9 . Structural Characteristics around the El Toro Mine and its Influence on the Unstability for Chambers, Colombia

コロンビア, El Toro 石灰岩鉱山周辺の地質構造と坑道内の不安定現象

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要旨：コロンビアの中部山地にある石灰岩体を対象とした El Toro 地下鉱山では掘削に伴って天盤の剥離・落石，鉱柱の破壊，既存ボーリング孔壁からのクラックの発生が多数認められ，さらに石灰岩体のなかに巨大な空洞が確認された．周辺を含めた地質構造の調査によれば，石灰岩体は結晶片岩に囲まれて NW － SE に伸び，境界はほぼ同方向の断層である．NW-SE の片理構造は結晶片岩だけでなく，石灰岩体にもわずかに認められた．不安定現象がいずれも NW-SE であり，節理や小断層もこれと同方向であることを考えると，その発生には片理・節理を含めた構造的異方性とともに，同方向への広域構造応力による圧縮もかかわっている可能性がある．

1. INTRODUCTION

The El Toro underground mine of the El Cairo Cements Co. is located in the Central Cordillera of the Colombian Andes as shown in Figure 1. A marble body elongating NW-SE, which is interbeded by strongly folded schistose rocks, is a target for mining.

The underground upper and lower access tunnels principally constitute mine with elevations from 1,140 to 1,160 m's' and 1,063 to 1,115 m, respectively. Many chambers have been excavated within the marble body. Each of the upper chambers is 90m long with section of 30m height ×14m width. The lower is 130m long with section of 65m height ×22m width. The thickness of each pillar between chambers is 6 to 10 meters, and a crown pillar between upper and lower tunnels is attains to 15 meters.

Unstable events have occurred in chambers and access tunnels as excavation proceeds. For example, block falling from roofs and walls, and extending of fracturing from boreholes can be cited in there. Moreover, dissolute caverns were often noted in the marble body. Although, these unstable events are various, however, distinct geometrical and mechanical similarities are recognized among them. Probably, the occurrence of such events may be strongly related to the complicated geological structures and anisotropic rock mass condition in and around the marble body. Hence to understand such phenomena mechanically, structural characteristics in the mining area and these phenomena have been studied.

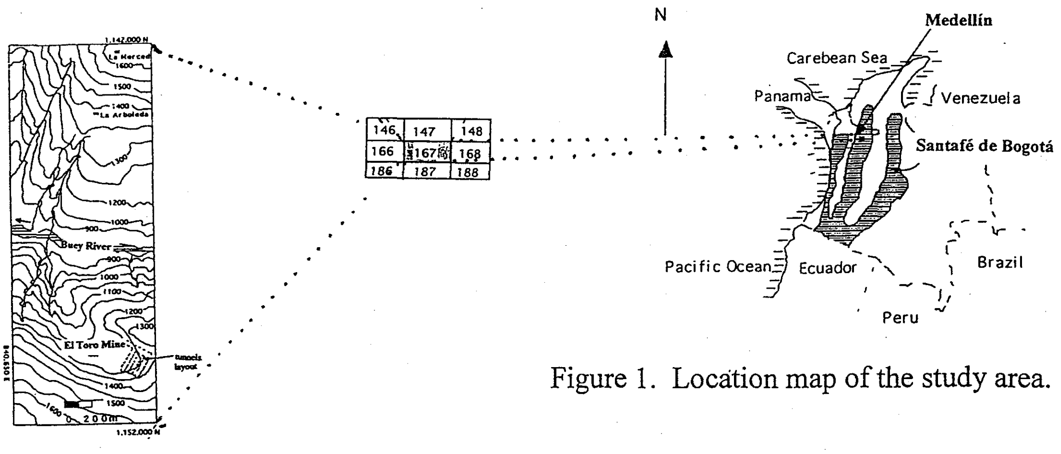

Figure 1. Location map of the study area.

