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NEW GEOLOGICAL AND GEOPHYSICAL CONTRIBUTIONS IN THE SECTION IBAGUÉ – ARMENIA, CENTRAL CORDILLERA - COLOMBIA

Carlos A. Vargas[1], Andreas Kammer[1], Mireya Valdes[2], Carlos E. Rodríguez[1], Alexander Caneva[3], Jhon J. Sánchez[4], Eliana Arias[5], Carlos A. Cortes[6], Héctor Mora[4]

[1] Departamento de Geociencias, Universidad Nacional de Colombia – Sede Bogotá , Colombia
Email: cavargasj@unal.edu.co
2 Instituto Colombiano del Petroleo –ICP, Bucaramanga, Colombia
3 Universidad Antonio Nariño, Dirección Nacional de Investigaciones, Bogotá, Colombia
4 Red Sismológica Nacional de Colombia, INGEOMINAS, Bogotá, Colombia
5 Incorporated Research Institutions for Seismology – IRIS, Washington DC, USA
6 Universidad de Manizales, Facultad de Ingeniería, Manizales -Colombia

RESUMEN

Ha sido interpretada la sección geológica entre las ciudades de Ibagué y Armenia basada en observaciones geofísicas y estructurales en busca de establecer el estilo estructural dominante y la configuración del basamento en profundidad. Inicialmente se realizaron mediciones gravimétricas y magnetométricas levantadas cada 500 m entre estas ciudades, las cuales permitieron soportar el desarrollo del experimento sísmico “Armenia-Quake”. El alcance del experimento sísmico permitió detectar reflectores hasta aproximadamente 17 km de profundidad en un área de influencia de aproximadamente 25 km. La interpretación integral de la información geológica y geofisica permite concluir que el Complejo Cajamarca define una estructura sinclinal amplia cerca al Municipio de Cajamarca. Partiendo de dicha información se pudo reconocer la presencia de un basamento compuesto por cuñas de rocas basálticas y sedimentarias asociadas a las formaciones Quebradagrande y Arquía. Igualmente se reconoce la existencia de una gran flexión de la paleo-placa oceánica relacionada a la formación Barroso, la cual se encuentra limitada al occidente por la falla Cauca-Almaguer. La estructura en flexión y la evolución compresiva del estado de esfuerzos en esta región de América del Sur podrían ser las responsables del depósito y posterior plegamiento de la formación Cinta de Piedra que constituye en gran medida la Serranía de Santa Bárbara.

Palabras clave: Armenia-Quake, experimento de sísmica activa, modelamiento geofísico, serpentinitas y terremotos.

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Carlos A. Vargas, Andreas Kammer, Mireya Valdes, Carlos E. Rodríguez
Alexander Caneva, Jhon J. Sánchez, Eliana Arias, Carlos A. Cortes, Héctor Mora

ABSTRACT

Based on geophysical and structural observations a geologic section between the cities of Ibagué and Armenia (Colombia) has been interpreted to establish the dominant structural style and the basement configuration at depth. Gravimetric and magnetic measurement were initially taken each 500 m along these cities, which helped in the development of the "Armenian-Quake" seismic experiment. The experiment illuminated reflectors down to approximately 17 km deep in an influence area of approximately 25 km. The complete interpretation of the geological and geophysical information allows concluding that the Cajamarca complex defines a wide synclinal near to Cajamarca town. With this information initially it was possible to recognize the presence of a basement compound for wedges of basaltic and sedimentary rocks associated to the Quebradagrande and Arquía formations. Then was recognized the existence of a great flexion of the oceanic paleo-plate related to the Barroso formation, which is limited at west by the Cauca-Almaguer fault. The flexion structure and the evolution of the stress in this region of South America could be responsible for the deposit and later folding of the "Cinta de Piedra formation" that constitutes the Santa Bárbara range.

Key words: Armenia-Quake, seismic active experiment, geophysical modelling, serpentinites and earthquakes.

INTRODUCTION

The tectonic configuration in the northern Andes has been interpreted as the product of at least three orogenic events resulting from the accretion of oceanic crust in the western margin of NW South America (Duke-Caro, 1990; Freymueller et al., 1993). Petrological and geochemical evidences of this process have been reported along the section that runs along the road between the cities of Armenia and Ibagué (Figure 1). According to these authors, the protolith that constitutes the lands in the Central Cordillera of Colombia was originated from intra-oceanic rocks and sediments of continental margins that have undergone processes of metamorphism. All these rocks evolved into an orogenic regime associated to intrusive and extrusive bodies that emerged throughout fractures affecting the crust in the region.

