

ENGINEERING GEOLOGY MAPPING IN THE SOUTHERN PART OF THE METROPOLITAN AREA OF SAN SALVADOR

MAPEO DE INGENIERÍA GEOLÓGICA EN PARTE SUR DEL ÁREA METROPOLITANA DE SAN SALVADOR

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Abstract: The use of classic geologic maps, where geological layers are grouped according to their age or origin, makes difficult the interpretation and use for civil engineer design or urban planning to people without deep knowledge in geology. Due to this reason engineering geological mapping has been carried out in the southern part of the Metropolitan Area of San Salvador using the stripe method. The objective of the methodology is that geological information, geological hazards and geotechnical recommendations as well, can be represented and grouped depending on the intrinsic characteristics of each zone. This information can be easily interpreted for urban planners, private builders and government agencies. The weakness in the compilation and research of geological and geotechnical information in El Salvador, are some of the reasons for the current problems that experiment the region, indicating the importance of improving risk management, as well as soil and rocks mechanics.

Key words: Engineering geology, stripe method, geology, San Salvador Formation, Balsamo Formation, Tierra Blanca.

Resumen: El uso de mapas geológicos clásicos que agrupan los estratos por edad u origen, dificulta la interpretación y uso para diseños de ingeniería civil o planificación urbana, para las personas sin conocimientos profundos en geología. Debido a esto se ha llevado a cabo mapeo de ingeniería geológica en sector sur del Área Metropolitana de San Salvador, haciendo uso de la metodología de bandas. El objetivo de la metodología es que la información geológica, peligrosidad

geológica y recomendaciones geotécnicas puedan representarse y agruparse dependiendo de las características intrínsecas de cada zona. Esta información puede ser fácilmente interpretada por los planificadores urbanos, constructores privados y agencias gubernamentales. La debilidad en la recopilación e investigación de información geológica y geotécnica en El Salvador, son unas de las razones de la problemática que experimenta la región, indicando la importancia de mejorar el manejo del riesgo, así como la mecánica de suelos y de rocas.

Palabras clave: Ingeniería geológica, método de bandas, geología, Formación San Salvador, Formación Bálsamo, Tierra Blanca.

INTRODUCTION

This project is the beginning of missing systematic engineering geology mapping for civil engineering purposes in El Salvador. One of the goals is to introduce a systematic method to represent the geological materials and potential geohazards; this will aid in urban planning and early stages of civil engineer design. The study area was chosen in the southern part of the Metropolitan Area of San Salvador (MASS) where pressure for urban growth was expected at the time.

Central America is located between the Pacific and Atlantic Oceans; tectonic and volcanism of the area is related to the Ring of Fire. This region (Gonzalez et al., 2004) is exposed to volcanic eruptions, earthquakes, floods, mass movements, drought and heavy rains that cause human victims, damages in the infrastructure and economical losses that prevent sustainable development of the countries.

These past years the problematic is more frequent in the countries of the area; for example in El Salvador heavy rains connected with tropical depressions or hurricanes like Mitch (1998), Stan (2005), Ida (2009), Alex (2010), Agatha (2010) and 12-E (2011), as well as earthquakes in 1986 and 2001 forced the local authorities to adjust the national and municipal budgets and ask for international loans to rebuild the infrastructure and assist the affected people. (MARN, 2009 and 2010; La Prensa Grafica, 2011; El Diario de Hoy, 2011)

According to the government the damage costs of the rains in October of 2011 (12-E) were 4 % of the Gross Domestic Budget (El Diario de Hoy, 2011) and for the 2001 earthquakes the economic losses were around 12% the GDB of 2002 (Gonzalez et al., 2004).

The lack of proper knowledge prior to build most of the housing projects and infrastructure in the MASS has been one of the reasons of the elevated vulnerability to geological hazards. Others reasons are rapid urbanization, connected with an elevated population density of 2 569 hab/km² (Ministerio de Economía. 2008). Also the migration to the city and persons of scarce economic resources that live in risky areas (Gonzalez et al., 2004) like steep slopes, next to the scarps or invading the floodplains and stream fans, raise the vulnerability to geological hazards.

For land-use planners, information like geology, geomorphology, geotechnical data, seismicity, hydrogeology among others; can give information like the necessary type of foundation, mass wasting processes, water resources and flood hazard. Recognition of these factors (Dearman, 1987) will improve planning and development of the city allowing rational decisions to be taken in the territory.

One of the tasks of the project of the Czech Republic Foreign Development Programme under guarantee of the Czech Ministry of Environment RP/6/2007 was improving land use decisions by proposing a methodology of engineering

geology mapping. The results of the field work and mapping completed during the year 2008 are presented next.

AREA OF STUDY

The Metropolitan Area of San Salvador (MASS) has an area of 609,9 km² (Fig. 1) consisting of 14 municipalities and is located between the San Salvador Volcano and the Ilopango Caldera (two active volcanoes) and the major part is inside of the Central Graben, a tectonic depression (Lexa

et al., 2001), which is connected to the subduction process in the Ocean. Inside the MASS most of the governmental agencies, industries, economic and financial institutions are concentrated.

The study area at the present is part of the natural protection zone proposed by the Ordinance of Protection and Conservation of the Natural Resources (Diario Oficial, 1998). Some of the reasons for been chosen for mapping, was the recent improvement of the roads in the sector that could increase the pressure for urbanization in the area; also the area is almost in its natural state and this made the mapping job easier.