2. GEOLOGICAL STRUCTURES IN AND AROUND THE ABEJORRAL MARBLE BODY

2.1. *General geology and structures*

Schistose rocks consist of intercalation of green schist, black schist, quartz-muscovite schist and quartz-sericite schists, and are widely distributed in the mining area. A marble body is interbeded in these rocks. The origin of the schistose rocks and marble body is estimated to be early Paleozoic in age (Nelson, 1962). However, metamorphic ages have been believed to be from Devonian to early Cretaceous Period. A small granodioritic body called as Buey stock of Jurassic Period intrudes these rocks.

Distribution of marble and schistose rocks and their structural outline are shown in a geological map (Fig. 2), vertical and horizontal sections on Figures 3 and 4.

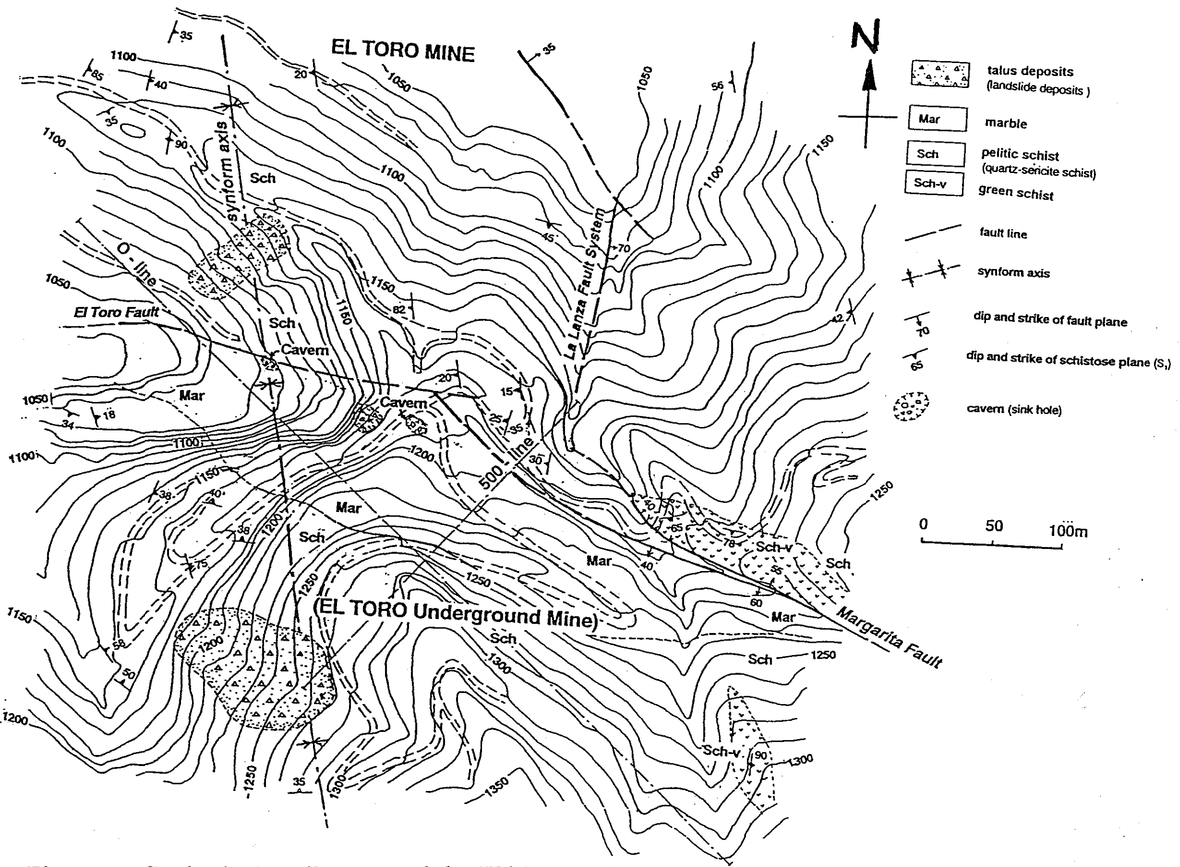

Figure 2. Geological outline around the "El Toro Mine".

