from seven of the plutons between Acapulco and Sta. Maria Huatulco. The empirical Al-in-hornblende geobarometer was first proposed by Hammarstrom and Zen [47] and later modified and refined by Hollister et al. [48]. Schmidt [49] experimentally calibrated the geobarometer and proposed the following linear relationship between pressure and total Al content of the amphibole:

\[ P(\pm0.6\text{ kbar}) = -3.01 + 4.78\text{Al}_{\text{tot}} \]

which is the formula we have used for the calculations presented in this paper (Table 1). The samples analyzed satisfy the mineralogical association criteria outlined by Schmidt [49]:

- two feldspars + quartz + biotite + hornblende
  - Fe – Ti oxides + titanite + apatite
without exception.

Quantitative chemical analyses of amphiboles were carried out independently at the Department of Geological Sciences of the University of Milan (by Pedro Corona) and at the Institute of Mineralogy and Petrography of the University of Munich (by Gustavo Tolson) using ARL-SMQ and CAMECA SX 50 electron microprobes, respectively. Measurements at Milan were performed using the technique of Bence and Albee [50] with alpha-correction factors of Albee and Ray [51]. At Munich, CAMECA software was used for the PAP corrections. The acceleration voltage and sample current were set to 15 kV and 20 nA, respectively, on both microprobes. The total counting time for each measurement was 100 sec. The structural formulae of hornblendes were normalized with the FORTRAN-NORM program of Peter Ulmer (ETH Zurich).

The results of the microprobe work are summarized graphically in Fig. 7. The data for all plutons range from 3 to 7 kbar, corresponding to depths between 11 and 26 km. Table 1 shows the chemical composition and computed structural formulae of representative hornblendes from each of the plutons studied, as well as the depth calculated using the Al content of the hornblende in question. The horn-
blende compositions in Table 1 correspond to those which yielded the median pressure for each pluton. Of the plutons analyzed, two are worthy of particular mention and discussion. The first, the Acapulco intrusive, which is the westernmost of this study, is a pluton of small areal extent (~ 70 km²) and is

![Graph of Al content vs. pressure for different plutons](image)

Fig. 7. Pressure versus Al content graphs showing the range of calculated pressures for the different plutons studied. Attention is drawn to the plot of the Huatulco pluton which appears to show a bimodal distribution. The lower pressure set of data points may reflect subsolidus reactions.
Fig. 8. Schematic representation of the trench–trench–transform triple junction displacement that accompanied the movement of the Chortis block. The displacement of the triple junction produced an approach of the trench toward the magmatic arc axis. Successive positions of the triple junction during the Oligocene and today are shown in map view with corresponding cross-sections. The position of the section lines remains fixed with respect to North America in both maps. The approach of the trench to the magmatic axis produced a gradual decrease in the depth of the interface between the subducted slab and the overriding plate. Subduction erosion of the overriding plate mainly affected the lithospheric mantle. Points x and y are discussed in the text.

petrologically diverse in comparison with other igneous bodies of the region. As stated previously, to the east it is quartz-syenitic grading westward to an alkali feldspar granite with rapakivi texture. This latter member was used for the geobarometric analyses and yielded pressures between 3.5 and 5 kbar. The detailed chemistry of individual phases also sets the Acapulco intrusive apart from the others studied, in particular the Ti content of the biotites is higher. Rb–Sr biotite ages of 43 ± 1 Ma [10] confirm that the Acapulco intrusive belongs to a different tectonic scenario. On the other hand, the Huatulco granodiorite is the easternmost pluton of this study and yielded the greatest spread in calculated pressures (3.7–7.0 kbar), although the data can be grouped into two sets: a lower set with pressures between 3.7 and 4.4 kbar and an upper set with pressures between 5.4 and 7 kbar. The lower of the two sets could be the result of subsolidus reactions.

Results obtained from Puente de Vigas and Cruz Grande intrusives yielded a median crystallization pressure of 4.6 kbar, whereas the San Marcos intrusive yielded 3.4 kbar. These values correspond to depths of emplacement between 13 and 18 km. The Rio Verde and Huatulco intrusives, in the southeastern segment of the region studied, yielded the maximum depths of intrusion (19.6 and 20.4 km, respectively). The depth calculated for the Santo Domingo intrusive, located between Huatulco and Rio Verde, is 14.3 km. The variations in the calculated depth of crystallization along the coast are not systematic and can be attributed to different amounts of crustal uplift.