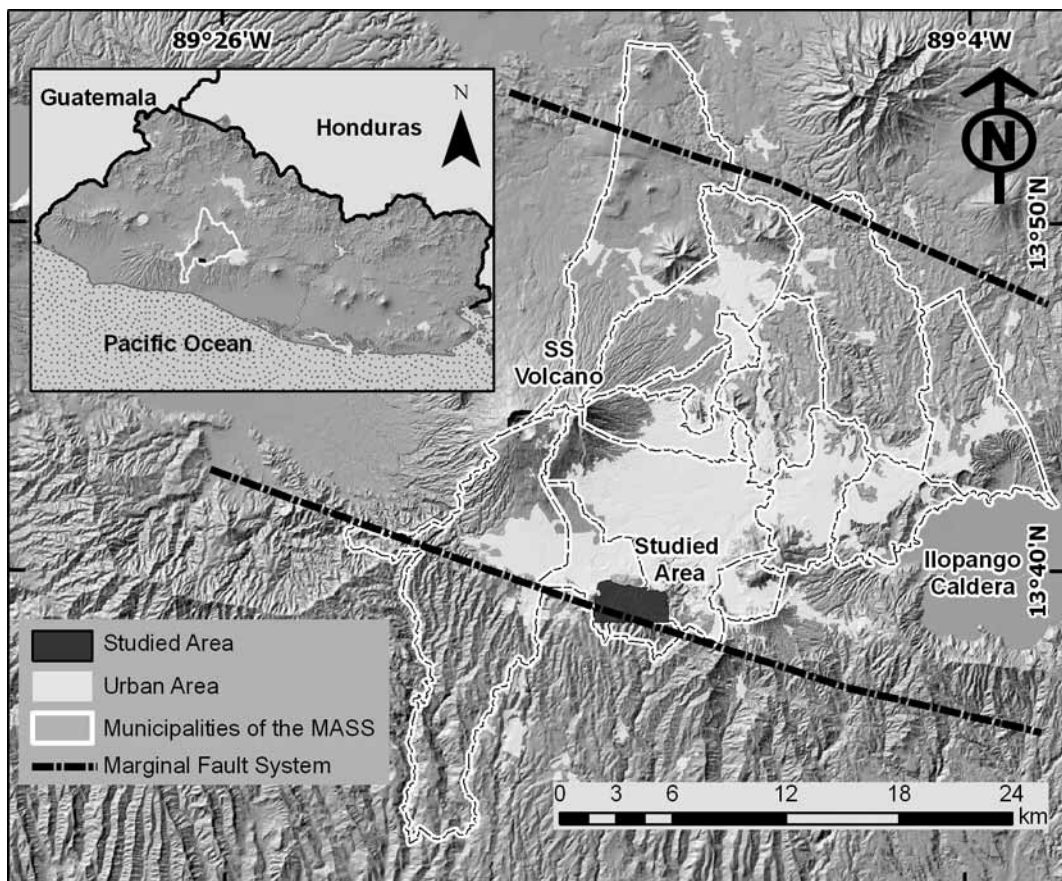


Fig. 1: Location of the study area in the Metropolitan Area of San Salvador, black lines indicate the approximate area of the Central Graben

The zone is in the upper part of the Bocana de Toluca basin. The actual land-use of the slopes in the region is coffee plantations, woods and rural environmental with crops in some slopes; the more problematic areas (mass wasting) are mostly located in the artificial road cuts (Fig. 2).

Some landfills and dumps were placed to increase the area of construction of some of the properties. During the field work it was observed that most of them weren't compacted properly and as a result cracking, mass movements and collapse was observed (Fig. 3).

Geology and Geomorphology

The basic geological map of the whole El Salvador, which is currently in use, was made by the German Geological Survey (Bosse et al., 1978) in a 1:100 000 scale; after that, the geological mapping was only limited to some areas, for example the 1:15 000 scale map of a sector of San Salvador (Centro de Investigaciones Geotécnicas, 1987) and the geological map 1:50 000 made for a seismic zoning after the 1986 earthquake (Consorzio Salvador-Geotermica Italiana, 1988). Lexa et al. (2011) made a 1:50000 geological map of the southern part of the MASS where the study area is located. Geomorphological assessments of the MASS was performed by Šebesta (2006, 2007a, 2007b) and Šebesta & Chavez (2010, 2011).

According to the geological map of Lexa et al. (2011), the study area has presence of the Late Miocene–Pliocene Bálamo Formation and the Late Pleistocene–Holocene San Salvador



Fig. 2: Small mass movements in the artificial road cuts of the area.

Formation (Fig. 4)

The Bálamo Formation (Lexa et al., 2011) is conformed by andesite lavas, tuffs and epiclastic volcanic breccias/conglomerates representing remnants of andesite stratovolcanoes. The San Salvador Formation includes products of basalt-andesite stratovolcanoes associated with the evolution of the Central Graben as well as interstratified silicic tephra/ignimbrites of the Coatepeque and Ilopango calderas.

According to Šebesta (2006) and Lexa et al. (2011) some faults connected with the Central Graben cross the area and for this reason part of the study area (Fig. 5) is composed by tectonic scarps and descending diastrophic blocks that are distributed very chaotically. Relative tectonic



Fig. 3: Landfills and dumps in the area where collapse and cracks were observed.

uplift and depression is inferred by the juxtaposition of recent and older deposits. The region has been impacted historically by earthquakes (Larde, 2000 and Šebesta, 2007a).

Mass wasting processes (Šebesta, 2006 and Lexa et al., 2011) are connected with slopes covered by tuffs of the San Salvador Formation, but also with other regions where rocks of the Balsamo Formation are exposed and there is presence of laterite or weathered tuffs. This situation happens principally in the steep slopes of the erosion hillsides in the upper part of the basin.

On the southern part of the Central Graben, remnants of old stratovolcanoes are present,

where the thickness of the laterite is important. In Finca la Labranza there is an area of polygenetic fill within a tectonic depression (Fig. 5) which is composed by accumulated material of volcanic eruptions and eroded material.

ENGINEERING GEOLOGICAL MAPPING

Part of the project, was to observe how the geotechnical work and risk management is made in El Salvador including the usual lab and field tests.

Currently in El Salvador the practice of soil and rock mechanics is weak, and that's one of the