2.2. *Folds and planar structures*

Multiple tectonic processes were resulted in complicated geological structures in and around the marble body. Remarkable planar structures with several types of folds are observed in mining area. One of them is a large synform structure, whose axis is NNW-SSE (Figs. 3-4). Closely related to this fold, planar structures S_1 of N16°W/42°W and N18°W/60°E are dominant in both chambers and exposures. These structures are believed to be formed in response to regional tectonometamorphism accompanied by green schist facies (graphite-chlorite-muscovite mineralogical assemblage) from Devonian to Triassic Period (Restrepo & Toussaint 1984).

In addition to S_1, other two types of planar structures S_2 and S_3 are recognized, S_2 is N18°W/70°E and almost coincides with the axial plane of the main fold of S_1 mentioned above. Microscopic observations in thin sections show that S_3 was developed as microcrenellation of S_2 in black schists. S_3 is low angle, and is interpreted to have been developed in lower P-T conditions indicated by the graphite-chlorite mineralogical assemblage zone of early Cretaceous

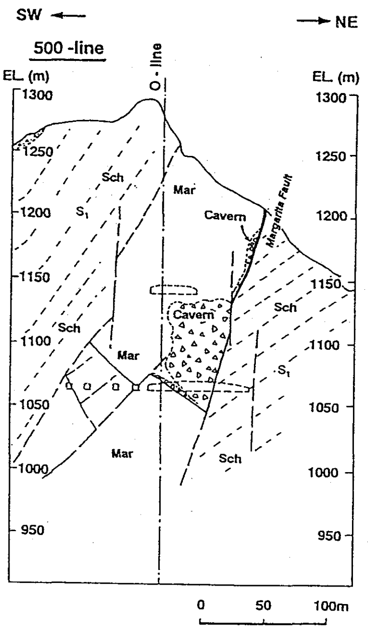

Figure 3. Topographical and geological profile of the El Toro Mine.

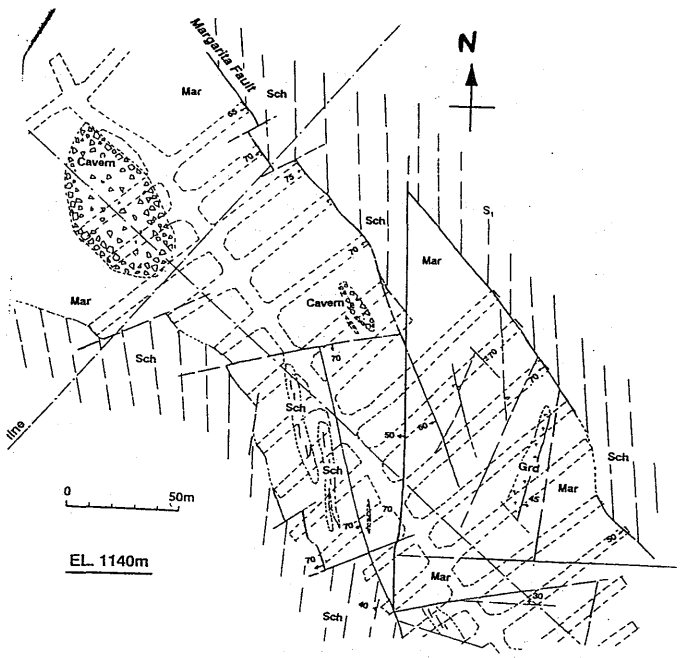

Figure 4. Horizontal section map including drift tunnels at elevation 1140 m.

Period in comparison with the other two tectonometamorphic conditions (García *et al.*, 1991; Roldán, 1993; Gil, 1996a, b; Gil and Yokota, 1998).

2.3. *Joints and Faults*

Besides, the above structures, many kind of joints and faults are also common on walls and roofs of the chambers and outcrops in mountain slopes. Figures 5(a), (b) and (c) show dominant direction of such discontinuities developed within marble and schistose rocks.

