

Editorial

# Introduction to the special volume “Subduction-related igneous activity in Central America – its nature, causes and consequences”

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## 1. Objectives of the Czech project in Central America

The regional research of Czech and Slovak geologists in Central America, under the auspices of the Ministry of the Environment of the Czech Republic and in the context of Foreign Development Aid of the Czech Republic took place during several stages. The first, (1997–2001) concentrated on the Nicaraguan part of the Central America Volcanic Front (CAVF). As a result, a geological map of the recent volcanic belt was compiled on a scale of 1 : 200 000 (Hradecký and Šebesta eds. 2006). Further stage focused on the highlands in central and northern parts of the country (2002–2009). Later, the research activity extended to El Salvador (2003–2005 and 2007–2009) and since 2006 also to Costa Rica (2006–2009).

The main emphasis was on geological studies and documentation of natural hazards in areas designated by the foreign partners. Large body of data was obtained during the thirteen-year project, especially on the Cenozoic volcanic sequences/plutons and metasediments.

## 2. Geotectonic setting of Central America and brief outline of geology in Nicaragua, Costa Rica and El Salvador

### 2.1. Crystalline basement

Opinions on the structure and tectonic development of Central America are being formulated since the 1940's (Weyl 1980). Ever since, the knowledge on geology, structure, petrology, magmatic and volcanic processes has advanced rapidly.

The individual areas of Central America differ especially in the nature of the basement. In studied areas, main

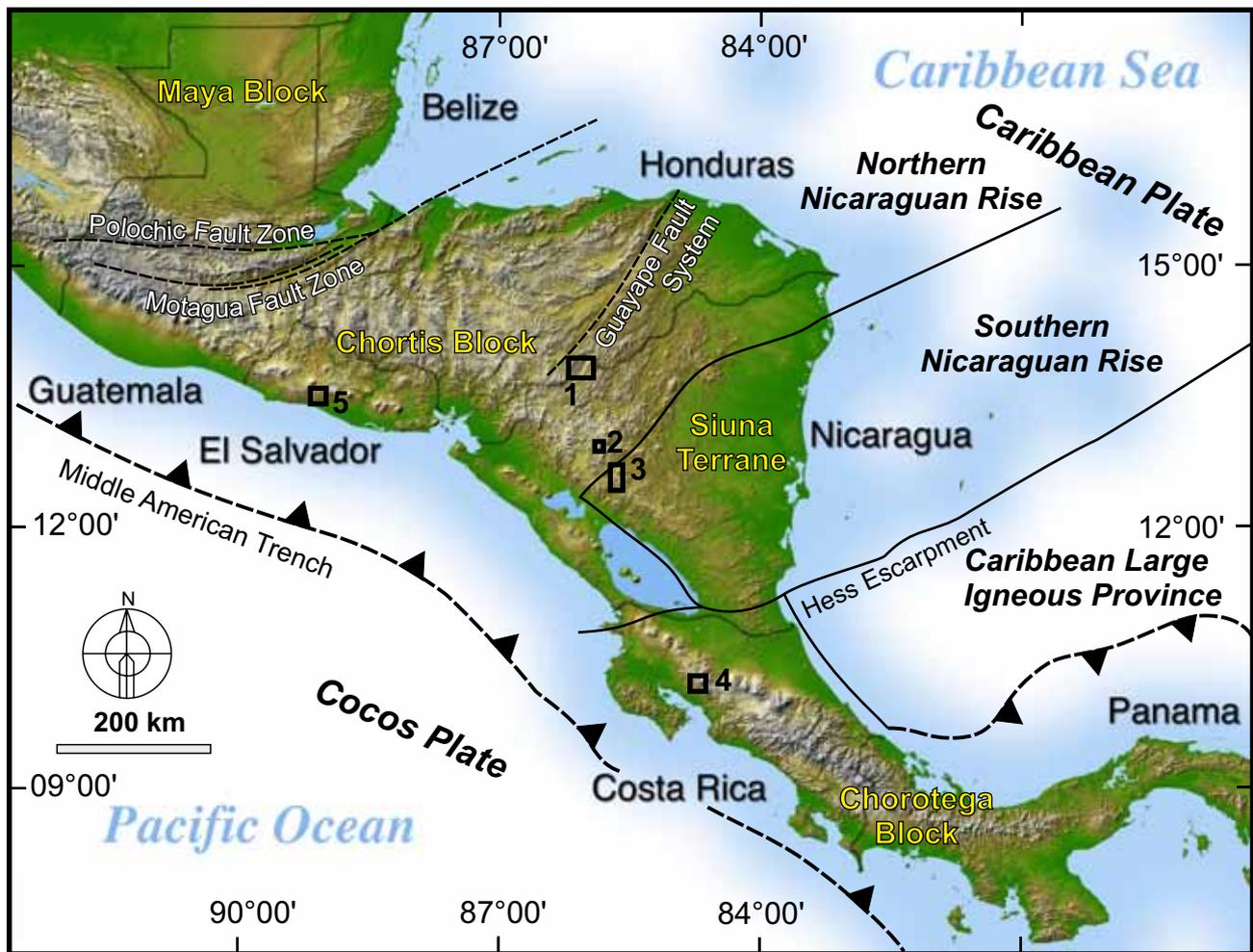
basement components are Chortis and Chorotega blocks (Fig. 1). The Chortis Block is bordered by Motagua Fault Zone and Hess Escarpment in NW El Salvador and NE Nicaragua, respectively. Its central part is underlain by Precambrian crust, separated from southern Mexico in Late Cretaceous–Paleogene (Mann et al. 2007). Eastern Chortis Block in NW Nicaragua rests upon Jurassic metasediments (Honduras Group, Agua Fria Formation – Rogers 2003). The age of metamorphism remains a matter of discussion in some areas. Crystalline basement is covered by Late Cretaceous to Paleogene continental sediments (the Totogalpa Formation in Nicaragua) and basic volcanites (in the neighboring Honduras). Occurrences of metabasic rocks to the east of the Chortis Block in central Nicaragua are interpreted as oceanic arc accreted to the Chortis Block in Late Cretaceous times (Siuna Terrane, Ranero et al. 2000). In the Late Miocene, entire Chortis Block was uplifted and the Siuna Terrane rocks are now exposed in small erosion windows.