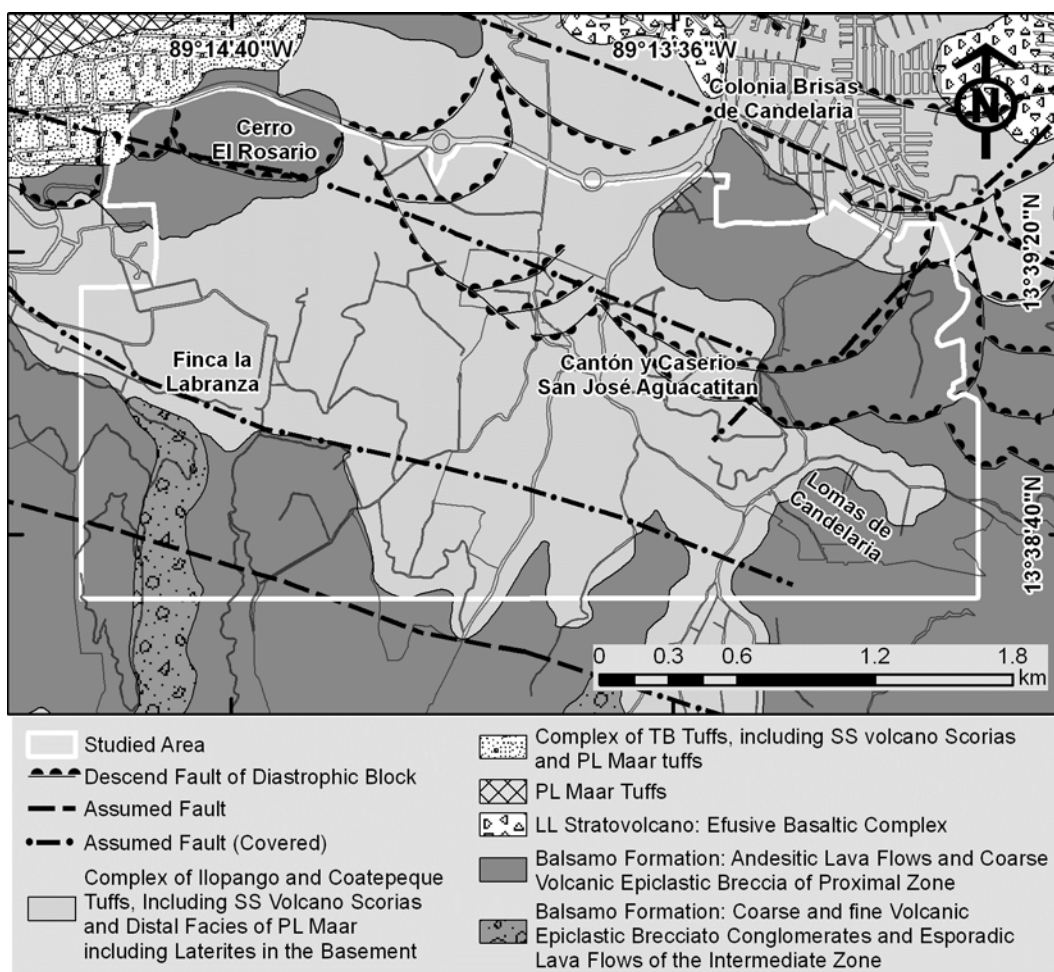


Fig. 4: Geological map of the area, scale 1:50 000. SS- San Salvador, PL- Plan de la Laguna, TB- Tierra Blanca, LL- Loma Larga (Lexa et al., 2011).

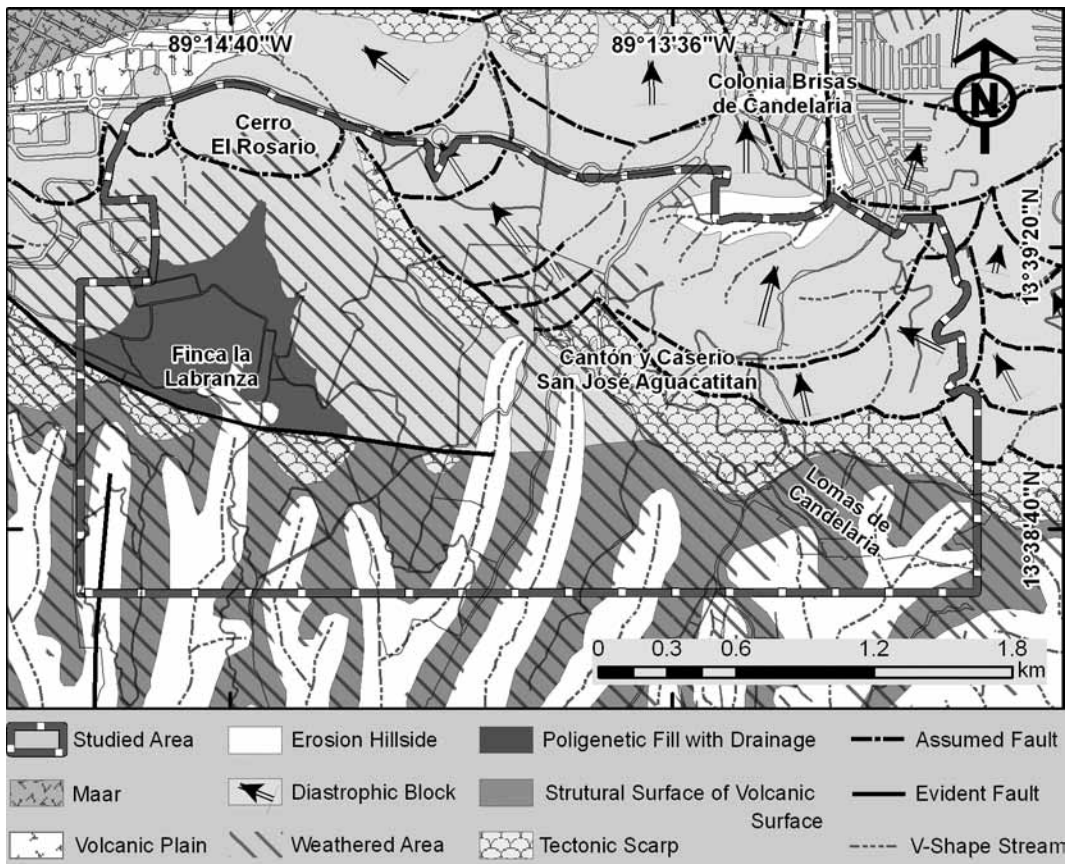


Fig. 5: Geomorphological map scale 1:25 000 of the area (Šebesta & Chavez, 2011).

reasons why the civil infrastructure like housing projects, roads, slopes and bridges are easily damaged after a major event (rain or earthquake), increasing the costs of rebuilding

When a project is prepared, the geological risk is not fully taken into consideration, and occasionally the project will originate, increase or be affected by a natural hazard. Investors, trying to save money, build in conditions, which sometimes are inadequate for construction; in addition the concentration of buildings in the cities is unreasonably high.

According to Anonymous (1972) one of the shortcomings of conventional geological maps, from the point of view of civil engineer, is that rocks with different engineering properties are

characterized as a single unit because they are of the same age or origin.

The aim of the engineering geological mapping (Commission on engineering geological maps, 1976) is the selection of the geological and engineering characteristics of rocks and soils which are more related, and group the layers consequently. The degree of simplification depends on the purpose and scale of the map, the accuracy of the information and the techniques of representation.

