

José Henry Carvajal

Abstract

The western part of the Colombian Caribbean coast is associated with Cenozoic accretionary prisms and influenced by mud diapirism, originated by density contrast between high-pressure muddy mass material containing gases and denser surrounding overburden, and by tectonic compression associated with oblique plate convergence. Mud diapirism surface manifestations are associated with land risings and differential tilting, locally called “mud volcanoes,” land mudflows, mud, and intermittent gas bubbles and accumulation of mud on the surface. These manifestations have been considered as curious and picturesque phenomena. However, paroxysmal phases constitute a geologic risk for the inhabitants and the infrastructure of the region. The region of Cartagena displays numerous examples of these phenomena and deserves a visit by the scientific community which will also appreciate the beauty of this well-preserved colonial city.

Keywords

Mud diapirism • Coastal geomorphology • Caribbean coast • Cartagena

3.1 Introduction

Mud diapirism originates due to both the density contrast between plastic high-pressure muddy materials charged with gases and their denser overburden, and tectonic compression associated with oblique tectonic plate convergence. The muddy diapiric material moves upward through fractures, generating uplift and rock fracturing, and results in mud and gas expulsion through mouths of varied shapes and sizes. This phenomenon is common along Cenozoic folded belts associated with convergent plate boundaries. It is found in Venezuela, Trinidad and Tobago, Ecuador, Panamá, as well as in Spain, Sicily, around the Caspian Sea, in Azerbaijan, Taiwan, and many other localities (Higgins and Sanders 1974; Kopf 2002).

Mud diapirism is a process of land deformation and it is partly responsible for the configuration of the central Colombian Caribbean coastal line (Carvajal 2011). Landforms such as homoclinal ridges, pressure ridges, cuestras, hogbacks, anticline and syncline ridges, marine terraces and islands, located near the continental shelf, owe their origin to mud diapirism that locally favors differential rising of the land, generated by the oblique convergence of the Nazca, Caribbean and South American plates (Verette 1985; Verette et al. 1992; Carvajal et al. 2010 in Carvajal 2011).

Mud volcanoes are attractive manifestations of mud diapirism, and they are locally considered as picturesque landforms of the Colombian Caribbean coast. In 1801, Humboldt A. and Fidalgo visited the area and the former described it (ACCEFYN 1999, Fidalgo 1794 in Mantilla and Cuadros 1958) (see Fig. 3.1, taken from Humbolt 1804, in MacGuillivray 2005) in the following words:

J.H. Carvajal (✉)
Servicio Geológico Colombiano, Bogotá, Colombia
e-mail: jcarvajal@sgc.gov.co



Fig. 3.1 Mud volcanoes at Turbaco. Drawing made by Louis de Rieux, during a visit made in the company of Humboldt in March 1801. From Humboldt 1804 in Mac Guilvray (2005)

The volcanoes of Turbaco are a deserted and lonely place amid the forest, where no bush grows in an extension of about 800 feet, the nearest is the *Bromelia Karatas*. This desert place is made of greyish mud, clay that (according to the theory of Basalt of Werner) is, everywhere, cracked by desiccation in figures of 5 and 6 sides. On this clay layer, many big and small cones rises in wonderful ways. The isolated one that is located farther toward the south part (in fact the one that the young Louis de Rieux drew so well), rises little by little on an extremely wide base to a height of 3 or 4 “toises” (1 toise = 1,946 m). In the summit of the cone there is a circular hole with a crater shape border, some inches wide and it is full water, from it spring up enormous bubbles of air in irregular lapses, approximately five times every 2 min, with a great deaf noise (Humboldt, in ACCEFYN 1999).

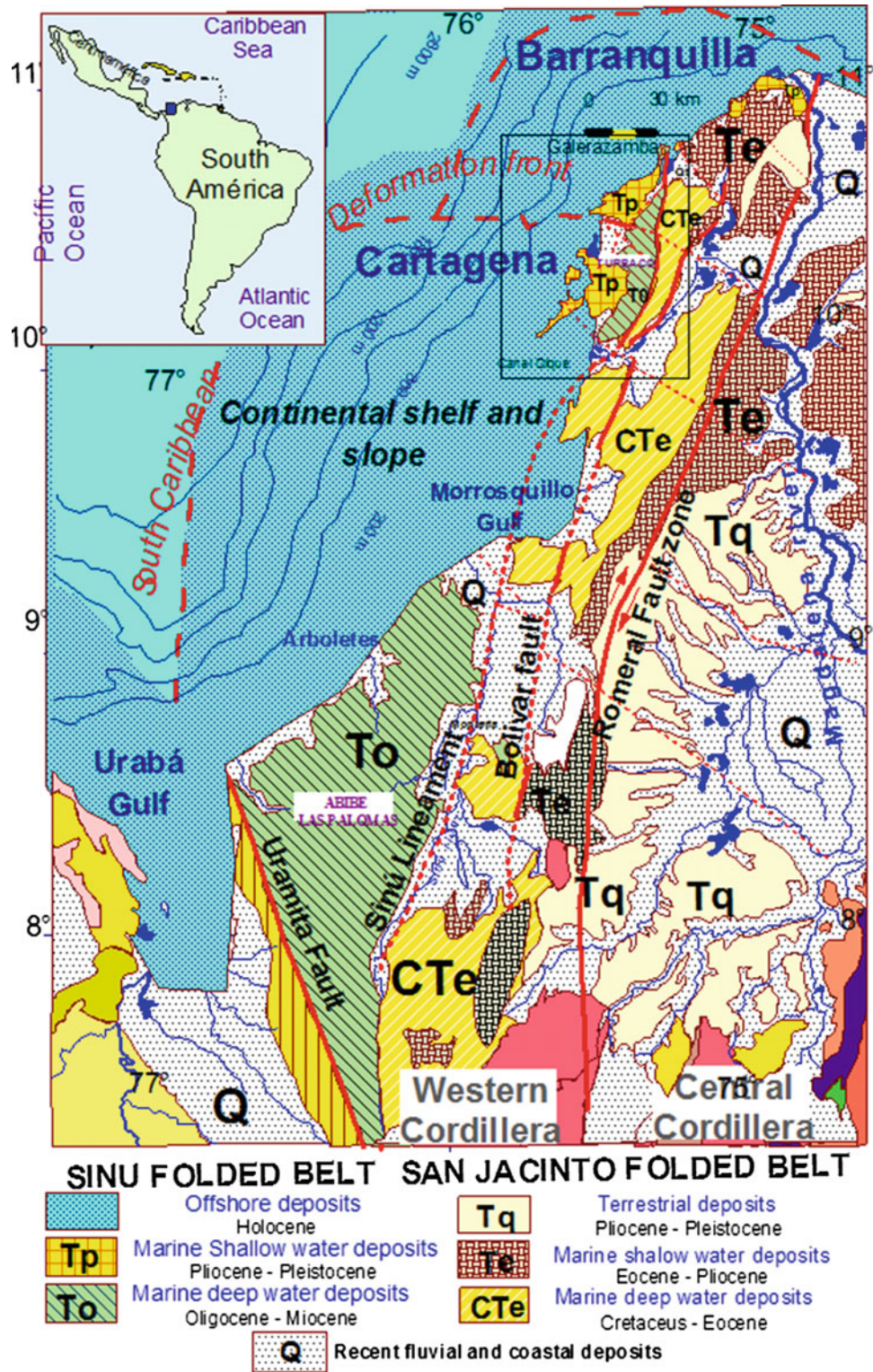
Mud diapirism is found from Barranquilla to the Urabá Gulf, including offshore and onshore areas. It is related to the Sinú and San Jacinto fold belts (Fig. 3.2), which are two wedges of sediments, accreted to the South American Plate, as products of the oblique convergence of the Nazca and Caribbean Plates (Duque 1979, 1984; Vernet et al. 1992; Kellogg et al. 2005). The region described here is located between Galerazamba and the Dique channel. It is characterized by a medium-dry tropical climate, with annual average temperatures of 28 °C, softened by the incidence of the trade winds between January and April.