The Chorotega Block rests upon the thickened ocean crust in Costa Rica. Continental crustal rocks are absent. Basic complex, i.e. peridotites, pillow basalts, basic intrusives and pelagic sediments is interpreted as a vestige of the Early Cretaceous ocean floor. Mesozoic picritic basalts with 20 % of MgO, resembling komatiites, are special features (Alvarado et al. 1997; Hauff et al. 2000).

### 2.2. Sedimentary cover (Mesozoic–Cenozoic)

The Late Cretaceous sediments, affected by several folding stages, are included in formations over the entire territory of Costa Rica. At the Pacific coast, the main uplift phase took place soon thereafter.

In Nicaragua, a strip of sedimentary and mixed volcano-sedimentary rocks crops out in five formations of Late Cretaceous–Pliocene age along the Pacific coast



**Fig. 1** Topography and tectonic setting of the Central America. After Rogers et al. (2007), modified. Individual studied areas: 1) Ocotal–Dipilto Pluton; 2) Cerro Tijerina, Matagalpa; 3) Boaco–Santa Lucia; 4) Segment of the Cordillera de Tilarán; 5) San Salvador and segment of the Cordillera de Bálsamo.

(Sandino Basin, Weyl 1980). Mesozoic volcanic rocks and folded sediments of the Metapán Group occur in northern El Salvador. Jurassic and Cretaceous sequences in El Salvador, correlated with similar developments in Guatemala and Honduras, have been recently confirmed palaeontologically. Paleocene Red Beds form the youngest sediments in NE of El Salvador.