Base on geophysical and structural measurements we defined the relation at depth and the current seismo-tectonic activity that could have triggered the January 25, 1999, Mw=6.2 Armenia earthquake (Monsalve and Vargas, 2002).

GEOLOGICAL FRAMEWORK

New observations have allowed to complement the geologic mapping by Nelson (1962) and Restrepo-Pace (1992) between the city of Ibagué and the town of Calarcá,and to extend the mapping as far as the town of Montenegro. This section represents one of the best outcrops in the Central Cordillera of Colombia where rocks of diverse composition and age can be observed. Generally, the stratigraphic base displays metamorphic rocks from the Cajamarca complex varying between amphibolic green schists, graphitic schists, phyllites and locally marble whose protolith age has been assigned to the early Palaeozoic (Figure 2). The Pericos fault brought these rocks into contact to the east with the Ibagué Batholith, an intrusive body of granodiorites of Jurassic age, and at to the west the San Jerónimo fault brought into contact the Cajamarca complex with meta-sedimentary rocks of marine origin that are interspersed with metabasalts from the Quebradagrande complex of Cretaceous age (Maya and González, 1995).

The Quebradagrande complex formed a tectonic wedge limited by the Silvia-Pijao fault to the west. To the western side of the Silvia-Pijao fault some meta-igneous rocks of continental origin and formally denominated the Arquía complex become visible (González and Núñez, 1991), which in turn are limited to the west by the Cauca-Almaguer fault. Again to the west of the latter appear meta-sedimentary and meta-basalt rocks of oceanic origin of Cretaceous age and denominated Barroso formation (Maya and González, 1995). The Barroso formation and the Quebradagrande complex are parts of the geological province associated to the same subduction event.

GEOLOGICAL AND GEOPHYSICAL OBSERVATIONS

Data

Initially, we performed a lithological and structural survey in the section Ibagué - Calarcá – Montenegro. Measurements every 500 m were taken and allowed the design of magnetometric and gravimetric profiles supporting the controlled source seismic experiment that we called “Armenia Quake”. This experiment was developed during June, 2004, detonating four explosive charges of Indugel AP+ at the Fayat Quarry near Calarcá. The charges ranked between 75 and 117 Kg. In this seismic experiment 36 seismographs REFTEK-125 and triaxial geophones (f_n = 4.5 Hz) from the IRIS-PASSCAL consortium were placed in 95 recording locations. Additionally, roughly 2000 hypocentral solutions reported by the Seismological Observatory of Quindío –OSQ- were used to support the geological and geophysical interpretations.

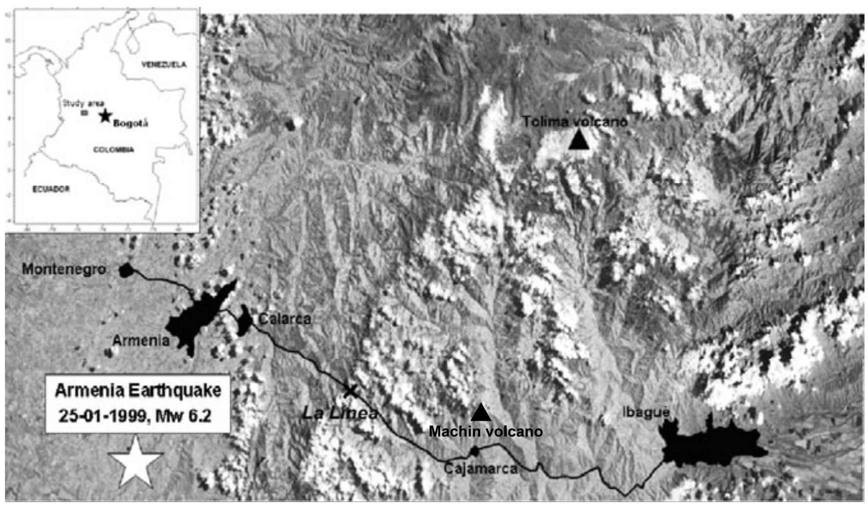

Figure 1. Geophysical profiles between Ibagué and Armenia cities along the main road (black line).