3.2 Geological Framework

The northwestern Colombian Caribbean coastal zone is framed by two areas with different geological characteristics. A stable platform is separated from an unstable region located west of the Romeral fault system, considered as a major paleosuture, which defines a clear boundary between continental and oceanic basements (Duque 1979, 1984; Toto and Kellogg 1992; Flinch 2003). The stable area is underlain by unfolded continental crust and defined at the surface by the lower Magdalena River basin. The unstable area is formed by two structural sedimentary wedges, defined by Duque (1979) as San Jacinto and Sinú fold belts, in the east and west, respectively. They have been considered as two sedimentary prisms, accreted to the northwestern Colombian margin and they are separated by the Sinú lineament, which defines an evident structural change (Duque 1979, 1984; Obando 2011 in Carvajal 2011).

The San Jacinto fold belt is structurally complex, associated with northwest-verging folds and thrust faults trending northeast. From south to north, it is divided into three structural elements: San Jerónimo, San Jacinto and Luruaco anticlinoriums, respectively (Fig. 3.2), formed by Upper Cretaceous pelagic rocks, a thick sequence of Tertiary rocks

Fig. 3.2 Geological and structural framework of the northwestern Colombian Caribbean coastal region. Modified from Duque (1979), (1984) and Guzmán et al. (2004)



of turbiditic origin and coral reef limestones, locally covered by Quaternary fluvial and lacustrine deposits (Duque 1979, 1984). This fold belt presents locally some mud volcanoes with transcurrent faulting trending NW–SE.

The Sinú fold belt, which extends from the Gulf of Urabá to the north of Barranquilla, includes the present offshore and onshore areas (Fig. 3.2). It is formed by a series of narrow mud-cored, NNE trending anticlines that limit wide

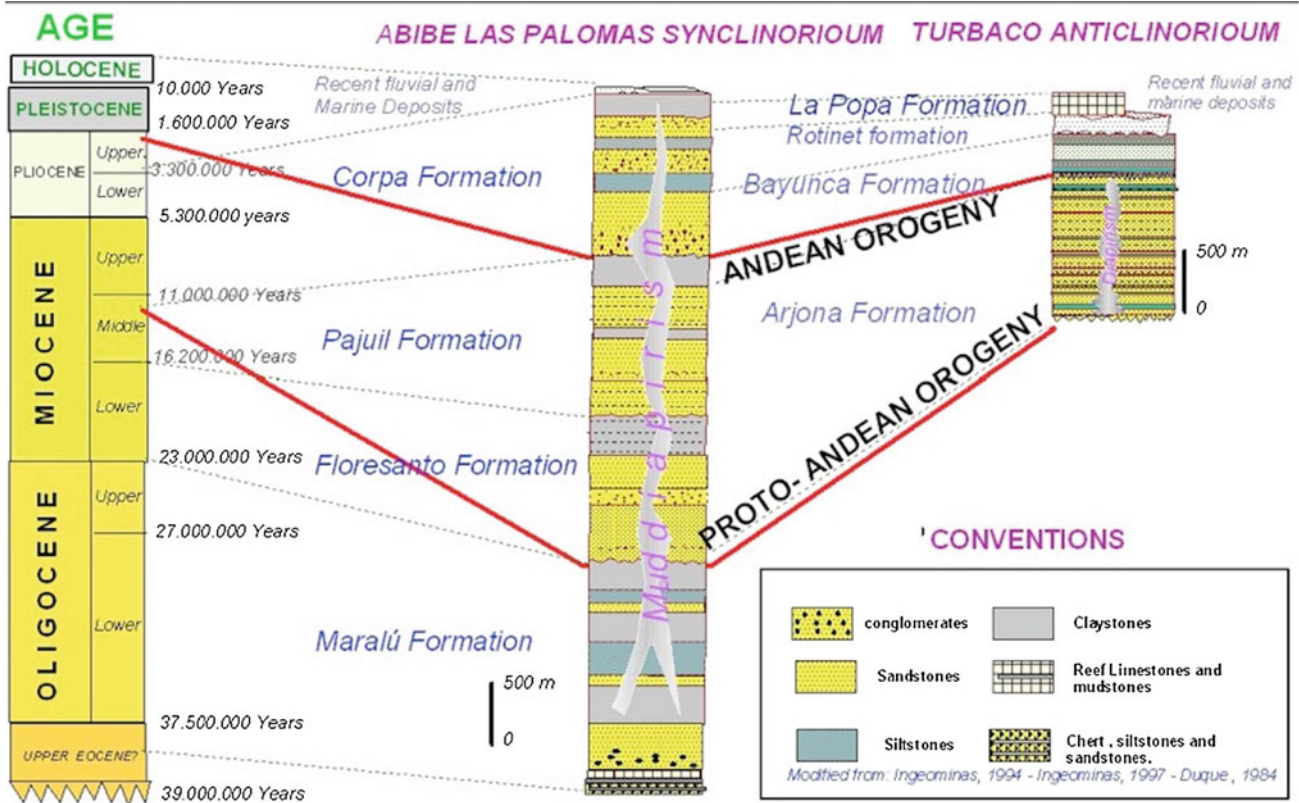


Fig. 3.3 Generalized stratigraphic columns of the Sinú fold belt for the Córdoba–Antioquia and the Turbaco region (Carvajal 2001)

and gentle synclines, particularly in their southern region (Duque 1979, 1984; Mantilla et al. 2009).