As shown in Figure 5(a), the dominant direction of joint planes within schistose rocks is NNW-SSE with steeply dips, and they almost coincide with S_1 strike. As shown in Figure 5(b), joint planes within the marble body are dominant in NNE-SSW, NNW-SSE with variable dips eastward or westward and almost coincides with those of fault planes.

Faults observed in chambers are divided into 3 groups by direction; *i.e.* NNE-SSW, NNW-SSE, and N-S with variable dips eastward and westward respectively (Figure 5(c)). Displacements and relative movements are also recognized along some of them in chambers and exposures.

The fault planes are slightly undulating and filled with rock fragments and soft clayey materials, while joint planes are smooth and are almost not filled with particles. These faults and joints were believed to have been formed along pre-existing planar structures mainly in the Miocene.

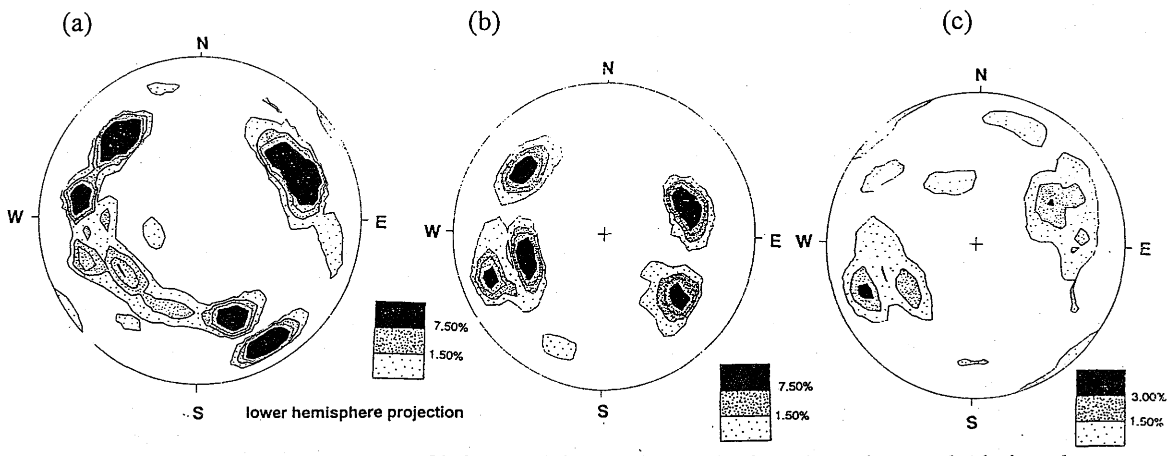

Figure 5. Dominant directions of joints and faults planes obtained in and around Abejorral Marble Body. (a) joints in schistose rocks; n= 97. (b)joints in marble body; n=396. (c) faults in marble body; n=238. All diagrams are on lower hemisphere projections.

3. EXCAVATION OF CHAMBERS IN THE ABEJORRAL MARBLE BODY AND UNSTABLE EVENTS.

Excavation of chambers has been gradually proceeded from the lower to upper levels. Unstable phenomena such as block falling and spalling from pillar walls or roofs occurred in some chambers and accesses tunnels as excavation proceeds. Some of unstable blocks are now partially supported with rock bolts. Examples are as follows:

Some tension cracks generated at rim of old holes and extended radially and longitudinally trough out of it at least two years after drill. The strike of generated cracks is almost N40°W and vertical (Fig. 6 (a)).

Many naturally dissolute caverns elongating in NW-SE trend exist within the marble body. One of the biggest is shown in Figure 6(b). It has 90m long and 35m width. Most of caverns are recognized along NW-SE trending fault planes. Probably, underground water dissolute narrow portion along these fault planes, which had been formed as extensional fractures.