5. Discussion

The broad exposures of batholithic rocks along the continental margin and the gradual northward increase in volcanic counterparts indicates that the axis of the uplift was on or close to the present coastline. Further, the western margin of the Chortis block shows no evidence of significant uplift during the Tertiary, which leads us to propose a causal relationship between the offshore passage of the Caribbean–North America–Farallon triple junction
and the uplift along the southern Mexican Pacific coast.

Geobarometric data calculated from the samples studied indicate that the presently exposed levels of the plutons were located at depths ranging from 13 to 21 km during crystallization. Since there are no indications of active crustal thinning due to extensional tectonics after the emplacement of the plutons, subaerial and/or basal erosion should account for most of the thinning of the offshore continental margin crust.

The timing of uplift is constrained by the intrusion ages of batholiths (33–27 Ma) and the beginning of marine sedimentation over previously eroded intrusives during the Early Miocene [12]. As discussed above, there are indications that uplift (30–25 Ma) was rapid compared with that along the continental margin northwest of Zihuatanejo. Factors that can account for this difference in the uplift rate may be linked to the displacement of the Chortis block from a paleoposition on the continental margin southeast of Zihuatanejo [10].

The reason for the uplift of the continental margin after passage of the triple point is neither entirely obvious nor trivial. There is no evidence for the collision of oceanic ridges or plateaux with this margin. However, the subduction of the Farallon Plate along two non-collinear trench segments (Fig. 8) must have produced a thickening of the subducted slab at the junction of the cylindrical flexures (bulges) along each trench segment. This is a geometrical necessity brought about by strain compatibility requirements, when a planar surface is folded along two non-parallel lines. We suggest that this thickening of the downgoing slab could contribute to the progressive uplift along the continental margin as the triple junction migrated towards the southeast.

The present-day geometry of the continental margin, directly underlain by the subducted slab (Fig. 4), indicates the removal of segments of lithospheric mantle and, probably, lower crustal segments by basal subduction erosion. The minimum age for the sharp decline in subduction erosion of sediments and of the landward migration of the trench is indicated by the beginning of the construction of the accretionary prism in the Late Miocene. The bathymetry curve for sediments landward of the accretionary prism indicates subsidence of the continental margin beginning in the Early Miocene [12]. This subsidence is followed by uplift since the Middle Miocene. Thus, the paleobathymetry data suggest that high rates of basal subduction erosion were dominant until the Miocene, at which time there was a decrease in the rates of basal removal of continental material.

High rates of subduction erosion could be attributed to high rates of convergence. The highest rates of convergence along this margin of North America occurred during the Eocene, when Chortis had not yet begun its southwesterly displacement. Thus, the region around Puerto Vallarta and the western margin of the Chortis block were probably the margin segments affected by accelerated rates of subduction erosion.

Given the Caribbean–Farallon–North America plate geometry and kinematics, there was a difference in the rate of convergence along the trenches on either side of the triple junction. Since the motion of Cocos and its predecessors with respect to North America has had an easterly component since the Early Tertiary [10], and since the dominant motion of the Chortis block is toward the east along the Motagua Polochic transform, convergence rates along the Chortis block trench are lower than those on the Mexican side of the triple junction. This difference in the rates of convergence along the two subduction zones could also contribute to different subduction erosion rates along Chortis and southwest Mexico.

Basal erosion and uplift of the margin newly exposed by the lateral removal of Chortis are a logical consequence of the passage of the trench–trench–transform triple junction. Fig. 8 is a sketch of the triple junction displacement that accompanied the movement of the Chortis block to the southeast. Given a generalized cross-sectional wedge geometry of the leading edge of the overriding plate, the thickness of the continental crust decreases toward the trench. The crustal thickness at two points, x and y, the first positioned on the trench and the second inland along the transform, would be 0 and 30 km (for example), respectively (Fig. 8). As the triple junction nears point y along the transform, the crust must be made thinner if the idealized wedge shape is to be maintained. Two possible mechanisms of ascent of the plate interface beneath the arc could be the removal of the lowermost portion of the overrid-
ing plate by basal erosion, or the uplift of the lithospheric section with the consequent subaerial erosion of the exposed crust. Regional tectonic features of the southwestern continental margin of Mexico point to the occurrence of both mechanisms in the reshaping processes of the margin since the Oligocene. Basal erosion of the overriding plate may have been favored by the thermally induced weakness of the lithosphere produced by the Late Oligocene plutonism.