The region analyzed in this chapter is located in the Turbaco anticlinorium of the Sinú fold belt (Duque 1979, 1984). It is limited to the east by the San Jacinto fold belt, by the Sinú River lineament (Villanueva fault in the Totumo region, north from Cartagena), whereas to the west, it is bounded by the south Caribbean deformation front and to the south by the Rocha lineament, associated with the Dique channel (Fig. 3.2).

The region from Galerazamba to Cartagena is characterized by broad and gentle synclines (troughs), curved in plan view and wedged eastward against the Villanueva—El Totumo fault; they are limited locally by narrow and tight anticlines associated with NW-verging thrust faulting, which bear mud volcanoes. This structural framework, trending NNE–SSW and NEE–SWW, was formed by transpressional–transensional processes, and it is locally bounded by left-lateral strike-slip faults trending NW–SE (Toto and Kellog 1992; Vernet et al. 1992; Cediél et al. 2003; Ordoñez 2008).

The Sinú fold belt, which was formed during the orogenic Andean phase, from the late Miocene to Pliocene, includes a 5000 m thick sequence of Oligocene, Miocene, and Pliocene pelagic and hemipelagic sediments and turbidites south of

Las Palomas synclinorium. At the Turbaco anticlinorium, sandstones, claystones, and siltstones of turbiditic origin (Arjona Formation) are found tectonically affected by compressive convergence between the Caribbean and South American Plates (Fig. 3.2) (Duque 1979, 1984; Geotec and Ingeominas 2000; Guzmán et al. 2004).

In the structural troughs and highs, these rocks are locally overlain by 4000 m of shallow marine Miocene to Pleistocene–Holocene fluvial and carbonates facies. These sedimentary sequences are made up of claystones, sandstones, gravels, and sands and locally of calcareous sandstones and reef limestones (La Popa Formation) that give to the Cartagena region its attractive landscape (Duque 1979; Reyes et al. 2001; Guzmán et al. 2004). Quaternary deposits present in the region are clays, sands, and clastic and bioclastic gravels of alluvial, aeolian, and marine origin (Fig. 3.3).

3.3 Geomorphological Characteristics

Landforms genetically related with mud diapirism are common in the Sinú folded belt. Mud diapirism is considered as a geological deformation process, being at least partly responsible for the morphological configuration of the coastline.

This province has been also modeled by denudational and accumulation processes and has been subdivided into hills and coastal plains, mainly of denudational, marine, fluvial, and aeolian origins (Carvajal et al. 2010 in Carvajal 2011; Carvajal and Mendivelso 2011) (Fig. 3.4).

3.3.1 Landforms Associated with Mud Diapirism

Morphostructural landforms such as cuestas, hogbacks, anticline ridges, homoclinal ridges, and pressure ridges represent different stages of tilting and deformation (Fig. 3.4). Link (1927) had already documented the morphological expression of numerous shore features along this coast, such as elevated Quaternary coral reefs, wave cut cliffs, elevated residual fluvial gravels, raised, superimposed and diverted streams, and explained their occurrence as the succession of strandline oscillations through stages of erosion, submergence, and emergence. Recent geomorphological mapping indicates that mud diapirism and “mud volcanoes” associated with regional faulting provide evidence of neotectonic activity (Martínez et al. 2010; Carvajal 2011) (Fig. 3.4).

Typical cuestas and hogbacks with sharp to rounded crests, defined by tilting of hard sedimentary rock, with inclinations smaller than 15° and larger than 35°, respectively, are associated with vertical tectonic movement and with mud diapirism. Some examples of this process are the Turbaco cuesta associated with a recently tilted reef coral platform, the considered self paleo-atoll of the Albornoz hill and the highest hill of Cartagena, La Popa (Figs. 3.5, and 3.6).

Pressure ridges develop through an advanced folding process, which begins with the formation of anticline folds, differentially deformed along the structure, called offshore turtle anticlines by Vernet (1985) and may contain positive and negative flower structures (Fig. 3.7). As a result of this process, both local verticality of the sedimentary sequences and “mud volcanoes” on top of the structure occur. The Punta Canoas pressure ridge, 4 km long and 60 m high, developed on folded sandstones and claystones of the Arjona Formation. It trends NE and is characterized by hilly morphology. It is fractured and dissected with a N30°E trend due to dextral strike-slip movements, which facilitated mud volcano occurrence on the summit (Fig. 3.8).

Offshore the Cartagena coastal zone, the effect of convergent tectonics and mud diapirism facilitates the formation of anticlinal ridges (turtle anticlines) and pressure ridges, in whose summits mud volcanoes may form. When these structures reach photic zones, they are colonized by corals, and form islands. This is the origin of the Rosario’s islands, Salmedina banks, Tierrabomba island, and Cascajo, and Arena Islands (Fig. 3.8). Processes associated with mud

diapirism in continental shelves have been well-documented by Sheppard et al. (1968), Vernet (1985), Vernet et al. (1988, 1990, 1992), Briceño and Vernet (1992), Martínez et al. (1990), Carvajal (1992), Correa et al. (2005), GIO (2005), Vinnels et al. (2010) and Carvajal (2011). Vertical tectonic activity in onshore areas has been evidenced by monitoring stations with GPS–GNSS (Mora 2010 in Carvajal 2011). Preliminary results indicate differential uprising in Tierrabomba and Cartagena (6–7 mm/year) and subsidence in Galerazamba (2 mm/year). It is important to signal a much higher subsidence (17–35 mm/year) in the stations located on top of “volcanic” buildings of Pueblo Nuevo (V-6) and Totumo (V-7), which had been previously associated with expansive clays.

Currently, a similar process occurs at the Arenas Island, located NE of the Cascajo island. This island is rising possibly due to mud diapirism, and causes wave refraction and diffraction processes, producing the progradation of the beach to the island (Fig. 3.8).