### 2.3. Extinct arc-related igneous activity

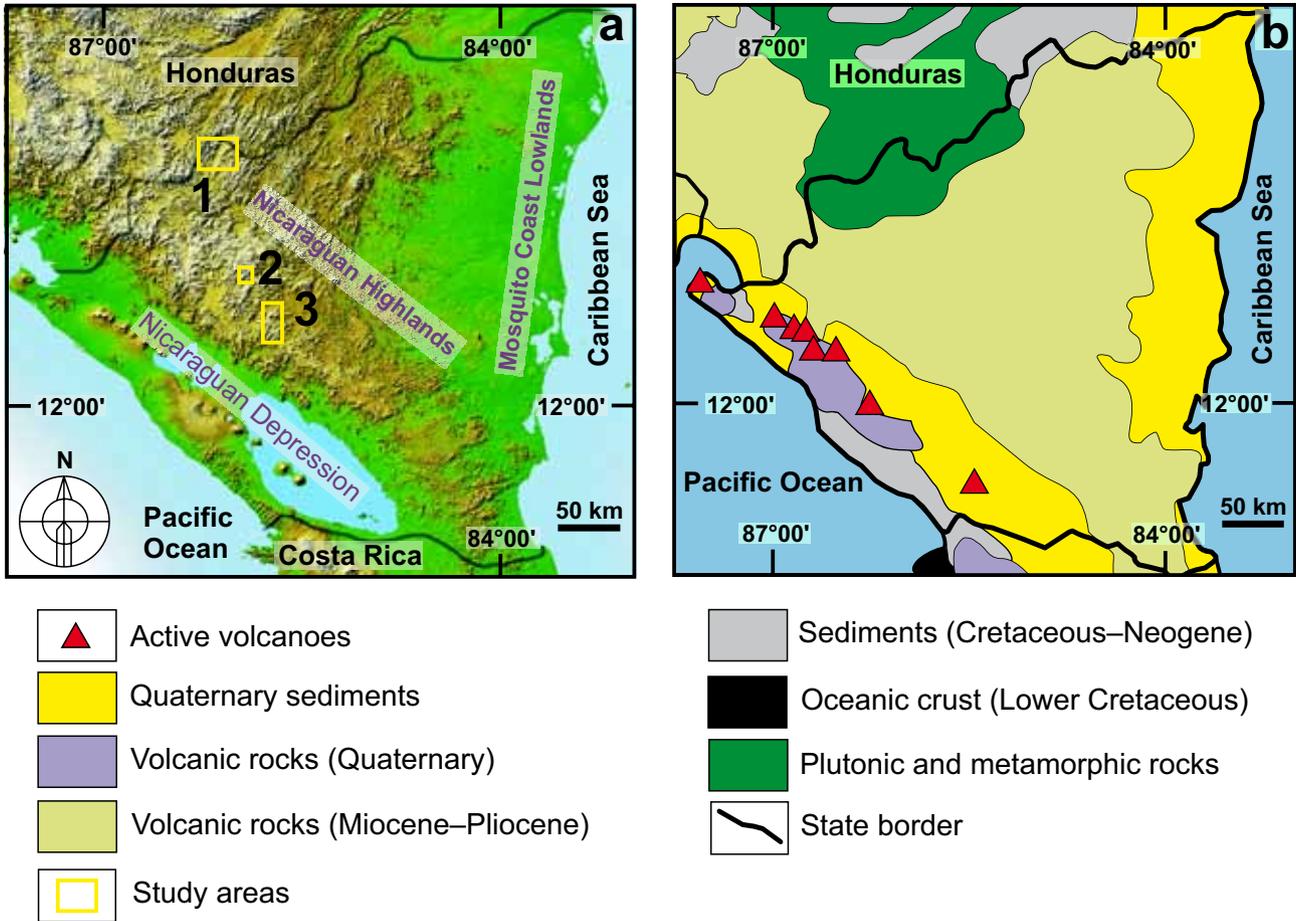
Remnants of the Oligocene–Miocene arc can be found throughout the Interior Highlands of Central America. Paleogene to Pleistocene calc-alkaline volcanic rocks with an extensive plateau of both silicic and andesitic ignimbrites predominate in the central and NW Nicaragua (Fig. 2). The main volcanic phase occurred in the Oligocene, when a number of rhyolite calderas were formed (Ehrenborg 1996).