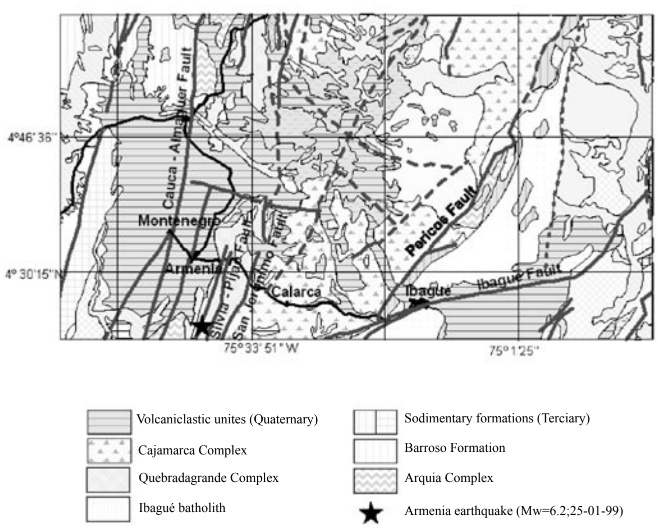

Figure 2. Geologic map of the study area. Continuous red lines are mapped faults. Dashed red lines are main lineaments.

METHOD

Preliminary interpretation of lithological and structural information suggests geological continuity at depth for some structures that are present in the region. Further processing using the Talwani Method (Talwani, 1959), of gravimetric and magnetometric data along an iterative adjust allowed to find a geological model that agrees with field observations.

Although the seismic experiment was designed to map a 45 km-deep section, the location of recording stations in urban areas with high noise levels made difficult quality results beyond 17 km depth. The selected seismic records were processed with a fourth order bandwidth filter (5 – 40 Hz), properly edited and stacked to assemble a section, and then corrected by Linear Move Out (LMO). The high topographical contrasts, the lateral variations of velocity and the complex geometry of the geological structures impeded an efficient application of Normal Move Out (NMO) and migration techniques. The section was used to improve the geologic pattern and the corresponding gravimetric and magnetometric models until a model that agreed with the observations was found.

RESULTS

The adjustments of the geologic model with the geophysical information allowed the detection of a subduction structure probably affected by the prevalent orogenic processes from the Mesozoic age in the NW Andes of South America (Figure 3a). It is possible to appreciate that the gravimetric and magnetometric information based on the physical characteristics of the rocks in this area (Table 1), is well adjusted to the proposed geologic model.

TABLE 1. DENSITY AND MAGNETIC SUSCEPTIBILITY VALUES ASSIGNED TO THE ROCKS OF THE DIFFERENT GEOLOGICAL UNITS IN THE STUDY AREA.

Geological Formation	Lithology	Density (g/cm^3)	Magnetic susceptibility (emu)
1. Ibagué Batholith	Granodiorite rocks	2.65	0.00030
2. Cajamarca complex	Amphibolic green schists, graphitic schists, phyllites and marbles	2.75	0.00010
3. Barroso Formation	Basalts and tuffes	2.95	0.00250
4. Subduction complex (Arquía compex)	Serpentinites	3.00	0.00440
5. Subduction complex (Arquía compex)	Amphibolites	3.00	0.00011
6. Quebradagrande complex	Basalts and tuffes	2.90	0.00900
7. Oceanic paleo-plate	Peridotites	3.15	0.01000
8. Continental crust	Amphibolites	2.80	0.00550

In this scenario, the Cajamarca complex appears to be related with a synclinal structure limited by the Pericos and San Jerónimo faults, and immersed in a fractured continental crust. The structures associated to the paleo-subduction process have been transformed into wedges to form the Quebradagrande complex and the Barroso formation. Probably the lithologies and structures located between the San Jerónimo and Silvia-Pijao faults correspond to the limit area where an old subduction process happened. Indeed, the presence of serpentine belts evidences the exhumation in the area where the old oceanic plate associated to the Barroso formation penetrated. The seismic section (figures 3b and 3c) highlights the reflectors that define the wedge of the Quebradagrande complex to depths beyond 10 km. On the other hand, the distribution of aftershocks related to Armenia earthquake and reported by the Seismological Observatory of Quindío (OSQ) suggests that the rupture process for this earthquake could be associated to weak planes in the old subduction zone (Figure 4). Therefore, the Silvia – Pijao fault may play a relevant role for the seismotectonic regime in region. The rupture process in the area, however, could be related to the same mechanisms responsible for the presence of serpentinite rocks with weak planes developed along the fibrous structure and parallel to the Silvia Pijao Fault.