Moreover, a big window appeared within a pillar as excavation proceeds as shown in figure 6(c). This window may be a collapsed portion of fractured zone of NW-SE trend. Its volume attains to 5×5×6 m^3. Similar phenomena were recognized at least on the other four pillar walls. Block falling is also occurred from walls and roofs.

All these phenomena are brittle, and no ductile deformation like swelling or squeezing on walls and roofs have been noticed in the chambers.

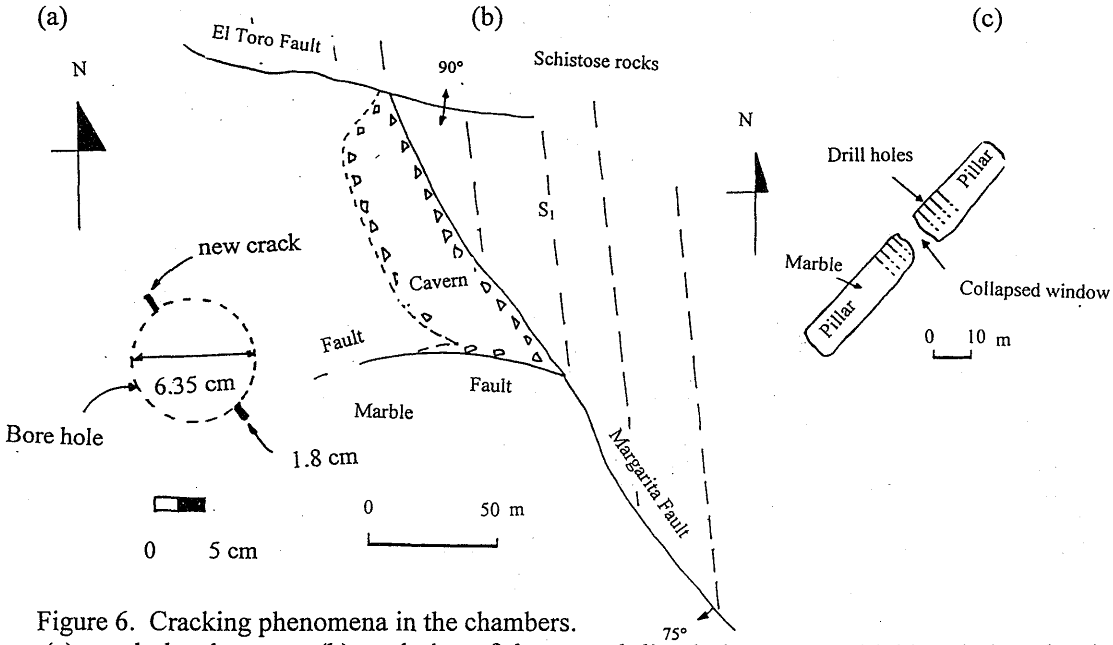

Figure 6. Cracking phenomena in the chambers.
(a) crack development. (b) evolution of the natural dissolution cavern. (c) big window development.

4. RELATIONS AMONG HETEROGEINITY OF ROCK MASS CONDITION AND UNSTABLE EVENTS

Distinct geometrical characteristics are recognized among these unstable phenomena appeared in chambers and access tunnels. They have a similarity that they occurred along NW-SE strike discontinuities or planar structures with vertical dip, and some of them are closely related to extensional fracturing. In other words, these phenomena have been occurred under the control of anisotropic rock mass condition.

Recent geodetic and seismological research shows that the principal axis of compression is almost NW-SE trend in Central Cordillera (Pennington, 1981; Page, 1981; Sarria A, 1990; Hincapie *et al.*, 1993; Gil *et al.*, 1995; Mora & Kellog, 1996; Gil, 1996b). The tensile principal