The Cordillera de Tilarán in Costa Rica (Fig. 3), built by several formations of mostly basaltic and andesitic

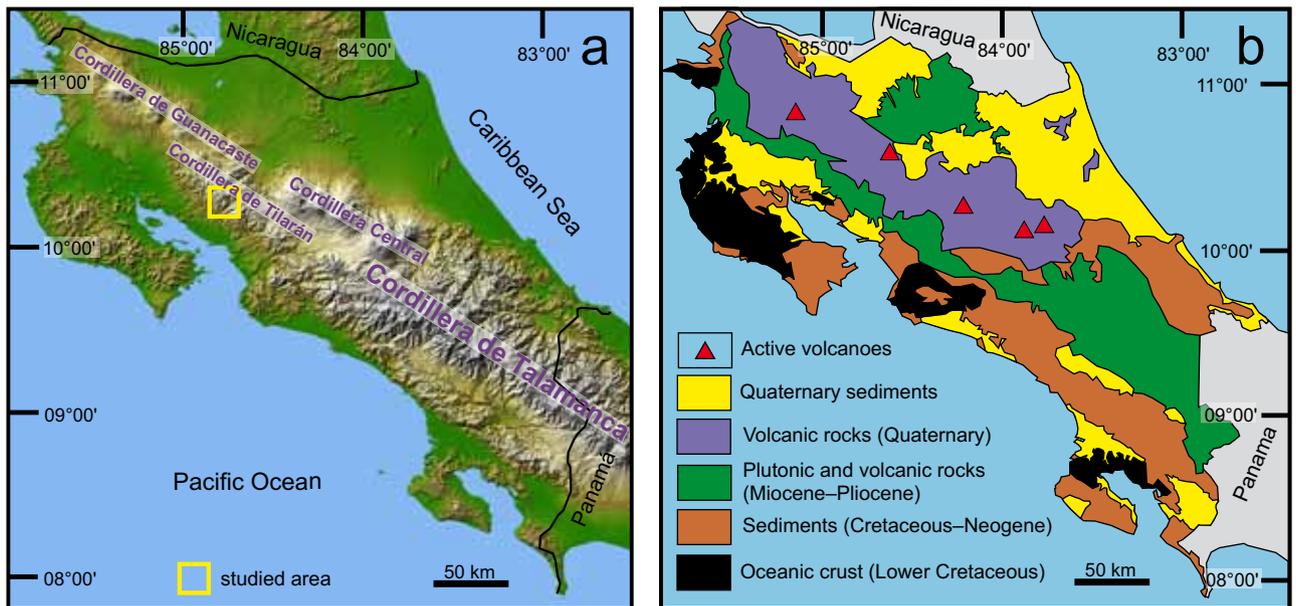
volcanic rocks, is of Miocene–Early Pleistocene age. In the neighboring Cordillera de Aguacate also silicic rocks are known.

In El Salvador, the extinct arc volcanism includes in the Chalatenango, Cuscatlán and Metapán formations (Miocene–Pliocene) and differs from the recent CAVF by higher contents of MgO and Nb and lower Ba/La ratios of the lavas. This was interpreted as a consequence of decompression melting of the mantle that was only slightly by modified subduction (Walker 1981; Rappich and Hradecký 2005).