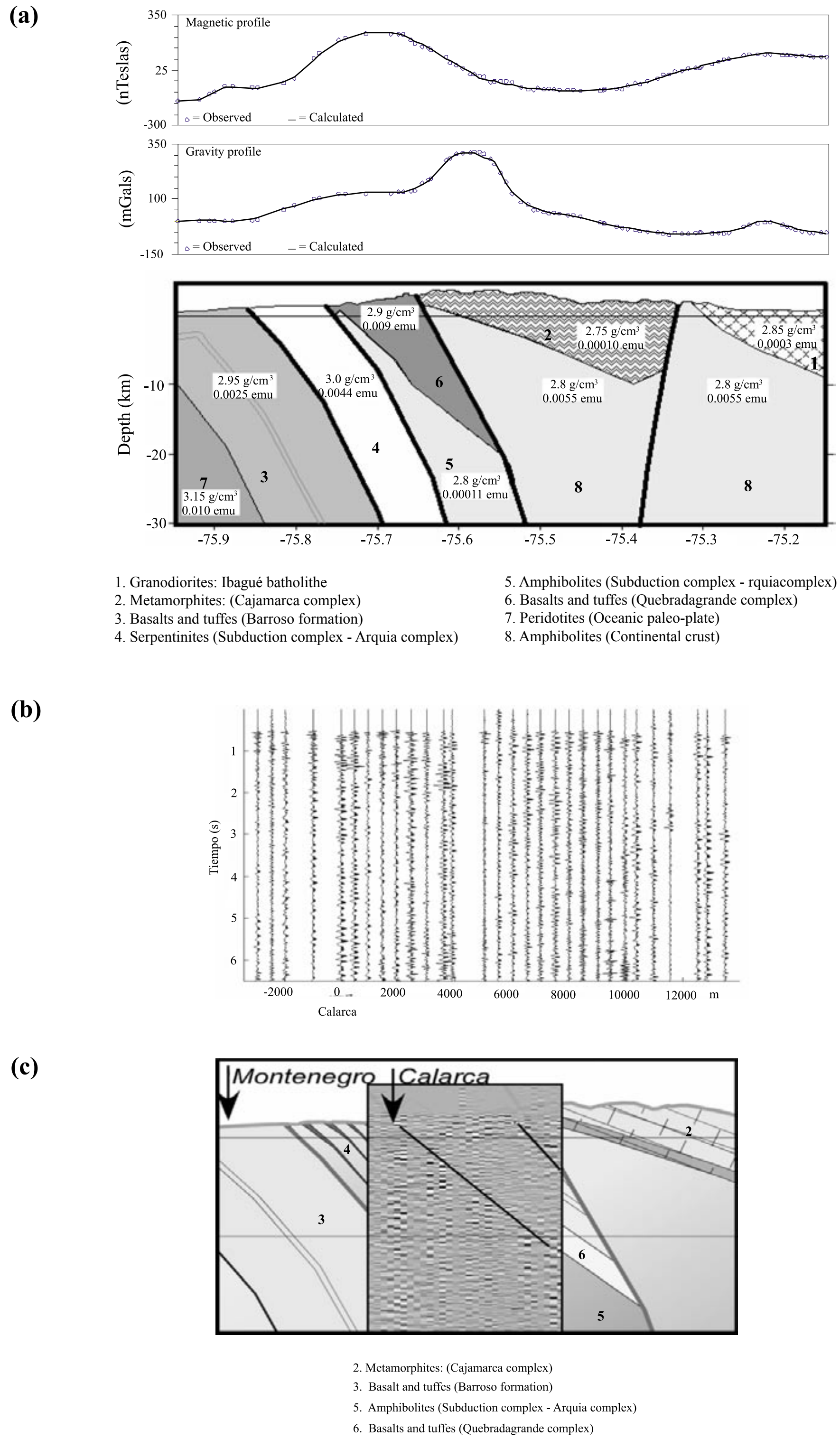

Figure 3. Geophysical interpretation of the Ibagué – Armenia section. (a) Density and magnetic susceptibility models. (b) Seismic profile processed with LMO. Distance in meters from Calarcá town. (c) Superposition of seismic profile onto geological model.