The most important tool during mapping was the correlation of soil and rocks in different places. The stratigraphy according to Hernandez (2008) was very helpful through the field work. Other aspects used were the interpretation

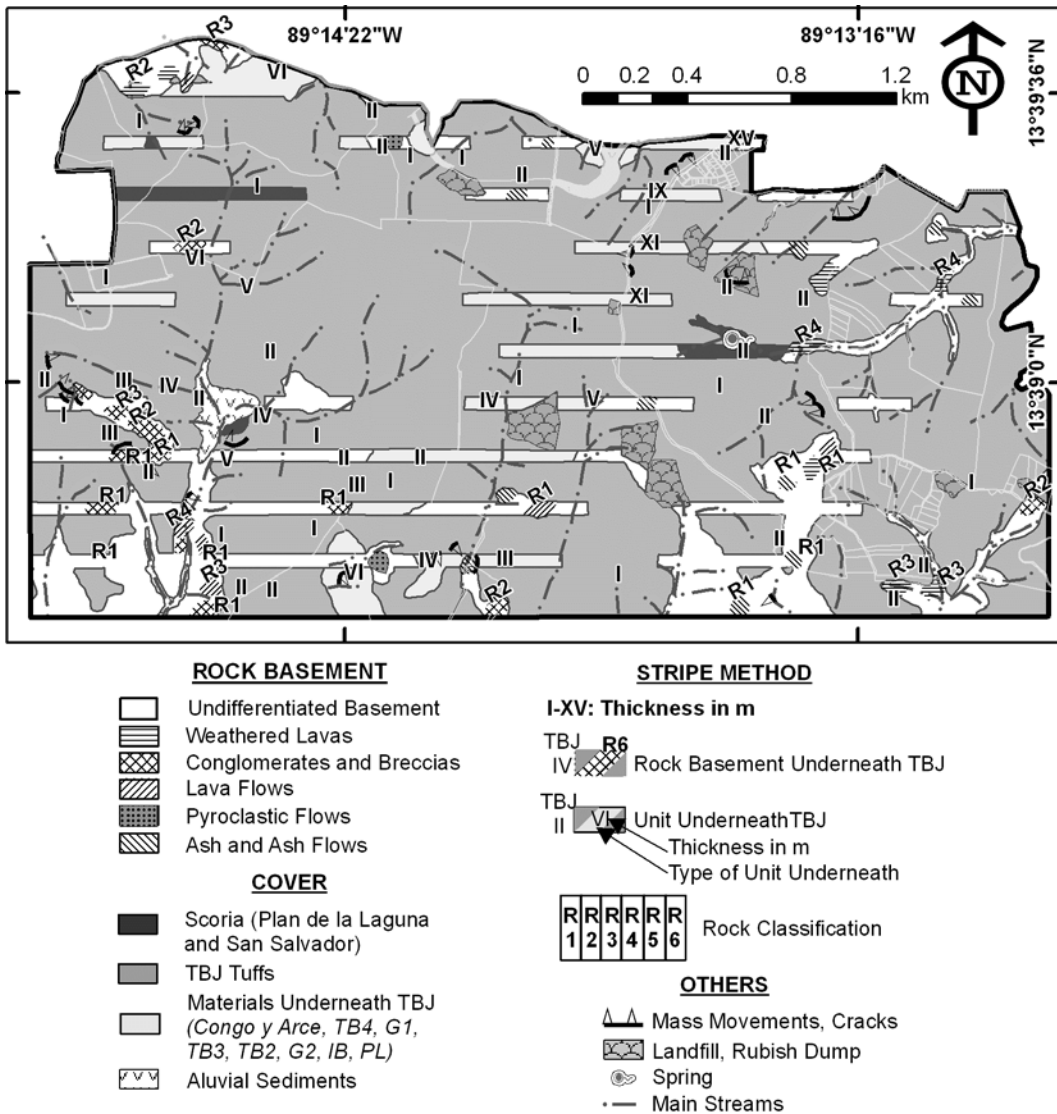


Fig. 6: Engineering geology map of the area.

of existing geological maps, field work, and evaluation of probable rock behavior from previous knowledge.

The engineering geology mapping was done without any drilling boreholes or geophysical measurements and it was based on the existent topographical cartography 1:25 000 (CNR, 1980 y 1981).

The stripe method was chosen to symbolize the engineering geological units that exist in the area. Dearman (1987) explains that the stripe method was originated in Czechoslovakia in the 60's and is analogous to trenching down through the surface layer of soil to the next layer below (rock base). The stripe method is the representation of the character of the existing layers and

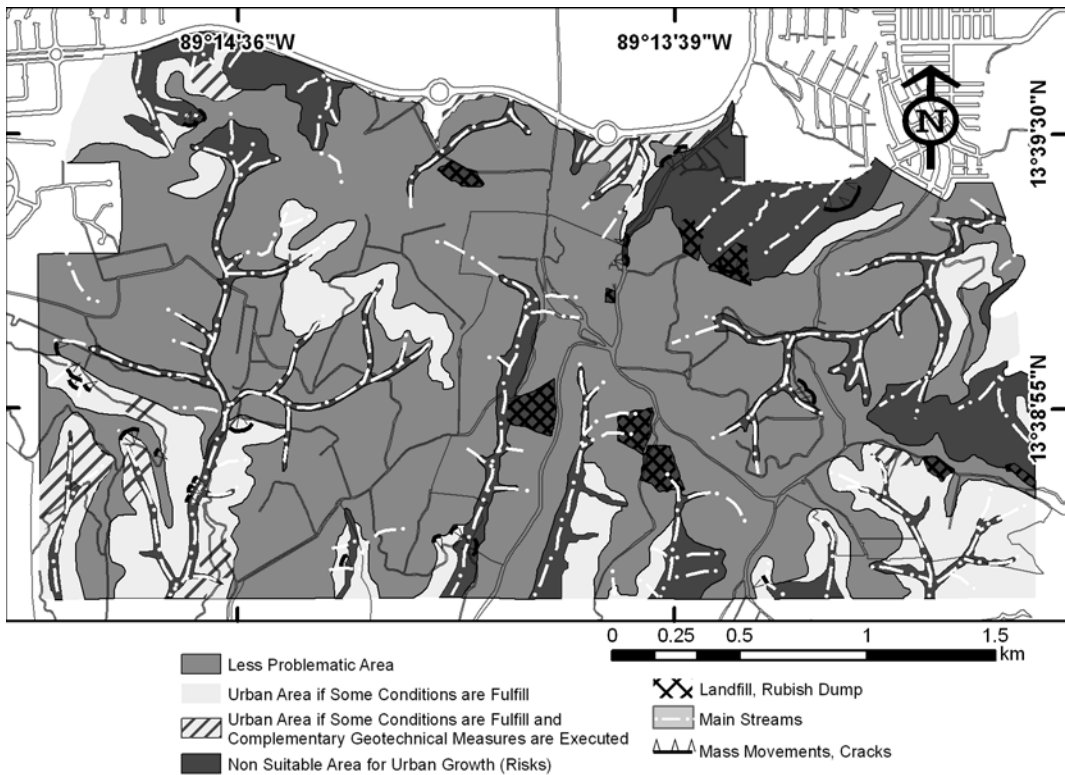


Fig. 7: Engineering geological map illustrating aptitude for urbanization.

the thickness of the top layer. The basement or intermediate layers can be shown by stripes (simulating a window) underneath the surface layer.