The Cenozoic ignimbrites, which are common throughout the Central America, have varied composition. Welded and non-welded, they account for the bulk of silicic calderas remnants in the Nicaraguan inland, northern El Salvador and in the volcanic *cordilleras* of Costa Rica. It is assumed that silicic magmas with high  $K_2O/Na_2O$  ratios could have formed by large-degree of fractionation in deep crustal reservoirs or partial melting of mantle-



**Fig. 2** Topographic (a) and geological (b) sketches of Nicaragua. Geology modified from Weyl (1980). Studies areas: 1) Ocotal–Dipilto Pluton; 2) Cerro Tijerina, Matagalpa; 3) Boaco–Santa Lucia (i.e. the same numbers as in Fig. 1).



**Fig. 3** Topographic (a) and geological (b) sketches of Costa Rica. Geology simplified from Denyer and Kussmaul (2006). Studied area is demarcated.

derived, lower crustal intrusions. Apart from melting of the Chortis Block continental crust, extraction of silicic residual melt from a crystalline mush crystallizing from mantle-derived magmas could have also contributed to silicic ignimbrite formation in the areas underlain by the Chorotega Block ocean basement (Vogel et al. 2006). A number of authors have studied the compositional variability and correlation of the Central American ignimbrite formations (e.g., Vogel et al. 2006; Hradecký 2006).

Precambrian–Pliocene plutonic rocks (Harry and Green 1999) form small bodies in the N and NW Costa Rica; their largest occurrence represents the Cordillera de Talamanca Massif. The relatively small Guacimal Pluton in the Cordillera de Tilarán is Late Miocene in age. In northern Nicaragua, the Cretaceous Ocotol/Dipilto Pluton extends to the Honduran territory and several small intrusive bodies are known in central and Pacific coastal parts of the country (e.g., San Juan del Río Coco and El Tránsito dyke). Granodiorite–granite Dulce Nombre de María Pluton in the centre of El Salvador and small monzonite stocks in the north are only intrusive bodies in that country.

#### 2.4. Modern volcanic front

The modern volcanic arc (CAVF) traces the Pacific coast of Central America from Guatemala as far as Panama. As the subduction of the oceanic Cocos Plate under the continental Caribbean Plate is slightly oblique, the overlying crustal block rotates counter clockwise (La Femina et al. 2002; Girard and van Wyk de Vries 2005). Thus, the CAVF is segmented into several sectors bound by right-lateral horizontal faults (Stoiber and Carr 1973).

The Deep Sea Drilling and later Integrated Ocean Drilling projects in Nicaragua and Costa Rica (Kutterolf et al. 2006) recognized two main groups of subducting sediments: pelagic carbonates and diatomic deep-oceanic clays. The main indication for subducting sediments in the arc magmas is the presence of Ba, which is enriched in the sediments as a result of biogenic activity (Carr et al. 2003).

In Nicaragua, volcanic front includes eight active volcanoes and a number of Tertiary to Pleistocene volcanic edifices of various forms and compositions.

The main Costa Rican CAVF volcanoes are of the shield type, with broad bases formed of basaltic lavas. The five still active among them are located in the Cordillera Guanacaste and Cordillera Central. The Arenal volcano is considered as the most active in Central America.

Four Salvadoran active volcanoes are clustered with small extinct edifices. Dormant volcanoes in Golfo Fonseca were studied by Czech project in 2003 (Rapprich et al. 2010).

A mantle wedge above the subducting slab is melted as a consequence of the influx of volatile components

and/or partial melts from the subducted plate (Carr et al. 2003). The crust is thin in Nicaragua and thus the magma is not very contaminated, largely preserving its pristine character. The Ba/La and U/Th ratios drop and, in contrast, La/Yb increase from NW Nicaragua along the arc to both Costa Rica and El Salvador. The highest Ba/La and lowest La/Yb ratios in NW Nicaragua were ascribed to highest subduction fluids flux and thus, higher extent of melting (Carr et al. 2003). On the other hand, La/Th ratios increased towards central Costa Rica were interpreted to indicate gradually diminishing input from the slab-derived fluid (Carr et al. 2007).