3.3.2 Mud Volcanoes

The most spectacular manifestations of mud diapirism are undoubtedly “mud volcanoes” located both onshore and offshore (Figs. 3.4, 3.5, 3.7, and 3.8). These mud volcanoes cause the verticality of the sedimentary sequences and facilitate mud movement through fractures and equally between friable and porous sandy layers or strata (Carvajal 2011; Carvajal and Mendivelso 2011). This situation has been evidenced by geophysical data (gravimetry, magnetometry, and profile geoelectric tomography) obtained in the sector of Pueblo Nuevo—El Totumo (Bolívar) (Obando and Vásquez 2010 in Carvajal 2011). Most mud volcanoes are located on the summits of either anticlines, homoclinal ridges, or pressure ridges associated with transpressional–transensional tectonics (Fig. 3.7). Locally, they can be found isolated along right-lateral strike-slip faults (Carvajal 2011). In the Cartagena area, the “volcanic” buildings have dome morphology with convex slopes between 15° and 20°, diameters 0.8–1 km, and heights of 50 m, but they may even reach 4.5 km in diameter (Carvajal 2011).

Craters may reach diameters of 500 m and display several mouths, which may also occur in the flanks of the structures (Figs. 3.9, 3.10, 3.11, 3.12, and 3.13). Mud volcano buildings are formed both by muddy material accumulation produced by eruptions, and by land deformation generated by the upward push of mud (hydrofracturation) (Fig. 3.14). Locally, they may show raised rims caused by the subsidence into the void left by the extruded material (Cañaveral “mud volcano”, Fig. 3.12).

Surface materials that constitute the mud volcano edifices are dark to brownish gray plastic clays, with dispersed clasts

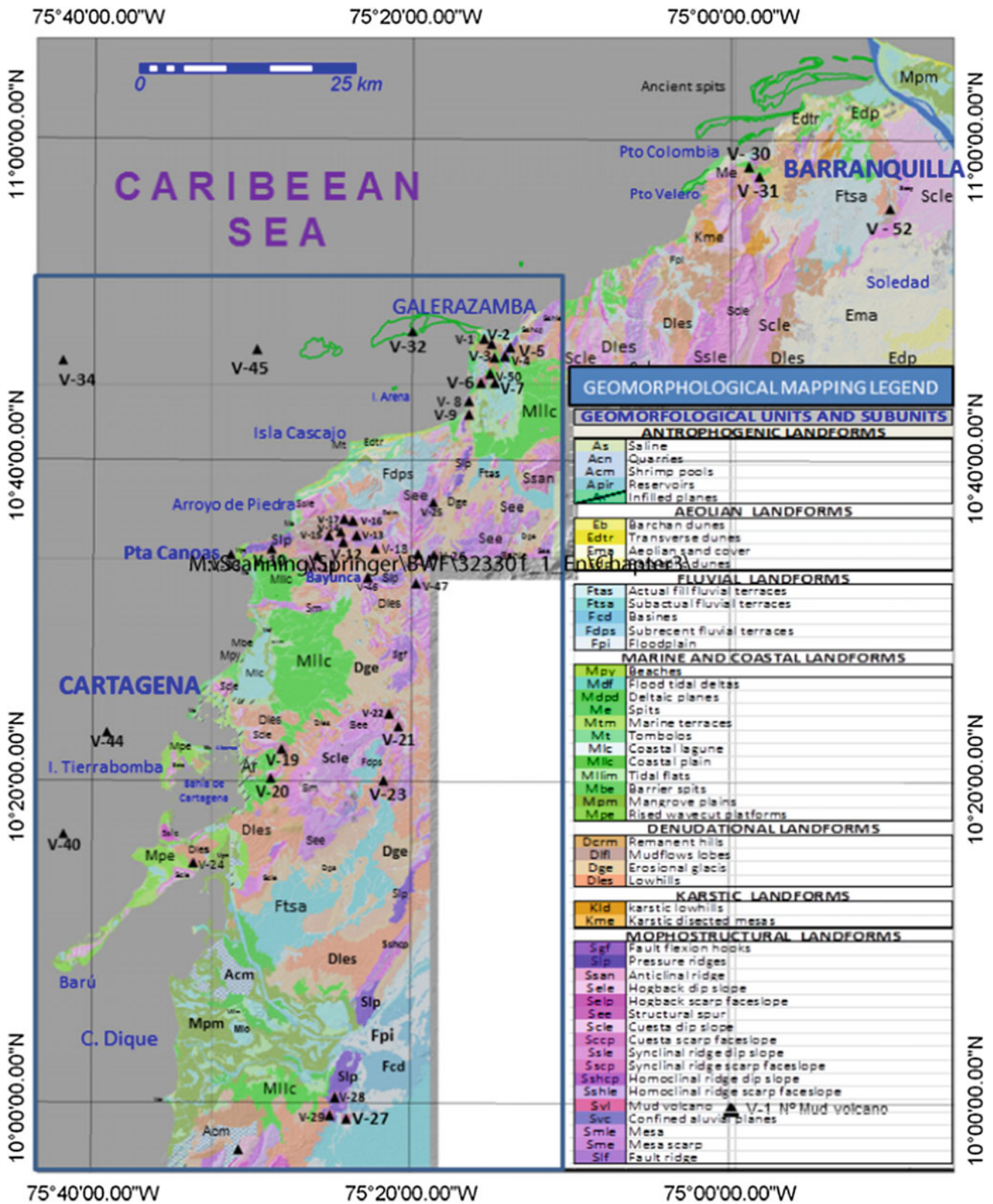


Fig. 3.4 Geomorphological map of the area showing the “mud volcano” locations. Note their common occurrence on and offshore, particularly in the Cartagena zone (blue line). Modified from Carvajal (2011)