In the stripe method a single color represents a single unit and the map unit patterns describe the lithological character (Dearman, 1987); for example lava, pyroclastic flows, epiclastic breccia, weathered lava and ashes.

An engineering geological map illustrating the aptitude for urbanization is presented in figure 7. To build this map information like mass wasting processes, slope inclination, human disturbance, flooding, lithology, weathering and

permeability were identified in the field. Then the areas with the same level of aptitude for urbanization were grouped according to the information compiled above, and general recommendations were proposed for the more problematic. Some hazards like the seismicity, extreme rains or volcanism were not evaluated though, because of the lack of complete information at the time of mapping.

The map legend represent: dark gray color for inadequate areas because of hazards; light gray color for suitable areas if some conditions are fulfill (more detailed research); light gray color with hatch lines for suitable areas if some conditions

are fulfill and where complementary geotechnical measures are necessary (walls, gabions etc.) but the solution has to be based on a detailed research; and gray color for areas where is possible to build from the geotechnical and engineering geological point of view, but always based on a proper research.

The engineering geological map (Fig. 6) evaluates geological aspects of the area (mostly quaternary geology), hardness, properties of soils and rocks, exogenous processes (weathering), morphology and hydrogeology using the stripe method.

The map is divided between the cover layers and the rock basement. Since most of the surface is covered by Tierra Blanca Joven (TBJ), the stripe method is able to present what is underneath it. The outcrops visited during the field work helped to define the areas of stripes in the map, representing simulated windows of layers with different level below TBJ. The surface layers of Plan de la Laguna and San Salvador scoria identified in the field were grouped together. Also the combined set of tuffs between TBJ and the rock basement (Arce and Congo, TB4, G1, TB3, TB2, G2, IB and PL) were grouped into one unit and represented with stripes in the map. Roman numerals in the map indicate the thickness of the engineering geological units.

The ISRM (1981) rock classification was used for the different rock basement units and is represented as text in the map above the corresponding unit (Figure 6 and table 1). The description of the units is presented next.

Description of rocks and soils

According to Hernandez (2008) the volcanic tuffs predominates in the surface, belonging mostly to the San Salvador volcano and to the

Ilopango Caldera, decreasing the thickness and changing the grain particle size as they move away from their source center. The location of the tuffs was controlled depending on the direction of winds, erosion processes and explosive force during the eruption; for these reasons in the outcrops there's no presence of all the layers.

Engineering geological units presented in the map are (Fig. 6):

The bedrock (Balsamo Formation) is comprised mainly of solid lava rocks with presence of boulders and blocks on the slopes, as well as epiclastic rocks product of debris flows and mud flows of the ancient volcanoes (Fig. 8). Lava and debris flows are located in different places and the depth decrease and disappear indicating how the original morphology depressions was used for their transport. This rock base is usually massive and it's affected by selective weathering (Figure 9). The result is that slightly weathered blocks of lava flow are surrounded by completely weathered lava flow (almost clayey material). The weathered material is exposed in slopes and there is a hazard of mass movements in many cases. According to Lexa et al. (2011) the weathered rocks (laterites) have presence of illite, Kaolinite/halloysite, smectite and goethite. The montmorillonite (smectite) presence is important since swelling can occur.

The surface layers described by Hernandez (2004, 2008) and Lexa et al. (2011) are the group of volcanic tuffs (Tierra Blanca 4 (TB4), G1, Tierra Blanca 3 (TB3), Tierra Blanca (TB2), G2, IB, Plan de la Laguna (PL), Tierra Blanca Joven (TBJ) including Arce and Congo) which are placed above the bed rock (Figure 10 and 11). This group is characterized by some weathering on the top (paleosols) which are interbedded in the volcanic materials, being very important for engineering geology purposes. According to Hernandez (2008) the deposits

Table 1

Simple field identification compressive strength of rock (From ISRM, 1981)

Class	Approx. Range of Strength σ_c (MPa)	Strength	Field Definition
R0	< 1	Extremely weak rock	Crumbles in hand
R1	1 to 5	Very weak rock	Thin slabs break easily under hand pressure
R2	5 to 25	Weak rock	Thin slabs break easily under heavy hand pressure
R3	25 to 50	Medium strong rock	Lumps on core broken by light hammer blows
R4	50 to 100	Strong rock	Lumps on core broken by heavy hammer blows
R5	100 to 250	Very strong rock	Lumps only chip with heavy hammer blows. Dull ringing sound
R6	> 250	Extremely strong rock	Rocks ring on hammer blows. Sparks fly

from the Ilopango Caldera that have paleosoils are TB4, TB3, TB2; and G1, G2 from the San Salvador Volcano. Congo and Arce are the deposits originated from Coatepeque Caldera and are weathered as well. The third unit is a surface of Tierra Blanca Joven (TBJ) cover with unknown thickness (Fig. 12), and is located in areas with no information due to poor accessibility or lack of outcrops; for this reason, extrapolation and interpolation was necessary.

Landfills were identified also, in order to avoid future problems if urban growth or constructions are established on them (Figs 3 and 6).