Scattered small volcanic centers of basic magma are located behind the active CAVF. The chemistry of lavas confirms an origin by decompression melting of OIB-like mantle source, with only limited, and to the east rapidly decreasing, subduction-related signal. Differences in composition of subducting slab in the NW Nicaragua against NE area influenced by the Galápagos hot-spot has been discussed by many workers (Walker 1981; Walker et al. 1990; Janoušek et al. 2010 and references therein).

#### 2.5. Structure, main features

The boundary between the two crustal blocks (Chortis and Chorotega) is formed by a fault zone known as Hess Escarpment, which continues offshore to the NE where it separates Nicaraguan Rise and Caribbean Large Igneous Province (CLIP) (Fig. 1).

The extinct Cenozoic volcanic zone (Coyol arc, Vogel et al. 2006) is bounded on the SW by the Nicaraguan Depression (Fig. 2a), a 600 km-long asymmetric graben, delimited by a transtensional fault zone. The depression has developed since the Pliocene, passes through Golfo Fonseca to El Salvador, forming there the so-called Central Salvadorian Graben and into northern Costa Rica in the opposite direction. Nicoya Bay is not a continuation of this structure, though.

The Nicaraguan depression is in a tectonic contact (right-lateral transtension) with the Las Sierras caldera system close to Managua. Laboratory modelling has demonstrated the pull-apart character of this volcanic structure (Girard and van Wyk de Vries 2005). A great many transverse and longitudinal fractures are manifested both in the basement (Nicoya in Costa Rica) and also in Mesozoic and Tertiary sediments close to CAVF in the three studied countries.

Tectonic forces affecting the roots of the Pacific zone of the continent generate dynamic and rugged morphology in Costa Rica (seismically active Chorotega Forearc Province) (Marshall 2006).

El Salvador is built by the W and N parts of the Chortis Block, of which the Motagua–Poloic Fault Zone forms its NW boundary. Various fault systems

have various importance. Principal one passes W–E and corresponds to the Salvadoran Depression. This system is also responsible for shallow earthquakes in the area.

## 2.6. Comments on geological hazards

Detailed vulnerability and possible hazard impacts assessment formed the substantial part of the CGS projects.

There are currently 17 active volcanoes and a number of geothermal fields in the CAVF zone in the three countries. Active volcanism is studied intensely both to eliminate the consequences of destructive eruptions and also for correlation of products in space and time (e.g., regional tephrostratigraphy from offshore drill cores for identifying highly explosive eruptions: GEOMAR Kiel). Regional research is combined with work in the field, remote sensing and the SRTM (Shuttle Radar Topography Mission) method with a resolution of 90 m on DEM relief. The seismic monitoring is becoming available in ever-better detail, as is information on areas affected by earthquakes and the related landslides.

Seismic monitoring of volcanic eruptions is nowadays done by sophisticated methods based on digital data transmission from broad-band seismometers located close to volcanoes. This enables the use of real-time data for Early Warning Systems. Well-equipped National seismic network in Nicaragua relies on 52 stations (2006) and round-a-clock monitoring by INETER personnel.

Landslides triggered by earthquakes represent a very important hazard factor all over the Central America – e.g. in Guatemala (1976 Motagua Fault Zone), Nicaragua (1998 Casita), El Salvador (2003 Las Colinas) or Costa Rica (2009 Cinchona). For their mitigation geological methods have been applied, e.g. slopes susceptibility models, studies of rock lithology and mechanical character, weathering, alteration processes studies, soil analyses and Quaternary events (erosion and aggradation) evaluation. These methods were also applied in the framework of the Czech projects, in cooperation with other colleagues, for example in Nicaragua (Dévoli 2008).

## 3. Contributions in this volume

### 3.1. Nicaragua

The area of crystalline complex of northern Nicaragua remained little known for a long time. **Buriánek and Dolníček** studied the contact aureole of the Cretaceous Dipilto/Ocotal tonalite–granite–diorite pluton with greenschists forming the Jurassic equivalent of Agua Fría Formation (Fig. 2a). Three stages of metamorphism were recognized: regional, contact and post-contact retrograde, accompanied by ductile deformation. Detailed petrologi-

cal and mineral data support the proposed model of the aureole evolution.