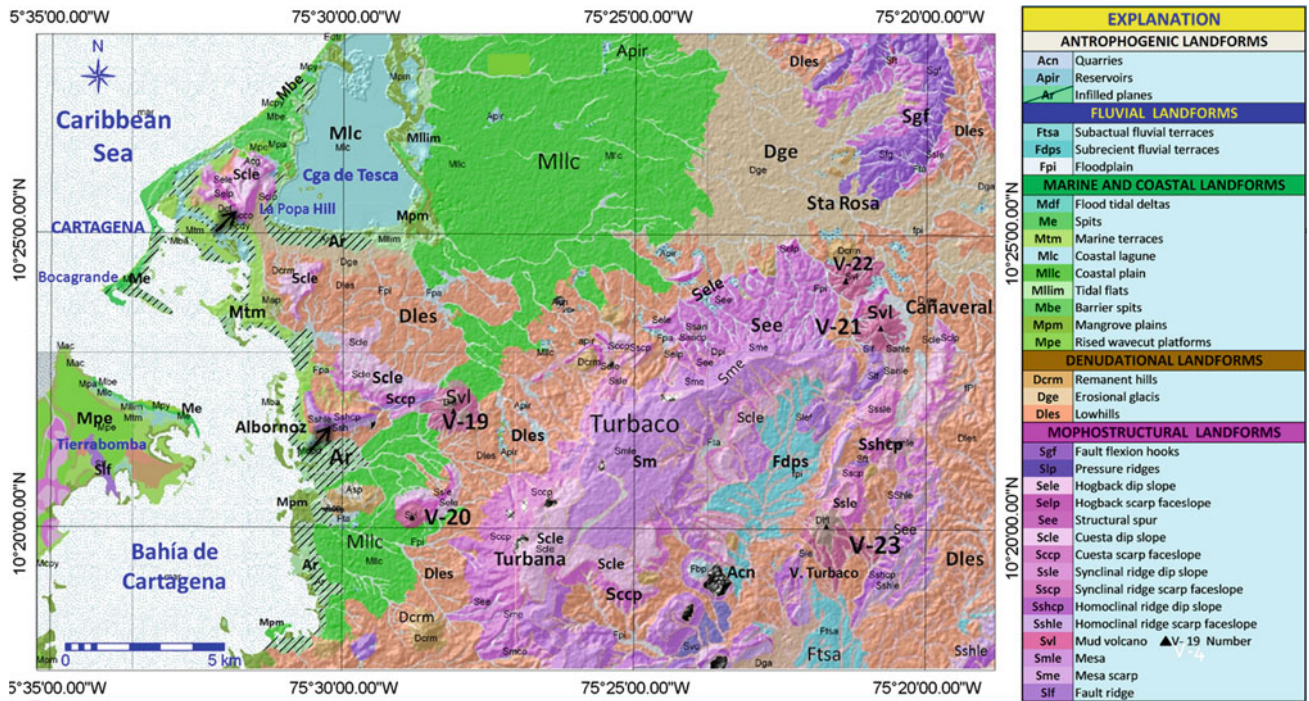


Fig. 3.5 Detailed geomorphological map of the Cartagena area. La Popa and Albornoz Hills are signaled by *black arrows* as El Rodeo, Membrillal, Cañaveral, and Turbaco mud volcanoes. Adapted from Carvajal (2001)



Fig. 3.6 North-looking view of the La Popa hill. Note the conical shape of the cuesta scarp, the accentuated surface erosion processes, and the presence of landslides

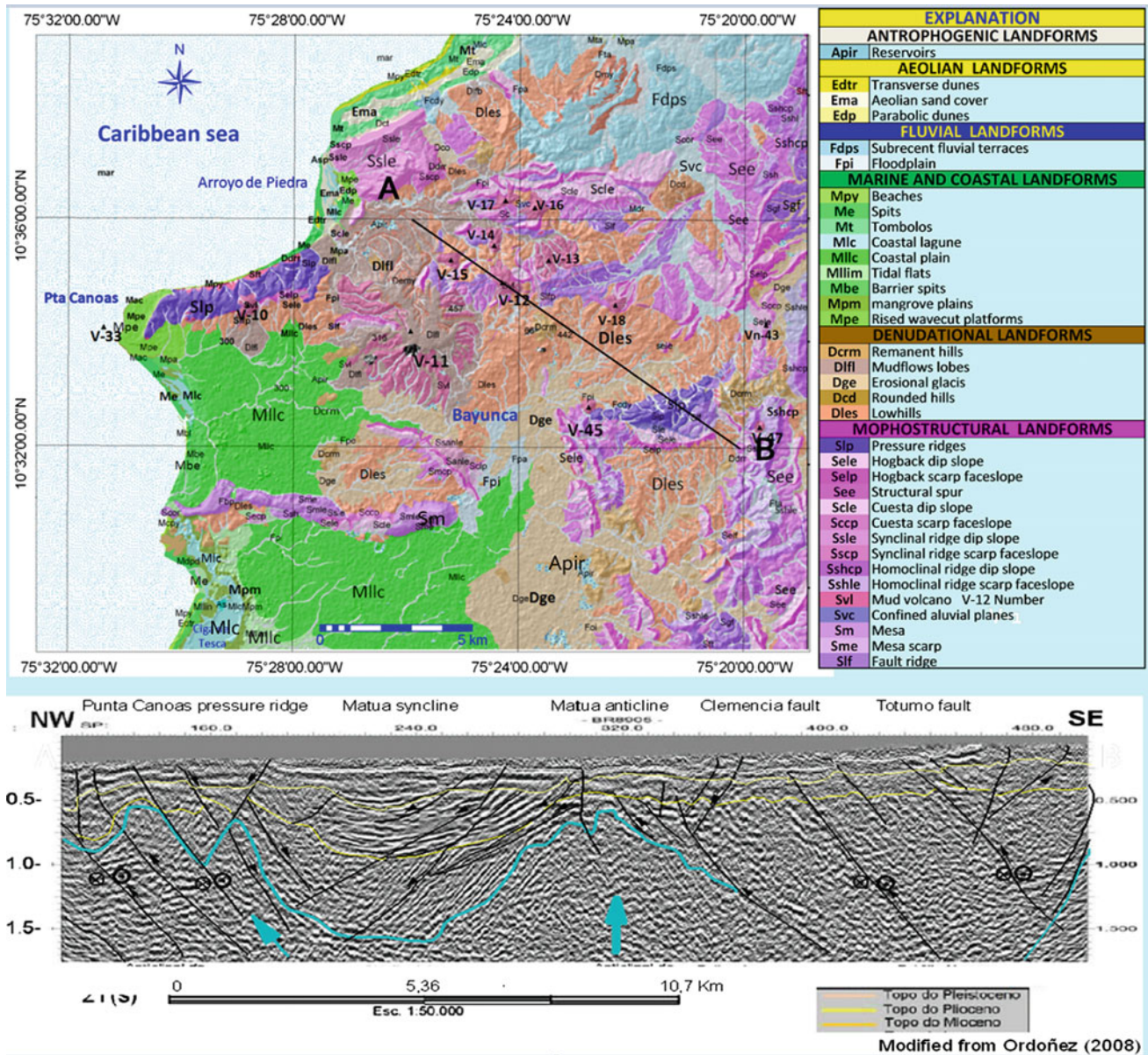


Fig. 3.7 Geomorphological map of the Punta Canoas–Bayunca zone. Mud volcanoes are located on the top of pressure ridges. Seismic cross-section, modified from Ordoñez (2008)

and blocks with diameters up to 1 m. These materials were produced by ancient eruptions which produced mudflows or mud breccias, predominantly composed of quartz feldspatic sandstones, claystones, siltstones, reef limestones and calcareous sandstones, calcite, and locally pyrite blocks (Carvajal and Mendivelso 2010, 2011; Carvajal 2011, 2012).