Geotechnical knowledge

In El Salvador the moisture content, particle size analysis, Atterberg limits, cohesion, angle of internal friction, compressibility, permeability and compressive strength are the parameters

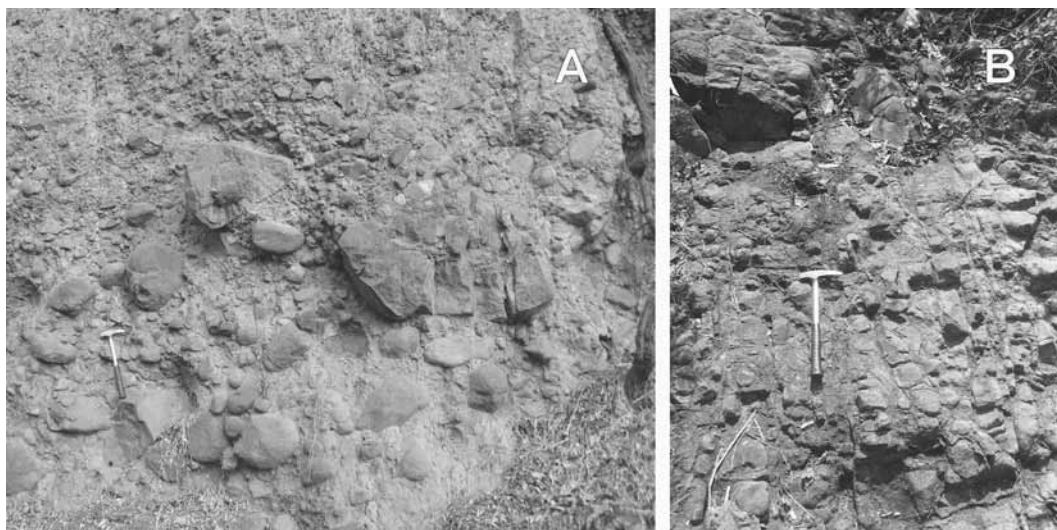


Fig. 8: Epiclastic breccias and lavas of Balsamo formation, A are volcanic epiclastic breccias of the intermediate and distal zone, photo B represents jointed lava flow of the proximal zone (photos Lexa, J., 2010.).



Fig. 9: Weathered lavas of Balsamo formation (photo Lexa, J., 2010).

usually obtained. Standard penetration tests (SPT) and Modified Proctor are the tests that normally are done. The triaxial and shear box tests, for saturated soils, using the ASTM norms are done also. For the rock mechanics drill-hole bores, geophysics and compressibility strength are done sometimes, depending on the importance of the project.

Tierra Blanca Joven (TBJ) is the most important volcanic tuff and is present in important sectors of the MASS (as is shown in Figure 6). TBJ is quite sensitive to erosion, water content change, natural or artificial vibrations and compressibility (Rolo et al. 2004; Hernandez, 2004; Šebesta, 2007b; Šebesta & Chavez, 2010). This material is also quite sensitive for slope stability problems (Figure 2 and 13).

Guzmán & Melara (1996); Amaya & Hayem (2000); Rolo et al. (2004); Hernández (2004); Molina et al. (2009) and Avalos & Castro (2010) studied the geotechnical and lithological aspects of the younger Ilopango tuffs Tierra Blanca Joven (TBJ). All of the authors characterized TBJ as silty sands and sandy silts.

At the present, the soil mechanics and theory for saturated soils is used in El Salvador. There are two distinct seasons throughout the year: summer and rainy season, and usually the groundwater level is deep, (35 m in urban areas according to Rolo et al., 2004), remaining almost the same all the year; this means that most soils in the country are unsaturated and there are capillary forces that act on the soil structure making that an “apparent cohesion” (suction) improve the strength of the soil; this situation makes that the slopes are almost vertical and temporally stable, but will collapse when wetted or dried.

For the present publication, the values of cohesion and friction angle of different authors were compiled and compared, (figure 14) showing scatter in the data. The authors that made the tests concluded that the strength of undisturbed or disturbed samples with natural moisture decreases, if they're saturated. In spite that most of the tests were made with the shear box, the results show disparity; since for unsaturated soils the combination of total stress σ , pore water pressure u_w , pore air pressure u_a and degree of saturation are needed. For unsaturated soils characterizing (Fredlund & Rahardjo, 1993), the use of two independent stress variables: net stress $\sigma - u_a$ and suction $u_a - u_w$ are needed. Murray & Sivakumar (2010) say that the most recent stage in the understanding of unsaturated soils is the analysis of the behavior in terms of constitutive relations linking the volume change, shear stress and deformation due to shear stress in elasto-plastic models. Nowadays considerable progress has



Fig. 10. Almost complete stratigraphy of the San Salvador formation; photo for reference was taken about 3 kms north of the studied area during the beginning of engineering geology mapping.

been achieved through this approach, because it's possible to explain some of the characteristics of soil behavior.

This brings out the necessity of researching about the behavior and constitutive modeling using the critical state and unsaturated soil mechanics, to avoid the dispersity of the results and have consistency into a more coherent framework. Rolo et al (2004, table 3) compared suction values from TBJ samples and concluded

that the negative pore pressure, weak interparticle bonding or cementation have a contribution to the shear strength, creating an apparent cohesion that is lost when is saturated or during seismic events. Guzman & Melara (1996) and Hernandez (2004) conclude the same.

There is almost no geotechnical information available for the other geological layers because it's not usual to identify the name of the layer that is tested during a project.

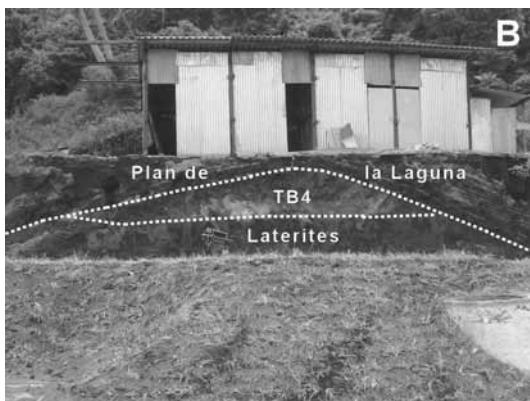
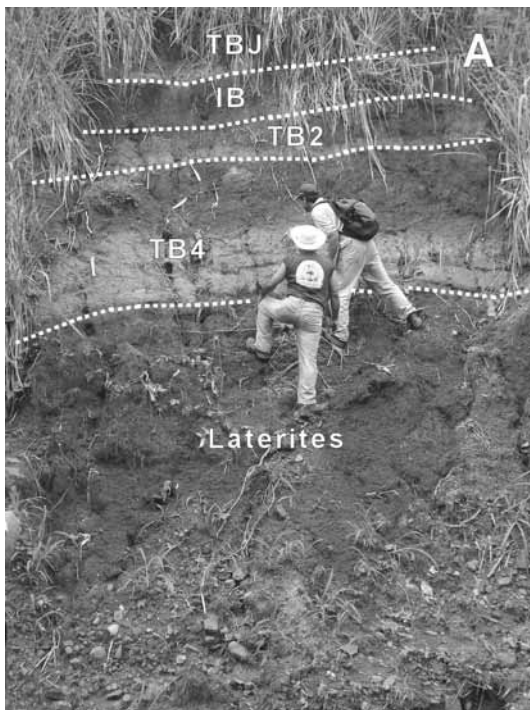


Fig. 11: San Salvador formation layers in the area of study.