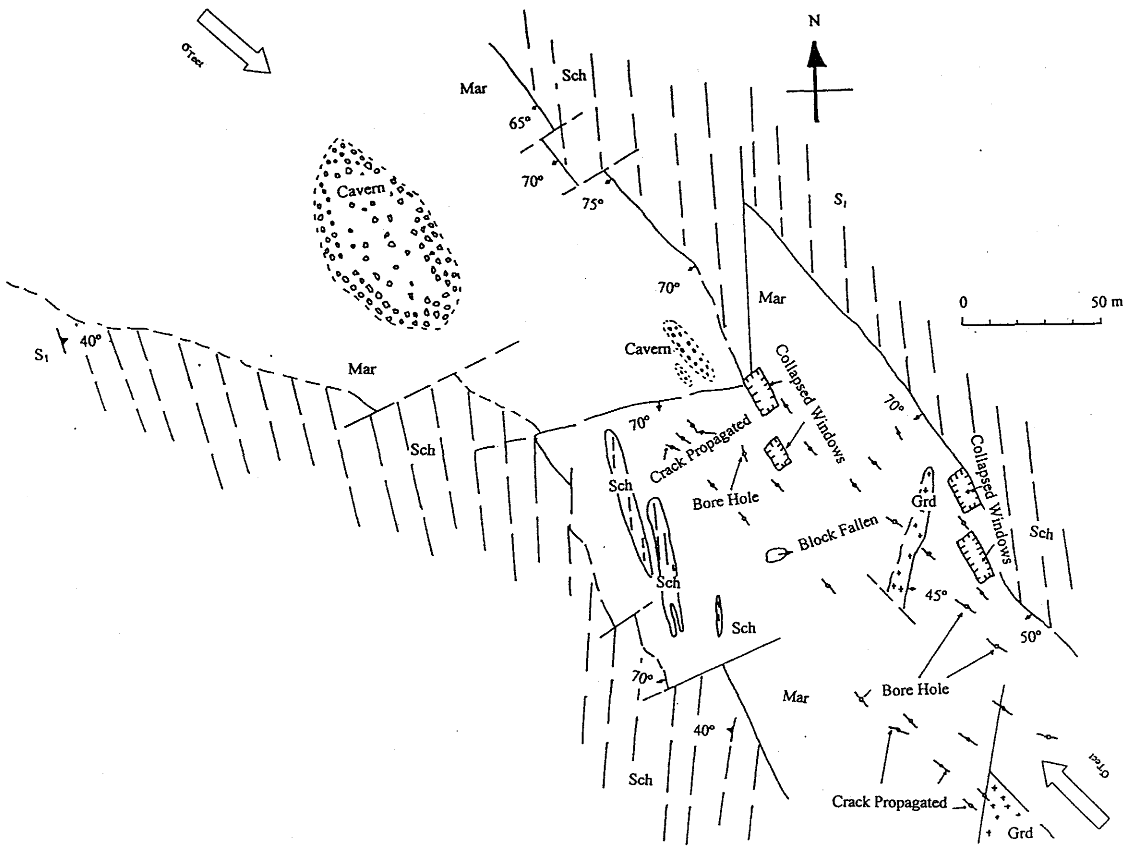

Figure 7. Relationship among heterogeneous condition, deformation and cracking and tectonic residual stress field.

stress follows NE-SW trend. The former almost coincides with the direction of cracks and the latter is perpendicular to them. Therefore, these phenomena may be interpreted to have been occurred within the anisotropy rock mass condition under residual tectonic stress field and its perturbation is due to artificial excavation (Fig. 7).

5. CONCLUSIONS

Although geological structures in El Toro Mine are complicated, a fundamental structure can be outlined as three-dimensional model, which are expressed by some vertical and horizontal sections.

(1) A marble body, one side of which is bounded by NW-SE trending remarkable fault system, is elongated in NW-SE trend and dips southwestward steeply. Schistose planar structures showing NW-SE to NNW-SSE trend form a large synform structure around the entrance of the mine.

(2) Among some unstable phenomena, cracks propagated from rim of old boreholes most of which have NW-SE trends and is concordant with dominant faults and joints. Therefore, they may be tension cracks generated under heterogeneous rock mass condition and effect of pre-existing faults in addition to NW-SE trending tectonic compression in this region.