The main characteristic of the rocky blocks expelled violently during mud eruptions is their high fracturing. This situation results from the high-gas content at depth and its expansion near the surface (Carvajal 2001, 2011). The source of these materials is considered the oldest rocks of Oligocene to Miocene age (Maralú Formation) south of Sinú folded belt, while in the north there is uncertainty about the

origin; however, rock fragments of the Arjona, Bayunca, and Rotinet formations are incorporated.

In the Totumo area, Obando and Vásquez 2010 in Carvajal (2011), based on detailed gravimetric, magneto-metric, and geoelectric measurements, indicate two sources of origin for the extruded materials. One is located at depth and is associated with the Miocene turbidites (Arjona Formation), while the second, shallower source, is related to Pleistocene materials of the ancient Magdalena River delta.

The mud that constantly emanates in a periodic way from the mouths is constituted predominantly of kaolinite (>40 %) and smectite type clays (10–40 %), and in smaller proportion of chlorite, illite, and pyrophyllite. Very fine quartz and low

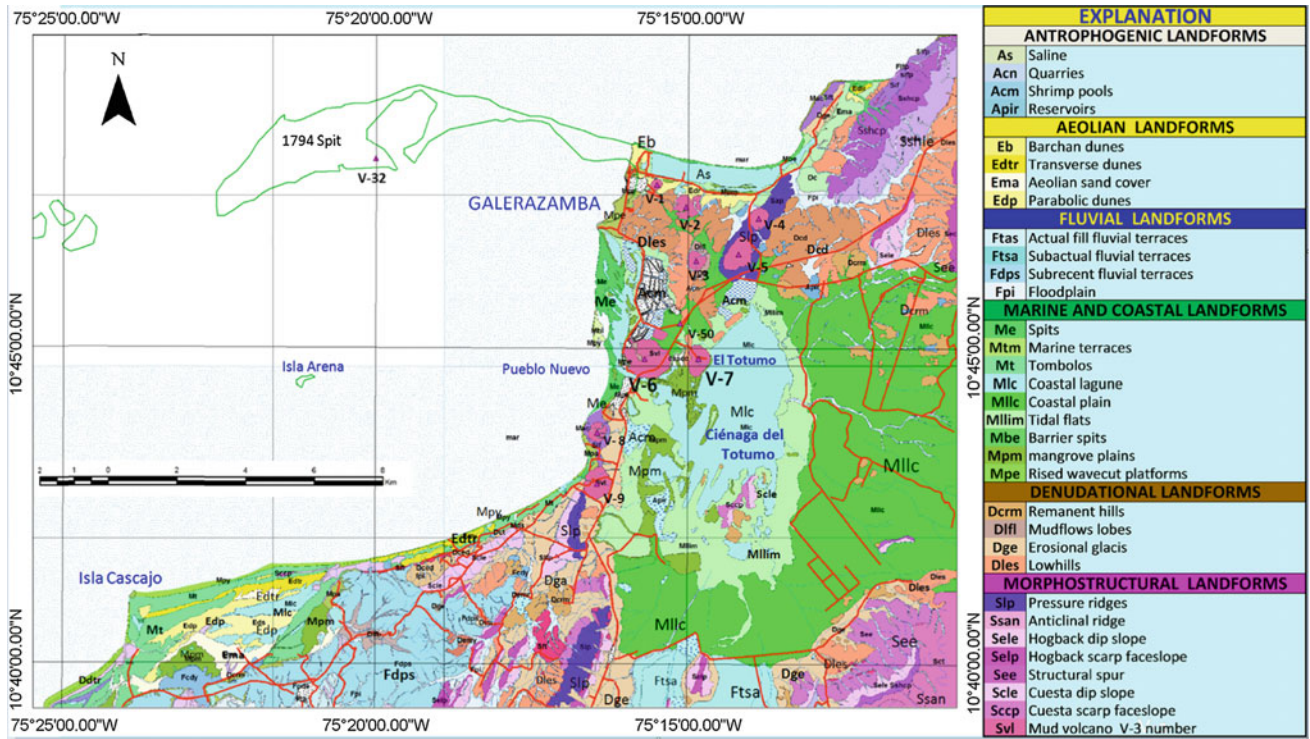


Fig. 3.8 Geomorphological map of the Galerazamba zone, showing both the tombolo of the Cascajo Island and the geomorphic processes associated with wave diffraction and refraction at the Arena Island. From Carvajal (2001)



Fig. 3.9 East-looking view of the Pueblo Nuevo mud volcano. Note the dome-like shape and the channelized 1999 mudflow. Image downloaded from Google Earth (2012)



Fig. 3.10 Panoramic westward view of the Totumo mud volcano. Note in the foreground the touristic *cone-shaped* mouth. Downloaded from Google Earth (2012)

percentages of feldspar, pyrite, gypsum and halite area are also present. Mud is constituted predominantly of silica, alumina, and smaller proportions of ferrous oxides and of calcium, potassium, magnesium, manganese, and titanium oxides. On the other hand, gases emanating continuously from springs are predominantly methane and in smaller proportion carbon dioxide of biogenic origin (Carvajal and Mendivelso 2010; Carvajal 2011).

The differences in density, viscosity, and degree of fluidity of these materials, when reaching the surface, control the shape of the holes or suckers of varied sizes (from 0.5 to 60 m in diameter) and the dimensions of cones (from 0.6 to 20 m high and from 1 to 30 m in base diameter). According to Higgins and Saunders (1974), mud mouths or springs of this type of “volcanoes” can be classified according to their form and the flank slope of the cones, in the following way (Figs. 3.15, 3.16, 3.17 and 3.18):

Type A = Cone with slopes $>20^\circ$

Type B = Cone with slope from 5 to 20°

Type C = Cone with slopes $<5^\circ$

Type D = Boiler shape or crater of several meters in diameter, and

Type O = Holes measuring few cm in width.

On those mud volcano slopes where piping processes occur and lead to collapse in an advanced stage, gullies up to 2.5 m deep may form. According to Carvajal et al. (2010) in Carvajal (2011), the common occurrence of these processes obeys to the low-degree consolidation of the expelled material, associated with gas oversaturation, and later percolation of runoff.