Fig. 12: Sector of Tierra Blanca Joven (TBJ) with unknown thickness.

CONCLUSIONS

There is a need to simplify the geological maps in order to help the interpretation for the developers and urban-planners. The experience has shown the necessity to introduce in each project a proper geological risk assessment to avoid future problems; taking into account the mass movements, seismic effects, floods, groundwater situation, geological material properties and erosion principally.

The engineering geological mapping can serve as first or final steps in planning an infrastructure and can have an emphasis according to the content or interests to evaluate. In the rocks and soils (Anonymous, 1972) the description of color, grain size, texture, structure, fracture state, weathered state, strength properties and permeability can indicate the properties and characteristics of them.

The presence of layers of laterites and paleosols are very problematic in the sector



Fig. 13: Tierra Blanca Joven (TBJ) problems, on the left erosion problems; and in the right liquefaction of TBJ after vibrations in the back of pick up vehicle.

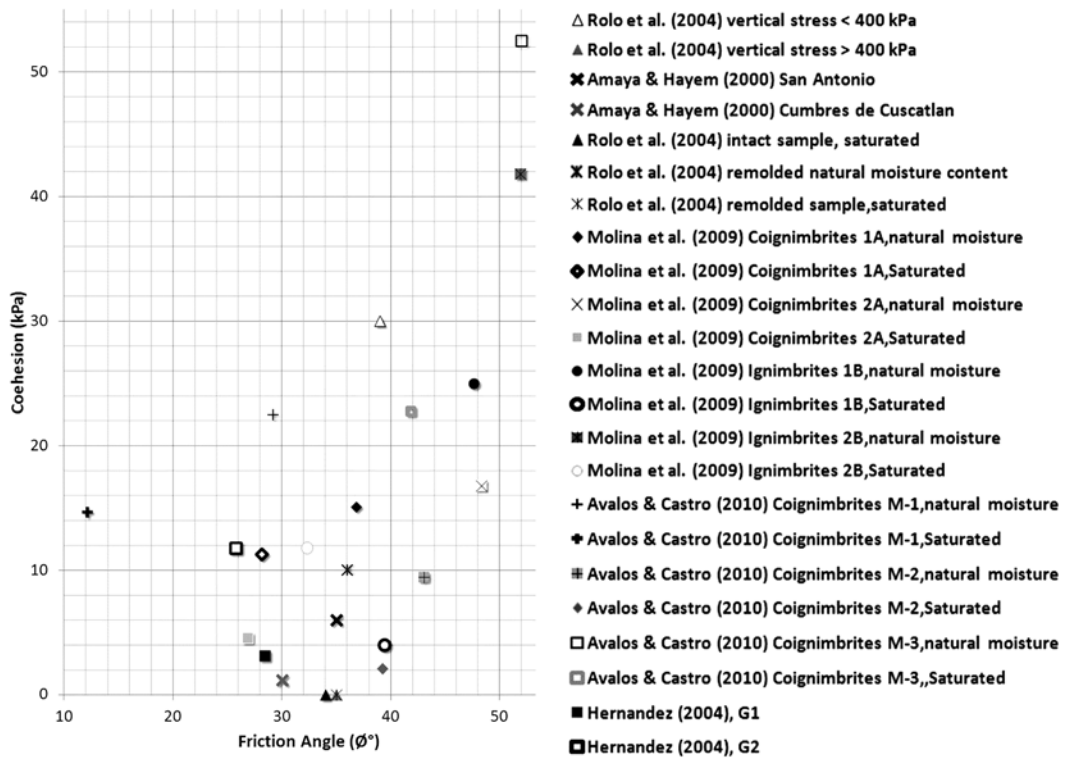


Fig. 14: Cohesion (kPa) and friction angle (ϕ) obtained using shear box and triaxial test (UU) of Tierra Blanca Joven surface layers by different authors and compiled for this publication.

but is important to note that in areas where there is significant presence and thickness of Tierra Blanca Joven (TBJ) is necessary to be careful with the loss of apparent cohesion, experienced when the suction or cementing decrease or when an earthquake affects the area (Rolo et al, 2004). Also the mass wasting processes acts intensively in the surface and above the ground of TBJ, the anthropic disturbance (for example broken pipes and urban growth) increase the problems. The volume changes (collapse or swelling) and the dynamic properties in the geological layers can cause damage to the structures; this situation makes imperative the introduction of the unsaturated soils mechanics in the design of the projects that will reduce the problems that the MASS is experimenting at the present.

It is recommended to continue systematic engineering geological mapping and data collection. The scientific research, probing, field and lab testing will improve the knowledge of the risk and properties of all the geological layers. The built of a public archive like the "Geofond" (<http://www.geofond.cz/en/homepage>) in the Czech Republic; with geotechnical and geological hazard data; which will be open to all (designers, engineering geologists, geotechnicians, state and town authorities, agricultural engineers, environmentalist etc.) would help improving the knowledge applied during the conception of the projects.

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REFERENCES

- AMAYA, C. & HAYEM, E., 2000: Introducción al estudio de suelos parcialmente saturados e inicio de la caracterización de la Tierra Blanca del AMSS.- 147 pp. Universidad Centroamericana José Simeón Cañas, San Salvador, El Salvador [Tesis Lic.].
- ANONYMOUS, 1972: The preparation of maps and plans in terms of engineering geology.- In: GRIFFITHS, J.S., (ed.): Mapping in engineering geology. - The geological society publishing house, UK.: 7-77.
- ASCENCIO, N. & ZÚNIGA, D., 2010: Tierra Blanca Joven: caracterización geológica y geotécnica de la unidad "D".- 97 pp. Universidad Centroamericana José Simeón Cañas, San Salvador, El Salvador [Tesis Lic.].
- BOSSE, H.R., LORENZ, W., MERINO, A., MIHM, A., RODE, K., SCHMIDT-THOMÉ, M., WIESEMANN, G. & WEBER, H.S., 1978: Mapa geológico de El Salvador.- Escala 1:100 000, CNR, San Salvador.
- BROWN, E. (ed.), 1981: ISRM suggested methods: Rock characterization, testing and monitoring. -211 pp. Pergamon Press.
- CASTRO, R. & AVALOS, J., 2010: Caracterización geológica y geotécnica de la unidad "G" de Tierra Blanca Joven.- 95 pp. Universidad Centroamericana José Simeón Cañas, San Salvador, El Salvador [Tesis Lic.].
- CENTRO DE INVESTIGACIONES GEOTÉCNICAS, 1987: Mapa Geológico del área de San Salvador y sus alrededores.- Escala 1: 15 000, CNR, San Salvador.