(3) Considering that big windows appeared in pillars has NW-SE trend and is located in a restricted zone adjacent to main fault, they may be closely related to fracture zones along the fault.

(4) Taking into account that natural caverns are developed along NW-SE trending fault and are elongated NW-SE and links to ground surface, they are understood to have been formed by ground water dissolution along faults and have spread out by fracturing due to same mechanism of windows and tension cracks mentioned before.

(5) According to the geometrical relation between the direction of planar structures and direction of cracking, unstable phenomena are considered to have occurred along such weak planes, which have been formed during multiple tectonic process in large residual tectonic stress and its perturbation due to excavation.

6. REFERENCES

Cairo S.A. 1995 Informe de exploración Licencia 8648. Geology Team of El Cairo Cements S.A. (Unpublished).

García R. Oseas; Restrepo B. Oscar; Roldán, Jorge M. 1991. Estudio geotécnico minero para la cantera de Abejorral de Cementos El Cairo S.A. Graduate thesis mining engineering and geologist engineering. . Faculty of mines. National University of Colombia P. 460.

Geominas ltda. 1978. Estudio regional para calizas en el Departamento de Antoquia. (Unpublished)

-------------. 1985. Informe final de exploración Licencia 8648. (Unpublished).

Gil E. Fabio A, Ortiz E, Valencia M. 1995. Aspectos geológicos de los alrededores mas cercanos septentrionales del Municipio de Santafé de Antioquia, Colombia. (Unpublished).

Gil E. Fabio A. 1996a. Aspectos geológicos de los cuerpos calcáreos de la región de La Merced (Parte Baja), Montebello (Antioquia). Graduate thesis geologist engineering. Faculty of Mines. National University of Colombia. P. 197.

-------------. 1996b. Petrogénesis y microtectónica de las metamorfitas del distrito minero de Abejorral. Abejorral, P.200. (Unpublished).

Gil E. Fabio A, Yokota Shuichiro. 1998. Structural characteristics around the Abejorral marble body and its influence on the unstability for chambers of the El Toro Mine, Antioquia, Colombia. *Proceedings of the 8th Intern. Cong. Eng. Geol.* Vancouver-Canada.

Hincapie Jaime O. *et al.* 1993. Algunas particularidades de la sismicidad del noroestecolombiano. Sixth Geology Colombian Congress, Medellín.

Mora H, Kellog J. 1996. Movimientos relativos de placas determinados con GPS a partir de las mediciones de CASA-91 y CASA-94 Seventh Geology Colombian Congress, Santafé de Bogotá, Colombia.

Nelson, H. W. 1962. Contribución al conocimiento de la coordillera central de Colombia. Sección entre Ibagué y Armenia. Bogotá. *Bol. Geol. Vol 10. P. 161-203.*

Page William. 1981. Tectonics of Northwestern Colombia, Implications to Seismic Hazzard Evaluations. Third International Seminar About Seismic Engineering. Universidad de Los Andes.

Pennington, Wayne D. 1981. Subduction of The Eastern Panamá Basin and Seismotectonics of Northwestern South America. *Journal of Geophysical Research, VOL 86, NO. B11, PAGES 10753-10770.*

Restrepo, J.J. & Toussaint, J.F. 1984. Unidades litológicas de los alrededores de Medellín. *Soc. Col. Geol. Mem. 1. P. 1-26.*

Roldan C. Jorge M. 1993. Contribución al conocimiento tectónico de la Cordillera Central del Sistema Andino Colombiano. Sixth Geology Colombian Congress. Medellín.

Sarria Alberto. 1990. Ingeniería sísmica. Ediciones unidas. Universidad de Los Andes. Bogotá.

Zapata S. Francisco R.; Vasquez. Edgar J. 1985. Análisis estructural de las rocas metamórficas localizadas entre el batolito de Sonsón y la cúpula de La Unión. Graduate thesis geologist engineering. Faculty of Mines. National University of Colombia. P. 142.