3.3.3 Natural Resources Associated to Mud Volcanoes

Mud volcanoes are one of the best tourist attractions of the region, not only for their landscape expression and the panoramic views they offer, but also for therapeutic and medicinal use of the muddy materials, taking advantage of



Fig. 3.11 East-looking view of the El Rodeo mud volcano located toward SE of Cartagena of Indias. Note the advanced urbanization of the flanks of the structure. Downloaded from Google Earth (2012)



Fig. 3.12 Panoramic view toward SW of the Cañaveral mud volcano. Notice the through or rim syncline around the “volcanic” structure. Downloaded from Google Earth (2012)

the their compositional and physicochemical characteristics. Their mineralogical composition is characterized by wetting properties, given by humidities between 1 and 5 % and pH between 7 and 8. They have fine to very fine textures, dark gray color, locally with stains of brown oil, which confers them good skin adherence (Carvajal and Mendivelso 2011).

The only place where this resource is used for these purposes is at the El Totumo mud volcano. According to Bernal et al. (2000), treatments and empiric massages are given with the expelled material from this mud volcano, consisting in total immersion in mud, while cleaning is done in waters from the nearby coastal lagoon. According to the

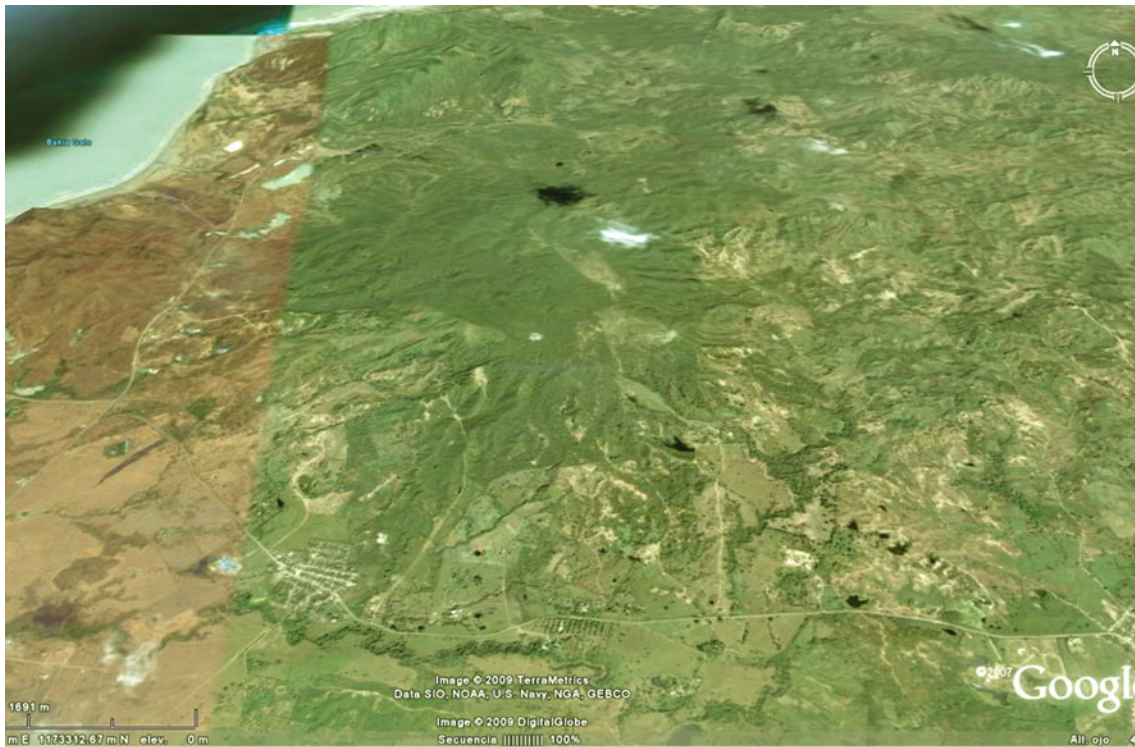


Fig. 3.13 Oblique aerial view toward the north of the Yerbabuena Mud volcano. Note details of the mud emission places associated with *white spots*. Downloaded from Google Earth (2012)

Fig. 3.14 “Mud volcano” schematic diagram. Mudflows were generated during the eruptive process

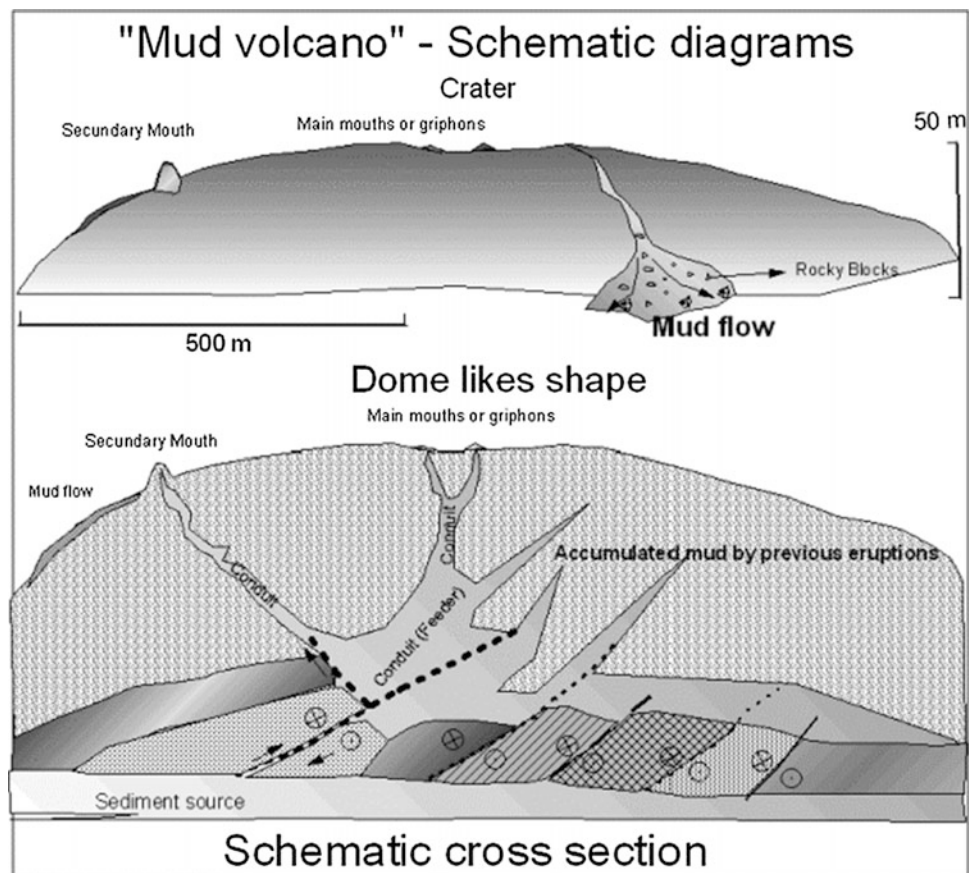




Fig. 3.15 View of a type A mouth at El Totumo mud volcano. *Cone* is about 16 m high



Fig. 3.16 Type B mouths located in the crater of El Reposo mud volcano. Mud is released slowly and mud cracks are conspicuous



Fig. 3.17 Type C mouth of mud volcano El Rodeo. Mud fluidity is conspicuous



Fig. 3.18 Panoramic view toward the NW of type D mouth of the Arboletes mud volcano. The mouth diameter exceeds 50 m

residents, people have obtained good results in the treatment of skin and articulation pathologies.