- CNR, 1980: Cuadrante cartográfico Panchimalco.- Escala 1:25 000, CNR, San Salvador.
- CNR, 1981: Cuadrante cartográficos Zaragoza.- Escala 1:25 000, CNR, San Salvador.
- COMMISSION ON ENGINEERING GEOLOGICAL MAPS, 1976: Engineering geological maps.- 79 pp. Ed. UNESCO press, Paris.
- CONSORZIO SALVADOR-GEOTÉRMICA ITALIANA, 1988: Mapa vulcanológico.- Escala 1: 50 000, San Salvador, Ministerio de Obras Públicas.
- DEARMAN, W.R., 1987: Land evaluation and site assessment: mapping for planning purposes.- In: GRIFFITHS, J.S., (ed.): Mapping in engineering geology. - The geological society publishing house, UK.: 223-229.
- DIARIO OFICIAL, 1998: Ordenanza de zonas de protección y conservación de los recursos naturales de San Marcos.- Diario Oficial 149, Tomo 340, 14 de agosto de 1998.
- DIARIO OFICIAL, 1998: Ordenanza de zonas de protección y conservación de los recursos naturales de San Salvador.- Diario Oficial 124, Tomo 340, 6 de julio de 1998.
- DIARIO OFICIAL, 1999: Ordenanza de zonas de protección y conservación de los recursos naturales y zonas no urbanizables de Antiguo Cuscatlán.- Diario Oficial 31, Tomo 342, 15 de febrero de 1999.
- EL DIARIO DE HOY, 15 octubre 2011, p. 5: Alerta por lluvias.
- EL DIARIO DE HOY, 1 noviembre 2011, p. 12 and 14: Daños y pérdidas por las lluvias suben a \$ 840 Mlls.
- FREDLUND, D. G. & RAHARDJO, H., 1993: Soil mechanics for unsaturated soils.- 510 pp. Wiley-Interscience Publications, New York.
- GONZALEZ, L., ROMANO, L. & SALAMANCA, L., 2004: Risk and disasters in El Salvador: Economic, environmental, and social aspects.- Geological Society of America, Special Paper 375: 461-470.
- GUZMÁN, M.A., & MELARA, E., 1996: Propiedades ingenieriles del suelo del área metropolitana de San Salvador, El Salvador.- Revista ASIA San Salvador, El Salvador, 122: 14-22.
- HERNÁNDEZ, E.W., 2004: Características geotécnicas y vulcanológicas de las tefras de Tierra Blanca Joven, de Ilopango, El Salvador.- 115 pp. Universidad Politécnica de Madrid y en la Universidad Politécnica de El Salvador, [Tesis M.Sc.].
- HERNÁNDEZ, E.W., 2008: Aspectos geológicos que influyen en las aguas subterráneas y en la respuesta sísmica del Área Metropolitana de San Salvador.- 19 pp. SNET [Internal Report].
- LARDÉ, J., 2000: El Salvador: Inundaciones e incendios, erupciones y terremotos.- 397 pp. Ed. Biblioteca de Historia Salvadoreña, Concultura, San Salvador
- LA PRENSA GRAFICA, 17 octubre 2011, p. 12: Emergencia por lluvias, tierra frágil.
- LEXA, J., ŠEBESTA, J., CHÁVEZ, J.A., HERNANDEZ, W. & PÉCSKAY, Z., 2011: Geology and volcanic evolution in the southern part of the San Salvador Metropolitan Area.- Journal of Geosciences, 56: 105-140.

- MARN, 2010: Tormenta tropical Agatha 31 de mayo de 2010.-11:45AM- 8 pp. El Salvador. Servicio Nacional de Estudios Territoriales.
- MARN, 2009: Informe Técnico de los sistemas Baja Presión en el Pacífico Huracán Ida y sus Impactos Ambientales.- 39 pp. El Salvador. Servicio Nacional de Estudios Territoriales.
- MINISTERIO DE ECONOMÍA DE EL SALVADOR, 2011: Anuario estadístico 2009.- 253 pp. El Salvador. Dirección General de Estadística y Censos.
- MOLINA, B., PÉREZ, G. & VÁSQUEZ, M., 2009: Caracterización geotécnica de las tefras Tierra Blanca Joven: unidad "G" en la zona proximal y obras de protección.- 133 pp. Universidad Centroamericana José Simeón Cañas, San Salvador, El Salvador [Tesis Lic.].
- MURRAY, E. J. & SIVAKUMAR, V., 2010: Unsaturated Soils- 284 pp. Wiley-Blackell, United Kingdom.
- ROLO R., BOMER, J., HOUGHTON, B., VALLANCE, J., W., BERDOUSIS, MAVROMMATI, P., C. & MURPHY, W., 2004: Geologic and engineering characterization of Tierra Blanca pyroclastic ash deposits.- Geological Society of America, Special Paper 375: 55-67
- ŠEBESTA, J., 2006: Mapa geomorfológico del Área Metropolitana de San Salvador.- Escala 1:25 000, 51 pp. OPAMSS, San Salvador [Internal Report, Czech Geological Survey Archive].
- ŠEBESTA, J., 2007a: Zonificación de morfoestructuras del AMSS y su relación con la actividad sísmica.- Escala 1:25 000, 32 pp. OPAMSS, San Salvador [Internal Report, Czech Geological Survey Archive].
- ŠEBESTA, J., 2007b: Geomorfología del AMSS y su relación con los movimientos de ladera.- Escala 1:25 000, 42 pp. OPAMSS, San Salvador [Internal Report, Czech Geological Survey Archive].
- ŠEBESTA, J. & CHAVEZ, J., 2010: Cartography and assessment to study the erosion processes in the Metropolitan Area of San Salvador.- El Salvador, Central America.- Escala 1:25 000, 85 pp. OPAMSS-Czech Republic Embassy in Costa Rica [Internal Report, Czech Geological Survey Archive].
- ŠEBESTA, J. & CHAVEZ, J., 2011: Mapa geomorfológico de la sub-región del Área Metropolitana de San Salvador.- Escala 1:25 000, 75 pp. OPAMSS, San Salvador [Internal Report, Czech Geological Survey Archive].