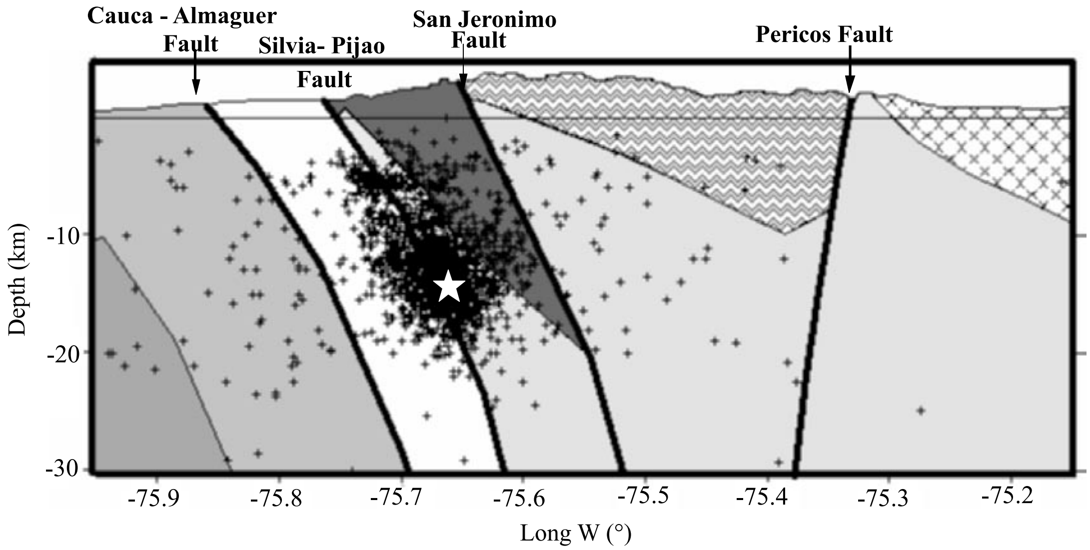

Figure 4. Aftershocks (crosses) of the Armenia earthquake (white star) superposed on the geologic section. The hypocentral solutions were reported by the OSQ.

Interpretation of the Geologic section Ibagué - Armenia

This section exposes in short distances lithologies of different tectonic blocks that became the basement of the Central Cordillera (from east to west). This basement is composed of a metamorphic complex of low pressure - temperature (P/T) conditions formed form rocks of the Cajamarca complex, and rocks of high P/T ratio associated to gneiss and amphibolites of Tierradentro (McCourt, 1984). Both complexes are separated by the Pericos fault. To the east of this fault the metamorphic basement of high P/T shows remnants of a Palaeozoic cover (Metasedimentary rocks of Santa Teresa). The Ibagué batholith intruded along this contact during a magmatic event during the Triassic – Jurassic limit. These two rocky units form a landscape characterized by a moderate relief and a dendritic drainage with a trend NW-SE (perpendicular to the direction of these units) that stands out.

The Cajamarca complex defines a wide synclinal near to the town of Cajamarca, in this place the rocks are heavily metamorphosed and folded. Our profile, however, does not have enough resolution to show the folds that are well documented in other works (Nelson, 1962; Restrepo-Pace, 1992). Near to the "La Línea" sector (Figure 1) this metamorphic sequence dips moderatelly toward east, defining a wide monoclinal (Figure 3a). In this place appears the "La Línea Gneiss", an intrusive body that constitutes a high to medium P/T ratio transition between basements.

The landscape conformed by the Cajamarca complex is dissected and is characterized by a rough topography. The drainage is segmented, with several families of alignments standing out. Again in this zone there are notable perpendicular (NW-SE) and parallel (SW-NE) alignments to the general direction. Other alignments show trends N-S and E-W.