Margin uplift could also be the result of underplating of material removed by subduction erosion. However, the seismic modeling data cited above indicate at most a thin (5 km) veneer of low-velocity material along the subduction shear zone, which would preclude significant uplift by this mechanism.

Cessation of arc magmatism along the continental margin was followed by a pause in the volcanic activity in most of southwestern Mexico. The change in the geometry of the subducted slab to a shallower dip angle can be cited as the main cause for this reduction in magmatic activity and its reactivation at the present-day Mexican Volcanic Belt.

Taking into account the time necessary for the leading edge (100 km depth) of the subducted slab to reach the latitude of the Mexican Volcanic Belt and to induce magmatism in it since the Pliocene, the minimum age of the beginning of its subhorizontal trajectory can be estimated at about 15 Ma. These results led us to propose a connection between the beginning of this trajectory and the most intense episodes of subduction erosion following the passage of the triple junction.

The thin continental crust along the southwestern continental margin of Mexico raises the question whether and to what extent the lower continental crust has been involved in basal subduction erosion. According to Von Huene and Lallemand [17], the subsidence of the most external part of the continental margin, at a convergent boundary, is the result of basal erosion of a lower crust segment. This implies that the present coastline could represent an approximate inflection point, dividing regions with and without basal erosion of the continental crust.

Geobarometric results of plutons distributed along the coast led us to estimate the crustal level of the present surface at the time of crystallization and, hence, to make some inferences about possible removal of lower crustal segments. The documented subsidence of the offshore zone at the southwestern margin of Mexico [12,52], strongly suggests the removal of sections of lower crust, but the lack of adequate samples prevents us from extending geobarometric inferences in order to assess quantitatively the amount of basal erosion.

One of the most critical points in attempting to evaluate the basal subduction erosion of the onshore lower continental crust is the estimation of the original crustal thickness of the southwestern margin of Mexico at the time of extensive Tertiary plutonism. There are some indications that the continental crust was not much thicker than it presently is in Central Mexico at the present locus of arc magmatism. Late Cretaceous and early Tertiary tectonic episodes do not account for an extreme shortening and thickening of the continental crust in southern Mexico; on the contrary, there are indications that the most intense Tertiary plutonism was preceded by trans-tensional tectonic episodes, accompanying the displacement of the Chortis block [23,9]. The emplacement of voluminous plutons produced accretion of mantle material to the crust, although it does not seem to have produced a thickening of the crust similar to that at margins with active shortening, such as the Andes [53].

Assuming that, at the end of voluminous Oligocene magmatism, the maximum crustal thickness of the southwest Mexico continental margin was similar to the present one of middle Mexico, we suggest that it was not greater than 40–45 km. These figures fit well with most of the mature calc-alkaline arcs of the circum-Pacific region with a similar tectonic framework [54–56]. Taking into account the interpreted present-day thickness along the coast (15–25 km) and the subaerially eroded crustal section, calculated from hornblende geobarometry, we would obtain paleo-thicknesses ranging from 35 to 40 km. These results indicate that, in the onshore region near the coast, less continental material was removed by basal subduction erosion than by subaerial erosion.

6. Conclusions

The extensive exposures of Tertiary middle-crustal plutonic rocks along the Mexican coast in conjunc-
tion with geochronological and structural data, indicate that the reshaping of the southwestern continental margin of Mexico was a direct result of the detachment and subsequent southwesterly displacement of the Chortis block.

Geobarometry provides evidence that uplift along the truncated continental margin has varied between 13 and 20 km since the Late Oligocene. Calculated cooling rates (~ 120°C/ Ma) along this margin are, in general, higher than those reported for the Puerto Vallarta batholith [46] and are indicative of rapid uplift.

The passage of the trench–trench–transform triple junction is the direct cause of the rapid uplift and of the cessation of arc magmatism. Sections of lithosphere once located in the magmatic arc were gradually involved in episodes of basal erosion, as a consequence of the approach of the trench to the arc, as the transform fault was replaced by the subduction zone. A decrease in the depth of the boundary between the subducted (Farallon/Cocos) and overriding (North America) plates is a geometrical necessity of TTF triple point migration.

The geobarometric data, in the context of the geophysical constraints regarding crustal thicknesses along the continental margin, suggest that the thickness of upper crustal rocks removed by subaerial erosion is greater than the thickness of the lower crustal rocks removed by basal subduction erosion.

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