The sector with more perspectives to exploit this geotouristic potential is the Galerazamba region (INGEOMINAS-CARDIQUE 1999; Carvajal and Mendivelso 2011).

3.4 Geological Hazards Associated to Mud Volcanism

Although areas where “mud volcanoes” are present can be exploited for touristic and medicinal purposes, it is important to take into account geologic hazards associated with them. Periodic and violent extrusion of muds, more or less every



Fig. 3.19 Type O mouth details (*left*), a few centimeters in diameter, located in the main crater of the Totumo mud volcano. In the *top right*, the touristic type A, mouth shown in detail in Fig. 3.15

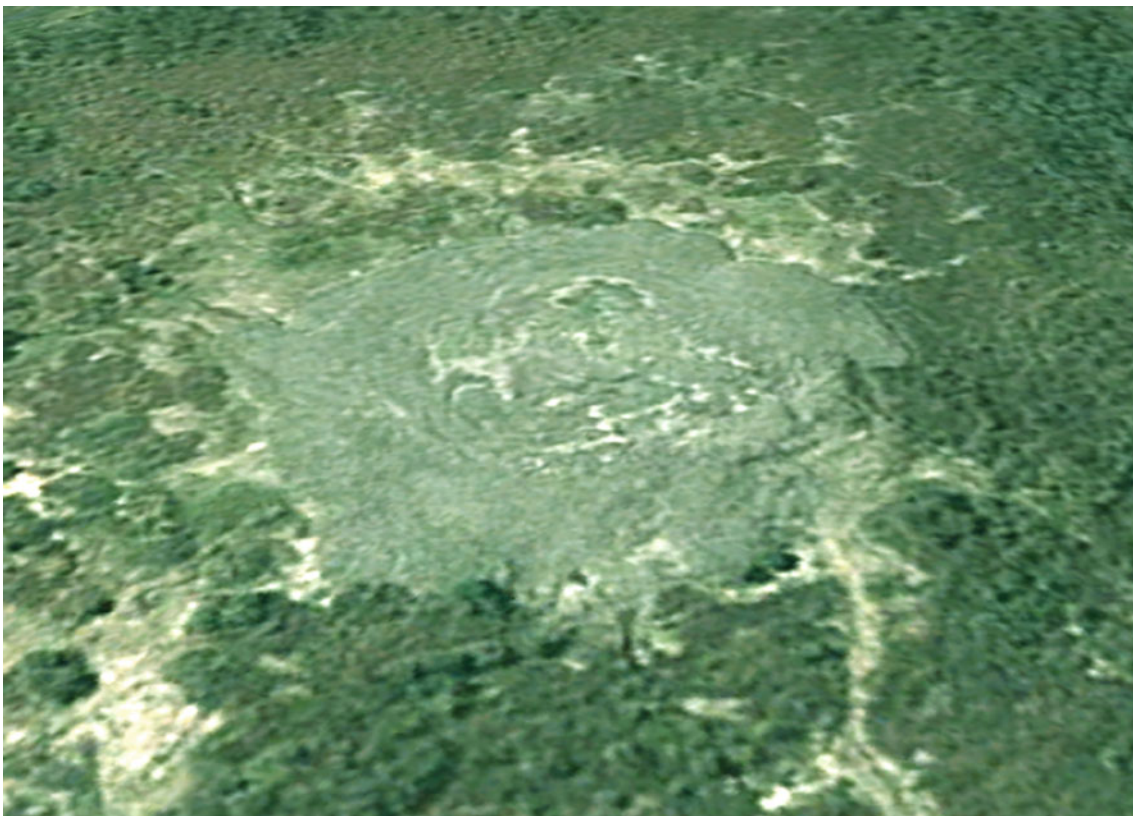


Fig. 3.20 Panoramic view of the *pan-shaped* mudflow 90 m in diameter, formed during the late 2012 eruption of the El Rodeo mud volcano. Downloaded from Google Earth (2013)



Fig. 3.21 Aspects of mudflows and fire generated during the October 2010 Santa Fe de Platas mud volcano eruption. Photo Juan Guillermo Cano



Fig. 3.22 Panoramic view of channeled mudflows at the northern part of the Santafe de Platas mud volcano during October 2010 eruption

15–20 years, can constitute a risk for people and man-made structures located close to the eruption centers. According to Kopf (2002), eruptive processes are triggered by one or more of the following factors: tectonic compression, high content of gases or density inversion associated with difference in densities among the materials confined in depth and the denser upper sedimentary cover.

The common behavior of mud volcanoes is characterized by slow mud emanation, accompanied by intermittent gas bubbling. This mud is dispersed slowly and laterally several meters around, and locally it is interdigitated with flows

from other mouths. If eruptions are violent and throw out mud and rockblocks to an approximate height of 15–20 m, they become dangerous.

Carvajal (2001) gives the following list of dangerous manifestations:

- Violent expulsion of mud and rocky blocks.
- Mud flows, channeled by drainages, or forming small mesas several tens of meters in diameter and 1–3 m in height.
- Fracturing of the surrounding terrain



Fig. 3.23 Sinkhole and graben structures generated in the SW sector of the El Reposo mud volcano crater, during the May 2012 eruption

Fig. 3.24 View of the pan-shaped mudflows generated during the December 2000 eruption of El Totumo mud volcano, which obstructed the road leading to the touristic mouth



- Emission of gases and local generation of fires by the ignition of methane (Carvajal 2001, 2011, 2012; Carvajal and Mendivelso 2010, 2011) (Figs. 3.19, 3.20, 3.21, 3.22, and 3.23).

The historical eruptive activity of these mud volcanoes have been well documented by Ramírez (1959), Carvajal

and Mendivelso (2010, 2011), Carvajal (2011, 2012), and Carvajal and Calderón (2013). Although in Colombia significant steps have been taken to define the hazards associated with mud volcanism, it is fundamental to improve the knowledge on this topic. Areas influenced by mud volcanism have been considered as risk terrains (Fig. 3.24).

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