As a very specific feature, this tectonic block is affected by an anomalously silicic volcanism that is best represented by Cerro Machín volcano. This volcano is formed for a complex of domes surrounded by thick sequences of piroclastic flow deposits. The crater has a diameter of 2.4 km and is occupied by dacitic domes with fumarolic activity (Cepeda et al., 1995; Cepeda and Cortés, 1999). This volcano shows an activity restricted to the Holocene (about 10.000 years) that is highly explosive of plinian type. The eruptions generated important piroclastic flows, which constitute continuous deposits in a diameter of 15 km from the volcanic amphitheater. Between the city of Ibagué and the high parts of the Toche, Amaine and Bermejón rivers seven piroclastic flows inserted in layers of ash whose ages vary among 45.000 to 800 years A.P. have been identified (Méndez, 2001).

Near to "La Línea", the San Jerónimo fault (also termed the Aranzazu-Manizales fault) is the limit between the metamorphic basement of the Central Cordillera and a tectonic complex that becomes a big flake roughly 5 km thick, composed of basaltic and piroclastic rocks of mid-Cretaceous age belonging to the Quebradagrande complex. These rocks are on the metamorphic basement (Cajamarca complex) and are characterized by a marked dipping toward east and by multiple fractures. The intense fragile deformation, the inclination of the beds and the marked topographical relief of the western flank of the Central Cordillera makes this unit susceptible to the erosion, rock falls and big landslides.

To the west of the Quebradagrande complex appears the Arquía complex, which constitutes the rock basement of the city of Armenia and the town of Calarcá. Because of the strong inclination toward the east, the Arquía complex belongs structurally to the Quebradagrande complex. It is composed of basement flakes with thickness of less than 2 km that are inserted with serpentines. The basement is composed predominantly of hornblendic schists. To the east the Quebradagrande complex is intruded by an elongated granodiorite body (the Córdoba stock). The contact of this body with the Quebradagrande complex is the Silvia-Pijao fault, with an area of deformation of several hundreds of meters wide.

In the western area, the rocky basement is composed by basaltic rocks of the Amaime formation that show a bigger flexion to the west of the Cauca-Almaguer fault and are dipping east. In the western foothill of Santa Bárbara range the rocks are affected by the Quebradanueva fault that folded a Paleogene sedimentary sequence called the "Cinta de Piedra" formation (McCourt et al., 1984). This sedimentary unit formed a barrier for the drainage that runs from the Central Cordillera and its existence explains how the volcanoclastic flows came from Machín and Tolima volcanoes and deposited its materials on the actual Quindío glacis.

"La Línea" structures

To the east of the San Jerónimo fault the rocks of the Central Cordillera are dipping consistently toward the east. The dip of the sedimentary rocks of Abejorral formation (González and Núñez, 1991) is affected by a set of normal faults that causes a sequence to be repeated (the "fault system effect"). Figure 5 shows these fringes east of the Campanario fault (a local name for the San Jerónimo fault).

The "fault system effect" is observed in a structural section some kilometres south from "La Linea" cutting the Cental Cordillera in a domino-like fashion (Figure 6). The spacing between faults varies between 1 to 2 km, and their continuity suggests a cut toward "La Línea tunnel". The "La Linea" tunnel promises to be the most important civil work to improve the transportation system in the central region of Colombia, thus considerations about the fault system are relevant. By extrapolating these faults as far as the Bermejón river valley makes evident that at least four (five?) of these faults are cutting the route planned for this important ground transportation structure (Figure 7).

The prolongation of the geologic profile 15 kilometers west from our lithologic, structural, and geophysical observations, suggests that the Cauca-Almaguer fault could be the structure that facilitated the elastic energy dissipation related to the flexion process of the oceanic paleo-plate that was originally subducted (Figure 8). It is possible that the continental rocks of Tertiary age ("Cinta de Piedra" formation) allowed the deposition of sedimentary basins with N-S orientation that are visible today along the fault.