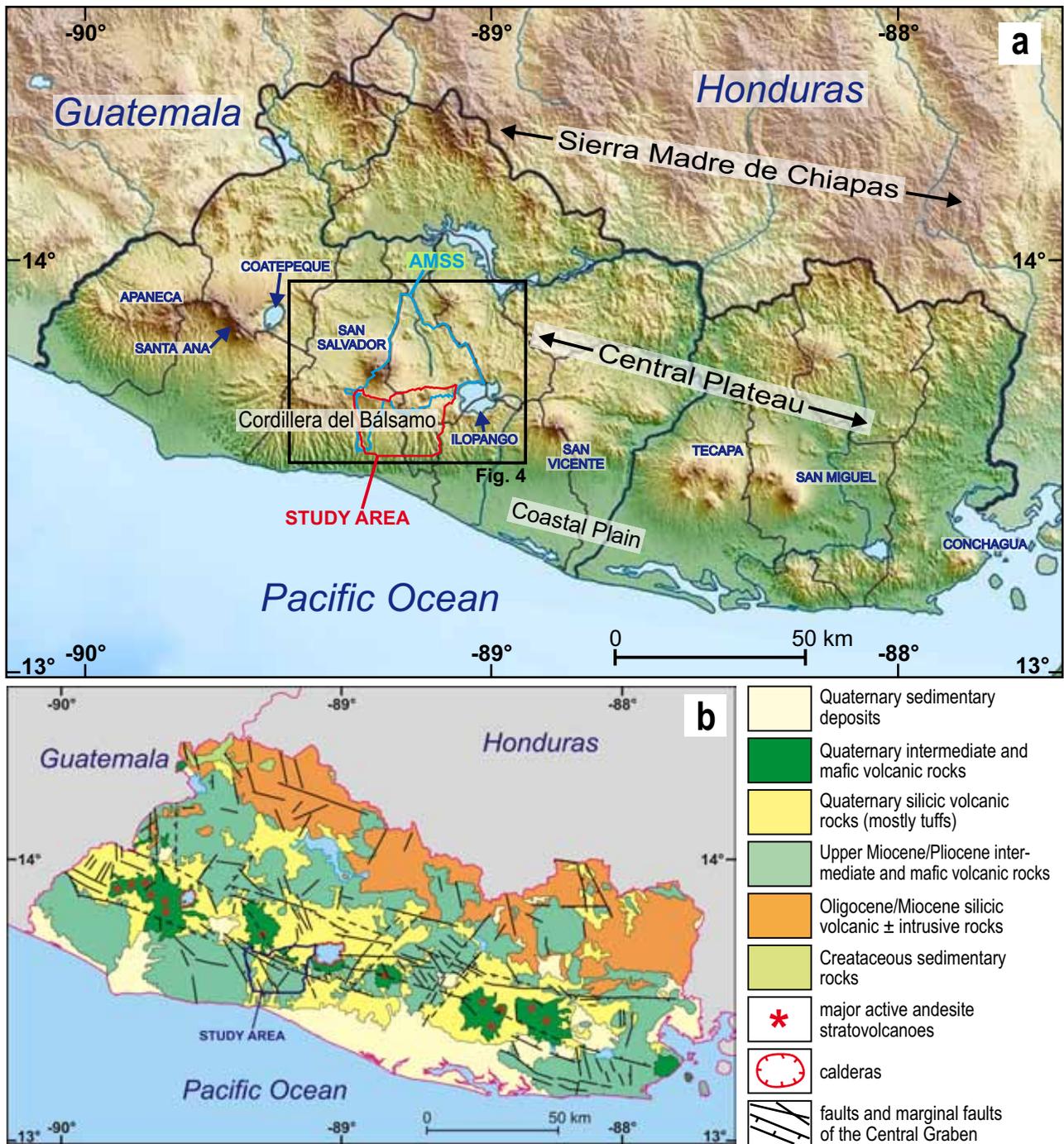
The Coyol volcanic arc in Nicaragua has been defined as a regional Mio–Pliocene belt composed of shield silicic volcanoes, with basaltic and andesitic stratovolcanoes of the Matagalpa and Coyol groups. **Buriánek and Hradecký** present the reconstruction and volcanic stratigraphy correlation of the Santa Lucia and surrounding volcanic edifices in central part of Nicaraguan Highlands. New model assumes the evolution of composed volcano starting with prominent explosive events producing mostly non-welded silicic ignimbrites, continuing by effusive activity and ending by the edifice collapse. Thick accumulations of debris flows and lahars are remarkable features. Correlation with La Luna and San Lorenzo volcanoes confirm similar volcanic products of every edifice. Differences occur in nearby Las Lajas caldera, which was earlier considered as Pleistocene, estimated by its fresh morphological appearance. Newly detected higher contents of Ba and U and higher ratios of Ba/La and Ba/Th in Las Lajas lavas may indicate a fluid flux from the subduction slab, which is typical of modern Nicaraguan CAVF volcanics.