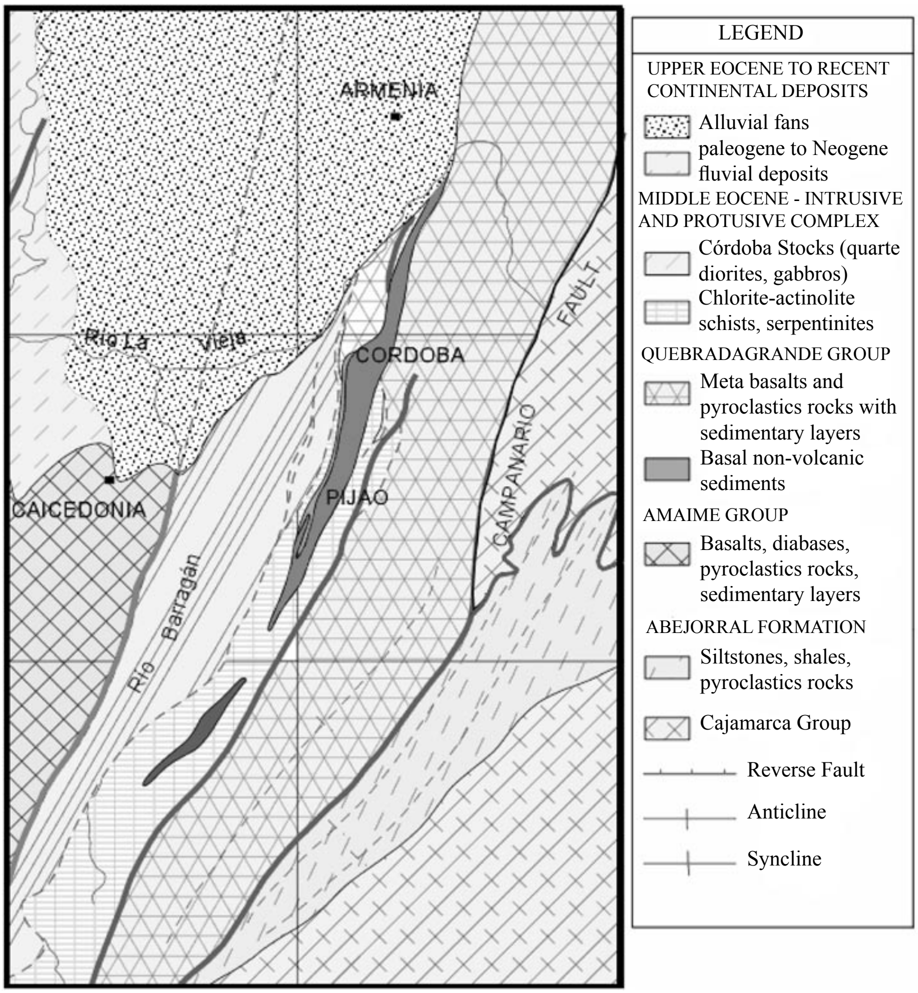

Figure 5. Geologic map of the region south of Armenia city.

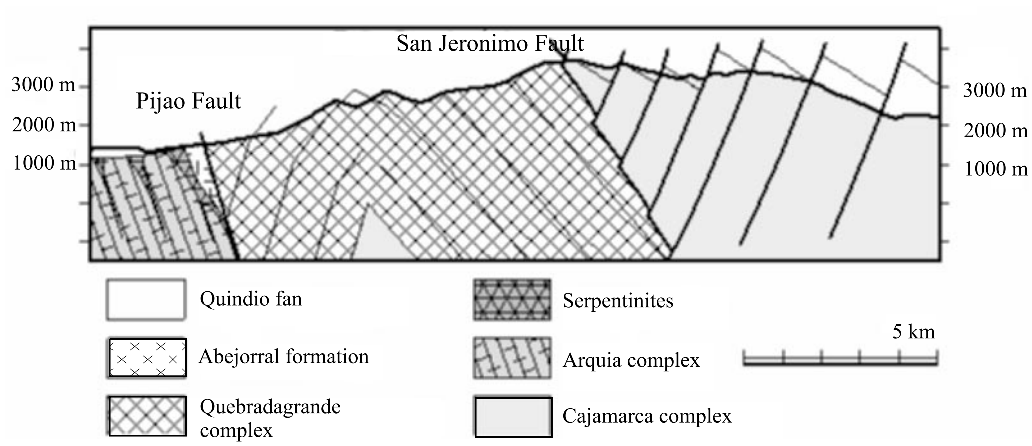

Figure 6. Geologic section at south of the town of Calarcá, where it is possible to see a set of antitetic faults that cut the Central Cordillera.

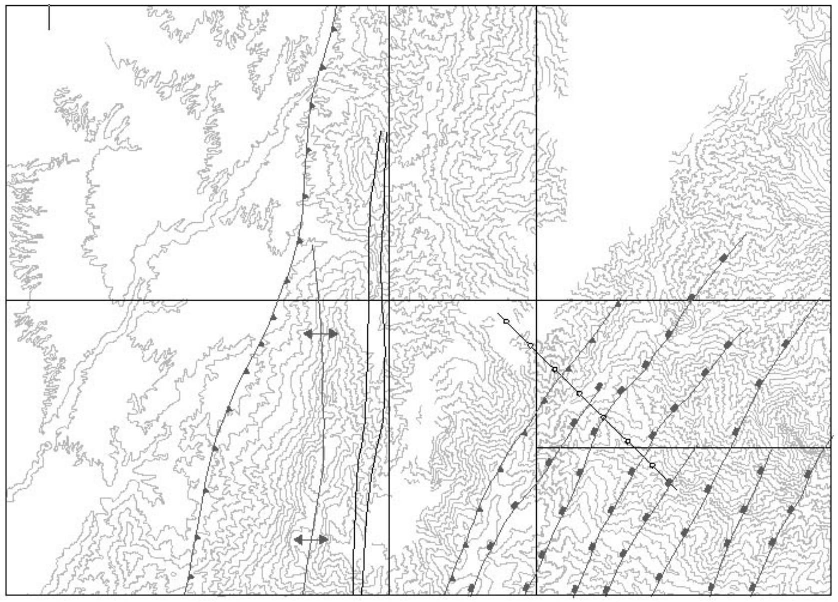

Figure 7. Topographic map of the region near "La Línea" tunnel (line with open circles). At least four (five?)normal faults are cutting the route designed for this transport structure.

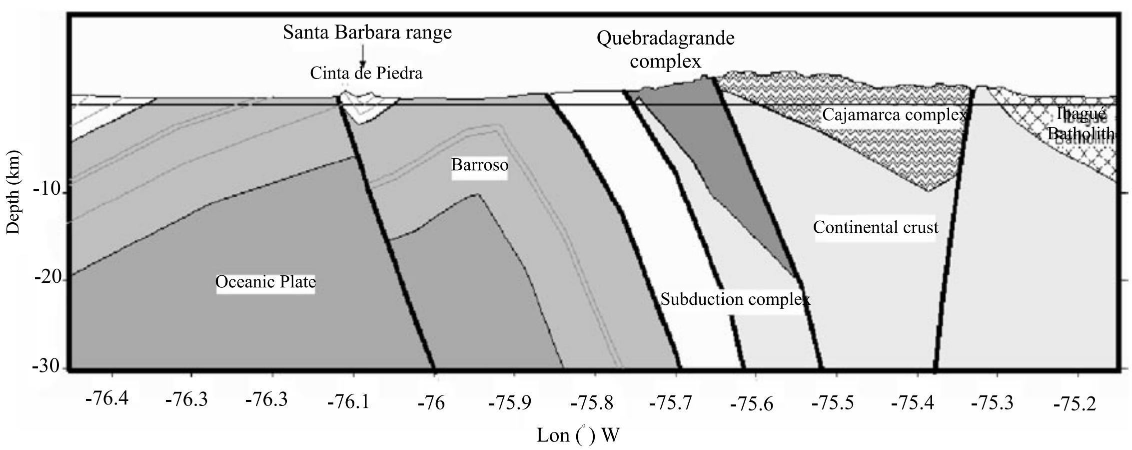

Figure 8. Geologic section (interpreted and extended) west of the study area.

CONCLUSION

Geologic and geophysical data used in this study suggest that the Cajamarca complex defines a wide synclinal near the town of Cajamarca. Its structural configuration allows the assemblage to the west of a basement composed by wedges of basaltic and sedimentary rocks of the Quebradagrande and Arquía formations. New structural evidence supported by gravimetric, magnetrometric and seismic data suggests the existence of a bigger flexion of the Barroso formation west of the Cauca-Almaguer fault which is dipping to the east. The flexion could be a factor for the deposition and folding of the “Cinta de Piedra” formation in the “Santa Bárbara” range. This sedimentary unit formed a barrier for the drainages that run from the Central Cordillera and its existence explain how the volcanoclastic flows came down from Machín and Tolima volcanoes and deposited their materials on the recent Quindío glacis.

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