Minute (max. 3 cm in diameter) obsidian balls (marekanite) are reported from Cerro Tijerina in Central Nicaragua by **Mrázová and Gadas**. Balls are formed by silicic glass (obsidian) with microphenocrysts and occur together with rhyolitic perlite. Both glass forms can be found in silicic, highly rheomorphic ignimbrite which lies atop the explosive–effusive Coyol sequence. It is believed that obsidian and perlite originated from the same silicic melt; differences are in the degree of hydration (higher in obsidian). No other comparable marekanite-bearing rocks are known from Nicaragua.

### 3.2. Costa Rica

Comprehensive study of the Guacimal pluton in Cordillera Tilarán is presented by **Žáček et al.** (Fig. 3a). This isolated monzogranite–granodiorite intrusion has been subject to field mapping, magnetic susceptibility measurements, whole-rock chemical analyses, evaluation of petrology and mineral chemistry, as well as U–Pb zircon dating. The Sr–Nd isotopic compositions are rather primitive and their only limited dispersion effectively rules out open-system processes such as magma mixing or assimilation of isotopically contrasting upper continental crust. Pluton emplacement occurred at the depth of *c.* 3 km. The Guacimal Pluton ranks among the youngest intrusions in the country (6.3–6.0 Ma, i.e. Late Miocene).

Ore mineralization in the Miocene–Pliocene Aguacate Formation in Cordillera de Tilarán is a subject of study by **Mixa et al.** This mineralized district was exploited for gold since 1815. Veins are controlled by extensional,



**Fig. 4** Topographic (a) and geological (b) sketches of El Salvador. Geology modified from Wiesemann (1976). Study area is demarcated.

NE–SW, N–S and NNW–SSE trending shear structures. Field collection of heavy minerals and stream sediments was followed by laboratory study of their petrology, mineral- and bulk composition. In addition, ore mineralogy and fluid inclusion studies were undertaken in gangue material from the historical mining regions. Gold occurs as particles enclosed in pyrite and arsenopyrite. Mineralization is a result of shallow hydrothermal circulation of

meteoric waters, driven by the thermal influence of the Guacimal Pluton.

### 3.3. El Salvador

Regional geological knowledge on the Salvadoran geology comes mostly from the German mapping Project (Wiesemann 1976). Detailed information on part of the

El Salvador territory are presented by **Lexa et al.**, who bring new data vital for understanding the geology, volcanology, volcanic stratigraphy and hazards assessment in the broader area of the country's capital (Fig. 4a). Volcanic reconstruction focused mainly onto the Late Miocene–Early Pleistocene Bálsamo Formation. Thirty new K–Ar datings constrain its age, generally comparable with the Coyol Group in Nicaragua. Volcanic evolution is documented by numerous instructive figures.

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